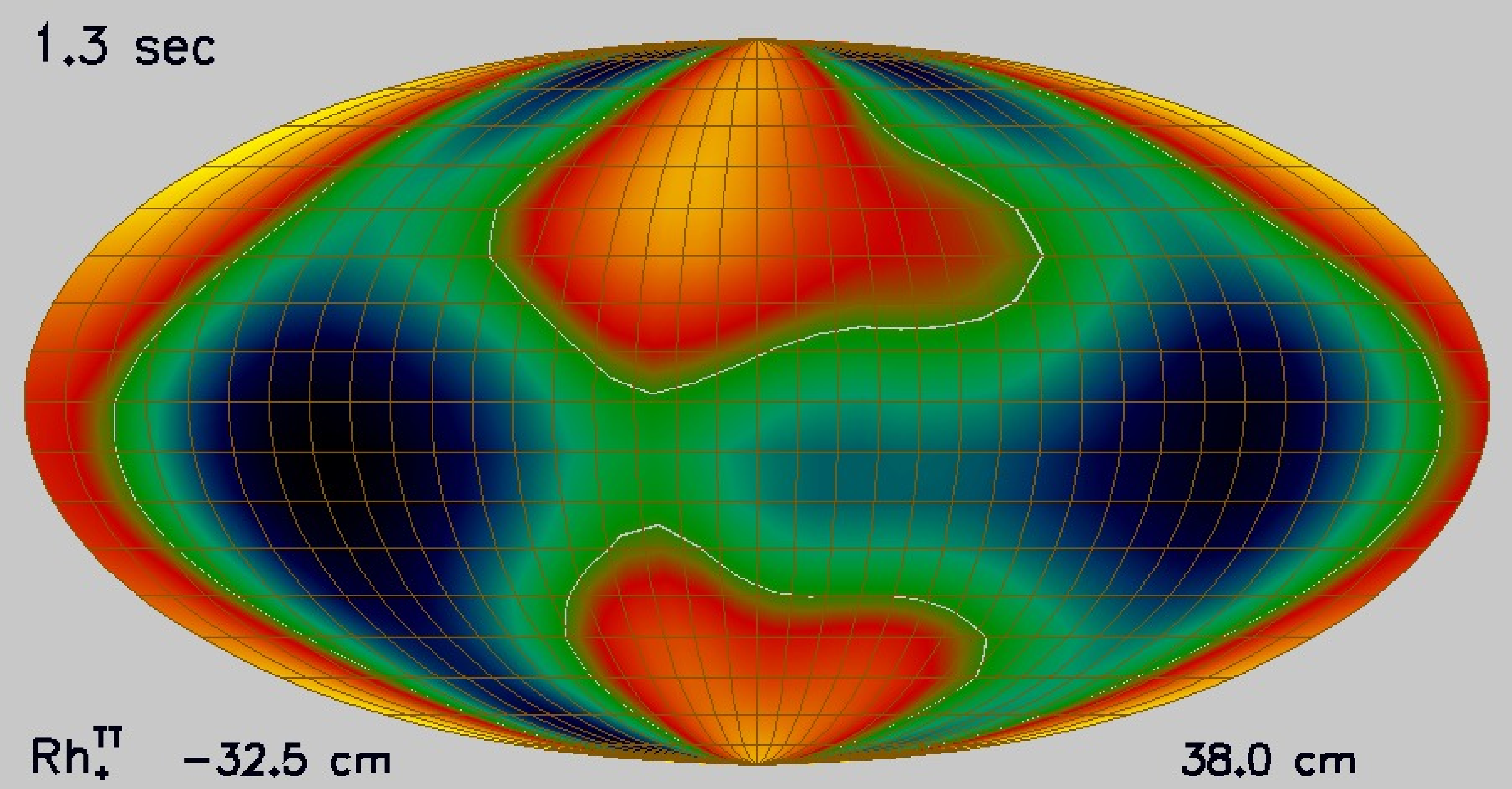
Gravitational waves from core collapse supernovae



Aim of the talk:

- review of the current status of models/simulations aiming to predict the gravitational wave signal of core collapse supernovae (CCSN)

Outline of the talk:

- why to occupy oneself with gravitational waves from CCSN?
- processes that generate gravitational waves in CCSN
- generic features of the gravitational wave signal from CCSN
- achievements and predictions of the most recent models

Disclaimer:

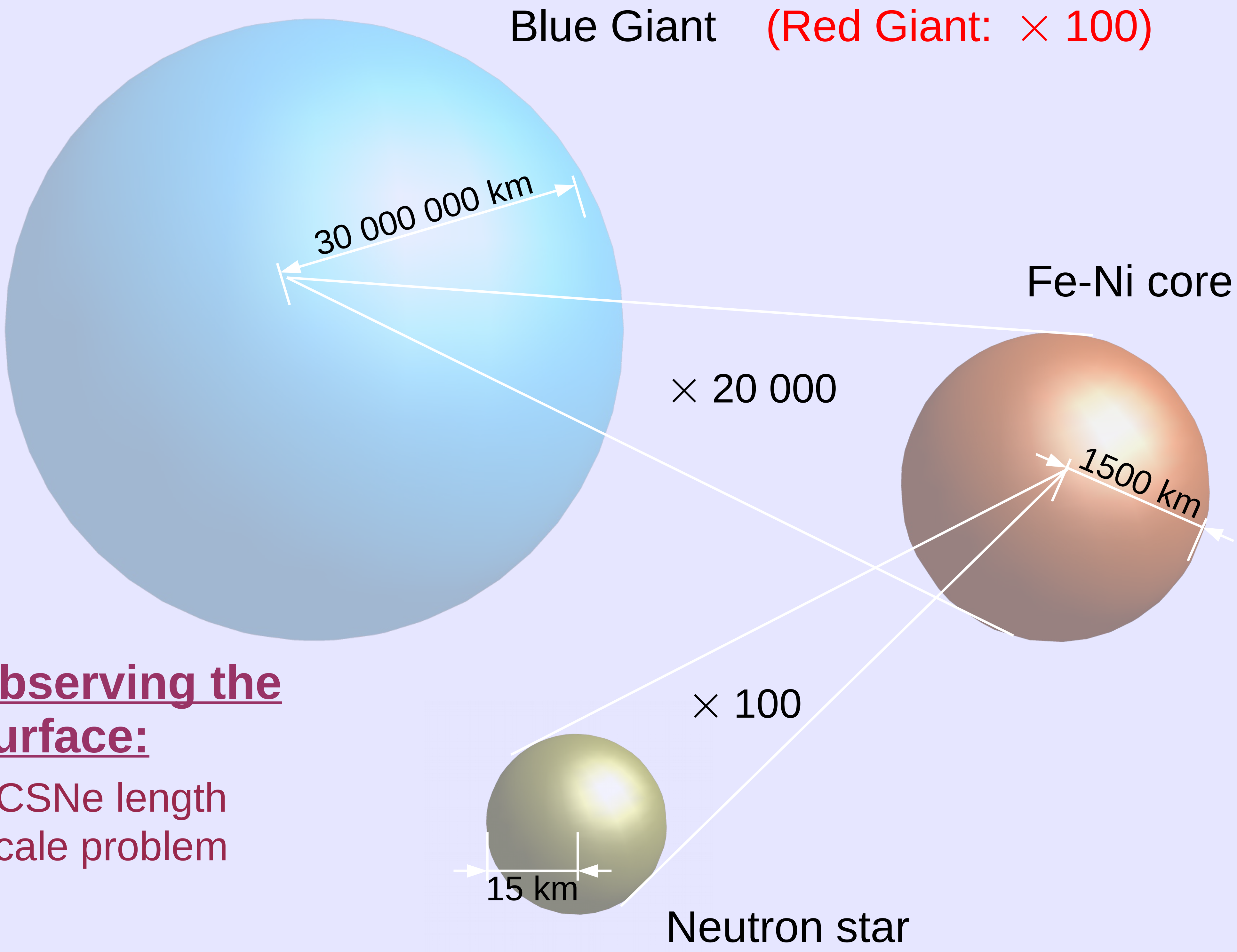
- only selected references are given, no attempt for completness
- more references, see:

http://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

Collaborators: Haakon Andresen, Thomas Janka, Bernhard Müller

Observing the surface:

CCSNe length scale problem



"Looking" into the "engine" of a core collapse supernova

- through observations of neutrinos

  up to now only SN1987A

- through observations of gravitational waves

  not yet occured! Would provide kind of Rosetta stone!

- through simulations

  already a 50 year effort ; extremely complex & expensive 6D radiation-hydrodynamics problem requiring ~50 million CPU-hrs / simulation

Core collapse supernovae: neutrino-driven delayed explosion

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

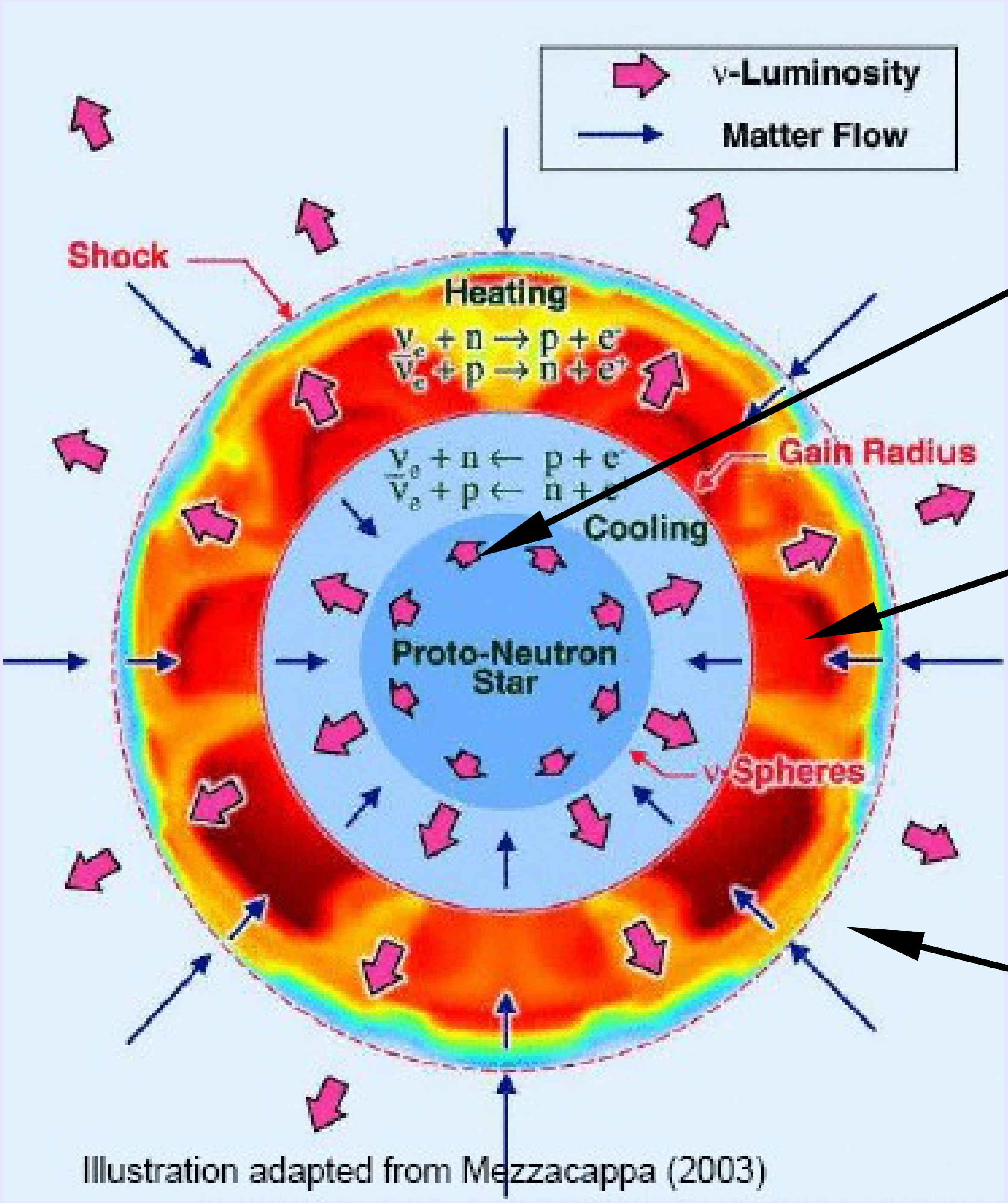


Illustration adapted from Mezzacappa (2003)

neutrinos diffuse out of opaque proto-neutron star

neutrinos heat matter in semi-transparent post-shock region --->

convection with coexisting downflows and rising hot bubbles sets in

neutrinos stream freely through stellar envelope

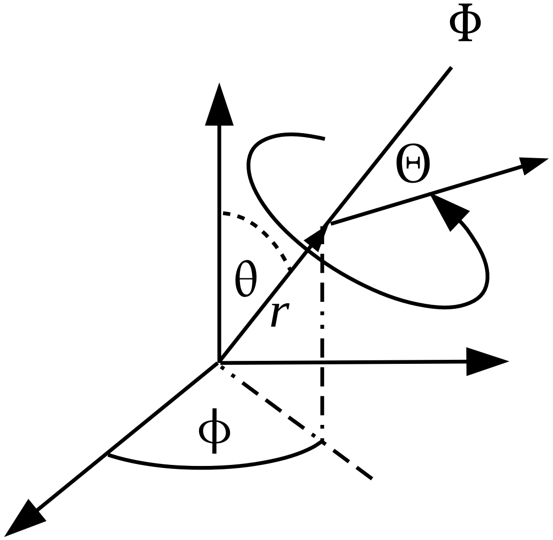
Explosion mechanism

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



Various modelling approaches	Required resources
• **3D** hydro + "**ray-by-ray-plus"** variable Eddington factor method: current method used at MPA (Janka et al.)	0.1 - 1 PFLOP/s
• **3D** hydro + **two moment closure** of Boltzmann equation (next feasible step)	1 - 10 PFLOP/s
• **3D** hydro + **6D** direct discretization of Boltzmann equation: no serious attempt yet	~100 PFLOP/s (sustained!)

Einstein quadrupole formula (adequate for CCSN (Shibata+ '05, Reiswig+ '11))

$$h_{ij}^{TT}(\boldsymbol{X},t) = \frac{2G}{c^4 R} P_{ijkl}(\boldsymbol{N}) \frac{\partial^2}{\partial t^2} Q_{kl}\left(t - \frac{R}{c}\right)$$

mass-quadrupole tensor

$$Q_{ij}(t) = \int dV \rho(\boldsymbol{x},t)\left(x_i x_j - \frac{1}{3}\delta_{ij}\boldsymbol{x}^2\right)$$

numerically more suitable form

(Nakamura & Oohara 1989, Blanchet+ 1990)

$$h_{ij}^{TT}(\boldsymbol{X},t) = \frac{2G}{c^4 R} P_{ijkl}(\boldsymbol{N}) \int dV \rho\left(2v^k v^l - x^k \partial_l \Phi - x^l \partial_k \Phi\right)$$

Gravitational waves

Einstein quadrupole formula $$h_{ij}^{TT} = \frac{2G}{c^4 R} \frac{\partial^2}{\partial t^2} Q_{kl} \sim \frac{R_S}{R} \frac{v^2}{c^2}$$

R_s = 3 km, v/c = 0.1, R = 10 kpc –-> h = 10^{-20} *

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

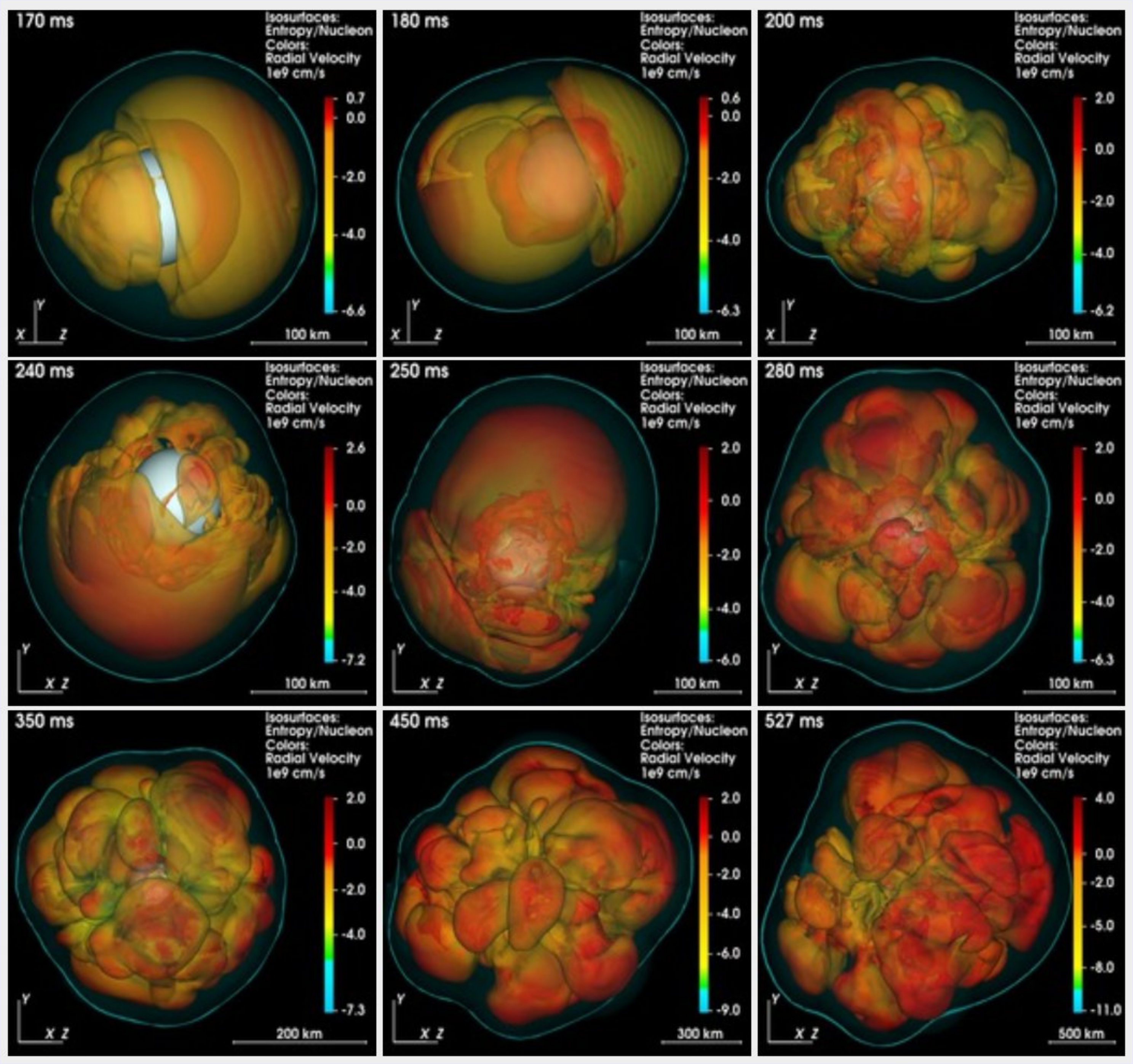
- convection in proto-neutron star
- convection in neutrino heated hot bubble
- anisotropic neutrino emission
- any other non-radial instability (e.g. SASI, AAC)

generically produced by any CCSN

and due to rotation and magnetic fields

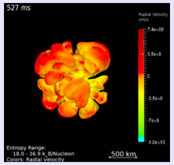
* [measuring the distance earth-sun with an accuracy of 1 nm]

state-of-the-art 3D simulation of a 20 solar mass model



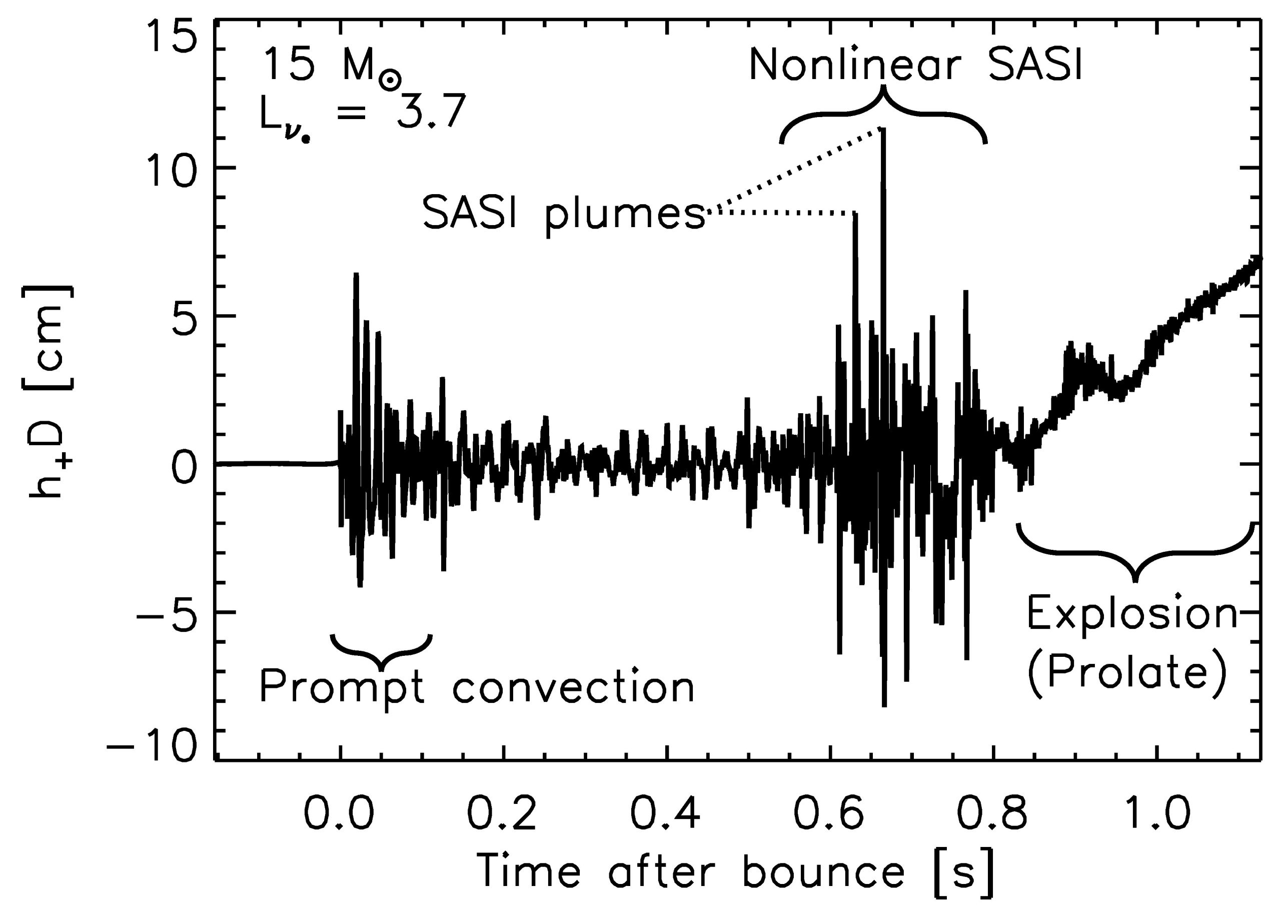
a moderate (g=1.26 - 0.2) strangeness-dependent reduction of the axial-vector coupling constant turns an unsuccesful model into a succesful one

(Melson+ '15, ApJL 808)



GW emission from postbounce phases

Murphy, Ott & Burrows, 2009



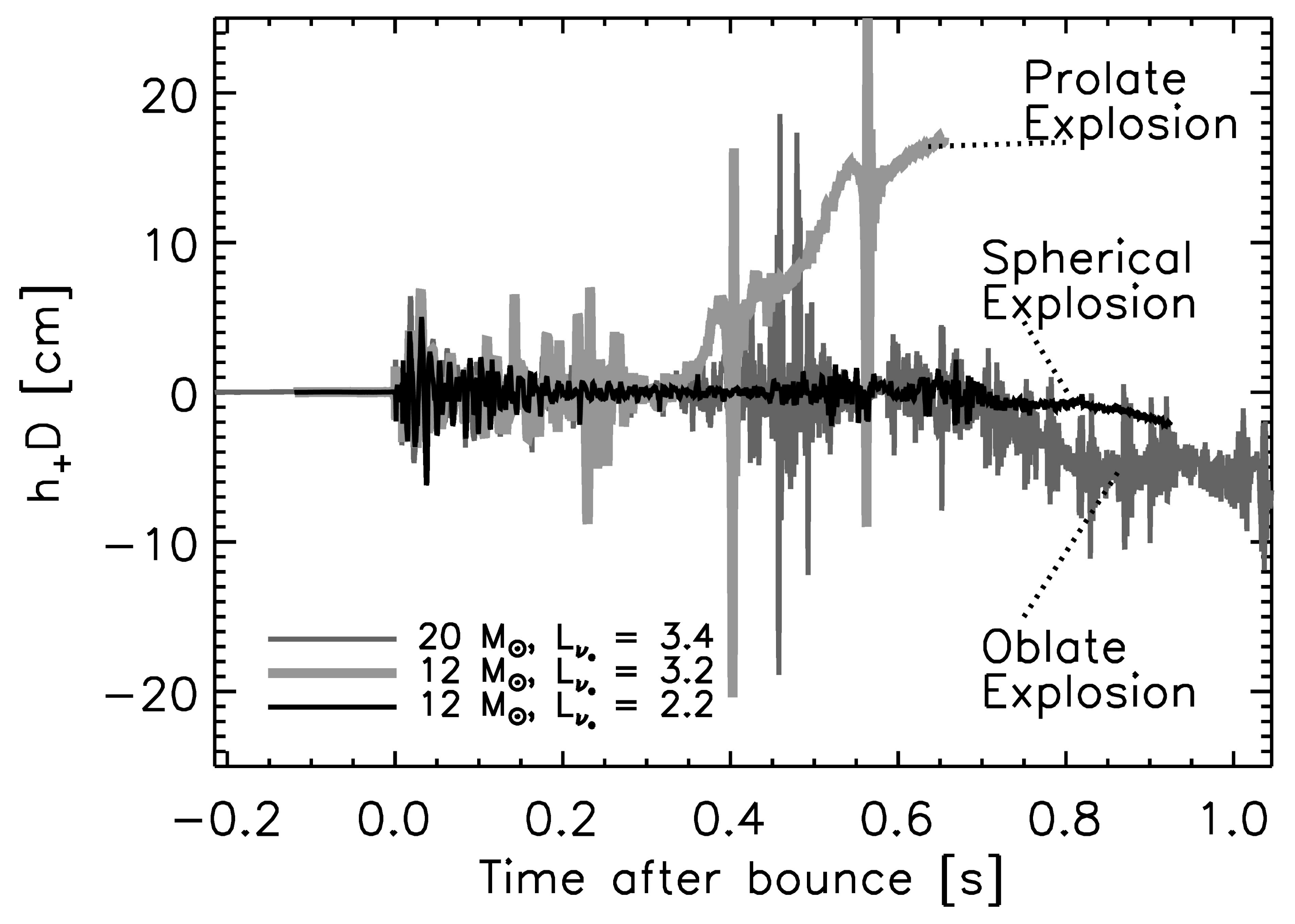
- progenitors of 12, 15, 20 and 40 solar mass
- 2D hydro (N)
- EOS: Shen+ '98
- approximate ν heating/cooling
- parametrized explosions

distinct phases of GW emission (non-rotating cores!):

- prompt convection (negative entropy gradient left by stalling shock; generic?)
- PNS & postshock convection
- SASI (spikes from narrow downflows striking the PNS "surface")
- explosion

GW emission from postbounce phases

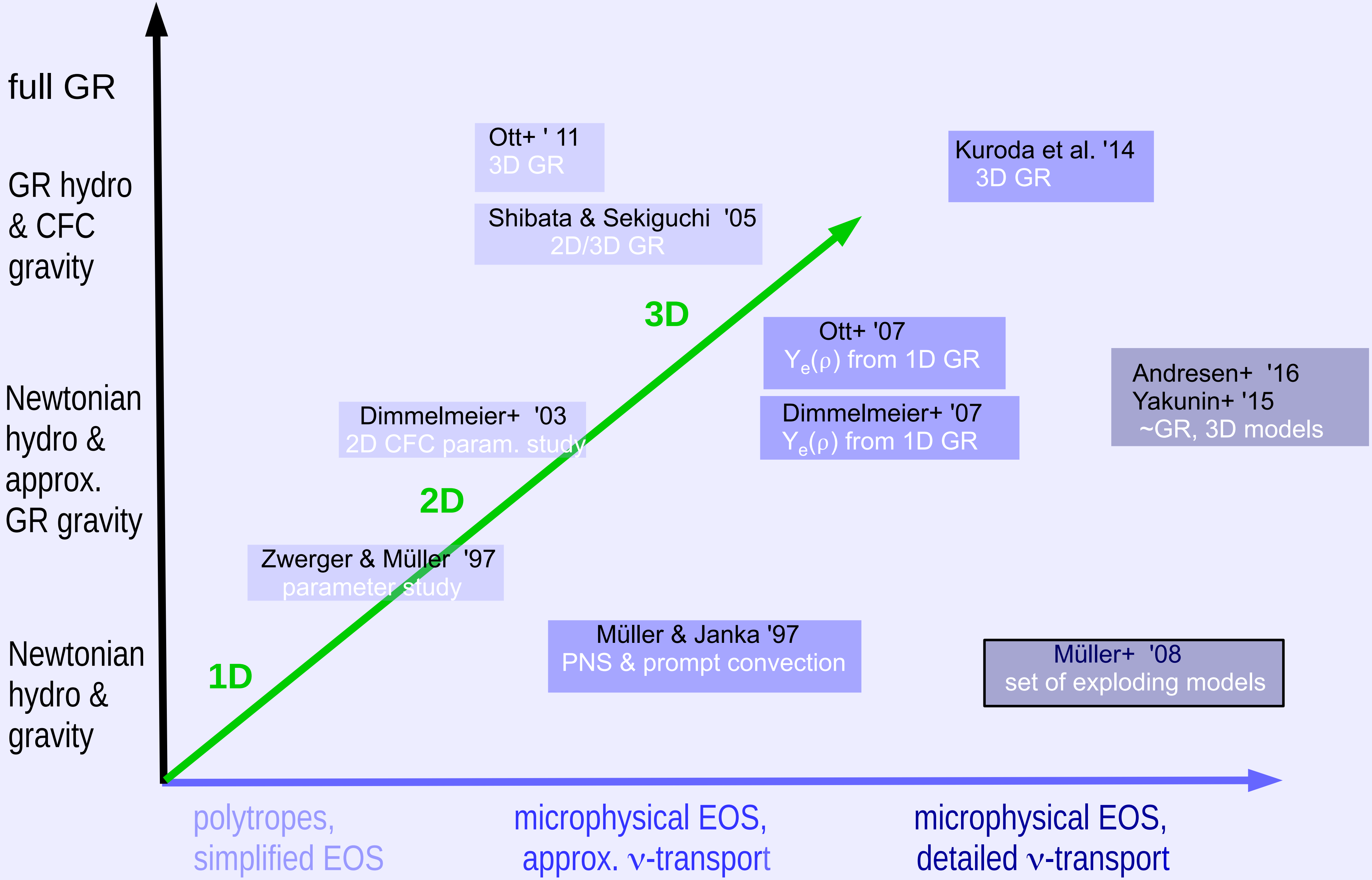
Murphy, Ott & Burrows, 2009



GW signal from explosion phase contains information of the effects of global asymmetries in explosion

Towards realistic theoretical GW signals from CSSN

<u>further "dimensions":</u> rotation, magnetic fields, initial models



full GR

GR hydro
& CFC
gravity

Newtonian
hydro &
approx.
GR gravity

Newtonian
hydro &
gravity

1D

2D

3D

Ott+ ' 11
3D GR

Shibata & Sekiguchi '05
2D/3D GR

Kuroda et al. '14
3D GR

Ott+ '07
$Y_e(\rho)$ from 1D GR

Dimmelmeier+ '07
$Y_e(\rho)$ from 1D GR

Andresen+ '16
Yakunin+ '15
~GR, 3D models

Dimmelmeier+ '03
2D CFC param. study

Zwerger & Müller '97
parameter study

Müller & Janka '97
PNS & prompt convection

Müller+ '08
set of exploding models

polytropes,
simplified EOS

microphysical EOS,
approx. ν-transport

microphysical EOS,
detailed ν-transport

Some achievements/discoveries from ~40 yrs of studies of the GW signature of CCSN

- spheroidal / ellipsoidal, one-zone models

Saenz & Shapiro '78, '79, '81

$\Delta E/Mc^2 \sim 10^{-6} \ldots 10^{-4}$

- 2D Newtonian hydro, prompt explosion models, evolutionary progenitor models, microscopic EOS

Müller '82; Mönchmeyer+l '89, '91

$\Delta E/Mc^2 \sim 10^{-10} \ldots 10^{-7}$

- 2D Newtonian rotating polytropes, parameter study

Finn & Evans '90; Yamada & Sato '95; Zwerger & Müller '97;
Rampp, Müller & Ruffert '98 (3D)

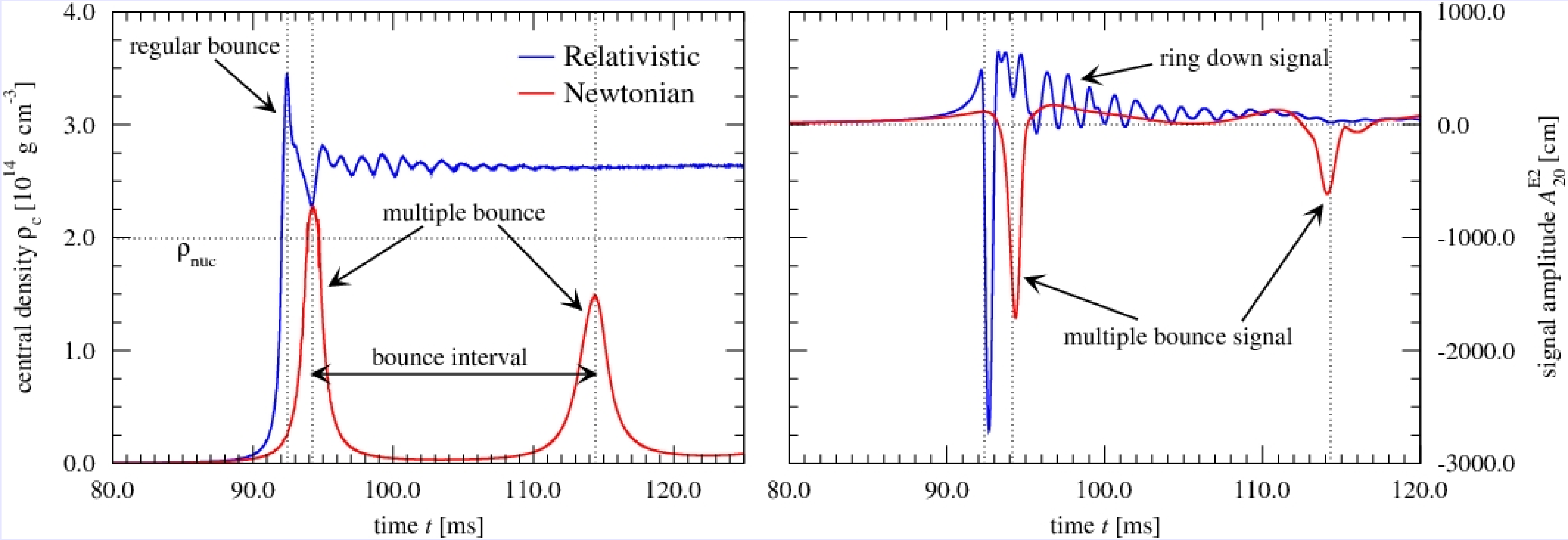
centrifugal bounce can occur

Some achievements/discoveries

- GR parameter study, 2D simplified EOS, no ν-transport

Dimmelmeier, Font & Müller '02 (CFC); Shibata '03; Shibata & Sekiguchi '05 (3D)

GR potential deeper --> larger bounce densities, more compact PNS
--> centrifugal bounce occurs only rarely



Some achievements/discoveries

- MHD models Kotake+ '04 (N); Yamada & Sawai '04 (N); Obergaulinger+ '06 (N & GR-pot); Scheidegger+ '08, '10 (3D, EOS, GR-pot),

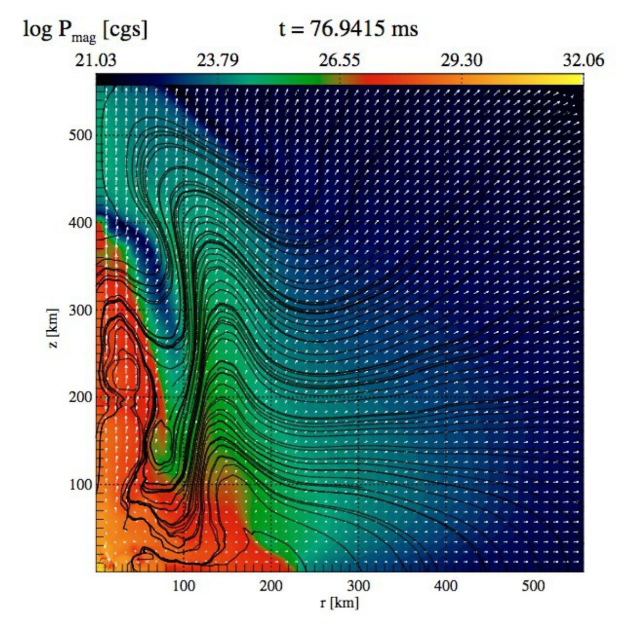
only strong initial fields (B > 10^{11} G) influence overall dynamics

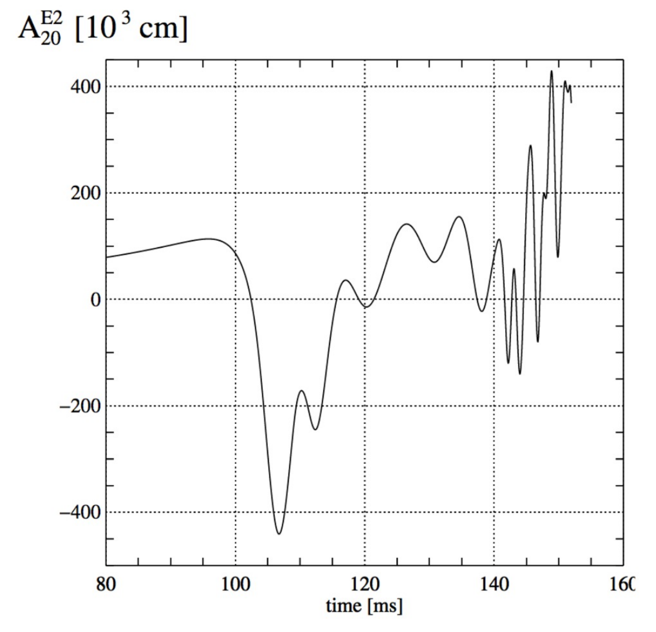
–--> GW amplitude affected by

* magnetic fields that contribute significantly to total energy density

* bipolor MHD driven jet outflow giving rise to a new signal type

* initially strong toroidal field: jet suppressed by fast growing spiral SASI





Some achievements/discoveries

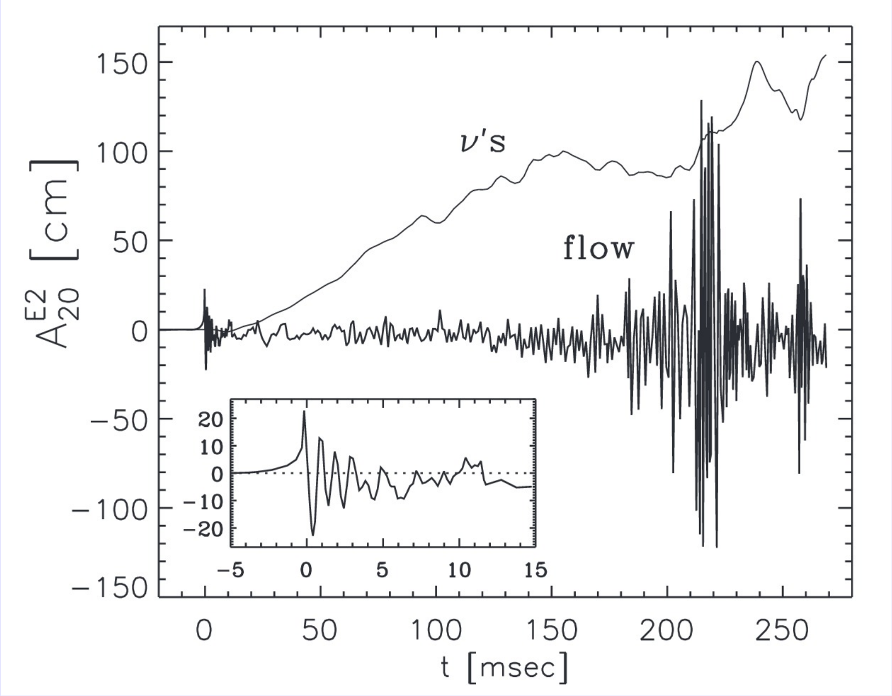
- GW from neutrinos (time-dependent asymmetric energy/mass flux)

  Müller & Janka '97, Müller+ '04 (2D, GR-pot)

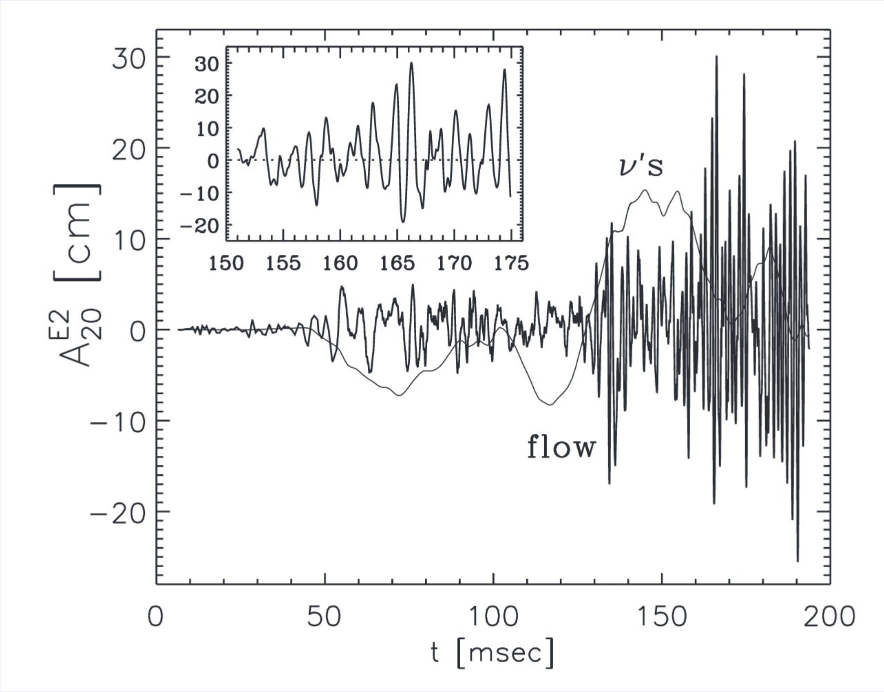
  * frequencies lower ($\lesssim$ 30 Hz) than those of matter signal (100 Hz … 1000 Hz)

  → harder to observe because of seismic detector noise

  * amplitudes overall larger



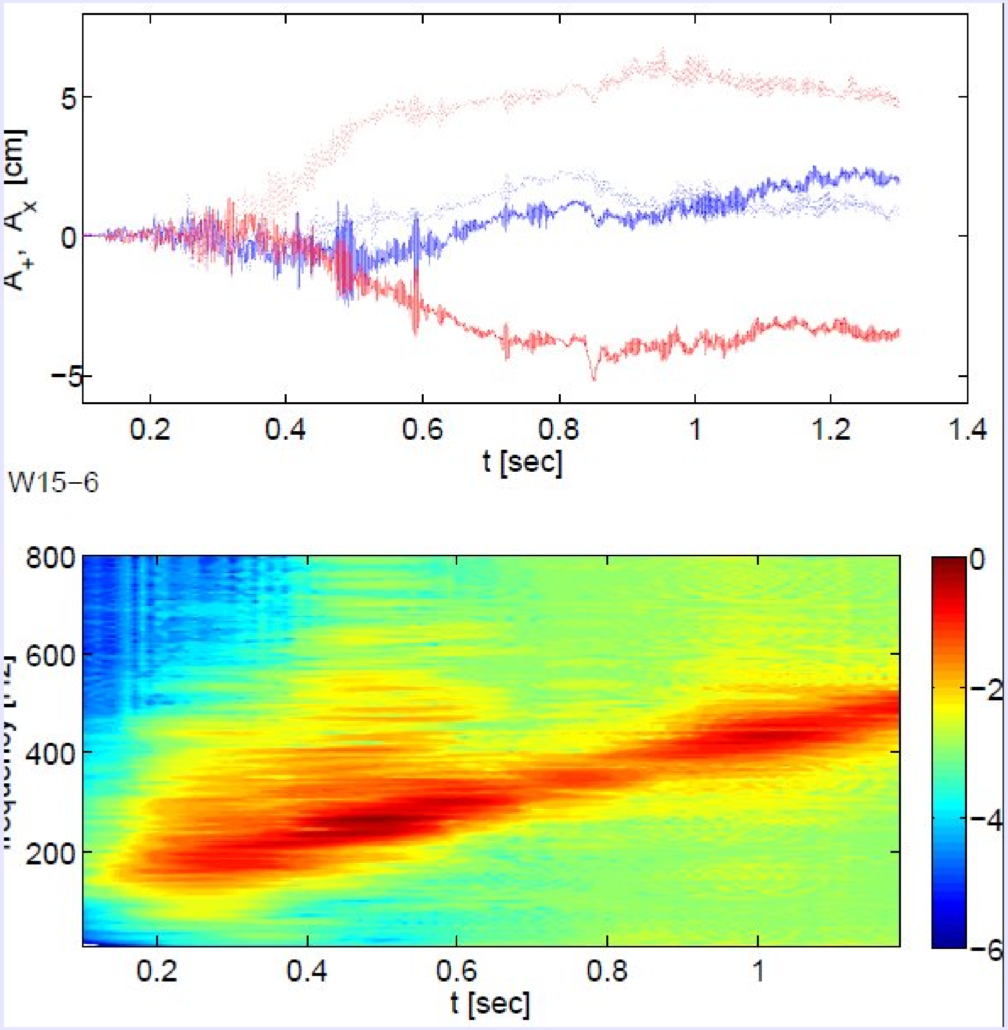
rotating 15 solar mass 2D model



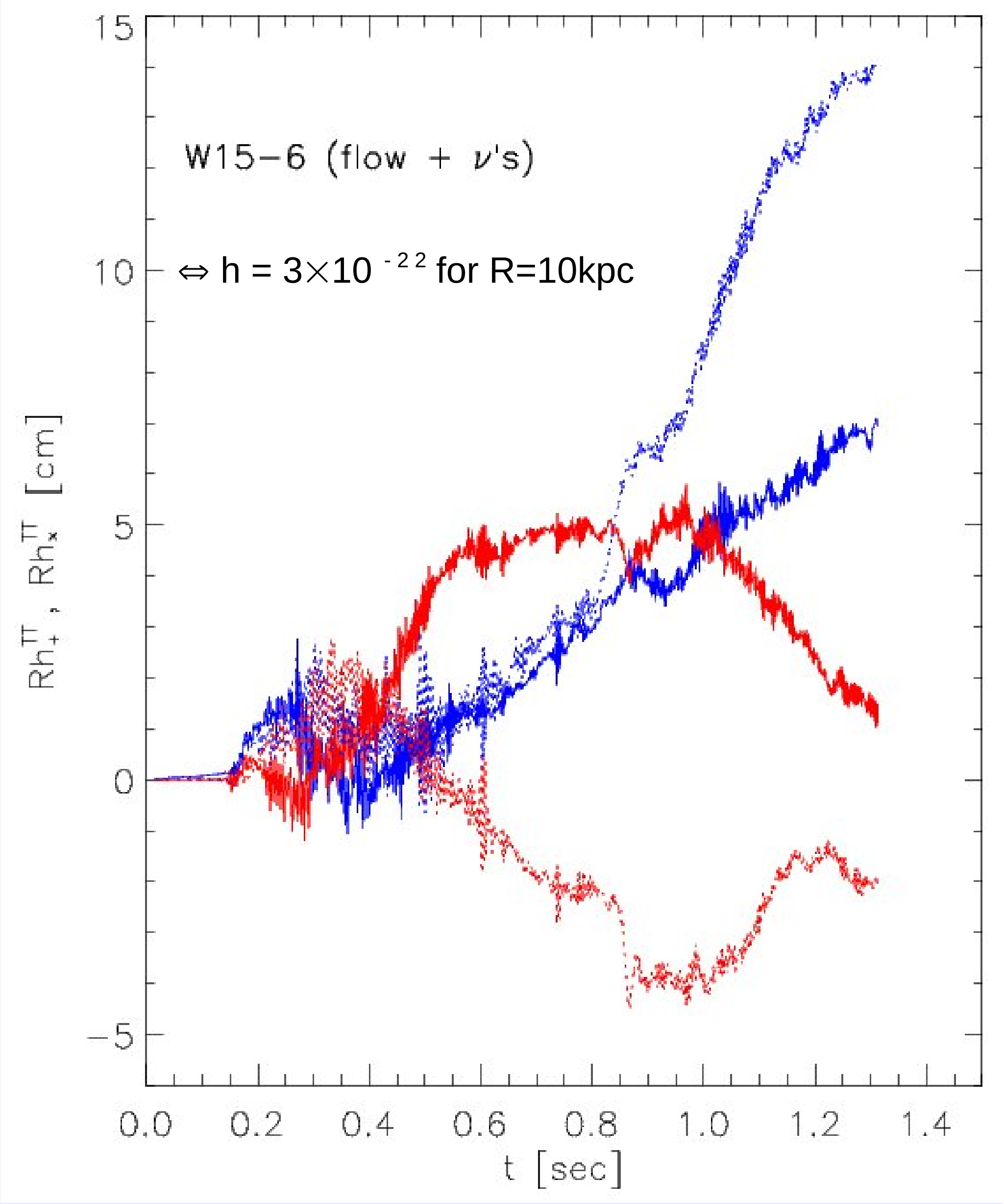
non-rotating 11 solar mass 2D model

Parametrized 3D models of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2012)

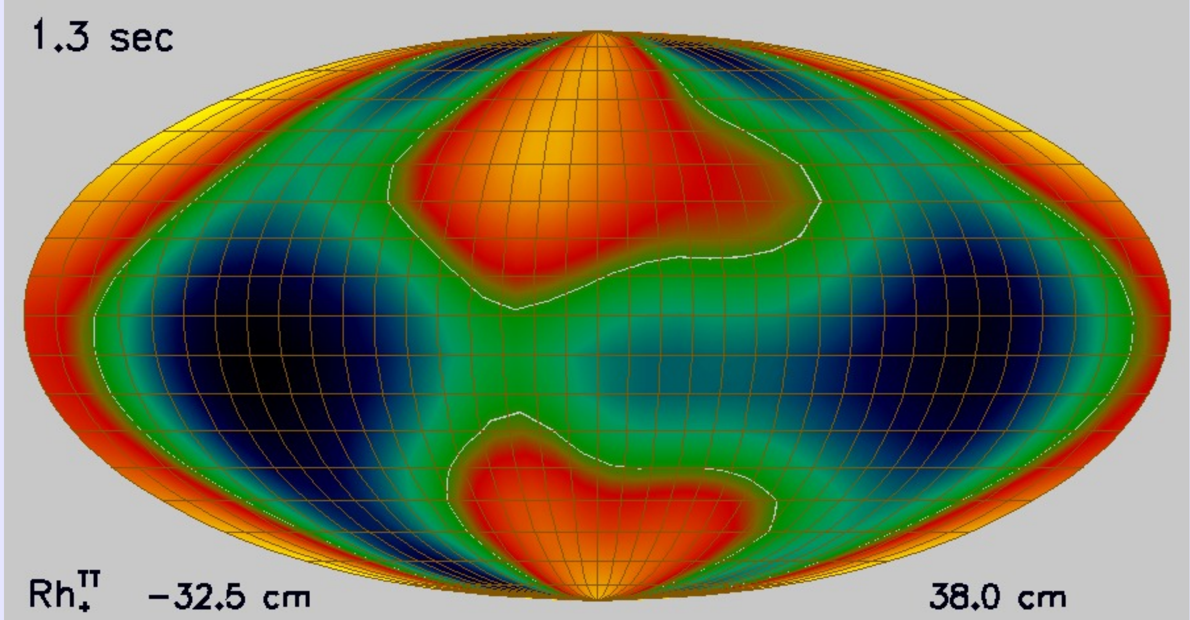


GW amplitudes due to aspherical flow
& corresponding spectograms $dE_M/d\nu$



total GW amplitudes (including ν)

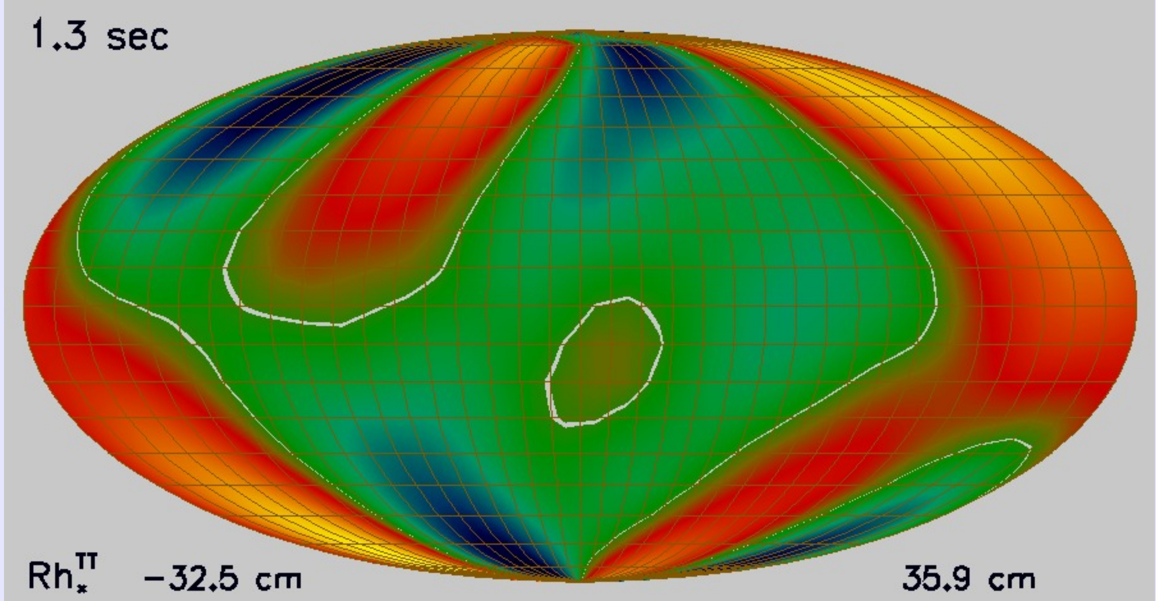
GW signature of parametrized 3D models



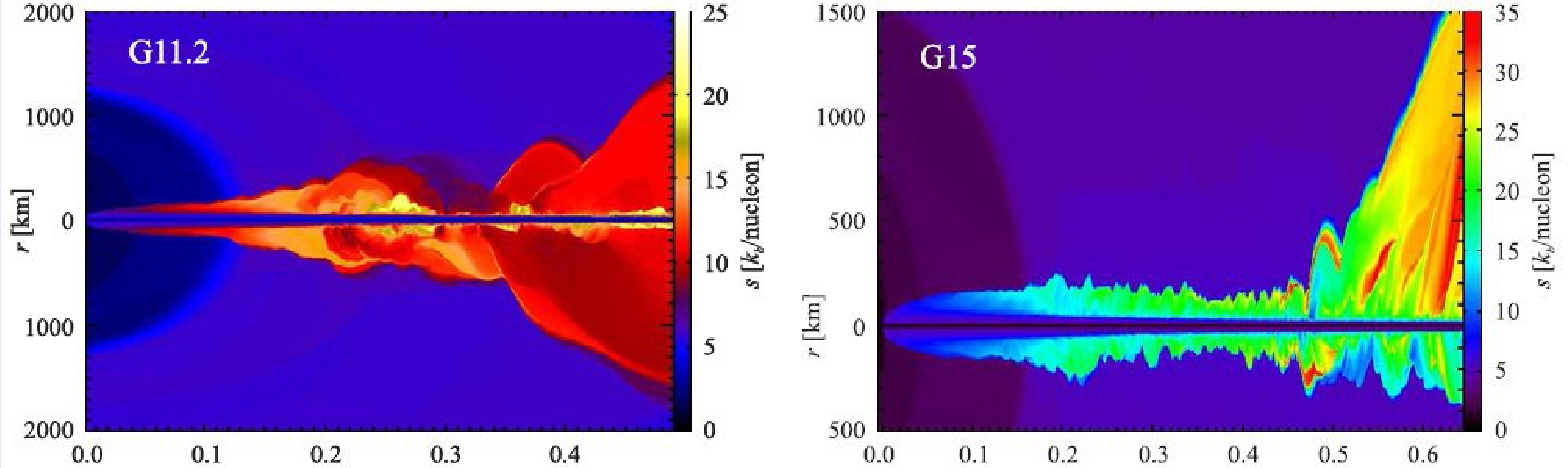
N20-2

observer angle dependent wave amplitudes

Müller, Janka & Wongwathanarat (2012)

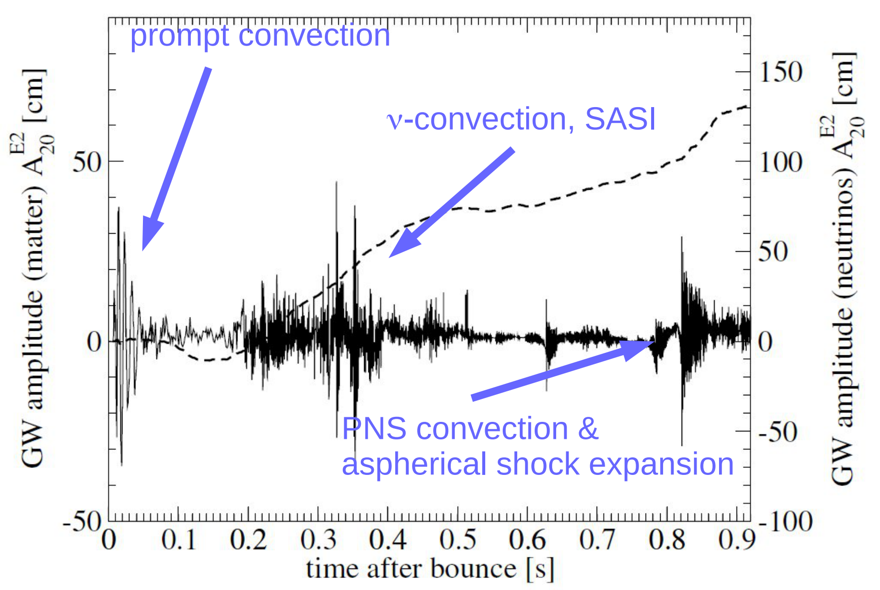


Some achievements/discoveries



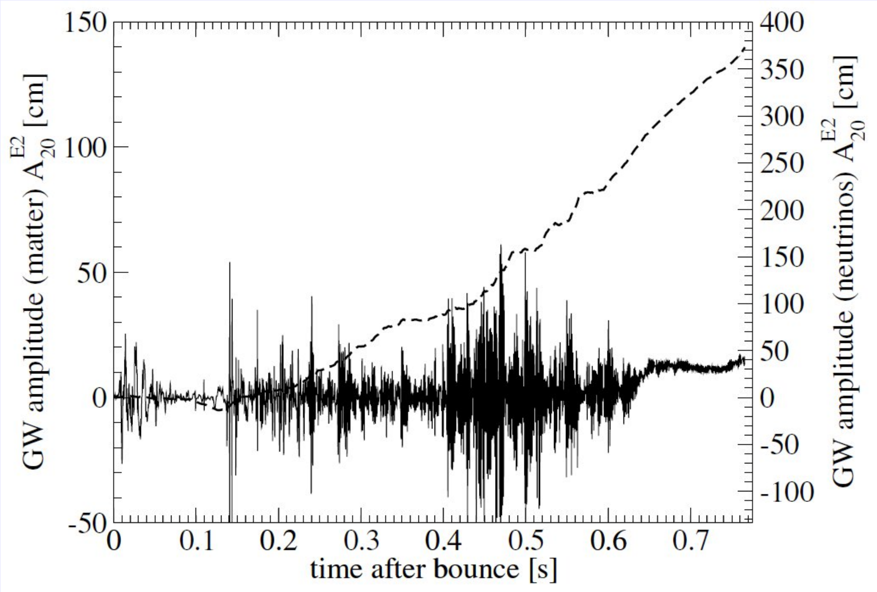
B.Müller, Janka & Marek 2013: 2D, CFC, multi-group three-flavor ray-by-ray-plus ν-transport

relativistic effects in combination with detailed ν-transport essential for quantitative predictions, determine structure of PNS surface layer and its characteristic g-mode frequency


prompt convection

ν-convection, SASI

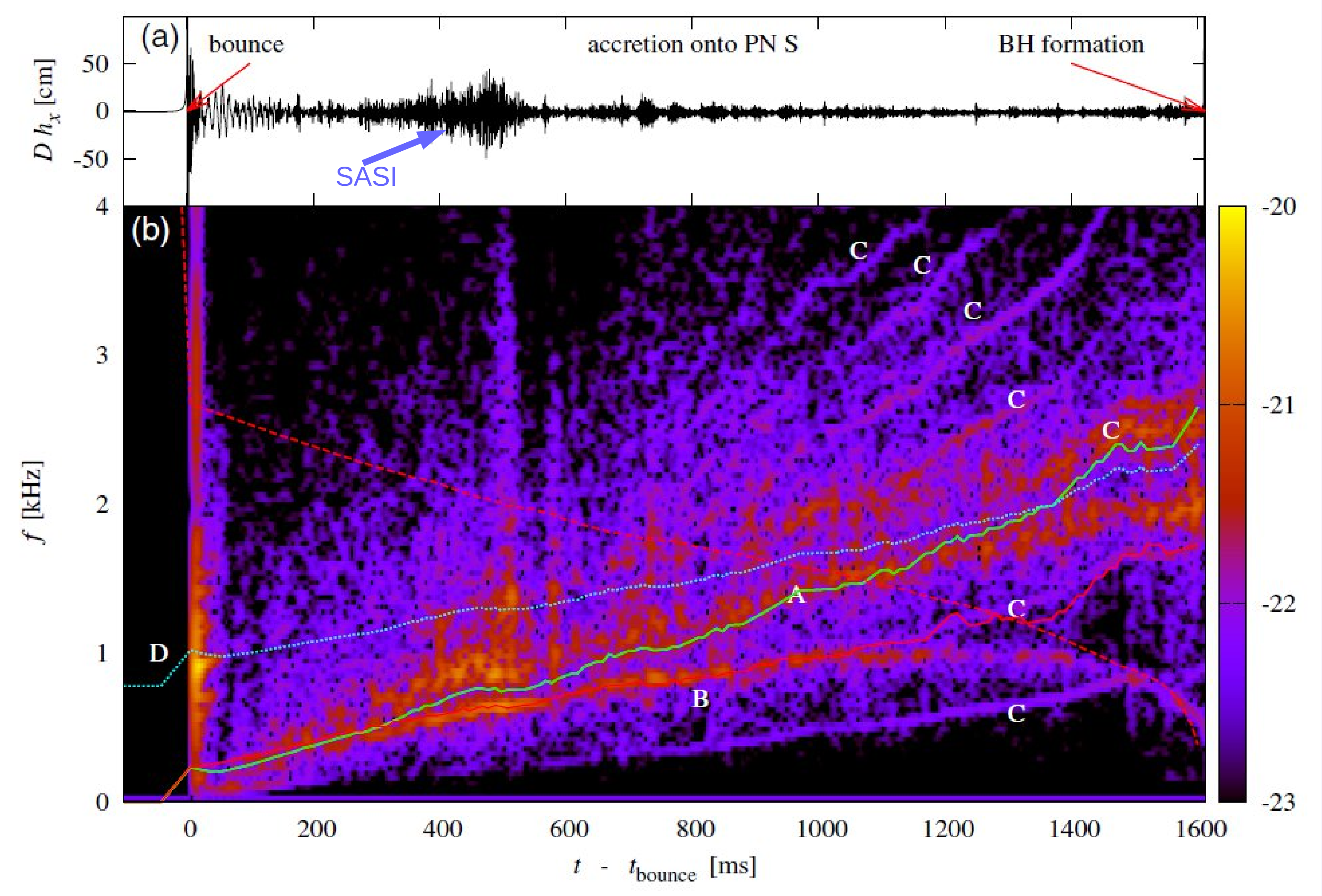
PNS convection &
aspherical shock expansion



solid lines: matter GW signal ; dashed lines: neutrino GW signal (different scales!)

Some achievements/discoveries

Cerda-Duran+ 2013: 2D, XCFC, 35 solar mass, rapidly rotating (2rad/s), low-metallicity progenitor,
gray ν-leakage scheme, LS220-EOS,
two models simulated until BH formation (M_{PNS} > 2.04 M_{sun})



lines show frequency evolution of g-modes at PNS surface (green), g-modes in cold inner core (solid red), quasi-radial mode (dashed red), and f-mode (dotted blue)

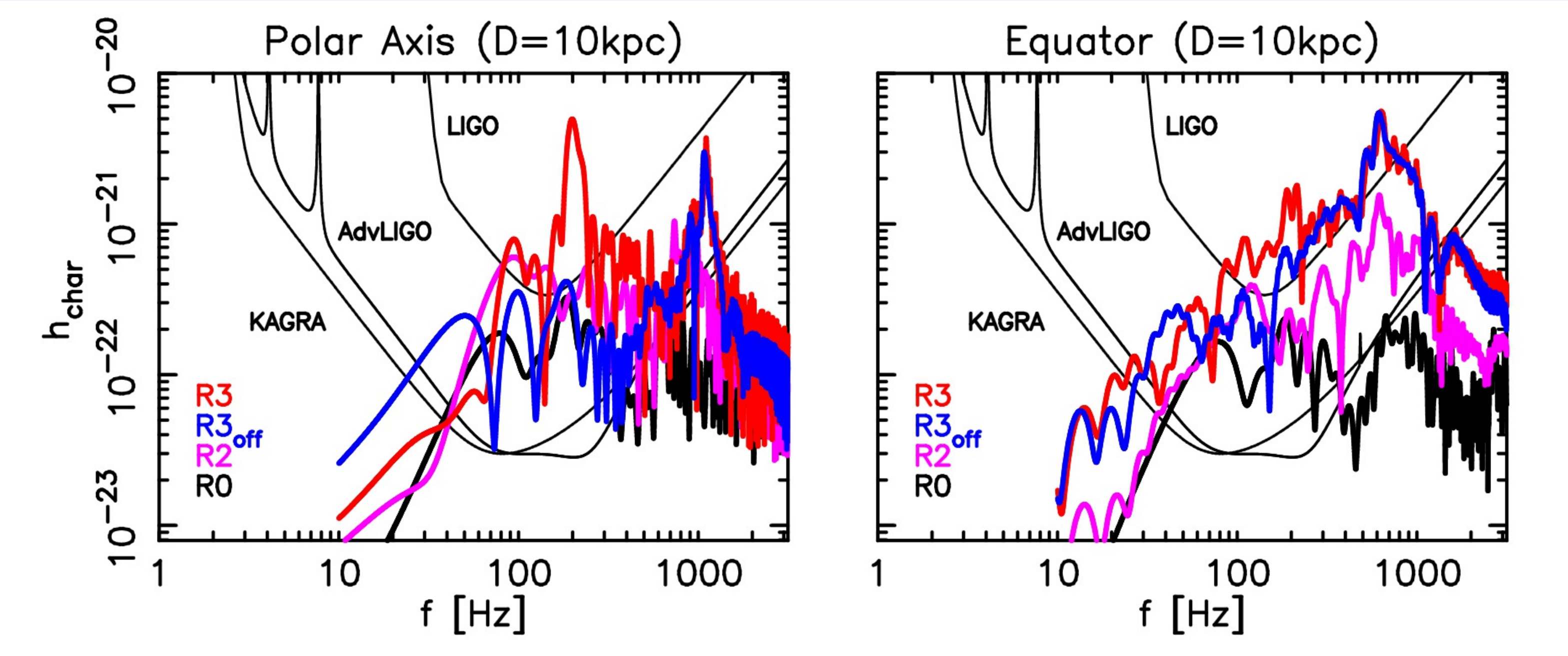
previous studies of collapsar scenario Sekiguchi & Shibata 2005, Ott+ 2011 used simplified EOS
→
unrealistically short time (~150 msec) until BH formation
→
miss important part of GW emission
(information about structure of PNS & accretion shock)

Some achievements/discoveries

Kuroda, Takiwaki & Kotake 2014:

3D, GR, 15 solar mass progenitor, 5 rotating models (Ω[rad/sec) = $\pi/6$, $\pi/3$, and π), Shen EOS, approximate ν-transport (M1 closure, variable Eddington factor of Levermore 1984)

- results consistent with previous work in 3D (Ott+ '07, '12, '13; simpler transport, softer EOS)
- signals from prompt convection qualitatively similar (except for most rapidly rotating model)
- nonaxisymmetric instabilities (spiral SASI) essential for GW signature of rotating models (see also 3D Newtonian study with ZEUS-MP of Kotake+ '11)



Hayama+ 2016: circular polarization of GW from CCSN provide a clear indication of rapid rotation rotation period < few seconds → galactic events detectable with network of 2nd generation detectors

Some achievements/discoveries

Andresen, B.Müller, E.Müller & Janka 2016:

3D, GR-pot, 11.2, 20, and 27 solar mass progenitors, LS-220 EOS, ray-by-ray-plus (Buras+ '06) energy-dependent two-moment multi-flavor ν-transport (VERTEX, Rampp & Janka '02)

See also: Kuroda, Kotake & Takiwaki '16, 15 solar mass model, different nuclear EOS,
grey ν-transport

- GW emission (in pre-explosion phase) strongly depends on whether post-shock flow is dominated by SASI or convection (driven by neutrino heating)

- SASI-dominated models:

  strong emission at low frequencies around 100 … 200 Hz; not present in 2D models!

  but low-frequency emission is no unambiguous signature of SASI,
  can also also occur after onset of explosion

- GW emission of 3D models differs considerably from that of 2D models
  amplitudes: $|A_{+,x}| \lesssim 4$ cm in 3D models, and ~ few 10 cm in 2D models

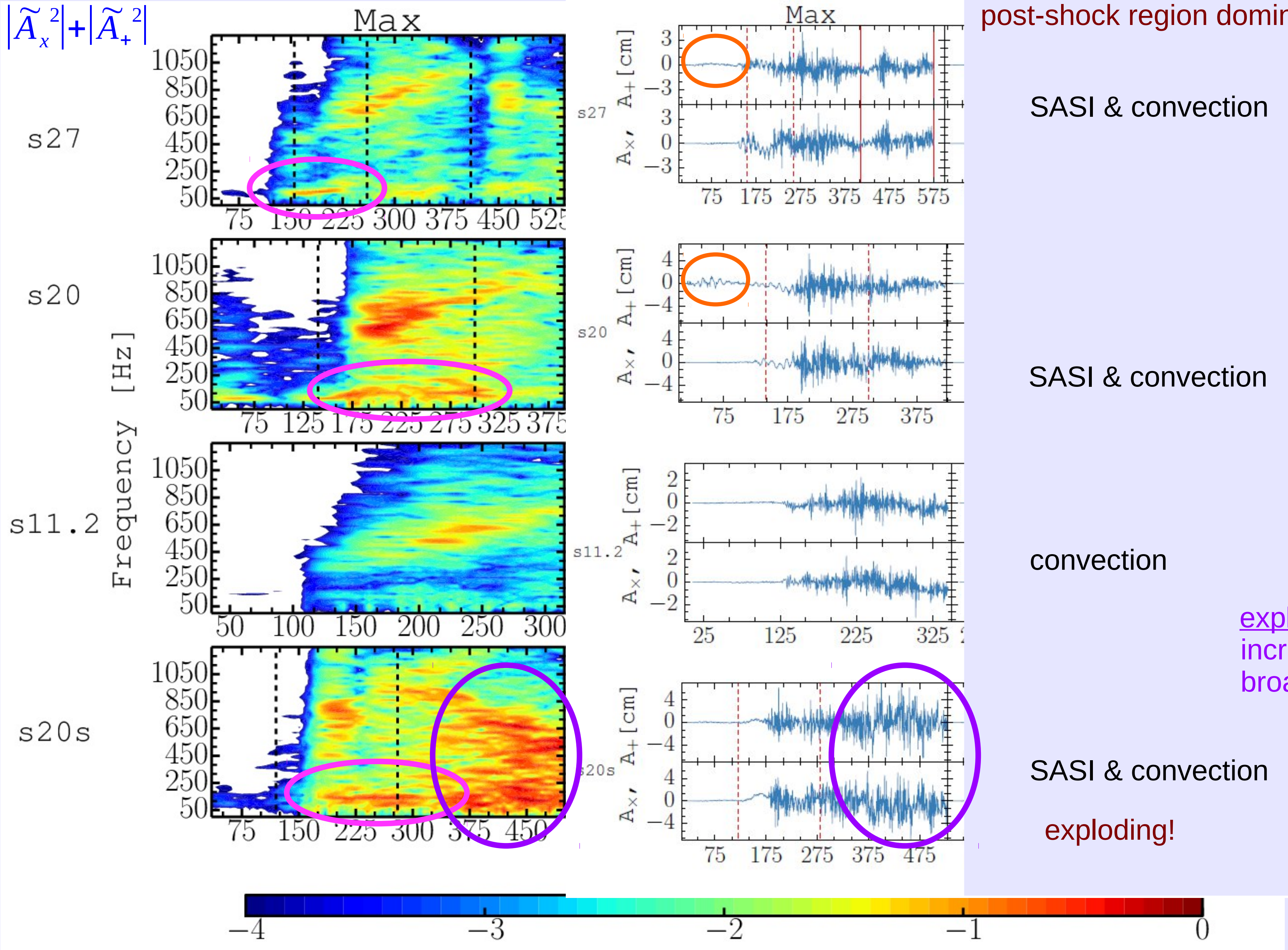
- shock revival in exploding 20 $M_\odot$ model results in enhanced low-frequency emission
  (preferred scale of convective eddies in PNS convection zone changes)

Some achievements/discoveries

Andresen, B.Müller, E.Müller & Janka 2016

low-frequency SASI emission

GW from prompt convection



post-shock region dominated by

SASI & convection

SASI & convection

convection

explosion signature
increase of
broadband power

SASI & convection

exploding!

Some achievements/discoveries

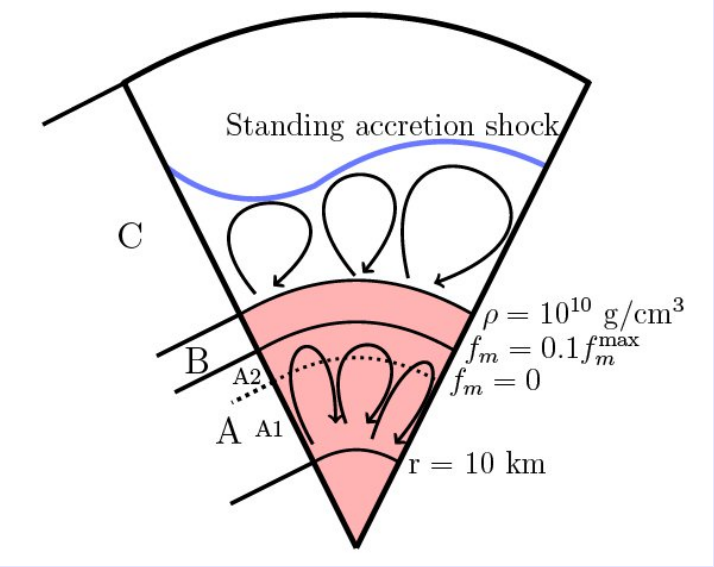
Andresen, B.Müller, E.Müller & Janka 2016:

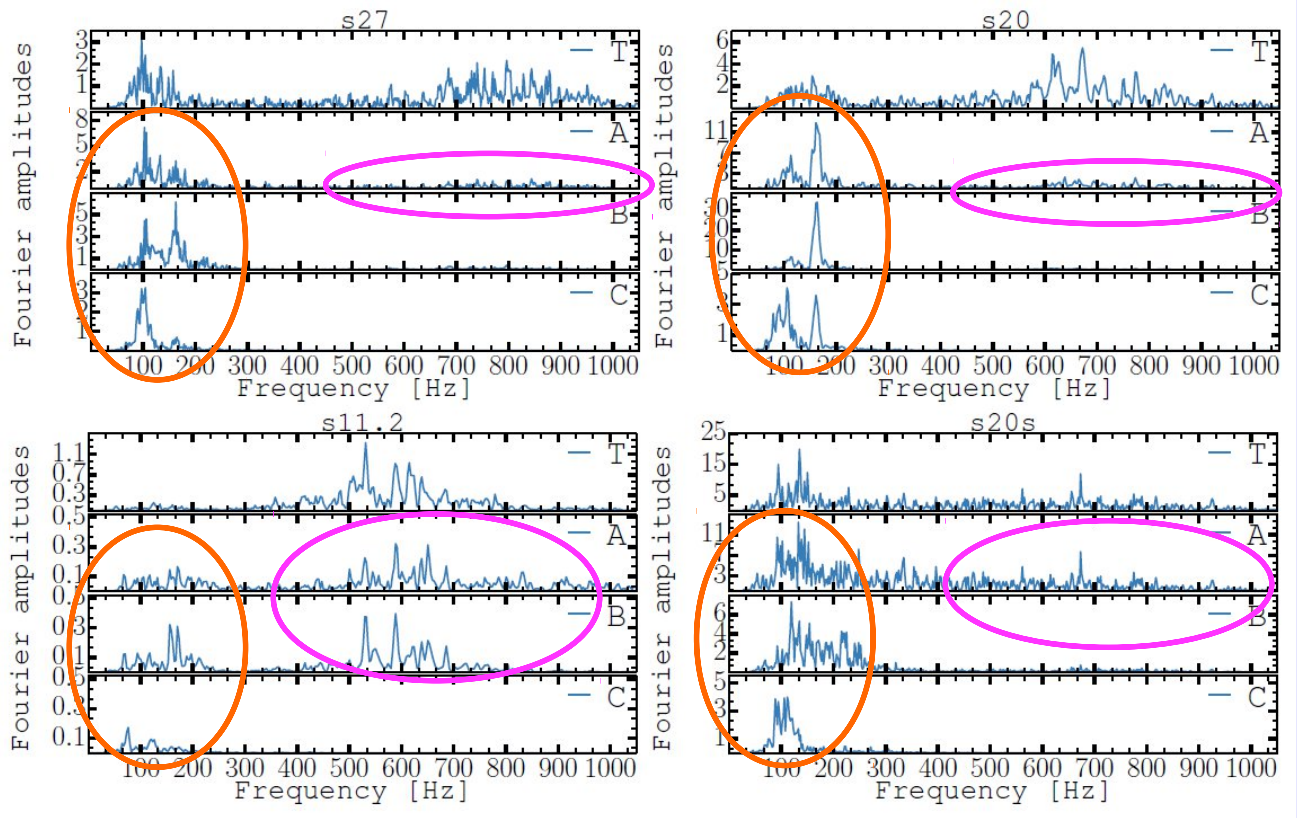
to determine origin of high-frequency and low-frequency components of GW signal the computational volume is divided into three layers

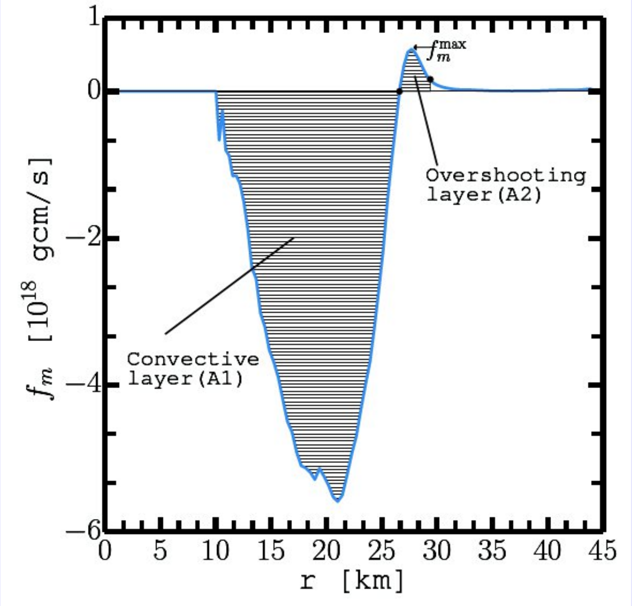
layer A: PNS convection zone

layer B: PNS convectively stable surface layer

layer C: region beyond the PNS"surface"







low-frequency emission: from all 3 layers (even for model s20s!)

high-frequency emission: mostly from aspherical motion in layer A

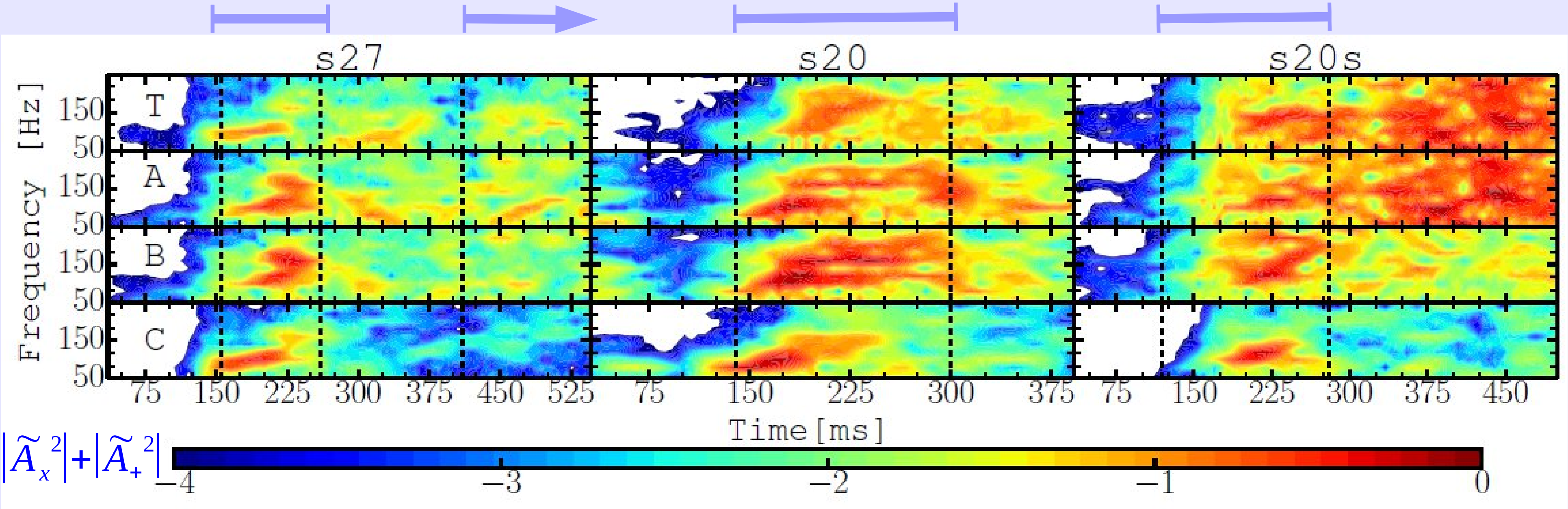
Some achievements/discoveries

Andresen, B.Müller, E.Müller & Janka 2016:

- SASI produces strong signal component in the frequency range 100 … 200 Hz

amplitude spectrograms of low-frequency GW signal arising from the three different layers

episodes of strong SASI activity are bracketed by vertical dashed lines



apparent temporal correlation of low-frequency emission with the SASI, because of a global modulation (3D≠2D!) of the accretion flow by the SASI

GW signal traces frequency of l=1,2 SASI modes, but with a frequency doubling for the l=1 spiral mode
(integral in d^2Q/dt^2 invariant to a rotation by π in any direction) → double-peak structure of low-frequency GW signal

OUTLOOK:

The detection of the gravitational wave signal from a CCSN will provide new & independent insights into the explosion dynamics

However, detection prospects appear rather bleak:
D$\lesssim$3kpc (2nd-generation), D$\lesssim$30kpc (3rd-generation) & closer events with high S/N

Predicting the gravitational wave signal of CCSN: 3 decades of fun & ordeal

Müller 1982

Müller+ 2012, Andresen+ 2016

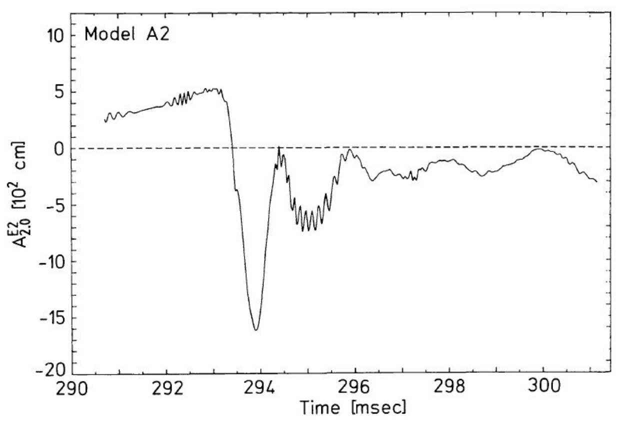


Fig. 1a. Quadrupole waveform for model A2