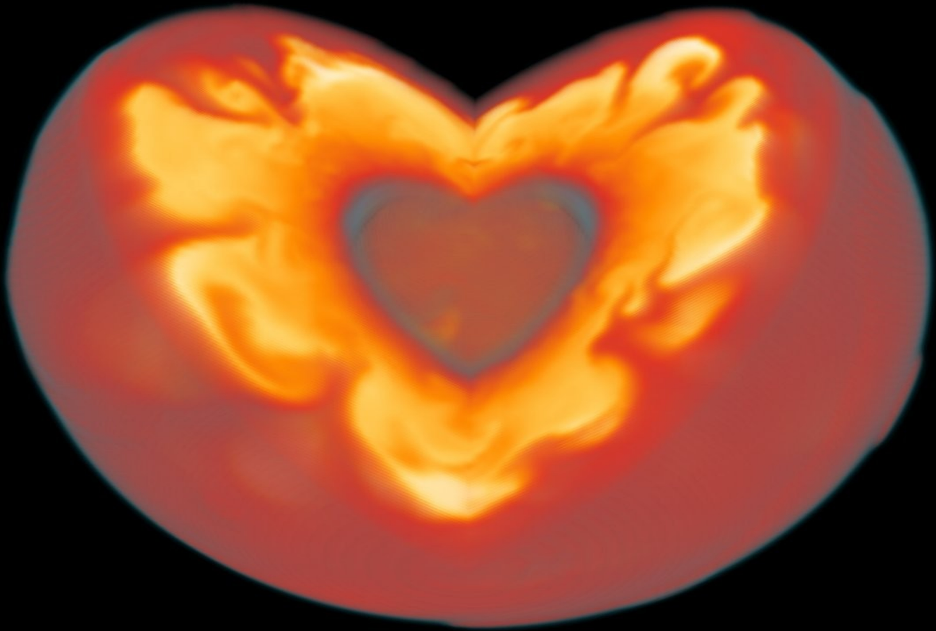
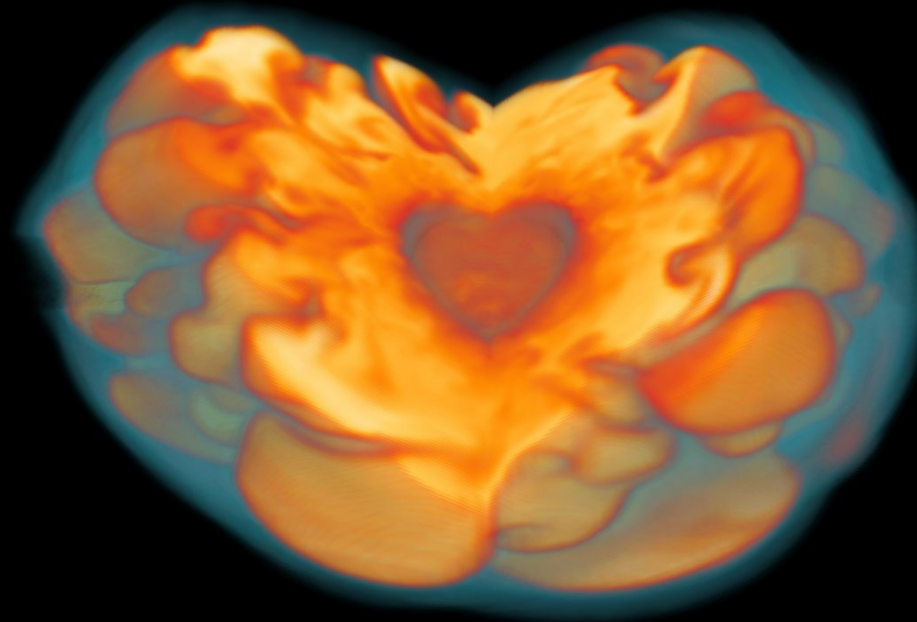
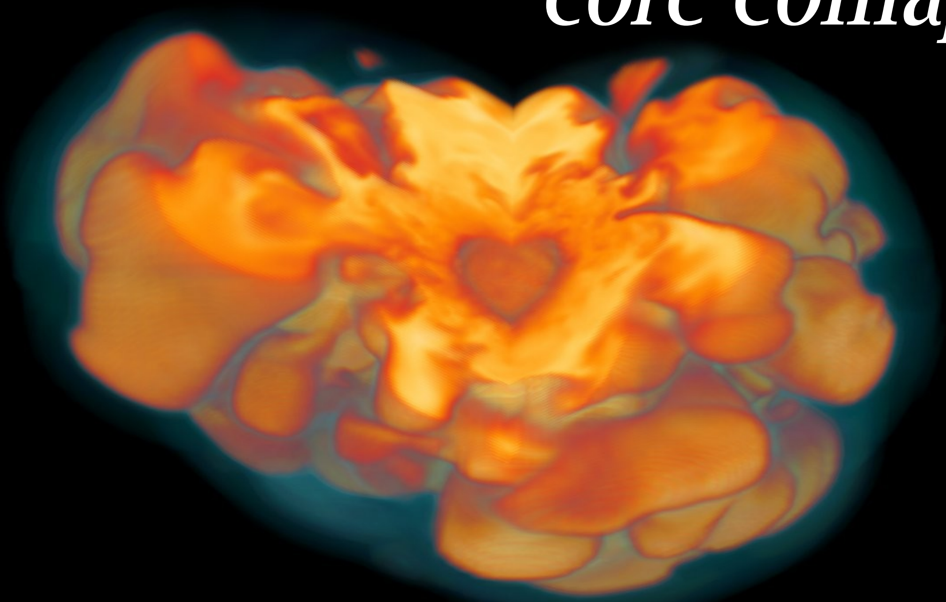
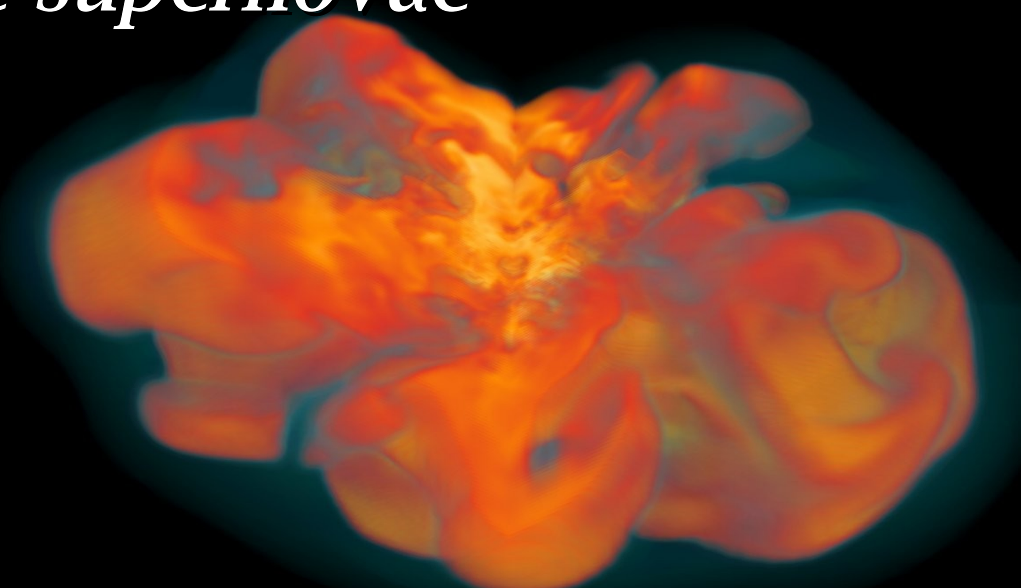




The gravitational wave signal of core colllapse supernovae





Ewald Müller Max-Planck-Institut für Astrophysik

in collaboration with

Hans-Thomas Janka

&

Harald Dimmelmeier, Andreas Marek, Bernhard Müller,
Martin Obergaulinger, Christian Ott, Leonhard Scheck,
Annop Wongwathanarat

supported by

SFB/TRANSREGIO 7 wwwsfb.tpi.uni-jena.de
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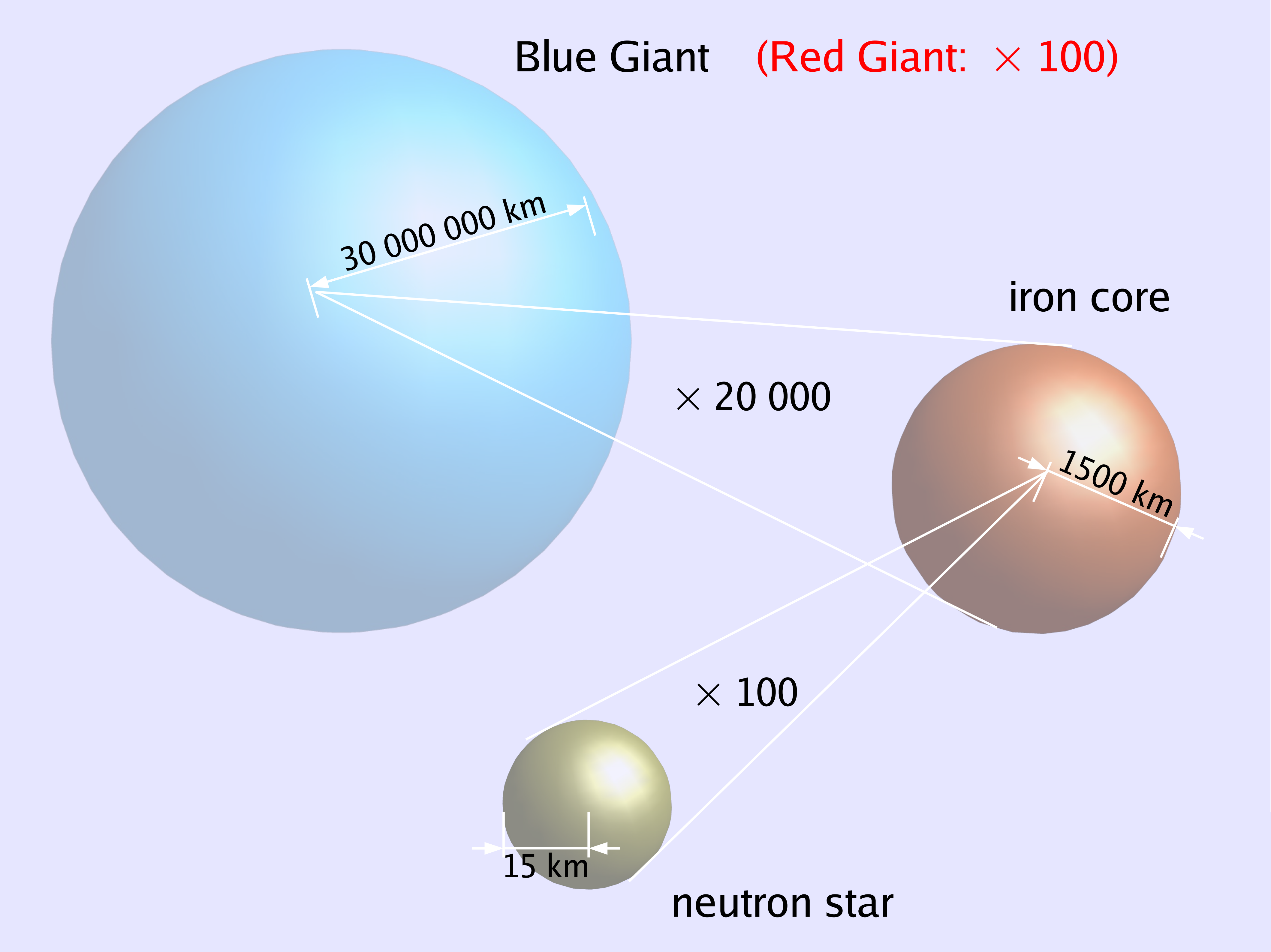


Blue Giant
(Red Giant: × 100)
30 000 000 km
iron core
× 20 000
1500 km
× 100
15 km
neutron star

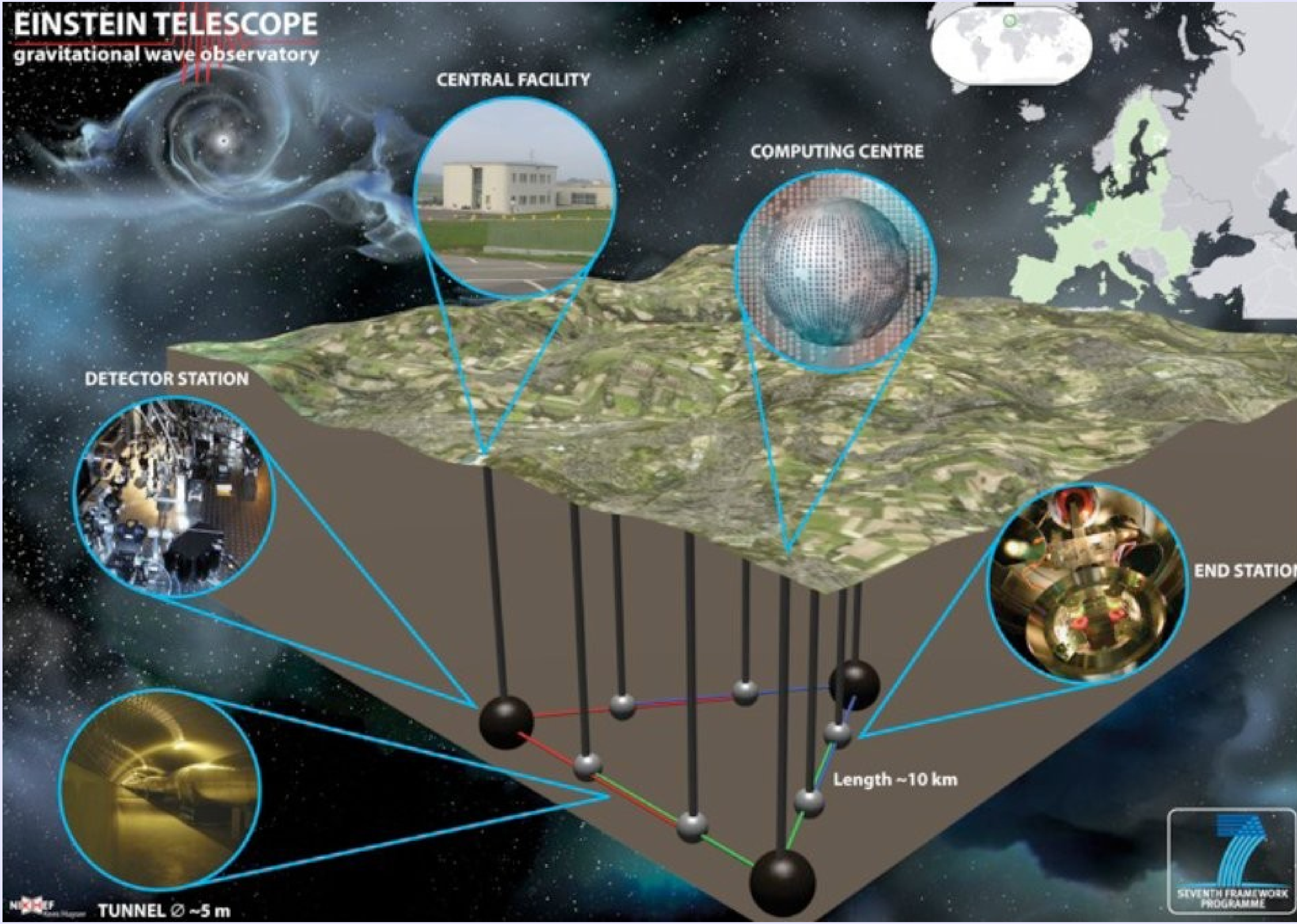
Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
GEO
AURIGA
EXPLORER
TAMA
VIRGO
NAUTILUS
LIGO
LIGO
ALLEGRO
NIOBE
gravitational wave research


LIGO-Hanford


VIRGO

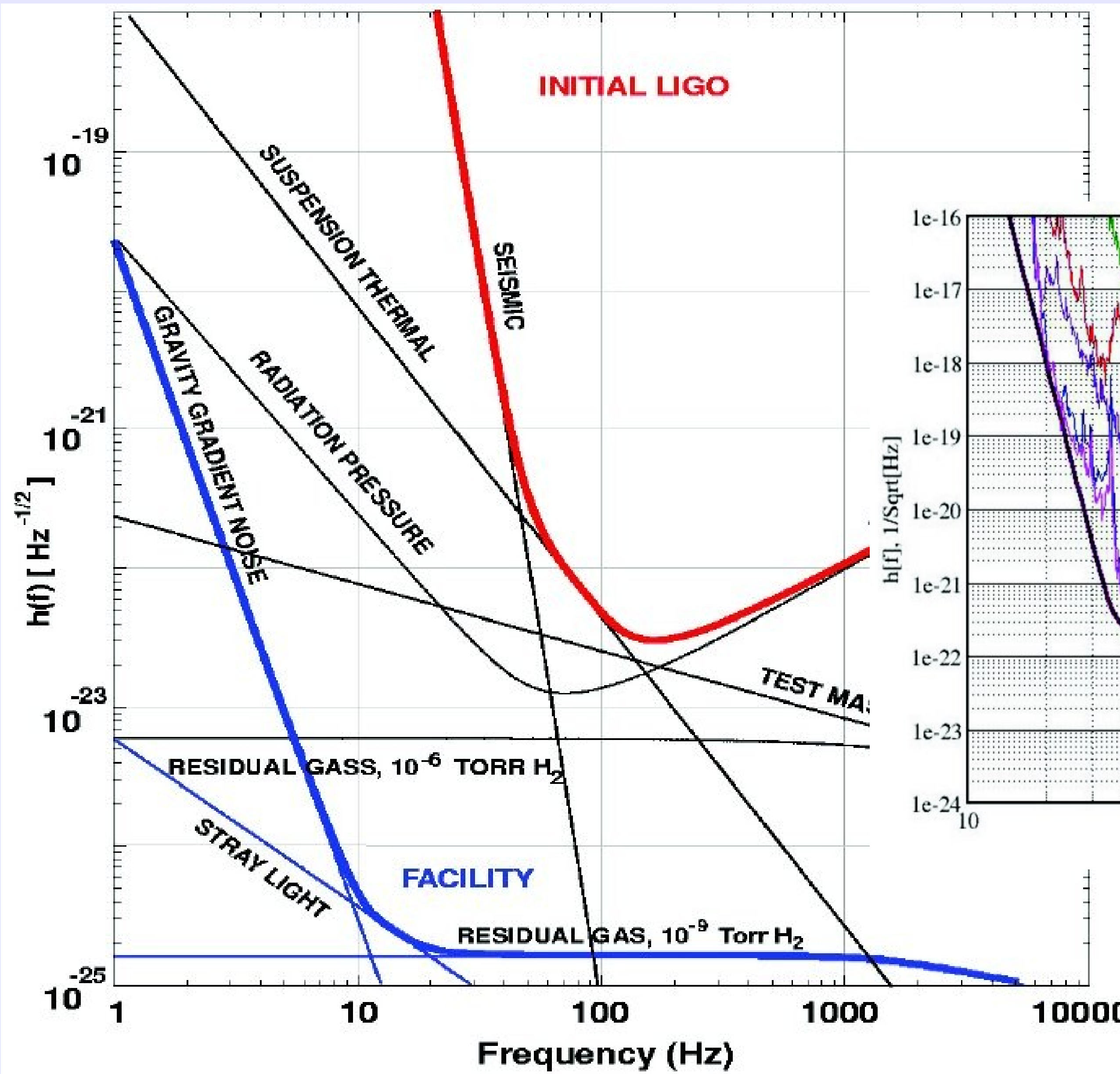

LIGO-Livingston

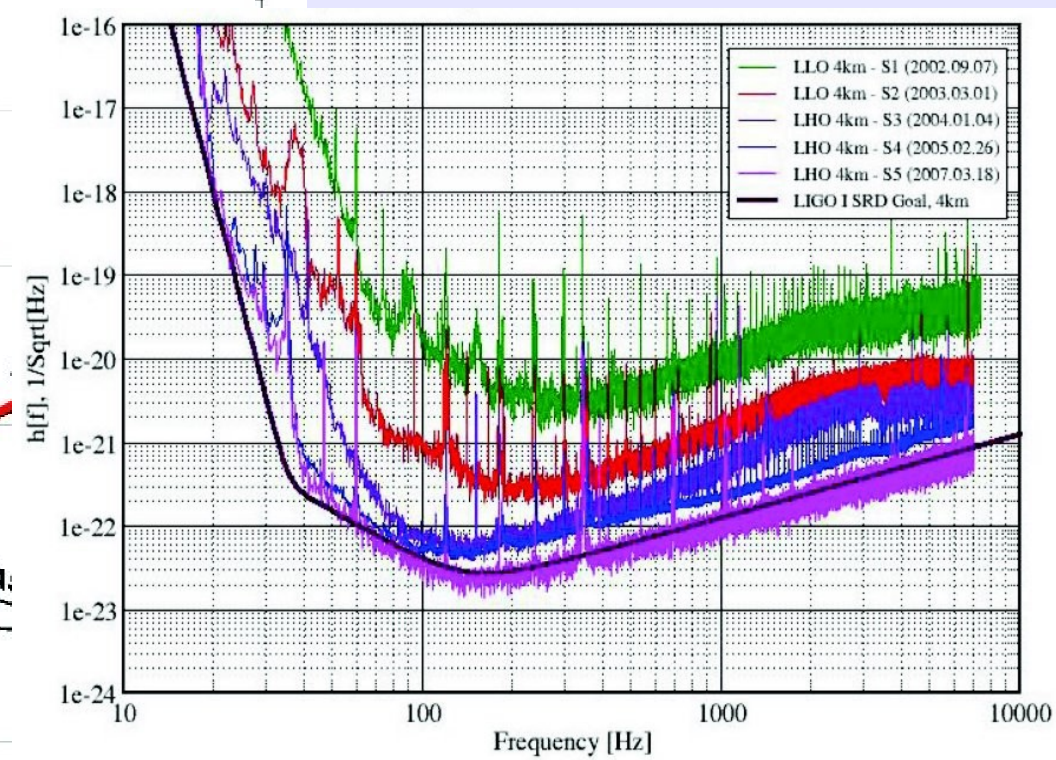

GEO600

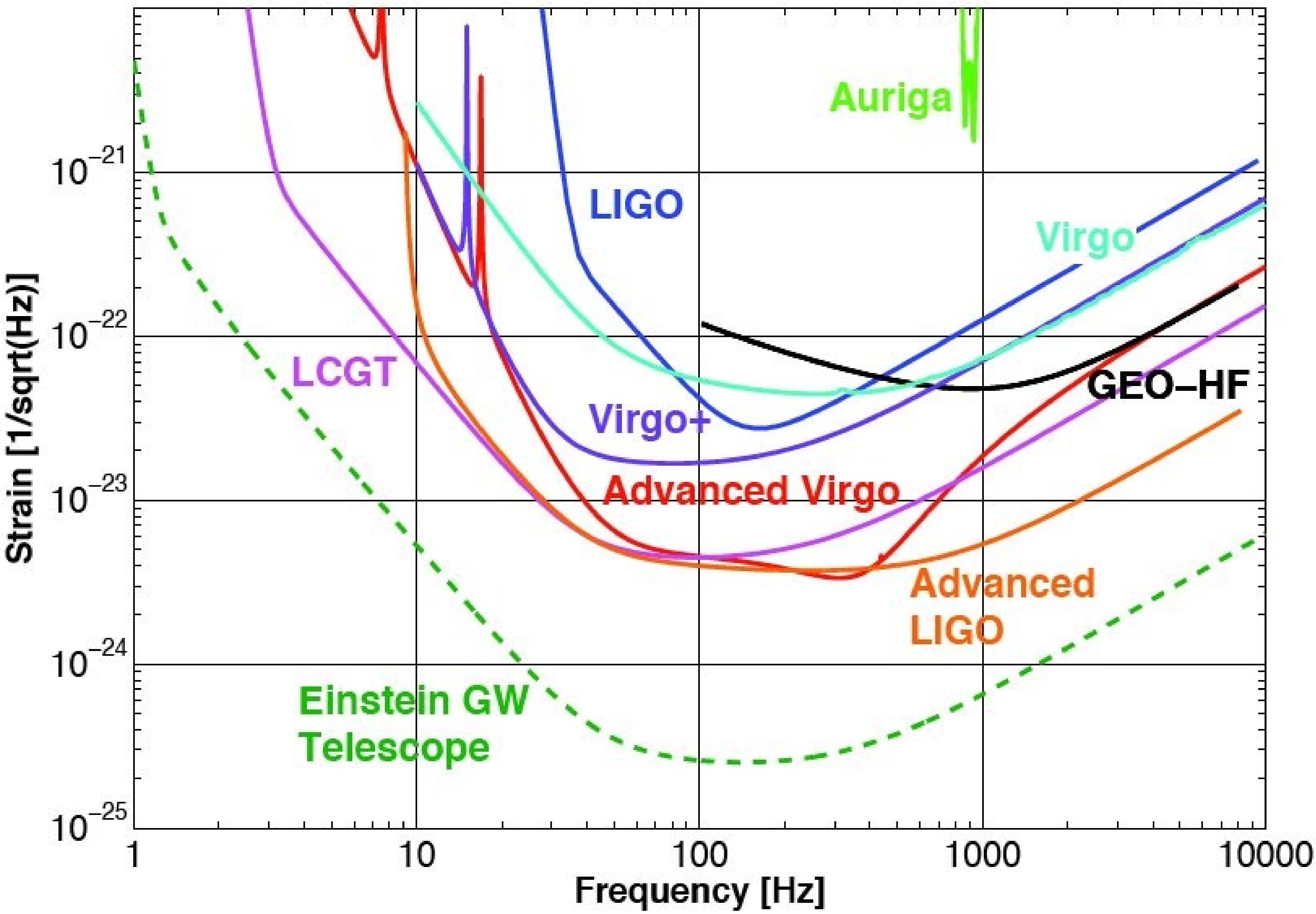

EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

Gravitational wave detectors: interferometer

noise sources complicate measurement






Auriga
LIGO
Virgo
LCGT
GEO–HF
Virgo+
Advanced Virgo
Advanced
LIGO
Einstein GW
Telescope
Strain [1/sqrt(Hz)]
Frequency [Hz]
10^−21
10^−22
10^−23
10^−24
10^−25
1
10
100
1000
10000

Gravitational waves

(Einstein quadrupole formula)

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

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

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

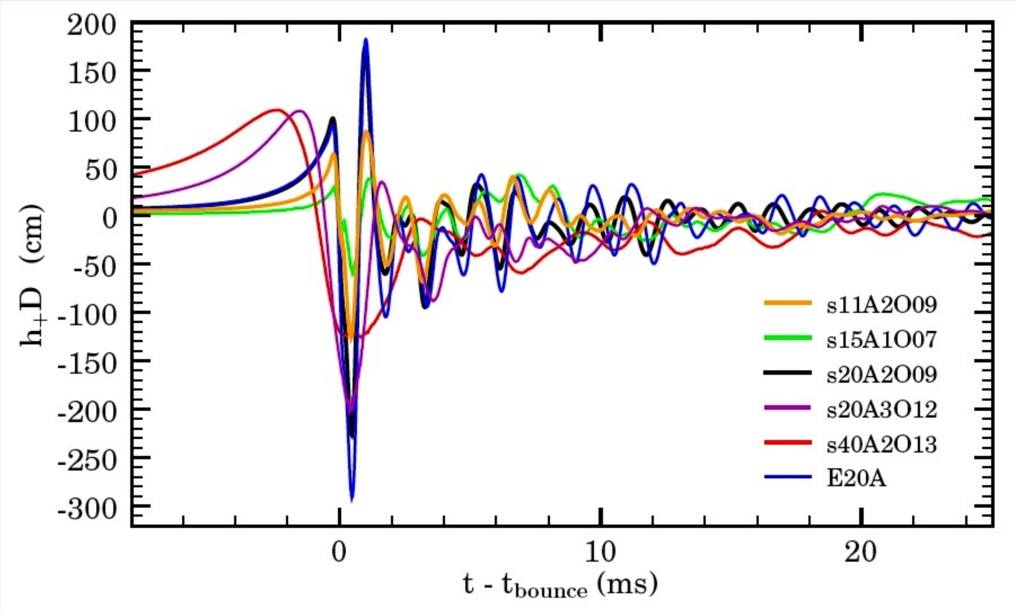
* [measuring the distance earth-sun with an accuracy of 1 nm]

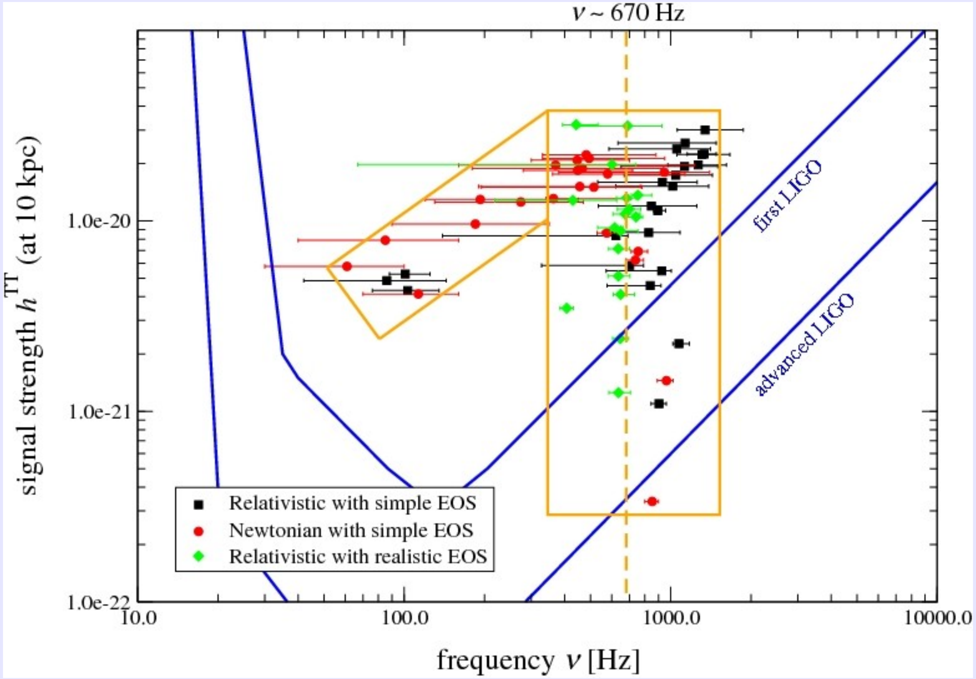
Towards predictive theoretical GW signals from CSSN: core bounce post-bounce

	polytropes, simplified EOS	microphysical EOS approx. ν-transport	microphysical EOS Boltzmann ν-transport
full GR	Shibata & Sekiguchi '04, '05 2D/3D, confirmation of CFC Shibata '03 cartoon method	Ott et al. '07 $Y_e(\rho)$ from 1D GR sim.	
CFC-GR hydro & gravity	Dimmelmeier, Font & Müller '02 parameter study	Dimmelmeier et al. '07, '08 $Y_e(\rho)$ from 1D GR sim.	Müller,B, Janka & Marek '11 2D models
Newtonian hydro & approx. GR gravity	Müller, B, Dimmelmeier & Müller '08 modified potential for rapid rotators	Yakunin et al. '10 2D exploding models Scheidegger et al. '08, '10 3D MHD parameter study	Müller, Janka & Wongwathanarat '11 3D parametrized models Marek, Janka & Müller '09 2D exploding models Müller et al. '04 2D, flow & ν contrib.
Newtonian hydro & gravity	Murphy, Ott & Burrows '09 2D, matter signal, p.b. phases Ott et al. '05 low T/W instability Rampp, Ruffert & Müller '98 3D simulations Zwerger & Müller '97 parameter study	Kotake et al. '07, '09, '11 leakage scheme, 3D Ott et al. '04, '06, '07 parameter study, g-modes Fryer, Holz & Hughes '04 3D SPH, initial perturb. Müller & Janka '97 PNS & prompt convection Burrows & Hayes '96 anisotropic ν-emission	

GW signals from core bounce

GR models with microphysical EoS and deleptonization
---> generic GW signals





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

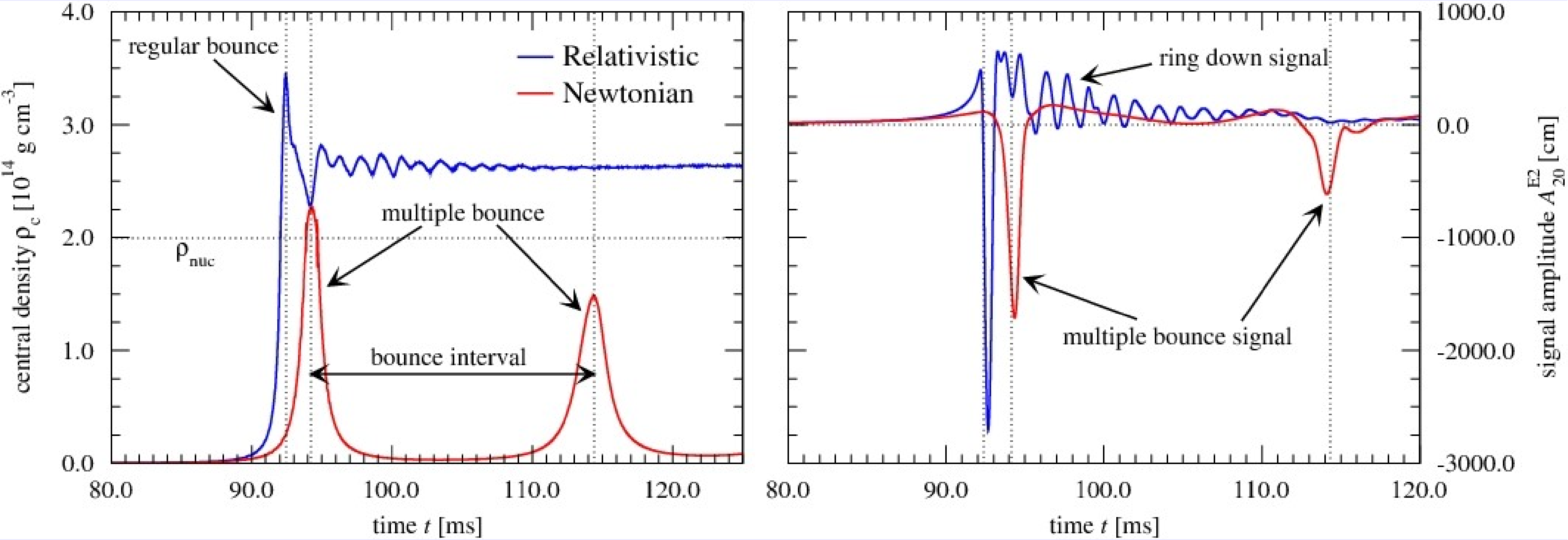
(Dimmelmeier & Ott et al., 2007, 2008)

Suppresion of centrifugal bounce by relativistic gravity

Newtonian study of the collapse of rotating polytropes (Zwerger & Mueller, '97)
repeated in relativistic gravity
(Dimmelmeier, Font & Muller, '02; Dimmelmeier et al., 05; Cerda et al., '05; Shibata & Segikuchi, '05, '06)

relativistics effects: deeper potential --> larger bounce densities, more compact PNS

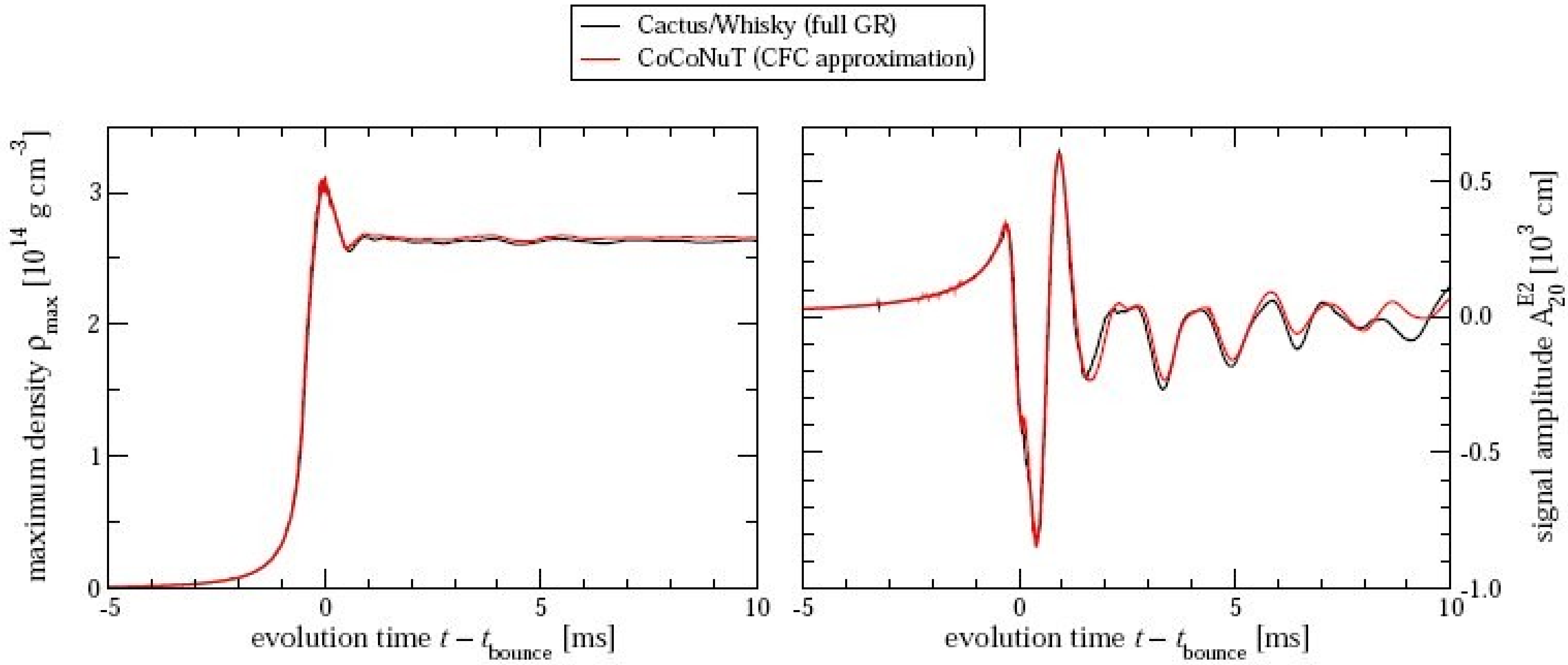
less multiple centrifugal bounces (less type II GW signals)



The Quality of the Conformal Flatness Approximation

Comparison of results obtained using Method CFC and full general relativity proves:
[Shibata and Sekiguchi, PRD, 2005; Dimmelmeier et al., Proc. Albert Einstein's Century Conference, Paris, 2006;
Ott et al., PRL, submitted]

CFC is excellent approximation of full general relativity for supernova core collapse!



Compared to differences between numerical codes and coordinate choices:

Differences between full general relativity and Method CFC are typically smaller!

Sub-dividing simulations of core collapse supernovae

GWs

full-fledged 2D ν-hydro simulations
until a few 100 msec after bounce
[0 km < r < 10^4 km]
(various research groups)

Step 1

Step 2

2D/3D hydro simulations
with simplified ν-transport
until ~1s post bounce
[(32 $\rightarrow$ 15) km < r < 2 10^4 km]
(Scheck et al. '06)

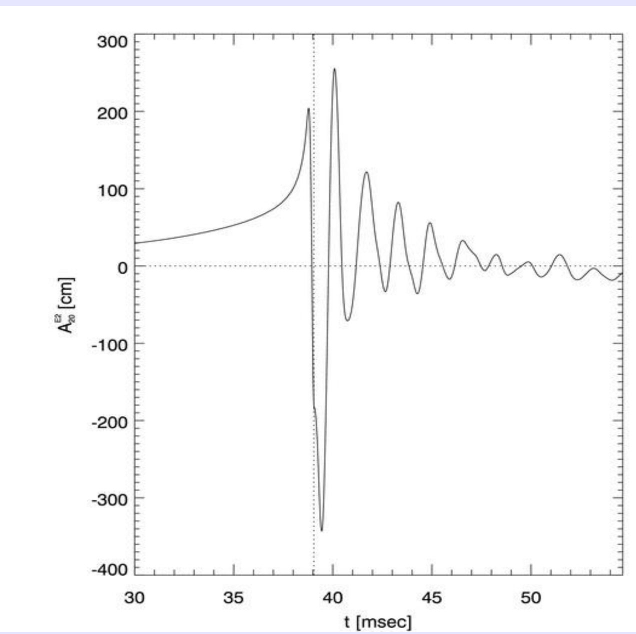
Step 3

2D/3D hydro simulations without
ν-transport until a few hours
post bounce
[10^3 km < r < 3 10^7 km]
(Kifonidis et al., Hammer et al.,
Wongwathanarat et al.

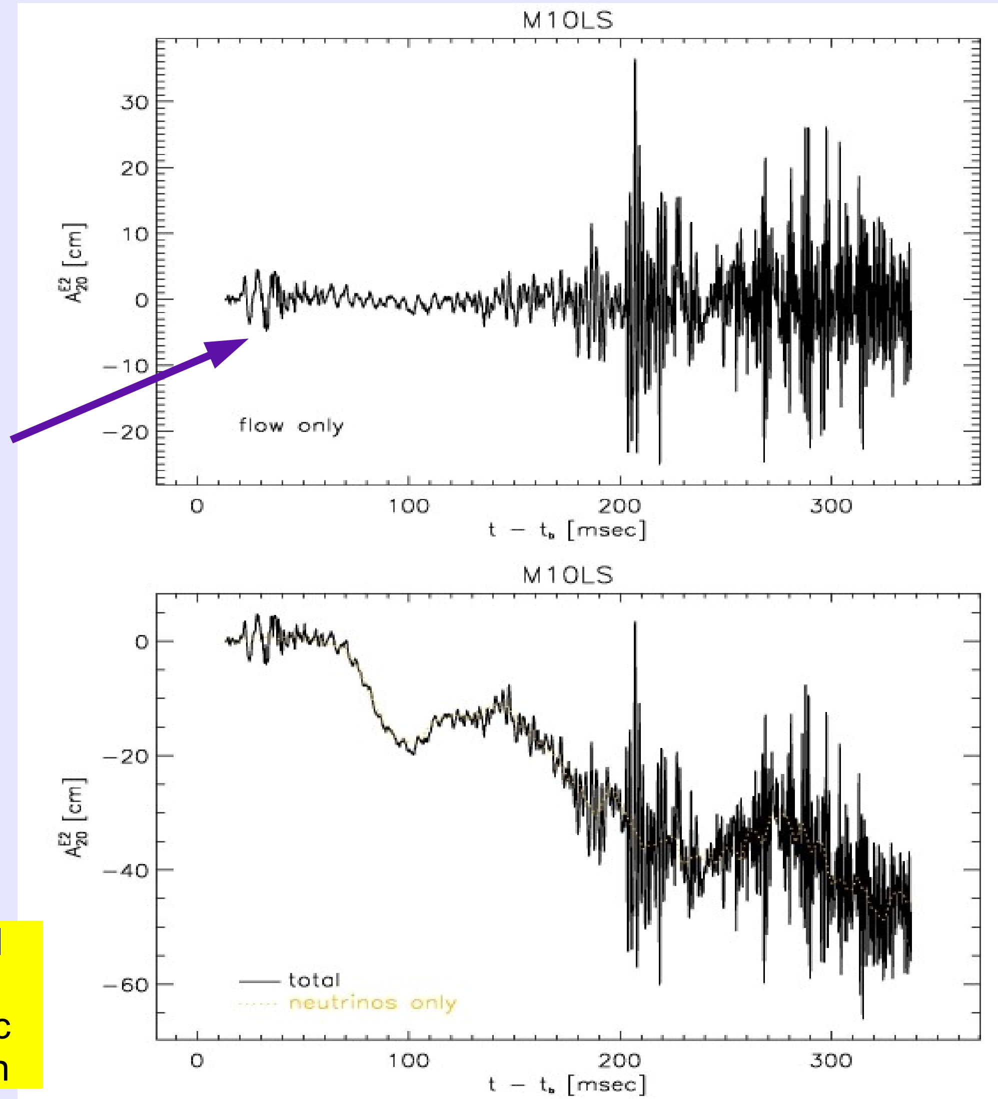
GW signature of CCSN

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!)



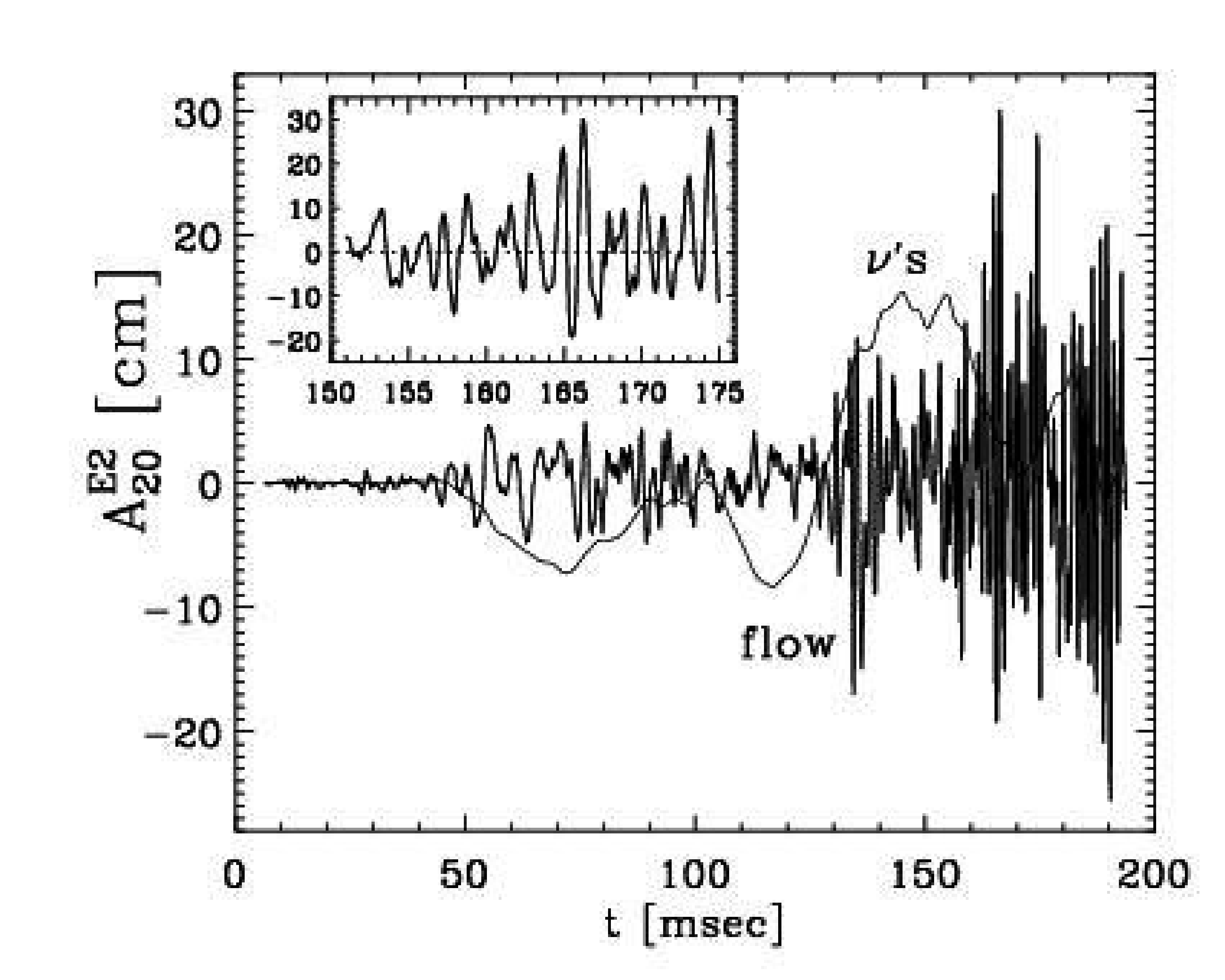
GW signal including anisotropic ν-emission

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)

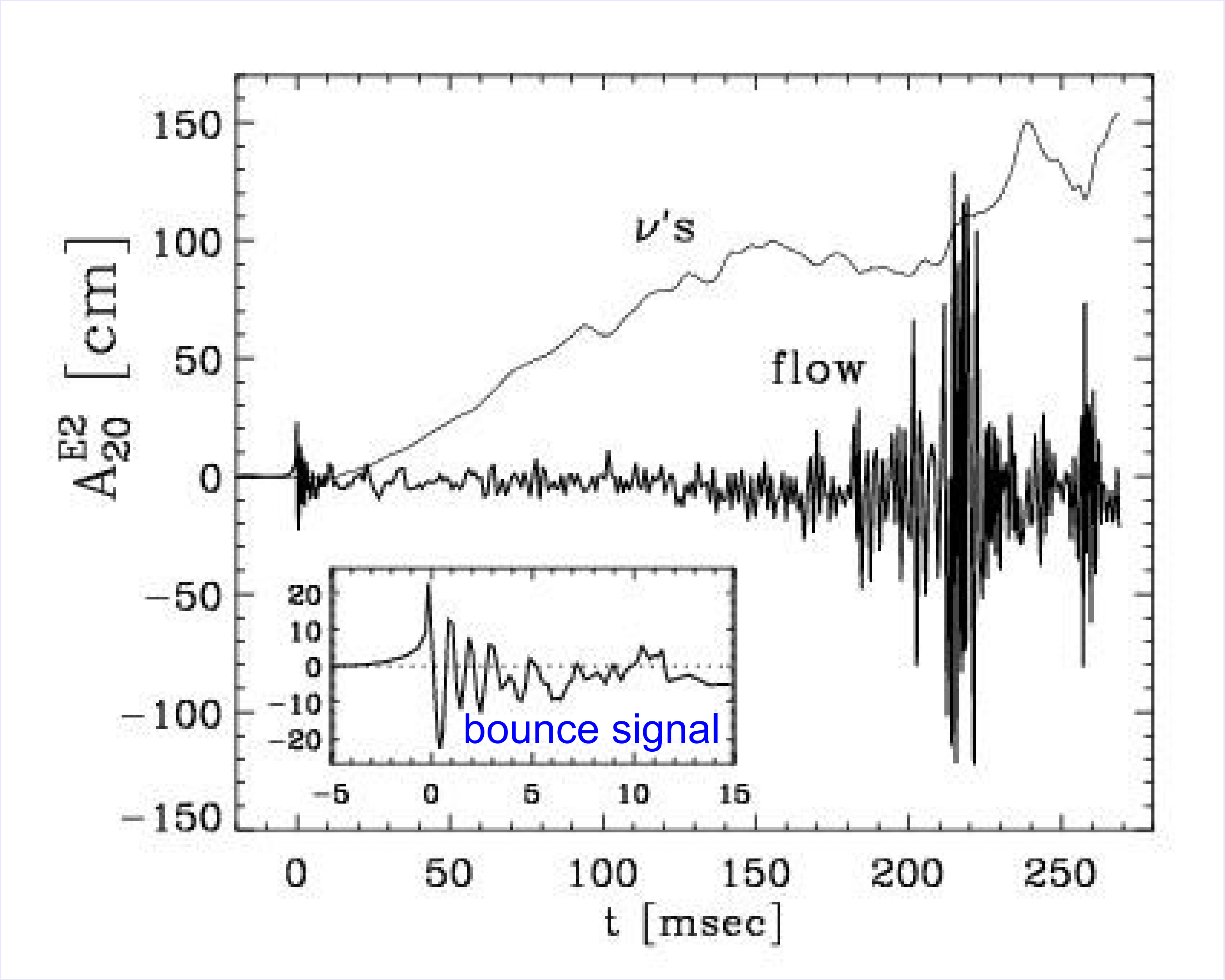
time

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



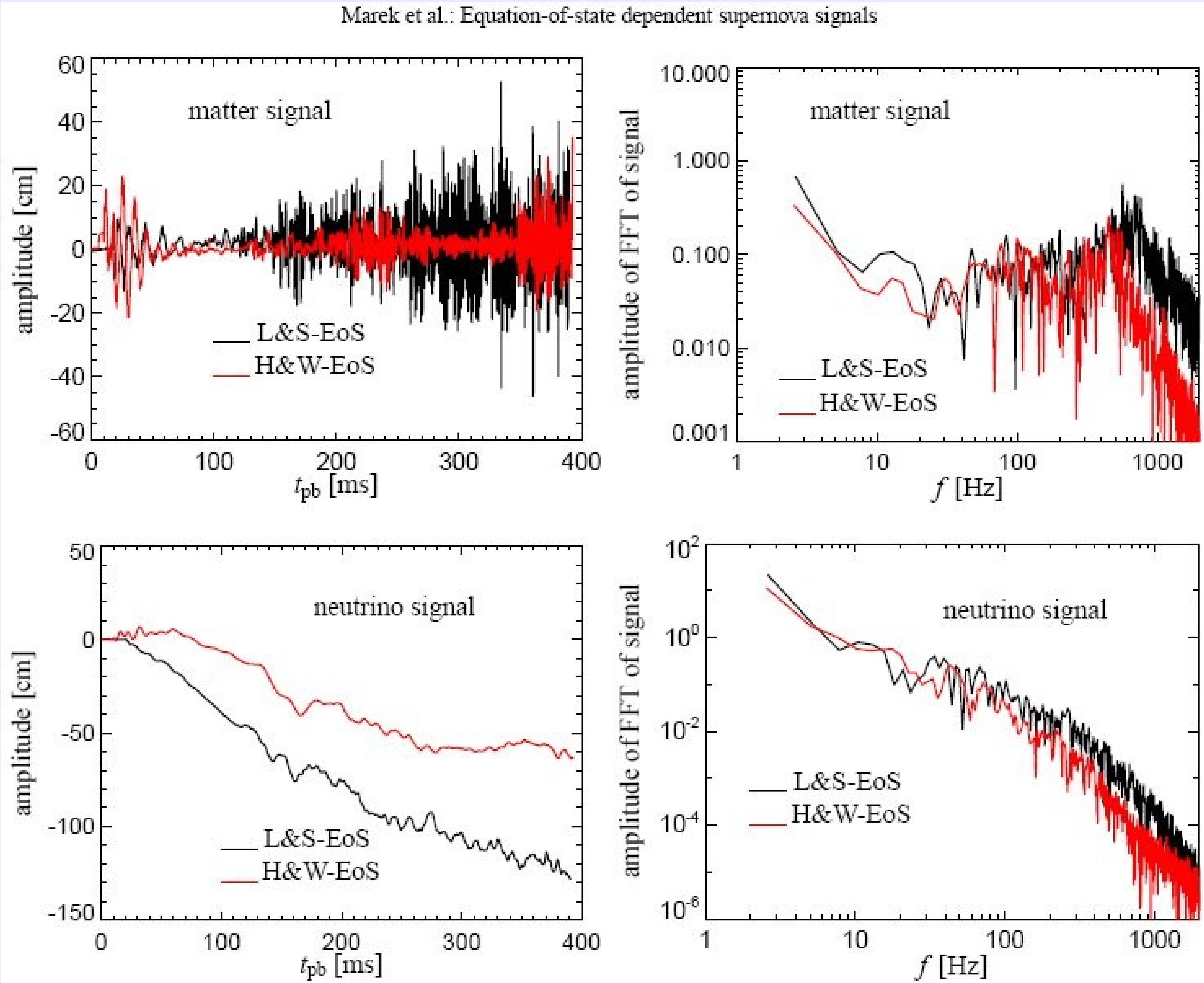
Models with detailed microphysics, transport physics, and effective relativistic gravitational potential (Müller, Rampp, Buras, Janka & Shoemaker '04)

GW signature of a slowly rotating 15 M_{sd} star



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

Same stellar progenitor, same input & transport physics / numerics



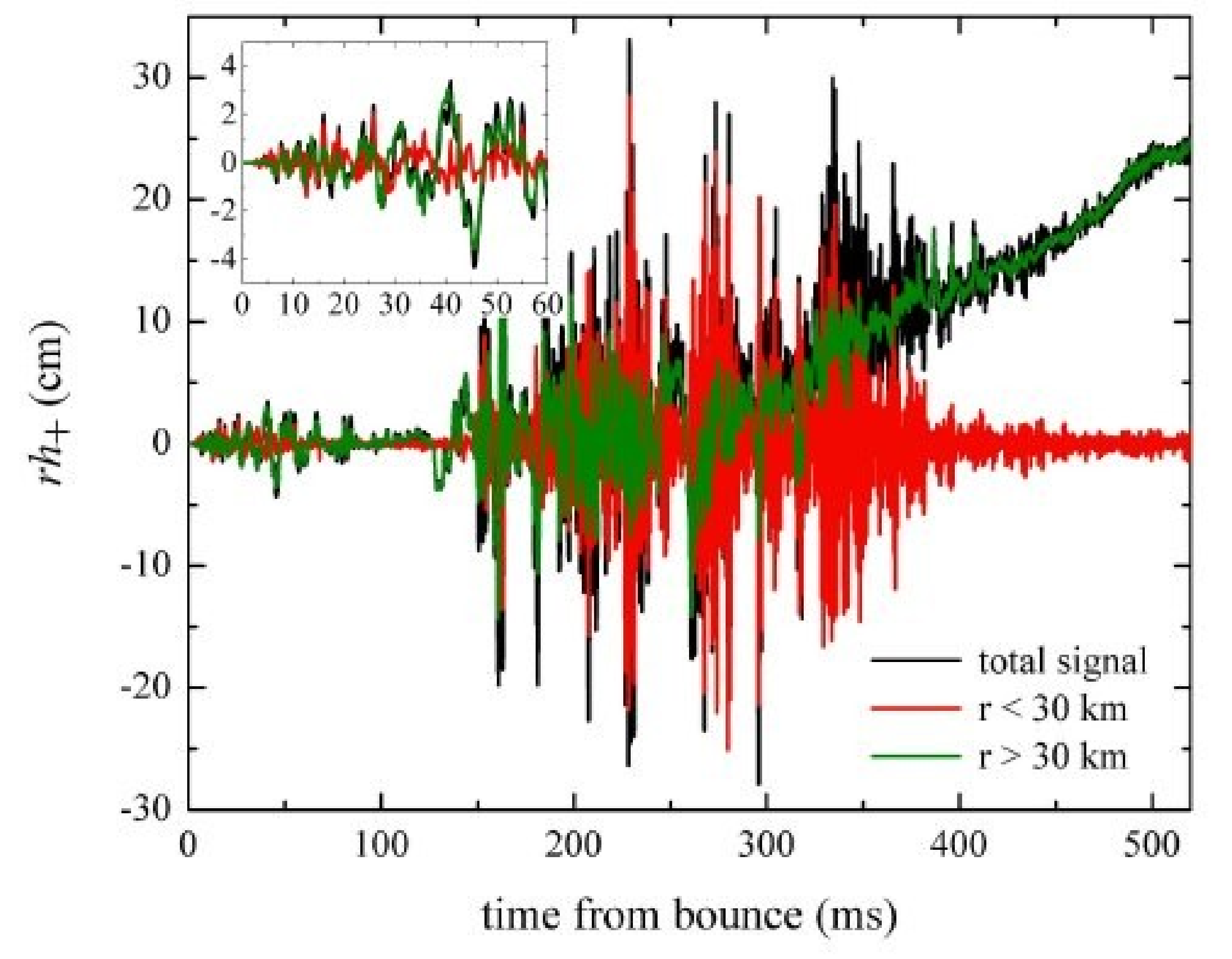
(Marek, Janka & Müller, 2009)

2D models, various progenitors

GW signals qualitatively similar, distinct phases

„tail phase" associated with (prolate) expanding shock

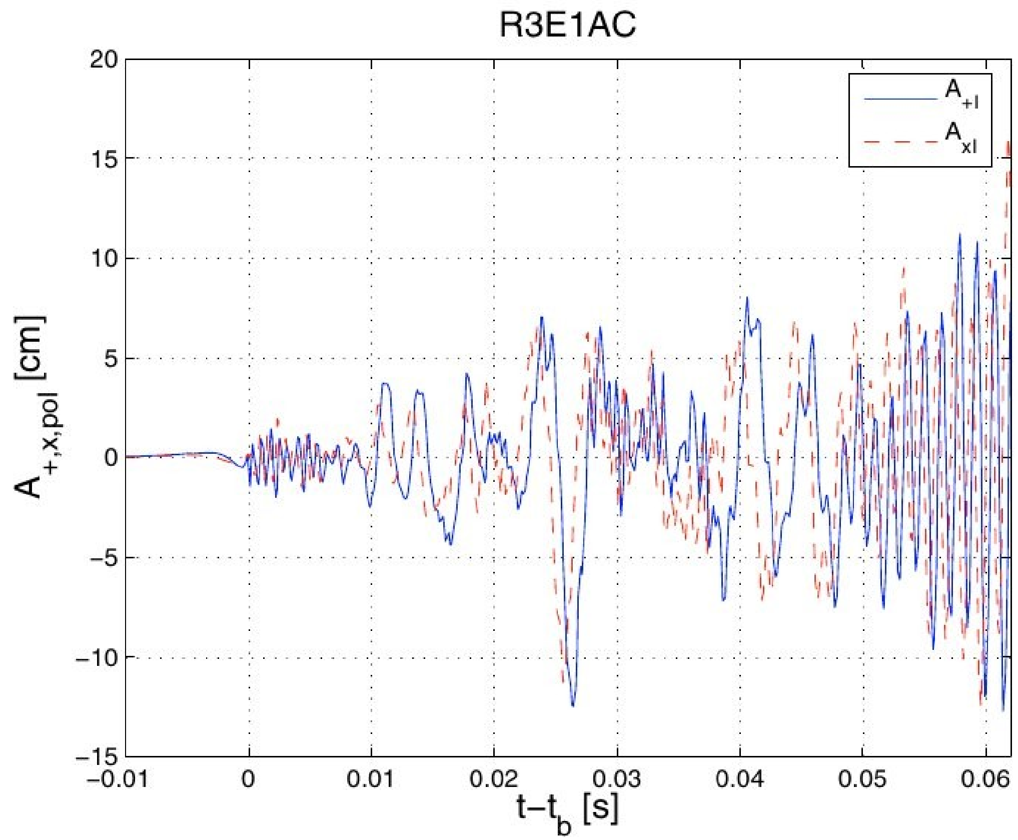
→ GW amplitudes show positive slope Yakunin et al. 2010



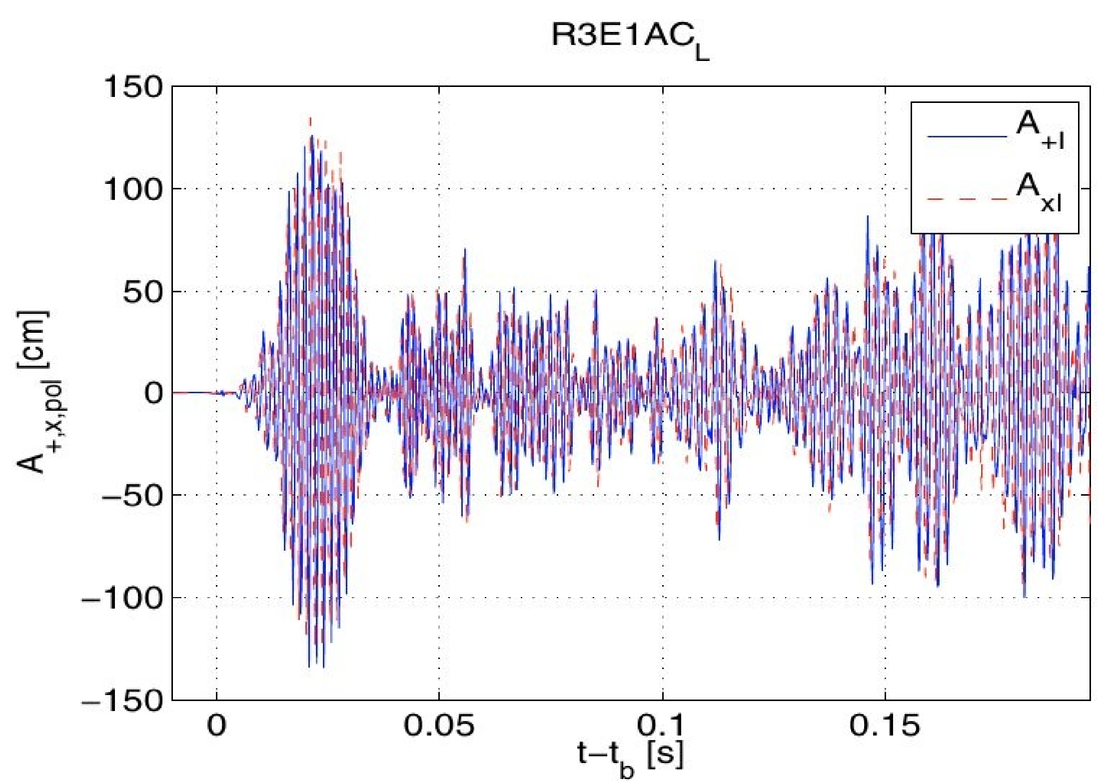
RED: signal from region inside R<30km Green: signal from region R>30km

3D MHD models with parametrized neutrino treatment

strong dependence of GW amplitudes on post-bounce ν-handling



Scheidegger et al. 2010



with ν-cooling --->

amplitudes increase by a factor 5-10

Sub-dividing simulations of core collapse supernovae

GWs

Step 1

full-fledged 2D ν-hydro simulations
until a few 100 msec after bounce
[0 km < r < 10^4 km]
(various research groups)

Step 2

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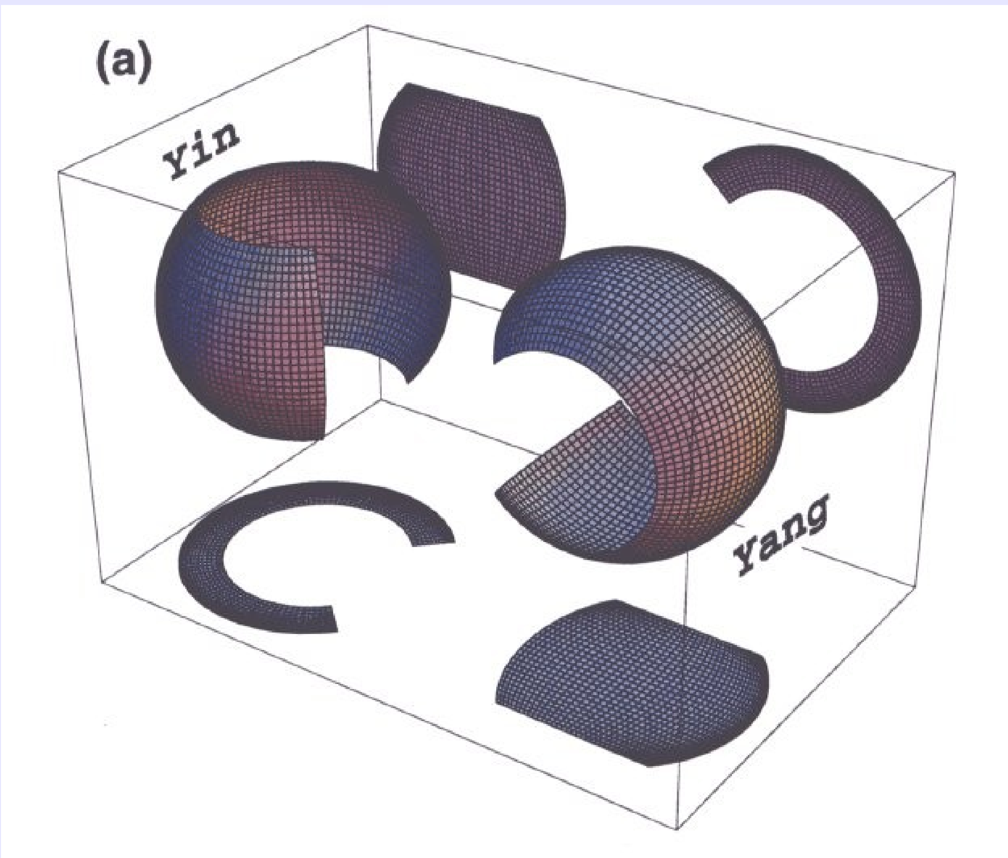
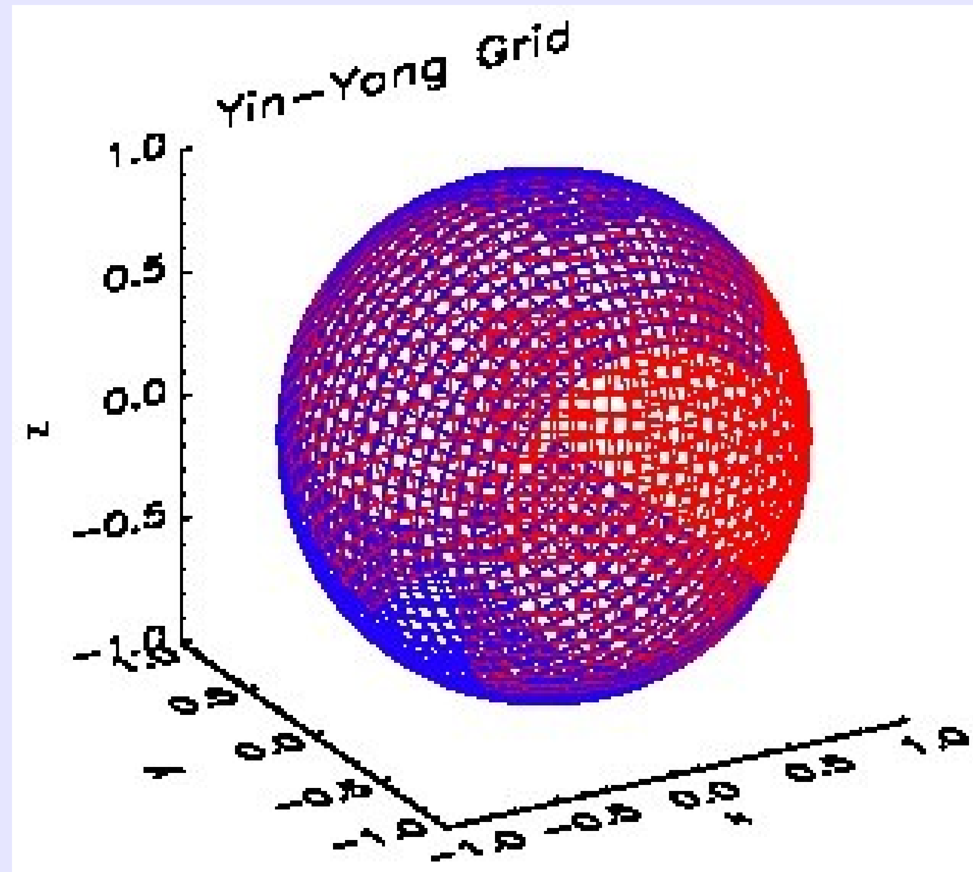
Step 3

2D/3D hydro simulations without ν-transport until a few hours post bounce
[10^3 km < r < 3 10^7 km]
(Kifonidis et al., Hammer et al.,
Wongwathanarat et al.

3D simulations using an axis-free overset grid in sphericl polar coordinates: the Yin-Yang grid

Wongwathanarat, Hammer, & Müller, 2010





- reduces CFL timestep restriction (~ order of magnitude)

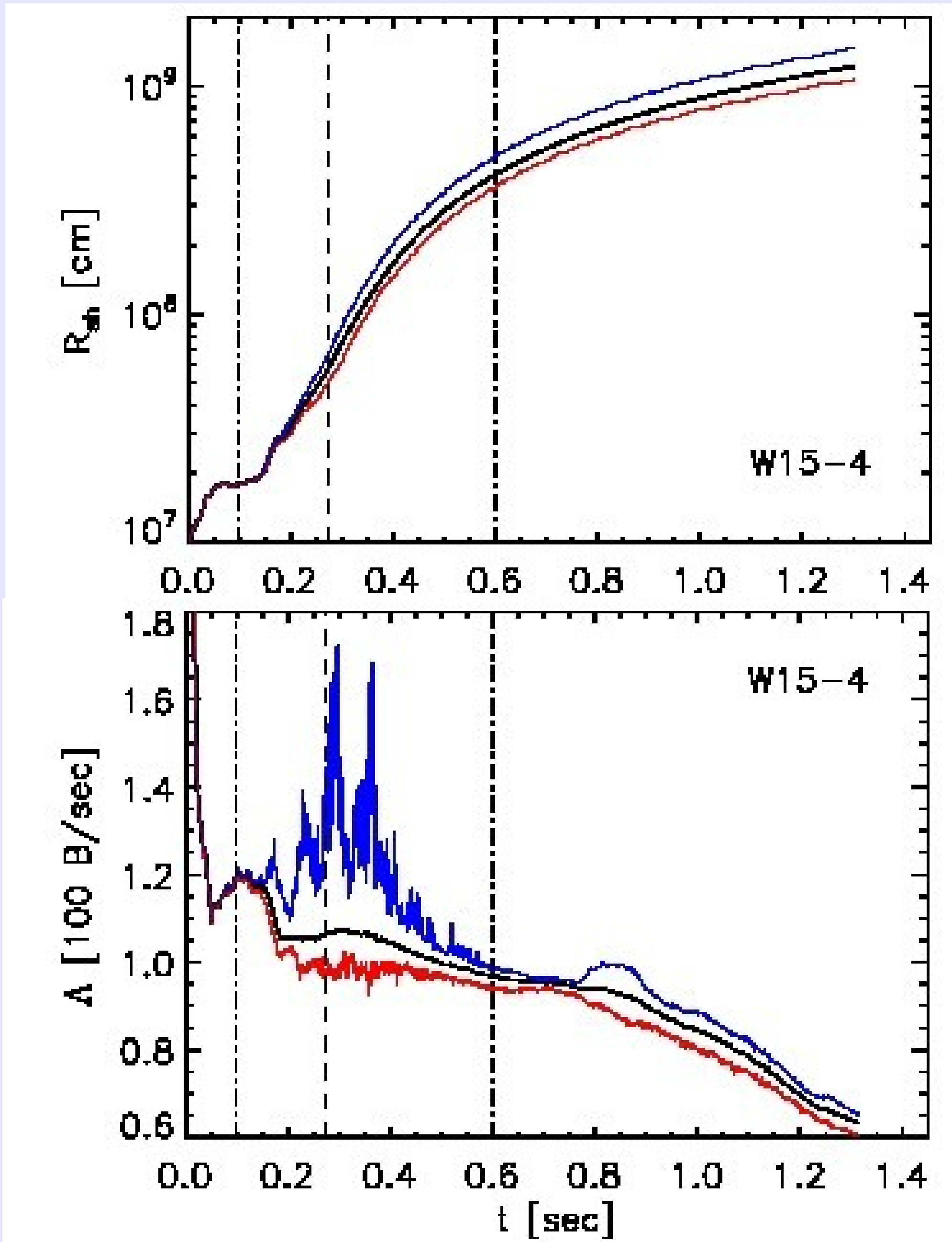
- avoids axes artefacts

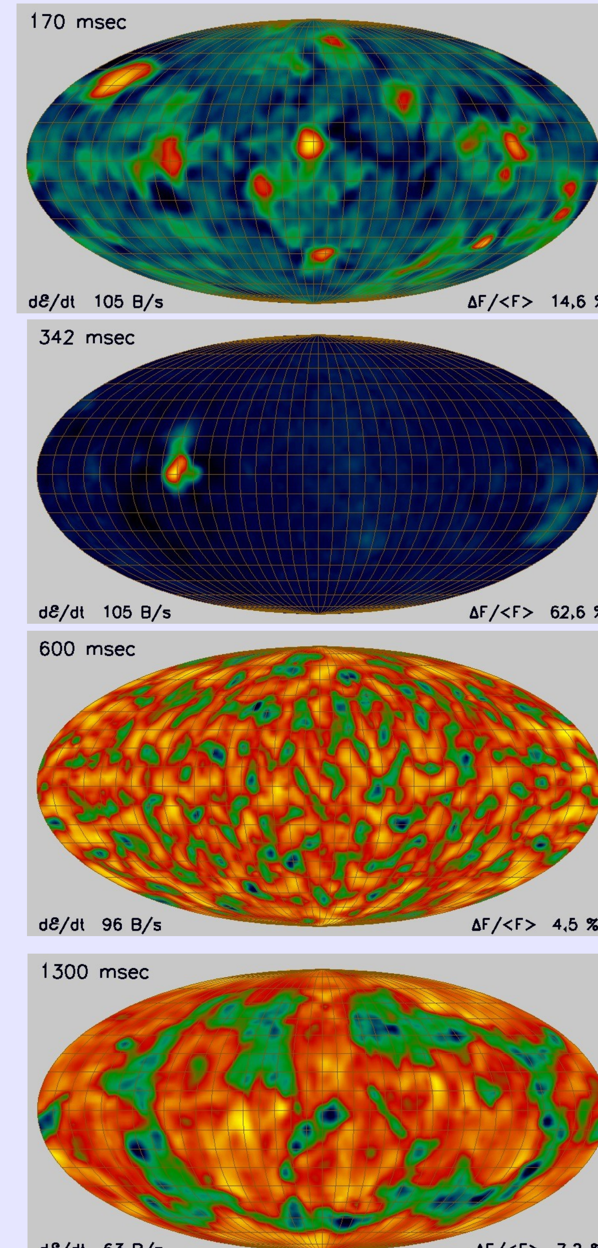
Post-bounce evolutionary phases of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011), see also Murphy, Ott, Burrows (2009)

shock radius

neutrino energy flux density $\times 4\pi R_o^2$





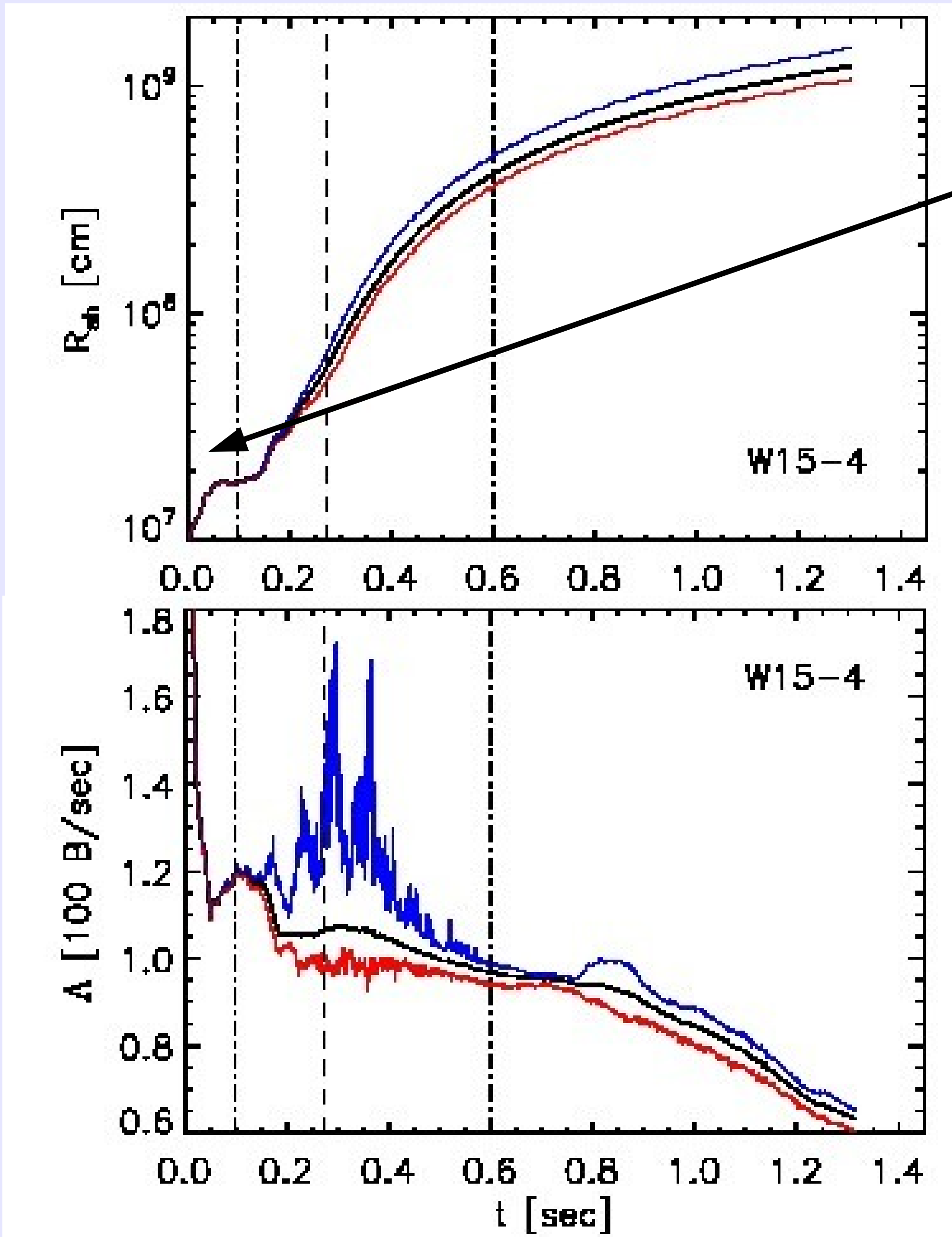
angular variation of ν-energy flux density

Post-bounce evolutionary phases of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011), see also Murphy, Ott, Burrows (2009)

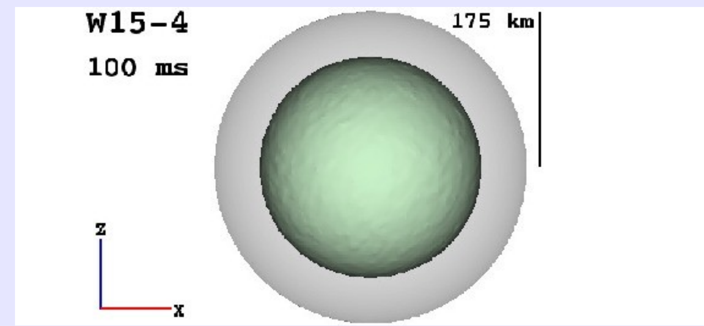
shock radius

neutrino energy flux density $\times\ 4\pi R_o^{\ 2}$



quasi-spherical shock expansion

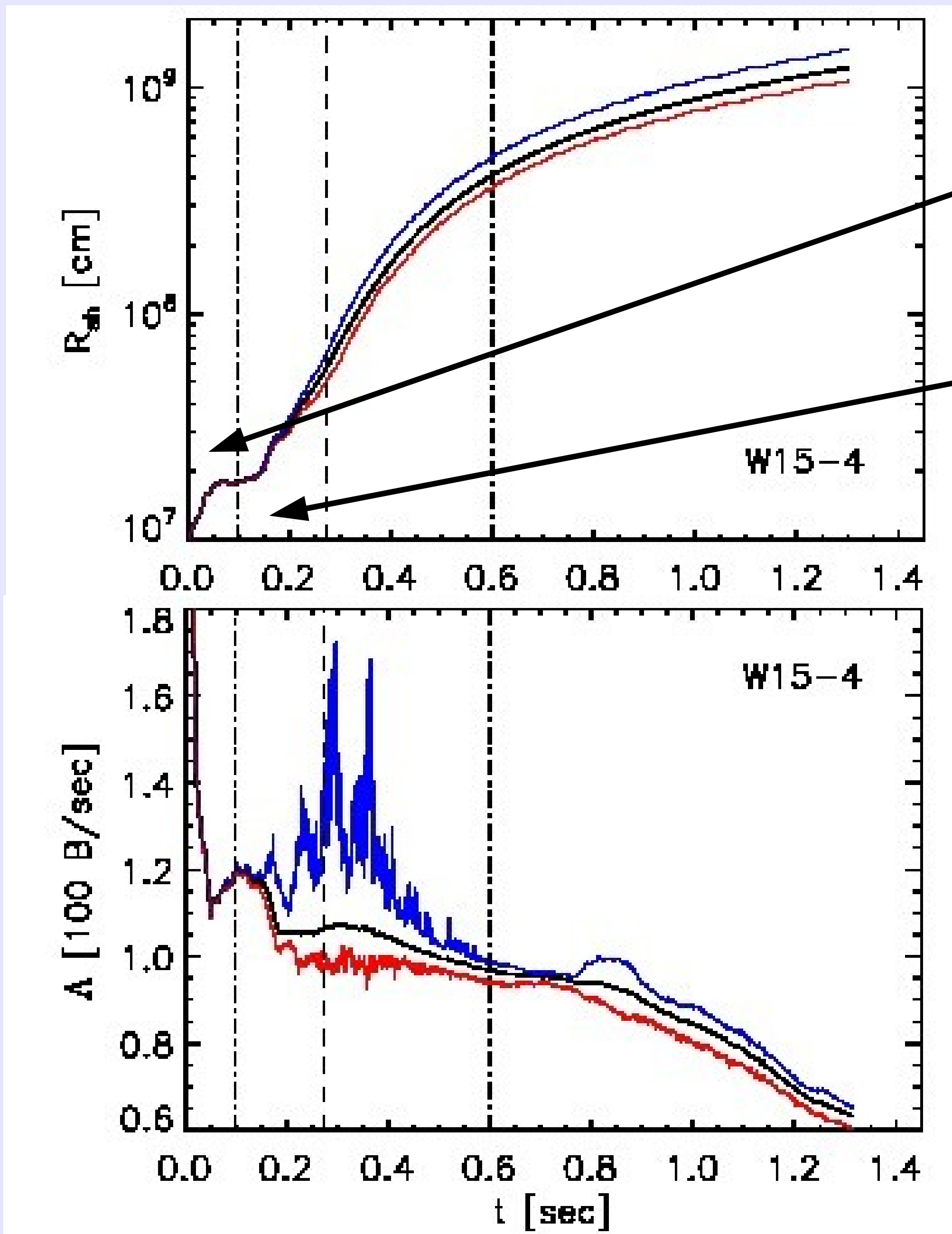
shock formation and expansion



Post-bounce evolutionary phases of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011), see also Murphy, Ott, Burrows (2009)

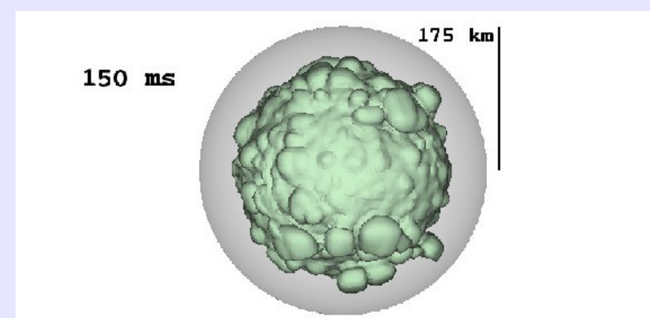
shock radius



neutrino energy flux density $\times\, 4\pi R_o^{\,2}$

quasi-spherical shock expansion
shock formation and expansion

pre-explosion phase
growth of post-shock convection and of the SASI

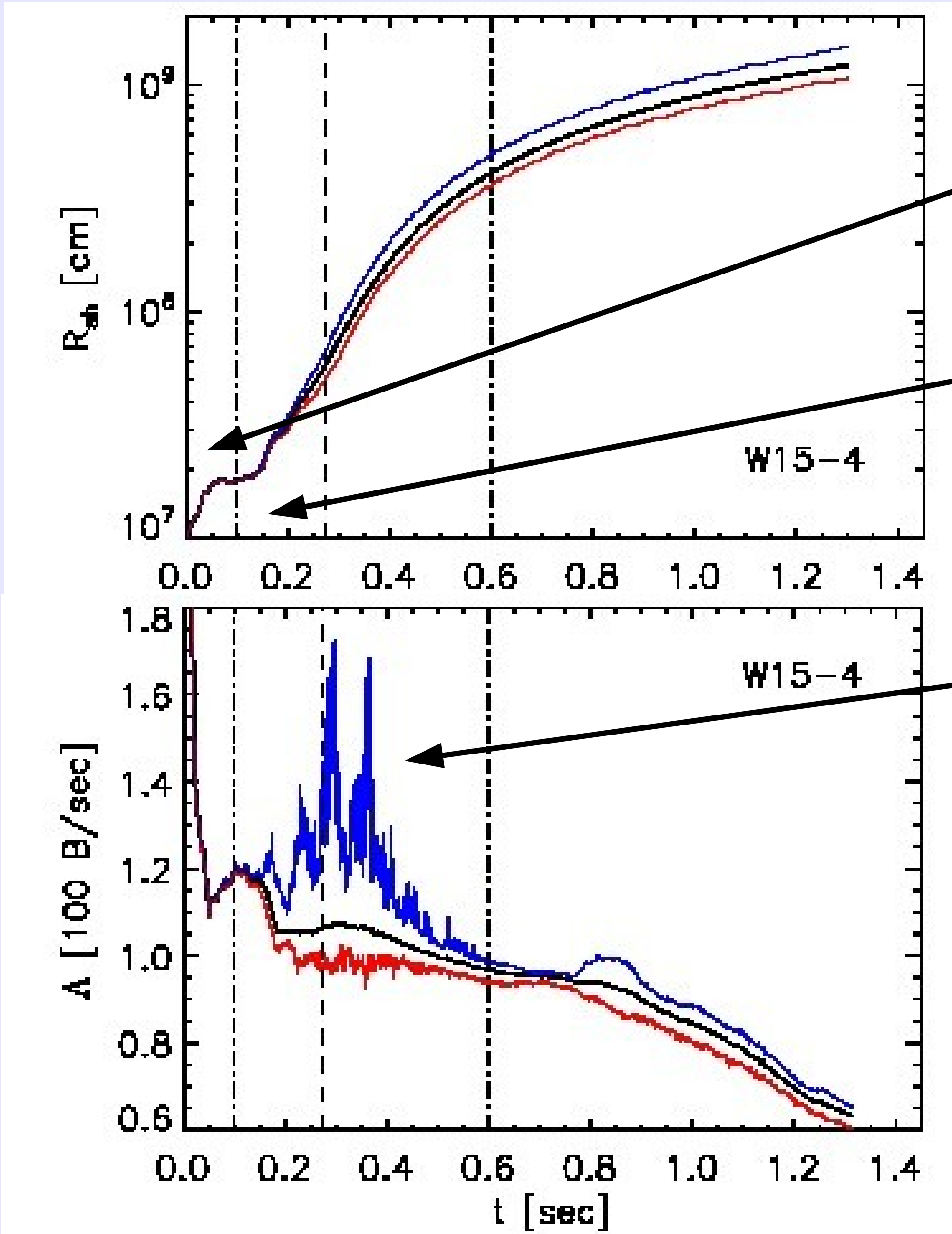


Post-bounce evolutionary phases of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011), see also Murphy, Ott, Burrows (2009)

shock radius

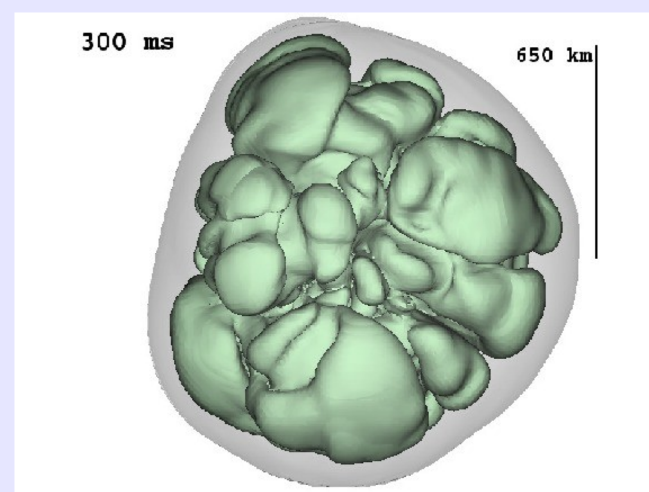
neutrino energy flux density $\times 4\pi R_o^2$



quasi-spherical shock expansion
shock formation and expansion

pre-explosion phase
growth of post-shock convection and of the SASI

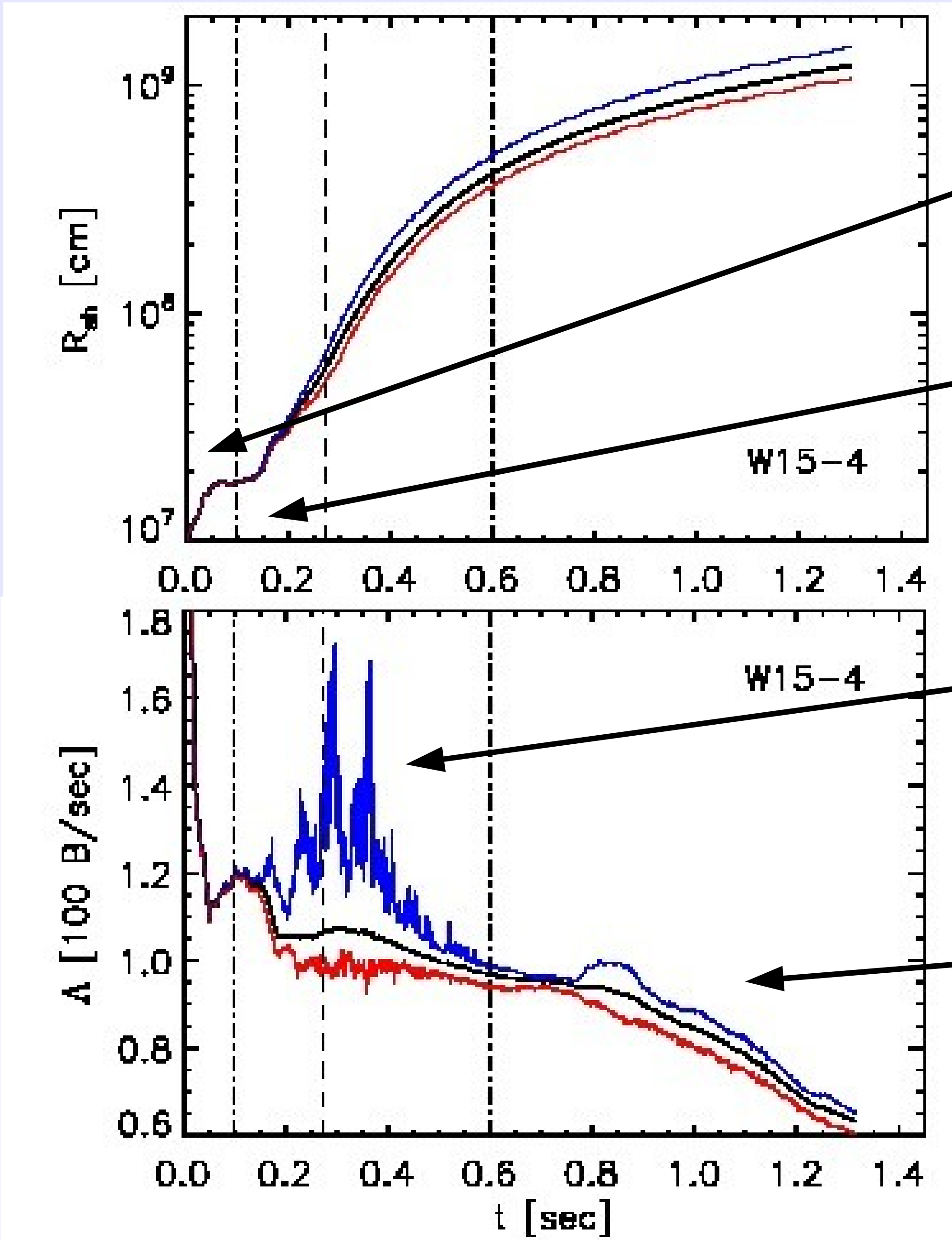
post-explosion accretion phase
shock revival, shock acceleration, ongoing mass accretionn



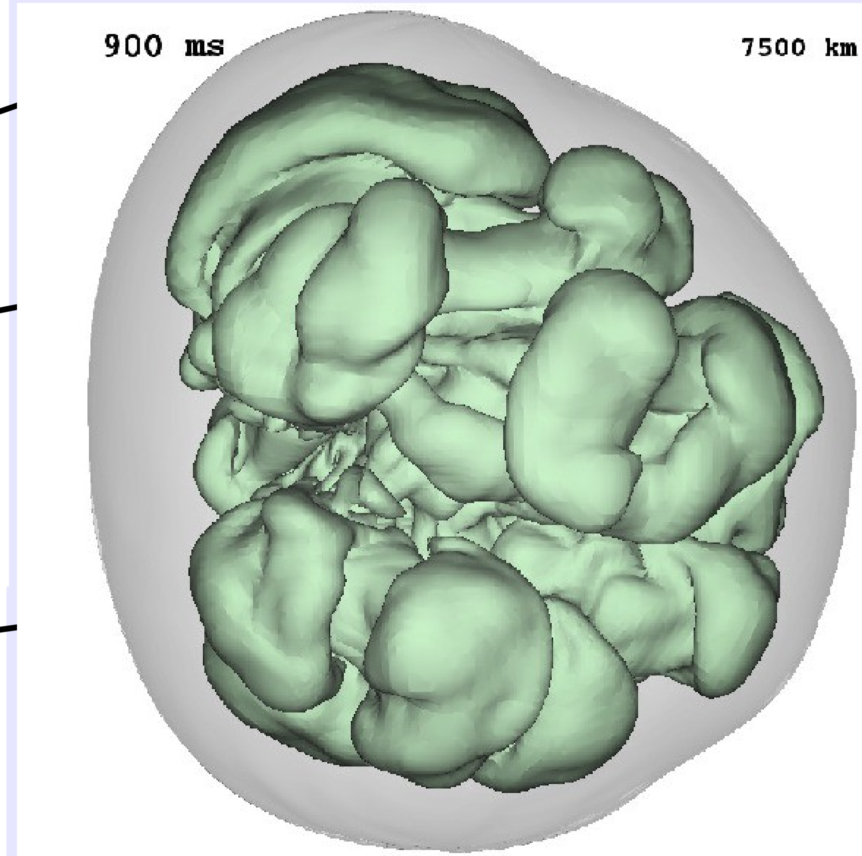
Post-bounce evolutionary phases of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011), see also Murphy, Ott, Burrows (2009)

shock radius



neutrino energy flux density $\times 4\pi R_o^2$

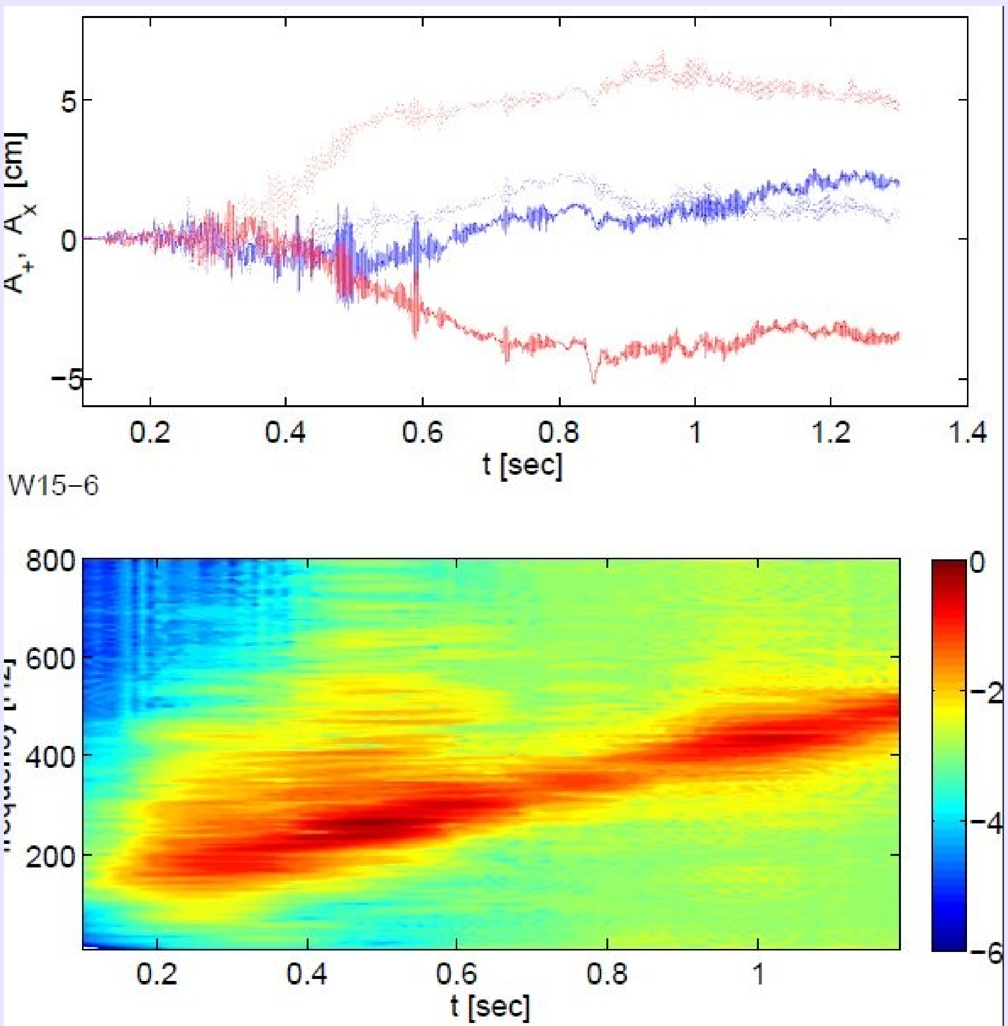


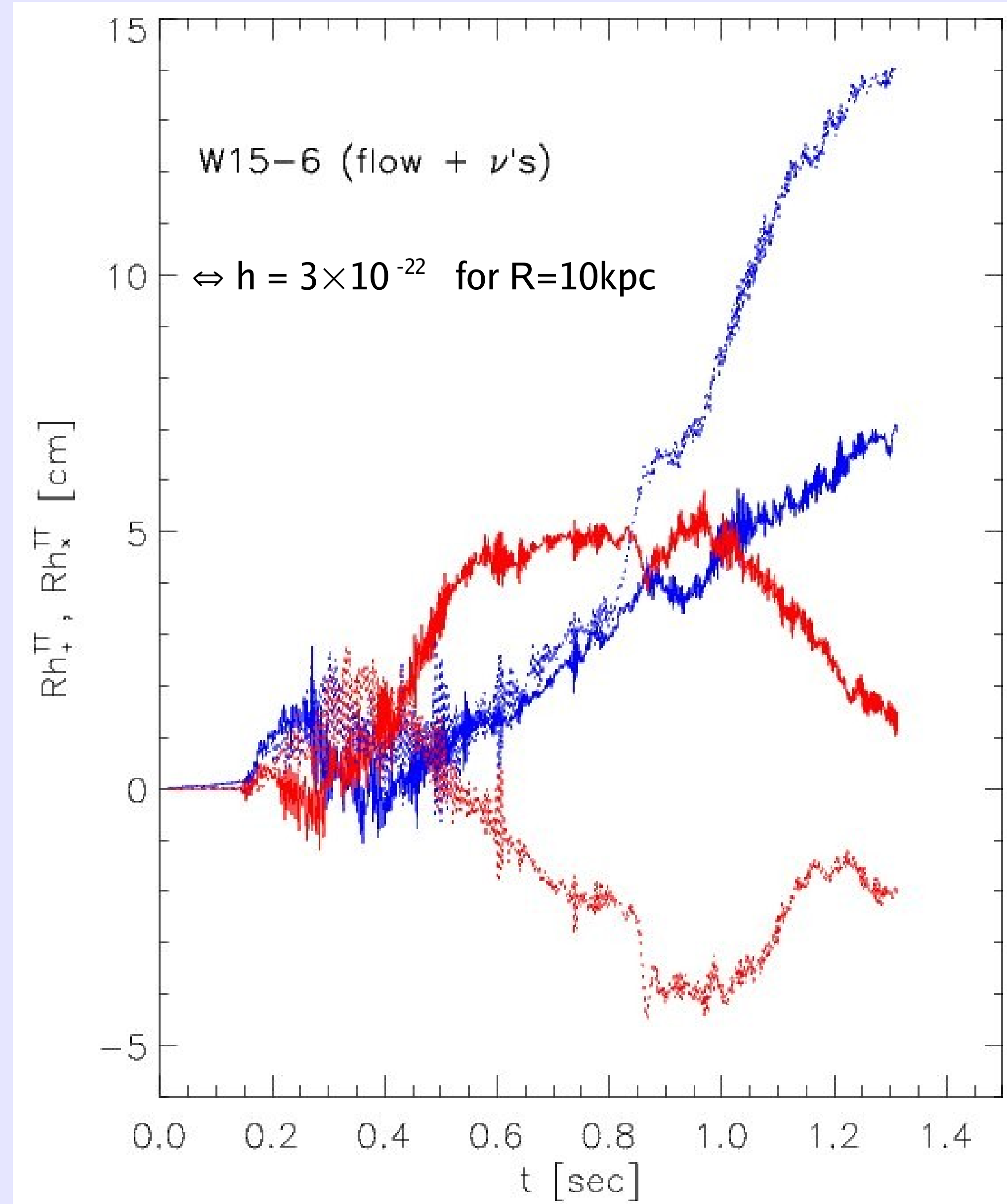
post-accretion phase

end of mass accretion, onset of a nearly spherical neutrino-driven wind

Parametrized 3D models of neutrino-driven core collapse supernovae

Müller, Janka, Wongwathanarat (2011))

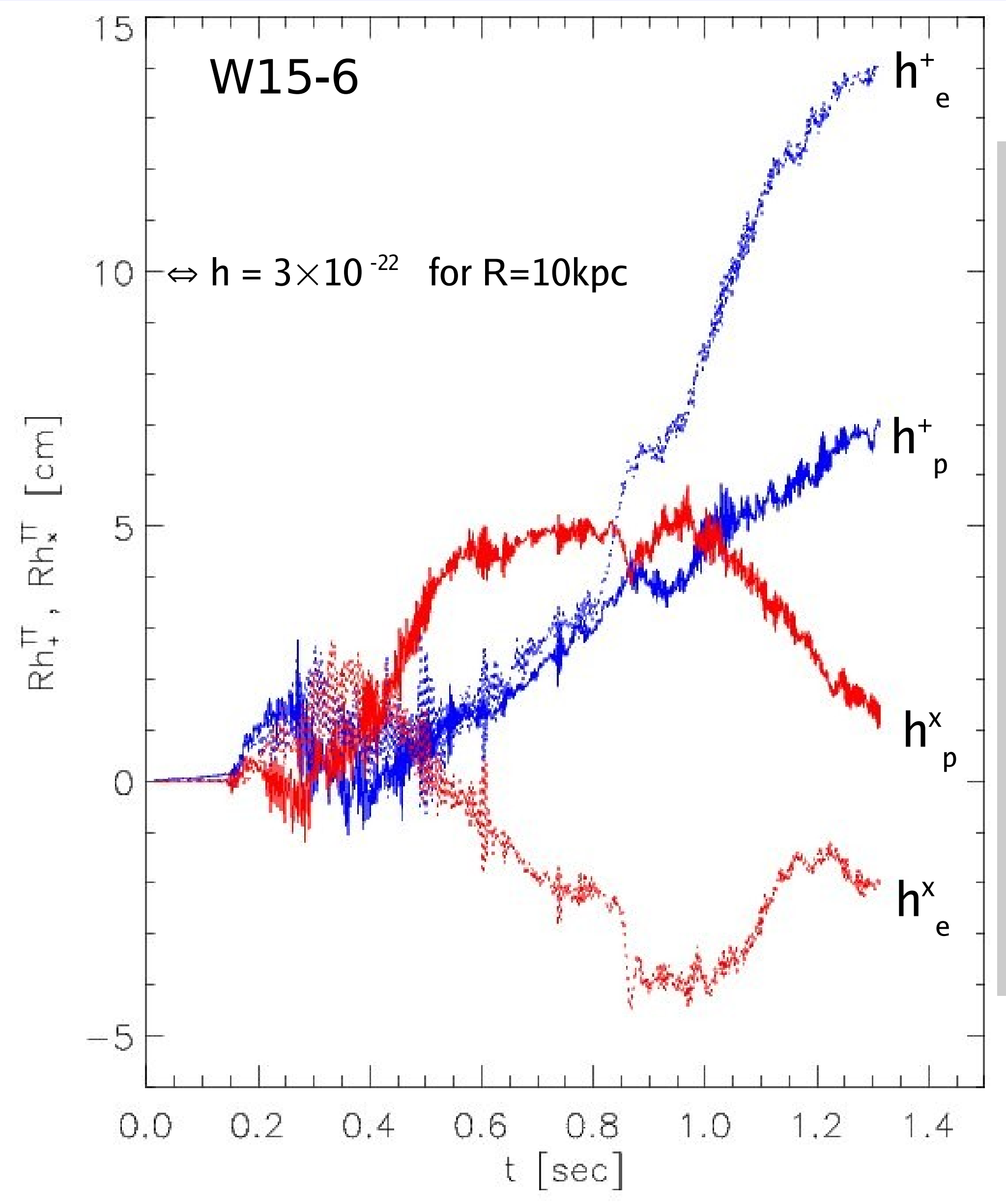


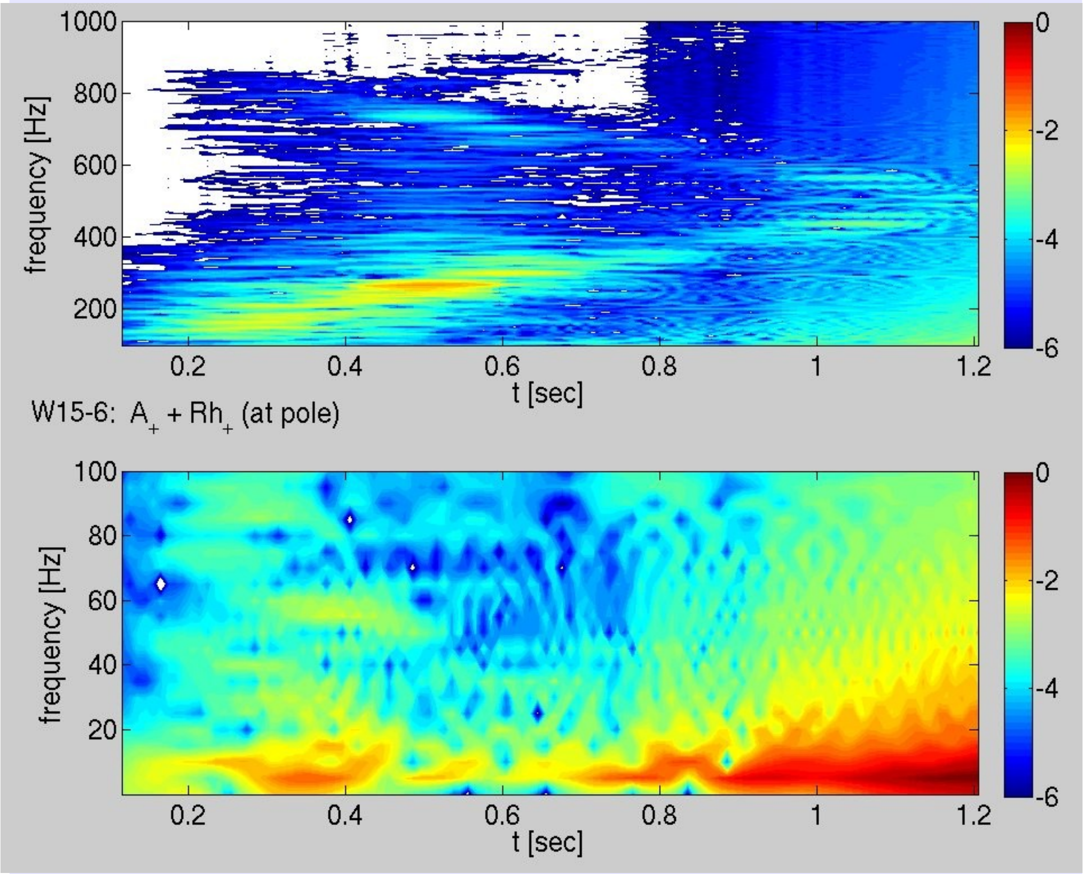


GW amplitudes due to aspherical flow & corresponding spectograms $dE_M/d\nu$

total GW amplitudes (including ν)

GW amplitudes of parametrized 3D models due to anisotropic mass flow and neutrino emission

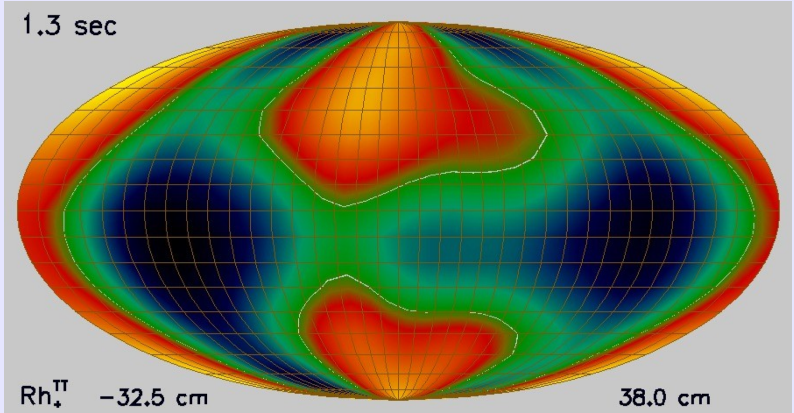




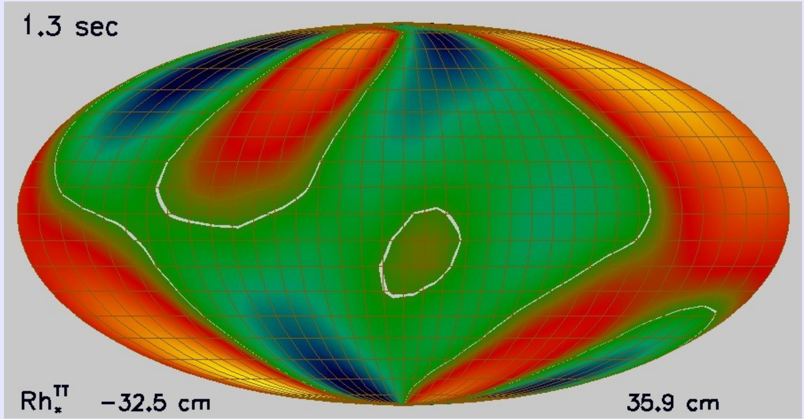
(normalized) total amplitude spectrogram

Müller, Janka & Wongwathanarat (2011)

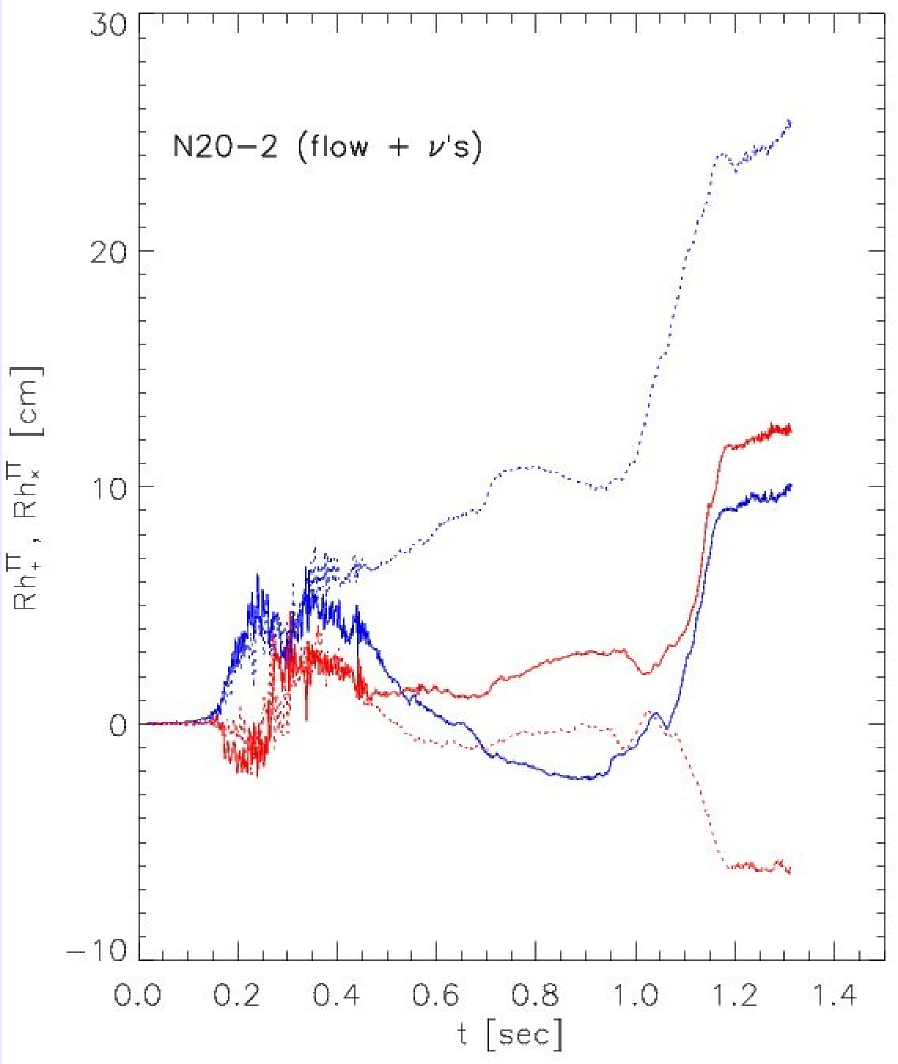
GW signature of parametrized 3D models



N20-2



observer angle dependent wave amplitudes



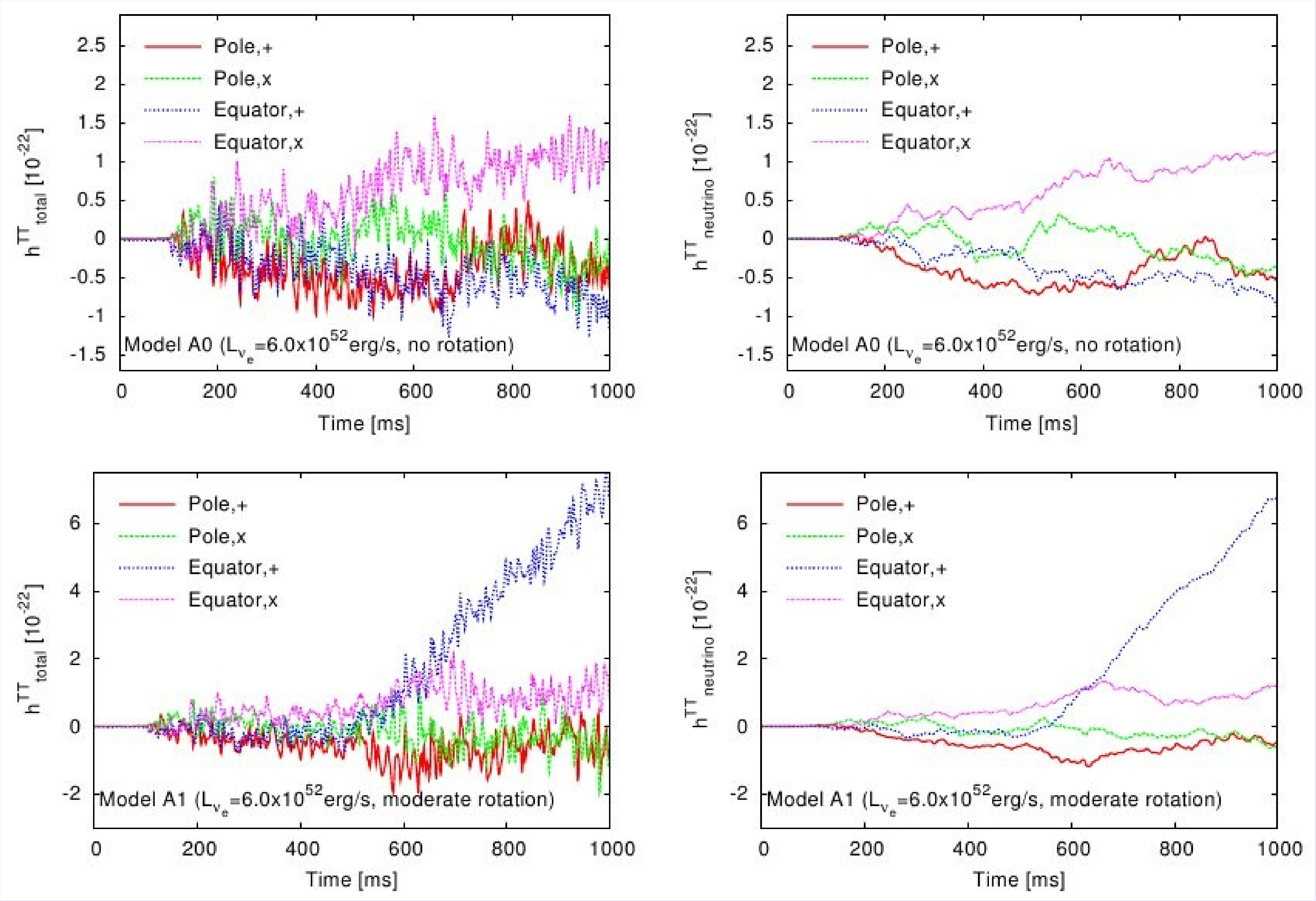
(normalized) total amplitude spectrograms

Müller, Janka & Wongwathanarat (2011)

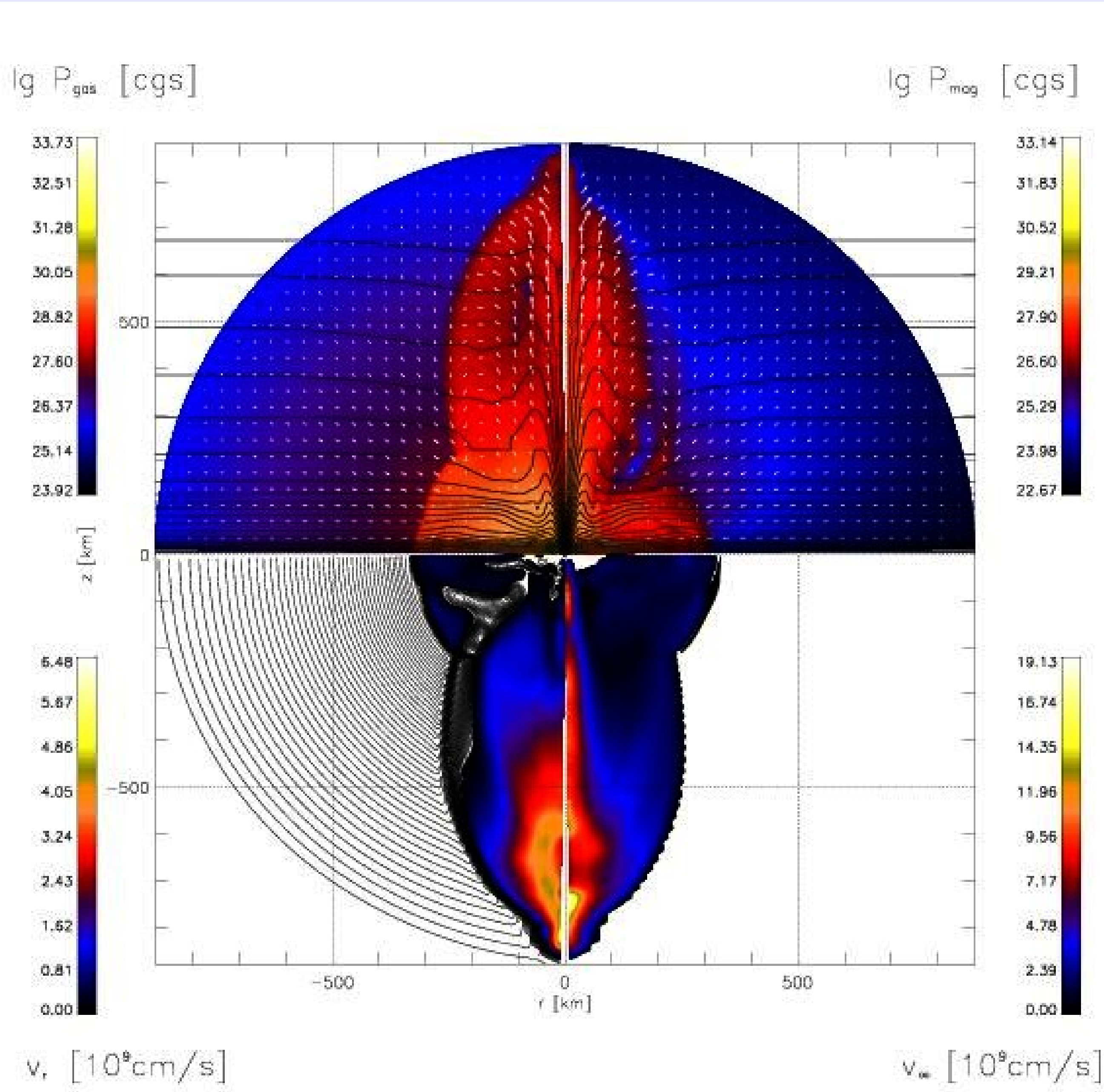
3D parametrized models: influence of rotation

rotation reduces stochasticity of GW signal
from anisotropic neutrino emission

Kotake et al. 2011



Snapshot (49 ms post-bounce) of a model with a strong initial B-field & rapid differential rotation --> collimated outflow



(Obergaulinger, Aloy & Müller 2006)

gas & magnetic pressure

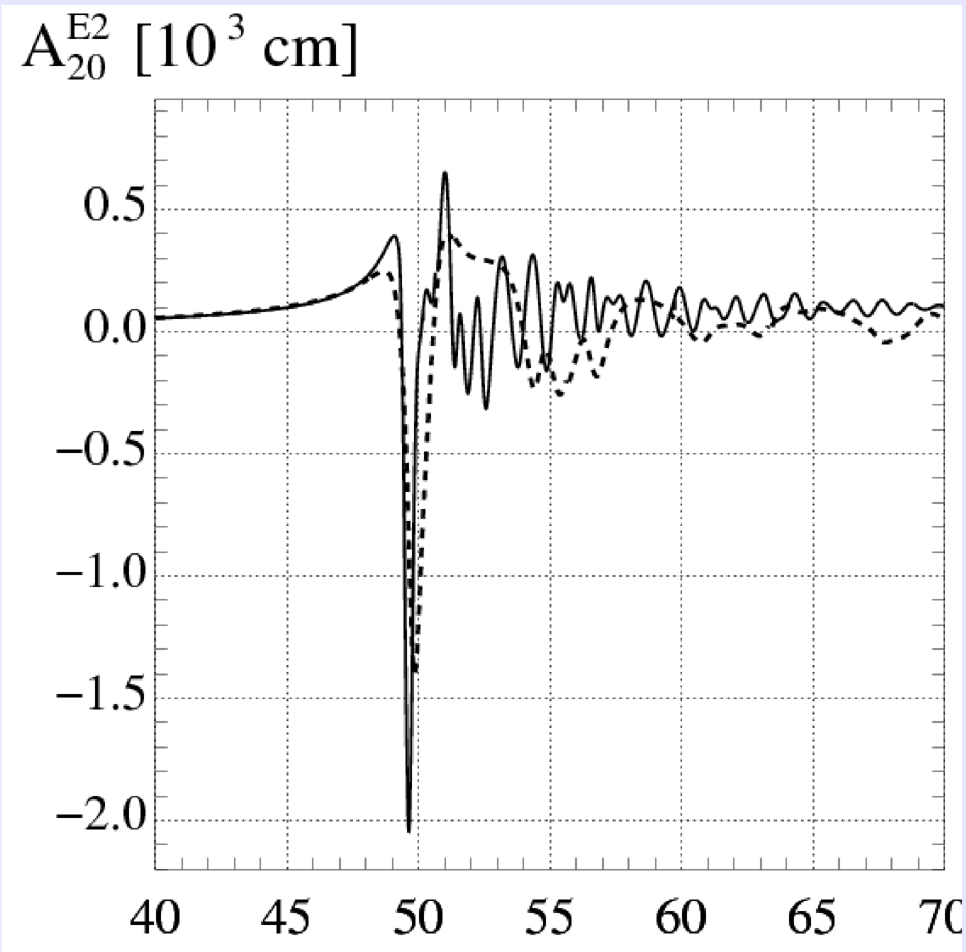
velocity & final velocity

(total energy -->
kinetic energy)

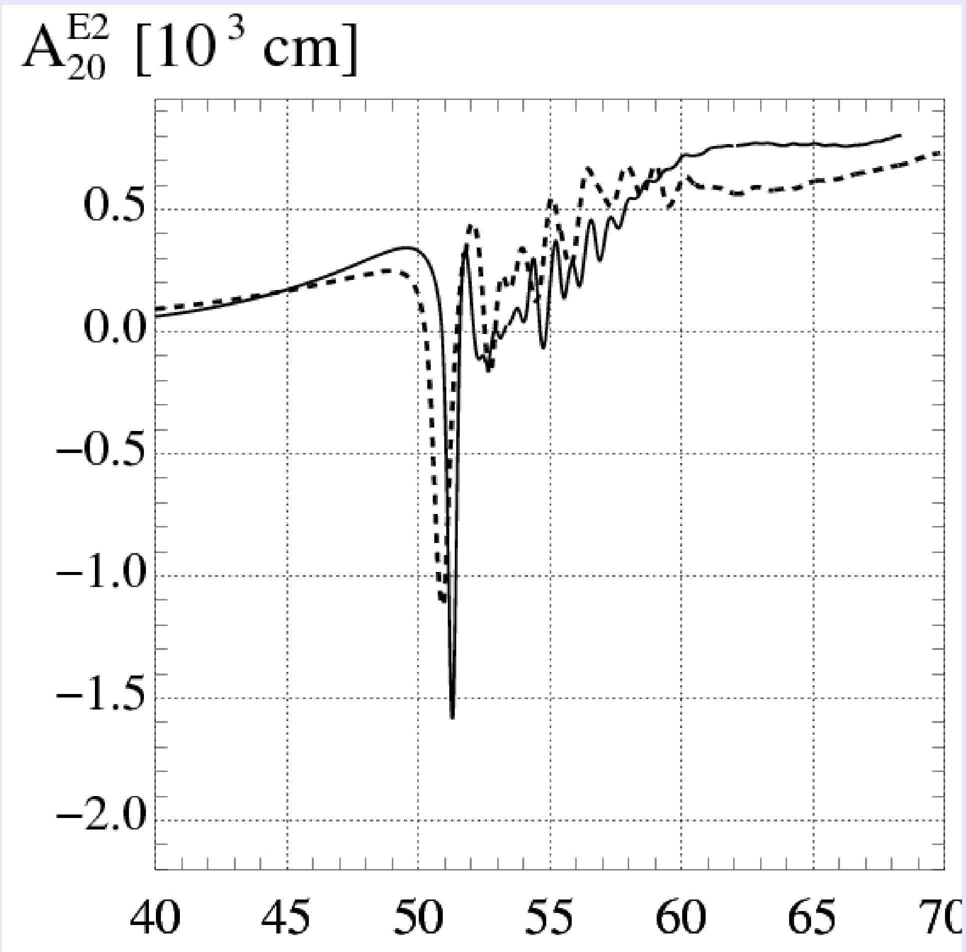
Gravitational wave quadrupole amplitude:

TOV (solid line) vs Newtonian (dashed line) rotating models:

(A3B3G3-D3M1x; Obergaulinger, Aloy & Müller '06)



10^{10} Gauss



10^{13} Gauss

Conclusions from MHD studies

- weak (realistic!) initial fields ($B < 10^{11}$ G) do neither change collapse dynamics nor resulting GW signal

- strong initial fields ($B \geq 10^{12}$ G)

  ---> - slow down core efficiently (even retrograde rotation occurs!)

  - qualitatively different dynamical evolution & GW signal

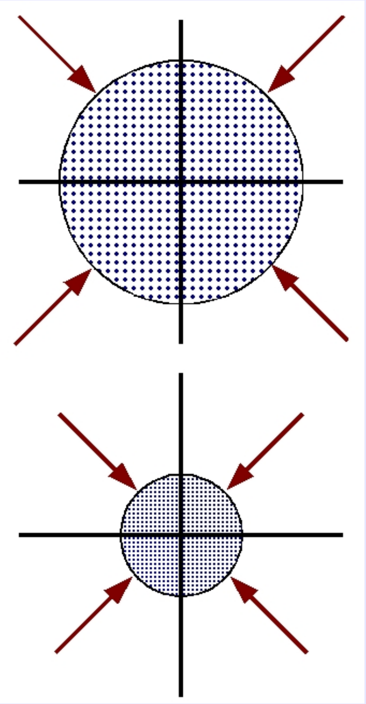
  - highly bipolar, mildly relativistic outflows

- shape of GW signal reflects dynamical behavior of the model (in particular the collimated outflow)

Are strong initial B-fields necessary?

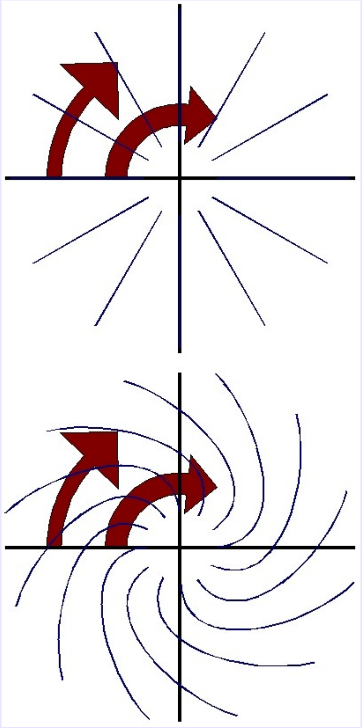
compressional amplification

- feeds off kinetic energy of infall
- amplifies field energy by a factor of 100 … 1000 during collapse
- works irrespective of field strength and geometry



winding by differential rotation

- creates & amplifies toroidal field component
- energy source: differential rotation
- requires poloidal seed field
- linear in time
  time scale set by rotational period



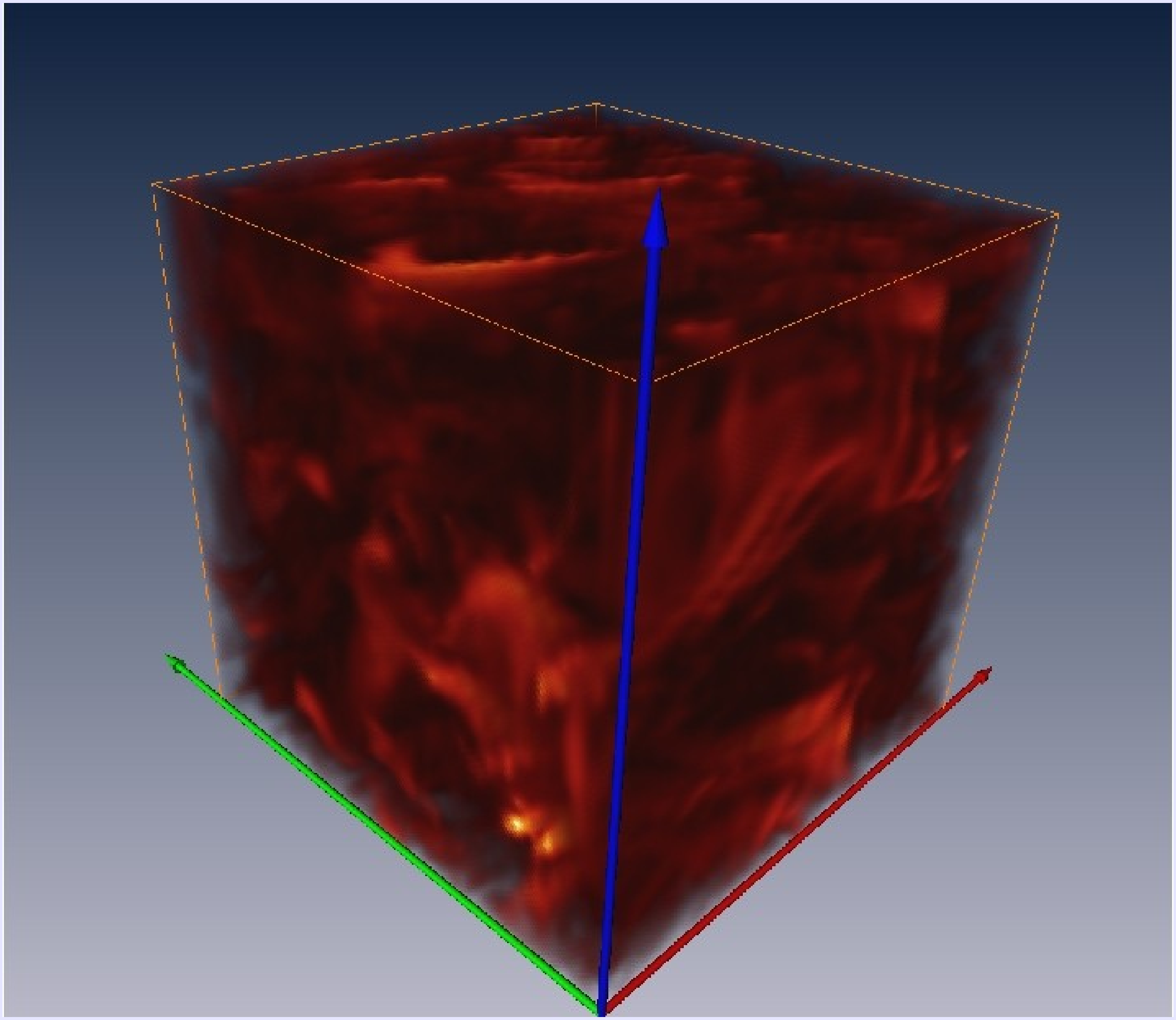
turbulent dynamo

- turbulence excited by

  shear flow (differential rotation)

  unstable stratification

- genuinely 3D effect



Obergaulinger, Cerda & Müller '08

The magneto-rotational instability

- main & original application: accretion disks
  (Balbus & Hawley 1991ff; based on Velikhov 1959 & Chandrasekhar 1960)
- energy source is differential rotation
- local linear instability with exponential growth

Semi-global simulations

Obergaulinger, Cerda & Müller '08

- MRI grows rapidly (within a fraction of a millisecond)
- saturation depends on the field geometry, the grid, and the dimensionality
- saturation level set by rotational equipartition (~ 10^{15} Gauss)

GW signal of core collapse supernovae: where do we stand in 2011?

- simplified models miss important physics (convection, SASI, anisotropic neutrino emission)
- intensively studied bounce signal is only a prelude to the GW emission in CCSN
- non-spherical (post bounce) flow occurs in <u>every</u> CCSN producing a GW signal dominated by a low-frequency ν-contribution
- only the rare galactic CCSN events seem to be detectable (in the local group with 3rd generation detectors)

- effects of relativistic gravity important for dynamics, but can be well modelled by means of an effective relativistic potential (for not too extreme models)
- CFC is an excellent approximation of GR for core collapse
- only very strong ($\geq 10^{12}$ Gauss) initial B-fields modify the dynamics and hence the GW (bounce) signal

What could the signal tell us?

- the time of bounce, if core is rotating
  (delay of neutrino signal relative to start of GW signal
  provides neutrino mass estimate)

- whether the explosion was globally asymmetric (tail signal)

- observational confirmation of SASI

- information about nuclear equation of state

- whether CCSN explosions involve strong ($\geq 10^{14}$ Gauss) magnetic fields

- unexpected new insights into the explosion mechanism