Max–Planck–Institut
für Astrophysik

SFB-TR7

SFB-TR27

Excellence Cluster
Universe

ILIAS WP2: Workshop on Supernovae, Neutrinos, and Gravitational Waves, EGO/Virgo site, Cascina, Italy, November 26, 2008

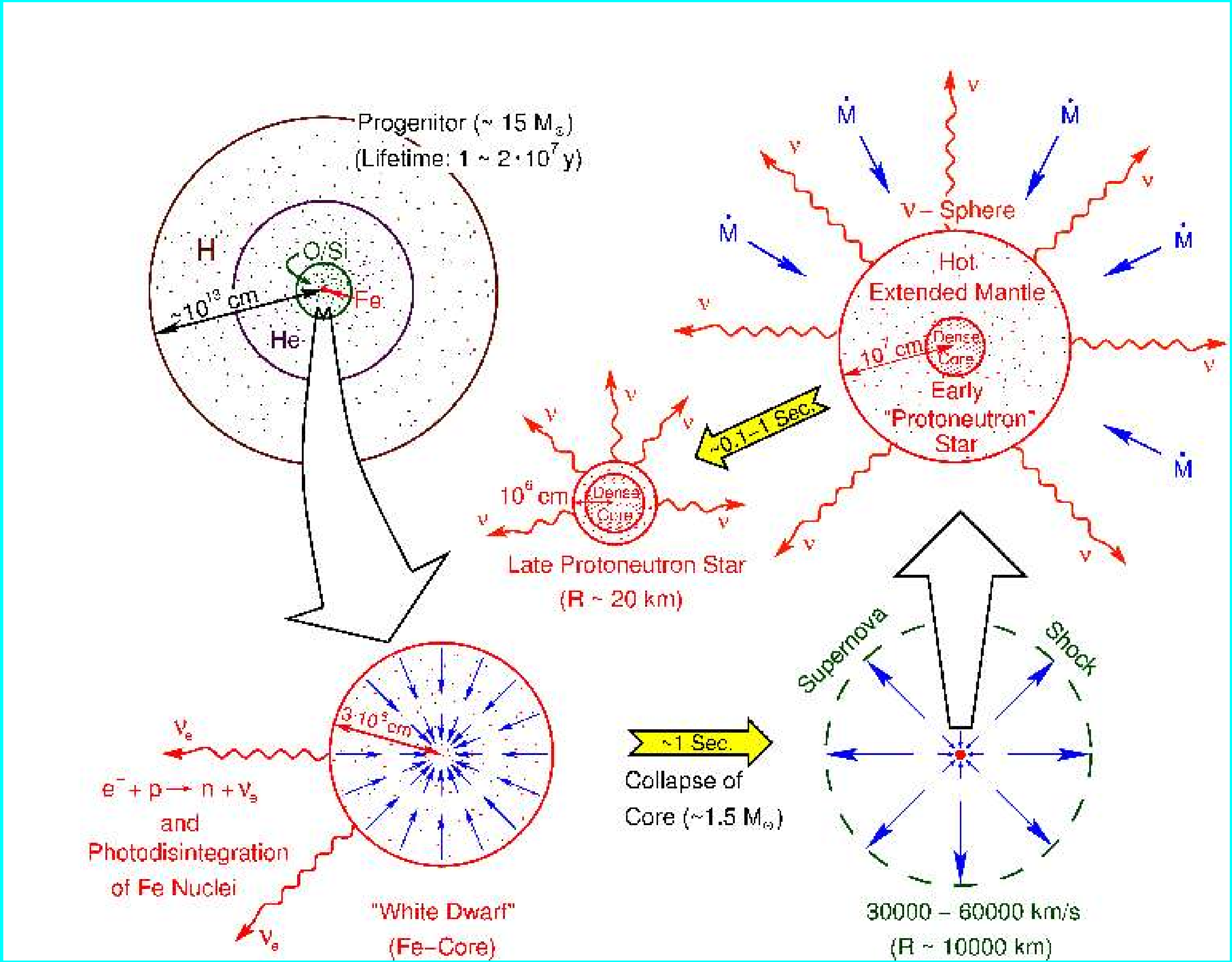
Neutrino Signals from Stellar Core-Collapse Events

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

Contents

- Types of core-collapse supernovae & neutrino signal characteristics
- Results of recent supernova explosion models
- Neutrino signals from stellar core-collapse models
- Conclusions

Stellar Collapse & Explosion



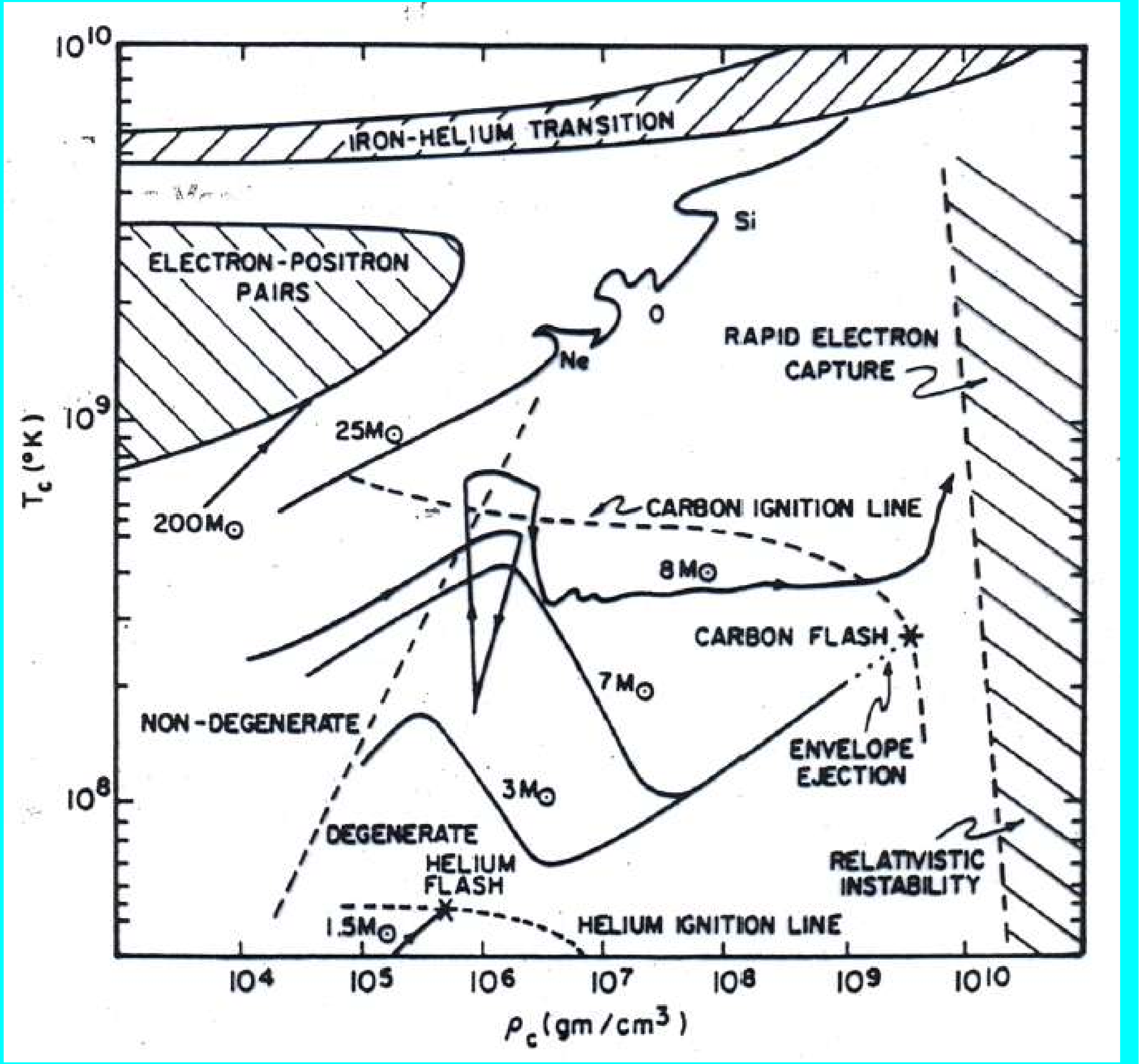
(adapted
from A.
Burrows)

Final Stages of Massive Star Evolution

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

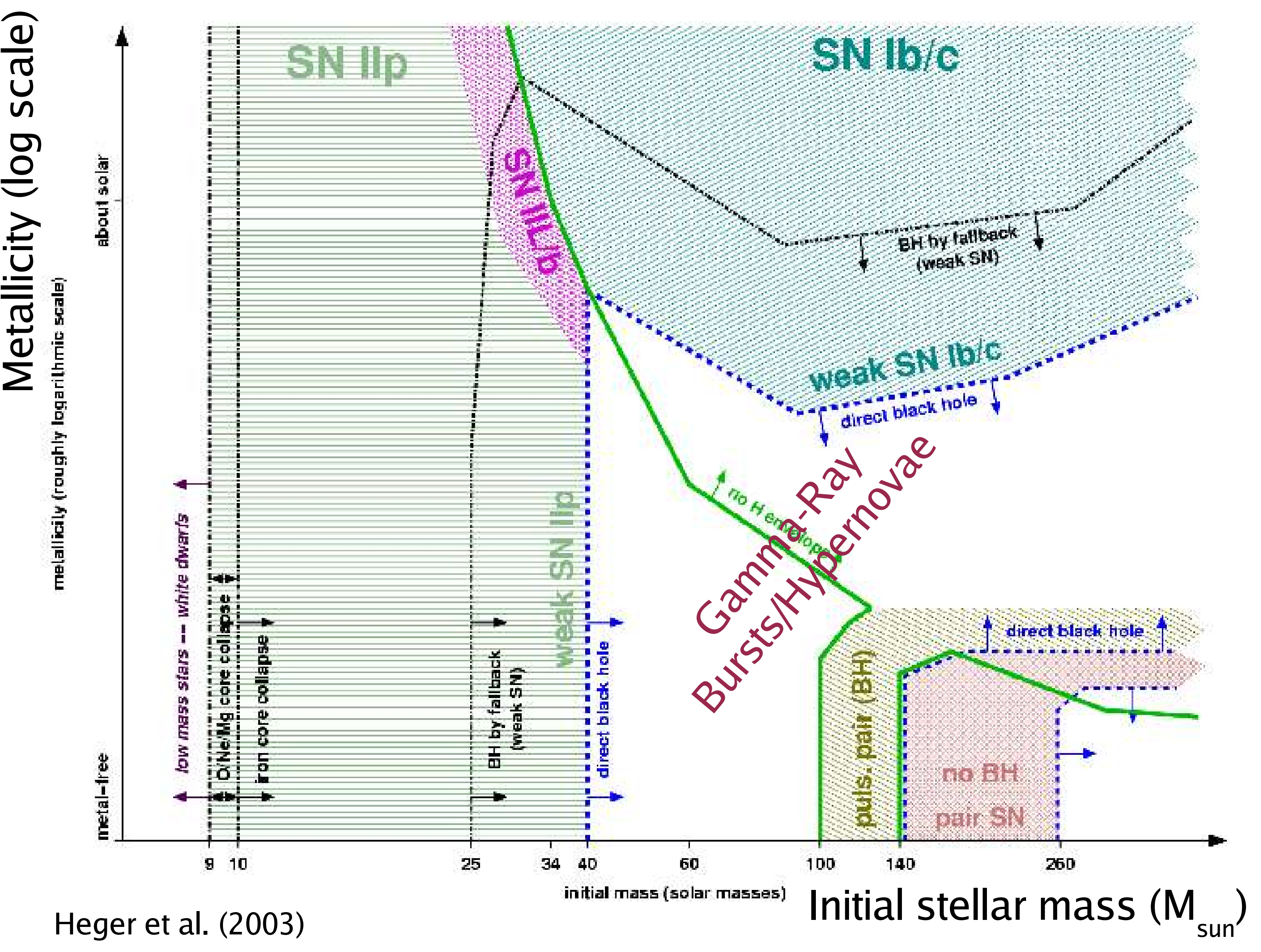
Massive stars with ~10–100 M_{sun} develop Fe cores
—> collapse by nuclear photodisintegration

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



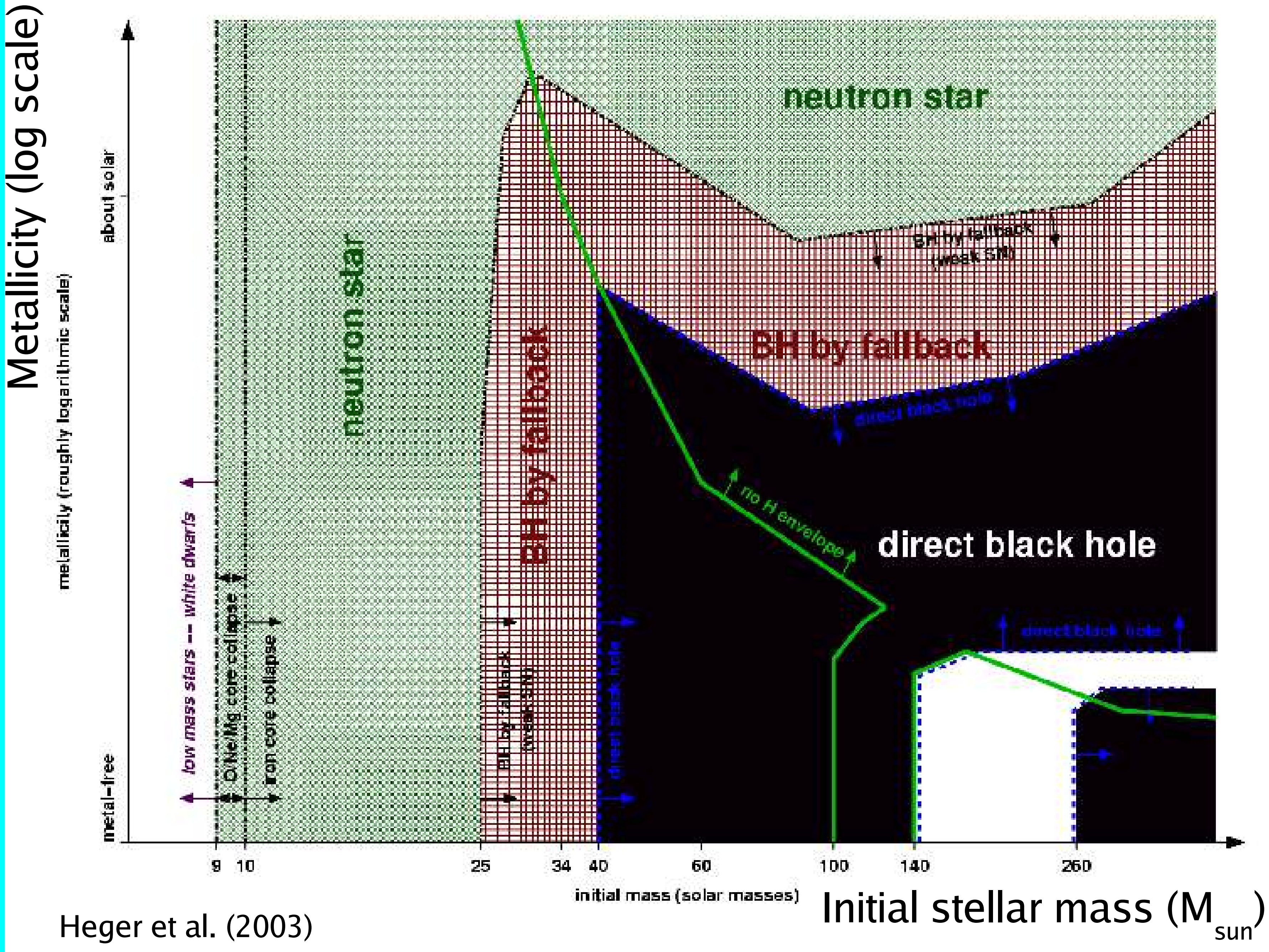
(Wheeler et al. 1990)

Core Collapse Events and Remnants



Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

Recent Results of Simulations

Stellar Core Collapse and Neutrinos

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

$E_\nu \sim 3x10^{53}$ erg $(M_{ns}/M_{sun})^2/(R_{ns}/10\ \mathrm{km})$ for NS

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

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

otherwise: $\xi \sim 0$

Neutrinos need to be included in supernova models!

Neutrino Signals and Astrophysics

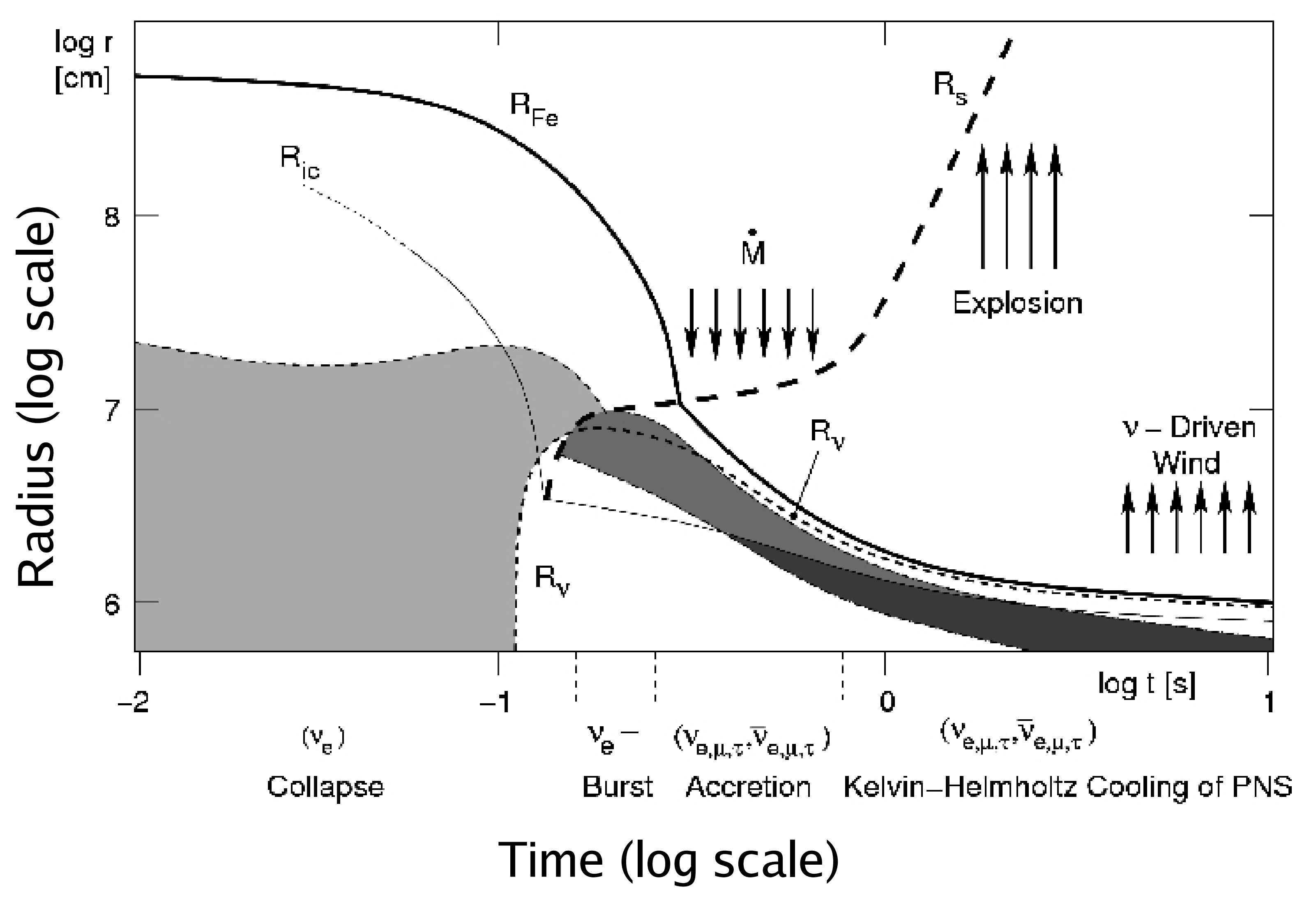
Important questions:

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

Relevant signal characteristics:

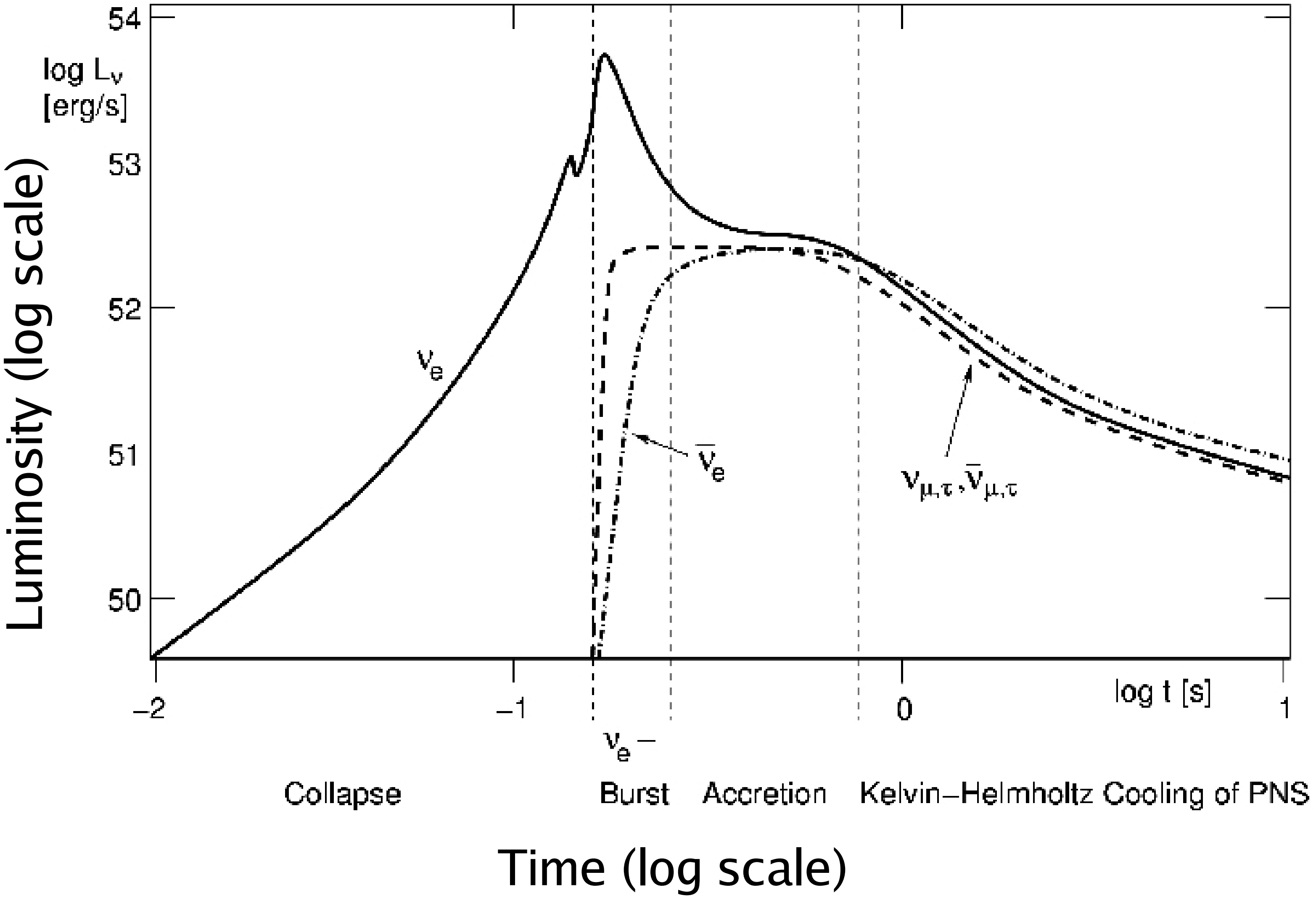
- Duration
- Total energy
- Mean neutrino energies
- Time structure
- Flavor distribution

SN Evolution Phases (schematic)



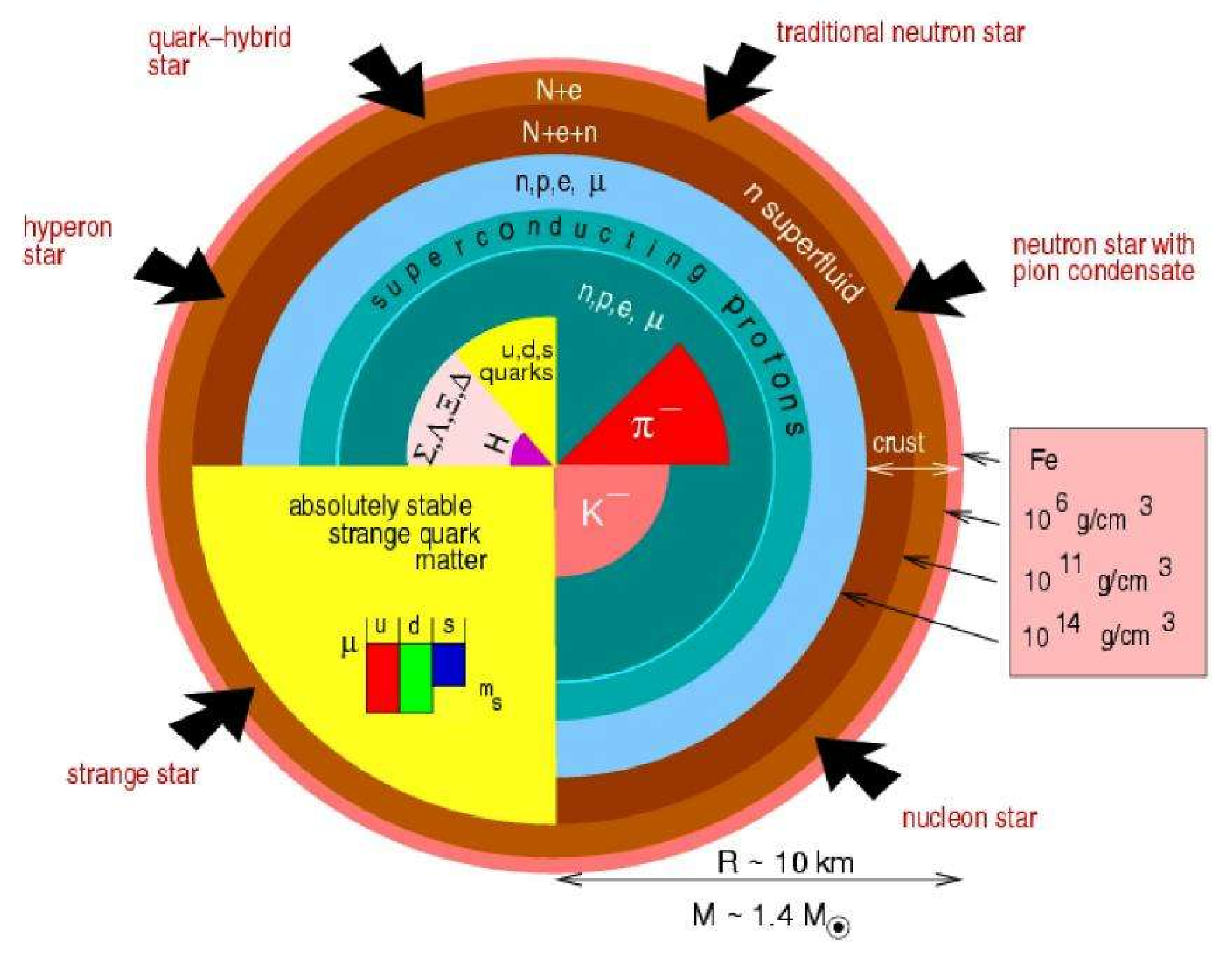
Neutrino Luminosities (schematic)

Neutrino signal for 3 active flavors, without neutrino oscillations



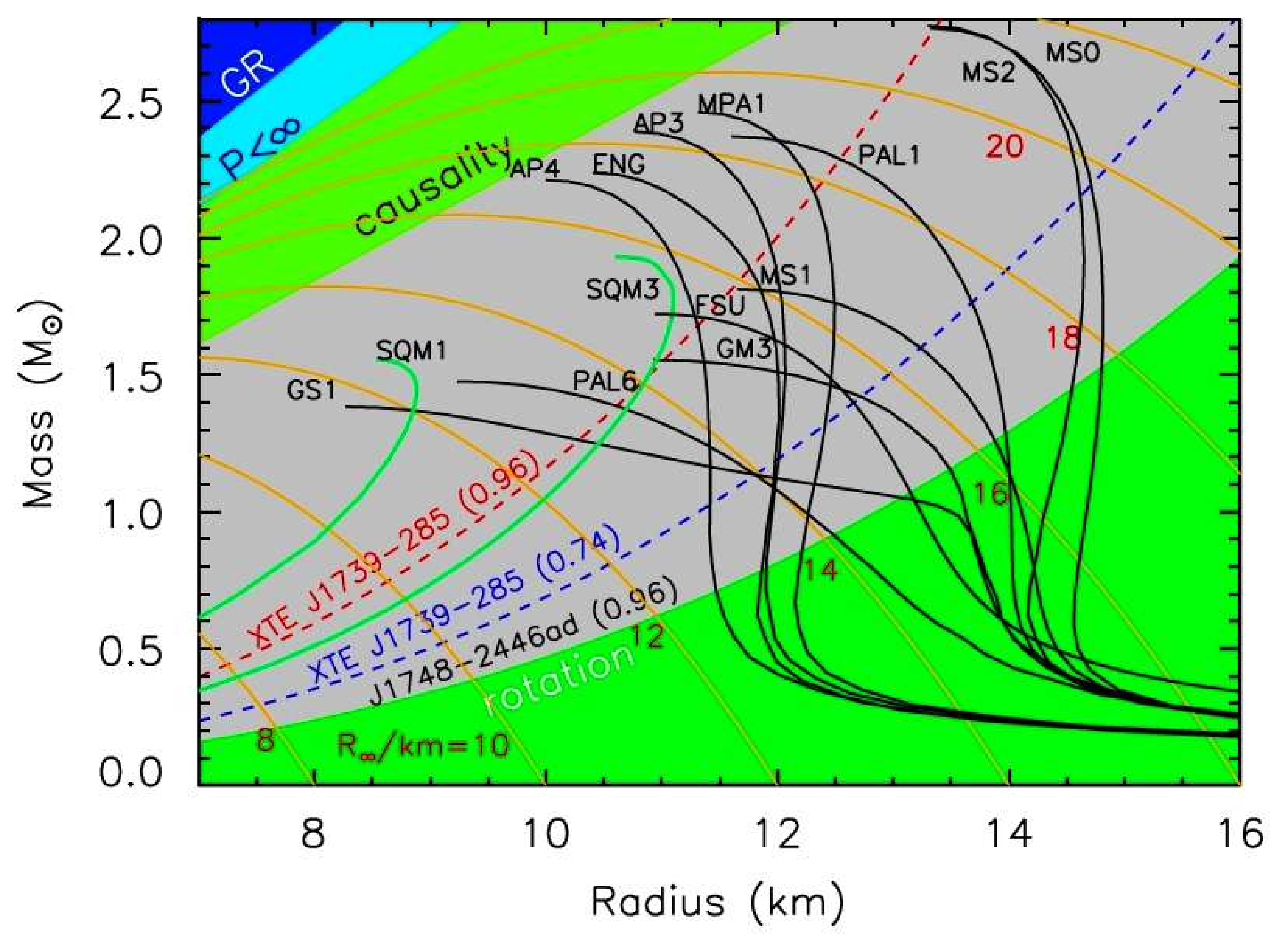
Neutron Star Equations of State

Neutron star EoS is crucial ingredient but highly uncertain!



(Source: F. Weber)

Neutron Star Equations of State



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

- 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!

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)

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

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

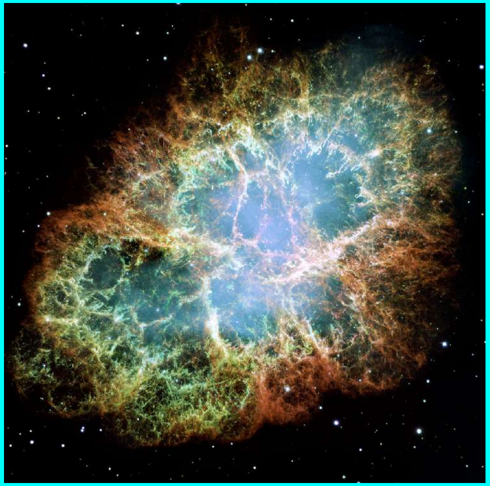
(====> rapidly decreasing mass accretion rate after core bounce)

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

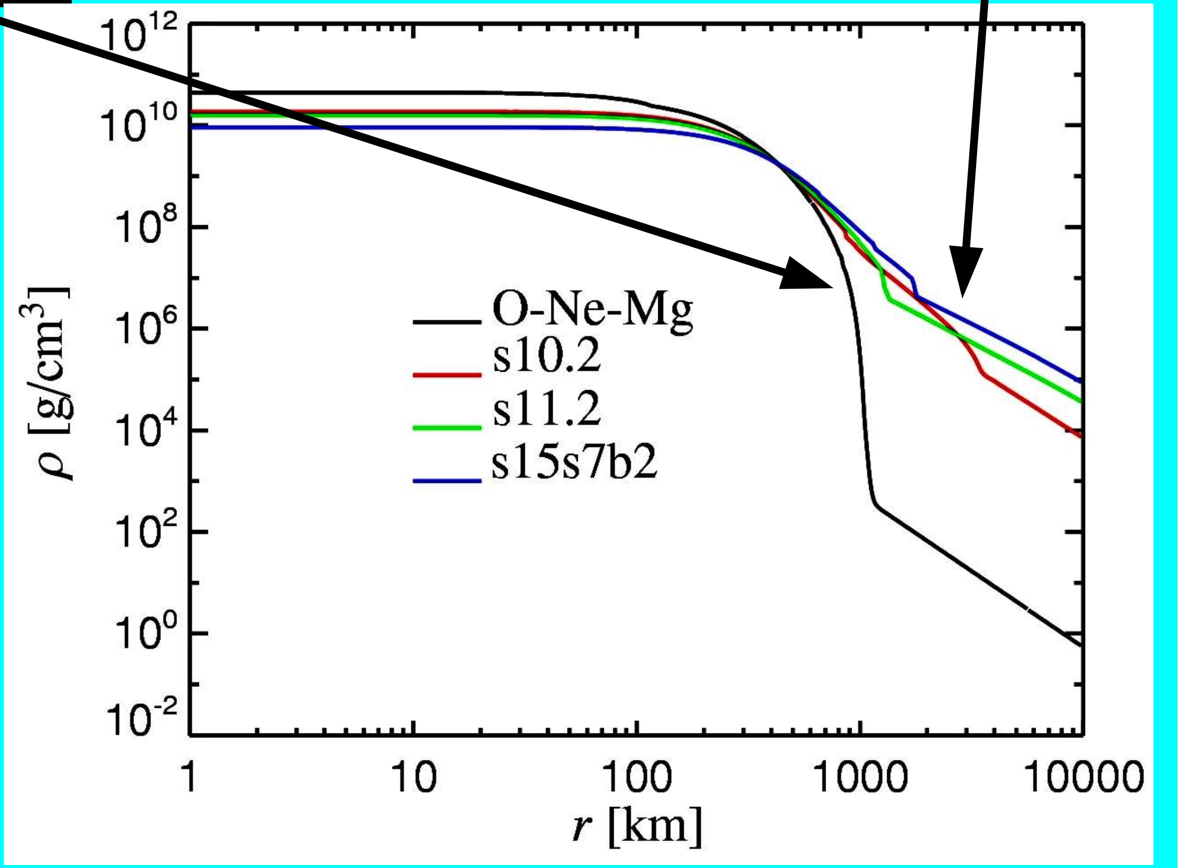
(e.g. Heger et al., Limongi et al., Nomoto et al., Hirschi et al.)

~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)

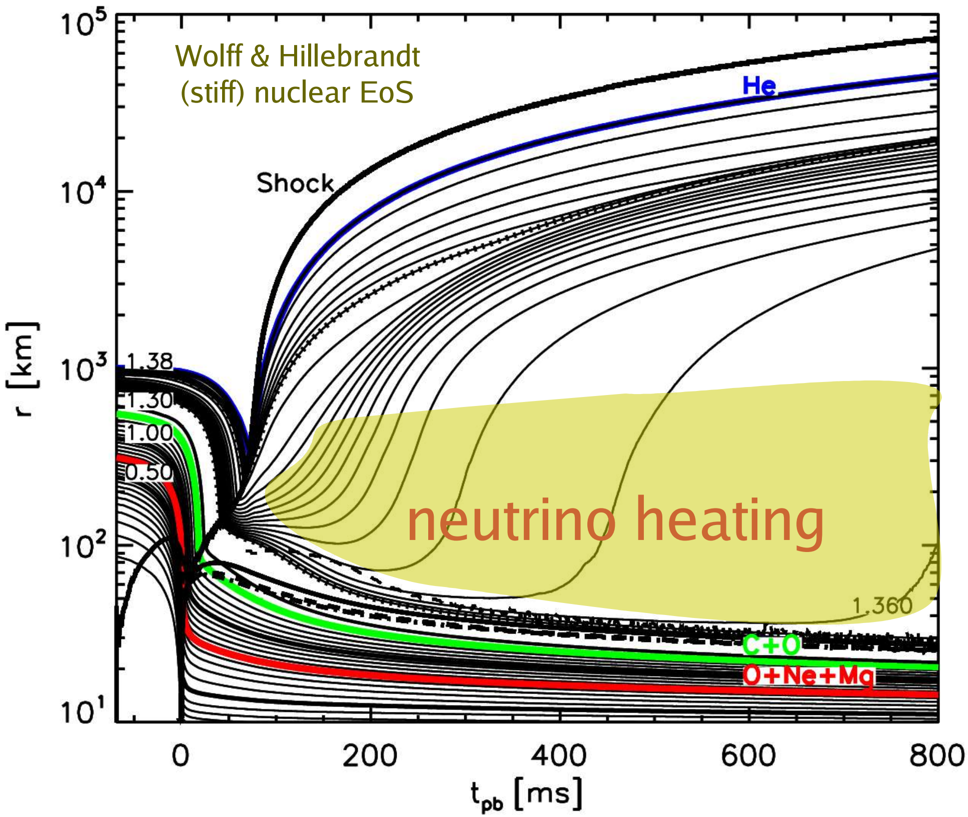


SN models and ejecta composition are consistent with CRAB



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

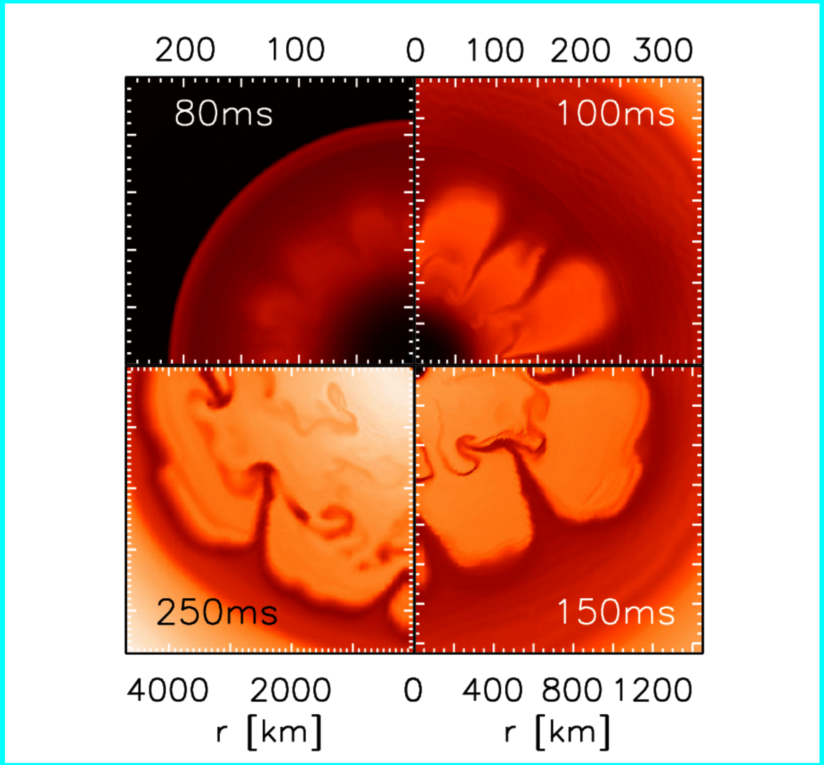
"Electron-capture supernovae"
or "ONeMg core supernovae"



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

- 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

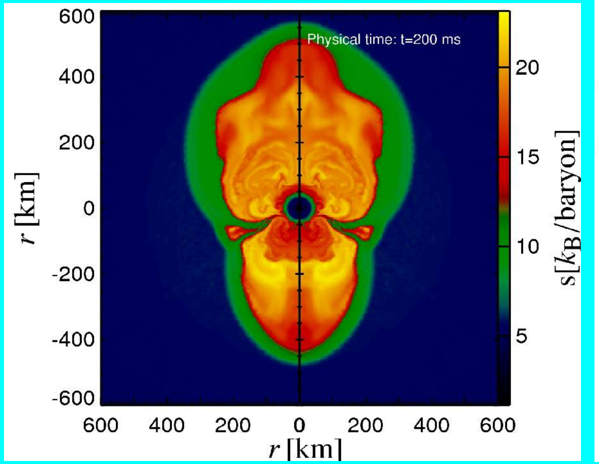


2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

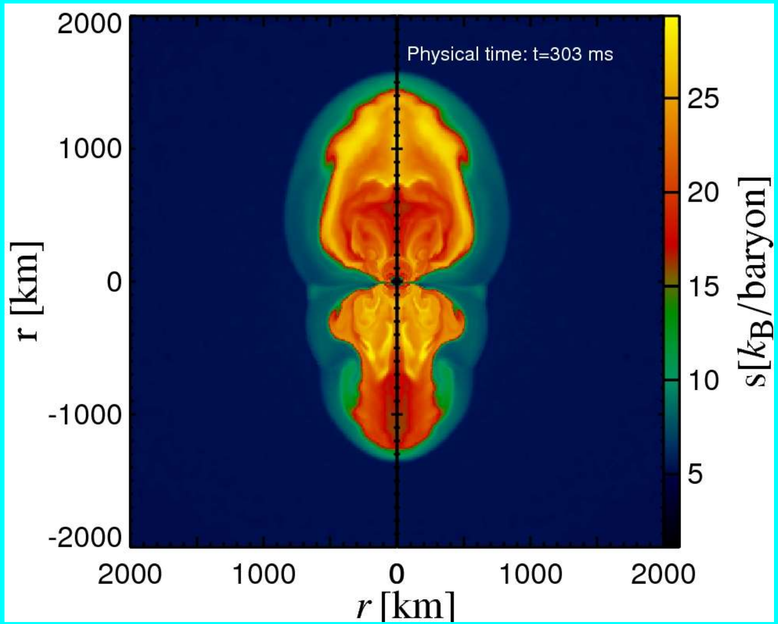
For explosions of stars with $M > 10\ M_{sun}$ multi-dimensional effects (nonradial hydrodynamic instabilities) are crucial!

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

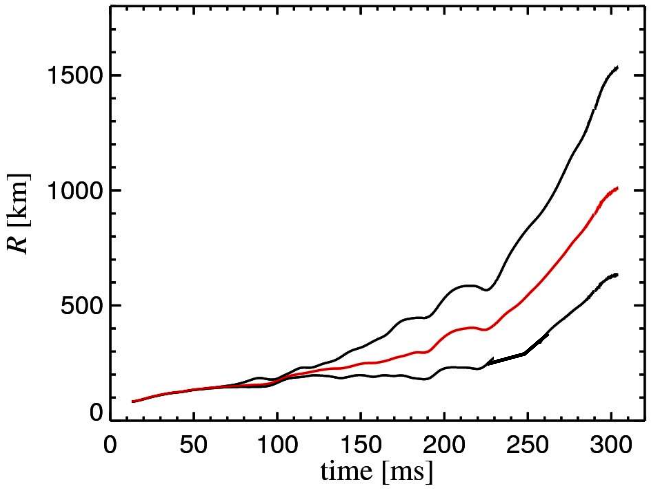
===> this improves conditions for strong neutrino heating and initiates a globally aspherical explosion by neutrino heating even without rotation



t = 0.200 s after core bounce

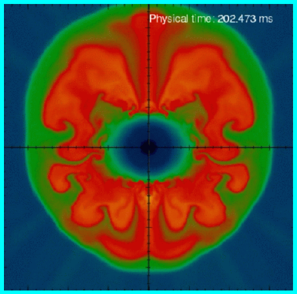


t = 0.303 s after core bounce

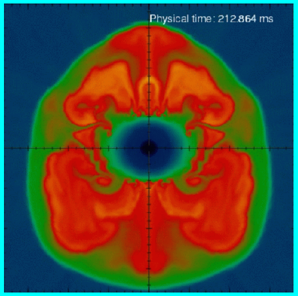


Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2008), in press

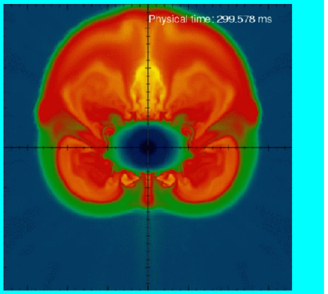
2D SN Simulations: $M_{star} \sim 15\ M_{sun}$



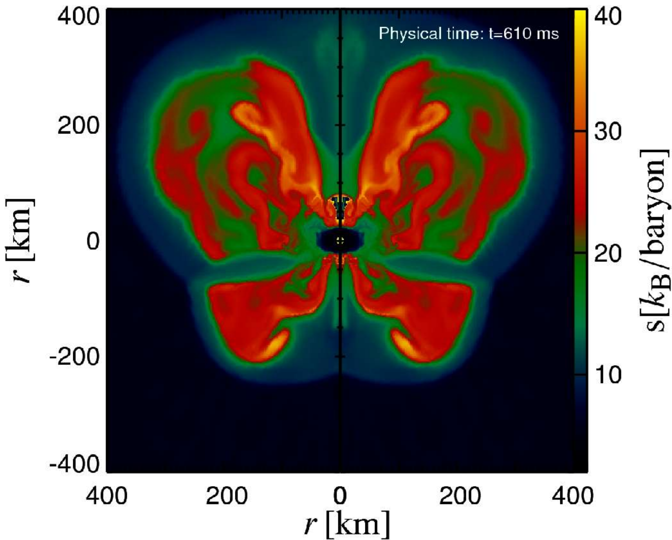
t = 0.202 s p.b.



t = 0.213 s p.b.



t = 0.300 s p.b.



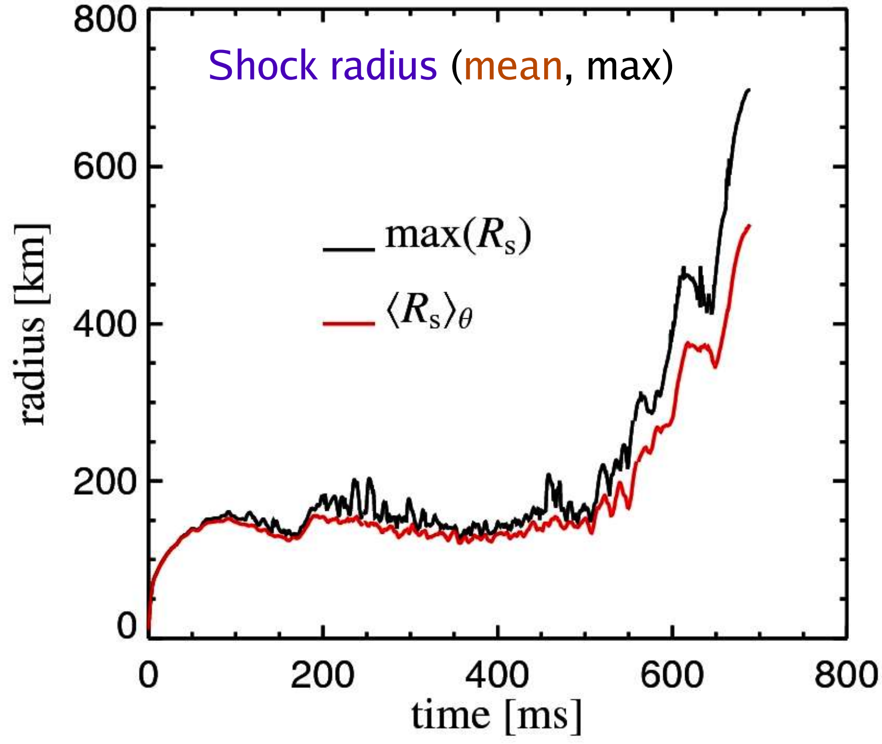
$15\ M_{sun}$ star

(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)



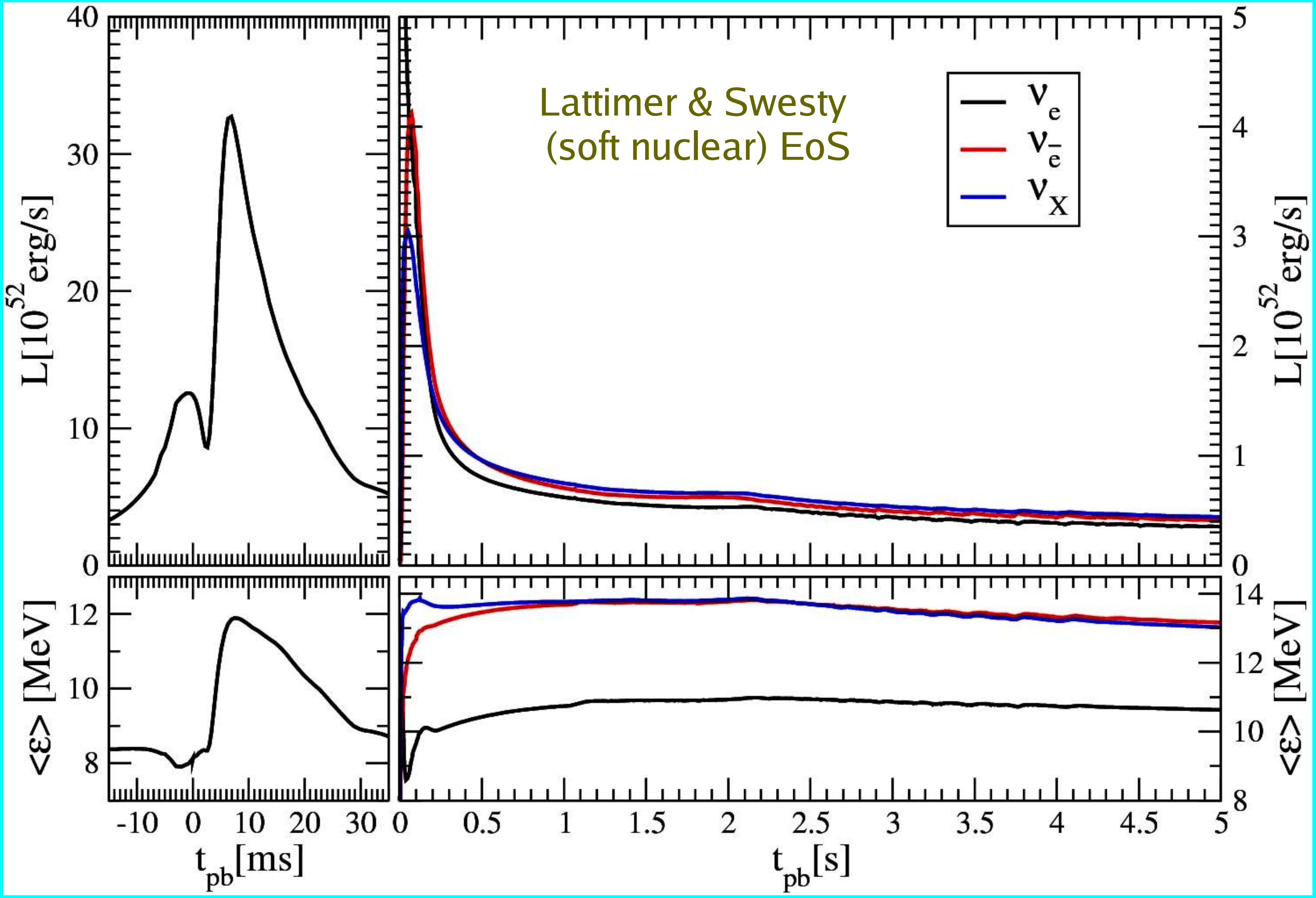
Consequences and Implications of Stellar Explosions

- 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

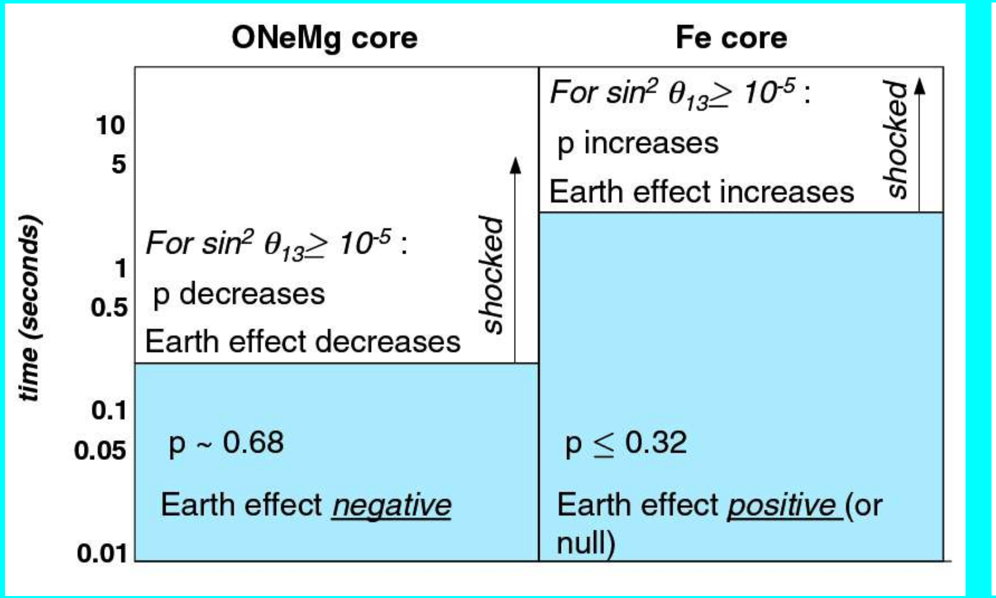
Neutrino luminosities and mean energies


Lattimer & Swesty
(soft nuclear) EoS

Müller et al. (in preparation)

Neutrino Oscillations

Flavor oscillations in star and earth modify the detectable SN neutrino signal.



ONeMg core

For $\sin^2\theta_{13} \geq 10^{-5}$:

p decreases

Earth effect decreases

$p \sim 0.68$

Earth effect *negative*

Fe core

For $\sin^2\theta_{13} \geq 10^{-5}$:

p increases

Earth effect increases

$p \leq 0.32$

Earth effect *positive* (or null)

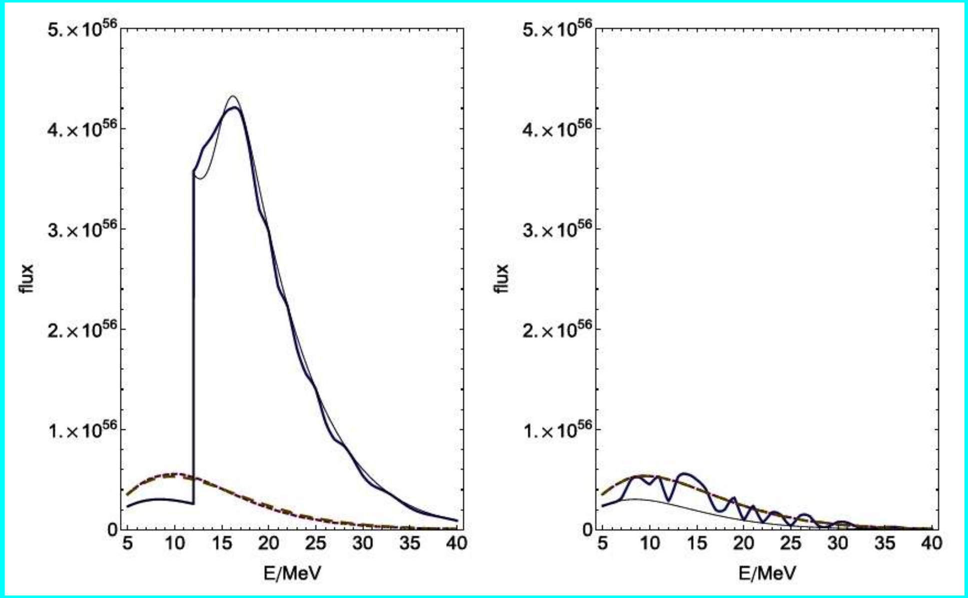


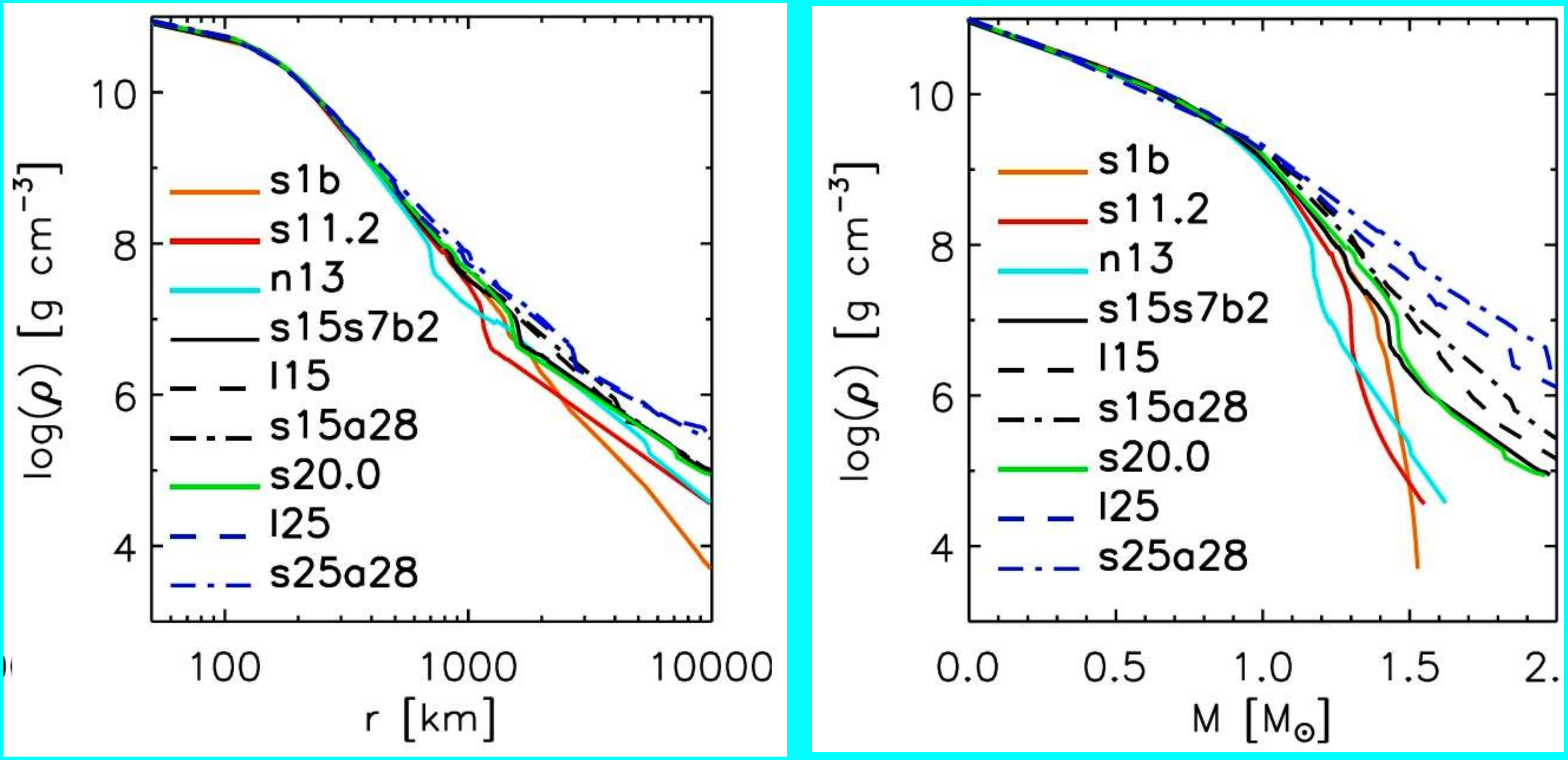
FIG. 9 (color online). Summary of the oscillation signatures of ONeMg-core supernovae compared to Fe-core supernovae at different times. They refer to the ν_e channel for the normal mass hierarchy; p is the ν_e survival probability. The shaded areas represent the preshock phase, defined as the time interval before the shock front reaches the location of the MSW resonances, while the white regions ("shocked") indicate the later times.

FIG. 10 (color online). Left column: predicted spectra of the ν_e flux in a detector for a ONeMg-core supernova, inclusive of oscillations in the star and in the Earth (nadir angle 60 degrees). Right column: the same spectra, but with the oscillation effects that are characteristic of a Fe-core supernova. $\sin^2\theta_{13} = 6\times10^{-4}$ The thick curves refer to different times: $t = 60$, 450, 700 ms (solid line, short-dashed line, and long-dashed line, respectively). For $t = 60$ ms we also show the spectrum in absence of Earth shielding (thin solid line). The vertical axis has units of $\mathrm{MeV}^{-1}\mathrm{s}^{-1}$.

Lunardini, Müller, & THJ (PRD 78, 2008)

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

Neutrino luminosities are probe for density structure of SN progenitor star

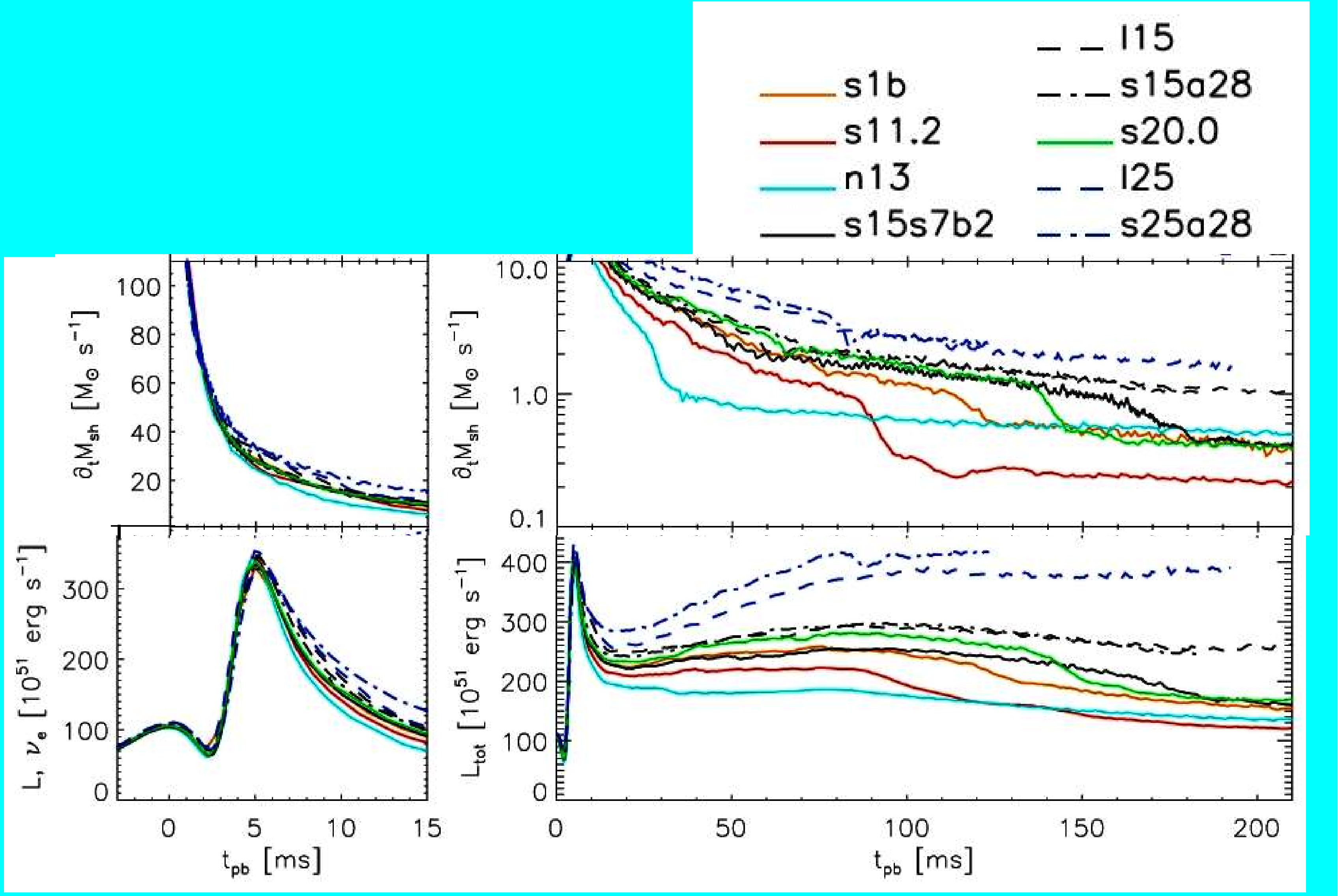


Buras et al., A&A 457 (2006) 281

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

Neutrino luminosities as functions of SN progenitor star

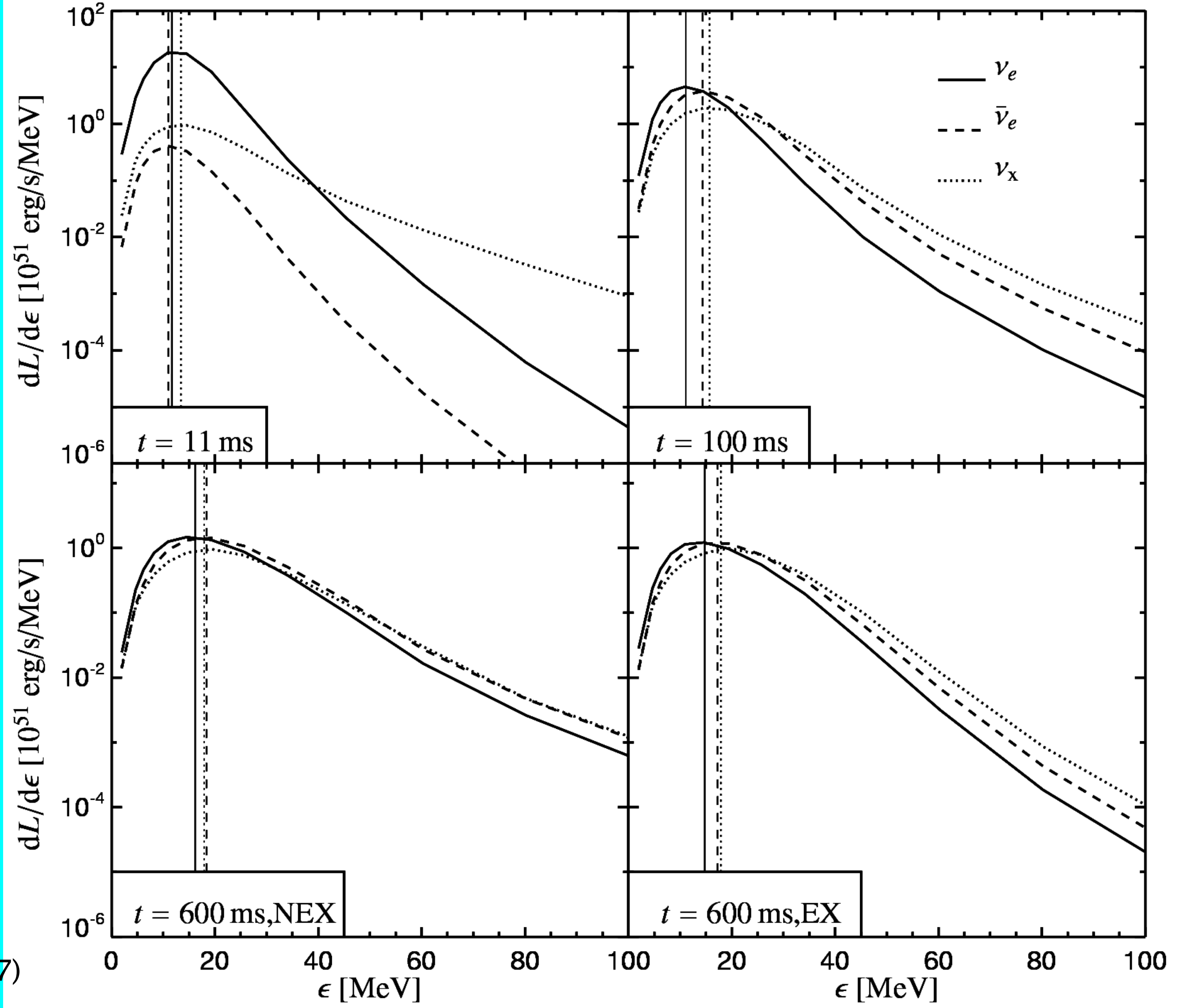
- Shock-breakout burst of ν_e is independent of progenitor
- Neutrino luminosities prior to explosion correlate with mass accretion rate of NS
- Onset of explosion leads to drop of ν luminosities



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

Radiated Neutrino Spectra

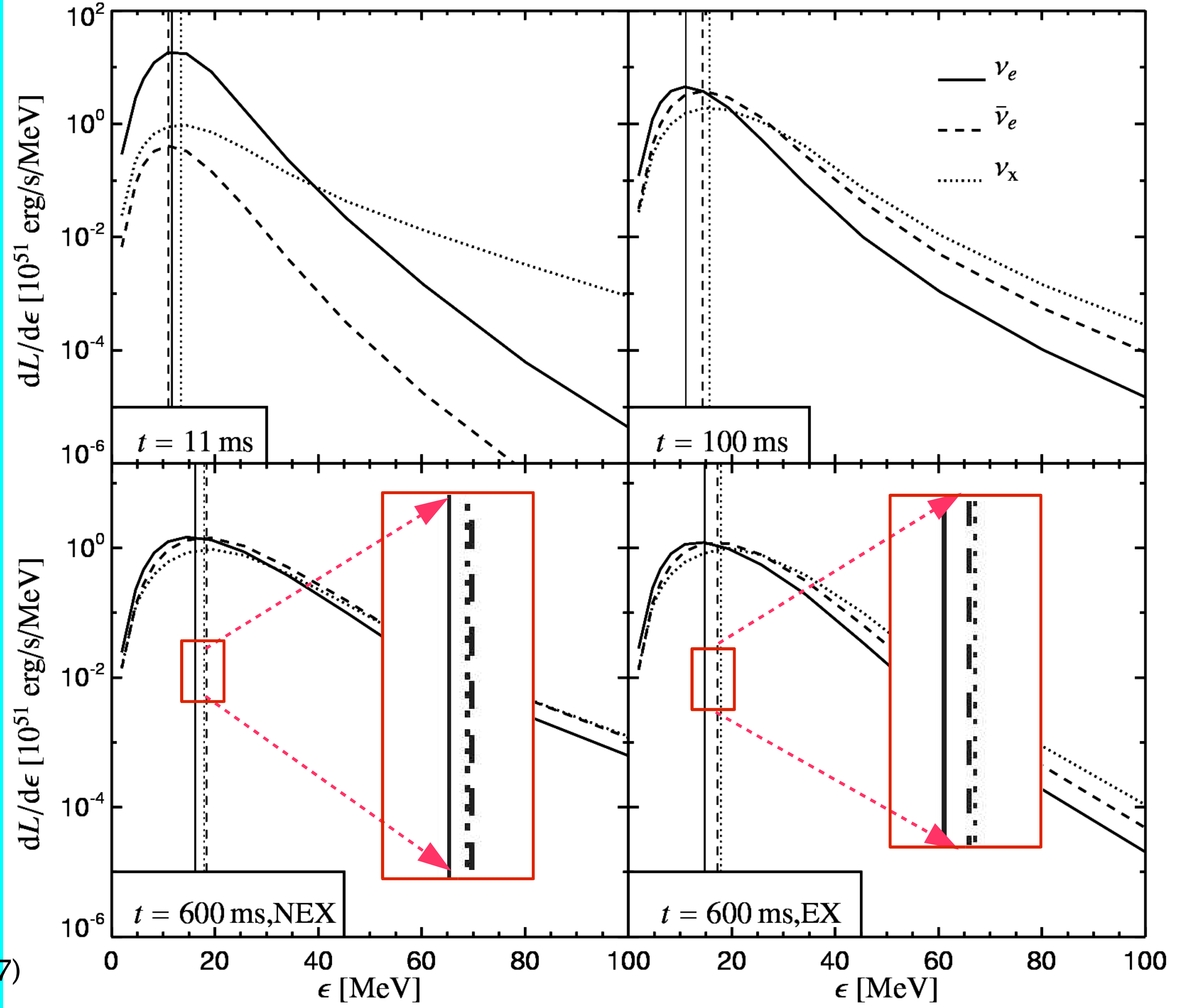
- Now: more accurate spectra
- muon and tau neutrino spectra are more similar to those of electron antineutrinos
- electron antineutrinos less energetic than previously
- For accreting neutron stars: mean energies of e-antineutrinos can become higher than those of muon-neutrinos



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

Radiated Neutrino Spectra

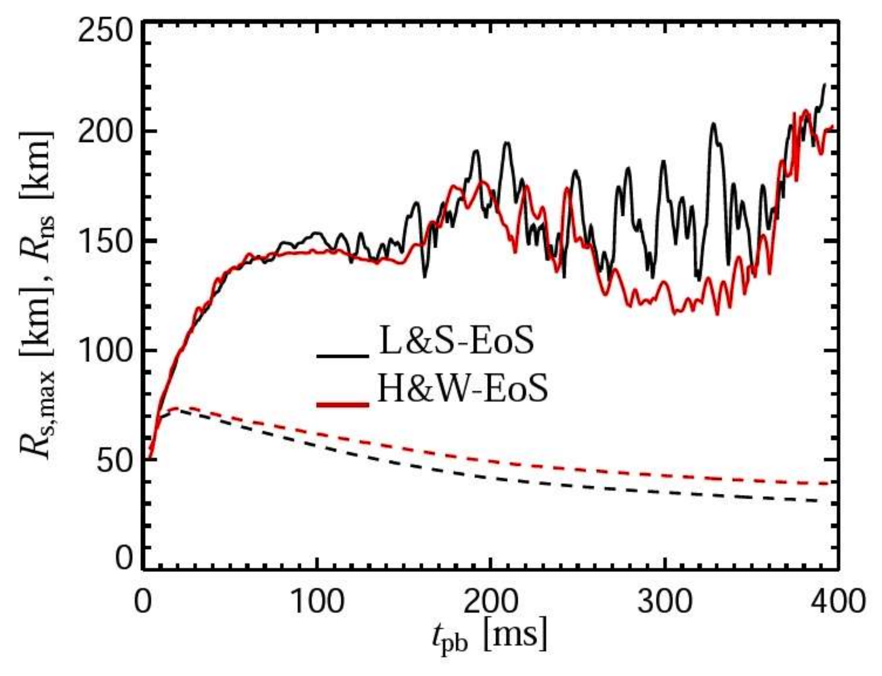
- more accurate spectra
- muon and tau neutrino spectra are more similar to those of electron antineutrinos
- electron antineutrinos less energetic than previously
- For accreting neutron stars: mean energies of e-antineutrinos can become higher than those of muon-neutrinos

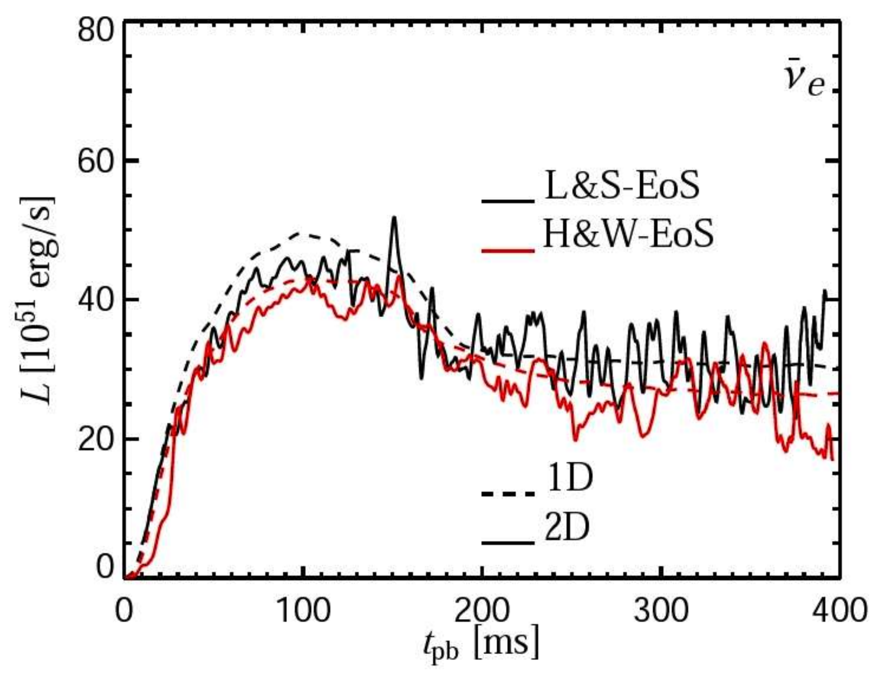


A. Marek (PhD Thesis, 2007);
Janka et al. (Phys. Rep. 442; 2007)

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

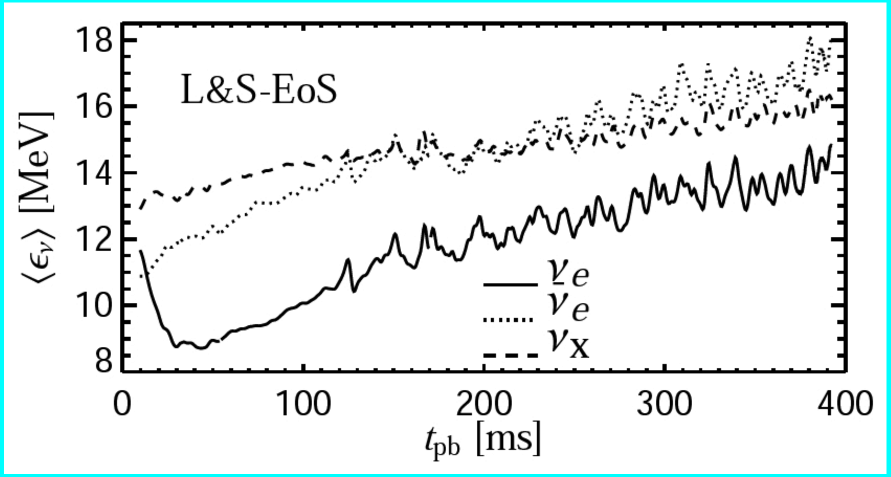
Wolff & Hillebrandt (stiff nuclear) EoS

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

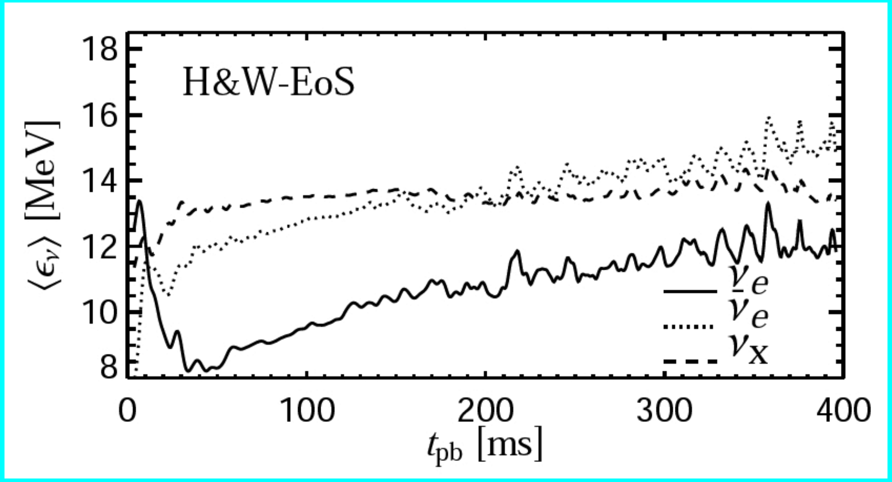
SASI Modulation of Neutrino Emission

- 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 :

$$\langle\epsilon_{\nu_e}\rangle < \langle\epsilon_{\nu_{\mu,\tau}}\rangle \lesssim \langle\epsilon_{\bar\nu_e}\rangle \qquad \text{but :} \qquad \langle\epsilon_{\nu_e}\rangle_{\rm rms} < \langle\epsilon_{\bar\nu_e}\rangle_{\rm rms} < \langle\epsilon_{\nu_{\mu,\tau}}\rangle_{\rm rms}$$



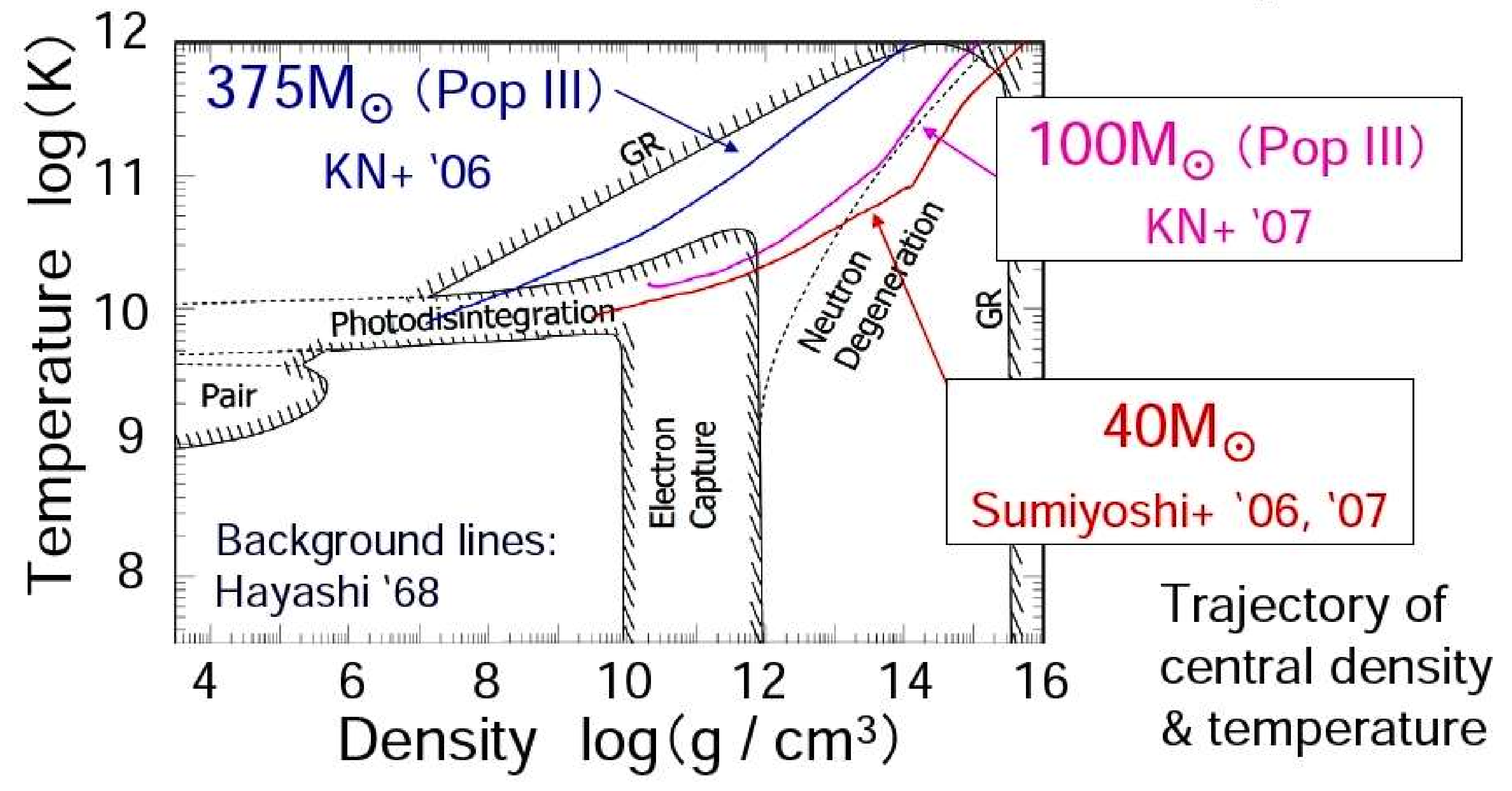
Lattimer & Swesty (soft nuclear) EoS



Wolff & Hillebrandt (stiff nuclear) EoS

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

Neutrino Signals from BH formation

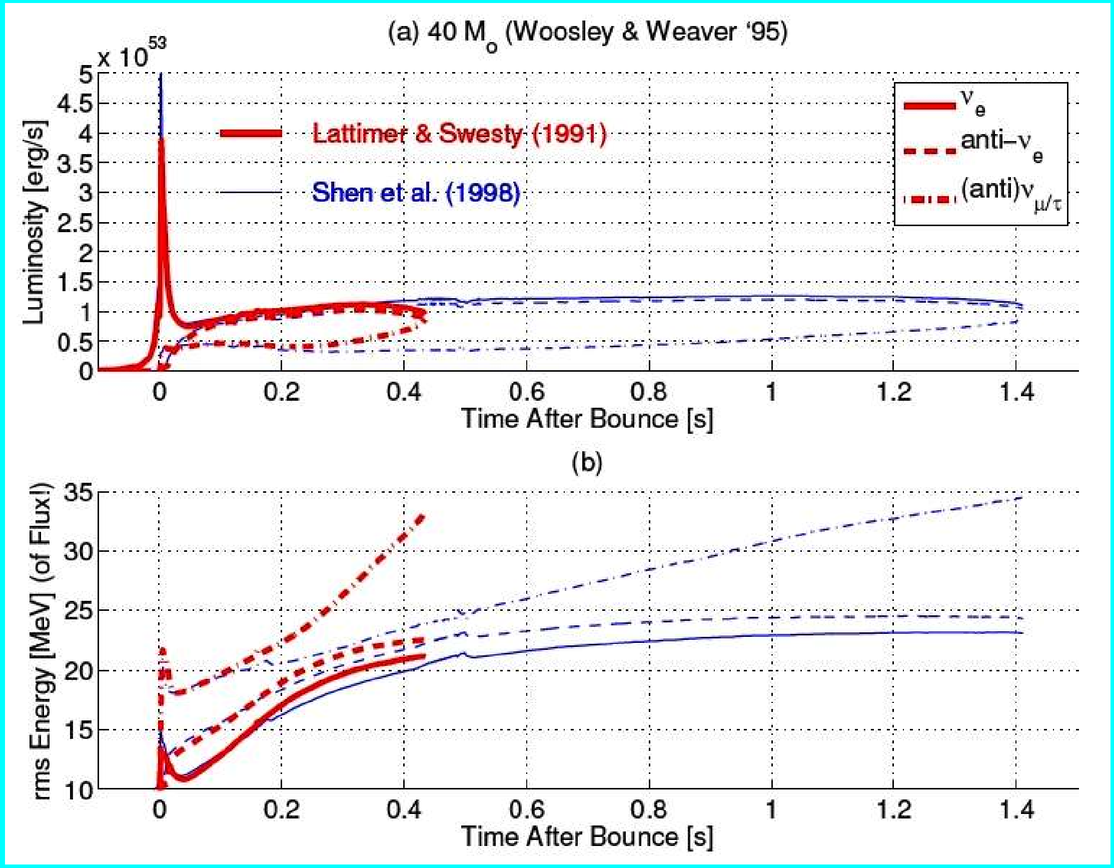


Trajectory of central density & temperature

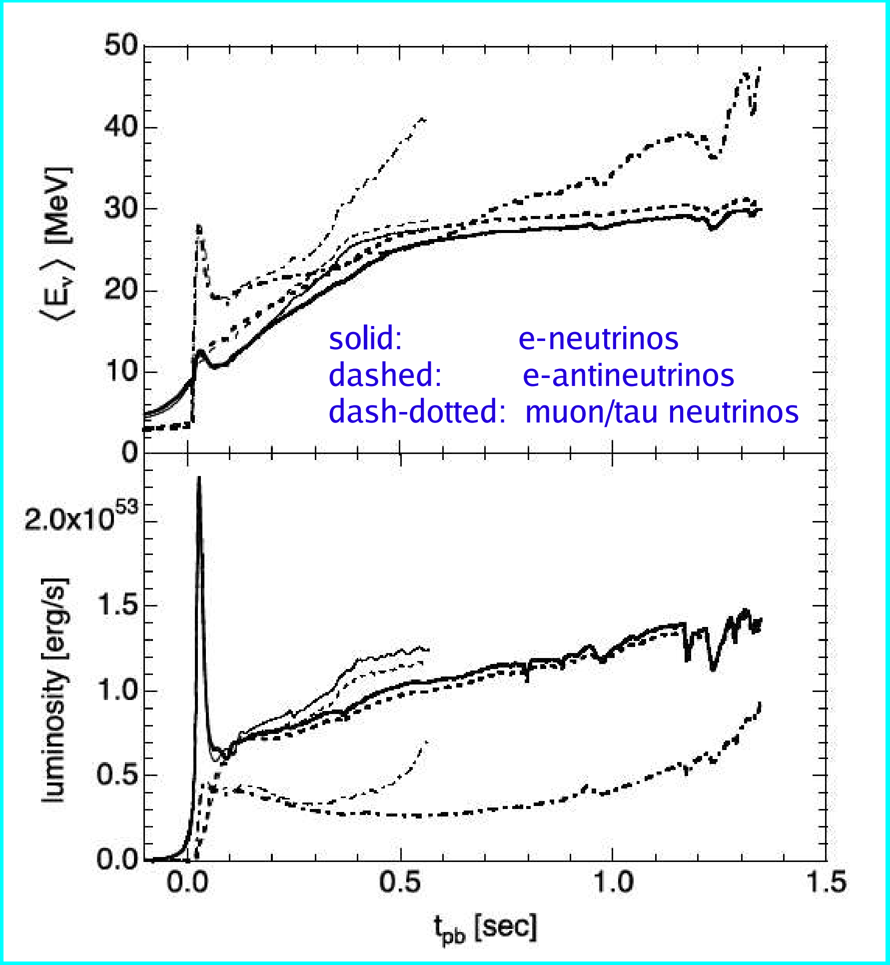
Nakazato, Ringberg Talk (March 2008)

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)

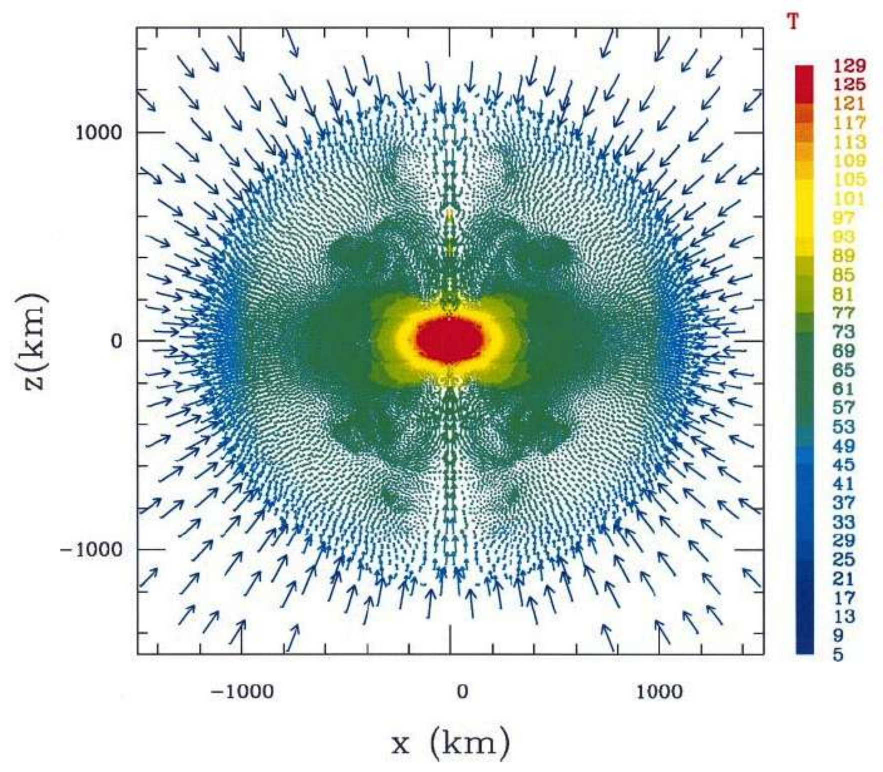


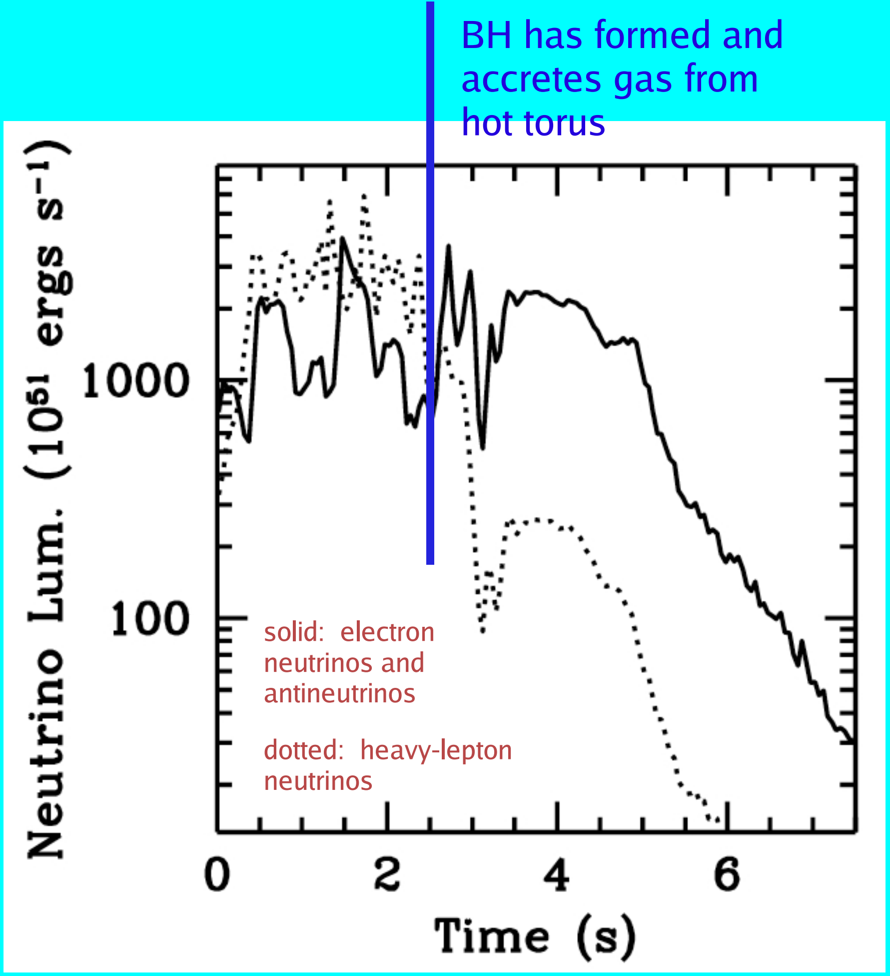
Sumiyoshi et al., PRL 97, 091101 (2006)

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

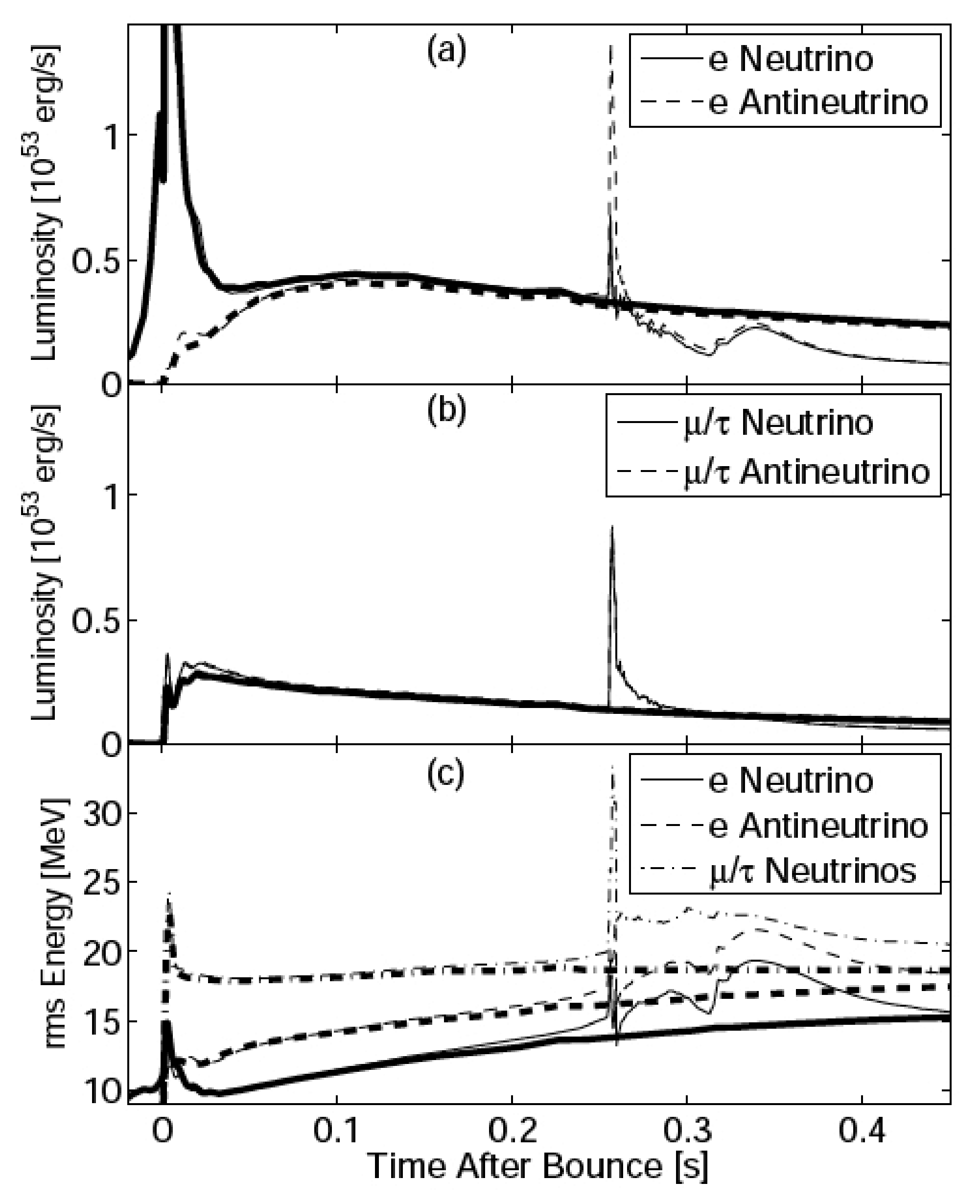
solid: electron neutrinos and antineutrinos

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

- Routes of core-collapse modeling:
  2D, 3D models with full GR, neutrinos, different microphysics;
  long-time simulations
- Direct observational constraints would be extremely useful!
- Neutrino and GW signals from CC supernovae are unique probes of the physics inside the supernova core and nascent NS
- Measuring SN neutrinos and GWs could help us understanding explosion dynamics/mechanism and properties of NS matter
- We may need luck to catch a Galactic supernova!
  Detectors with long run times are necessary!
  (low Galactic event rate: 2-3 SNe/100 years)

  Sensitivity for detection of SN signals from Virgo Cluster (>20 Mpc) highly desirable!