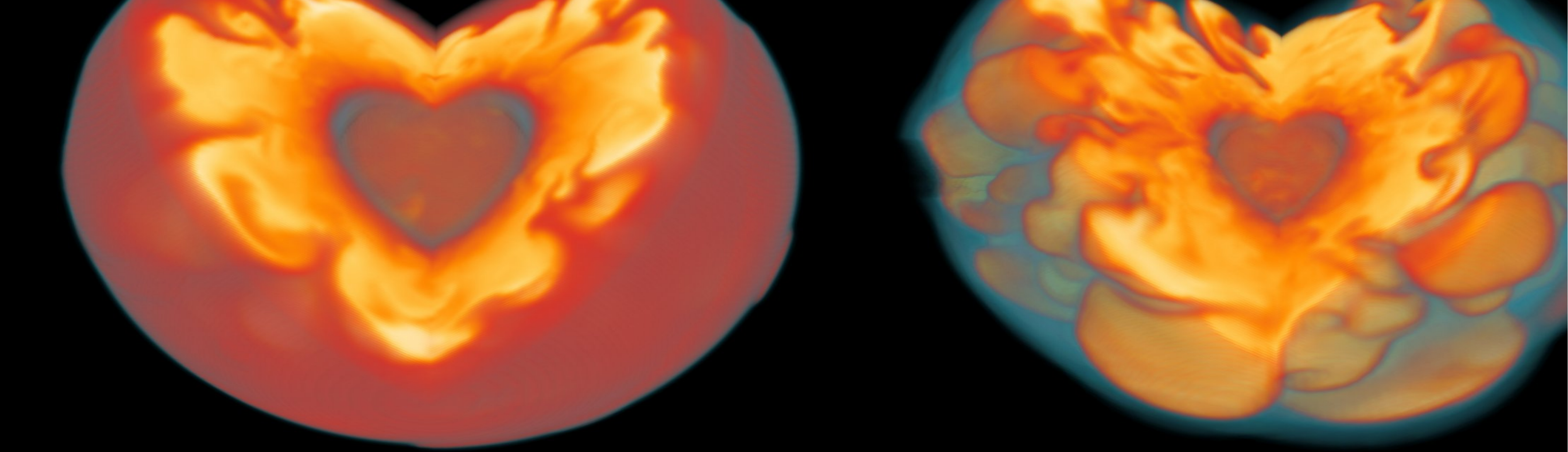
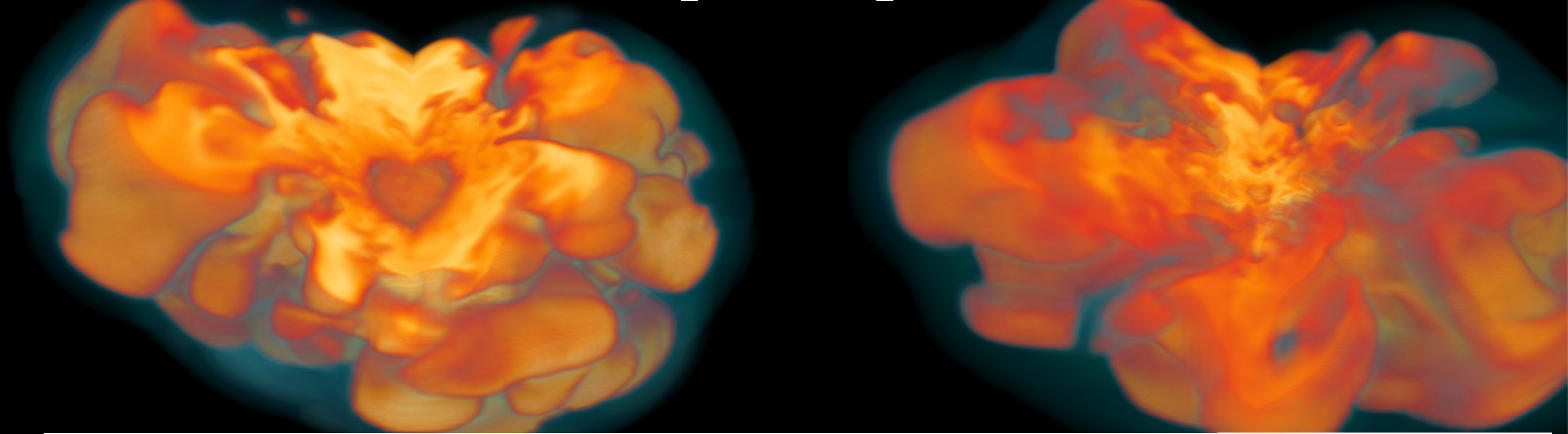


The gravitational wave signal of core colllapse supernovae



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supported by

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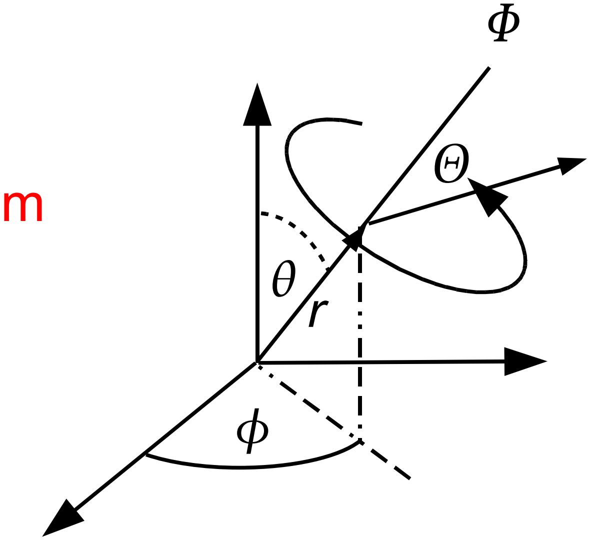
The Computational Challenge



6D time-dependent radiation hydrodynamics problem

Boltzmann equation determines neutrino distribution function in phase space

Integration over momentum space yields source terms for hydrodynamics

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

Simulating the evolution for ~1 sec requires ~10^6 time steps --->

- ~10^{21} operations / simulation -->

  ~1CPU-yr @ 30 Teraflop or ~2CPU-weeks @ 1 Petaflop

Core collapse supernovae: neutrino-driven delayed explosion

(Colgate & White '66, Wilson ´82,
Bethe & Wilson '85)

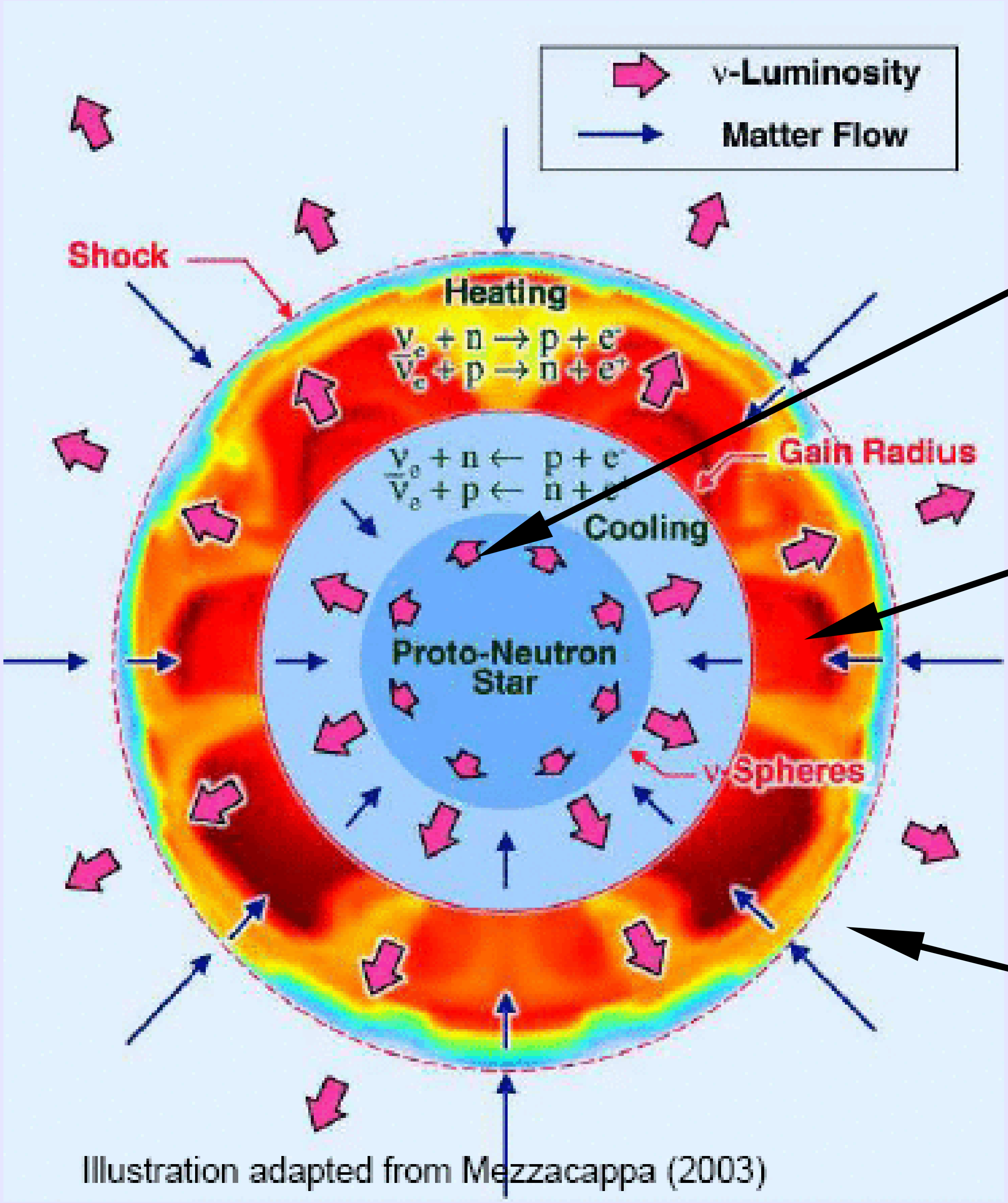


Illustration adapted from Mezzacappa (2003)

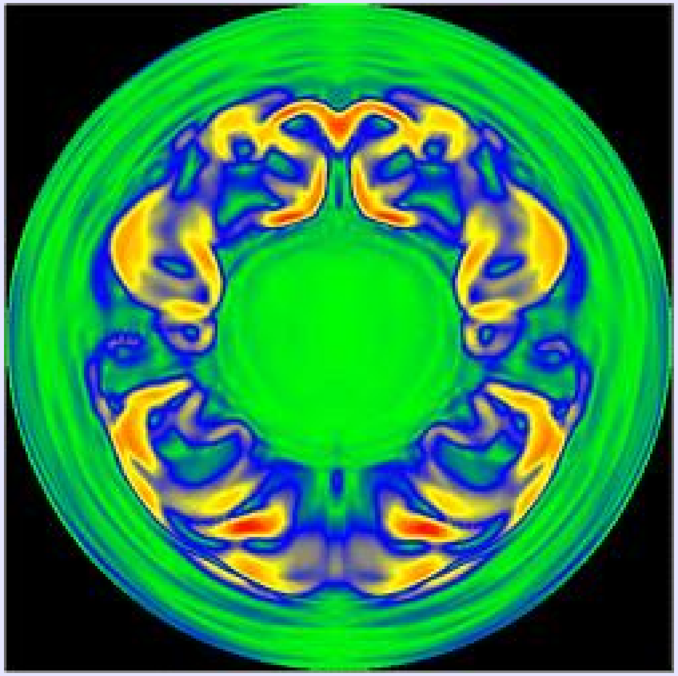
neutrinos diffuse out of opaque proto-neutron star ($\tau_\nu \sim 1$)

neutrinos heat matter in semi-transparent ($\tau_\nu \sim 1$) post-shock region ---> convection with coexisting downflows and rising hot bubbles sets in

neutrinos stream freely through stellar envelope ($\tau_\nu << 1$)

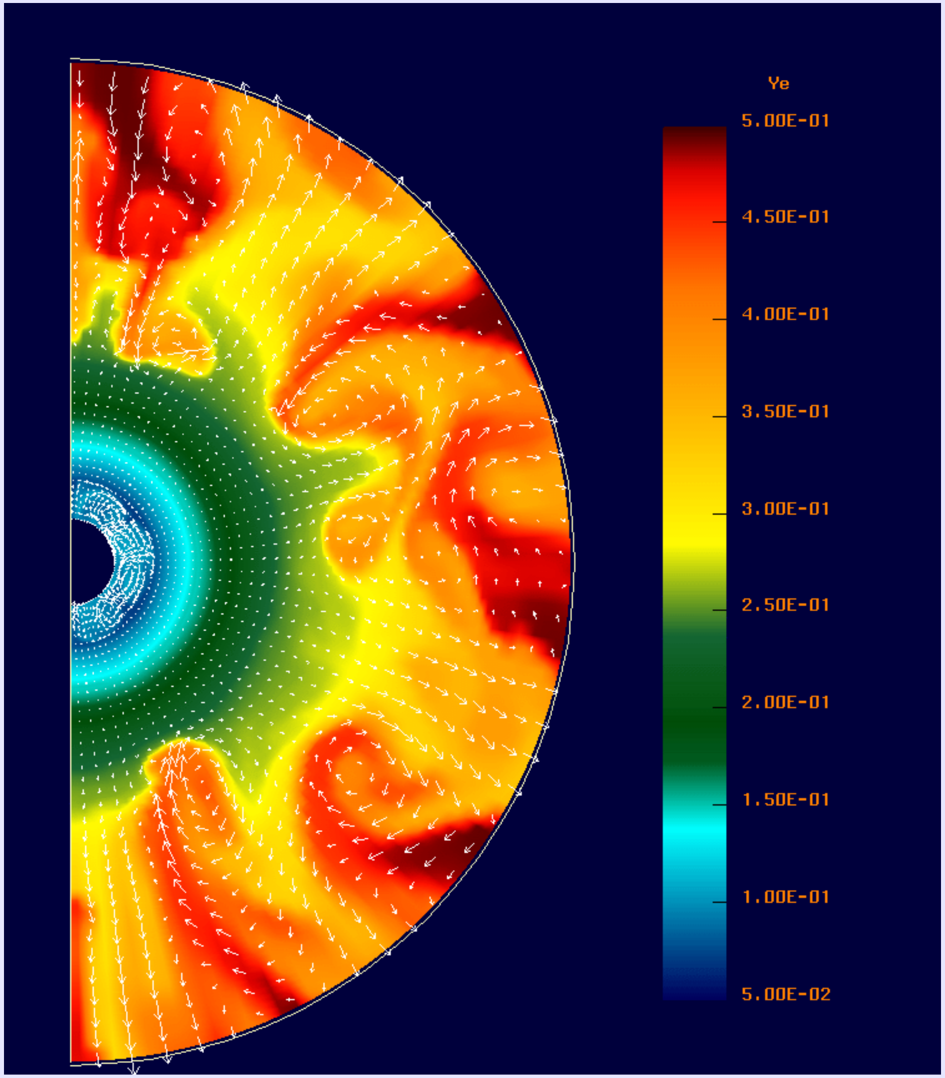
Convective processes & hydrodynamic instabilities play an important role

(Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996).



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

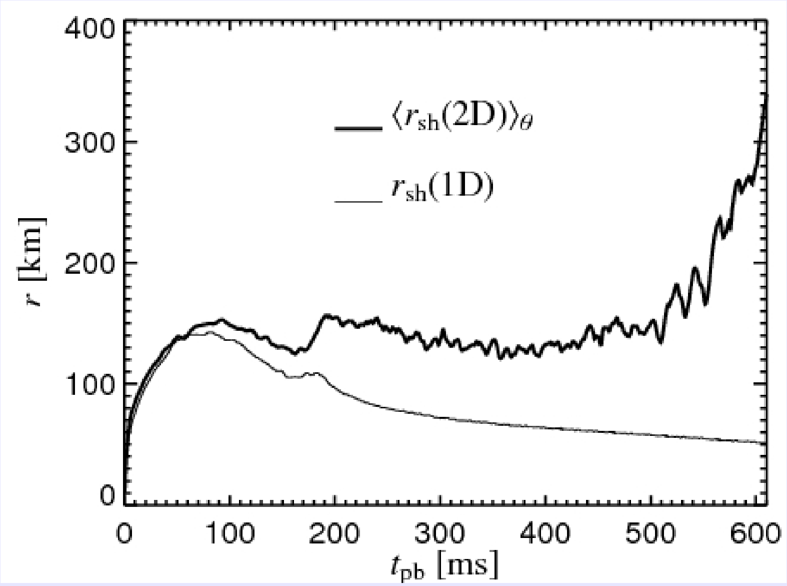
asymmetric ν-emission
(few sec) and flow (~100 sec?)



Convection in the surface layers of the proto-neutron star and in the hot bubble

recent developments towards successfull (i.e. exploding!) radiation-hydrodynamics supernova models

- allowance for multi-d flow essential for obtaining an explosion

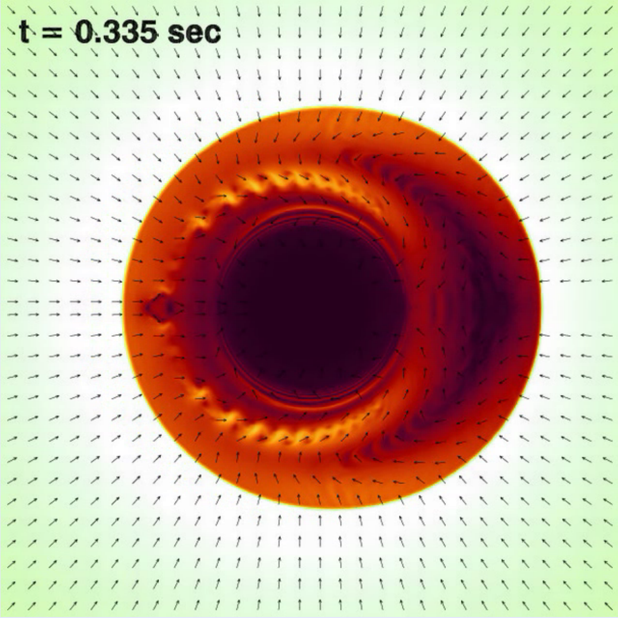


- neutron star g-mode oscillations instigated by the time-dependent accretion flow may energize the shock via sound waves (Burrows et al. '06; see however Weinberg & Quataert '08)

- Standing Accretion Shock Instability provides more favorite conditions for delayed explosion (Marek & Janka '07)

Standing accretion shock instability (SASI)

Blondin et al., '03, '05



- low-mode oscillatory instability
  occuring also in situations which are
  convectively stable due to an amplifying
  advective acoustic cycle
  (Foglizzo '01, '02)

- growth of dominant low order (l=1,2) modes
  in 2D and 3D simulations
  (Scheck et al., '03, '06, '08)

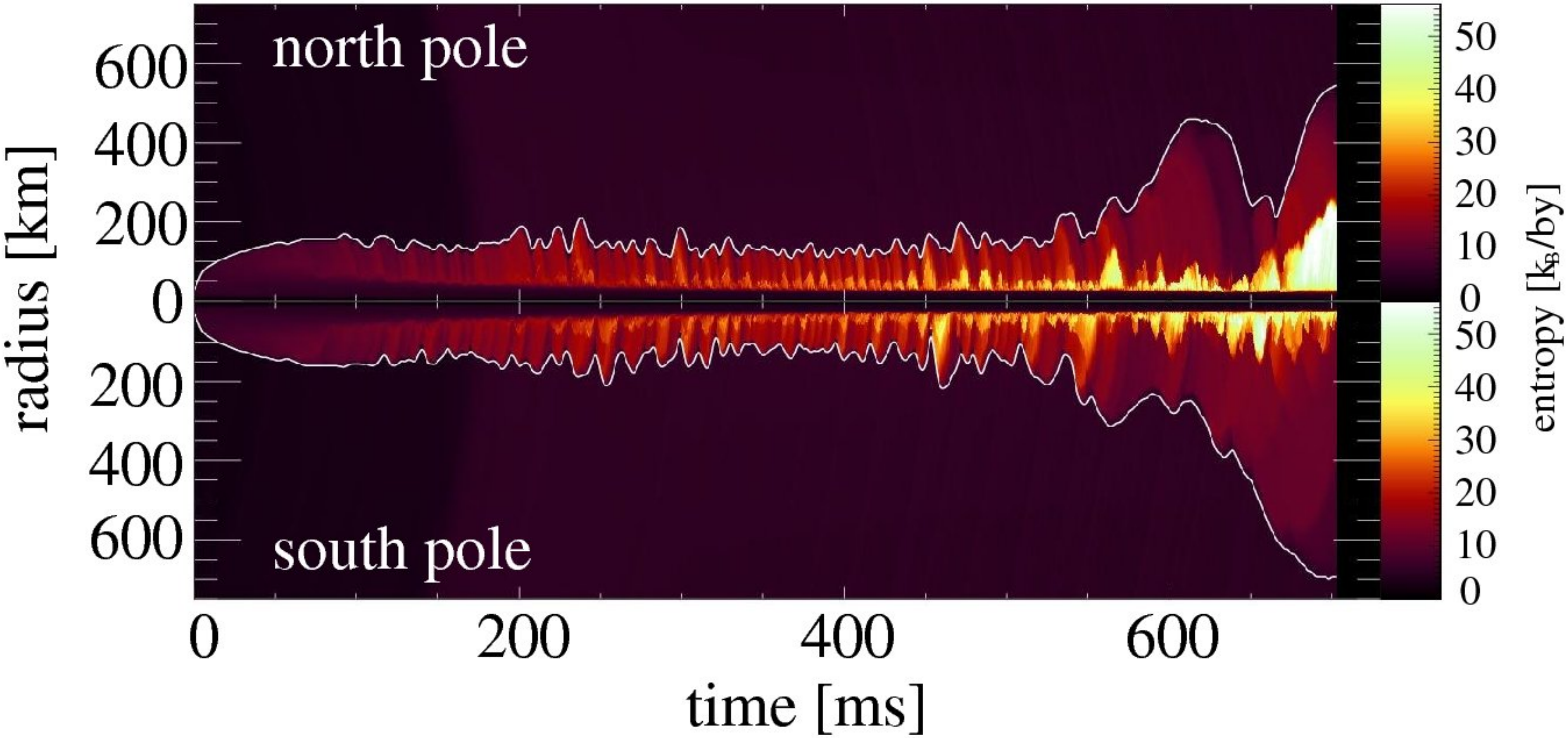
---> without strong B-fields, exotic neutrino physics, fast rotation, etc.

large neutron star kicks (up to 1200 km/s)
large-scale mixing of ejecta (Kifonidis et al. '06)

example of a state-of-the-art 2D radiation-hydrodynamics simulation of a SASI-supported neutrino-driven delayed explosion

(Marek & Janka '07)

180° axisymmetric (2D) simulation of a modestly fast rotating 15 M_{sun} progenitor (Ω = 0.5rad/s)



radial position of the shock near the north and south pole (white lines) & entropy per nucleon (color coded) of the stellar gas

Gravitational waves

(Einstein quadrupole formula)

$$h_{jk} = \frac{2G}{c^4}\frac{1}{R}\frac{d^2Q_{jk}}{dt^2} \sim \frac{R_s}{R}\frac{v^2}{c^2}$$

$R_s = 1$ km , $v/c = 0.1$, $R = 10$kpc ---> **$h \sim 10^{-20}$** *

time-dependent mass-energy quadrupole moment in core collapse supernovae due to

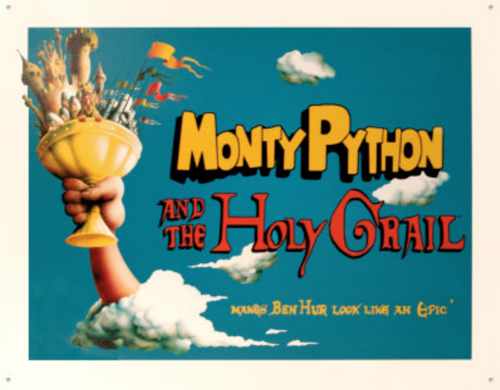
- convection in proto-neutron star
- convection in neutrino heated hot bubble
- anisotropic neutrino emission
- any other non-radial instability (e.g. SASI, NS g-modes)

generically produced by any CCSN

and due to rotation and magnetic fields

* [measuring the distance earth-sun with an accuracy of 1 nm]

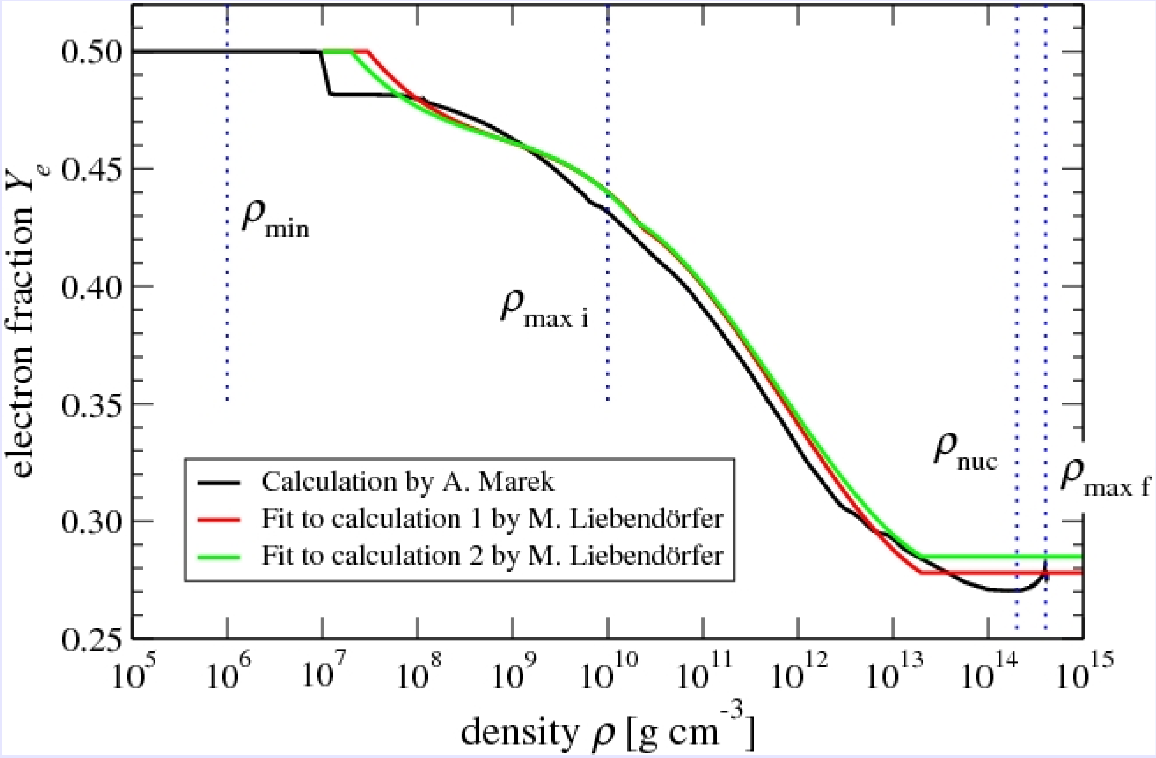
Towards predictive theoretical GW signals from CSSNe: core bounce 🟥 post-bounce 🟪

	polytropes, simplified EOS	microphysical EOS approx. ν-transport	microphysical EOS detailed ν-transport
full GR	🟥 Shibata & Sekiguchi '05 2D/3D simulations 🟥 Shibata & Sekiguchi '04 confirmation of CFC 🟥 Shibata '03 cartoon method	🟥 Ott et al. '07 $Y_e(\rho)$ from 1D GR sim.	
CFC-GR hydro & gravity	🟥 Cerda-Duran et al. '05 CFC+, parameter study 🟥 Dimmelmeier, Font & Müller '02 parameter study	🟥 Dimmelmeier et al. '07, '08 $Y_e(\rho)$ from 1D GR sim.	
Newtonian hydro & approx. GR gravity	🟥 Müller, Dimmelmeier & Müller '08 modified potential for rapid rotators		🟪 Marek, Janka & Müller '08 exploding models 🟪 Müller et al. '04 flow & ν contributions
Newtonian hydro & gravity	🟥 Ott et al. '05 low T/W instability 🟥 Rampp, Ruffert & Müller '98 3D simulations 🟥 Zwerger & Müller '97 parameter study	🟪 Ott et al. '04, '06, '07 parameter study, g-modes 🟥 Kotake, Yamada & Sato '03 leakage scheme 🟥 Fryer, Holz & Hughes '02 3D simulations 🟥 Müller & Janka '97 PNS & prompt convection 🟥 Burrows & Hayes '96 anisotropic ν-emission	

most sophisticated simulations of GR rotational core collapse up to now include: (Dimmelmeier & Ott et al. '07, '08)

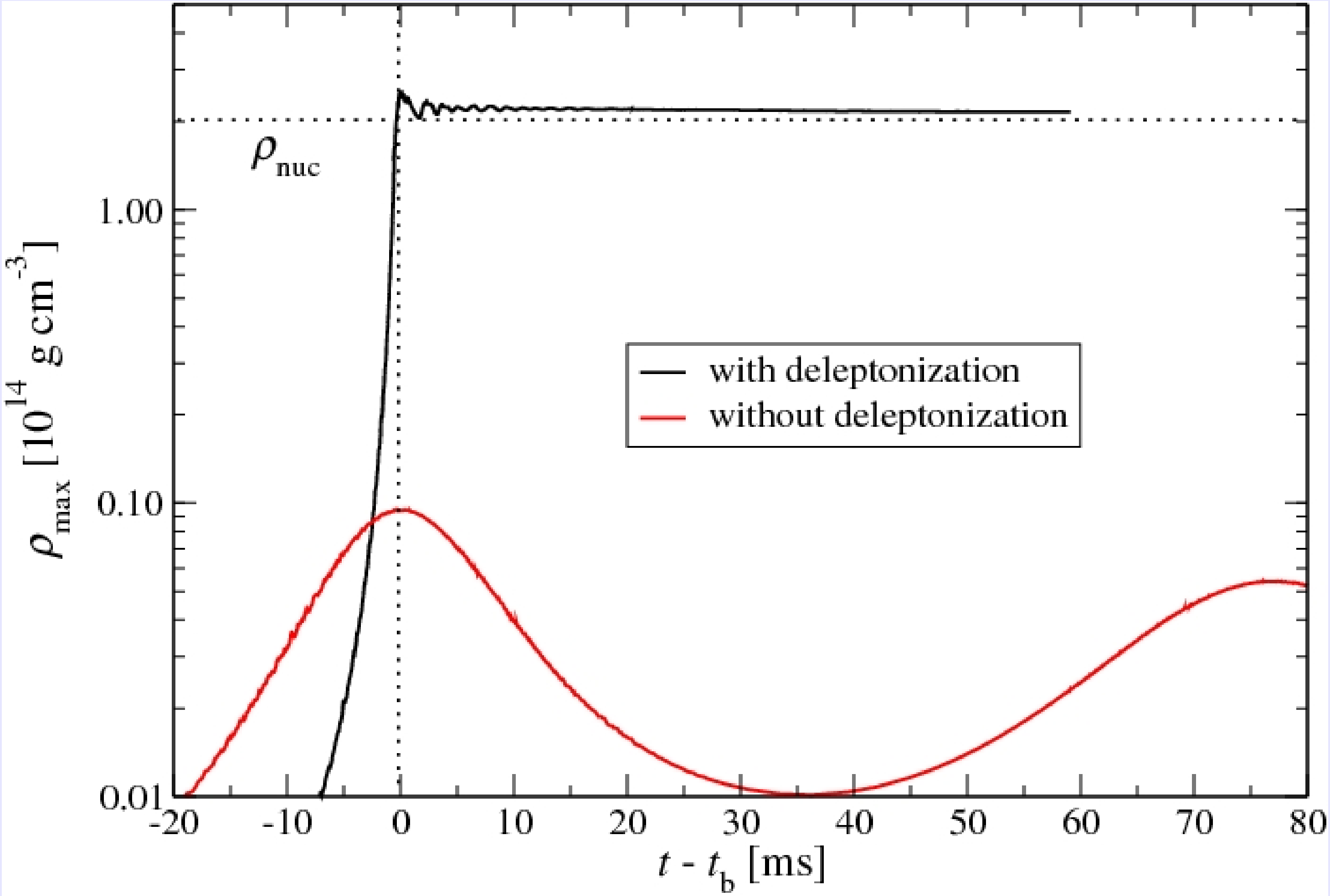
- coupled relativistic gravity (BSSN, CFC) and GRHD
  (Cactus/Carpet/Whisky & CoCoNut codes)
- tabulated microphysical EOS (Shen et al. '98 ; Marek et al. '05)
- Newtonian quadrupole formula for GW signal (still!)
- parameterized, approximate
  treatment of deleptonization
  (Liebendörfer '05: 1D!!)

fine until shortly after bounce!



with microphysical EOS (Dimmelmeier & Ott et al. '07, '08)

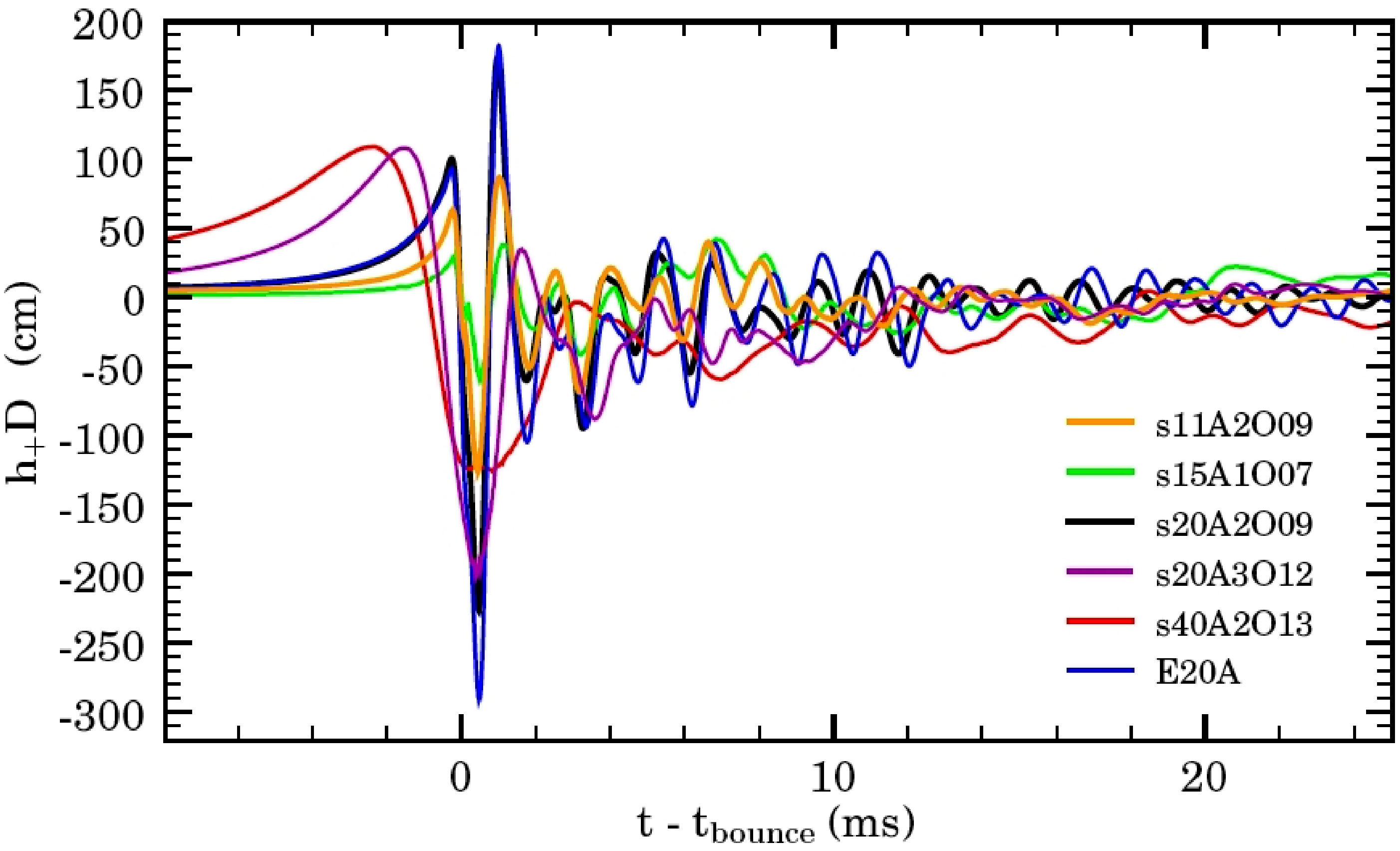
- influence of rotation on dynamics & GW signal less pronounced
- when including effects of deleptonization: no centrifugal multiple bounce found! (neither in Newtonian nor GR gravity)



GW Signals from Core Bounce

GR models with microphysical EoS and deleptonization yield
GW signals that are generic and of so-called "Type I"

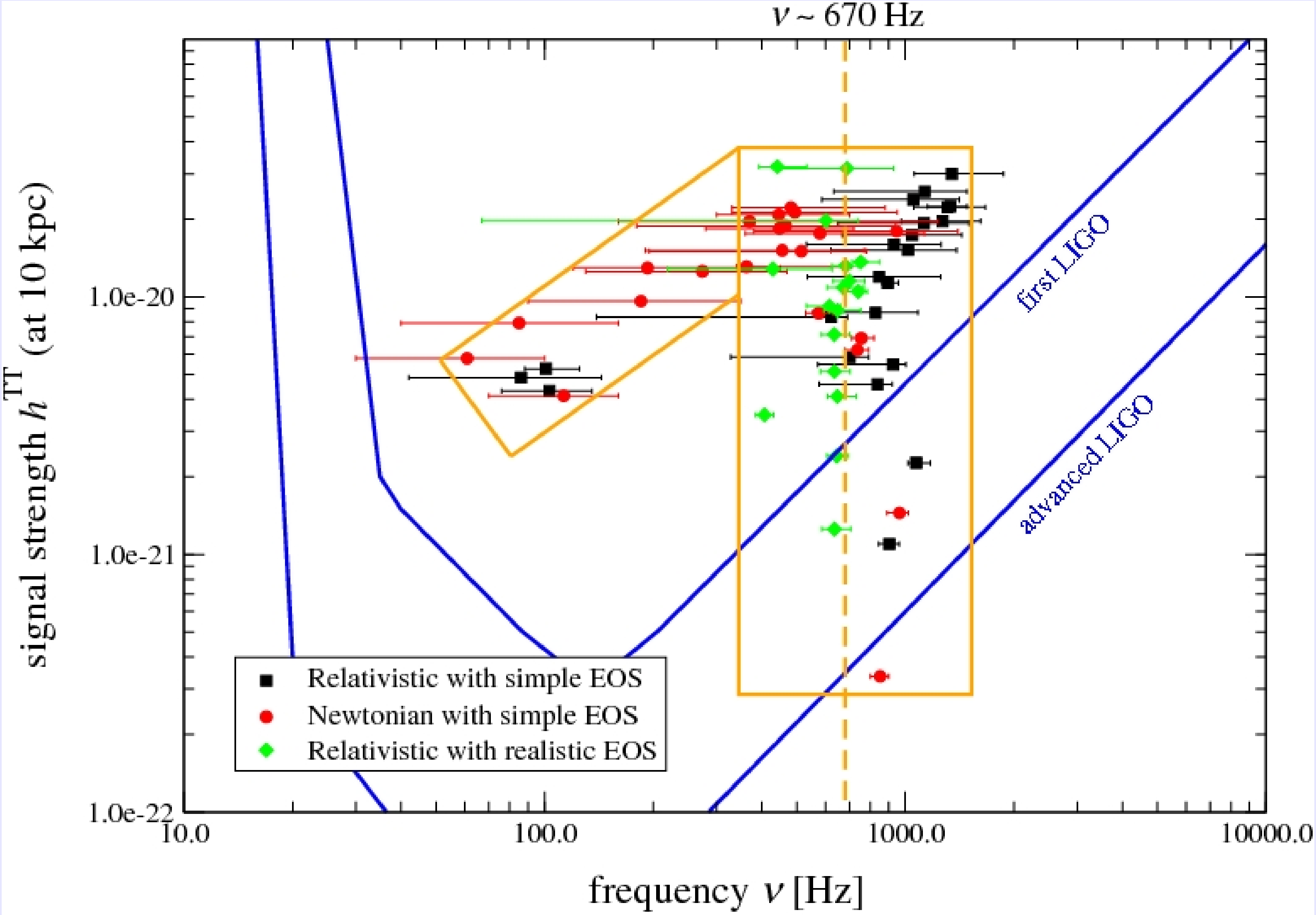
for pressure-dominated & centrifugally supported bounce,
a very wide range of initial rotation rates & profiles,
and for soft & stiff EoS at bounce



Dimmelmeier et al. '07, '08

Detection prospects of GW from core collapse (to NS)

- bounce signal of a galactic supernova detectable by current detectors
- microphysical EOS: GW signal frequency range significantly narrower



low frequency GW signals (i.e. multiple centrifugal bounces) are suppressed in simulations with GR and a microphysical EOS!

(Dimmelmeier & Ott, et al., 07)

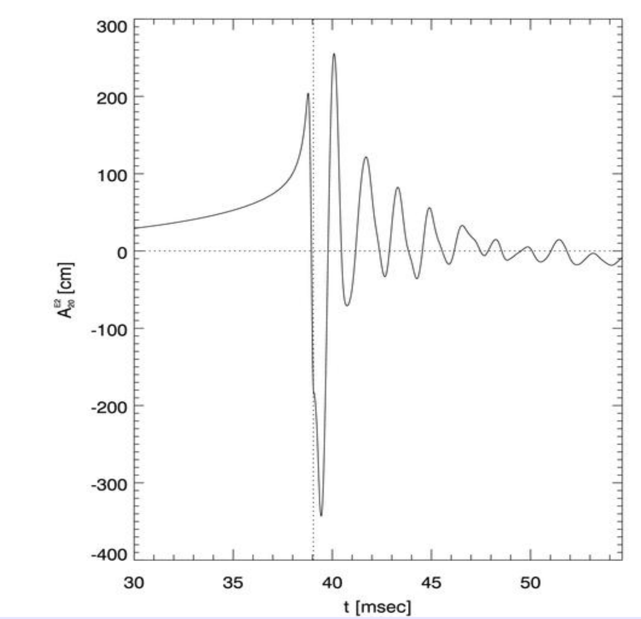
GW signature of CCSNe

CCSN "explosion phase" with models including detailed microphysics and ν-transport

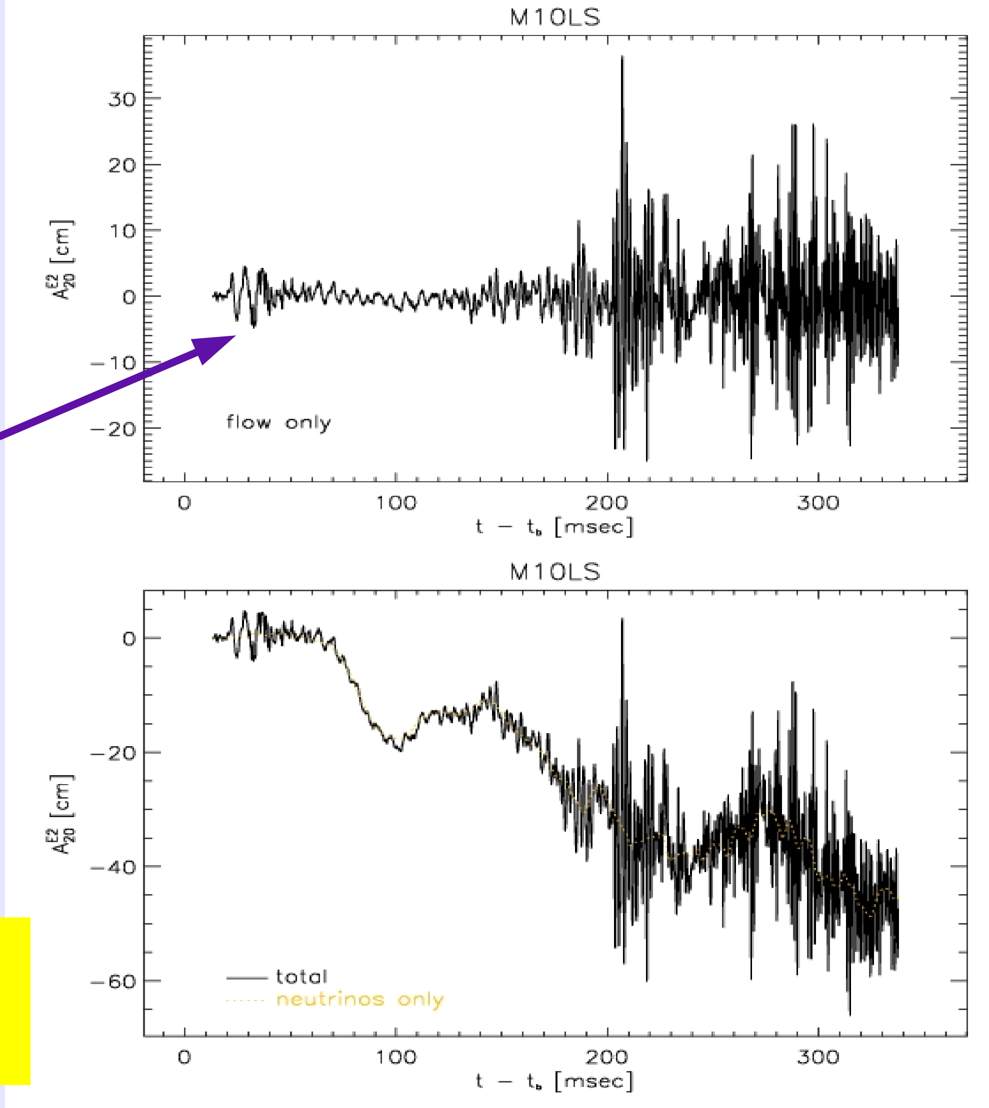
(Müller et al. '04, Marek et al. '08, Müller et al., in prep.)

past studies: "early evolution", simplified microphysics, rapidly rotating parametrized initial models

(e.g., Zwerger & Müller '97)



GW signal from prompt post-bounce convection
(not generic!)



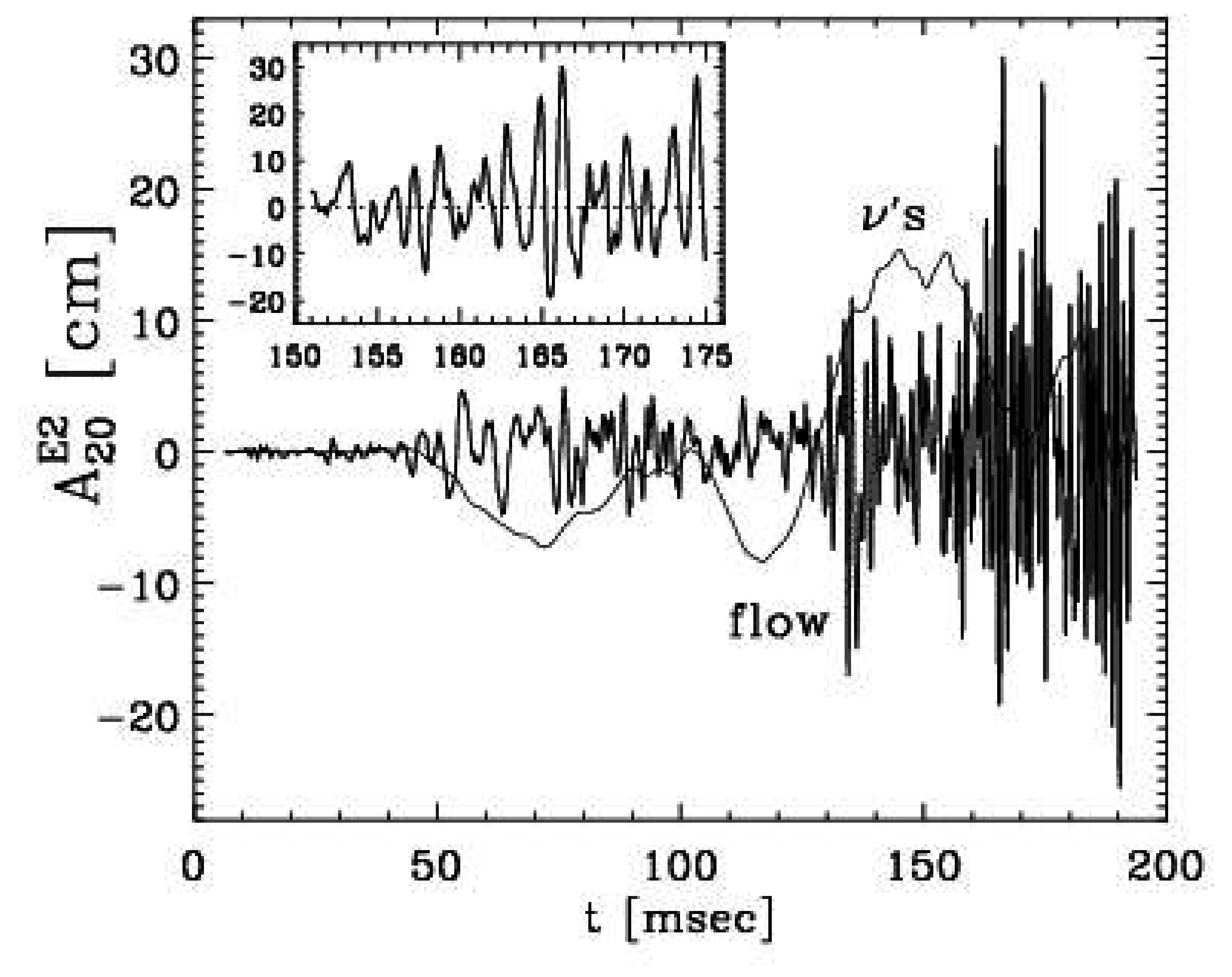
GW signal including anisotropic ν-emission

core collapse, core bounce, and early post-bounce evolution
(few 10 milliseconds)

ν-heating, onset of ν-driven convection, and growth of SASI instability
(several 100 milliseconds)

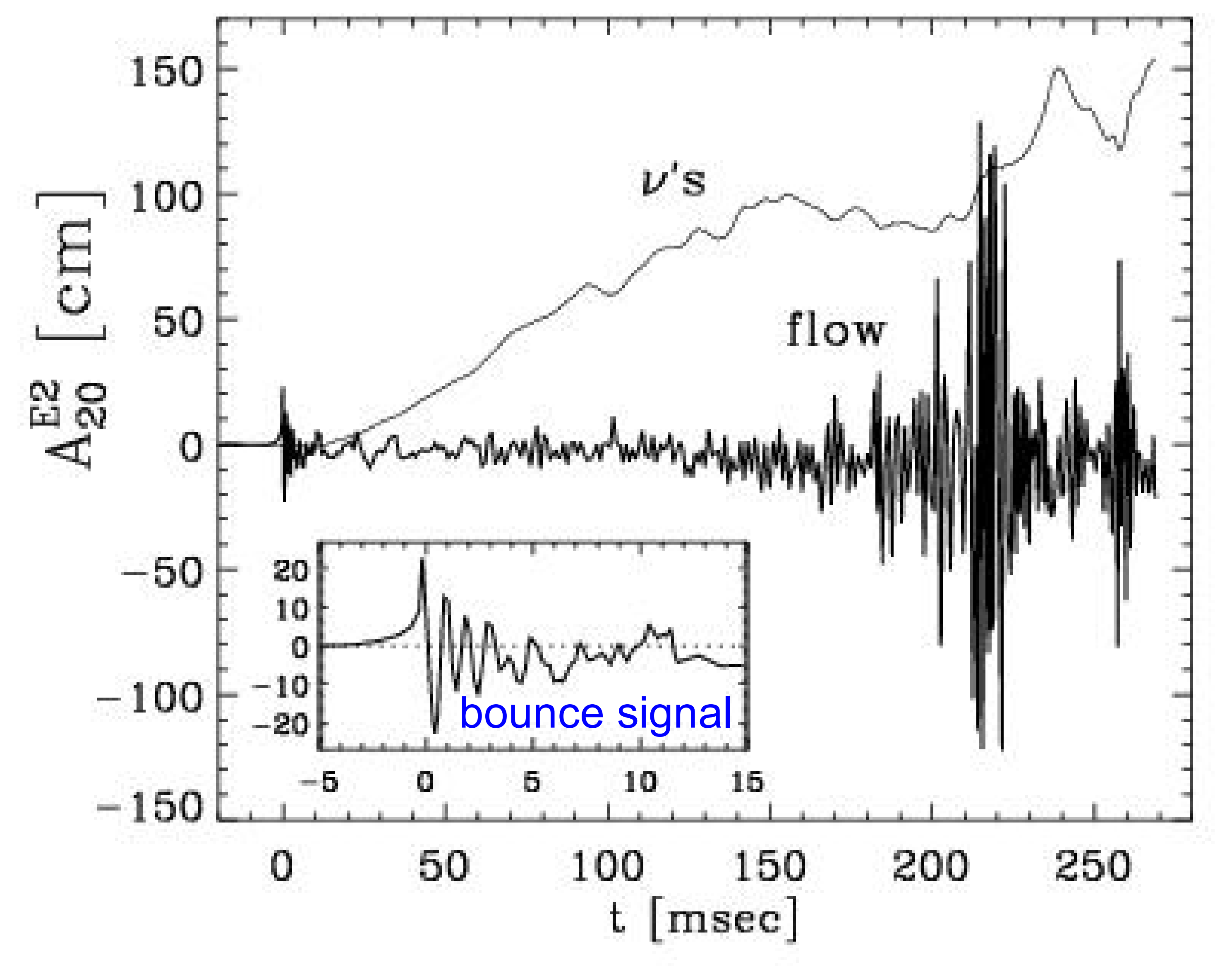
time

GW signature of a non-rotating 11.2 M_{sol} star



Models with detailed microphysics, transport physics, and effective relativistic gravitational potential (Müller, Rampp, Buras, Janka & Shoemaker '04)

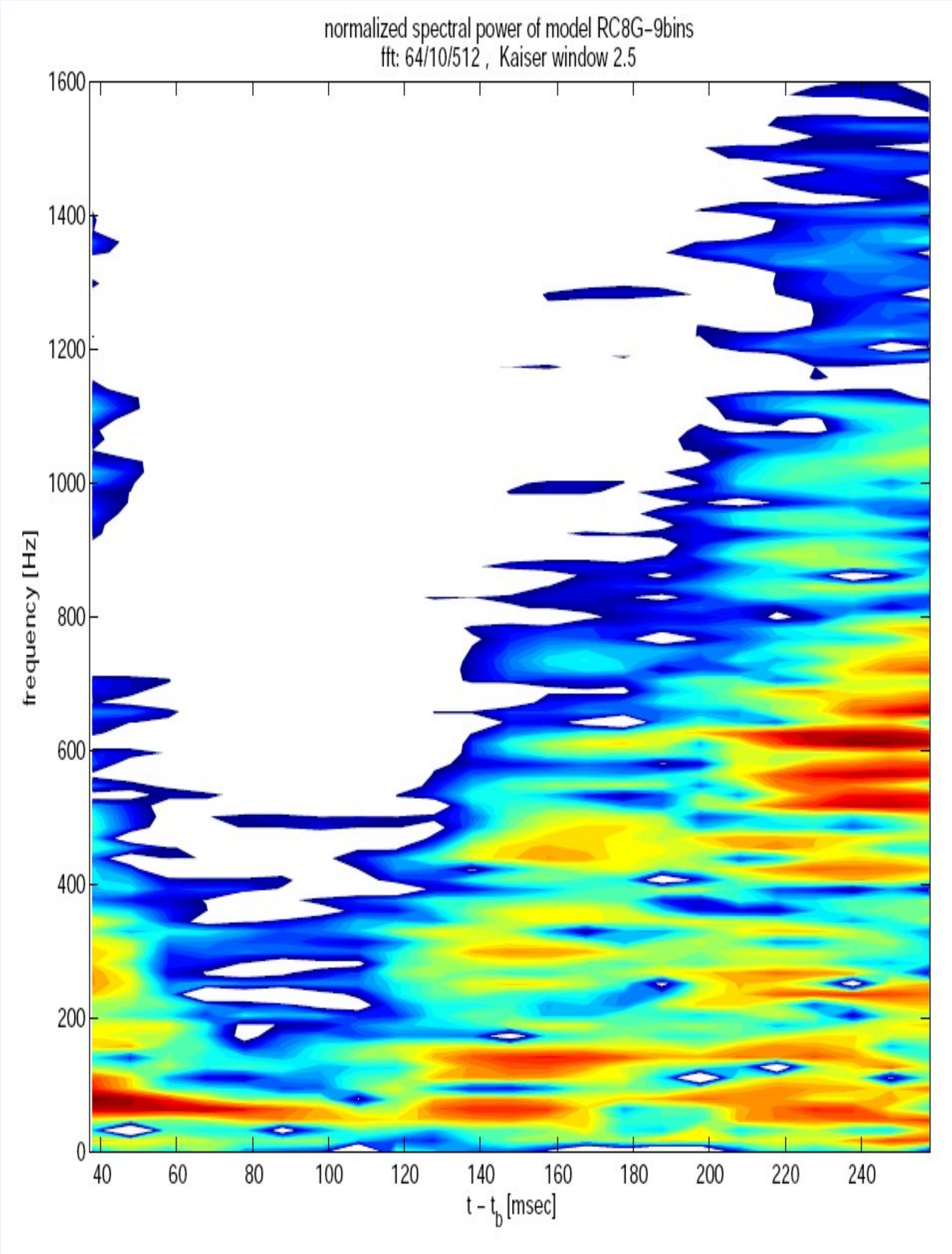
GW signature of a slowly <u>rotating</u> 15 M_{sol} star



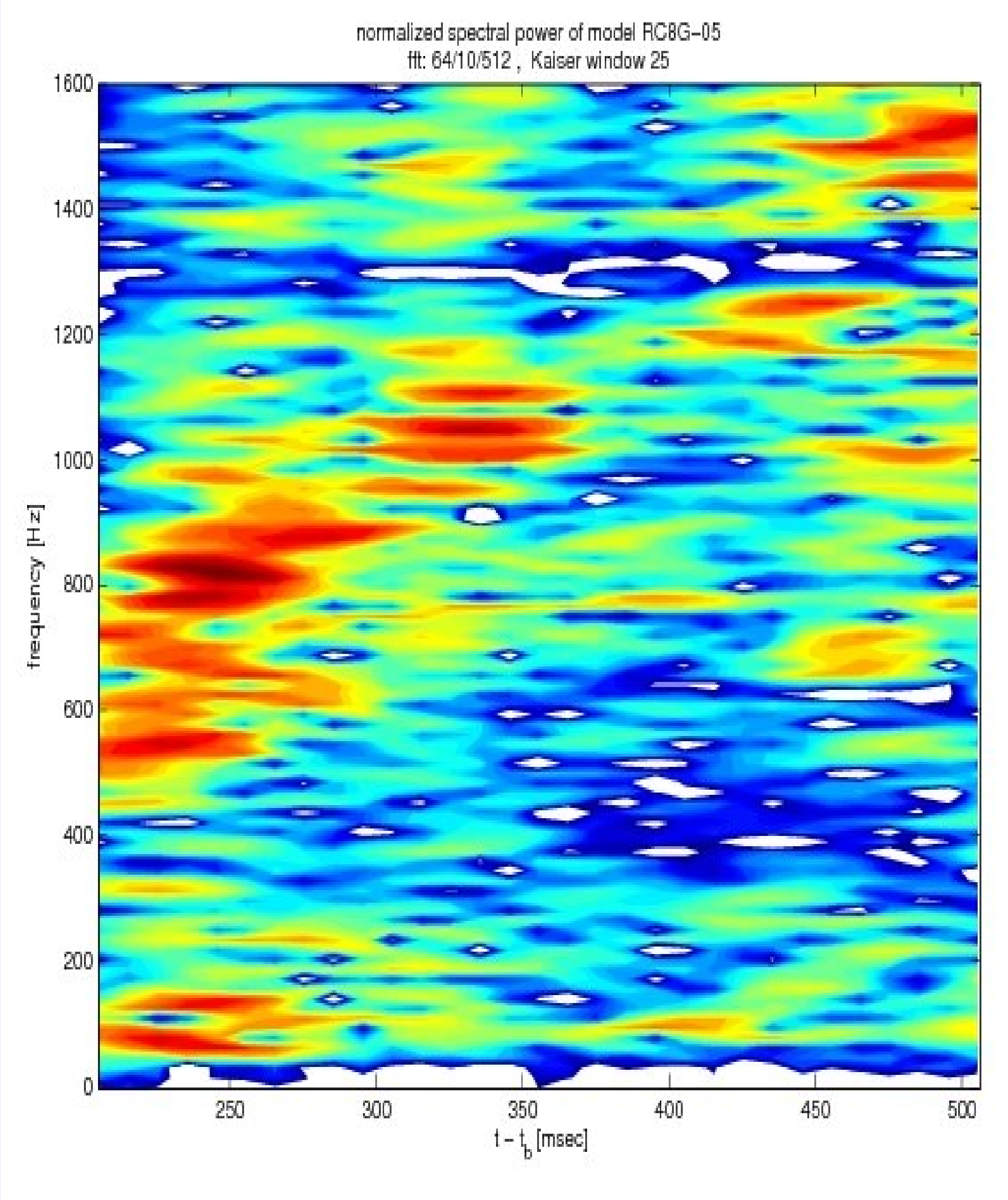
Müller, Rampp, Buras, Janka & Shoemaker (2004)

GW spectrogram (of a slowly rotating 15 M_{sol} star) may provide further insights

Müller et al., in prep.

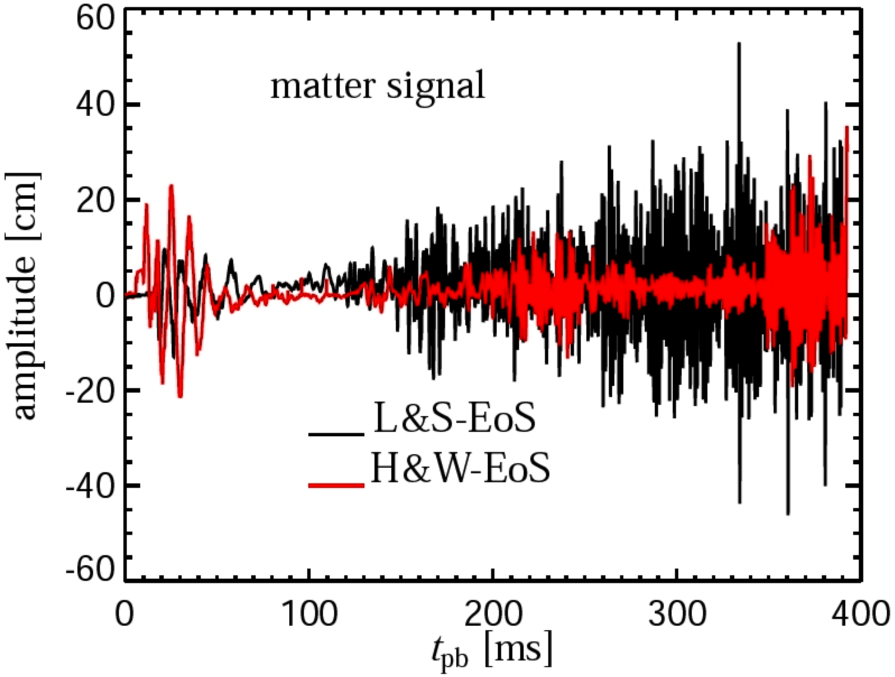


normalized spectral power of model RC8G-9bins
fft: 64/10/512 , Kaiser window 2.5

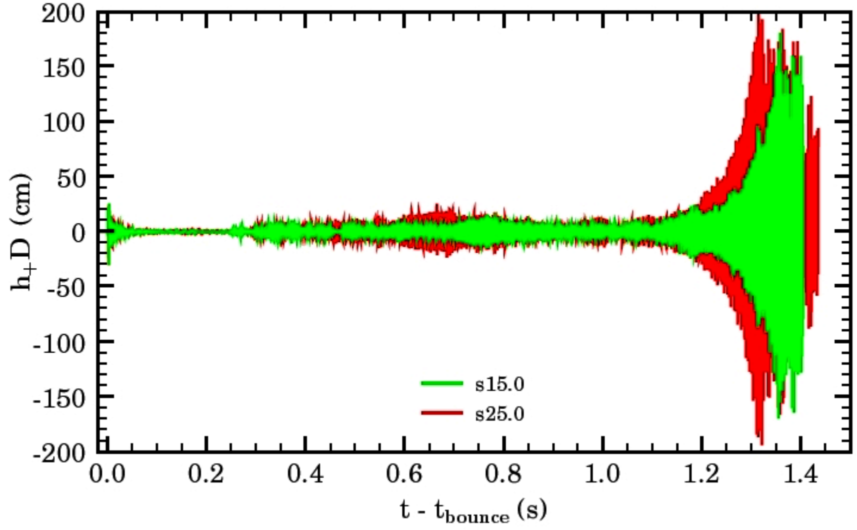


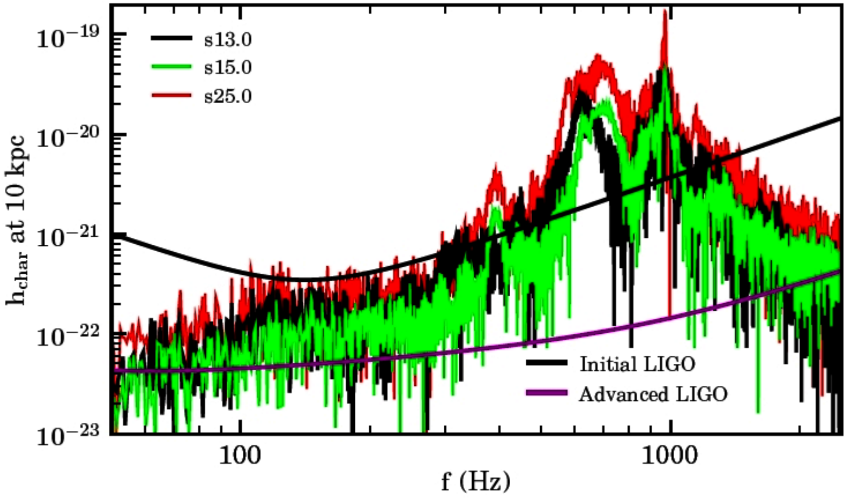
normalized spectral power of model RC8G-05
fft: 64/10/512 , Kaiser window 25

GWs due to SASI activity



Marek et al. (2008)

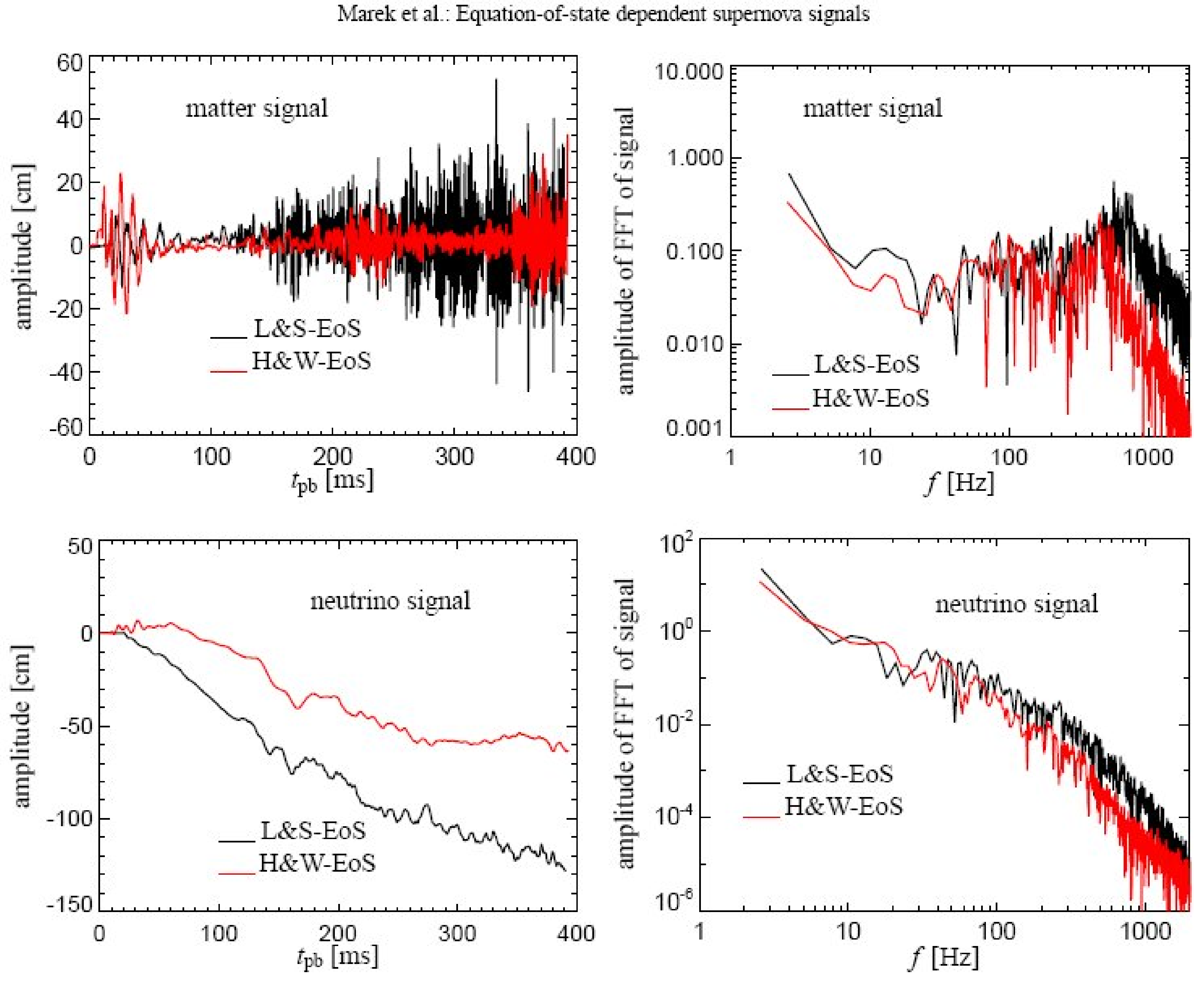




Ott (2008)

- GW amplitude from SASI phase depends on nuclear EoS in NS
- If NS core g-mode oscillations occur (acoustic explosion mechanism?)
  ---> ~10 times larger GW amplitudes

Same stellar progenitor, same input & transport physics / numerics



Marek et al.: Equation-of-state dependent supernova signals

(Marek, Janka & Müller, 2008)

Conclusions

GW radiation from CCSNe: where do we stand in 2008?

- simplified models miss important physics
  (convection, SASI, anisotropic neutrino emission)

- intensively studied collapse & bounce signal is only a prelude

- non-spherical post bounce flow occuring in every CCSN produces GW signal dominated by low-frequency ν-contribution

- only rare galactic events seem to be detectable

- effects of relativistic gravity important for dynamics, but can be well modelled by means of an effective relativistic potential

- CFC is an excellent approximation of GR for core collapse

- narrow-band, generic GW bounce signal