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NNN08, International Workshop on Next Nucleon Decay and Neutrino Detectors, Paris, September 11–13, 2008

Current Understanding of Core-Collapse Supernovae and Neutrino Emission

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Contents

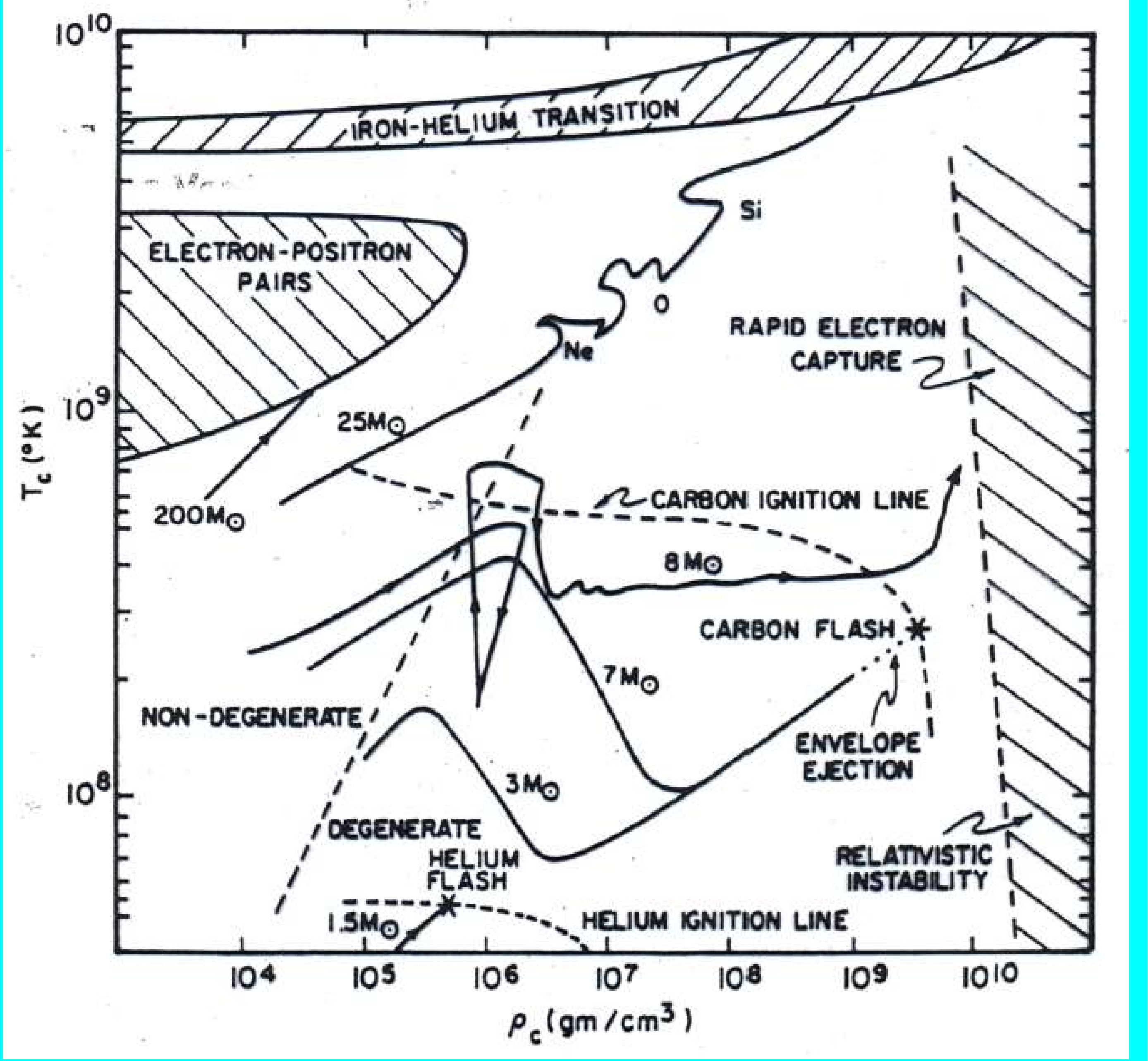
- Types of core-collapse supernovae & neutrino signal characteristics
- Supernovae and explosion mechanism
- Neutrino signals from supernova models
- Conclusions

Final Stages of Massive Star Evolution

Massive stars with ~8–10 M_{sun} develop degenerate ONeMg cores
—> collapse by e-capture

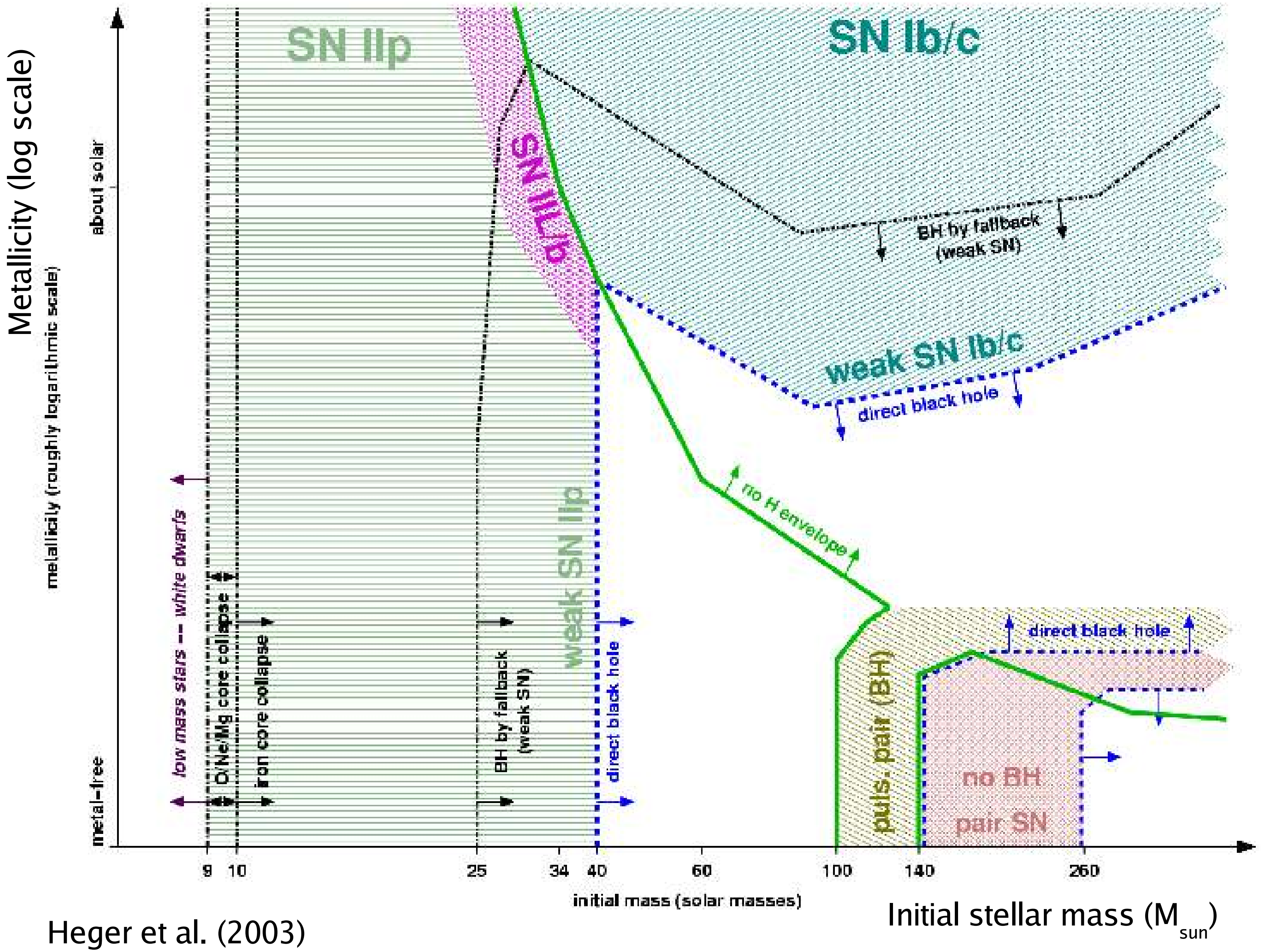
Massive stars with ~10–100 M_{sun} develop Fe cores
—> collapse by nuclear photodisintegration

Massive stars with > 100 M_{sun} do not develop Fe cores
—> collapse by pair-instability



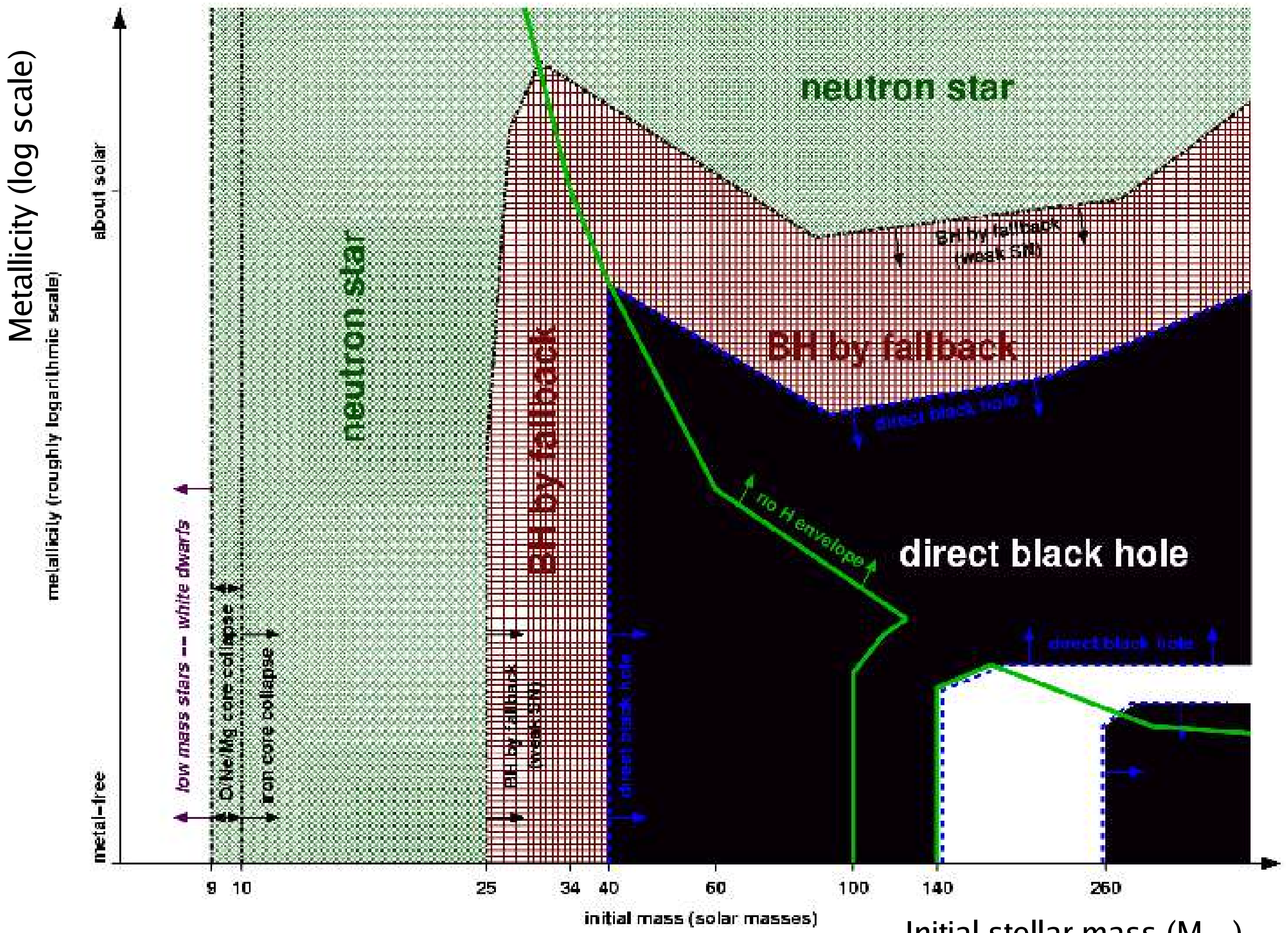
(Wheeler et al. 1990)

Core Collapse Events and Remnants



Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

Stellar Core Collapse and Neutrinos

The collapsing stellar core and forming & accreting neutron star (NS) or black hole (BH) radiate neutrinos:

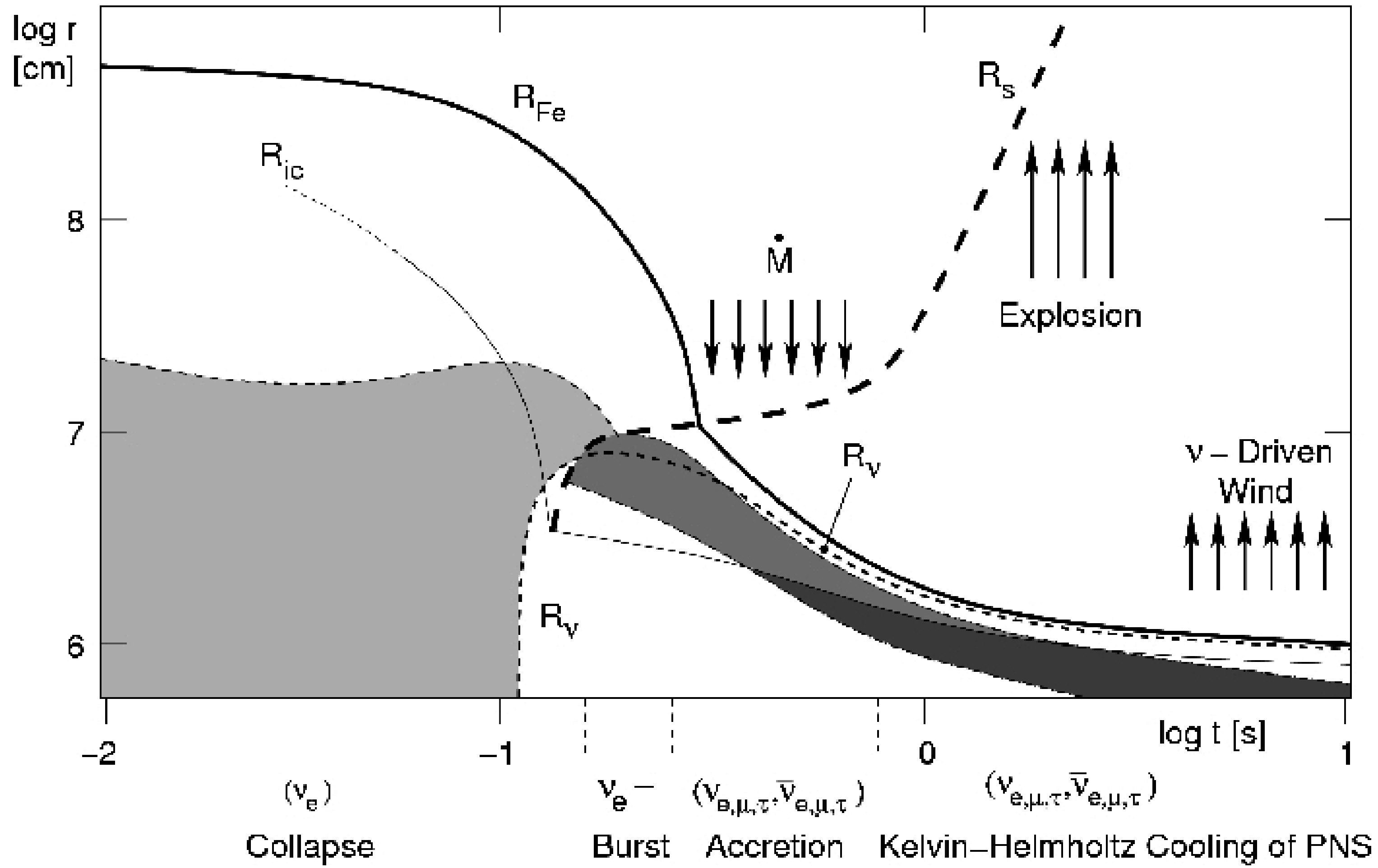
$E_\nu \sim 3\mathrm{x}10^{53}$ erg $(M_{ns}/M_{sun})^2/R_{ns}$ for NS

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

in the case of rotation: $\xi \sim 0.05-0.42$

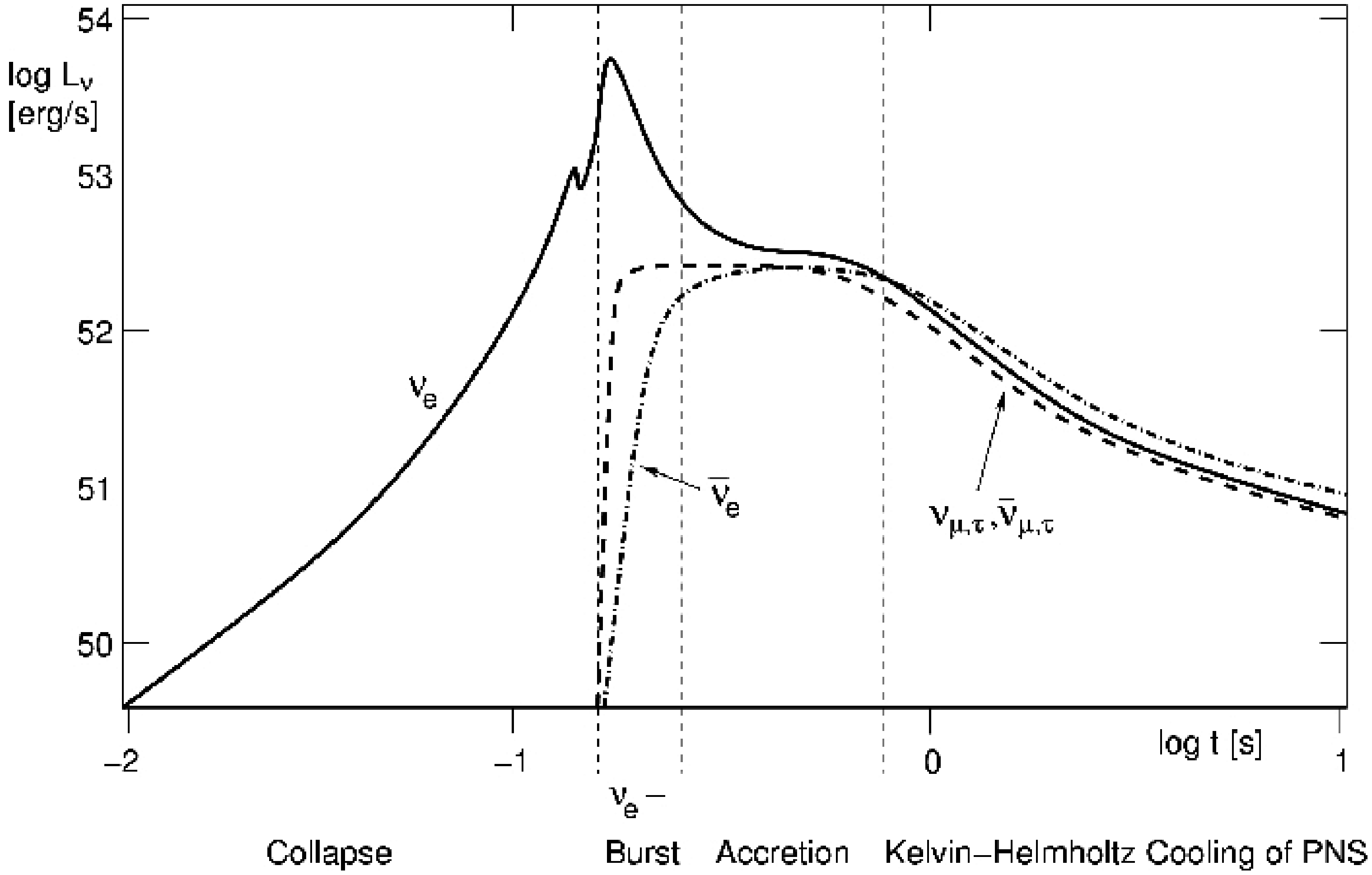
otherwise: $\xi \sim 0$

SN Evolution Phases (schematic)



Neutrino Luminosities (schematic)

Neutrino signal for 3 active flavors, without neutrino oscillations



Neutrino Signals and Astrophysics

Important questions:

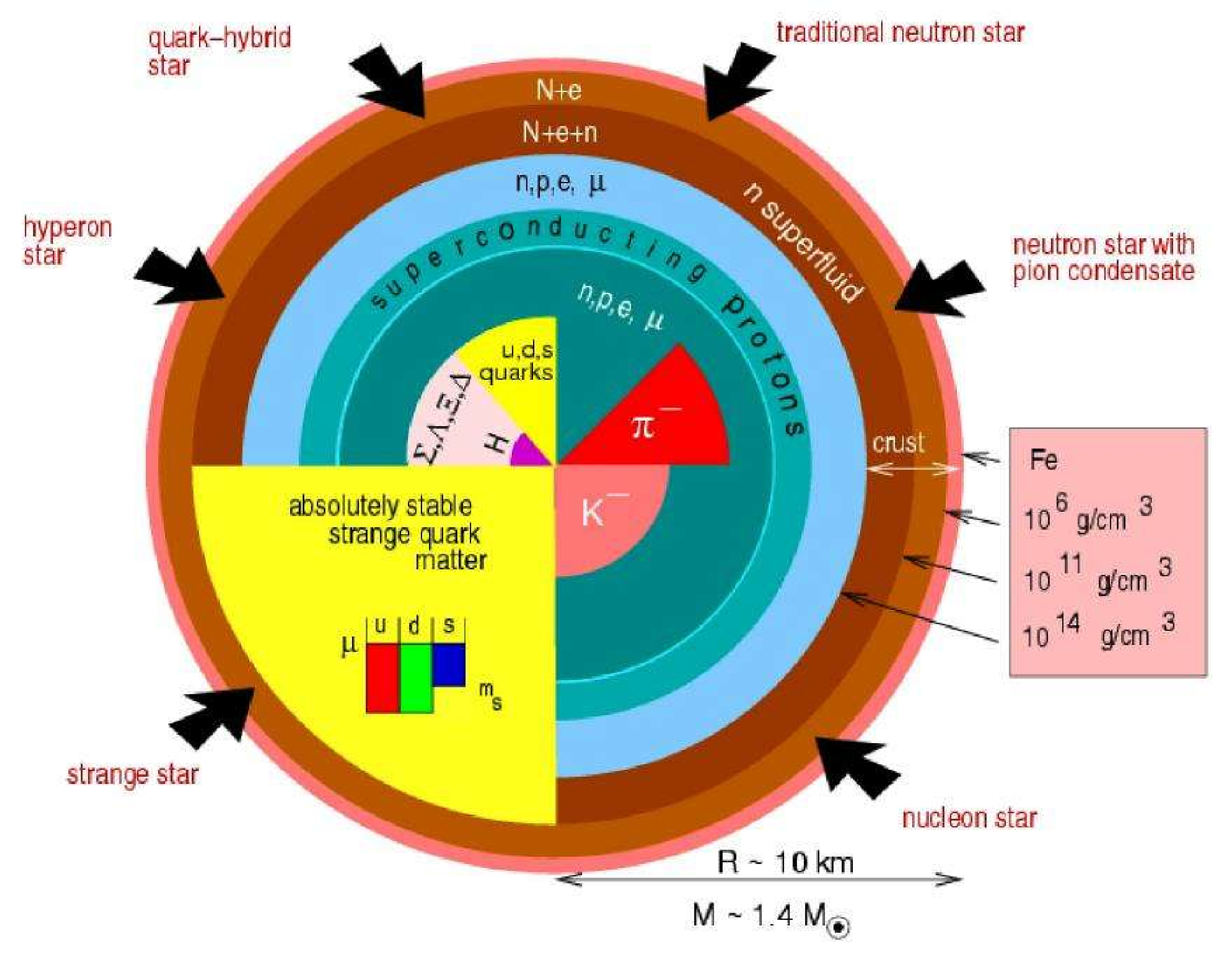
- Supernova explosion dynamics
- BH formation?
- Properties of hot NS matter (nuclear equation of state)

Relevant signal characteristics:

- Duration
- Total energy
- Mean neutrino energies
- Time structure
- Flavor distribution

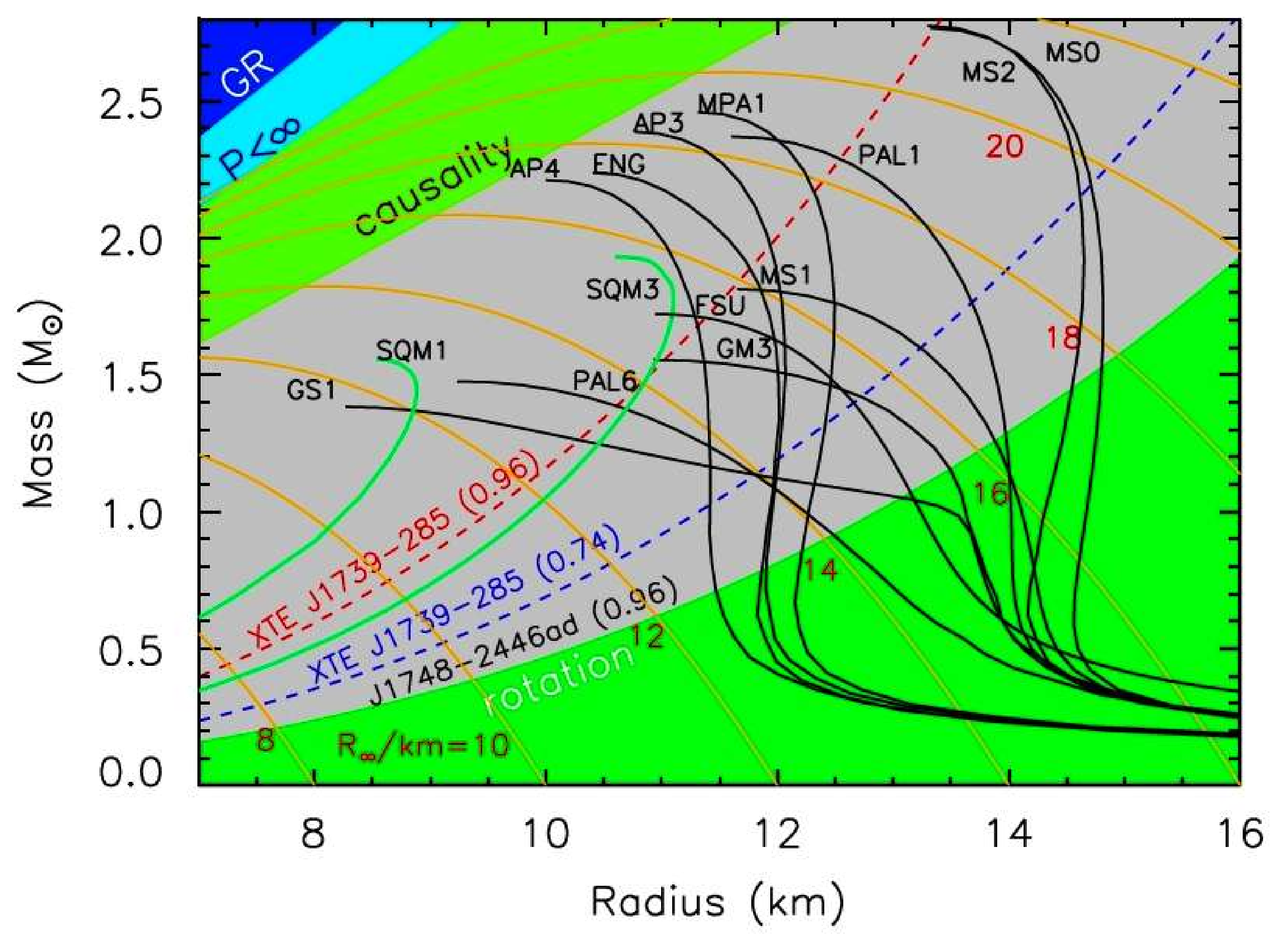
Neutron Star Equations of State

Neutron star EoS is crucial ingredient but highly uncertain!



(Source: F. Weber)

Neutron Star Equations of State



- Collapse and bounce show dependences on the EoS properties below and around nuclear saturation density ρ_0
- SN explosion and protoneutron star cooling are sensitive to the high-density EoS above ρ_0 through the compactness of the proto-neutron star
- Neutrino signal contains information about the nuclear EoS!

Lattimer & Prakash, Phys. Rep. 442 (2007)

Neutrino Reactions in Supernovae

Neutrino rates:

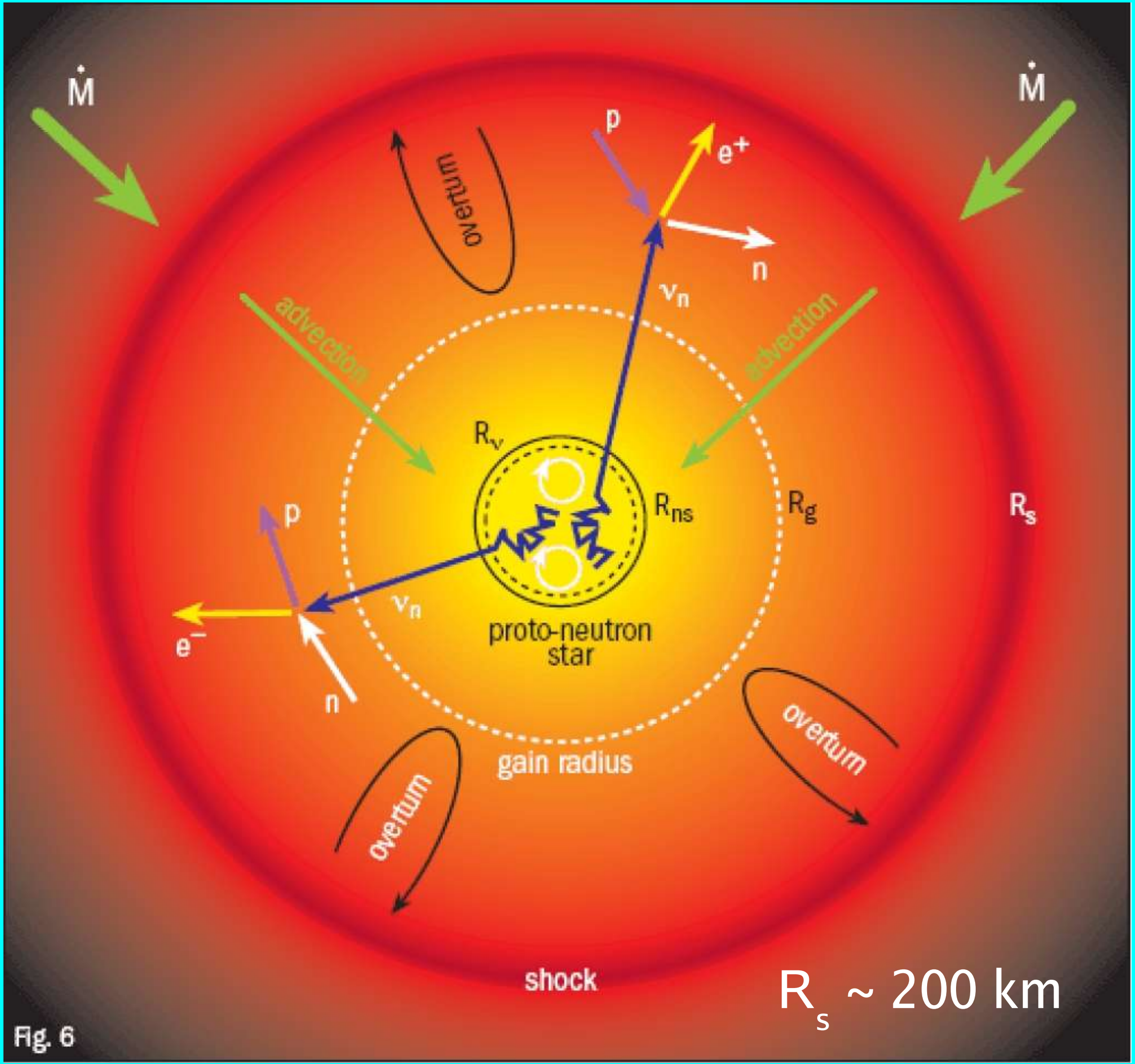
- Rate treatment mostly based on Bruenn (1985), Bruenn & Mezzacappa (1993a,b, 1997)
- Neutrino-nucleon interactions include recoil, fermion blocking, correlations, weak magnetism, effective nucleon mass (Burrows & Sawyer 1998, 1999)
- Nucleon-nucleon bremsstrahlung (Hannestad & Raffelt 1998)
- Neutrino-neutrino interactions (Buras et al. 2002)
- Electron capture on nuclei for >300 nuclei in NSE (A= 45–112), FFN+LMP+hybrid rates, SMMC calculations (Langanke et al., PRL 2003)
- Inelastic neutrino-nuclei scatterings (Langanke et al., PRL, subm., 2007)

- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$
- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

What Causes the Explosion?

Neutrinos &Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism

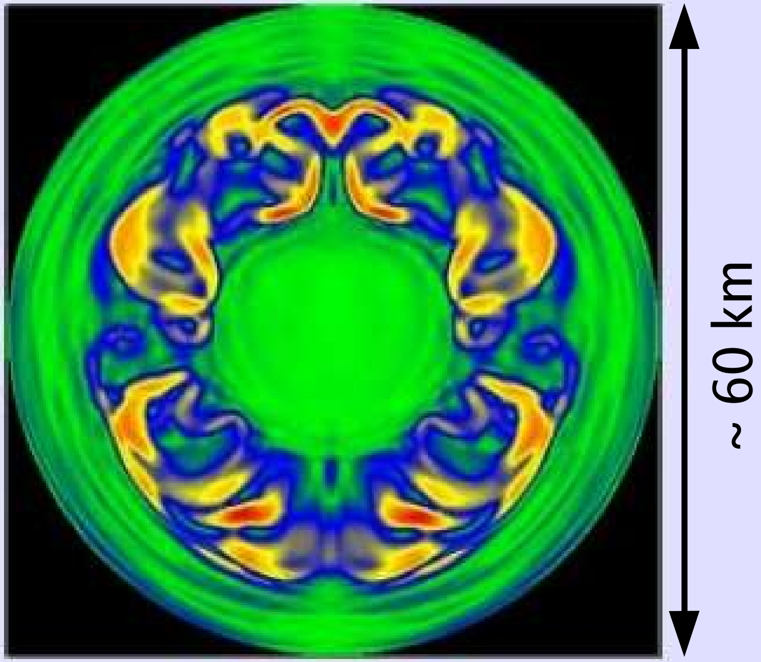


R_s ~ 200 km

Fig. 6

- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities play an important role (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996).

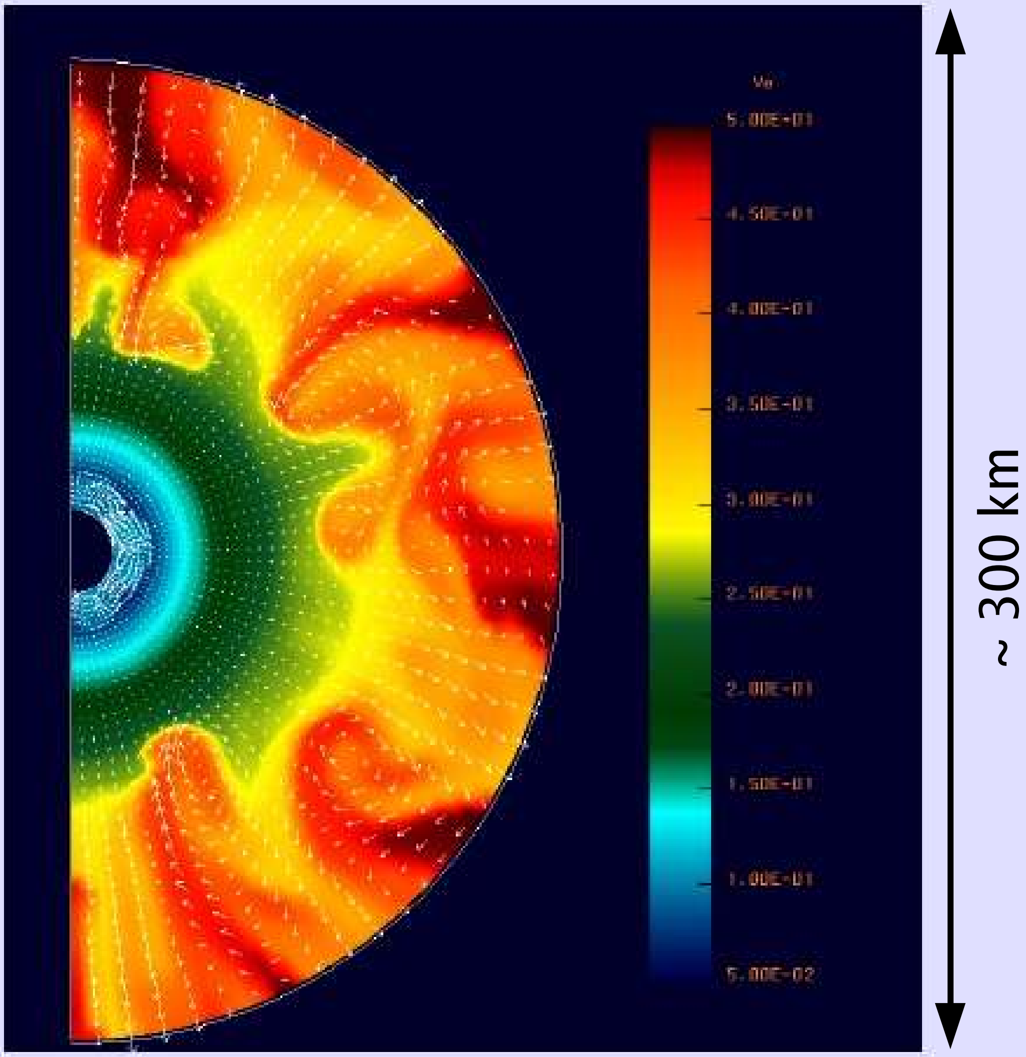
Core collapse supernovae need multidimensional modeling !



~ 60 km

Ledoux convection inside proto-neutron star due to negative lepton and entropy gradients (Keil, Janka & Müller '96)

- asymmetric ν-emission (few sec) and flow (~100 sec?)



~ 300 km

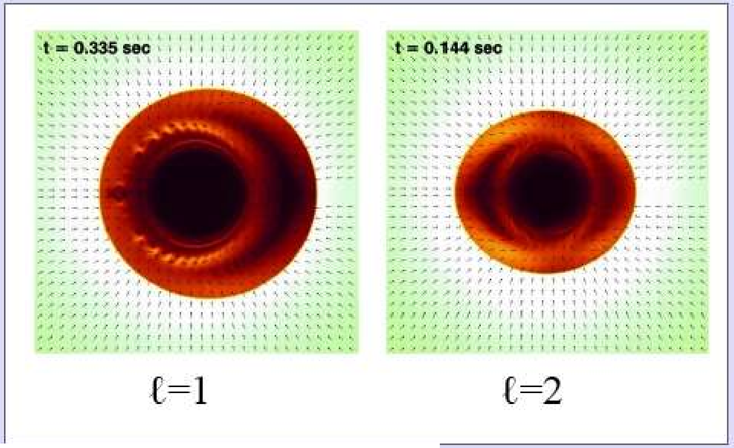
Convection in the surface layers of the proto-neutron star and in the hot bubble 78 msec after core bounce (Janka & Müller '96)

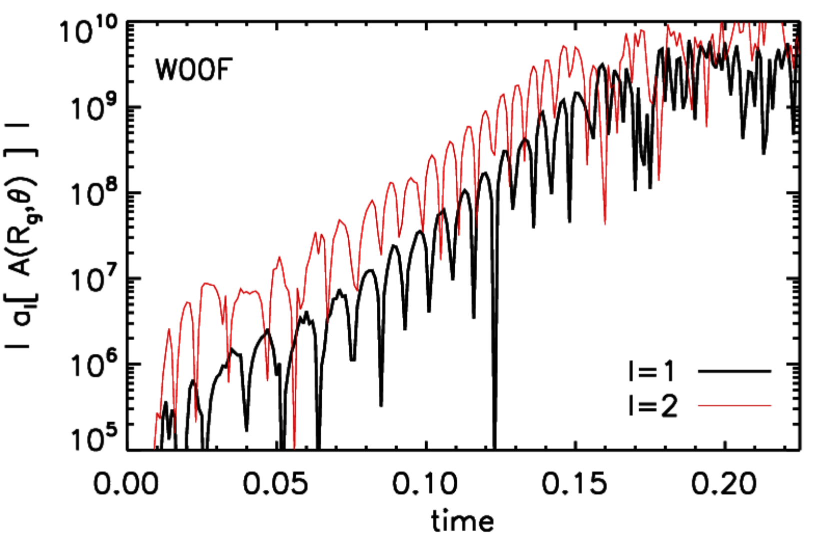
Movie NS convection

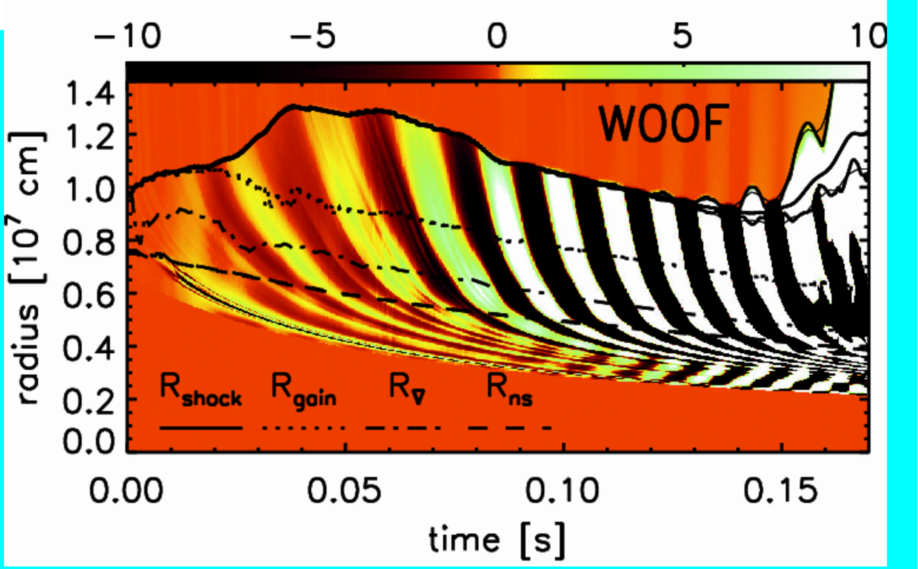
SASI in SN Cores

"Standing Accretion Shock Instability" (Blondin et al. 2003)

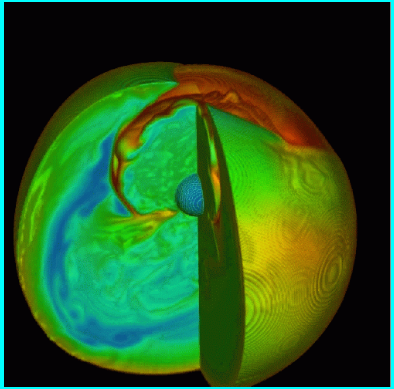
- SASI and convection are two different hydrodynamic instabilities
- SASI occurs even when convection is suppressed or weak
- SASI grows in oscillatory way
- SASI l=1, 2 modes grow fastest
  ====> global asymmetry
- SASI is caused by an "advective-acoustic feedback cycle" (Foglizzo & Galletti 2005, Scheck et al. 2007)
- SASI properties analysed analytically and numerically
  (see works by Blondin et al. 2003, Scheck et al. 2004, Blondin & Mezzacappa 2006, Foglizzo & Galletti 2005, Ohnishi et al. 2005, Yamada & Yamasaki 2006, Foglizzo et al. 2007, Burrows et al. 2006)
- SASI seen in 2D as well as 3D simulations
  (Blondin & Mezzacappa 2006)







Scheck et al., A&A (2007)



Blondin & Mezzacappa (2006)

Recent Results of Simulations

SN Progenitors: Core density profiles

~8–10 M_{sun} (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface

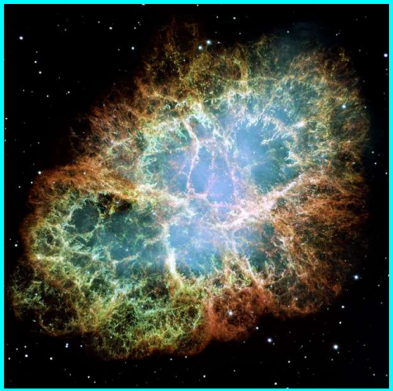
(====> rapidly decreasing mass accretion rate after core bounce)

>10 M_{sun} stars have much higher densities outside of their Fe cores

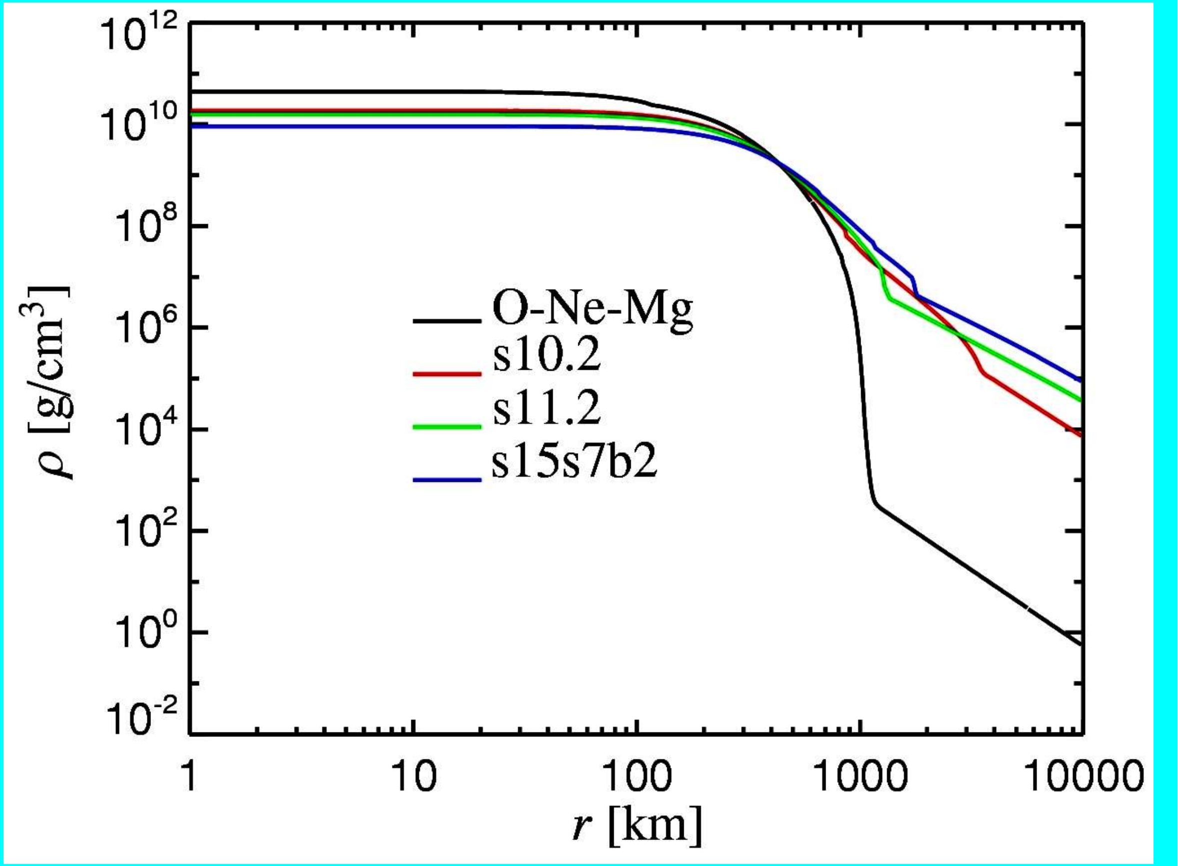
(e.g. Heger et al., Limongi et al., Nomoto et al., Hirschi et al.)

~30% of all SNe (Nomoto et al. 1981, 84, 87)

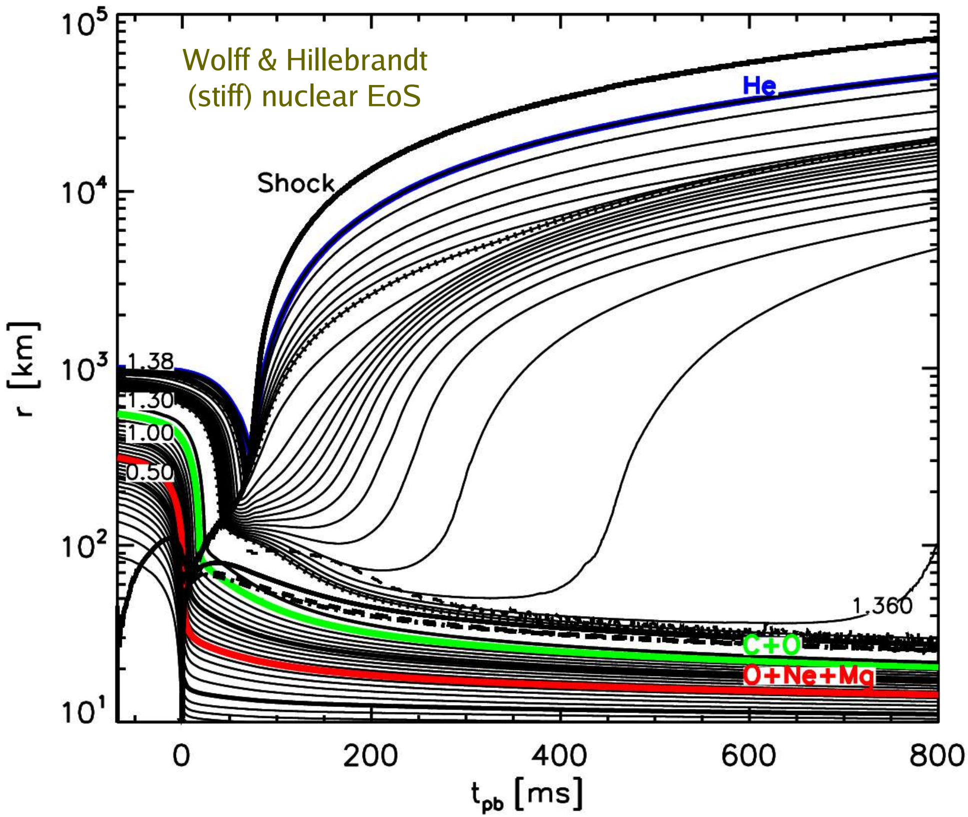
(8.75 M_{sun} < M_{ZAMS} < 9.25 M_{sun}: < 20% of all SNe; Poelarends et al., arXiv:0705.4643)



SN models and ejecta composition are consistent with CRAB



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

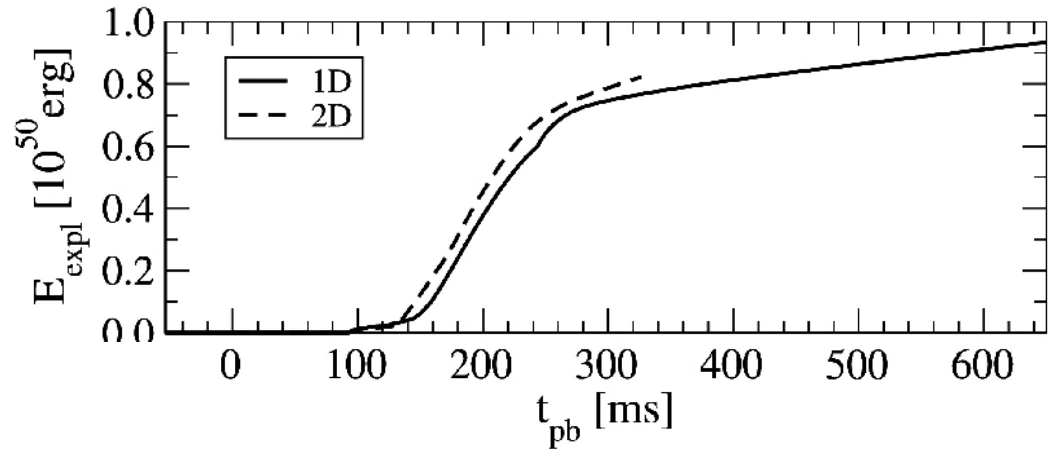


"Electron capture supernovae" or
"ONeMg core supernovae"

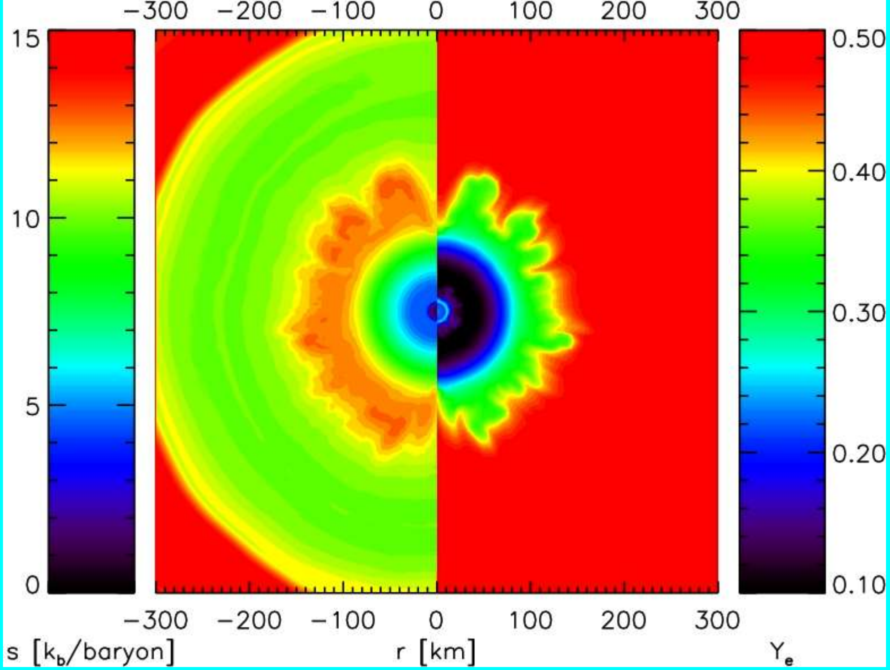
- No prompt explosion
- Mass ejection by neutrino-driven wind
  (like Mayle & Wilson 1988
  and similar to AIC of WDs; see
  Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Convection is not essential for explosion but increases the explosion energy and causes anisotropies

Kitaura et al., A&A 450 (2006) 345

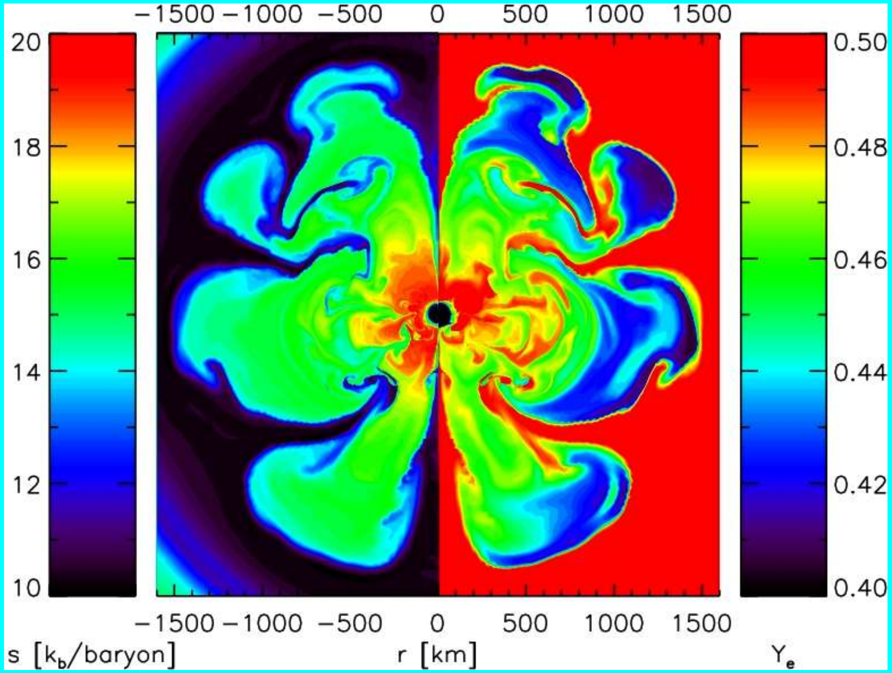
$8.8\ M_{sun}$ progenitor model
(Nomoto 1984):
$2.2\ M_{sun}$ H+He,
$1.38\ M_{sun}$ C+O,
$1.28\ M_{sun}$ ONeMg



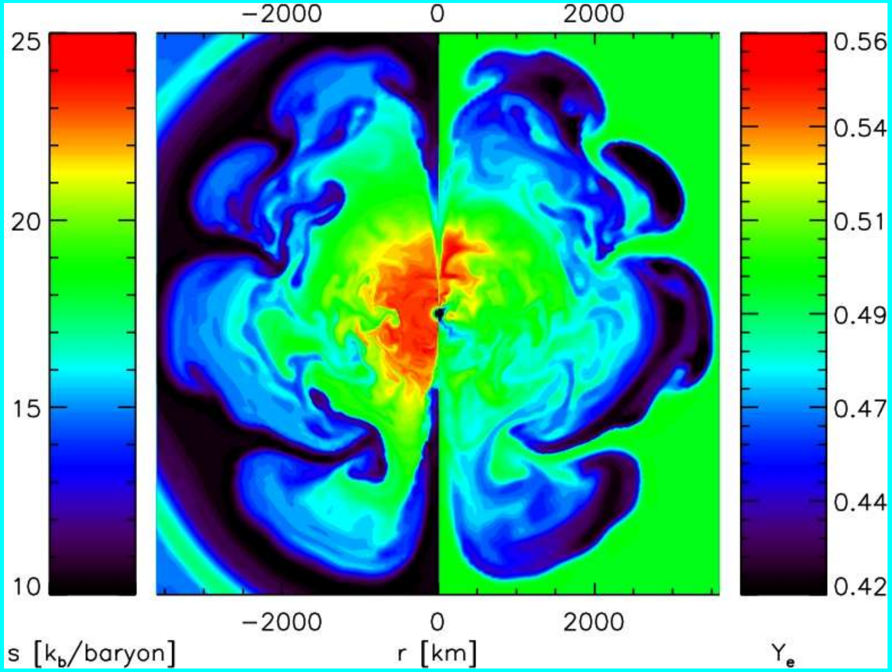
Müller et al. (in preparation)



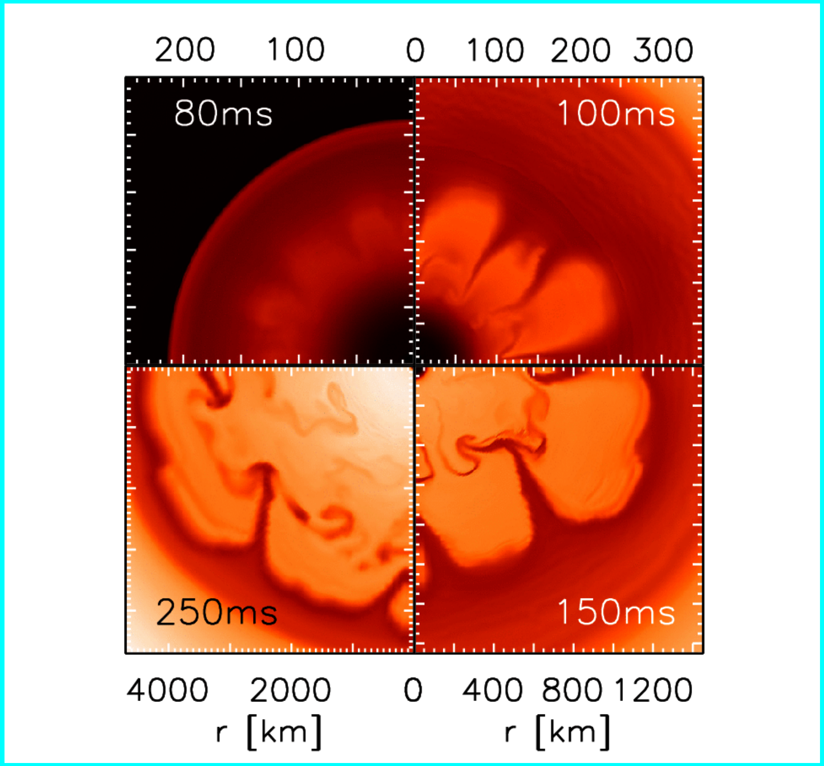
t = 0.097 s after core bounce



t = 0.144 s after core bounce



t = 0.262 s after core bounce

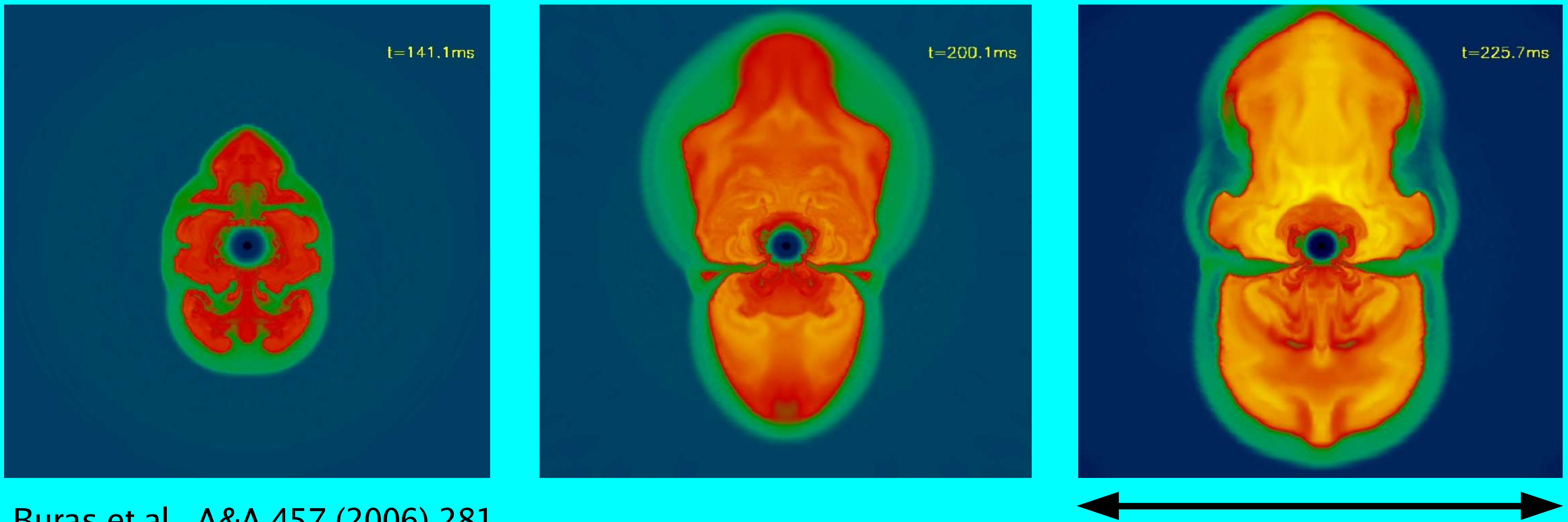


2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

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

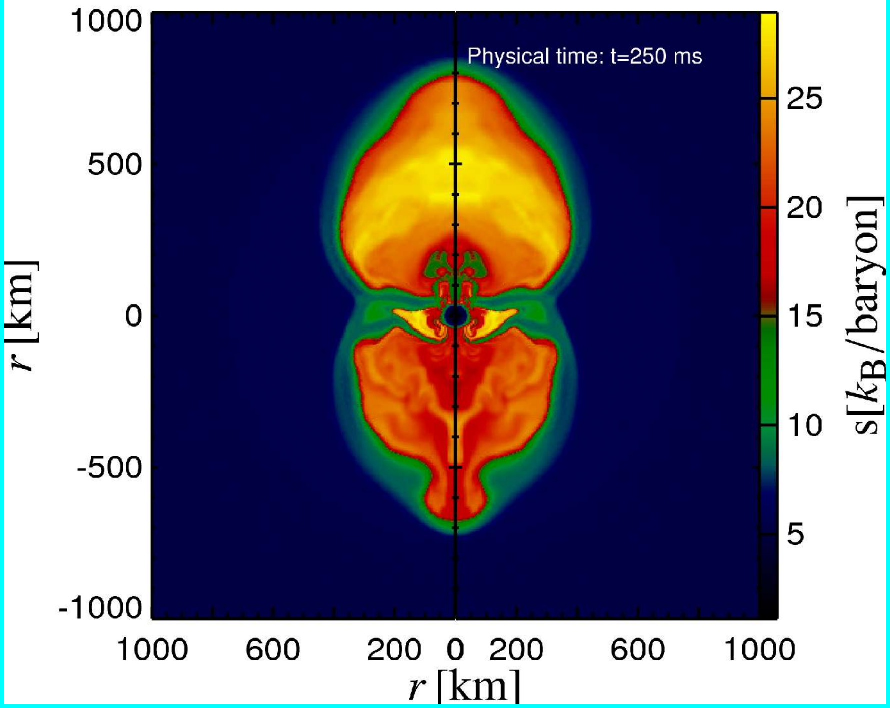
===> this improves conditions for strong neutrino heating and thus initiates a globally aspherical explosion by neutrino heating even without rotation


t = 0.141 s after core bounce

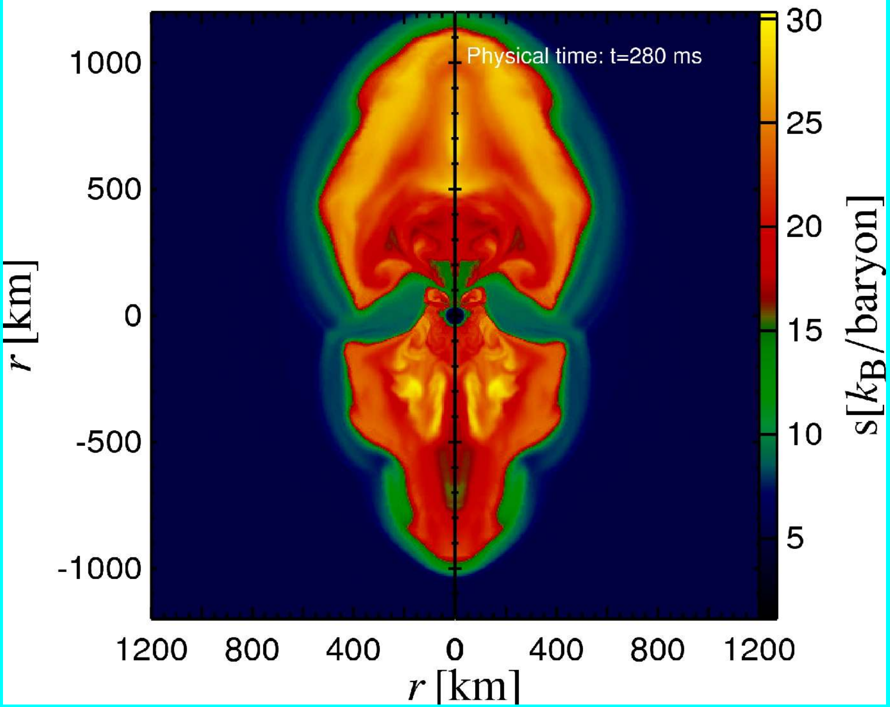
t = 0.200 s after core bounce

t = 0.226 s after core bounce

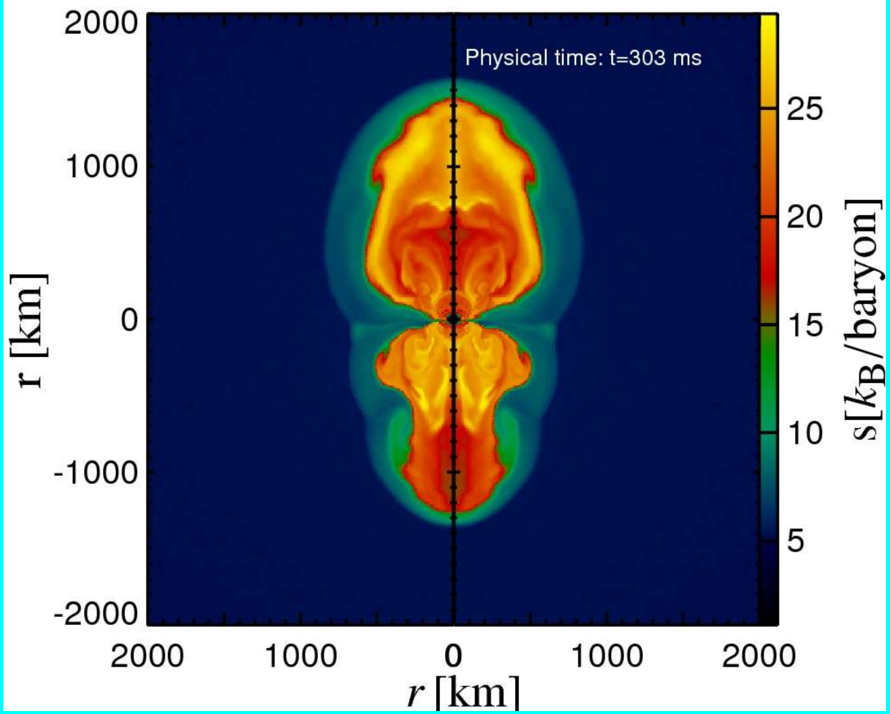
Buras et al., A&A 457 (2006) 281



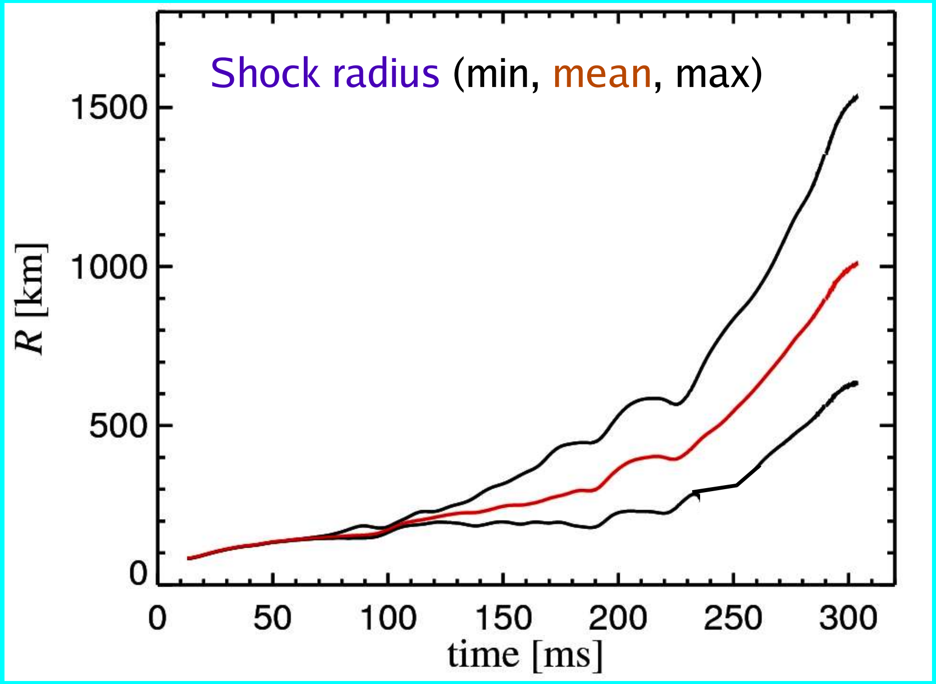
t = 0.250 s after core bounce



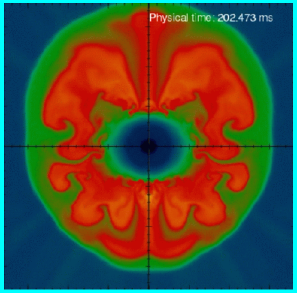
t = 0.280 s after core bounce



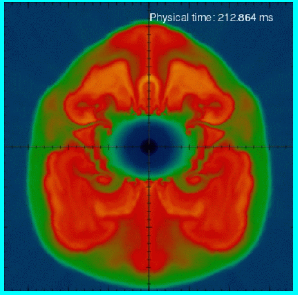
t = 0.303 s after core bounce



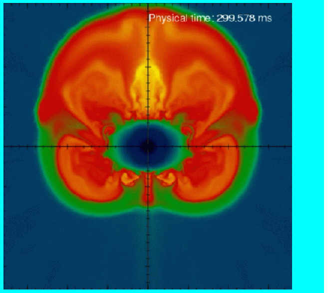
2D SN Simulations: $M_{star} = 15\,M_{sun}$



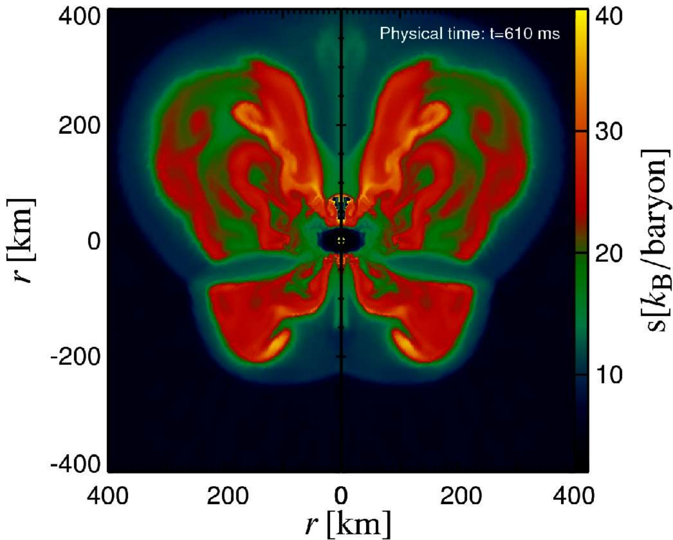
t = 0.202 s p.b.



t = 0.213 s p.b.



t = 0.300 s p.b.

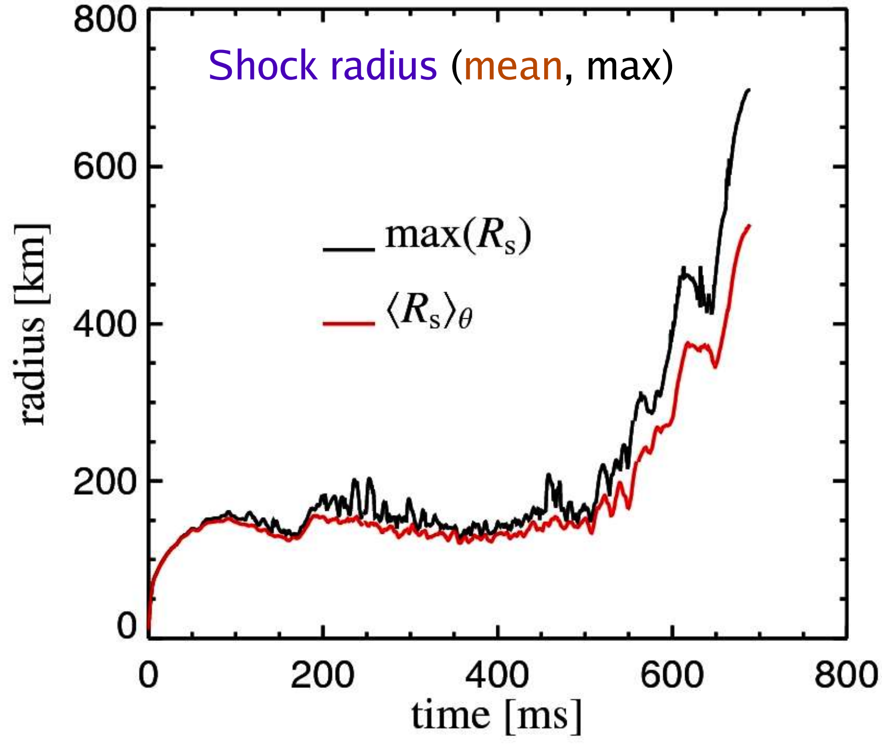


$15\,M_{sun}$ star
(Woosley model s15s7b2)

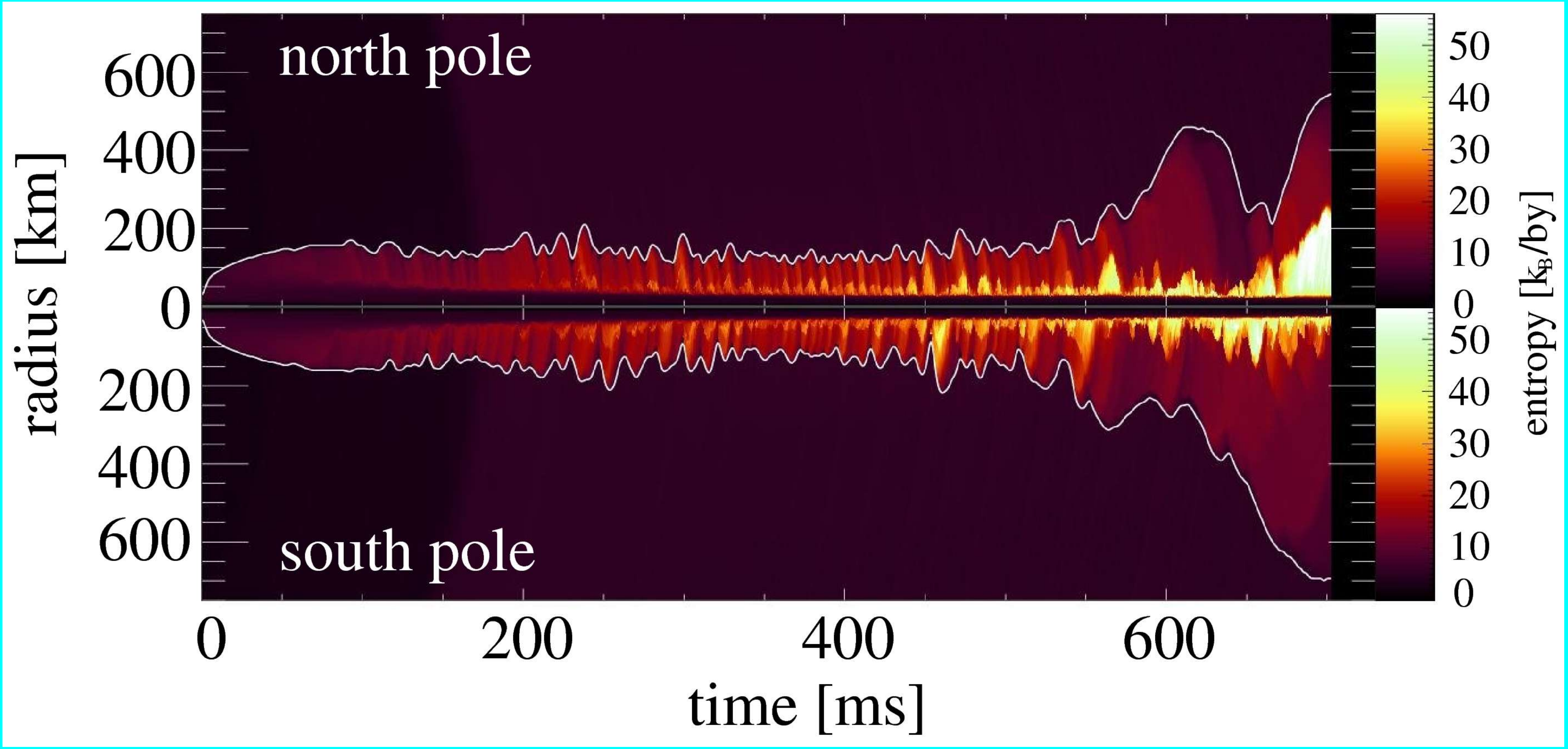
t = 0.610 s p.b.

Violent SASI oscillations, ν-driven explosion sets in at t ~ 600 ms p.b.

(Marek, PhD Thesis 2007;
Marek & THJ, arXiv:0708.3372)



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



Marek & THJ, arXiv:0708.3372

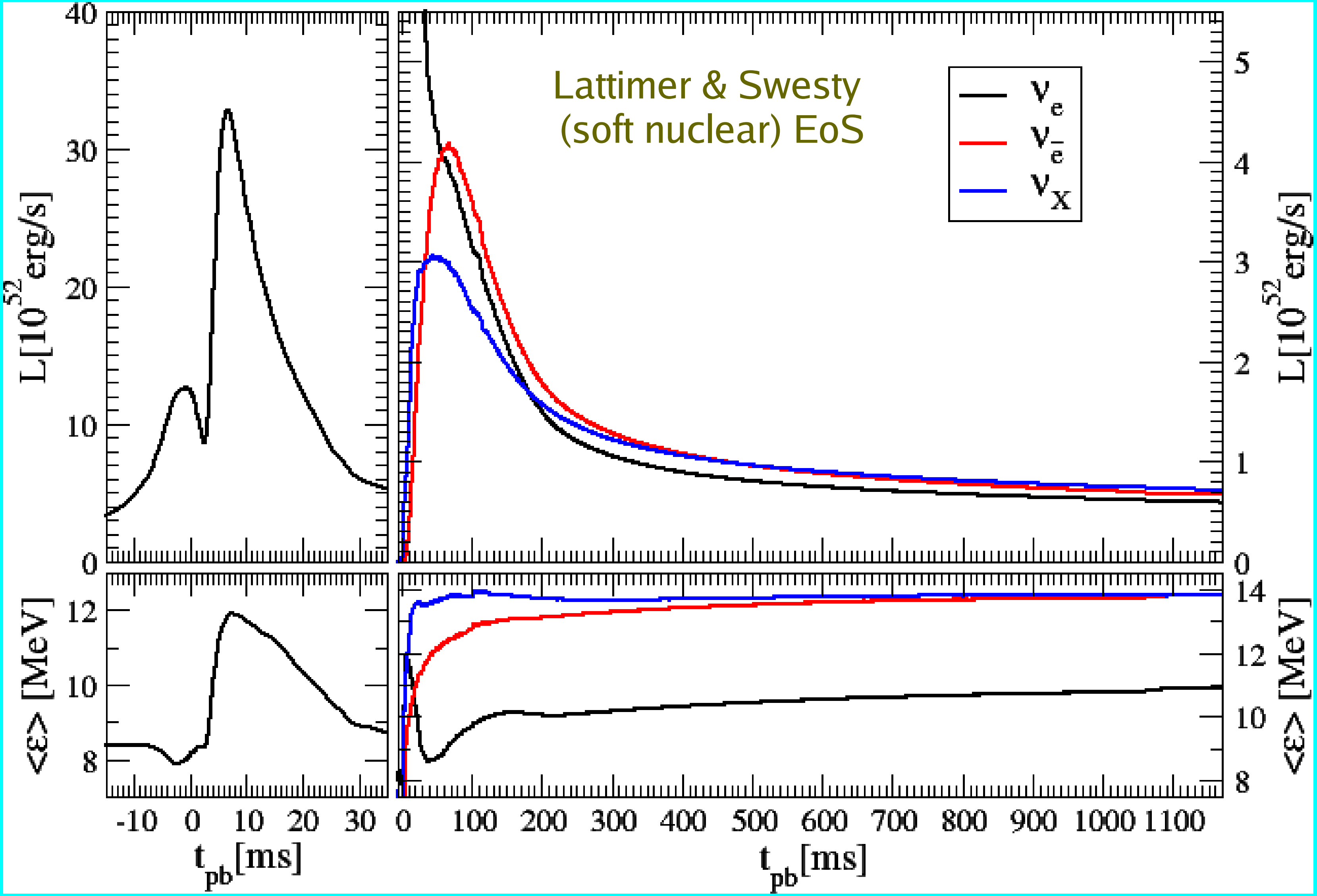
Consequences and Implications of Stellar Explosions

- Neutron star kicks
- Asymmetric mass ejection
- Neutrino signals
- Gravitational wave signals
- Heavy element production
- Gamma-ray bursts

Neutrino Signals

Neutrinos from 8...10 M_{sun} Explosions

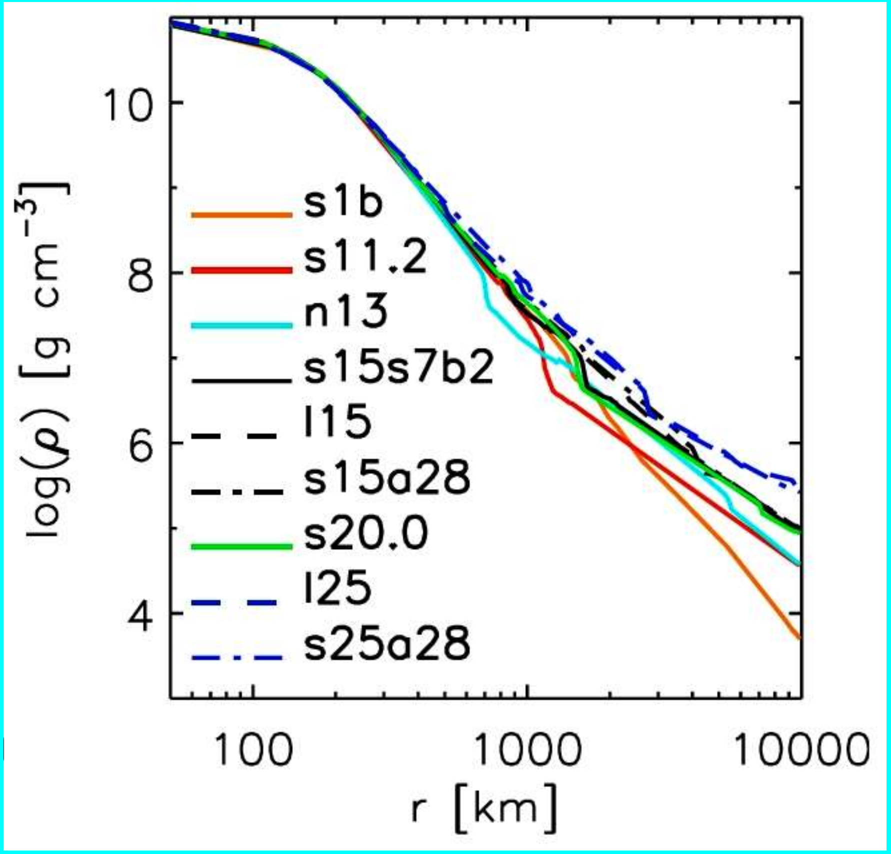
Neutrino luminosities and mean energies

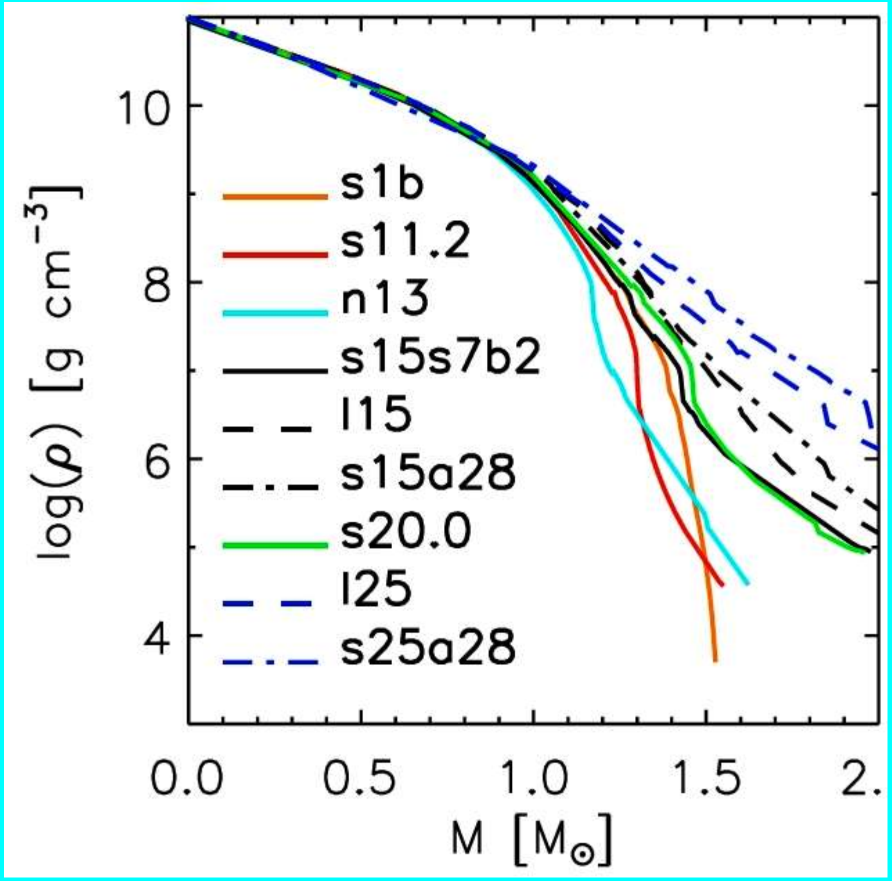


Müller et al. (in preparation)

Neutrinos from $M_{star} > 10\ M_{sun}$ Explosions

Neutrino luminosities are probe for density structure of SN progenitor star



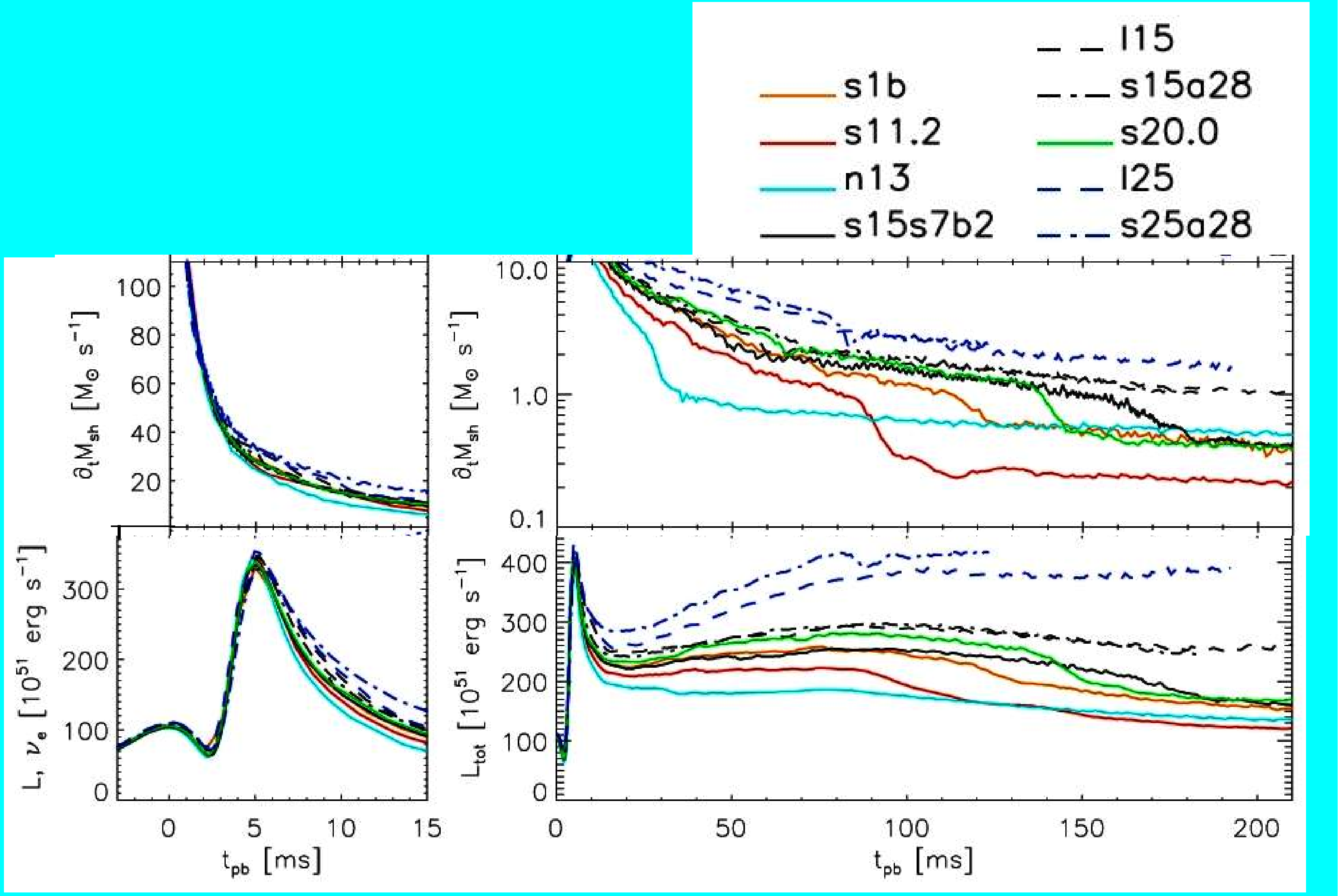


Buras et al., A&A 457 (2006) 281

Neutrinos from $M_{star} > 10\ M_{sun}$ Explosions

Neutrino luminosities as function of SN progenitor star

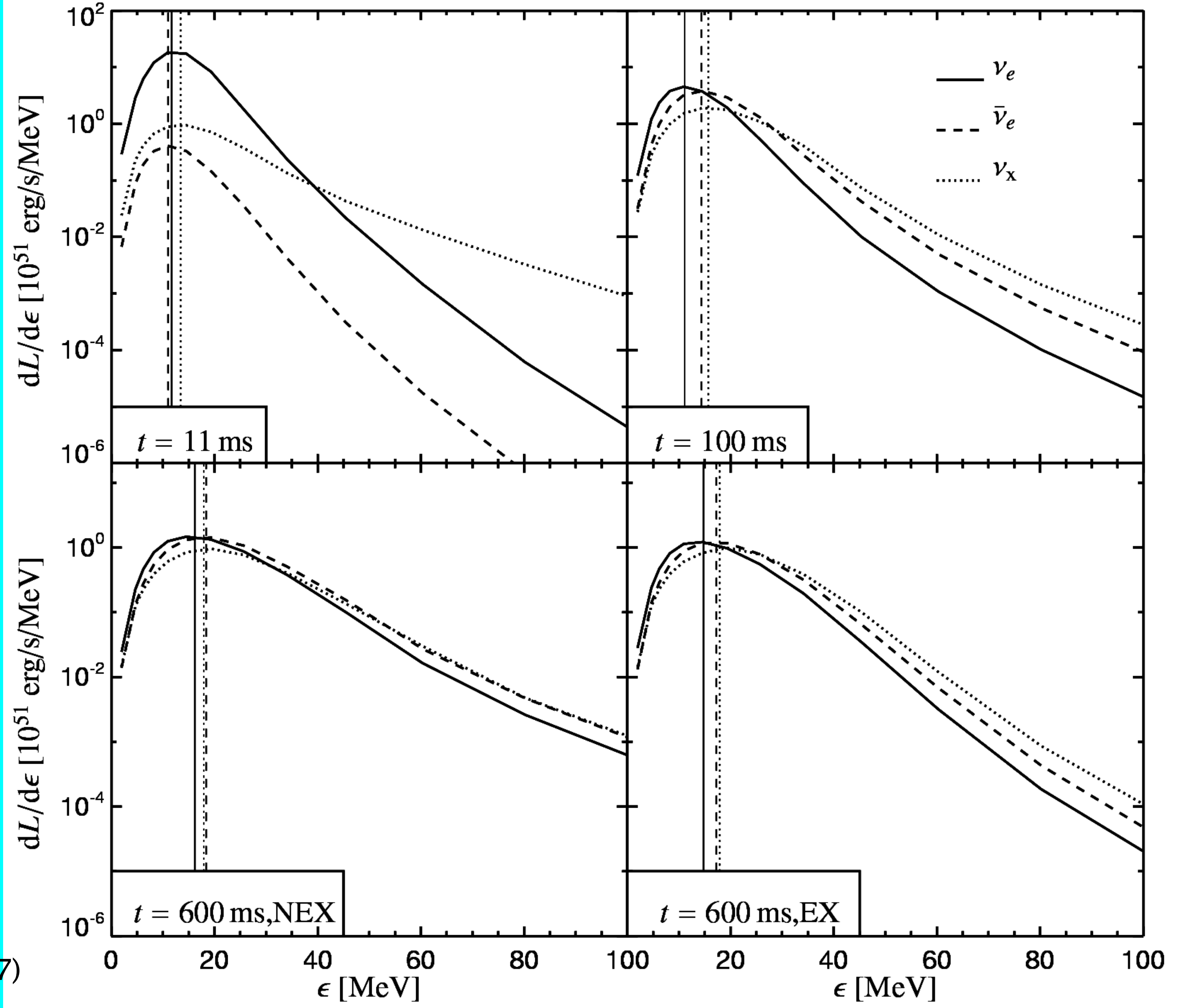
- Shock-breakout burst of ν_e is independent of progenitor
- Neutrino luminosities before explosion scale with mass accretion rate of NS
- Onset of explosion leads to drop of ν luminosities



Buras et al., A&A 457 (2006) 281 (similar results by Liebendörfer et al. 2003)

Radiated Neutrino Spectra

- Now: more accurate spectra
- muon and tau neutrino spectra are more similar to those of electron antineutrinos
- electron antineutrinos less energetic than previously
- For accreting neutron stars: mean energies of e-antineutrinos can become higher than those of muon-neutrinos



A. Marek (PhD Thesis, 2007);
Janka et al. (Phys. Rep. 442; 2007)

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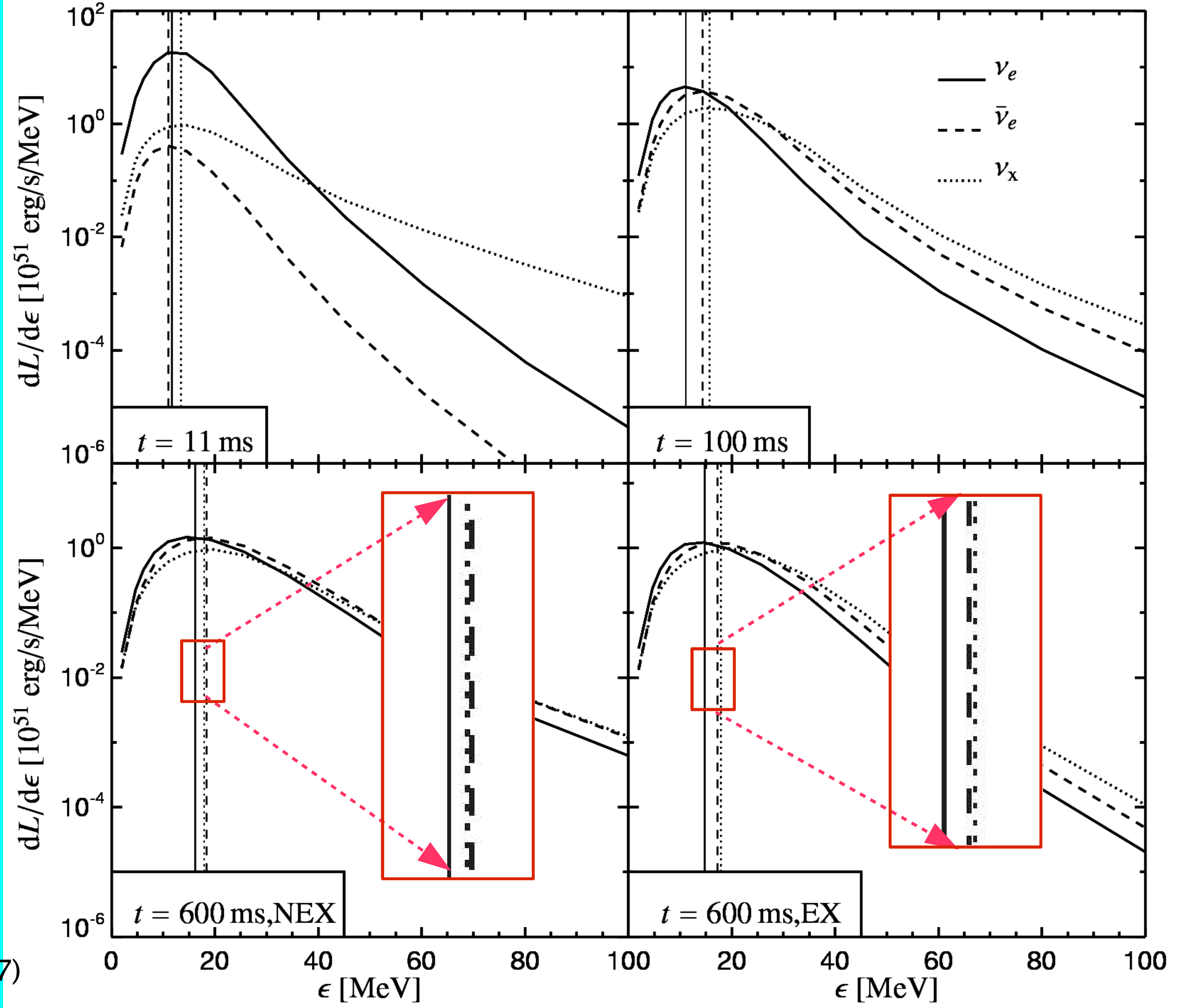
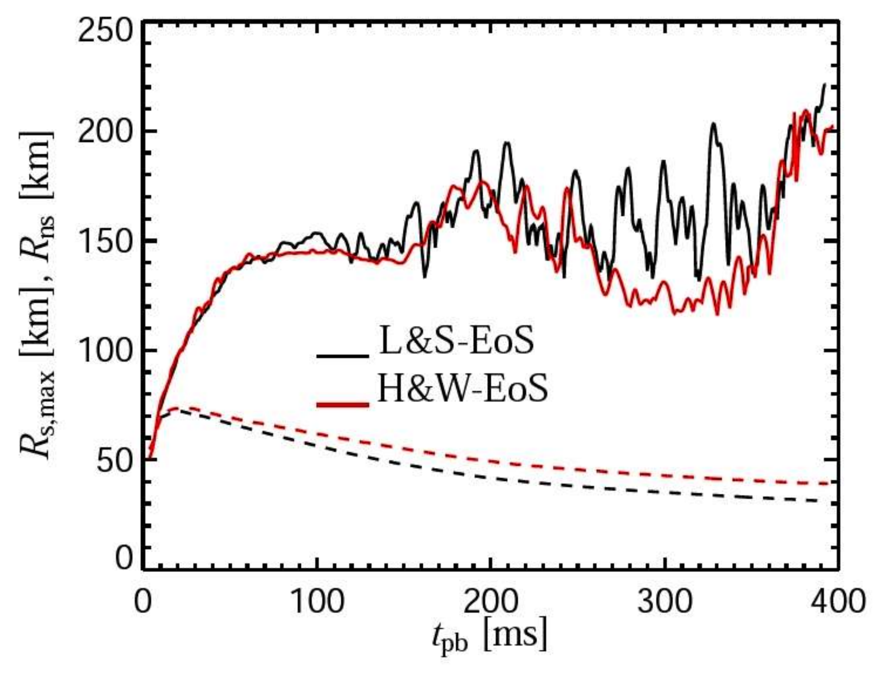
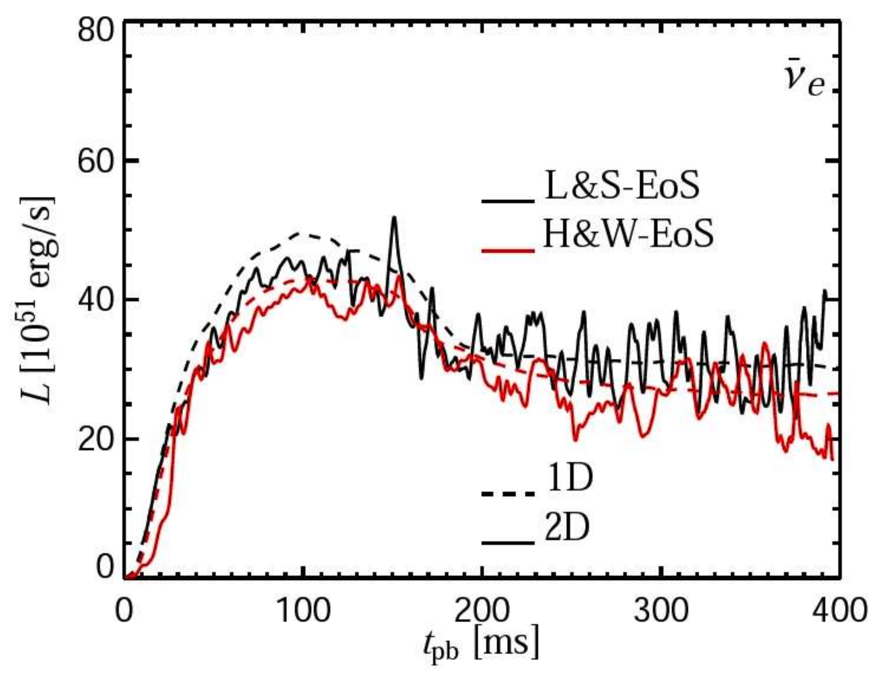


A. Marek (PhD Thesis, 2007);
Janka et al. (Phys. Rep. 442; 2007)

SASI Modulation of Neutrino Emission

- Neutrino luminosities (of all flavors) show ~30% variations due to SASI shock motion
- Dominant frequencies of modulation: 20–200 Hz
- Luminosities and time variability depend on nuclear EoS in neutron star





Lattimer & Swesty (soft nuclear) EoS

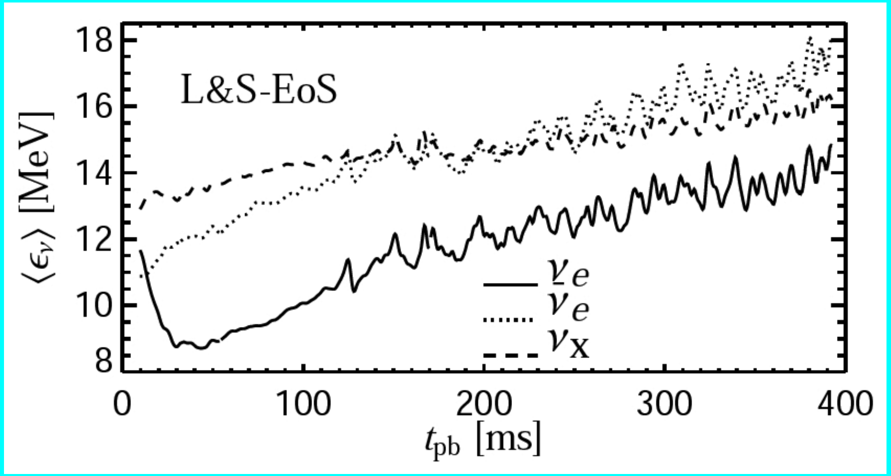
Wolff & Hillebrandt (stiff nuclear) EoS

Marek et al. (2008), A&A, submitted;

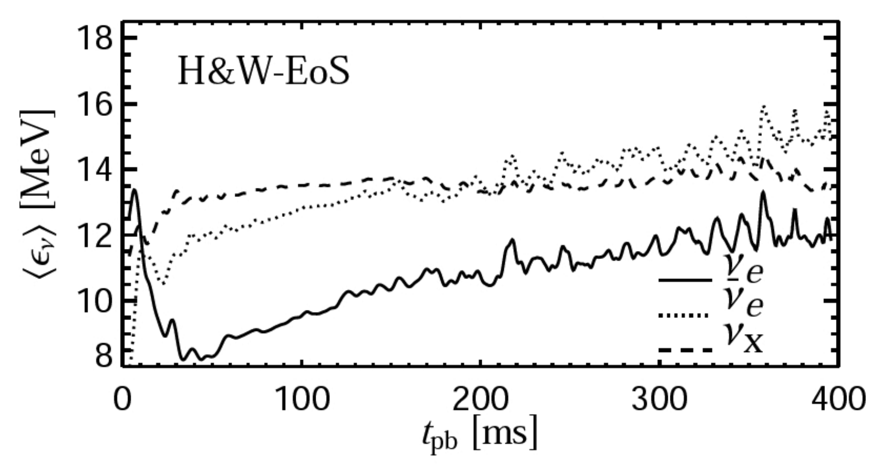
SASI Modulation of Neutrino Emission

- Mean energies of radiated neutrinos (of all flavors) exhibit ~10% variations due to SASI shock motion
- Mean neutrino energies depend on nuclear EoS in neutron star
- Inversion of hierarchy of mean neutrino energies for accreting neutron star :

$$\langle\epsilon_{\nu_e}\rangle < \left\langle\epsilon_{\nu_{\mu,\tau}}\right\rangle \lesssim \langle\epsilon_{\bar{\nu}_e}\rangle \qquad \text{but :} \qquad \langle\epsilon_{\nu_e}\rangle_{\mathrm{rms}} < \langle\epsilon_{\bar{\nu}_e}\rangle_{\mathrm{rms}} < \left\langle\epsilon_{\nu_{\mu,\tau}}\right\rangle_{\mathrm{rms}}$$



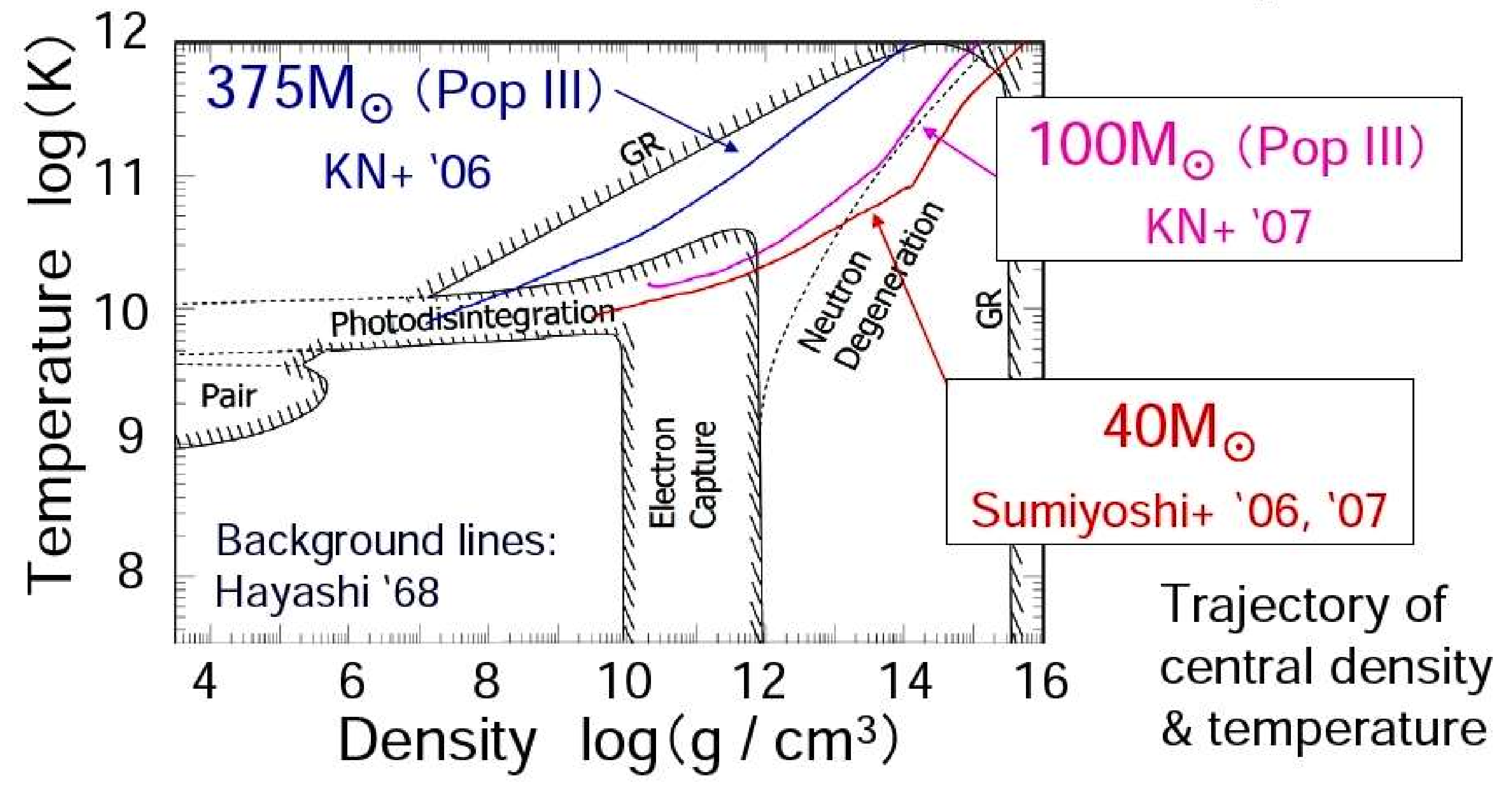
Lattimer & Swesty (soft nuclear) EoS



Wolff & Hillebrandt (stiff nuclear) EoS

Marek et al. (2008), A&A, submitted;

Neutrino Signals from BH formation

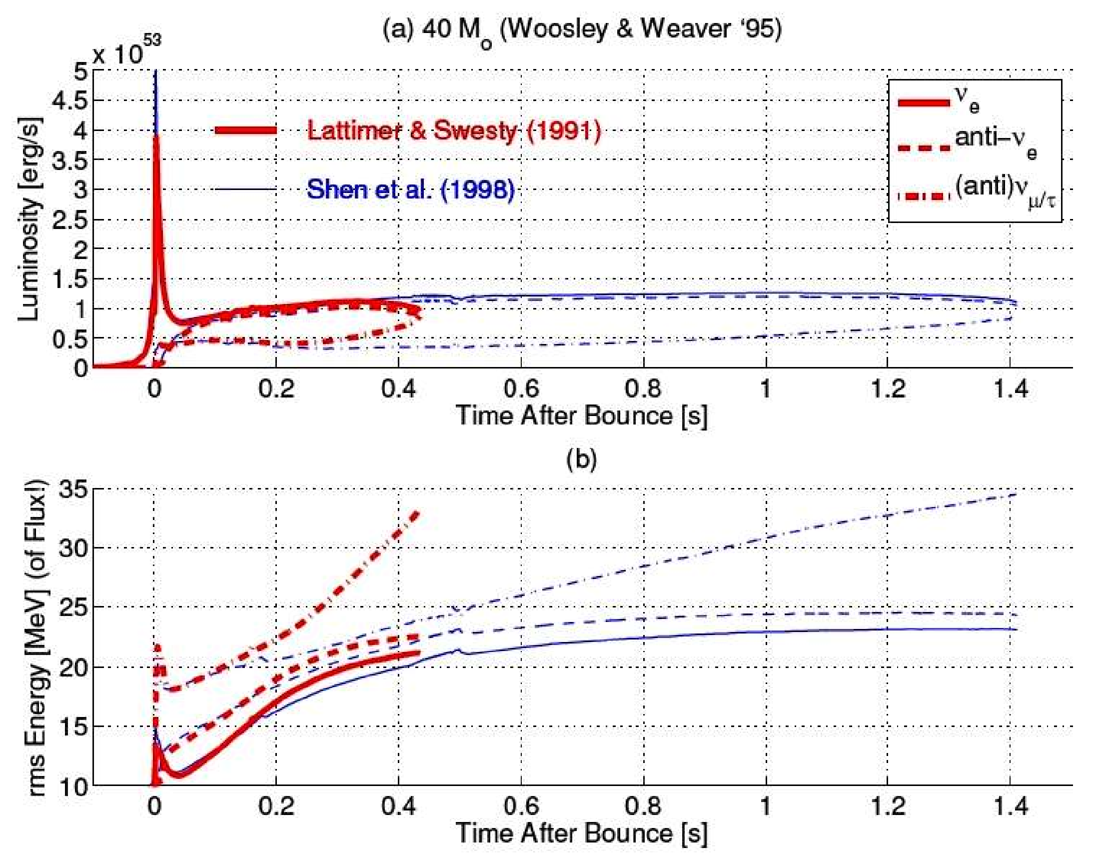


Trajectory of central density & temperature

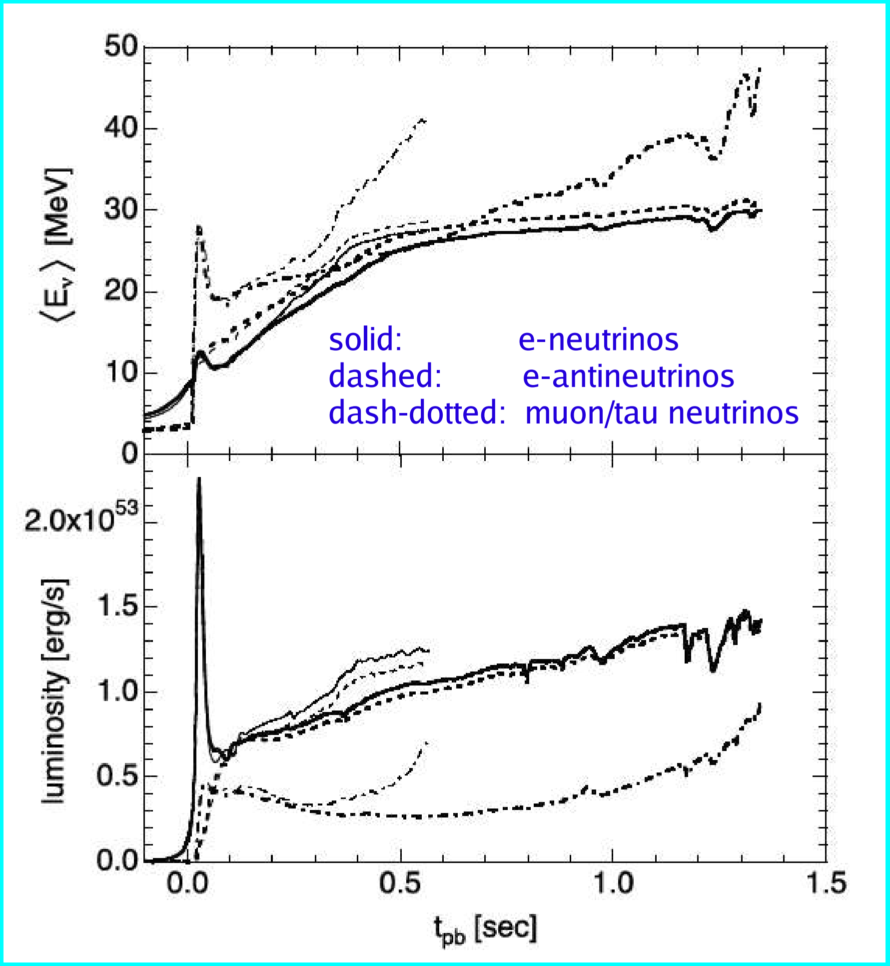
Nakazato, Ringberg Talk (March 2008)

Collapse of 40 M_{sun} Star

- Time of NS instability and collapse to BH depends on nuclear EoS
- Abrupt termination of neutrino emission
- Characteristic preceding rise of mean energy of muon and tau neutrinos



Fischer et al., AIP Conf. Proc. 1016 (2008)



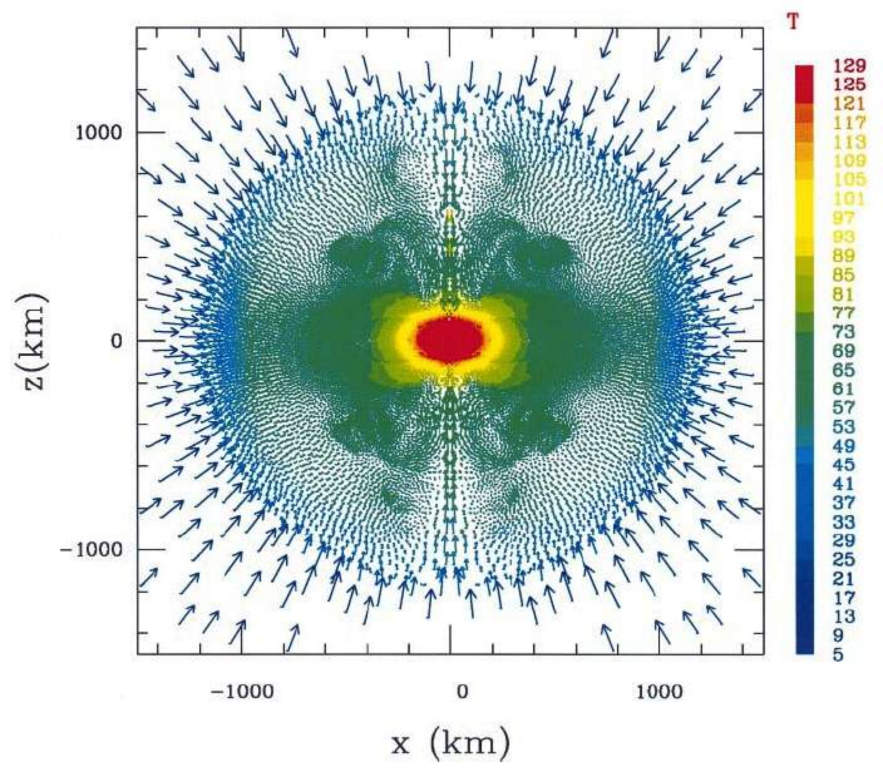
solid: e-neutrinos
dashed: e-antineutrinos
dash-dotted: muon/tau neutrinos

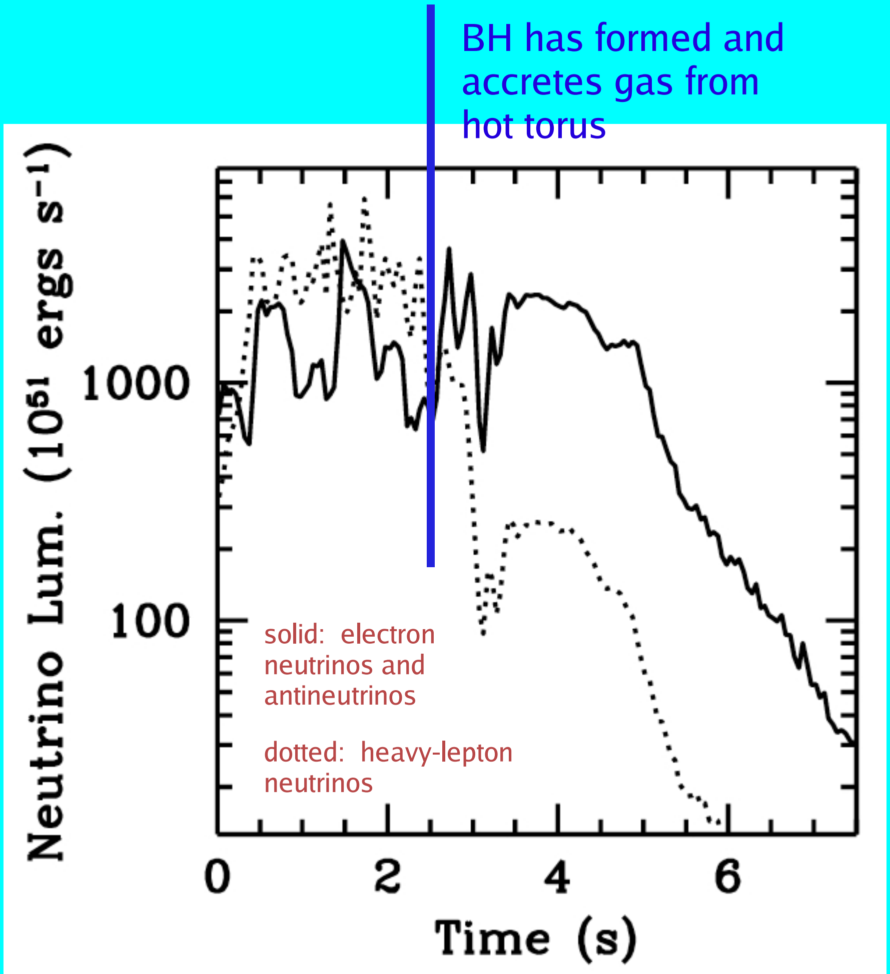
Sumiyoshi et al., PRL 97, 091101 (2006)

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

Proto-BH 0.5 seconds before BH formation





BH has formed and accretes gas from hot torus

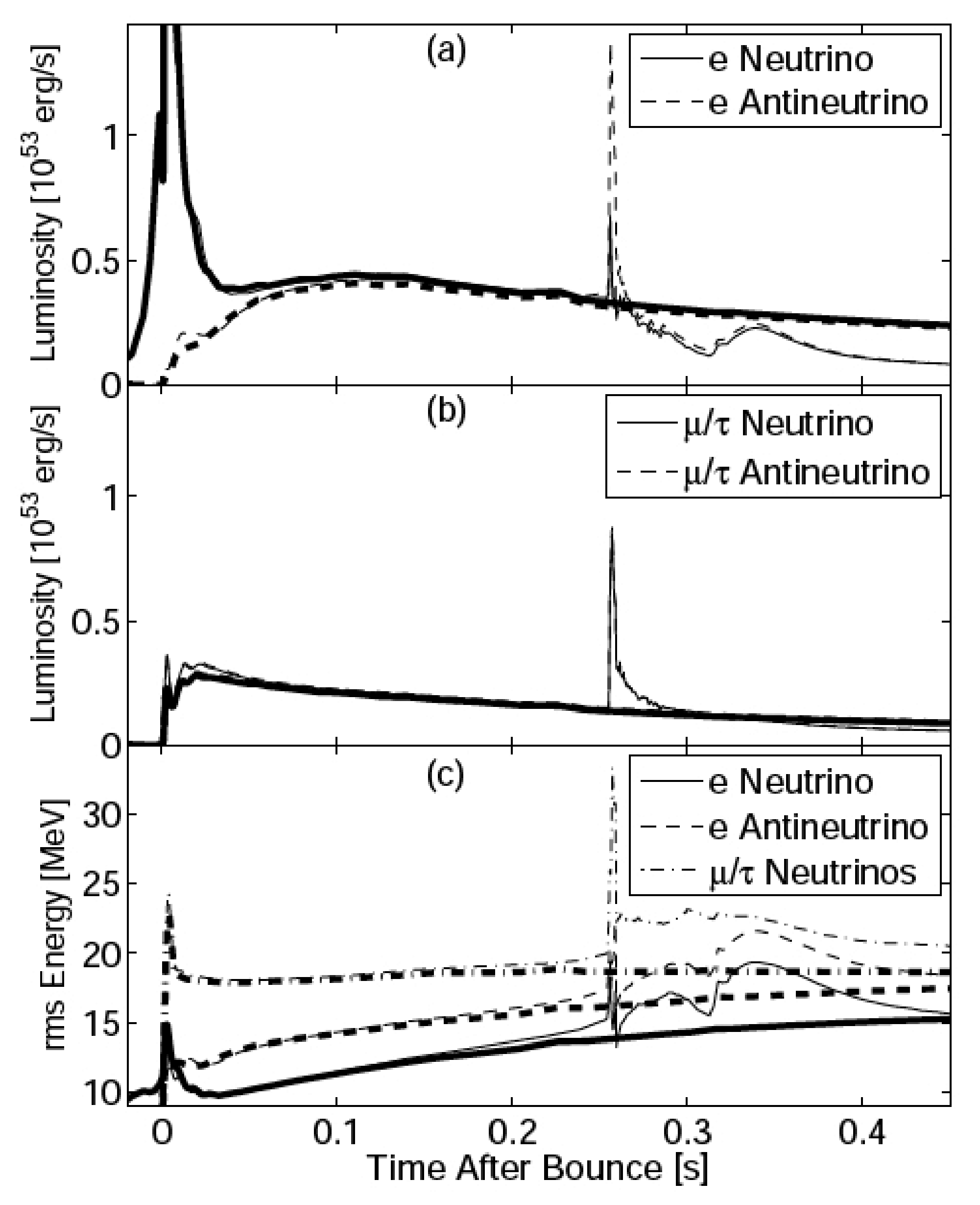
solid: electron neutrinos and antineutrinos

dotted: heavy-lepton neutrinos

Fryer et al., ApJ 550, 372 (2001)

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, submitted (2008)

Summary

- Neutrinos signals from CC supernovae are unique probes of the physics inside the supernova core and nascent NS
- Measuring SN neutrinos could help us understanding explosion dynamics/mechanism and properties of NS matter
- Detectors with long run times are needed (low Galactic event rates: 2-3 events/100 years)!

- My dream as a neutrino astrophysicist:
  A detector for capturing neutrinos from supernovae in the Virgo Cluster !