Max-Planck-Institut für Astrophysik

SFB-TR7

TUM LMU Excellence Cluster Universe

Realtime Astroparticle Physics
Bonn, February 4-6, 2013

Predictions of Neutrino and Gravitational-Wave Signals from Stellar Explosions

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Supernova and neutron star merger research is team effort

Heinzi-Ado Arnolds (MPA, 2012)

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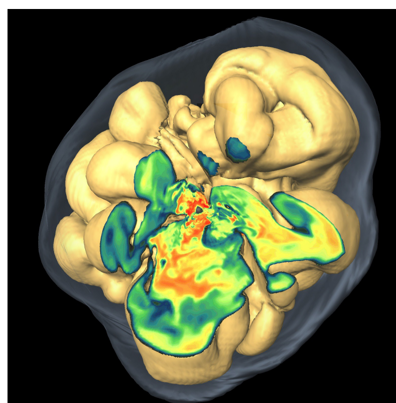

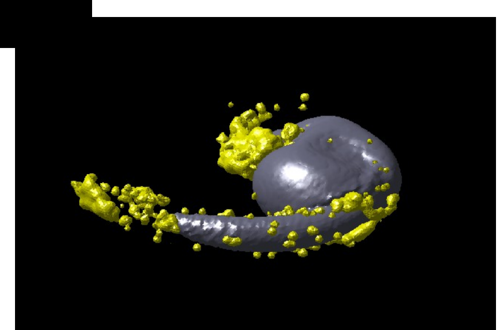

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For concise reviews of most of what I will say, see

ARNPS 62 (2012) 407, arXiv:1206.2503
and
PTEP 2012, 01A309, arXiv:1211.1378

REVIEWS IN ADVANCE

Explosion Mechanisms of Core-Collapse Supernovae

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Outline

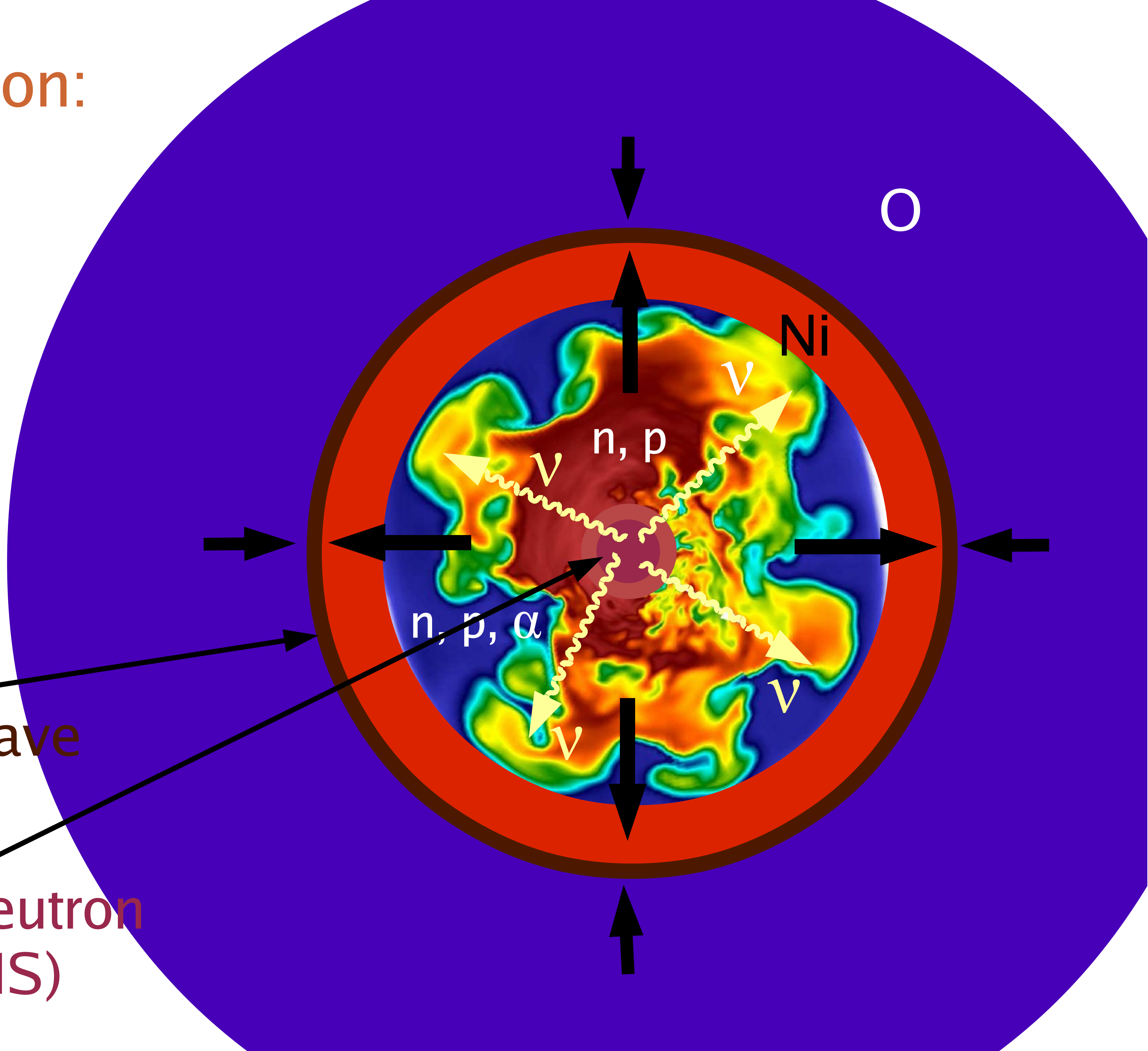
- Introduction to core-collapse supernova dynamics; the neutrino-driven mechanism
- Status of self-consistent models in two and three dimensions
- Neutrinos and gravitational-wave signal predictions for supernovae
- Neutron-star mergers: Constraining the NS EOS by measuring gravitational waves and optical counterparts

Explosion Mechanism
by
Neutrino Heating

Explosion:

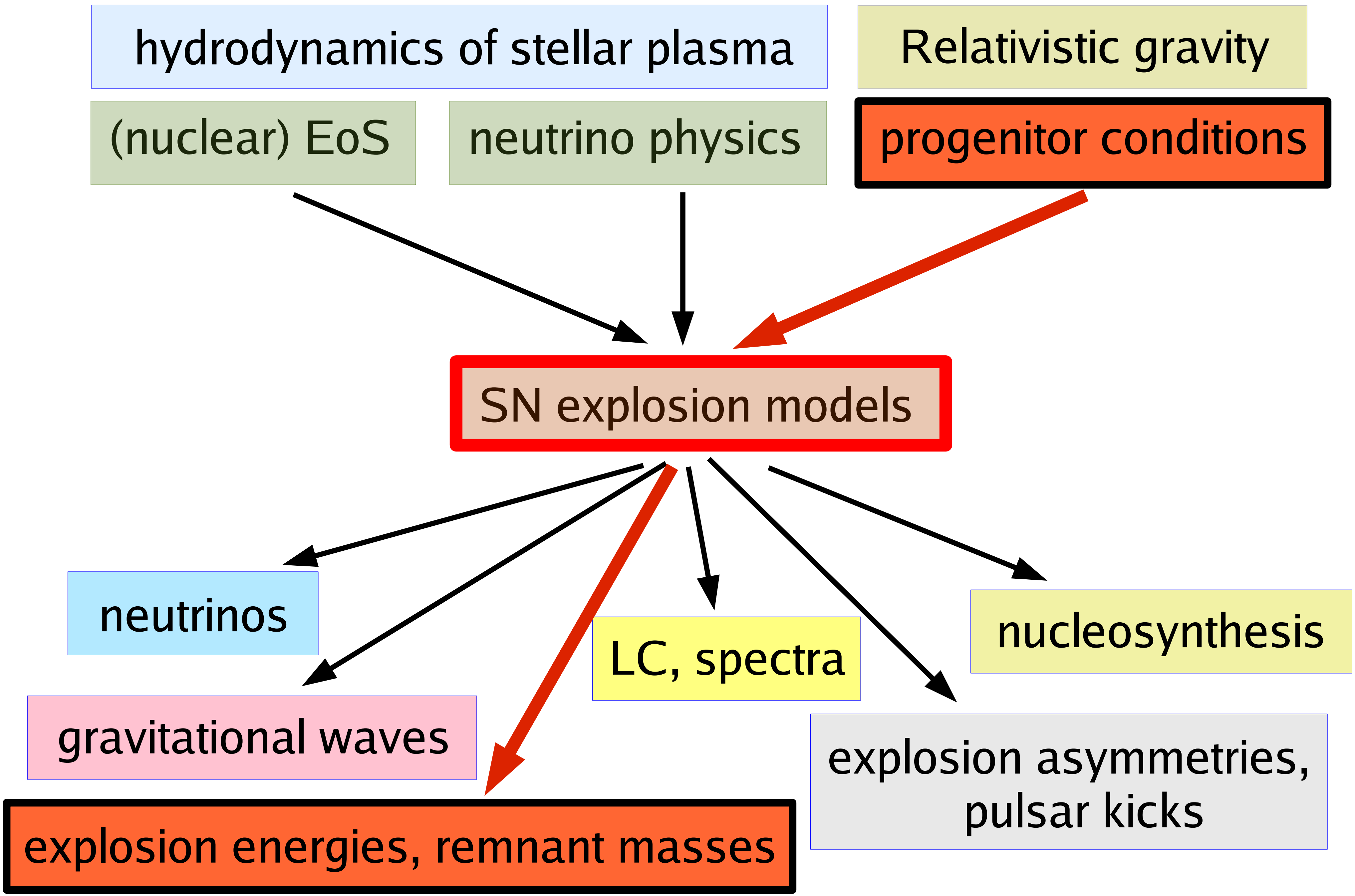
Shock wave expands into outer stellar layers, heats and ejects them.

Creation of radioactive nickel in shock-heated Si-layer.



Explosion Mechanism: Most Sophisticated Current Models

Predictions of Signals from SN Core



General-Relativistic 2D Supernova Models of the Garching Group

(Müller B., PhD Thesis (2009); Müller et al., ApJS, (2010))

GR hydrodynamics (CoCoNuT)

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

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

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

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

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

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 (VERTEX)

$$\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:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

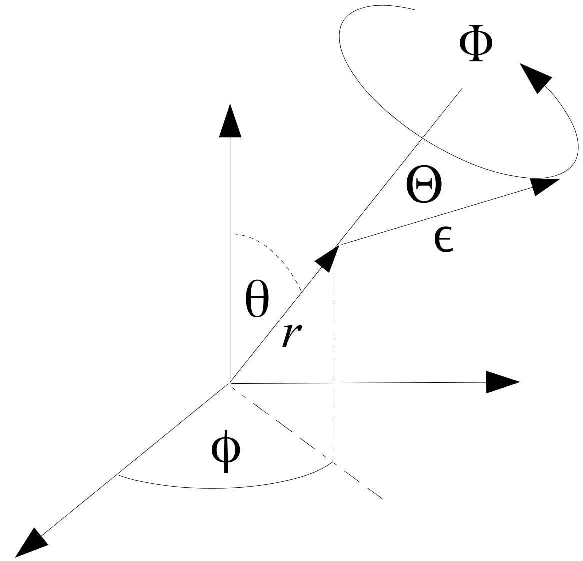
The Curse and Challenge of the Dimensions

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

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

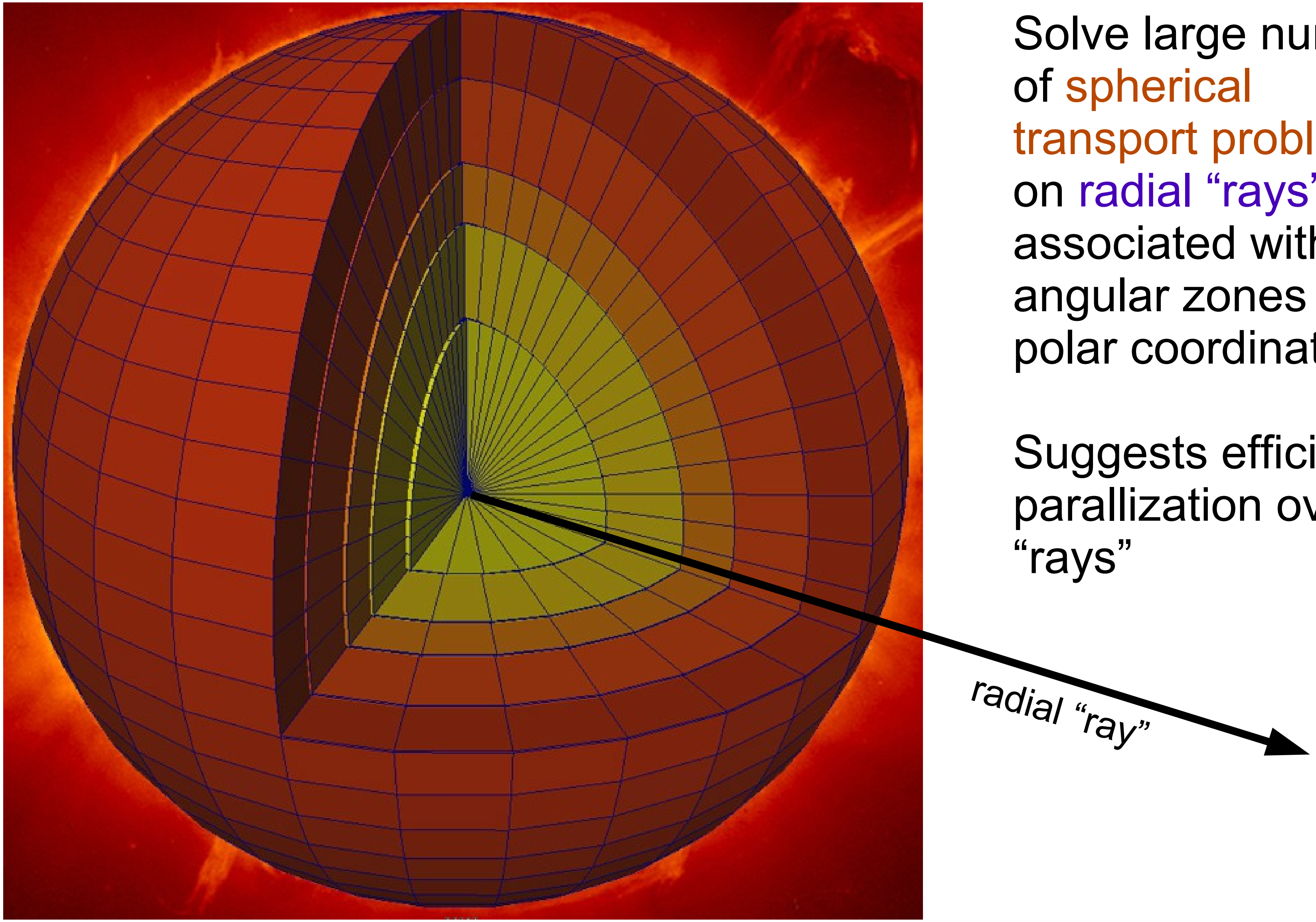
Integration over 3D momentum space yields source terms for hydrodynamics

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



Solution approach	**Required resources**
• **3D** hydro + **6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12)	• ≥ 10–100 PFlops/s (sustained!)
• **3D** hydro + two-moment closure of Boltzmann Eq. (next feasible step to full 3D; cf. Kuroda et al. 2012)	• ≥ 1–10 Pflops/s, TBytes
• **3D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• ≥ 0.1–1 PFlops/s, Tbytes
• **2D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• ≥ 0.1–1 Tflops/s, < 1 TByte

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



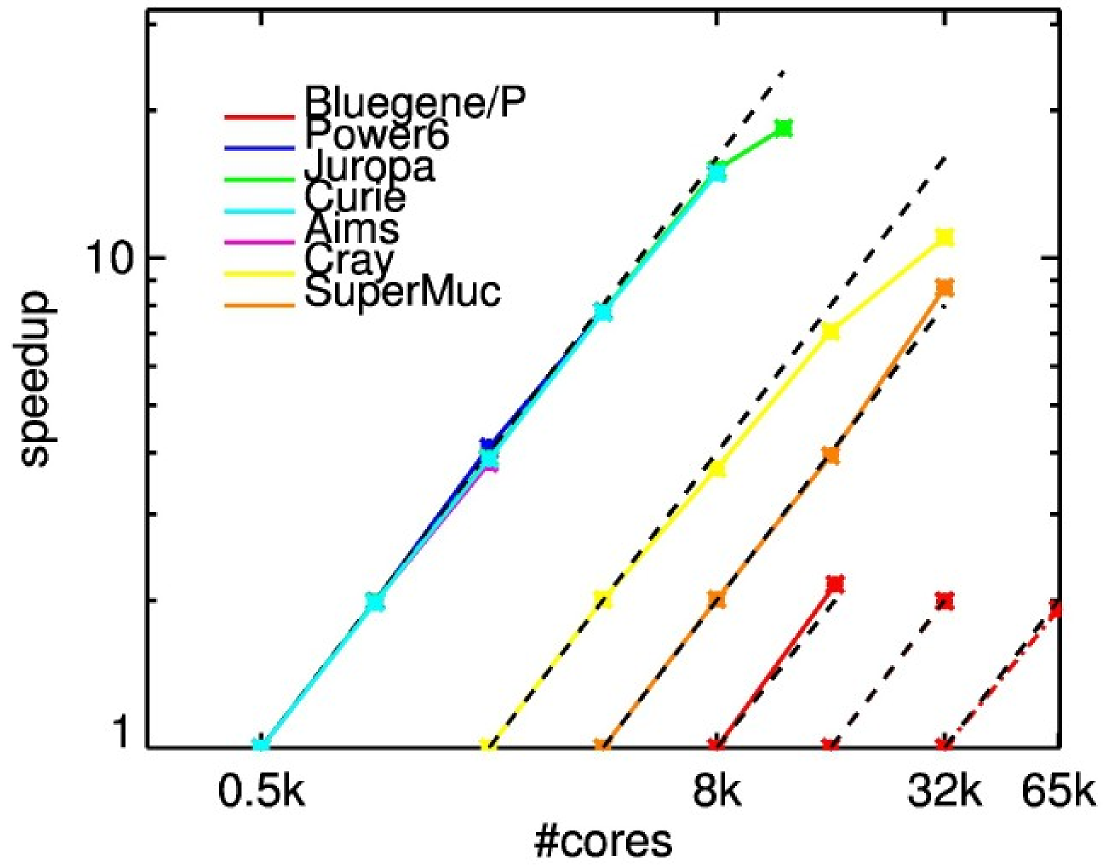
Solve large number of spherical transport problems on radial "rays" associated with angular zones of polar coordinate grid

Suggests efficient parallization over the "rays"

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

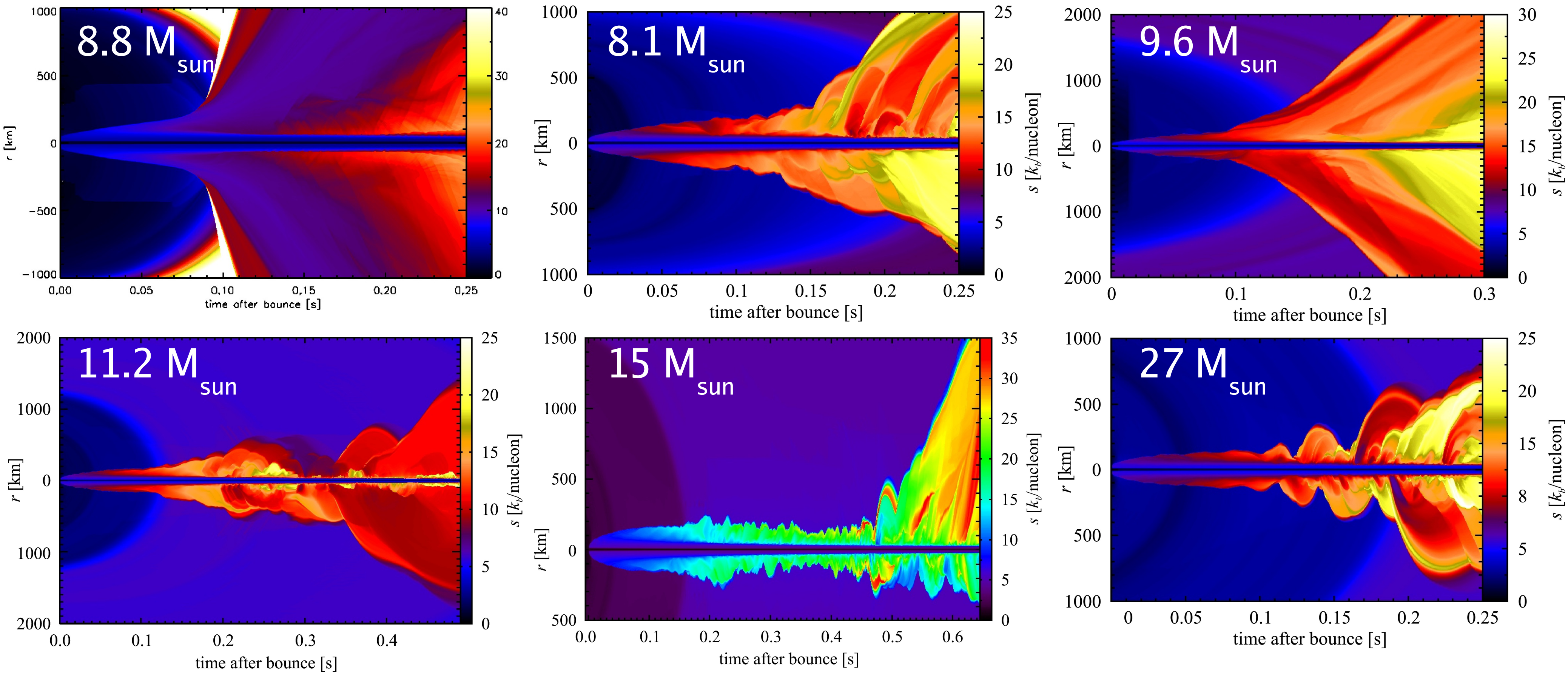
- Code employs hybrid MPI/OpenMP programming model (collaborative development with **Katharina Benkert, HLRS**).
- Code has been ported to different computer platforms by **Andreas Marek, High Level Application Support, Rechenzentrum Garching (RZG).**
- Code shows excellent parallel efficiency, which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

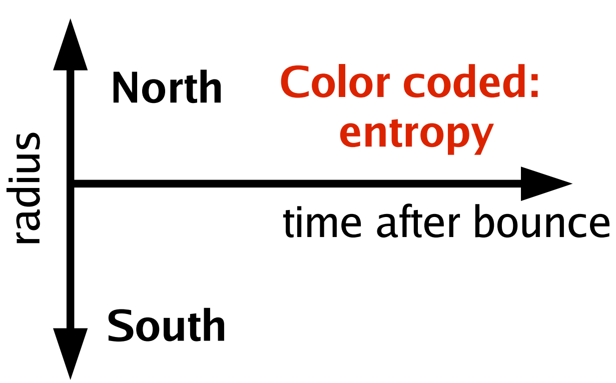
Strong Scaling



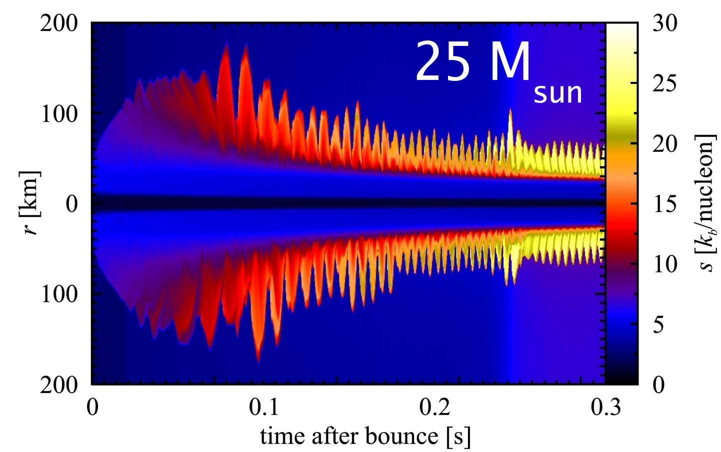
Andreas Marek, RZG (2012)

Relativistic 2D CCSN Explosion Models





Color coded: entropy

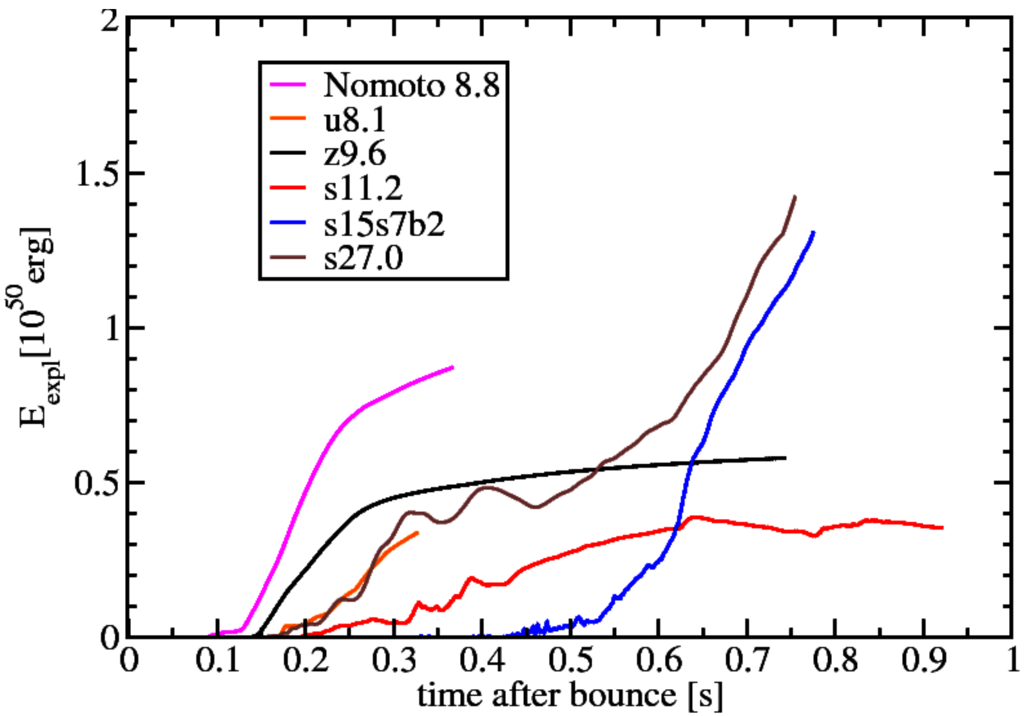


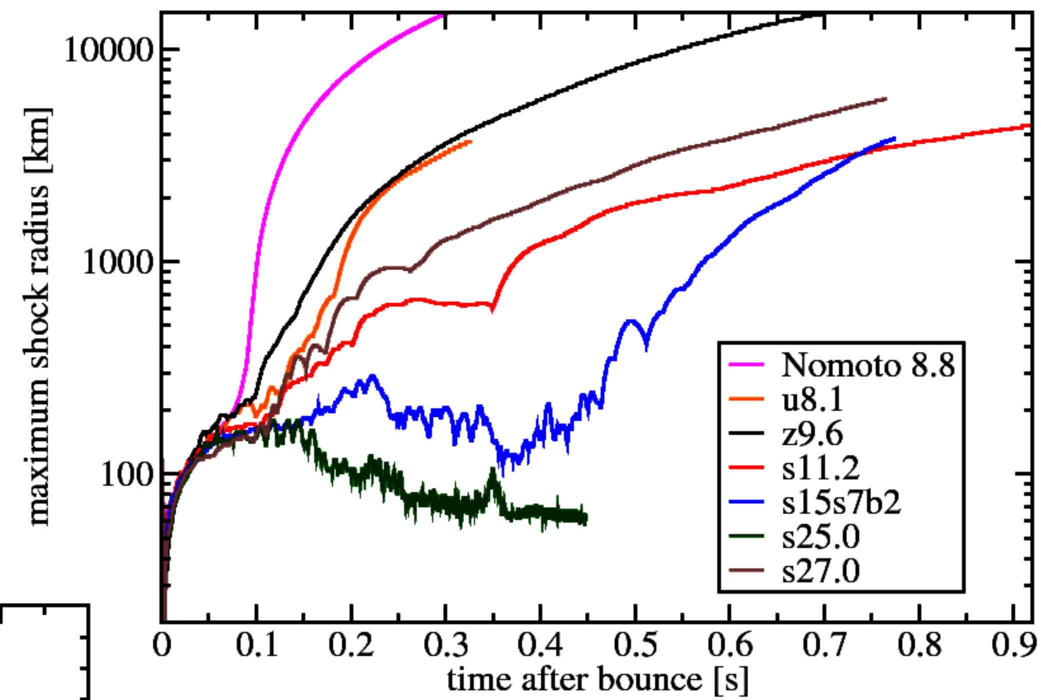
Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, arXiv:1210.6984

Basic confirmation of previous explosion models for 11.2 and 15 M_{sun} stars by Marek & THJ (2009)

Relativistic 2D CCSN Explosion Models

"Diagnostic energy" of explosion

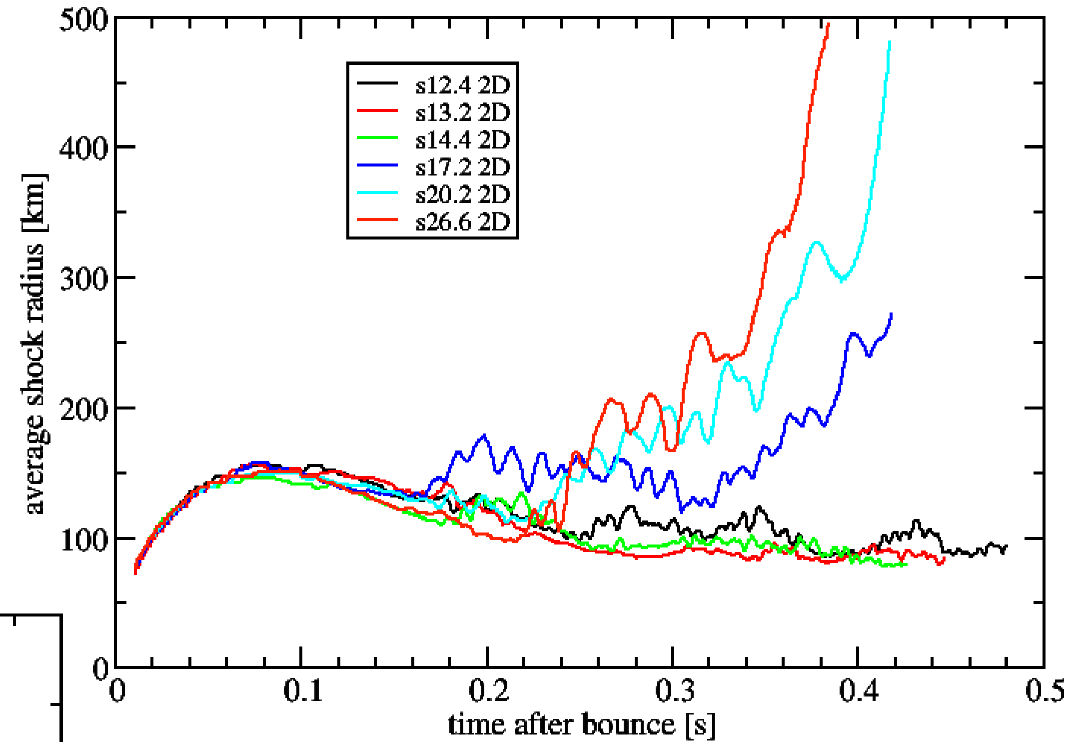




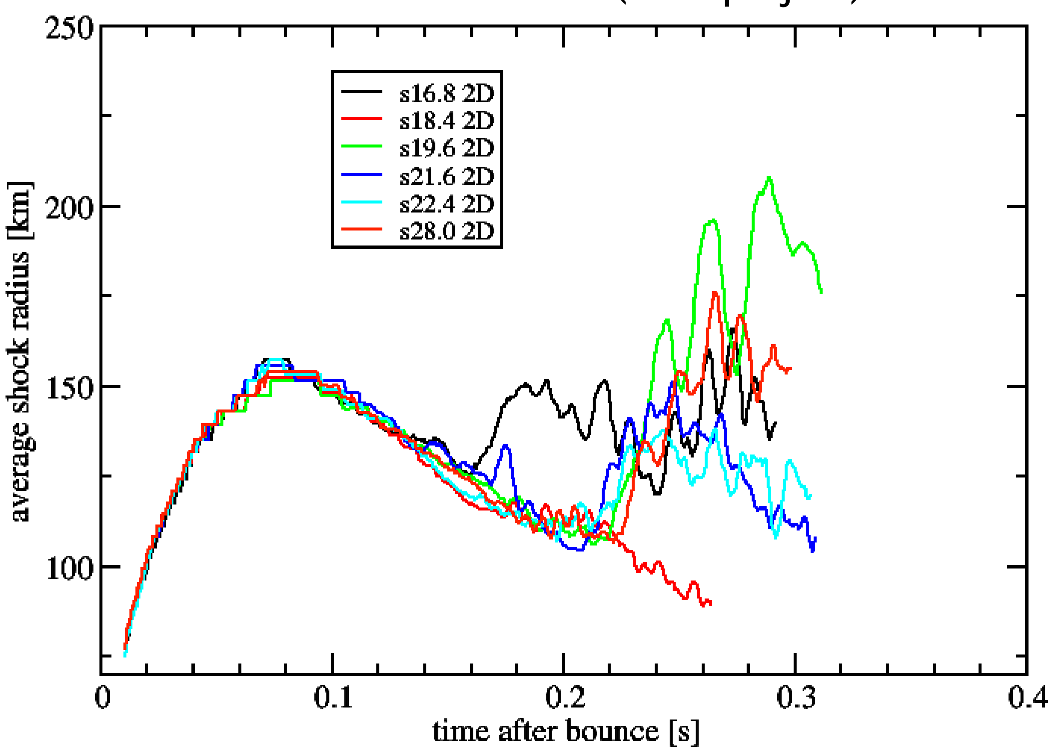
Maximum shock radius

Growing set of 2D CCSN Explosion Models

Average shock radius



Florian Hanke (PhD project)



Full-Scale 3D Core-Collapse Supernova Models with Detailed Neutrino Transport

3D Supernova Models

PRACE grant of 146.7 million core hours allows us to do the first 3D simulations on 16.000 cores.

PRACE
Partnership for Advanced Computing in Europe

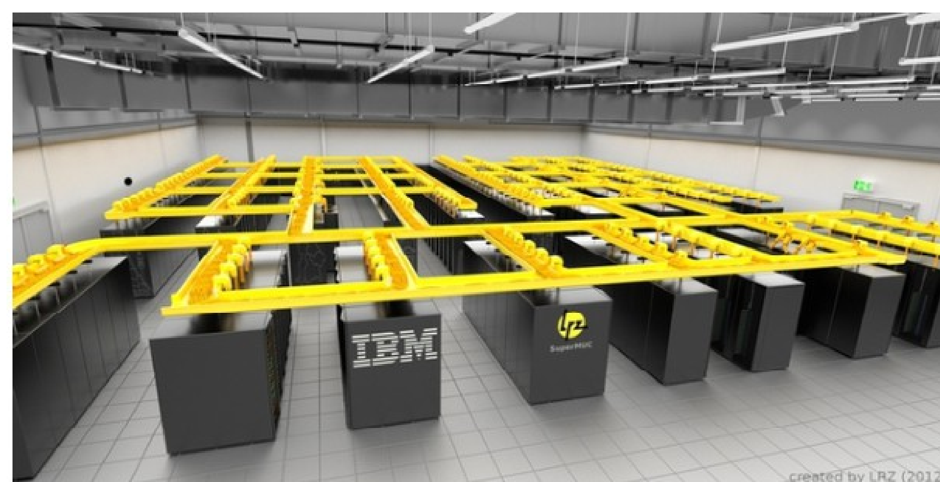
GENCI

TGCC Curie

TGCC

Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

SuperMUC Petascale System



Computing Requirements for 2D & 3D Supernova Modeling

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

CPU-time requirements for one model run:

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

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

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

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

PRACE Partnership for Advanced Computing in Europe

NIC

John von Neumann Institut für Computing

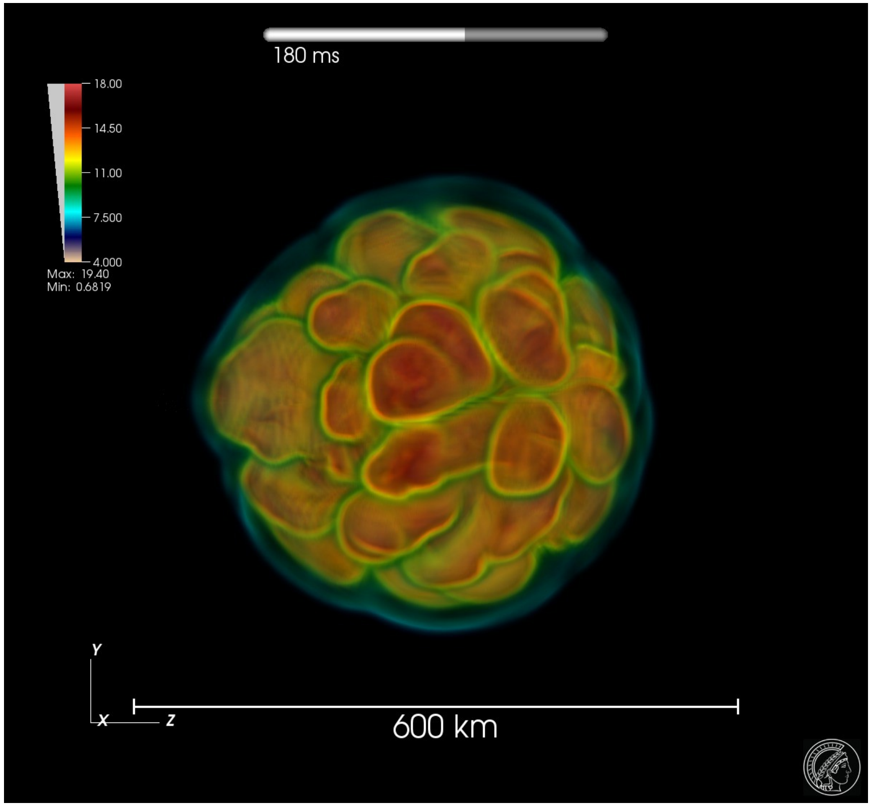
HLRS

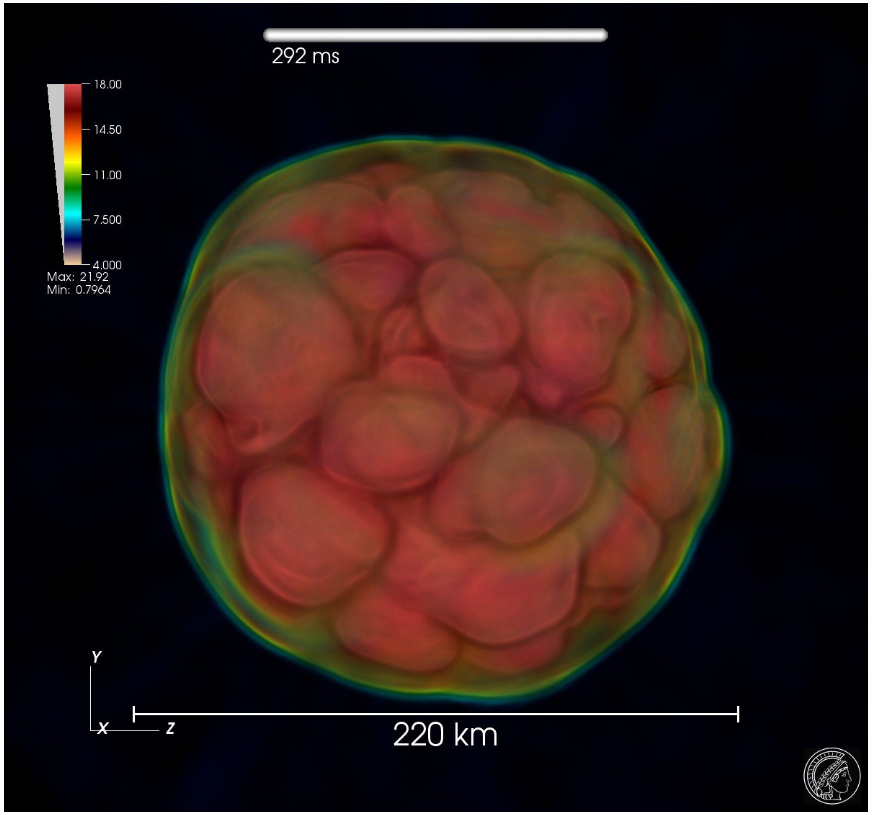
rzg IPP Rechen-Zentrum Garching

Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

3D Core-Collapse Models

11.2 M_{sun} progenitor

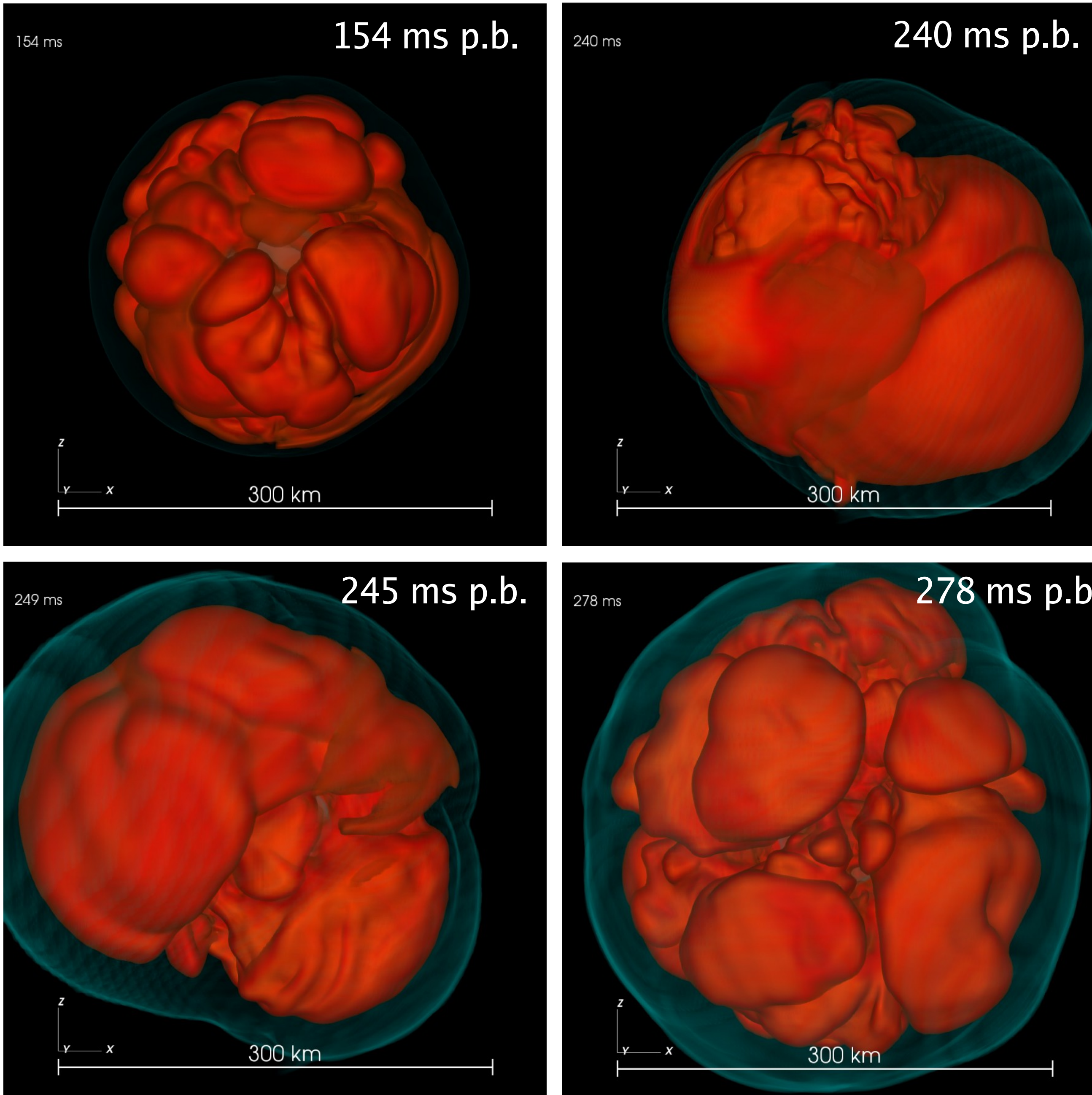




Florian Hanke, PhD project

3D Core-Collapse Models

27 M_{sun} progenitor

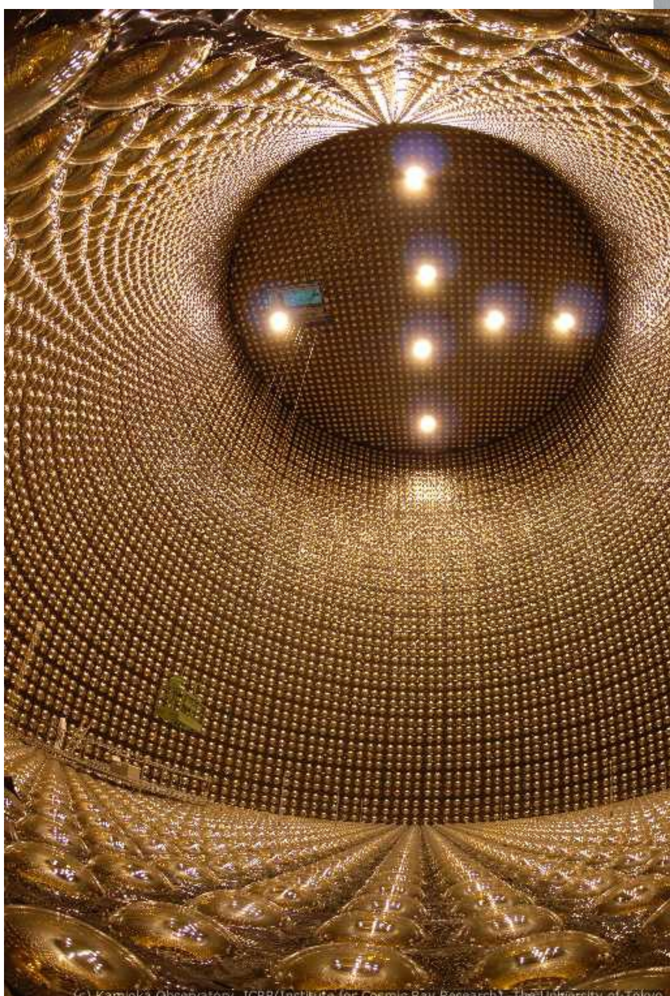


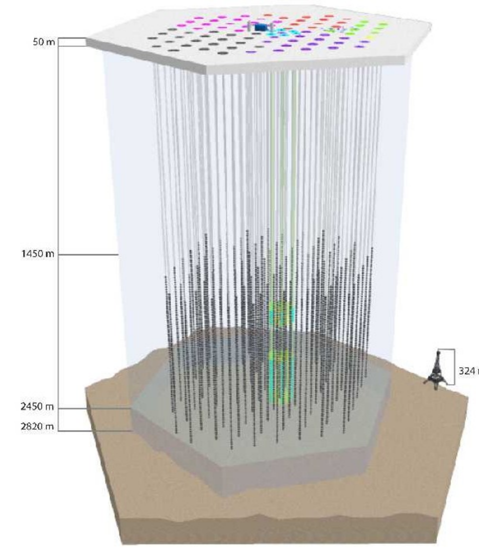
Florian Hanke,
PhD project

Neutrinos and Gravitational Waves from 2D & 3D Explosions

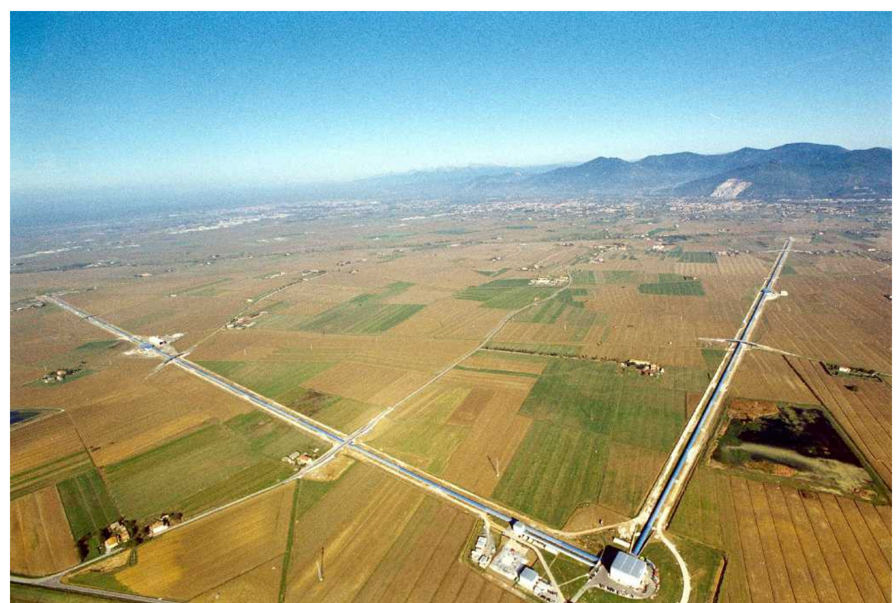
Detecting Core-Collapse SN Signals

Superkamiokande





IceCube

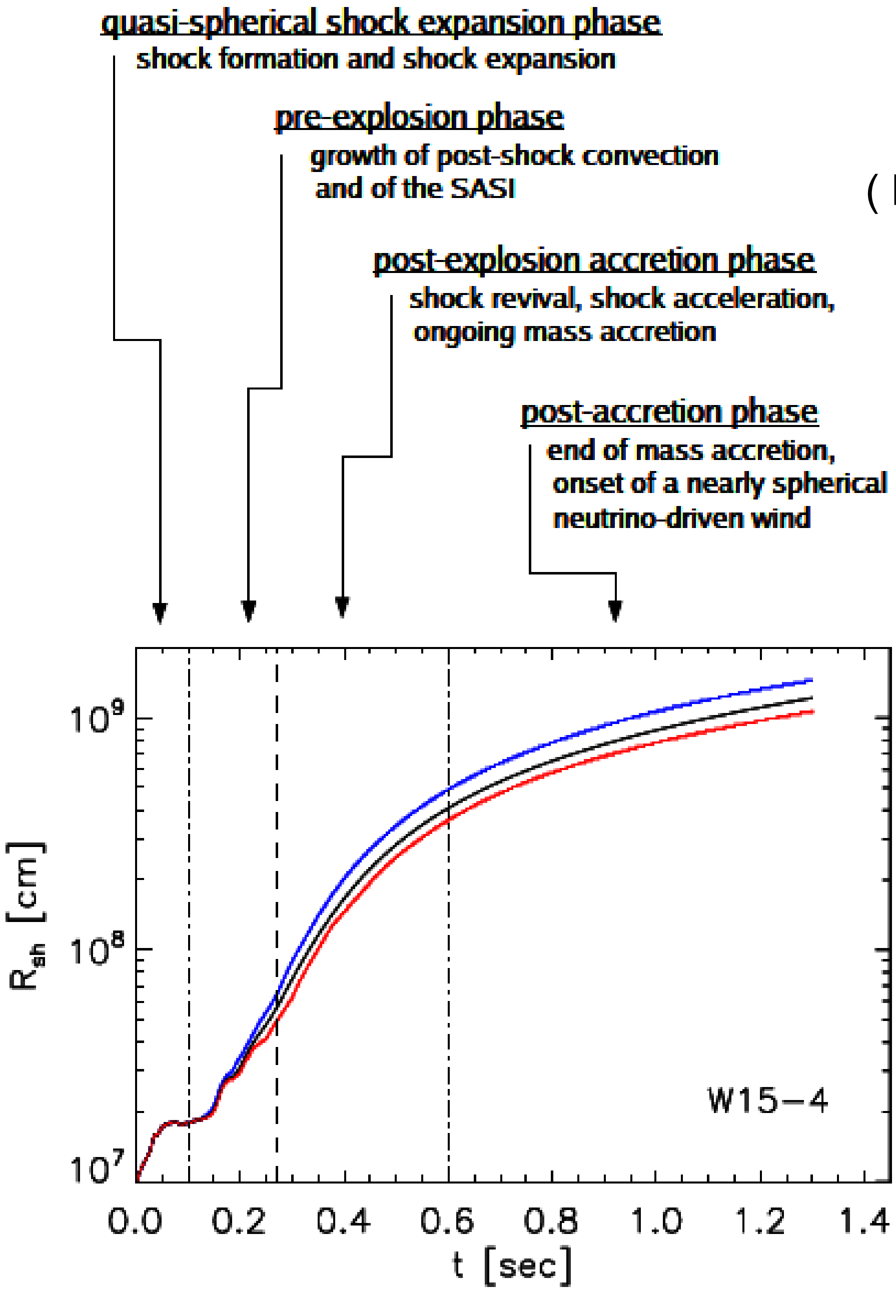


VIRGO

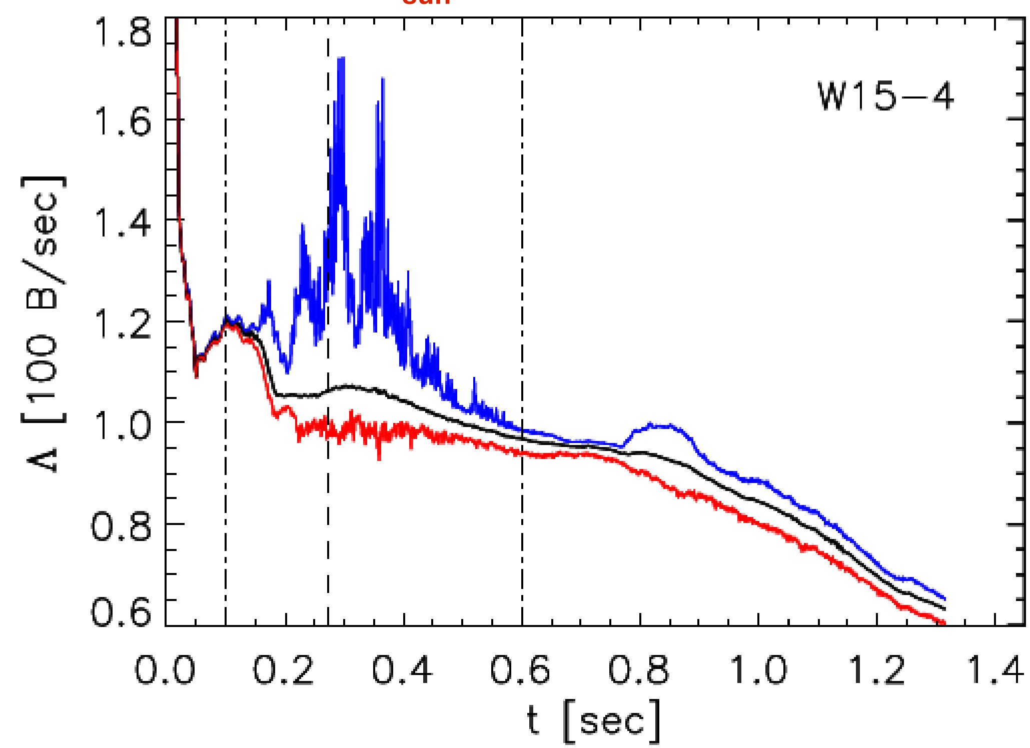
SN Explosions: Neutrinos and Gravitational Waves

Activity phases after core bounce

(Müller E., THJ, Wongwathanarat, A&A 537 (2012) A63)



15 M_{sun} progenitor star



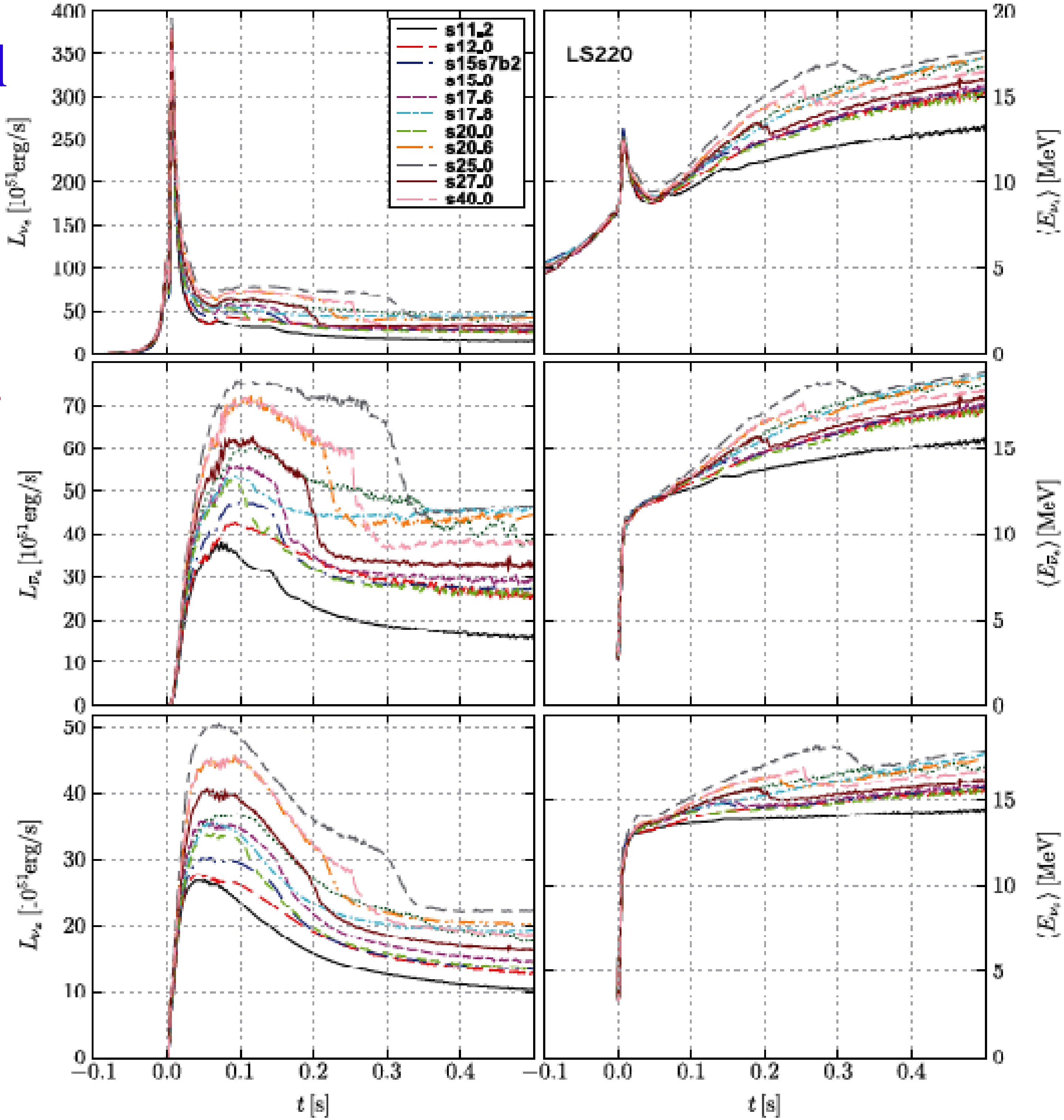
Neutrino Signal Phases

- Neutrino deleptonization burst and first ~50–100 ms after bounce are generic, i.e.,fairly independent of stellar conditions;
  measurement may allow to constrain neutrino properties, e.g. mass hierarchy.

- Subsequent accretion phase depends on progenitor star and SN explosion mechanism;
  measurement will provide valuable information about SN dynamics.

- Post-explosion neutrino signal from cooling proto-neutron star depends sensitively on neutron star properties;
  measurement may help to constrain nuclear (NS) equation of state.

Neutrino Signal After Core Bounce

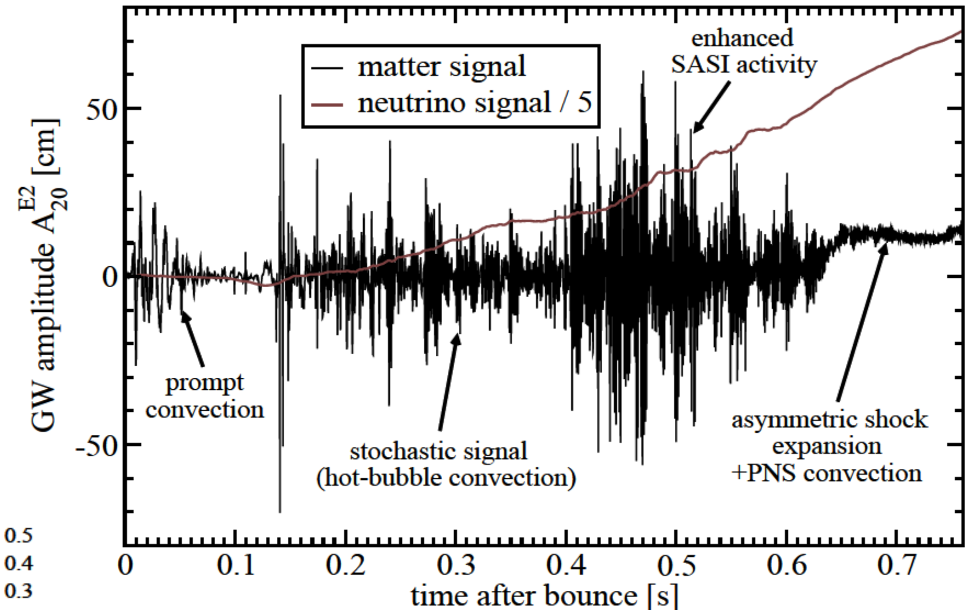


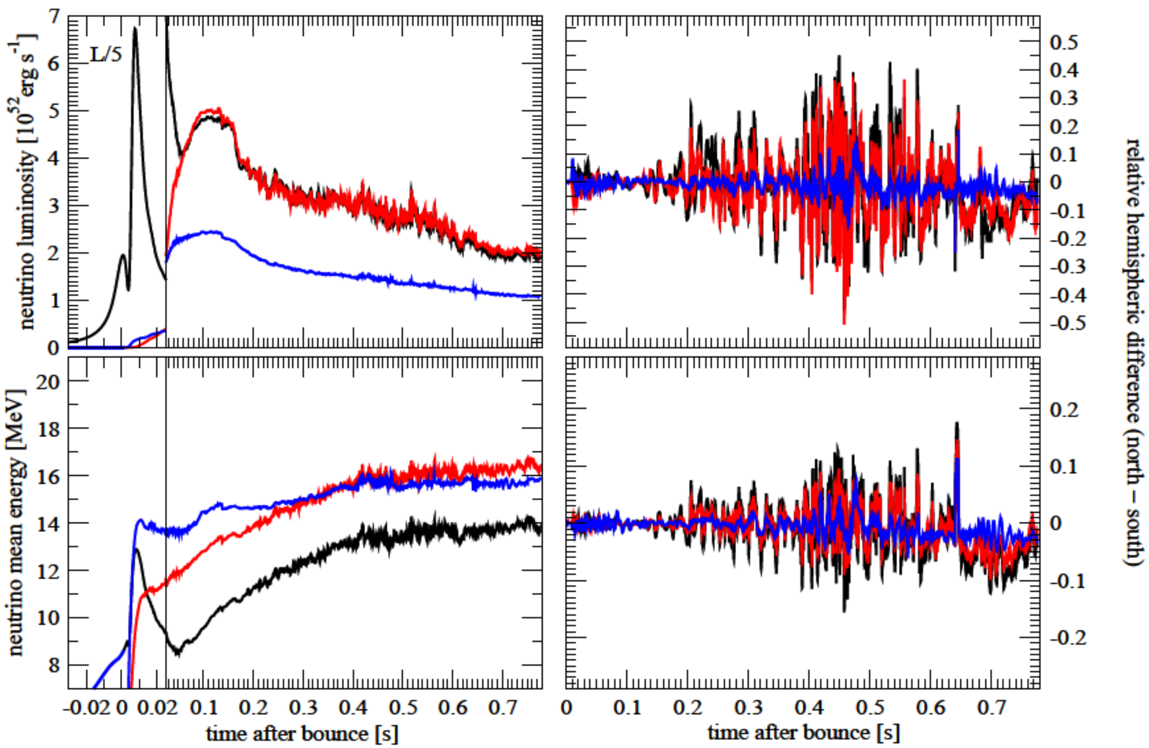
Deleptonization burst and first ~50–100 ms are generic

L. Hüdepohl, PhD Project;
THJ et al. (PTEP, 2012)

SN Explosion Models: Neutrinos and Gravitational Waves

(Müller B., THJ, Marek, ApJ 756 (2012) 84;
Müller B., THJ, Marek, arXiv: 1210.6984)

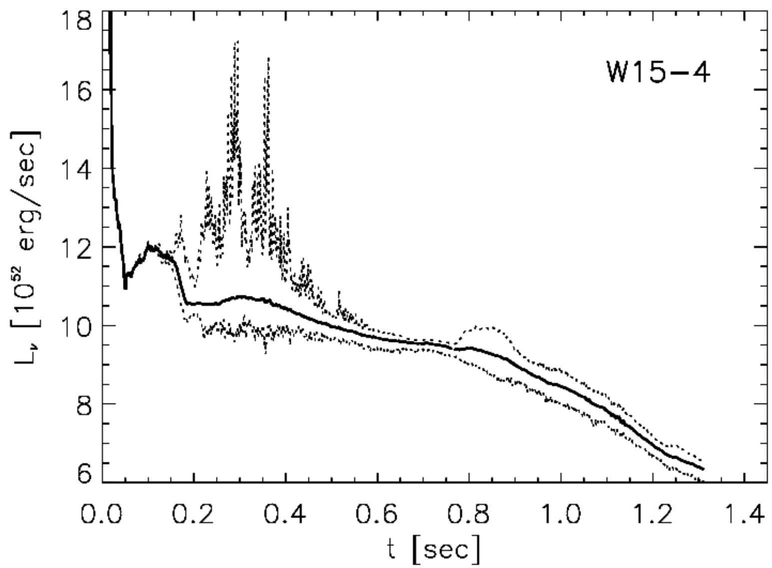


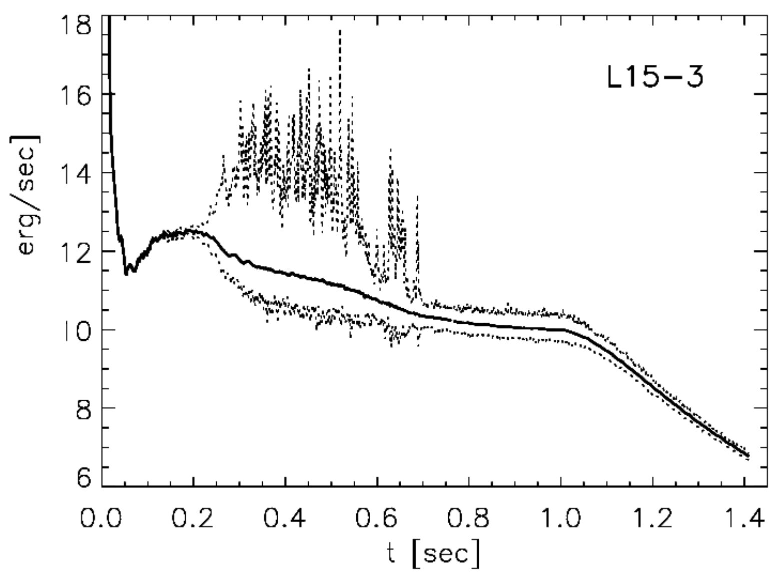


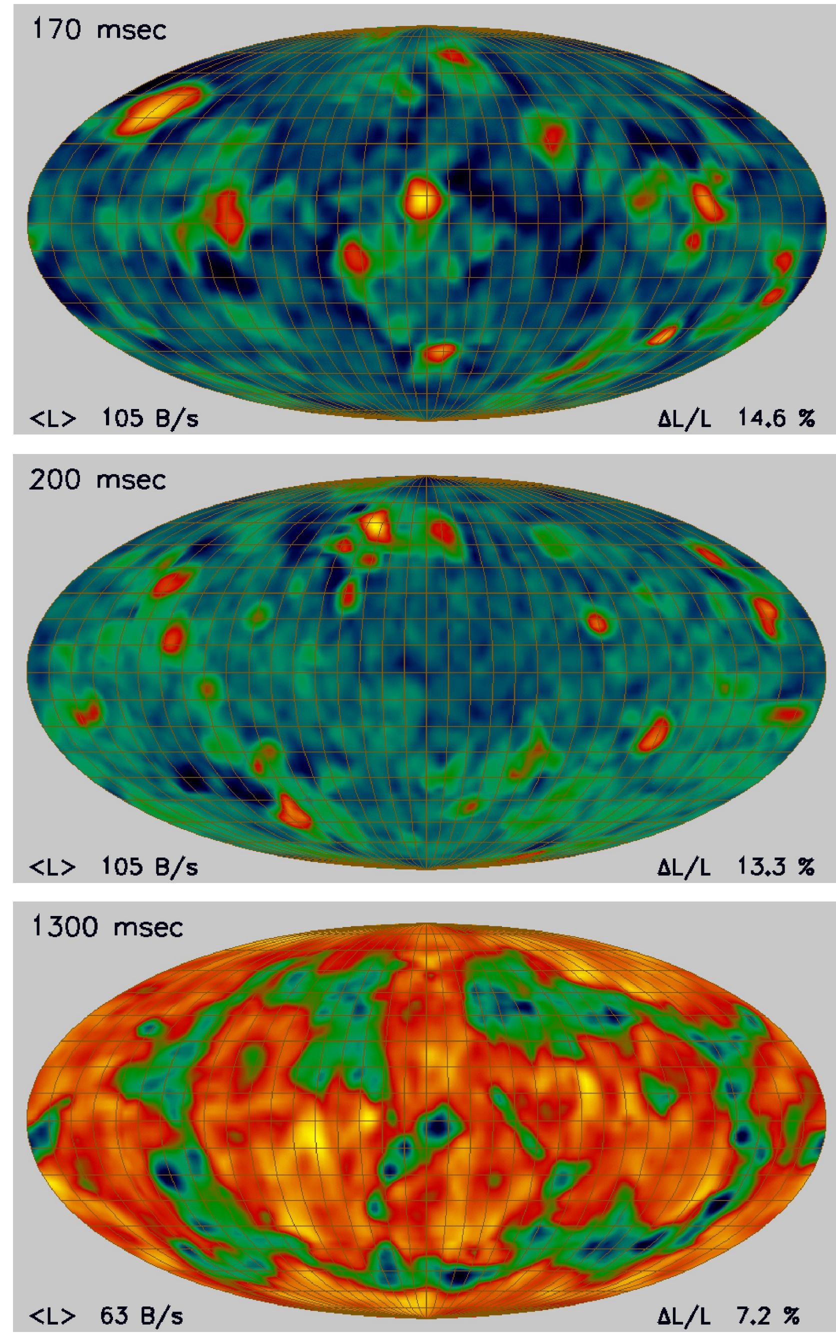
15 M_{sun} progenitor star

Neutrinos from 3D SN Models

Neutrino luminosities and emission asymmetries for 15 M_{sun} explosion.



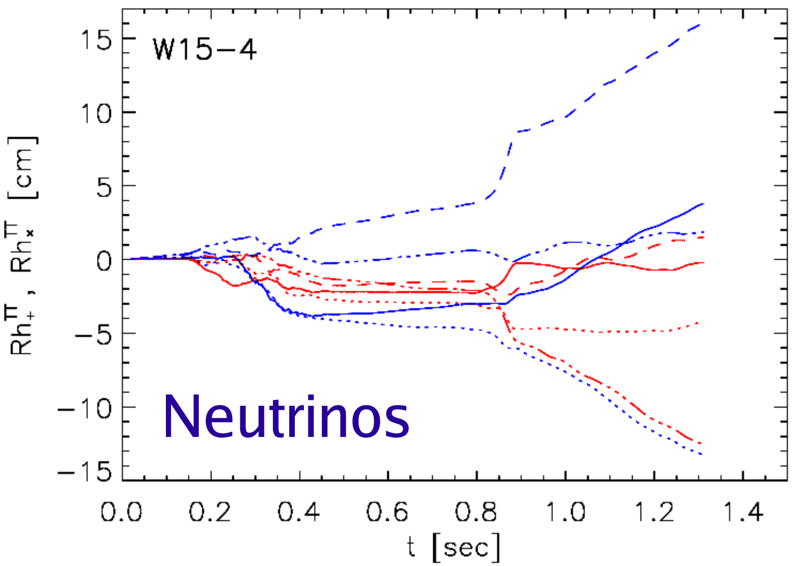


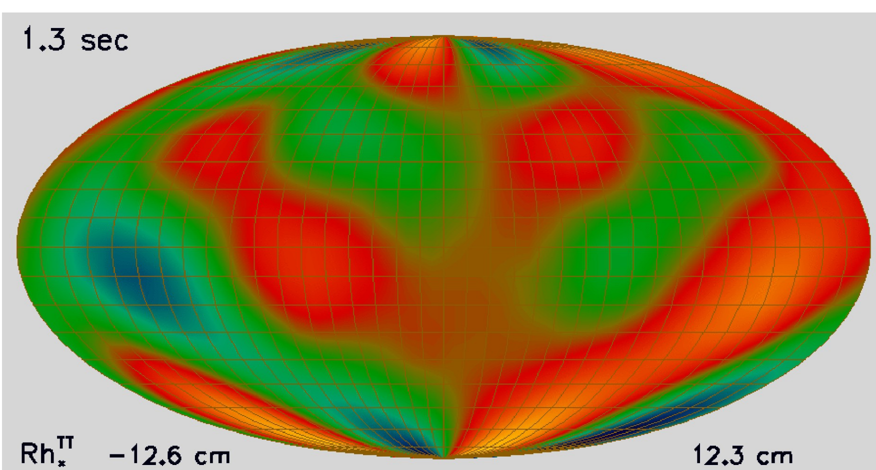


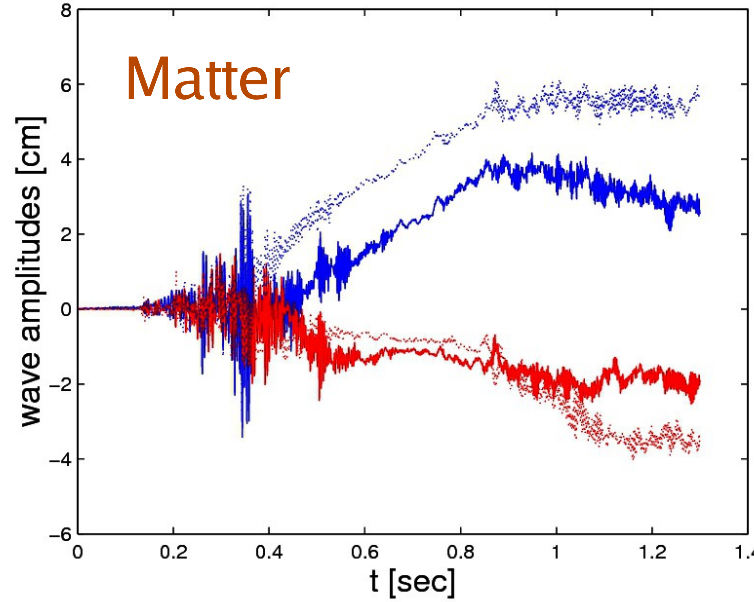
(Müller E., THJ, Wongwathanarat, A&A 537 (2012) A63)

Neutrinos from 3D SN Models

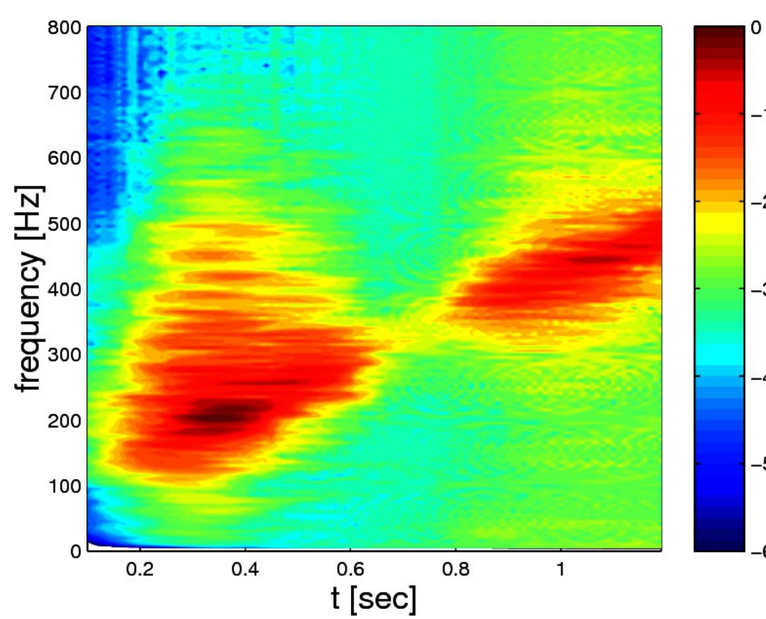
Matter and neutrino gravitational-wave signals for 15 M_{sun} explosion.





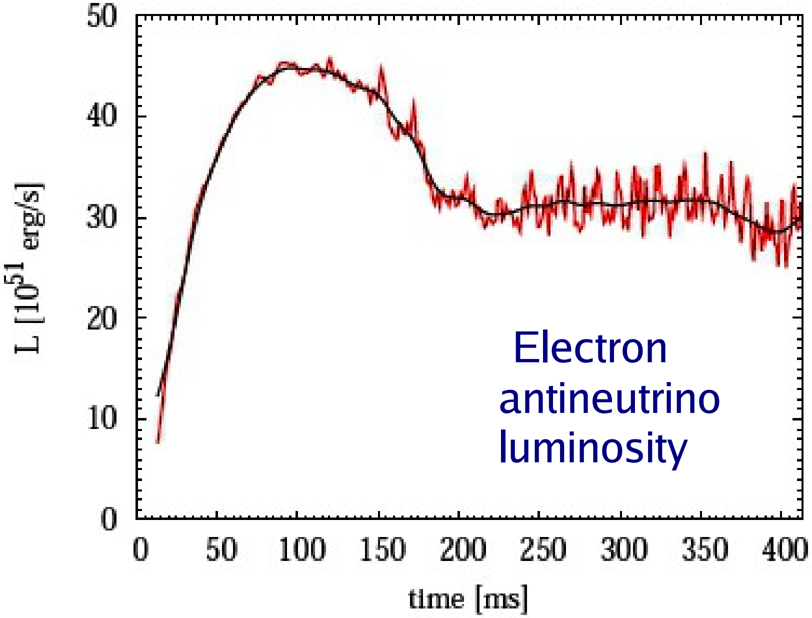


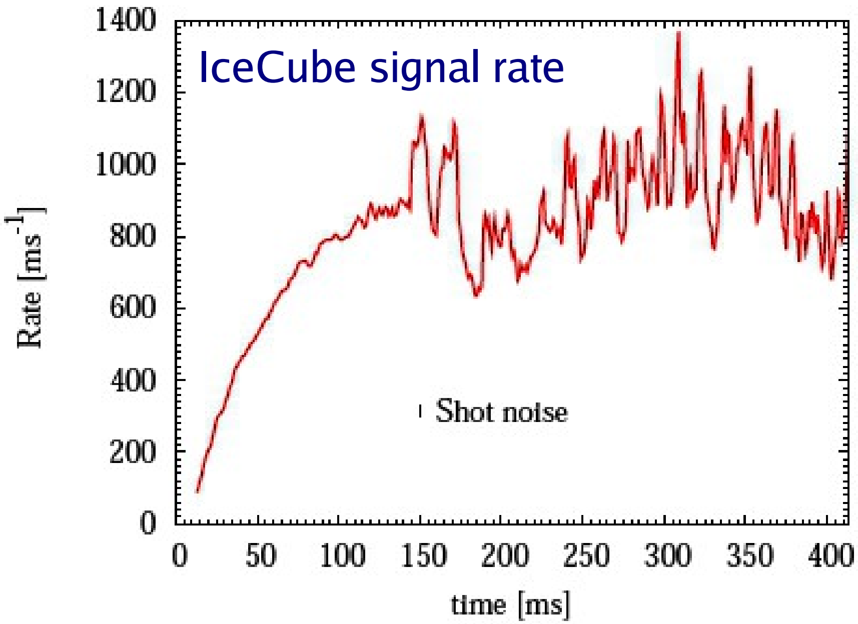
W15−4



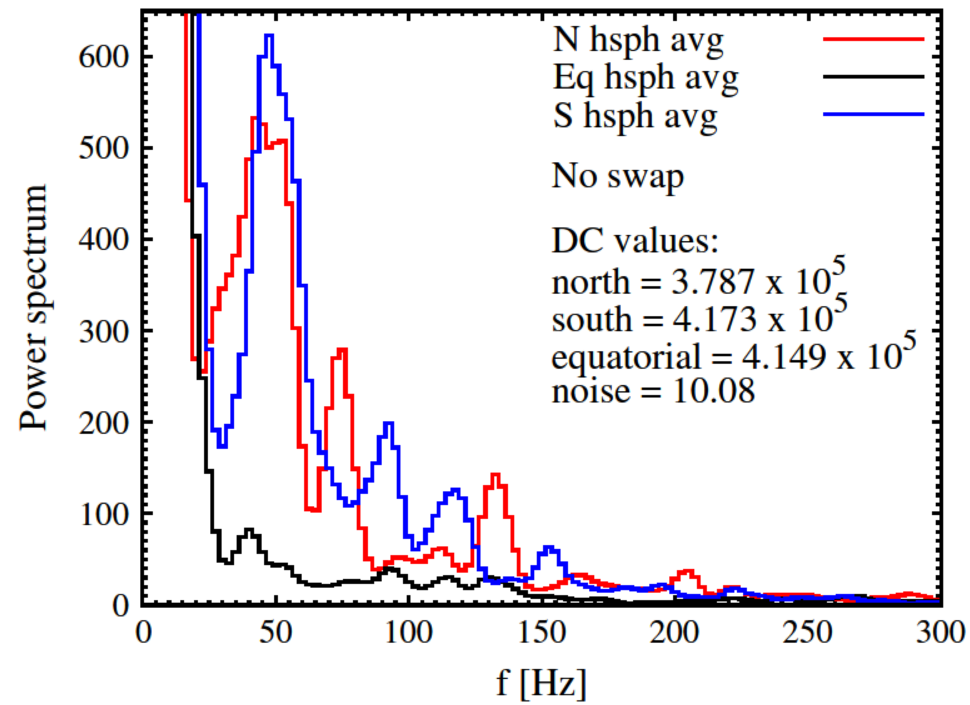
(Müller E., THJ, Wongwatharanat, A&A 537 (2012) A63)

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





Lund et al., PRD 82 (2010); PRD 86 (2012)

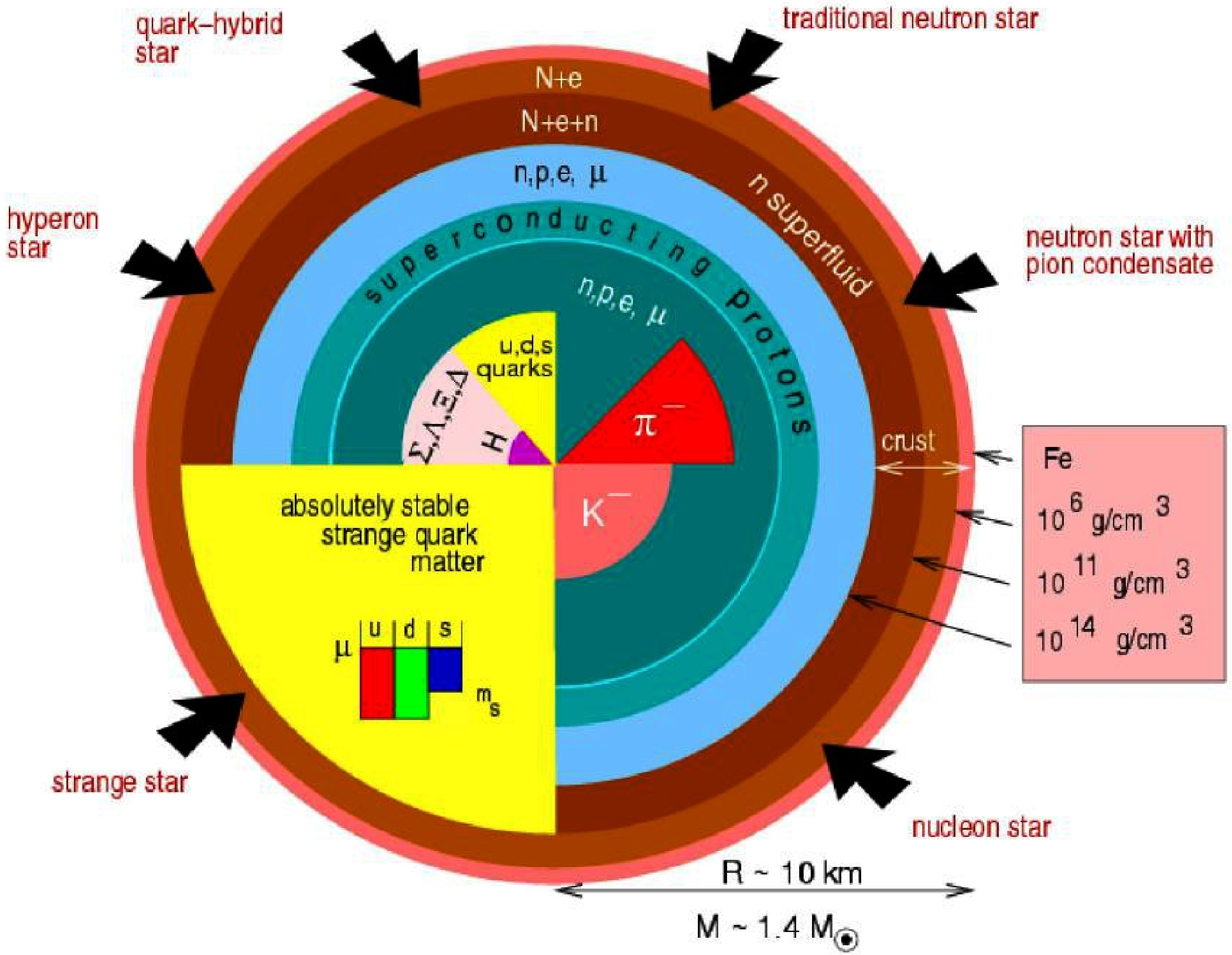


For a galactic supernova:

- Variations of neutrino emission clearly detectable with ICECUBE for D(SN) = 2...10 kpc
- Gravitational waves should be observable with advanced LIGO and VIRGO

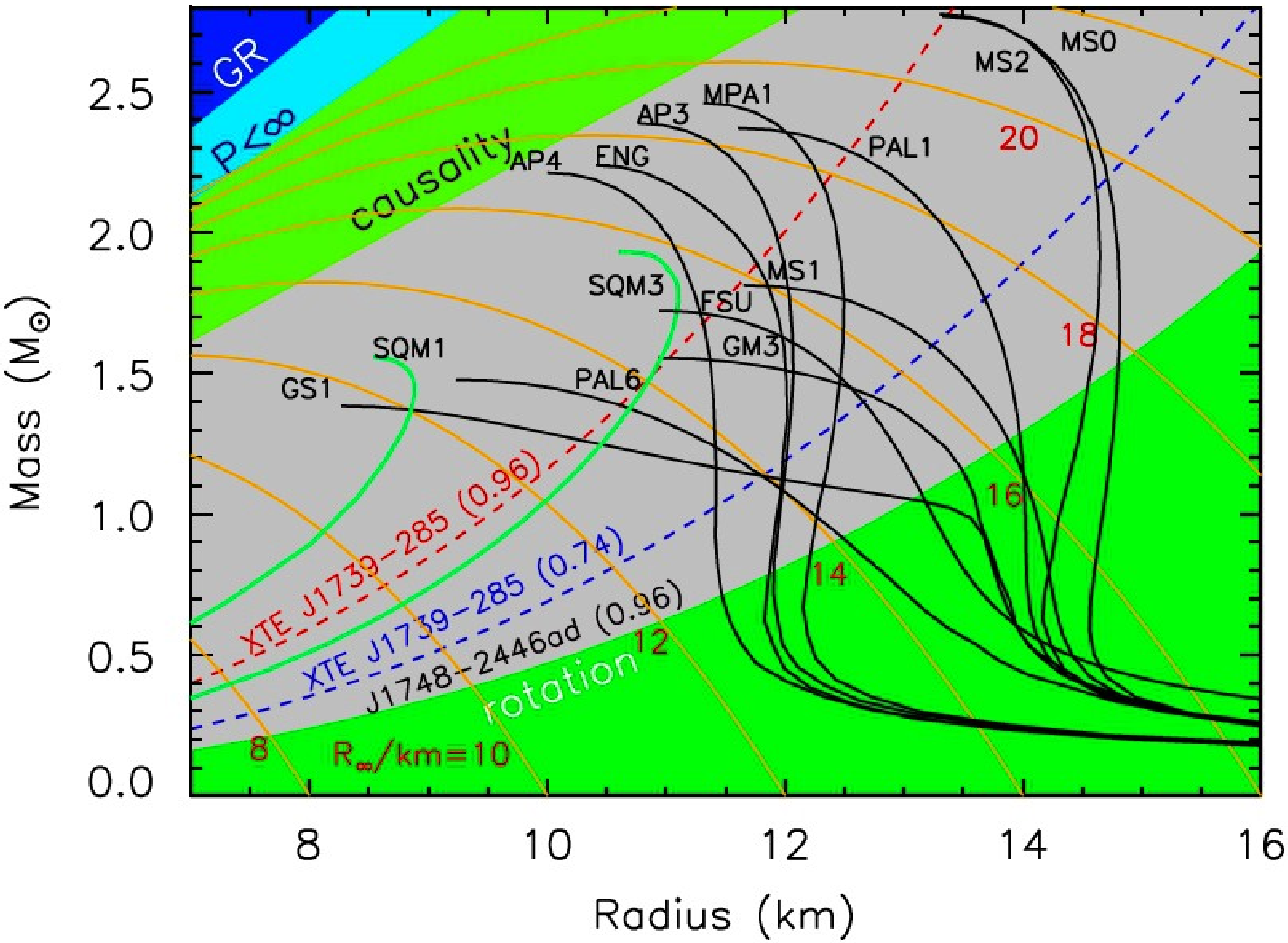
Neutron Star Equations of State

Neutron star EoS is crucial ingredient but incompletely known!



(Source: F. Weber)

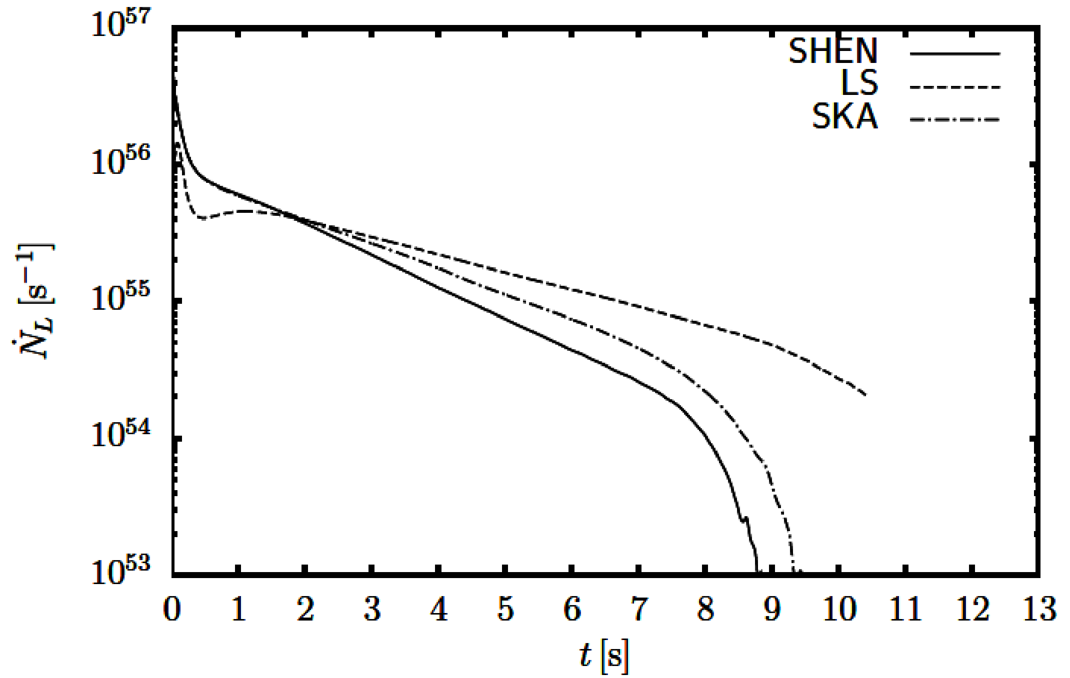
Neutron Star Equations of State



- 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!

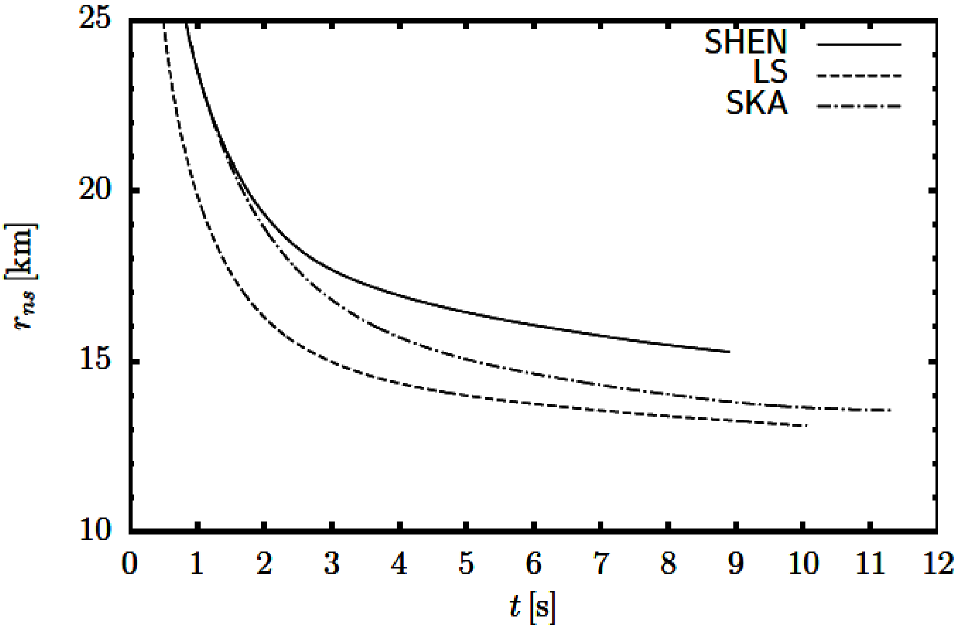
Lattimer & Prakash, Phys. Rep. 442 (2007)

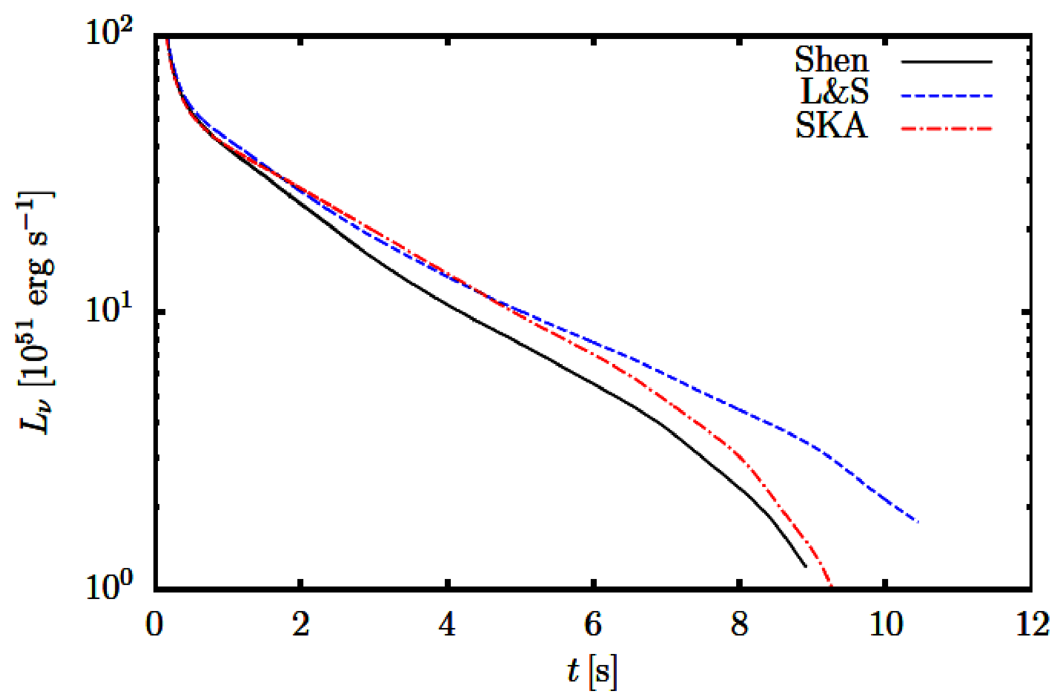
Proto-Neutron Star: Neutrino-Cooling Signal



Signal duration and decline depends on the nuclear equation of state and NS properties.

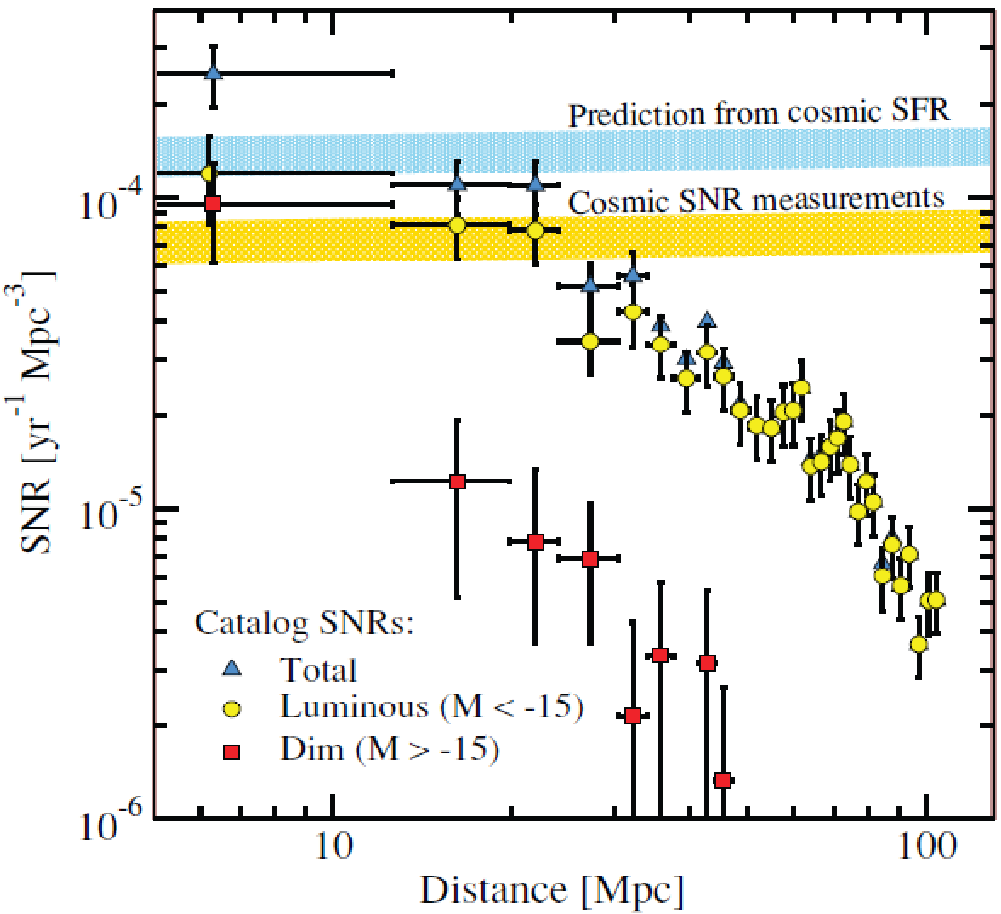
L. Hüdepohl, Diploma Thesis, TUM (2009)



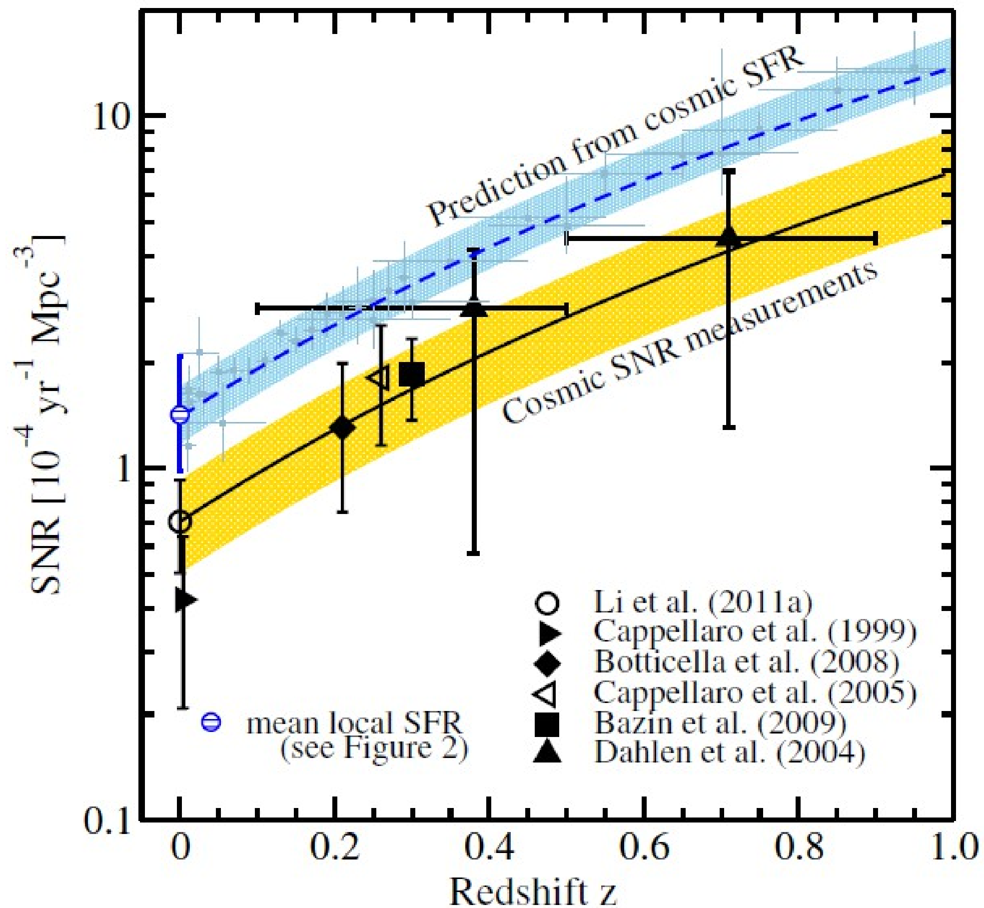


Star Formation Rate and Supernova vs. Black Hole Formation Rate

SFR and SNR in local universe



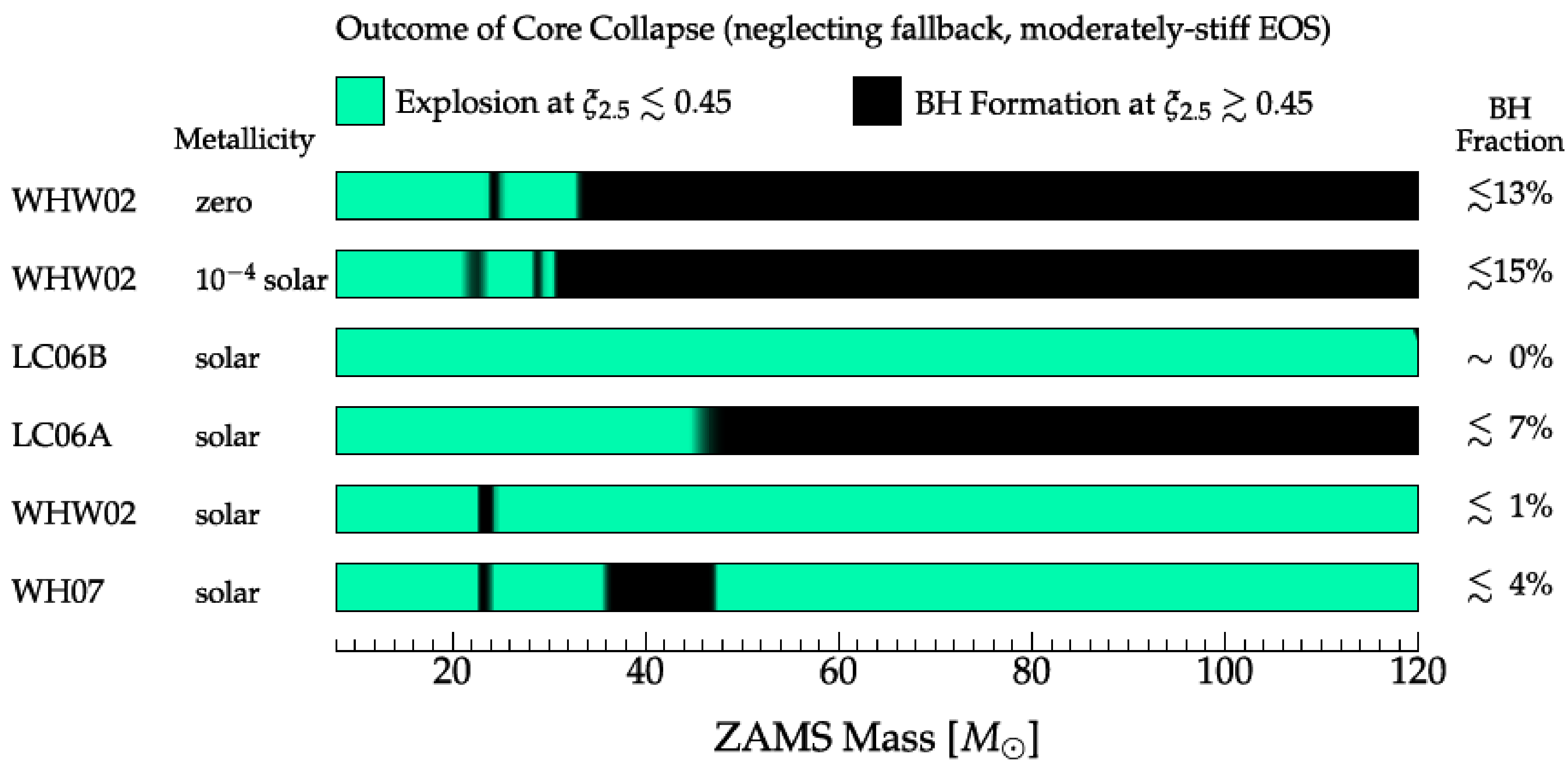
SFR and SNR in distant universe



Horiuchi et al., ApJ 738 (2011) 154

Progenitor-Explosion and SN-Remnant Connections

NS and BH Regimes



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

Large Set of 1D SN Explosion Models

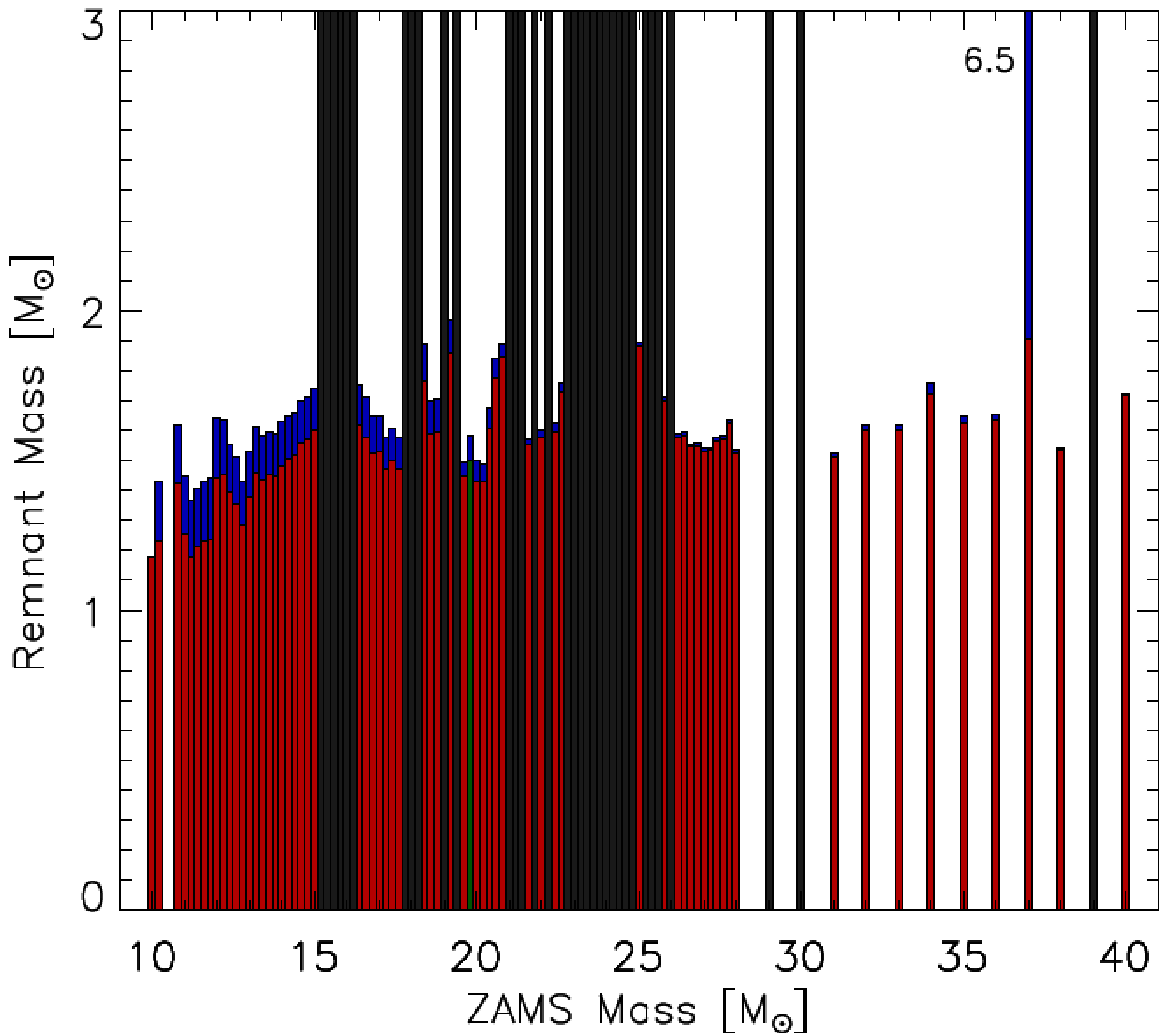
(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

- Hydrodynamic simulations of neutrino-driven explosions in 1D:
  After onset of explosion follow neutron-star cooling for 15–20 s, continue to track SN explosion with fallback for days to weeks

- Core-collapse simulations for 101 solar-metallicity progenitors
  (from Woosley, Heger, & Weaver 2002)

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

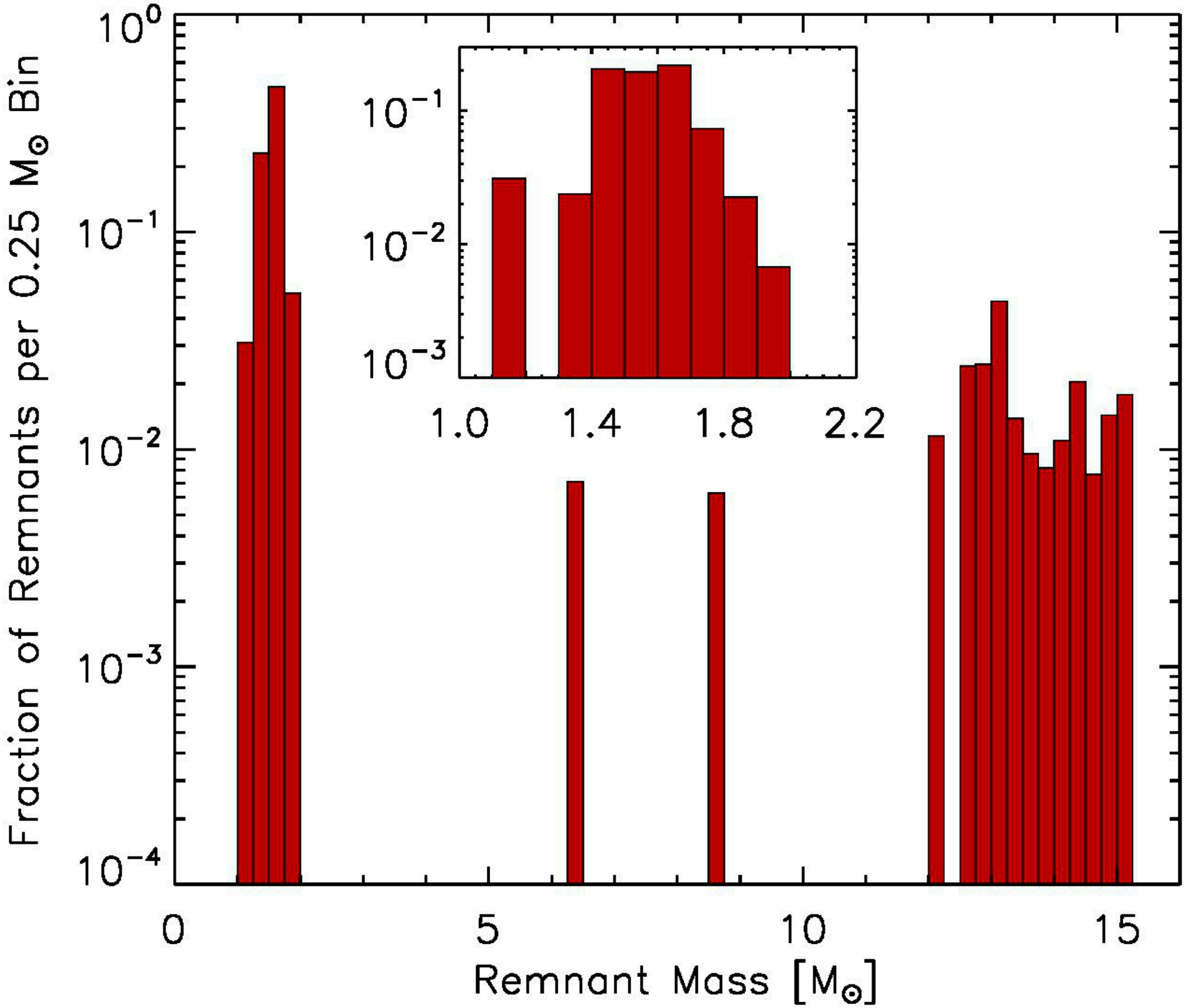
Compact Remnant Masses



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

Remnant Mass Distribution

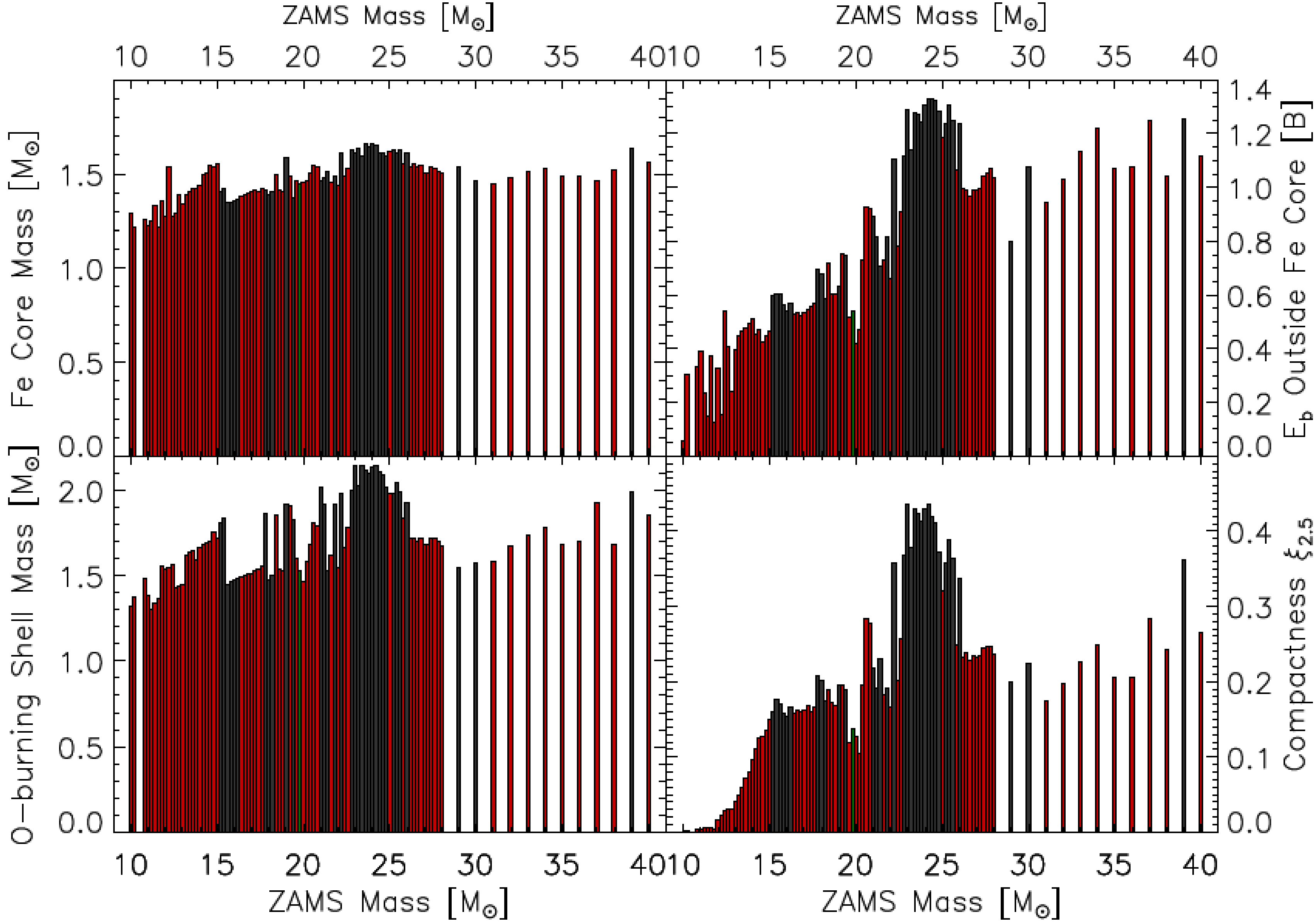
Model results folded with Salpeter IMF:
23% of all stellar core collapses produce BHs



Baryonic Remnant Mass

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

Progenitor Properties



Grey = BH formation cases

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

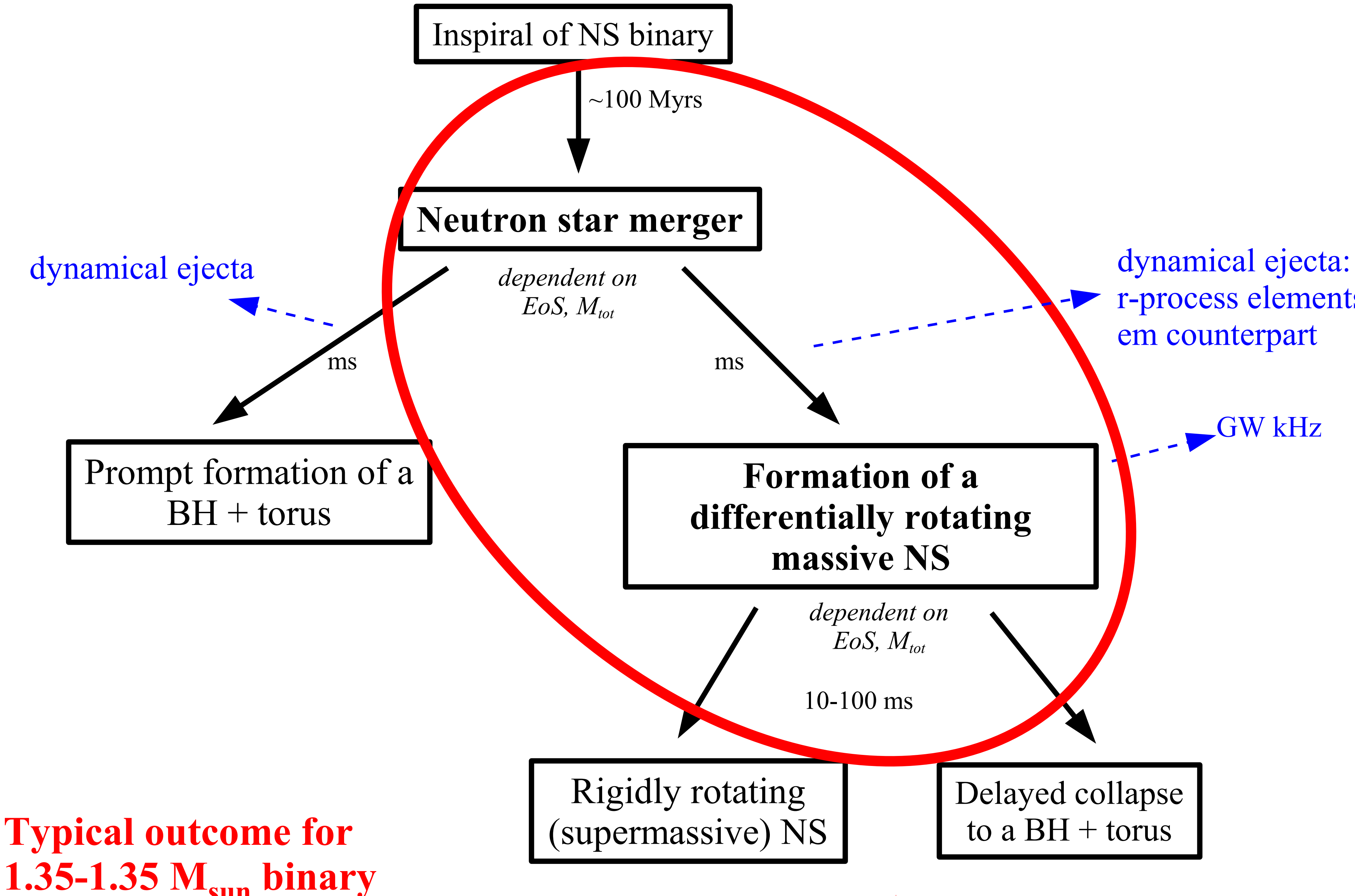
Summary

- Modelling of SN explosion mechanism has made considerable progress in 1D and multi-D.
- 2D relativistic models yield explosions for "soft" EoSs. Explosion energy tends to be on low side (except recent models by Bruenn et al., arXiv:1212.1747).
- 3D modeling has only begun. No clear picture of 3D effects yet. **But SASI can dominate (during phases) also in 3D models!**
- 3D SN modeling is extremely challenging and variety of approaches for neutrino transport and hydrodynamics/grid choices will be and need to be used.
- Numerical effects (and artifacts) and resolution dependencies in 2D and 3D models must still be understood.
- Bigger computations on faster computers are indispensable, but higher complexity of highly-coupled multi-component problem will demand special care and quality control.

Neutron-star mergers:

Gravitational waves, mass ejection, r-process nucleosynthesis, optical transients

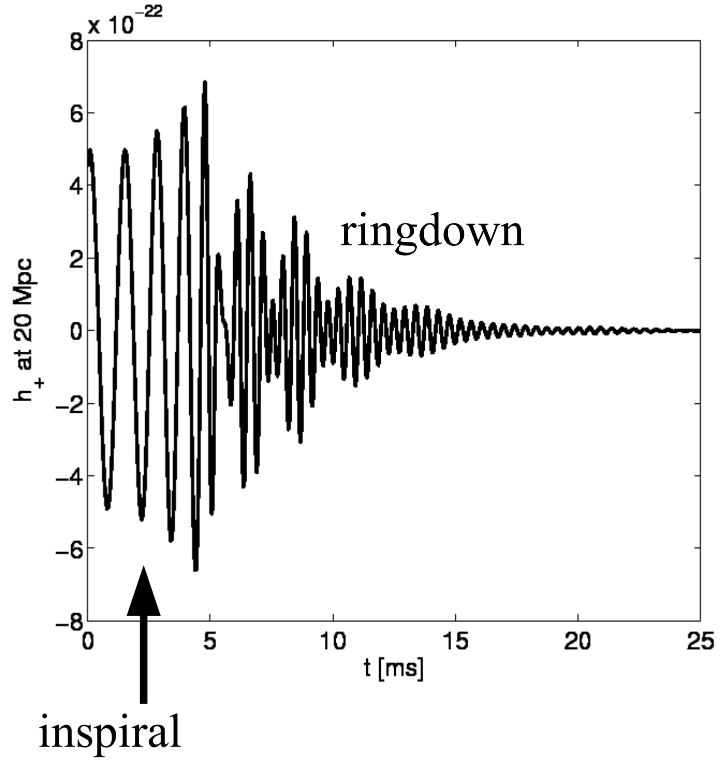
Based on relativistic hydrodynamical simulations
(Andreas Bauswein & THJ)

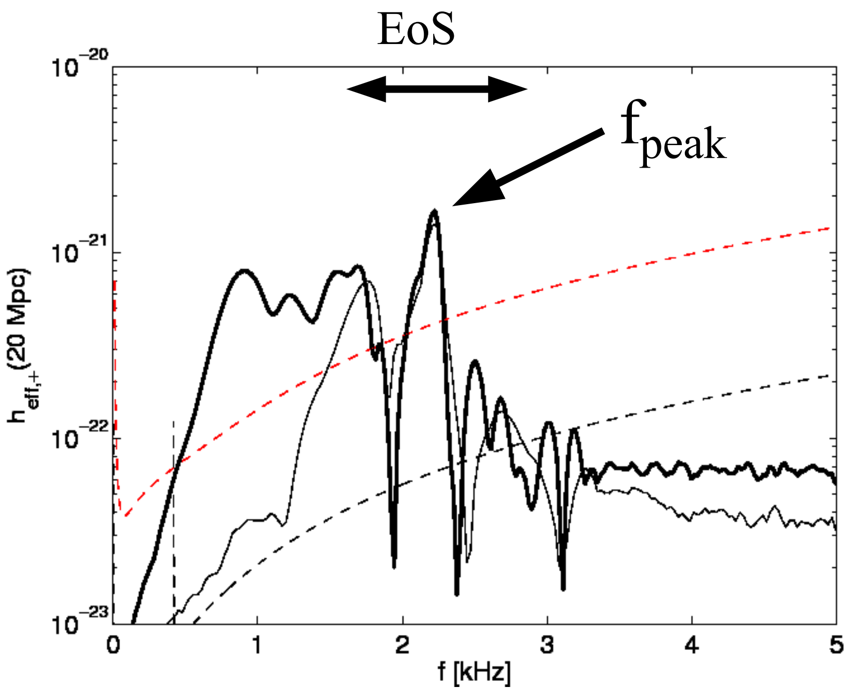


Inspiral of NS binary
~100 Myrs
Neutron star merger
dependent on
EoS, M_{tot}
dynamical ejecta
ms
ms
dynamical ejecta:
r-process elements
em counterpart
GW kHz
Prompt formation of a BH + torus
Formation of a differentially rotating massive NS
dependent on
EoS, M_{tot}
10-100 ms
Rigidly rotating (supermassive) NS
Delayed collapse to a BH + torus
Typical outcome for
1.35-1.35 M_{sun} binary

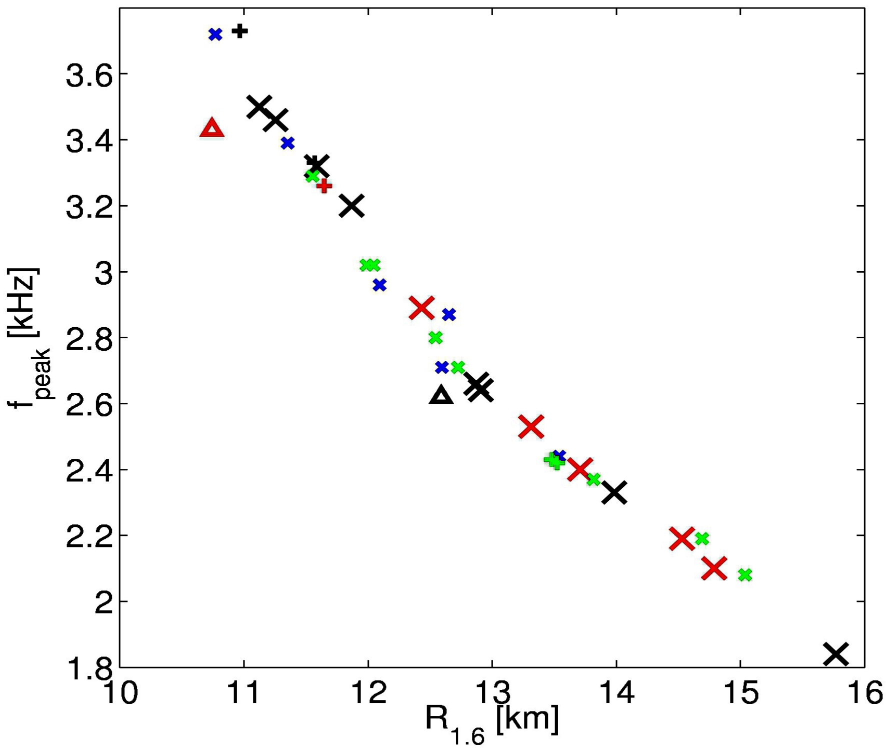
Gravitational-wave amplitude and spectrum

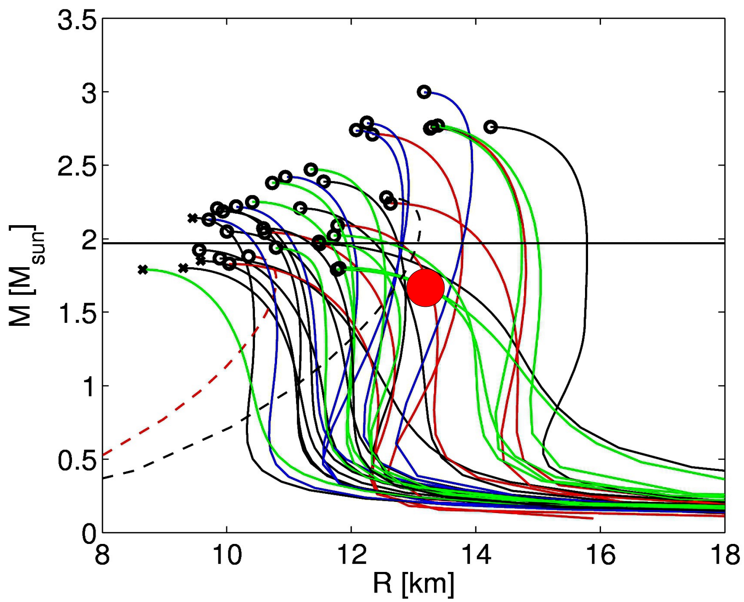
1.35-1.35 M_{sun} Shen equation of state (EoS)





Gravitational waves – EoS survey



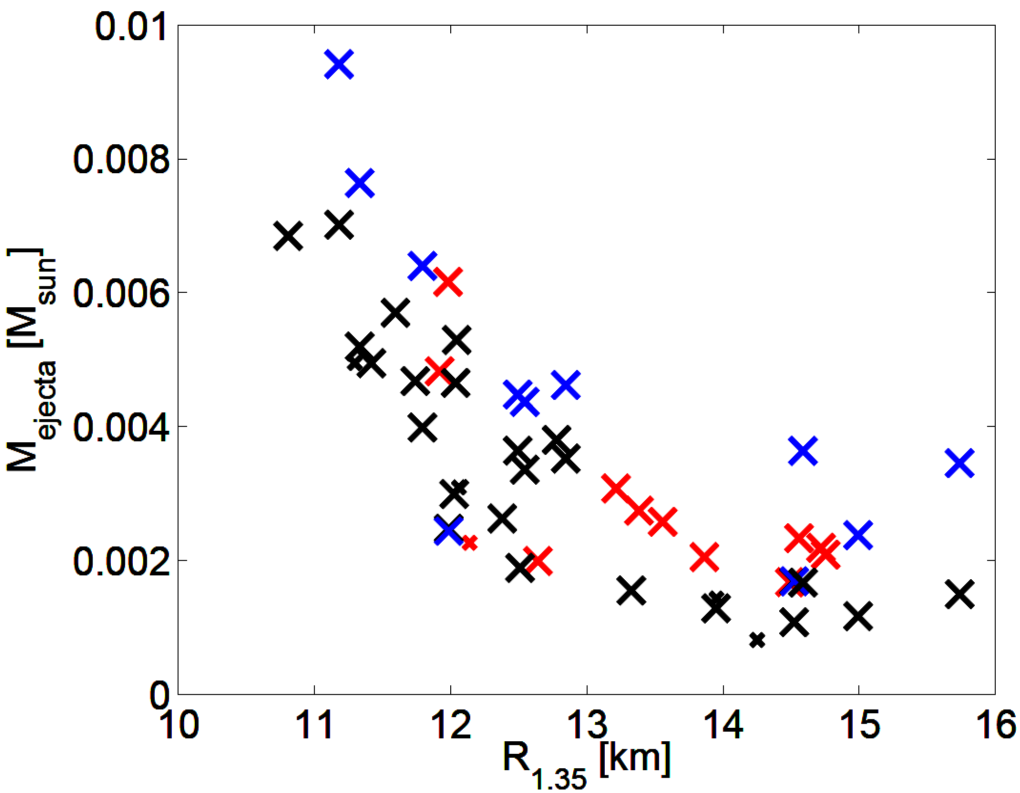


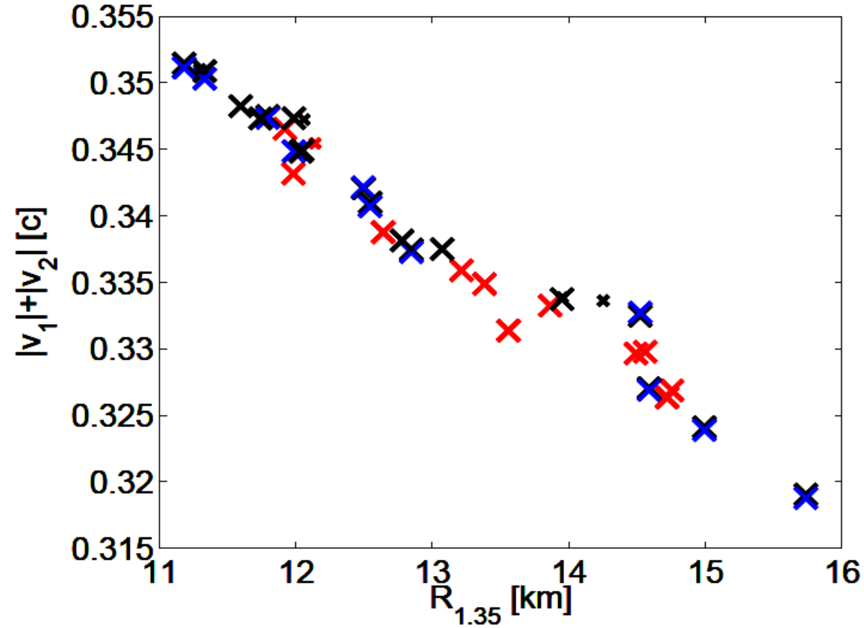
characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

- f_{peak} dominant gravitational-wave frequency of the post-merger phase
- Detection determines neutron-star mass and radius (within ~200 meters)
- Event rate for Advanced LIGO 0.01-1 per year (conservative)
- Strong constraint on high-density equation of state and other NS properties

Ejecta masses

for 1.35-1.35 binaries (most abundant in binary population)



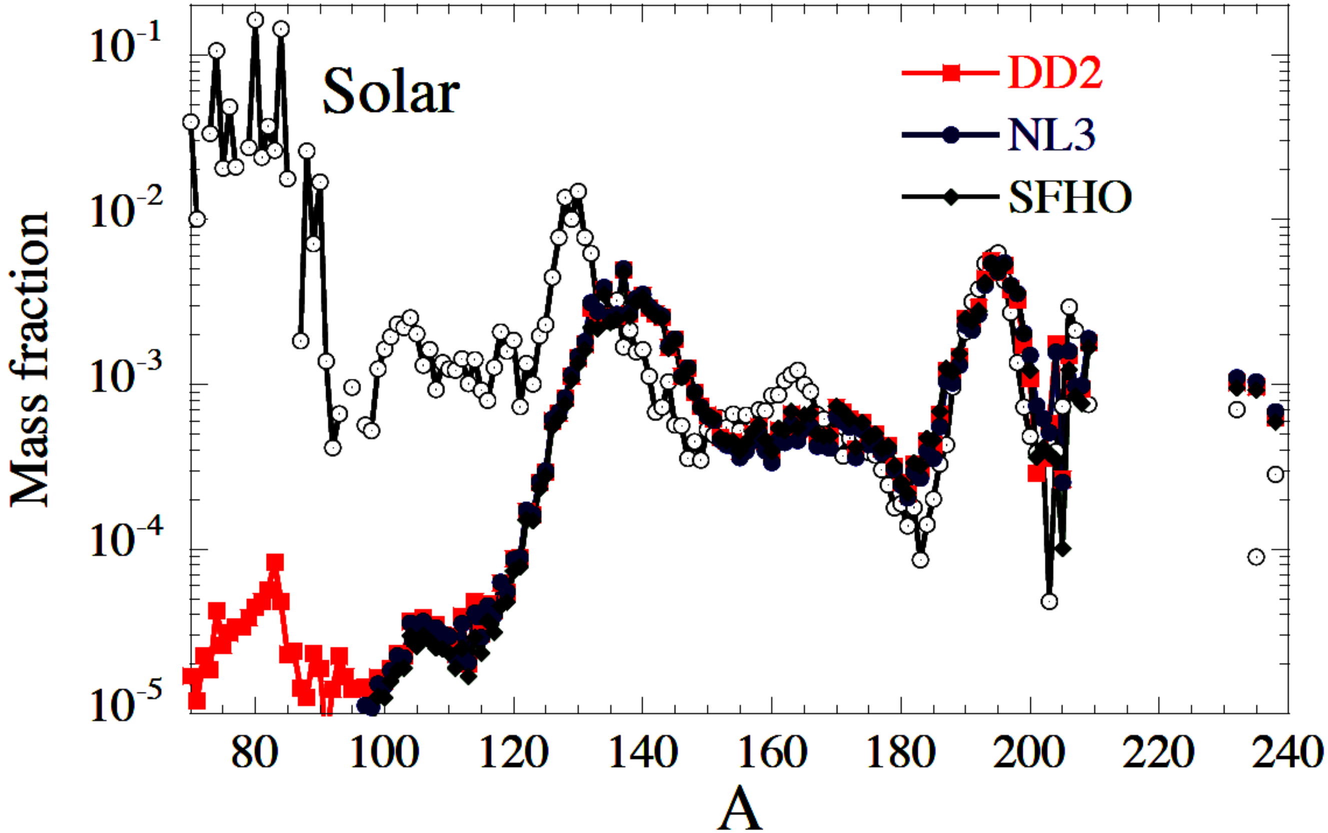


Impact velocity

- NS compactness is the crucial parameter affecting ejecta
- i.e. determines amount of nucleosynthesized ejecta
- Similar results for 1.2-1.5 binaries

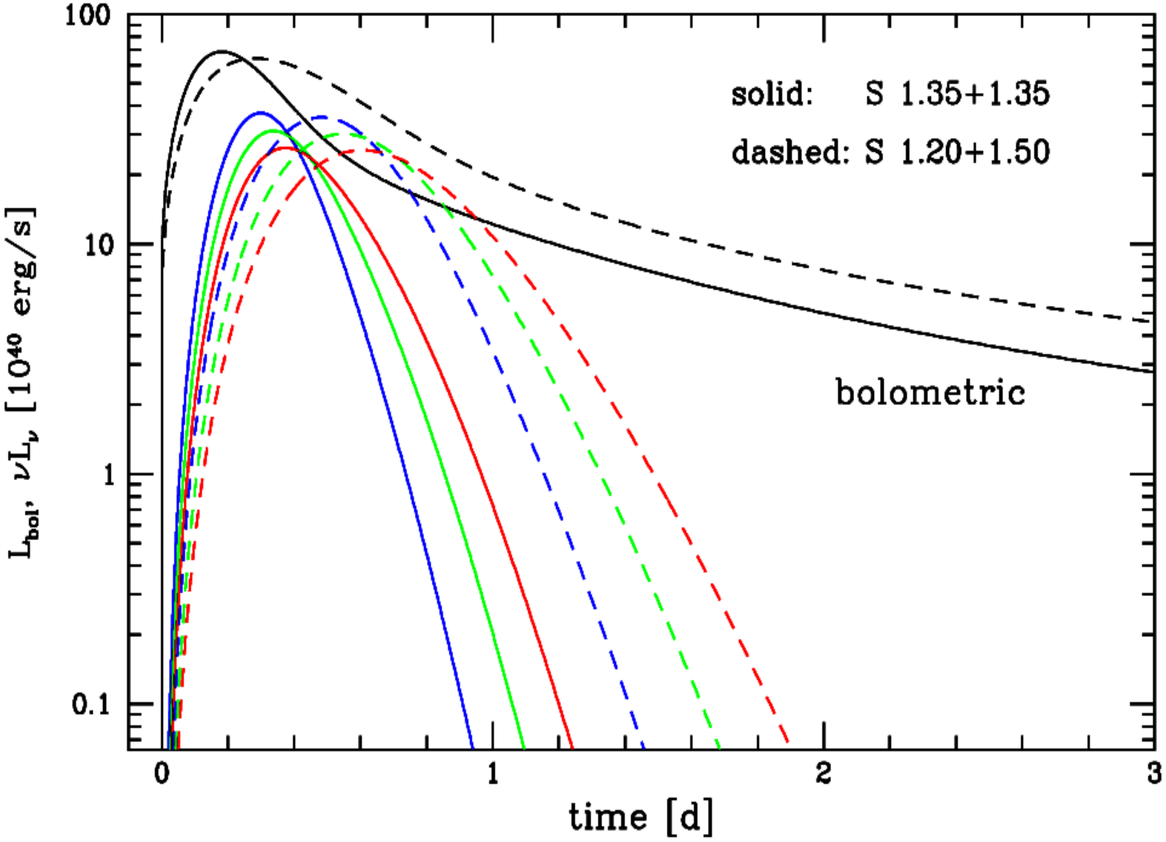
R-process nucleosynthesis

for 1.35-1.35 binaries (most abundant in binary population)



- Robust r-process with solar abundance above A ~130
- Insensitive to high-density equation of state
- Radioactive decays power optical transient

Optical transients: lightcurve



Shen EoS

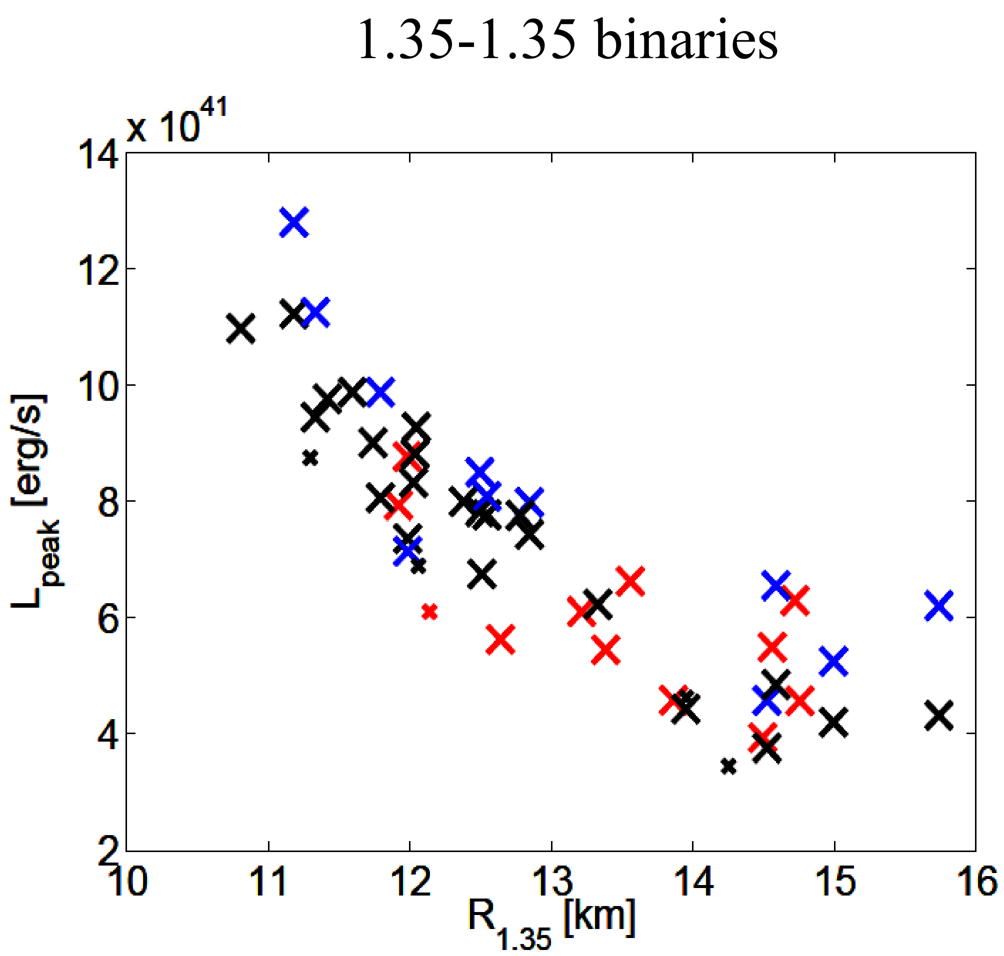
from one-zone model

Estimates: $L_{bolo} \sim 7.5*10^{41}$ erg/s $(v/0.1c)^{1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

$t_{peak} \sim 0.5$ d $(v/0.1c)^{-1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

$T_{eff} \sim 1.4*10^{4}$ K $(v/0.1c)^{-1/8}$ $(M_{ejecta}/10^{-2}M_{sun})^{-1/8}$

Optical transients: Peak luminosity



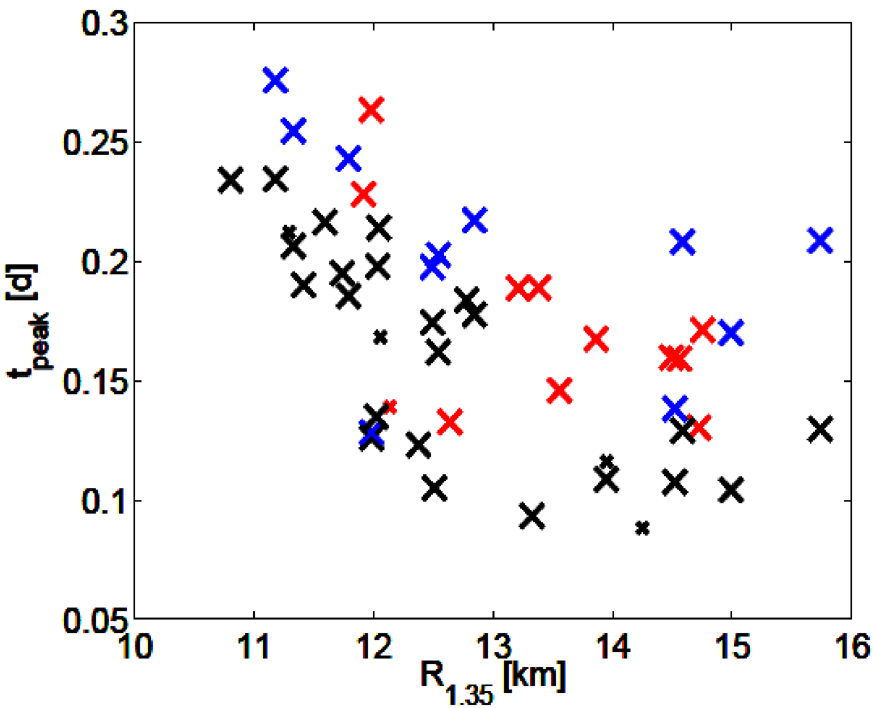
→ also peak time and effective temperature show scaling

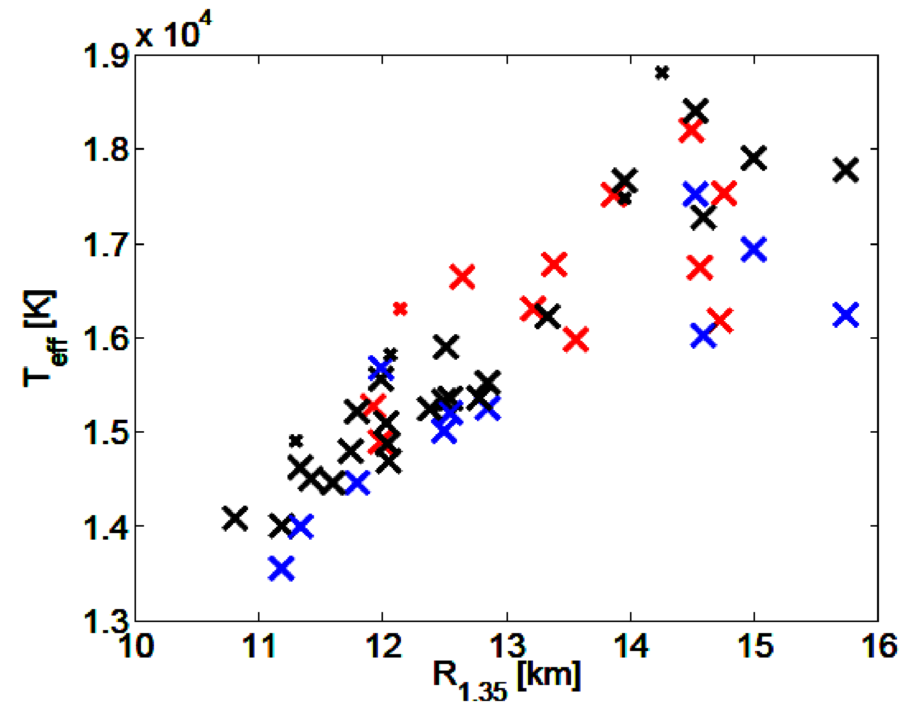
→ potential constraint for NS radius from optical observations

(similar findings for asymmetric binaries)

Peak time and effective temperature

1.35-1.35 binaries





- Timescales substantially reduced compared to Newtonian models
- Implications for observations?

Summary and conclusions

- Survey of equation of state influence on neutron star mergers
- Generic outcome of 1.35-1.35 M_{sun} merger: formation of a differentially rotating NS → Pronounced peak in the GW spectrum
- Peak frequency scales very well with the radius of a nonrotating NS with 1.6 M_{sun}: measurement with an accuracy of 100-200 meters possible
- Correlations / constraints for other EoS properties
- Ejecta mass and features of optical counterparts are strongly and systematically affected by EoS
- Nucleosynthesis insensitive to EoS

Details: Bauswein & Janka, PRL 108, 011101 (2012)

Bauswein et al., PRD 86, 063001 (2012)

Bauswein, Goriely, Janka, in preparation