The Gravitational Wave Signature of Core-Collapse Supernovae (and what we can learn from it)

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It’s the ~~economy,~~ multi-D, stupid.

It’s all about convection, the SASI, rotation with MHD, and the g-modes! **Mr. Chairman, if we have to run this model for 100 years to get the answer, we will do just that!** Even the French, Japanese, Swiss, and Germans are doing it!!!

Did he just say g-modes?!? Won’t they emit gravitational waves like crazy?

Yeah right, show me robust and powerful 2D neutrino-driven explosions! Got to go straight to 3+1 GRRMHD, Bill!

It’s a gravity bomb!

The election year 2008 in the light of recent advances in core-collapse supernova theory.

Blowing up Massive Stars: Core-Collapse SN Mechanisms

- Standard Neutrino mechanism works in 1D for lowest-mass massive stars (O-Ne-Mg cores). [Kitaura et al. 2006, Burrows 1987, 2007c]
  2D: accretion induced collapse with rapid rotation. [Dessart et al. '06, '08]
- More massive progenitors: **Multi-D effects probably crucial:** Convection, accretion shock instabilities, **rotation**, MHD, **PNS pulsations**.

2D/3D Neutrino Mechanism

+ ν energy deposition.
+ Convection/Standing-Accretion-Shock Instability (SASI) & soft EOS.
  -> 11.2 M_{SUN}, 15 M_{SUN}
  [Buras et al. '06, Marek & Janka '07]
+ Si/O burning.
  [Bruenn et al. '06, Mezzacappa et al. '07]

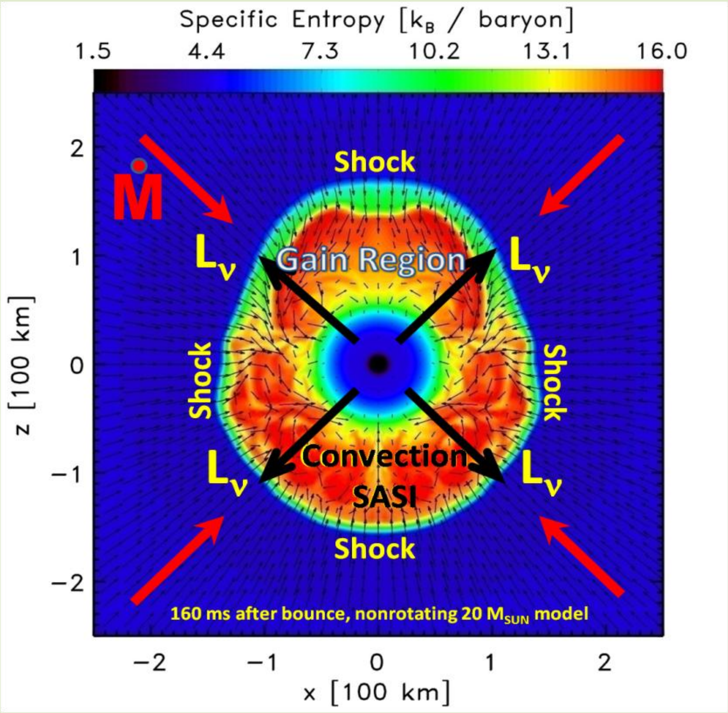
MHD-Jet Mechanism

+ Rapid Rotation
+ B-field amplification: flux compression, MRI, winding, dynamos
+ Robust, early jet-driven explosions (up to 10 B).
  [e.g., Burrows et al. '07, Wilson et al. '05, Yamada & Sawai '04, Mizuno et al. '04, Akiyama et al. '03, '05, Shibata et al. '06]

Acoustic Mechanism

+ Excitation of PNS *g*-mode pulsations by accretion/ SASI/turbulence.
+ Damping via emission of strong sound waves that steepen to shocks.
+ Robust, late explosions.
  [Burrows et al. '06, '07, Ott et al. '07, but: Weinberg & Quatert '07]

Constraining the Core-Collapse Supernova Explosion Mechanism



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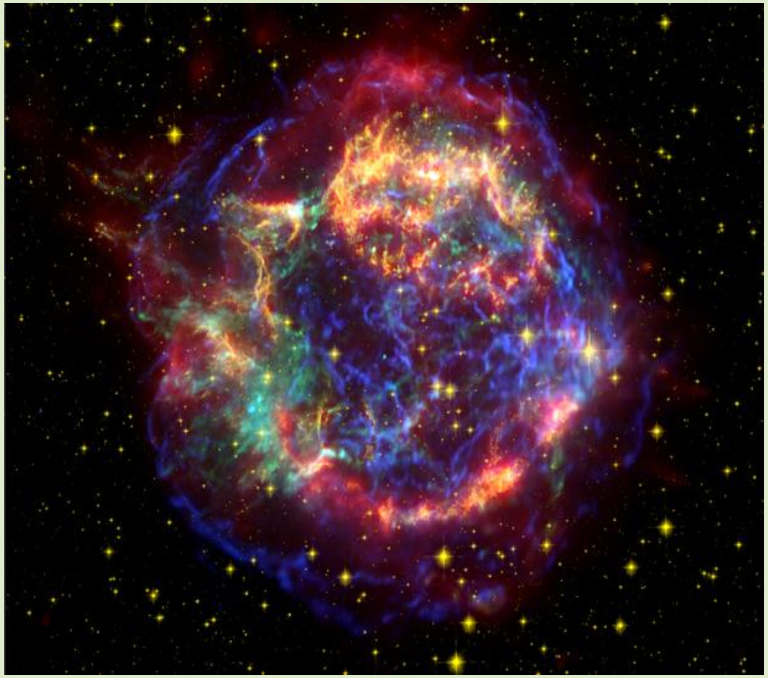
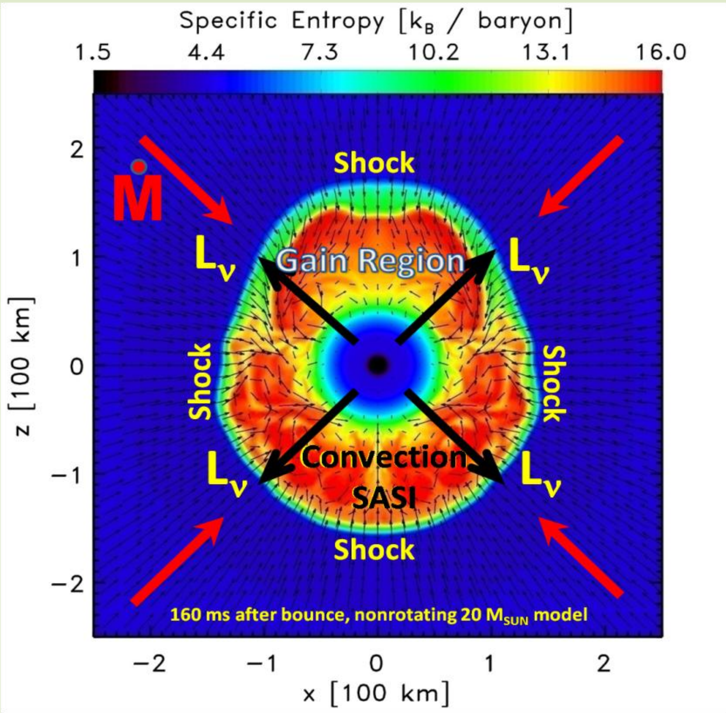


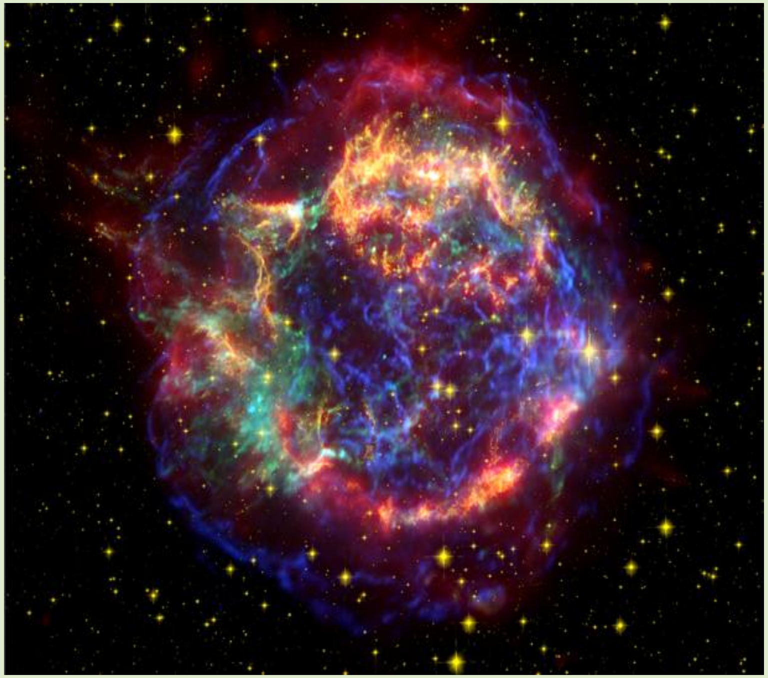
Secondary Observables

Classical Observational Astronomy:

- Explosion morphology, lightcurve, energy, chemical composition.
- Progenitor type / mass.
- Pulsar kicks.
- Neutron star mass.

Constraining the Core-Collapse Supernova Explosion Mechanism





Chandra

Neutrino and Gravitational Wave Astronomy

- Direct "live" information from the supernova engine.
- **GWs: Directly linked to the ubiquitous multi-D dynamics in the postshock region and in the PNS.**

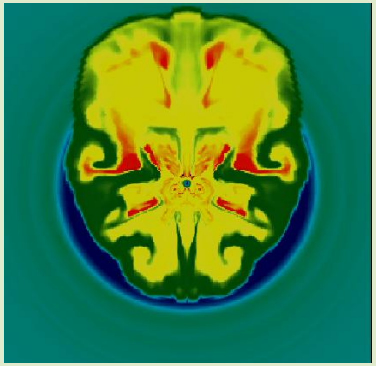
Primary Observables

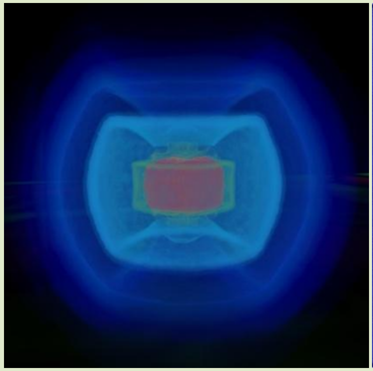
GW Emission Processes in Core-Collapse SNe

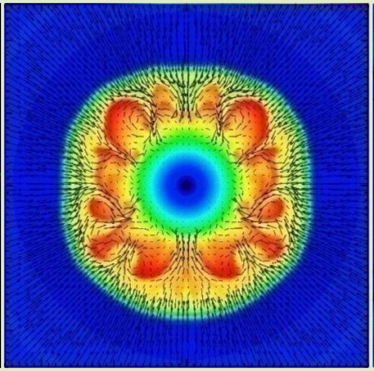
- Rotating core collapse and core bounce.
- Postbounce convection and SASI.
- Anisotropic neutrino emission.
- PNS core pulsations.
- PNS dynamical rotational 3D instabilities.
- Aspherical outflows
  (jets; precollapse asymmetries)

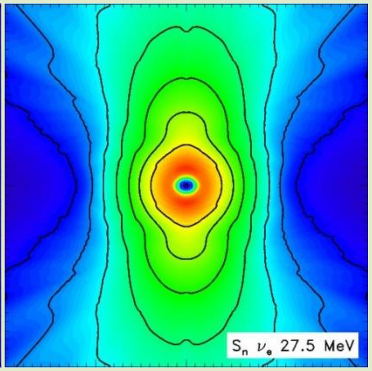
Newtonian Quadrupole Formula:

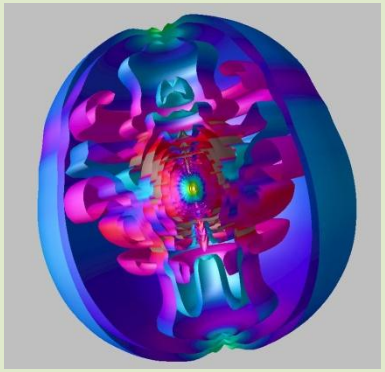
$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t-\frac{|\vec{x}|}{c})\right]^{TT}$$

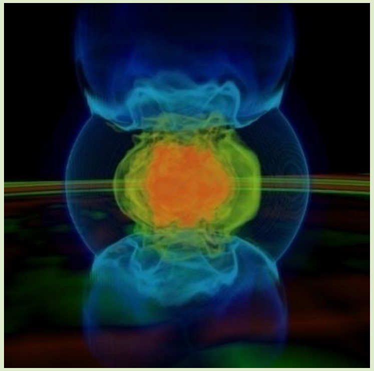






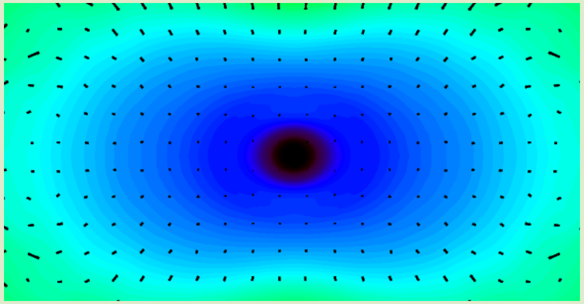






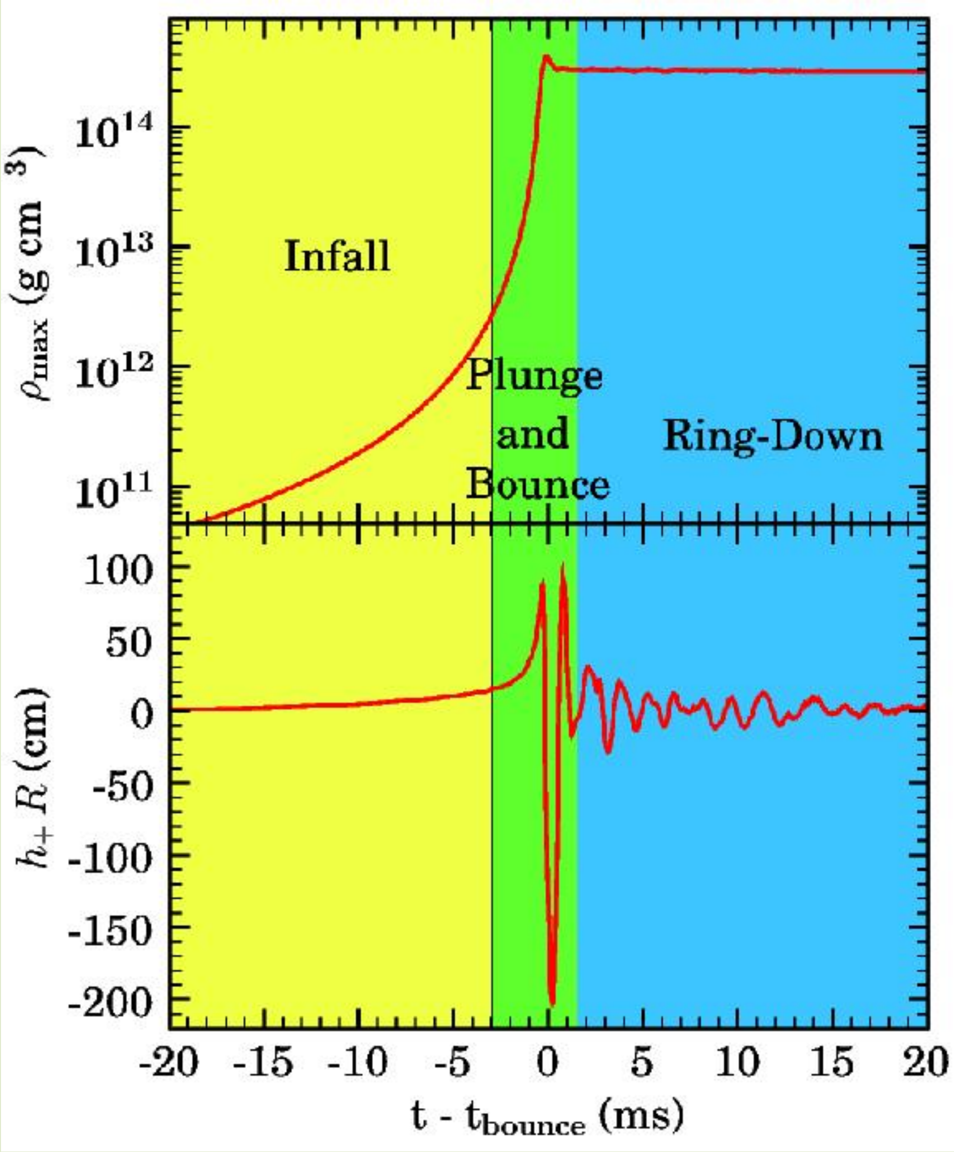
Rotating Core Collapse and Bounce

- Collapse: Angular momentum conservation leads to spin up & rotational deformation of inner core.



- At core bounce: Very large accelerations -> rapidly changing mass quadrupole moment.
- Most extensively studied GW emission in core collapse:

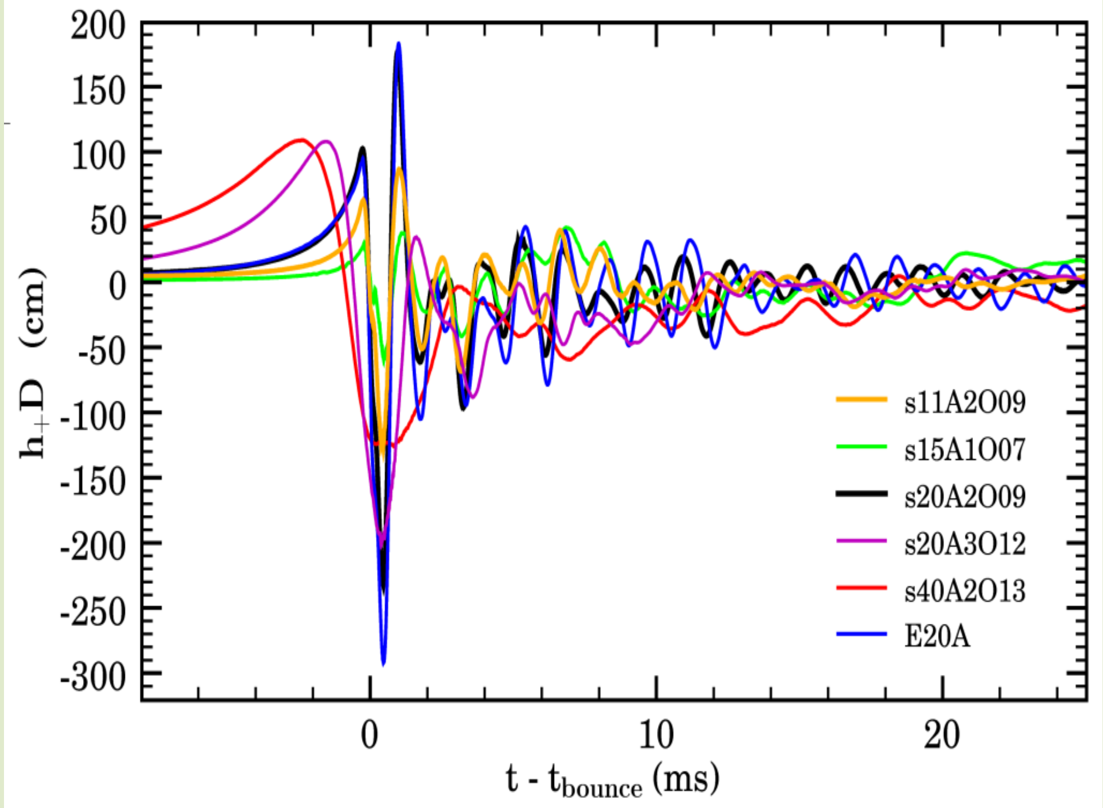
Ruffini & Wheeler 1971
Thuan & Ostriker 1974,
Saenz & Shapiro 1978-1981
Moncrief 1979
Mueller 1981
Detweiler & Lindblom 1981
Turner & Wagoner 1979
Seidel et al. late 1980s
Finn & Evans 1990
Moenchmeyer et al. 1991
Bonazzola & Marck 1993
Yamada & Sato 1995
Zwerger & Mueller 1997
Dimmelmeier et al. 2002
Ott et al. 2004
Shibata & Sekiguchi 2004



New Results: Rotating Collapse and Bounce

[Dimmelmeier et al. 2008, Dimmelmeier et al. 2007, Ott et al. 2007, Ott 2006]

- First 2D/3D **GR** simulations with hot microphysical EOS & **deleptonization** during collapse.
- GW signature determined by inner core mass, **inner core angular momentum**, and (to some extent) nuclear EOS.
- GW signal of generic shape; no "multiple centrifugal bounce" or fizzlers.
- GWs from "quickly" spinning cores (precollapse $P_0 < \sim 10$ s) "detectable" throughout the Milky Way.

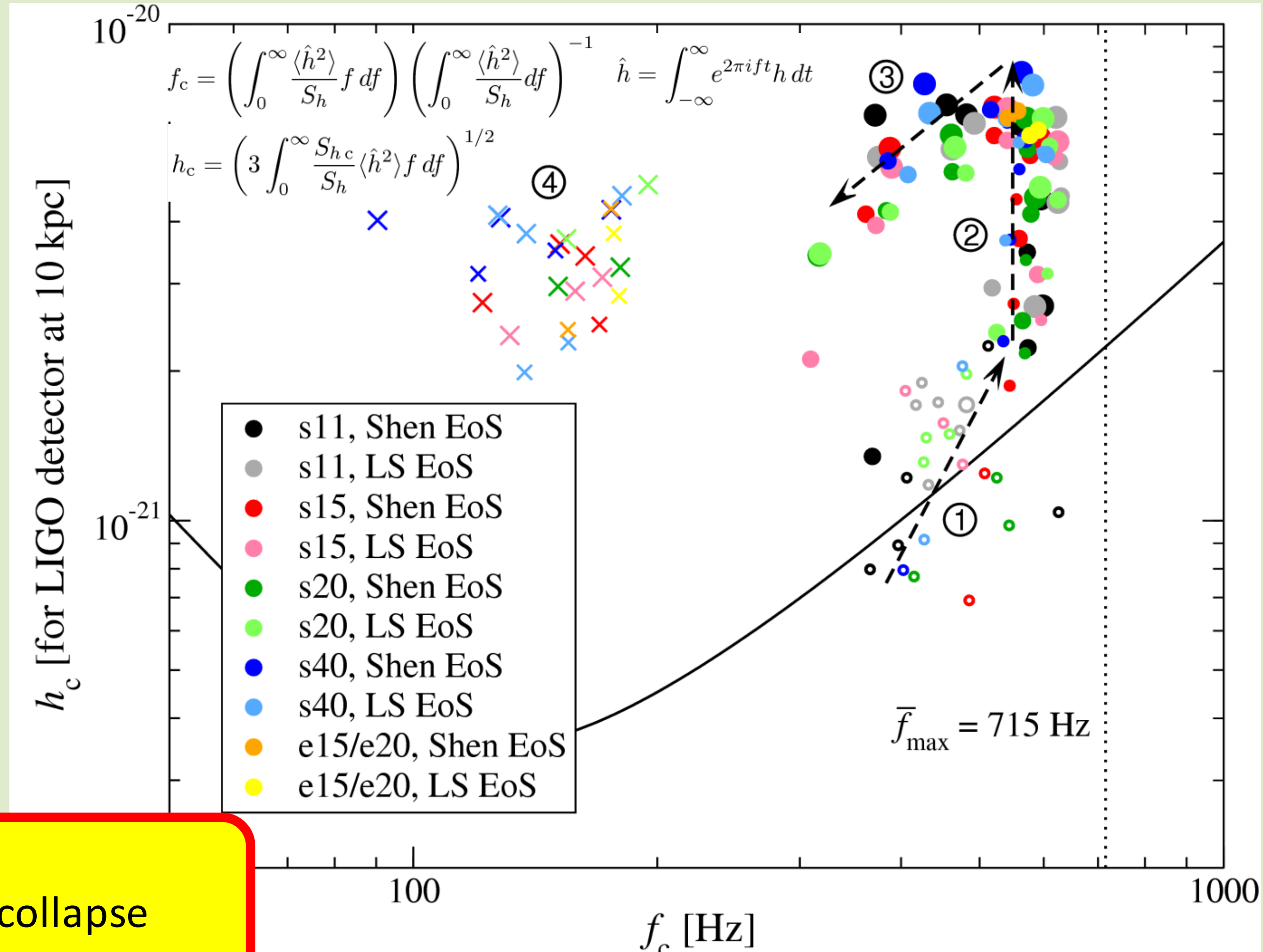


- Important finding:
  Cores stay axisymmetric through bounce and early postbounce phase.

New Extended 2D GR Model Set

[Dimmelmeier, Ott, Marek, and Janka 2008 submitted, Dimmelmeier et al. 2007ab, Ott et al. 2007]

- >140 2D GR models with $Y_e(\rho)$ parametrization.
- 6 presupernova models.
- Slow to very rapid rotation.
- Solid-body to moderately differential rotation.
- 2 finite-temp. nuclear EOSs.



Results

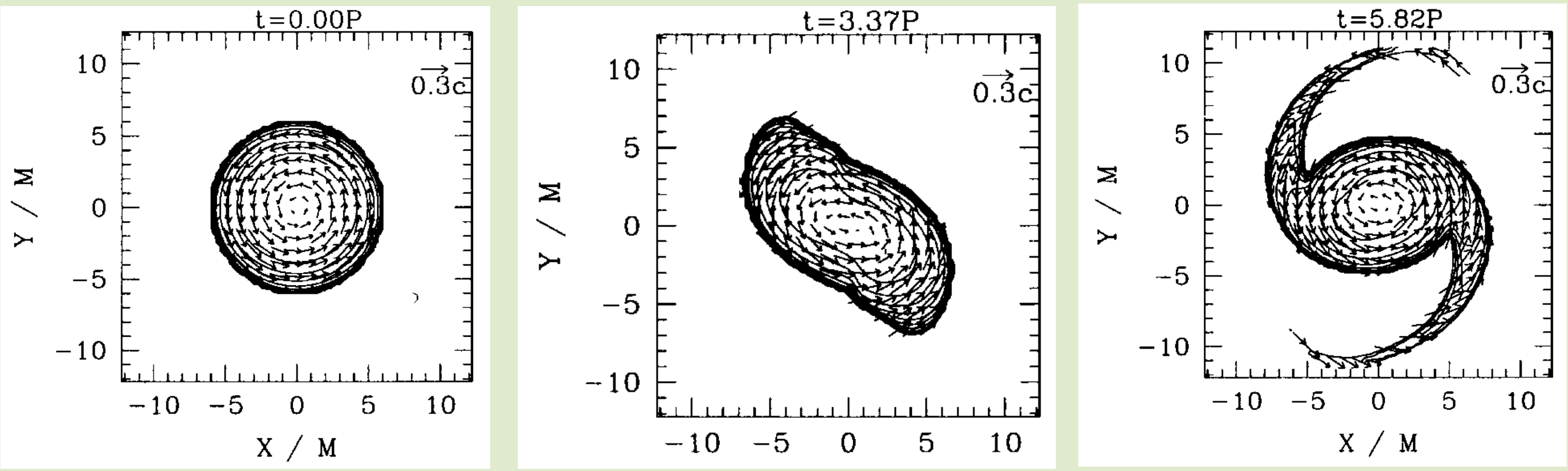
- GW signature of rotating collapse multi-degenerate.
- Key parameters:
  - Precollapse central Ω.
  - Precollapse iron-core mass/entropy.

1) slow rotation, pressure-dominated bounce, prompt convection
2) moderately-rapid rotation, pressure-dominated bounce
3) rapid rotation, pressure-dominated, rotation-influenced bounce
4) single centrifugal bounce.

PNS Spin and Rotational Instabilities

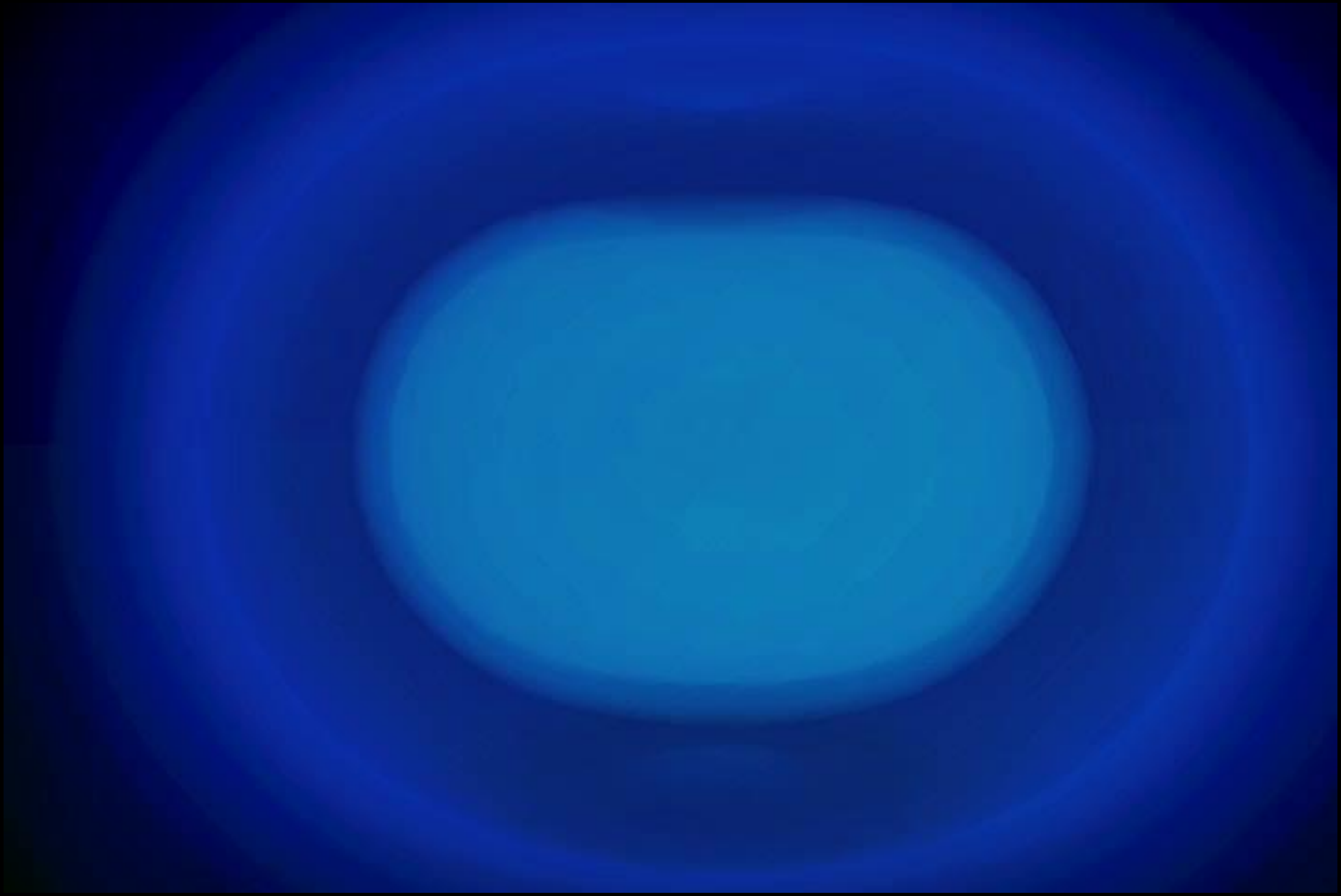
[Dimmelmeier et al. 2008, Ott et al. 2007, Ott et al. 2006]

- Classical picture: **High T/|W| instabilities**.
  Azimuthal modes $\propto \exp(im\varphi)$. m=2 "bar-modes"
  $(T/|W|)_{dynamical} = 0.27$, $(T/|W|)_{secular} \approx 0.14$. [e.g., Chandrasekhar 1969]
  Numbers hold roughly in GR and moderate differential rotation.
  [e.g., Baiotti et al. 2007]



[Shibata et al. 2000, 3+1 GR simulations]

Rapid Rotation and Nonaxisymmetric Dynamics



3D GR simulation Ott 2006, rendition by R. Kähler, Zuse Institute, Berlin

WARNING: Crazy toy model!!!

PNS Spin and Rotational Instabilities

[Dimmelmeier et al. 2008 arXiv 0806.5953, Ott et al. 2007, Ott et al. 2006]

- Classical picture: **High T/|W| instabilities**.
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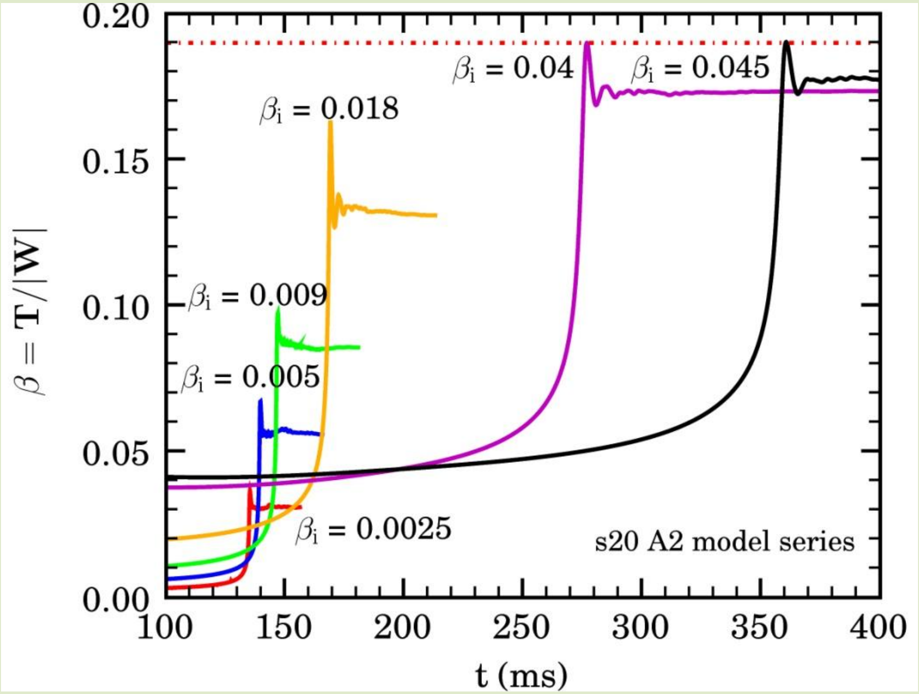
  [e.g., Baiotti et al. 2007]

- **Can a realistic PNSs reach such high T/|W|?**



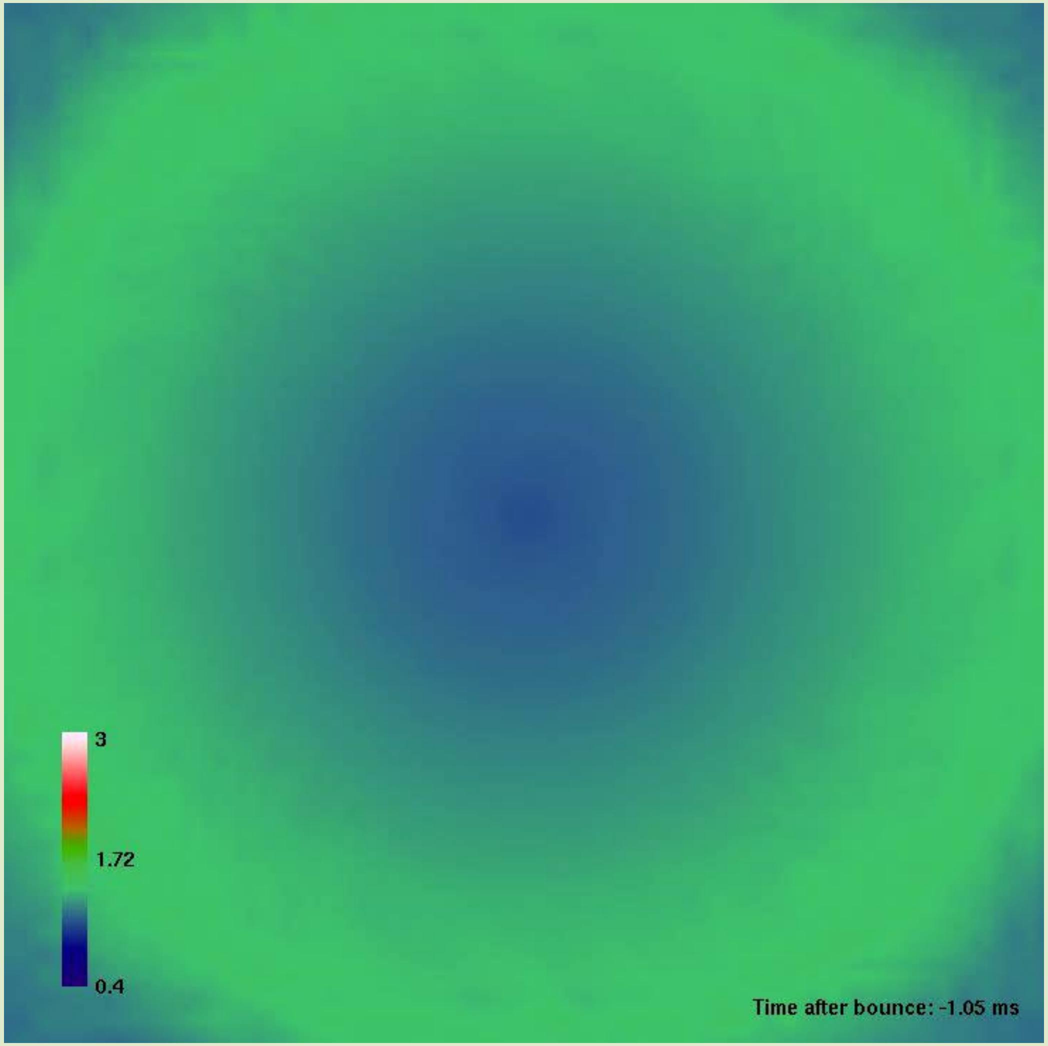
- Direct numerical simulation: No – Collapsing cores hit rotational barrier.
  [Ott et al. PRL 2007 & CQG 2007, Dimmelmeier, Ott et al. 2008, arxiv 0806.4953]
- Critical T/|W| (secular/ dynamical) attainable during PNS cooling.
- Don't forget MHD!

A Low-T/|W| Rotational Instability

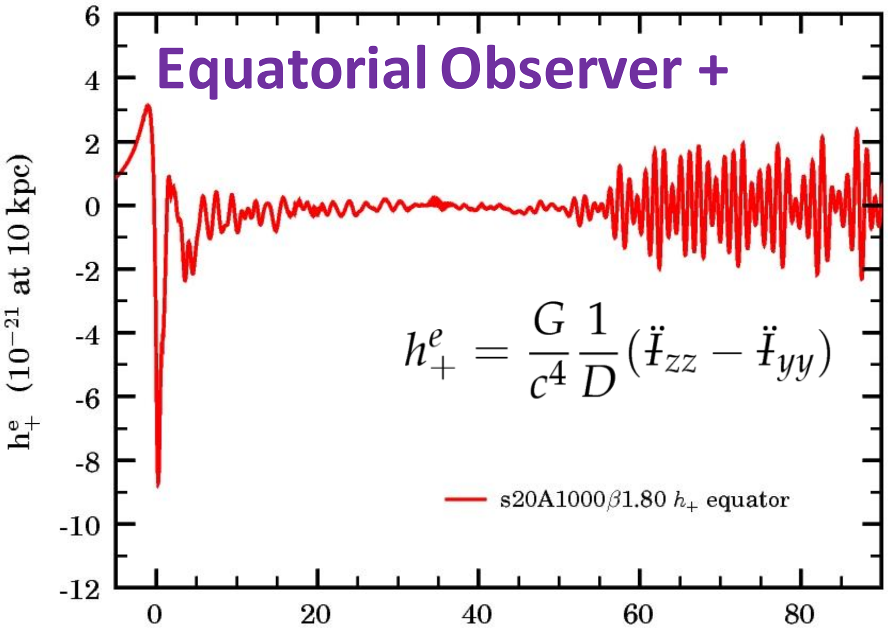
- Dynamical rotational instability at low T/|W|.

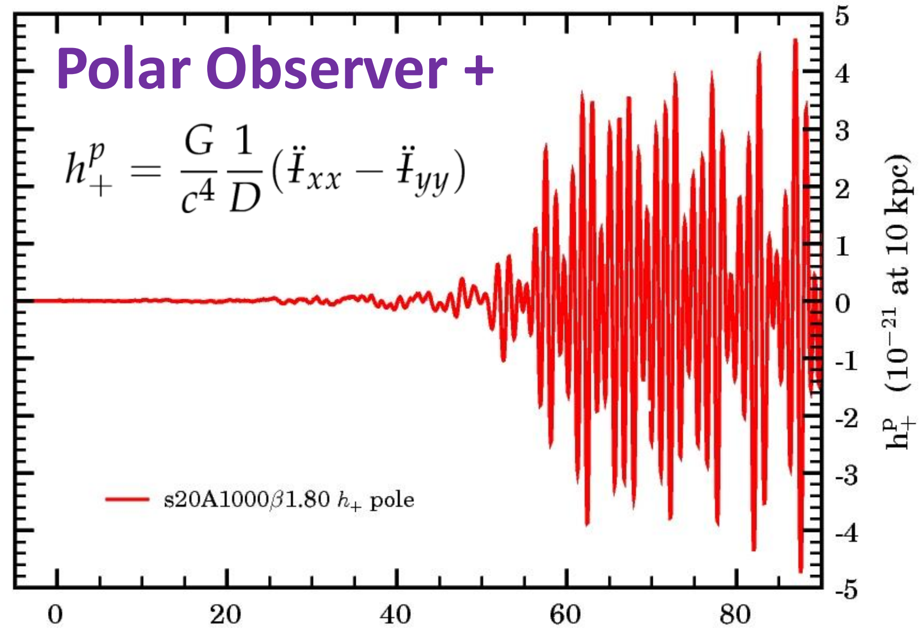
[e.g., Centrella et al. 2001, Saijo 2003, Saijo & Yoshida 2006, Ott et al. 2005, Ou & Tohline 2006, Cerdá et al. 2007b]

- Dominant m=1 mode; m={2,3} modes mixed in (radial & temporal variation).
- Mechanism: Corotation instability (?) Resonance of unstable mode with background fluid at corotation point(s).
- Spiral density waves – relationship to accretion and galactic disks? *SASI?* -> angular momentum transport.

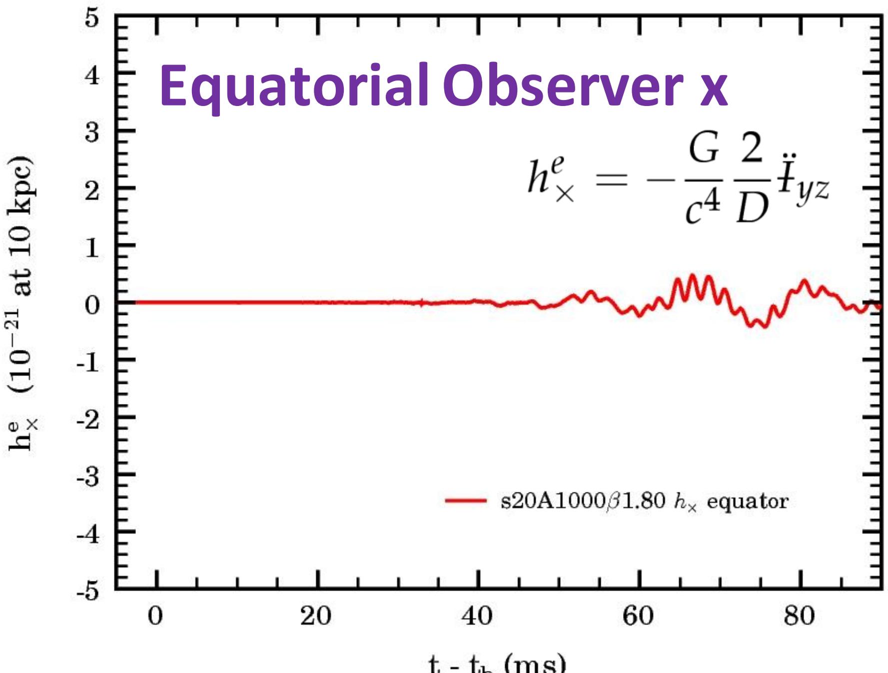


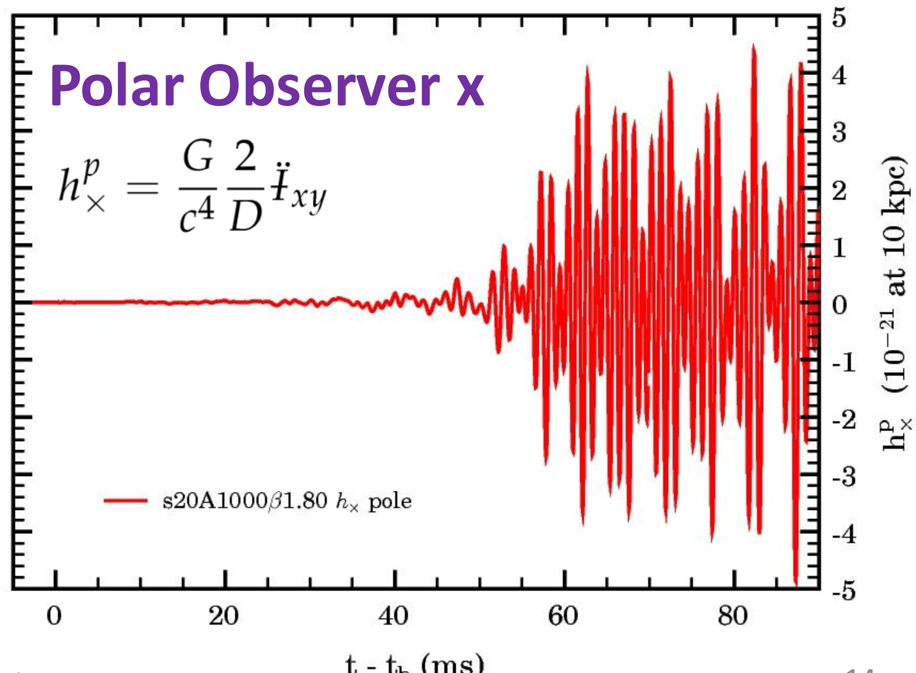
- Note: PNS embedded in SN core and continuously accreting angular momentum. **Cannot be described by an equilibrium NS model!**





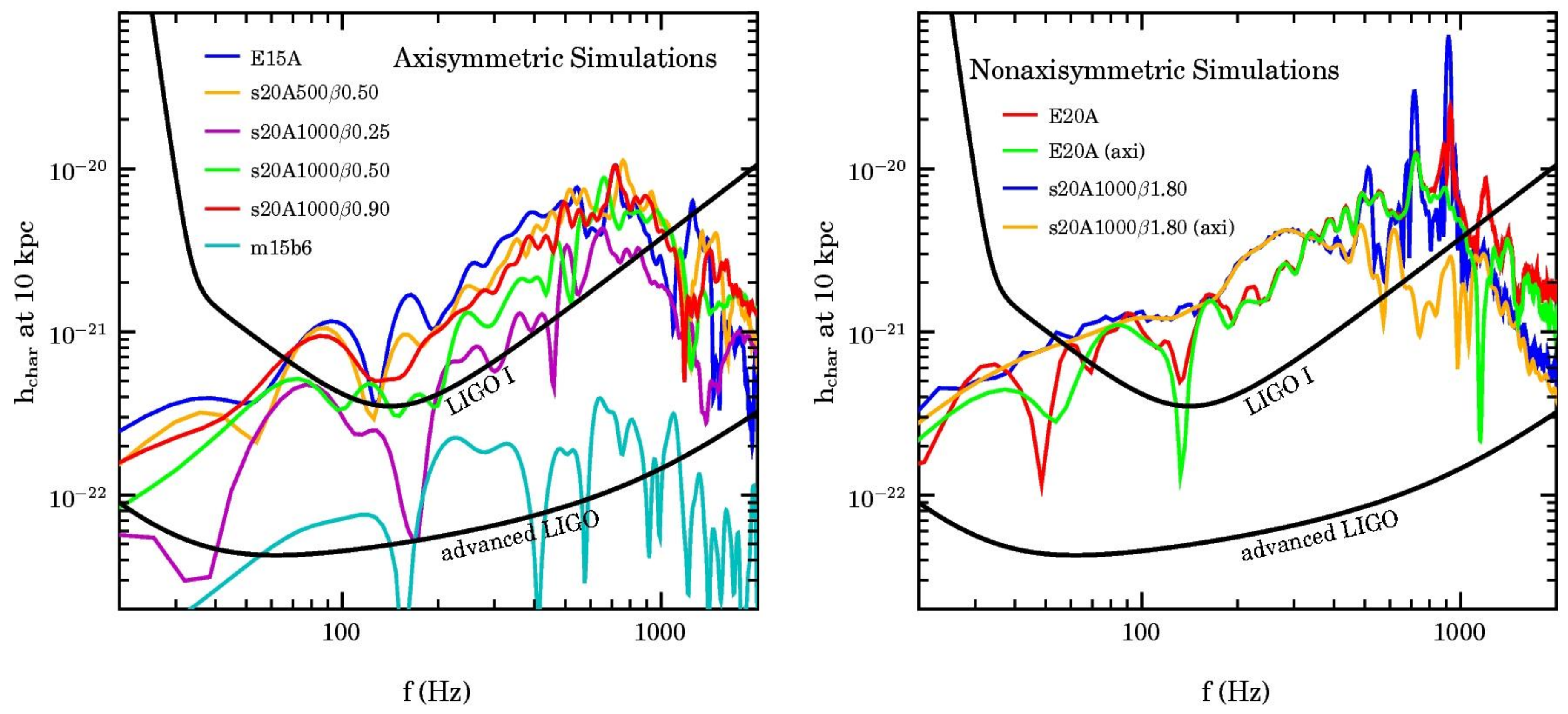
GW Emission, Model s20A2B4





GW Emission vs. Detector Noise

$$h_{\mathrm{char}} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\mathrm{GW}}}{df}} \qquad S/N = \sqrt{\int_0^\infty d\ln f\,\frac{h_{\mathrm{char}}^2}{h_{\mathrm{rms}}^2}} \qquad h_{\mathrm{rms}} = \sqrt{f S(f)}$$



- 3D component: lower in amplitude than core-bounce GW spike, but greater in energy! Emission in narrow frequency band around 900—930 Hz (~2 x pattern speed of the unstable mode!) models.

Switching Gears:

GWs emitted by

Convection, SASI, Neutrinos,
Global Asymmetries,
&
PNS core g-modes

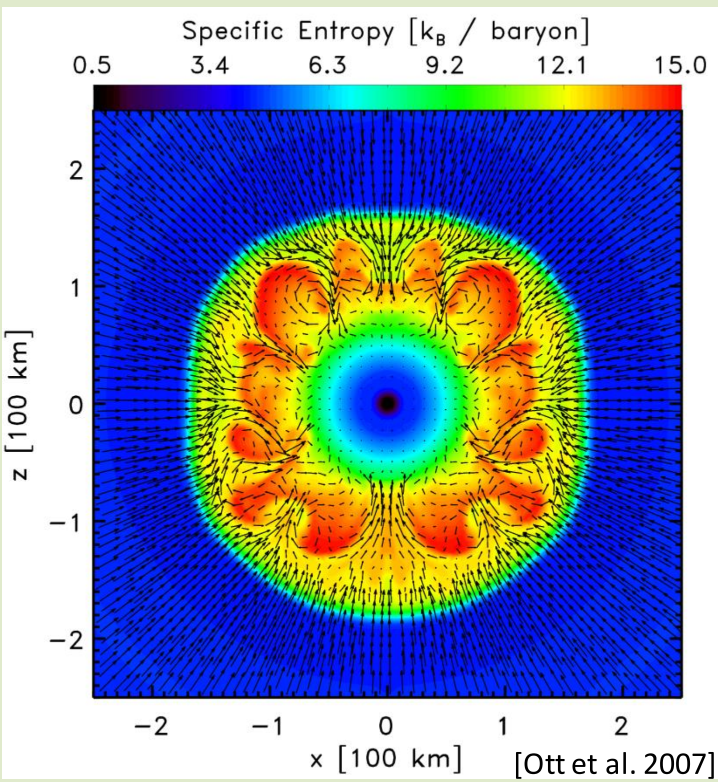
(Most) Calculations performed with the axisymmetric Newtonian VULCAN/2D radiation-(magneto)hydrodynamics code.

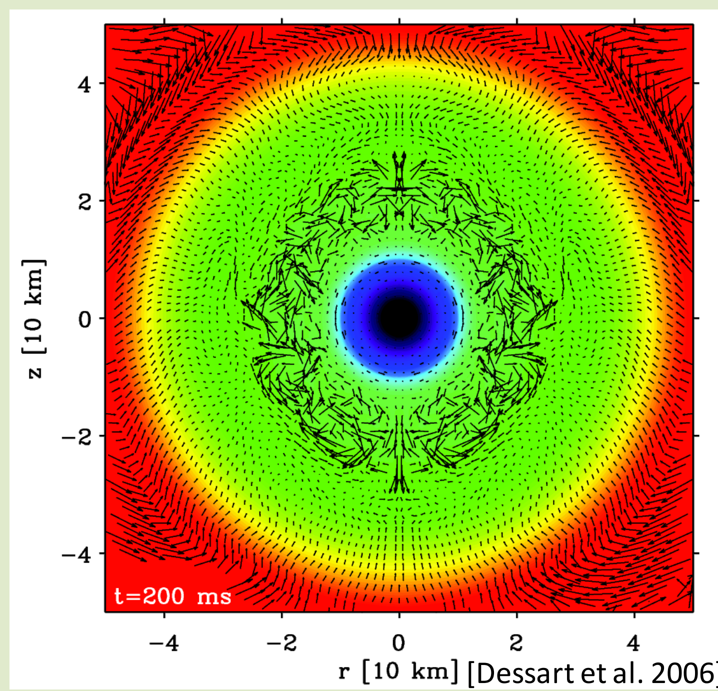
[Livne et al. ‘93, ‘04, ‘07, Burrow et al. ‘06, ‘07abc, Dessart et al. ‘06,ab ’07, Ott et al. ‘06ab, ‘08]

Convection

[e.g., Janka & Müller 96, Burrows et al. 95, Mezzacappa et al. 98, Swesty & Myra 06, Dessart et al. 06 & references therein.]

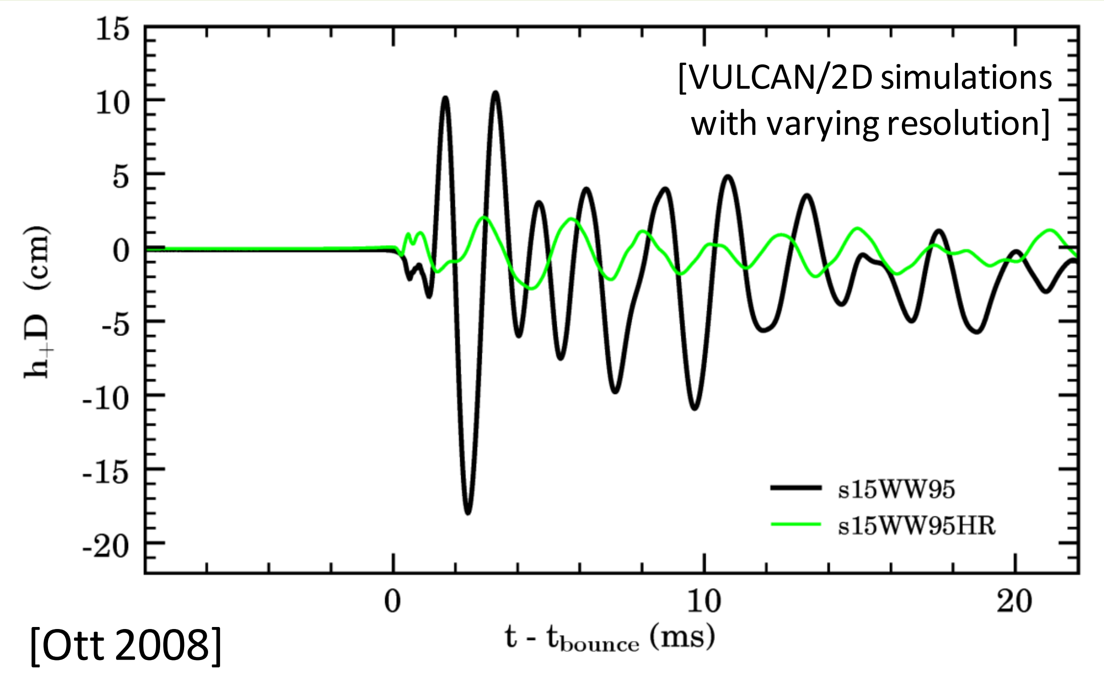
- Prompt postbounce convection.
- Postbounce neutrino-driven convection in gain layer generic to all non- and slowly rotating SN cores.
- PNS core convection.





GWs from Prompt Convection

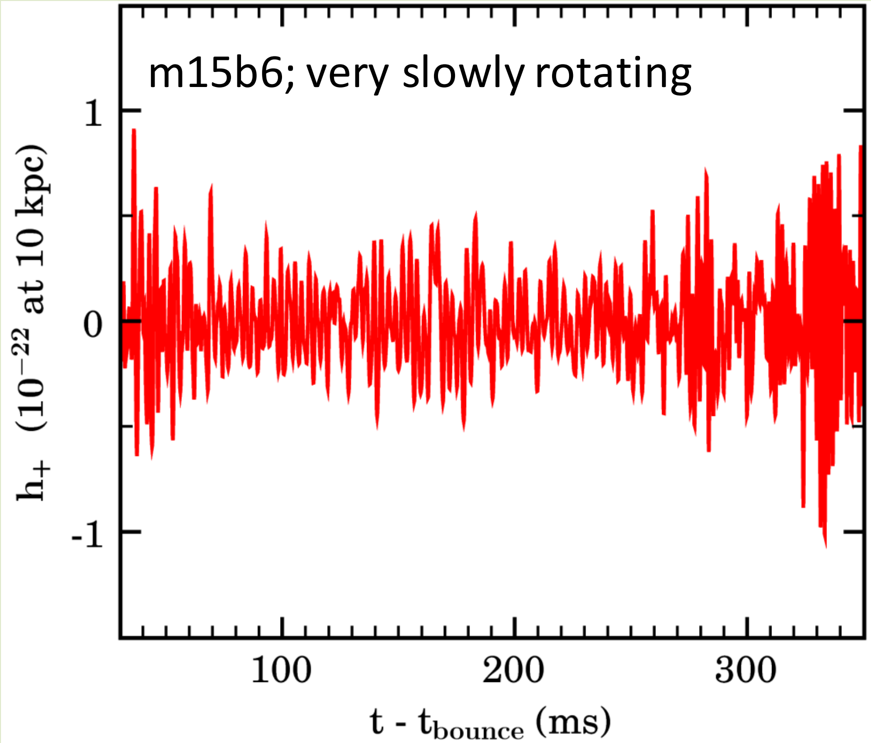
[**Ott 2008 submitted**, Dimmelmeier et al. '08, Scheidegger et al. '08, Ott et al. '06, Kotake et al. '03]

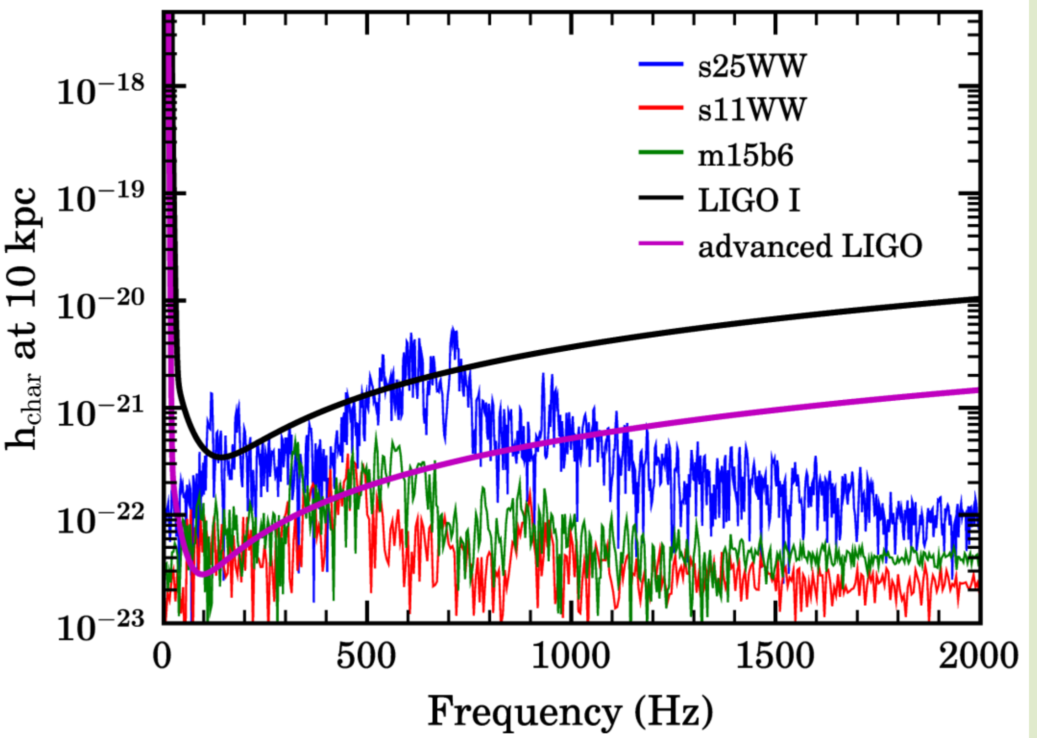


- Negative entropy gradient left behind by stalling shock drives prompt postbounce convection. [e.g., Burrows & Hayes 1992]
- Gradient to some extent smoothed out by neutrino emission.
- Growth and duration of convection strongly dependent on seed perturbations. -> Need parameter study to understand systematics.
- Real stars inevitably will have seed perturbations. Magnitude unclear.

GWs from Convection & SASI

[Ott et al. 2008 in prep., Ott et al. 2006, Müller et al. 2004, Müller & Janka 1997]





- Mixture of PNS and post-shock convection/turbulence.
- Convection (partially) stabilized by rapid rotation (positive *j* gradient)
- Broad-band, low-amplitude GW emission.
- $E_{GW} < 10^{-11} — 10^{-9} M_{\odot}c^2$
- In addition: low-frequency emission due to neutrinos.
  (not shown here; **see talk by Kei Kotake this afternoon!**)

GWs from Anisotropic Neutrino Emission

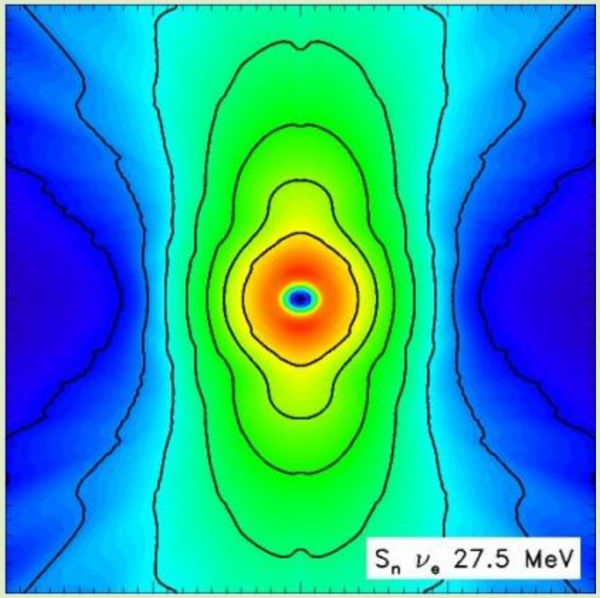
[Epstein 1978, Burrows & Hayes 1996, Janka & Müller 1997, Müller et al. 2004, Dessart et al. 2006, Ott 2006, Ott et al. 2008 in prep.]

- Any accelerated mass-energy quadrupole will emit GWs. Anisotropic neutrino radiation:

$$h^{TT}_{+,e}(t) = \frac{2G}{c^4 D}\int_{-\infty}^{t-D/c} \alpha(t')L_\nu(t')dt'$$

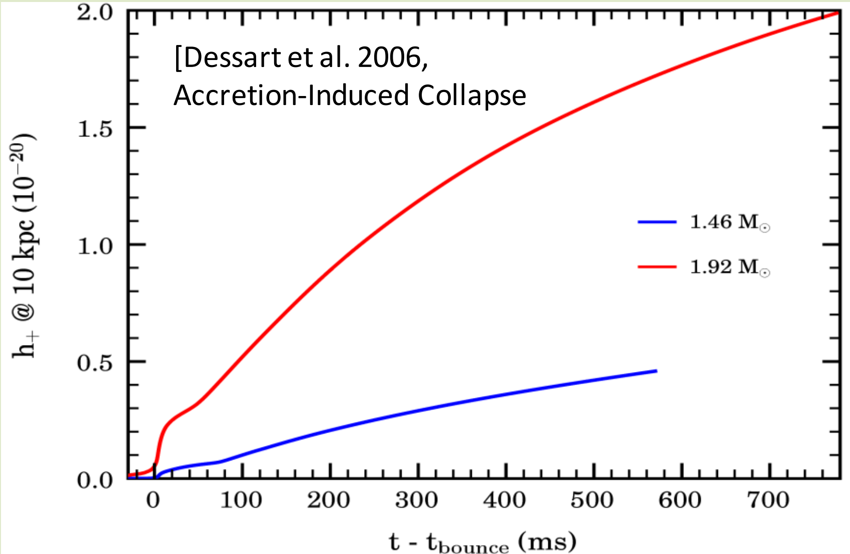
$$\alpha(t) = \frac{1}{L_\nu(t)}\int_{4\pi} \Psi(\vartheta',\varphi')\frac{dL_\nu(\vec{\Omega}',t)}{d\Omega'}d\Omega'$$

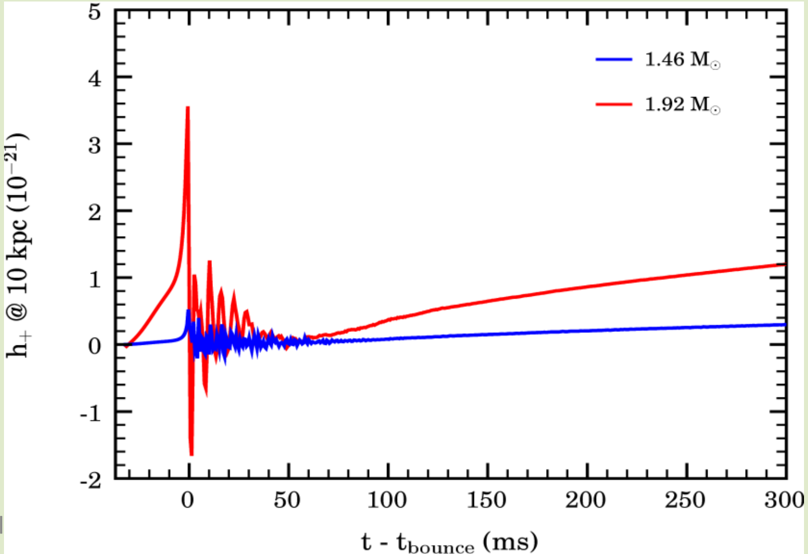
- GW "Memory"



[Ott et al. 2008 ApJ submitted!]

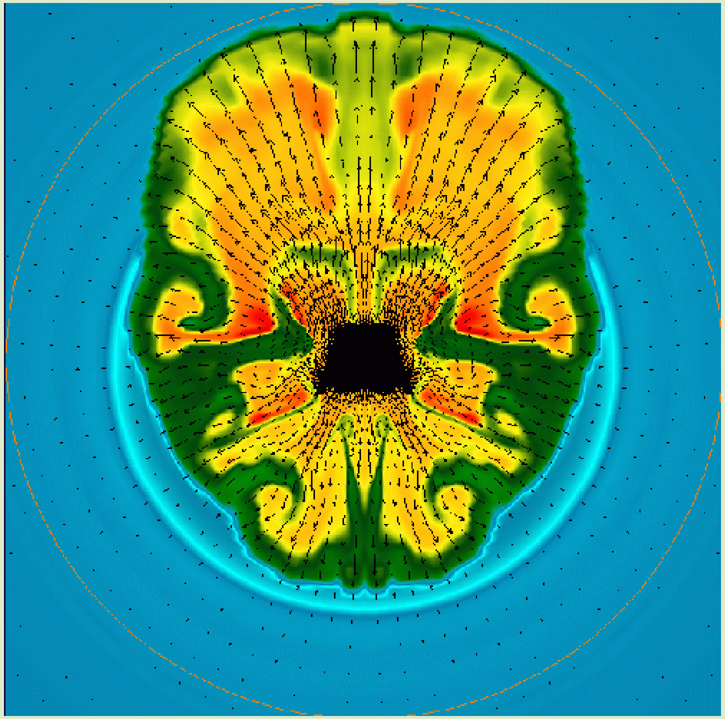
- Anisotropic neutrino emission in core-collapse SNe:
  - **Convective overturn**: small-scale variations.
  - **Rapid rotation**: large-scale anisotropy.
  - **Large-scale asymmetries**: large-scale anisotropy.

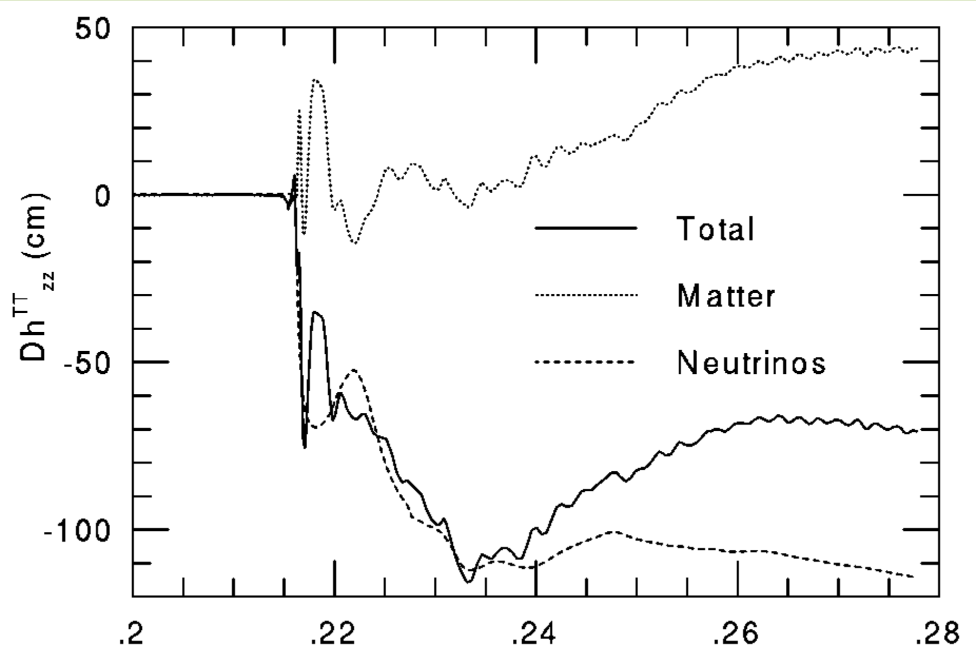




GWs from Aspherical Outflows

[Burrows & Hayes 1996, Fryer et al. 2004; in the MHD context: Kotake et al. 2004, Obergaulinger et al. 2005, 2006]





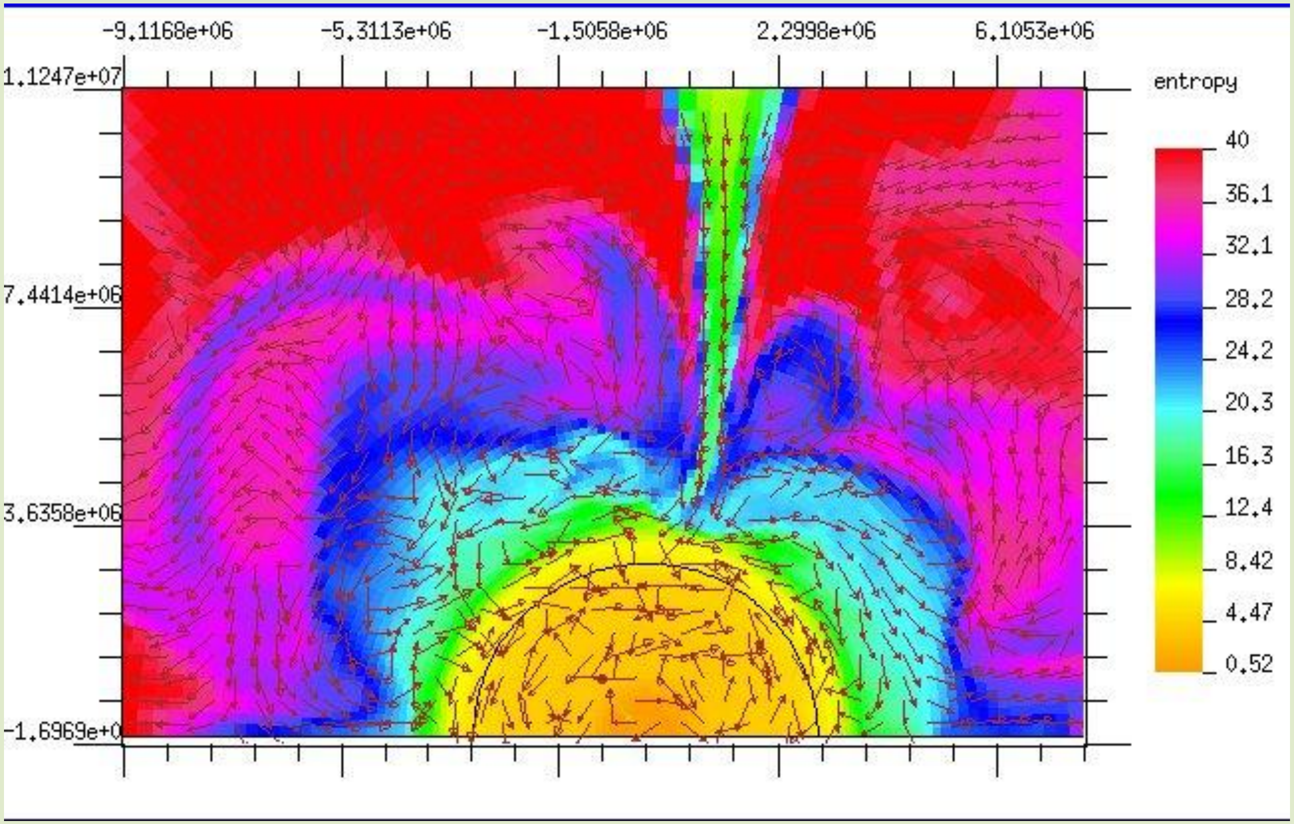
[Burrows & Hayes 1996]

- Precollapse inhomogeneities in nuclear silicon/oxygen burning may be large, leading to density perturbations O(10%). [Bazan & Arnett '97, Meakin et al. '06].
- May result in asymmetric explosions (-> pulsar recoils) and emission of GW burst (with memory!) from mass motions and neutrinos.
- Somewhat unexplored: Only 2 studies; most stellar evolution is done in 1D. Would need large parameter study.
- Aspherical outflows also in jet-driven explosions: See Kei Kotake's talk!

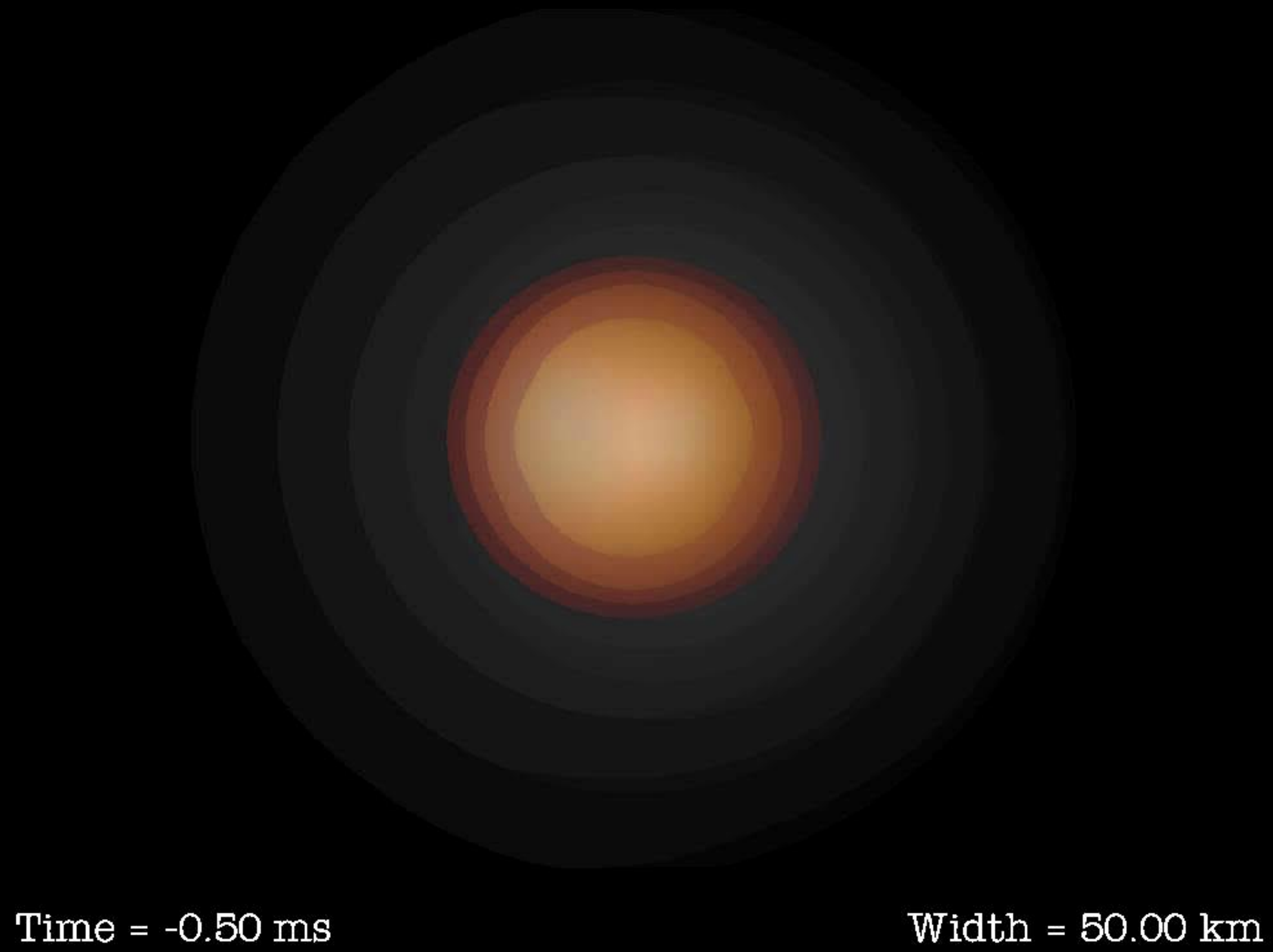
Unstable Protoneutron Star Core g-modes & The Acoustic Supernova Mechanism

[Burrows et al. 2006, 2007b/c, Ott, Burrows et al. 2006]

- SASI-modulated supersonic accretion streams and SASI generated turbulence excite lowest-order (l=1) buoyancy mode in the PNS. Eigenfrequency f $\approx$ 300 Hz $\pm$ 30%.



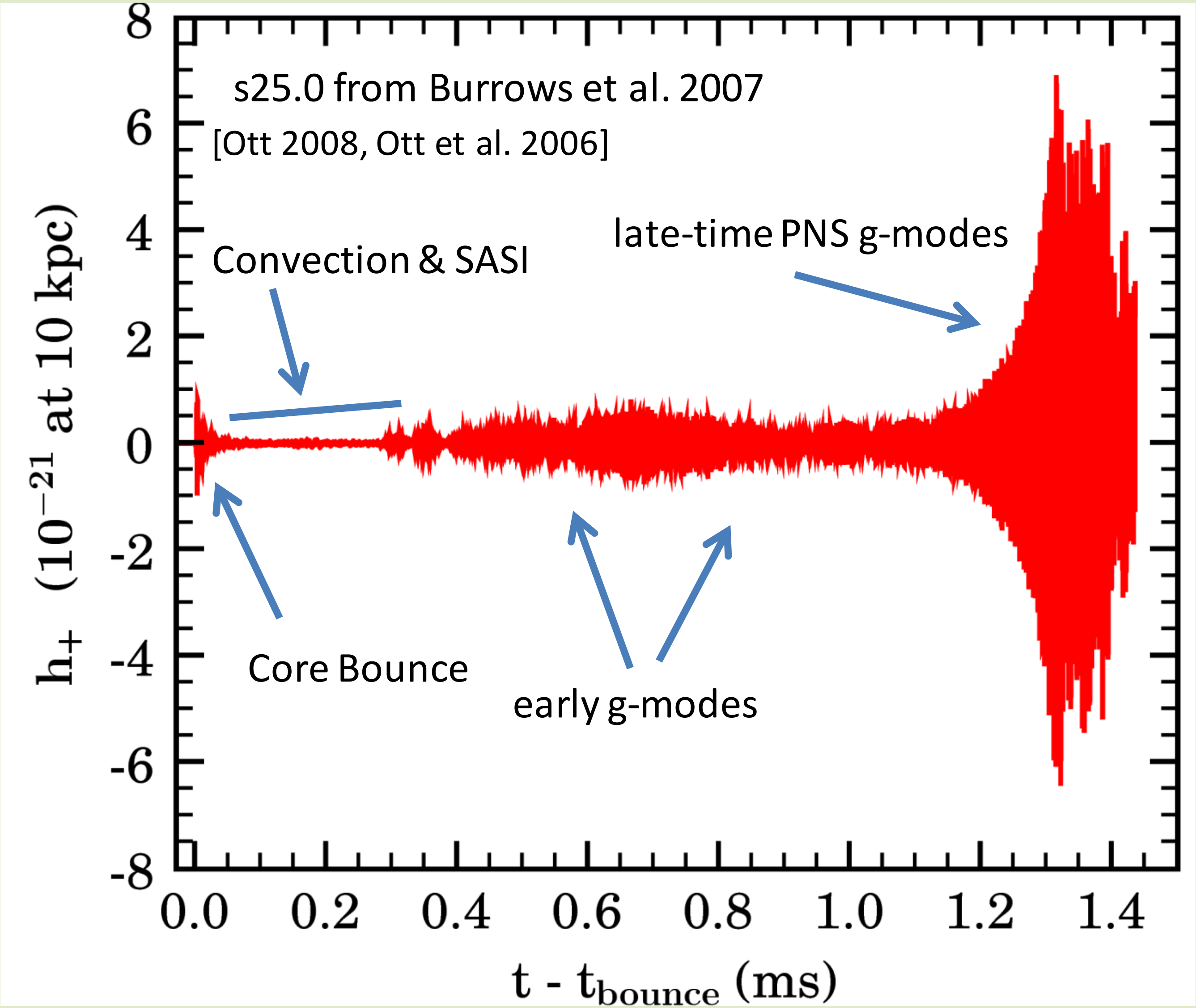
- g-modes reach large amplitudes ~600—1000 ms after bounce.
- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.
- Drive ~1 B explosions at late times.



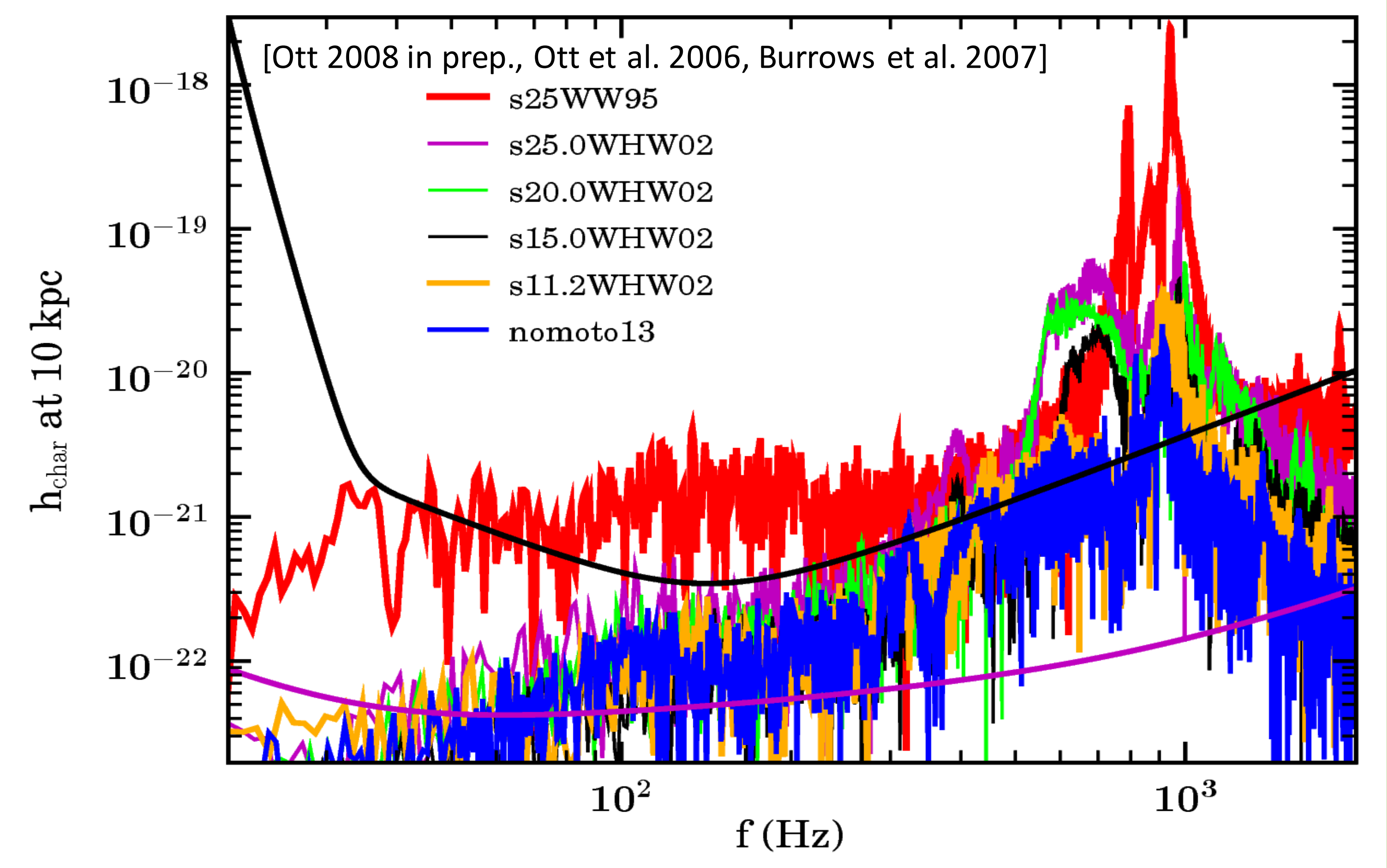
PNS core oscillations, Burrows et al. 2006, 2007; Ott et al. 2006

GWs from PNS core g-modes:
The GW Signature of the Acoustic Mechanism

- Core bounce: Rotation, perturbations, prompt convection.
- Convection: PNS and ν-driven.
- g-modes: l=2 components emit GWs.
- But: g-modes may saturate at low level. [Weinberg & Quatert 2008]

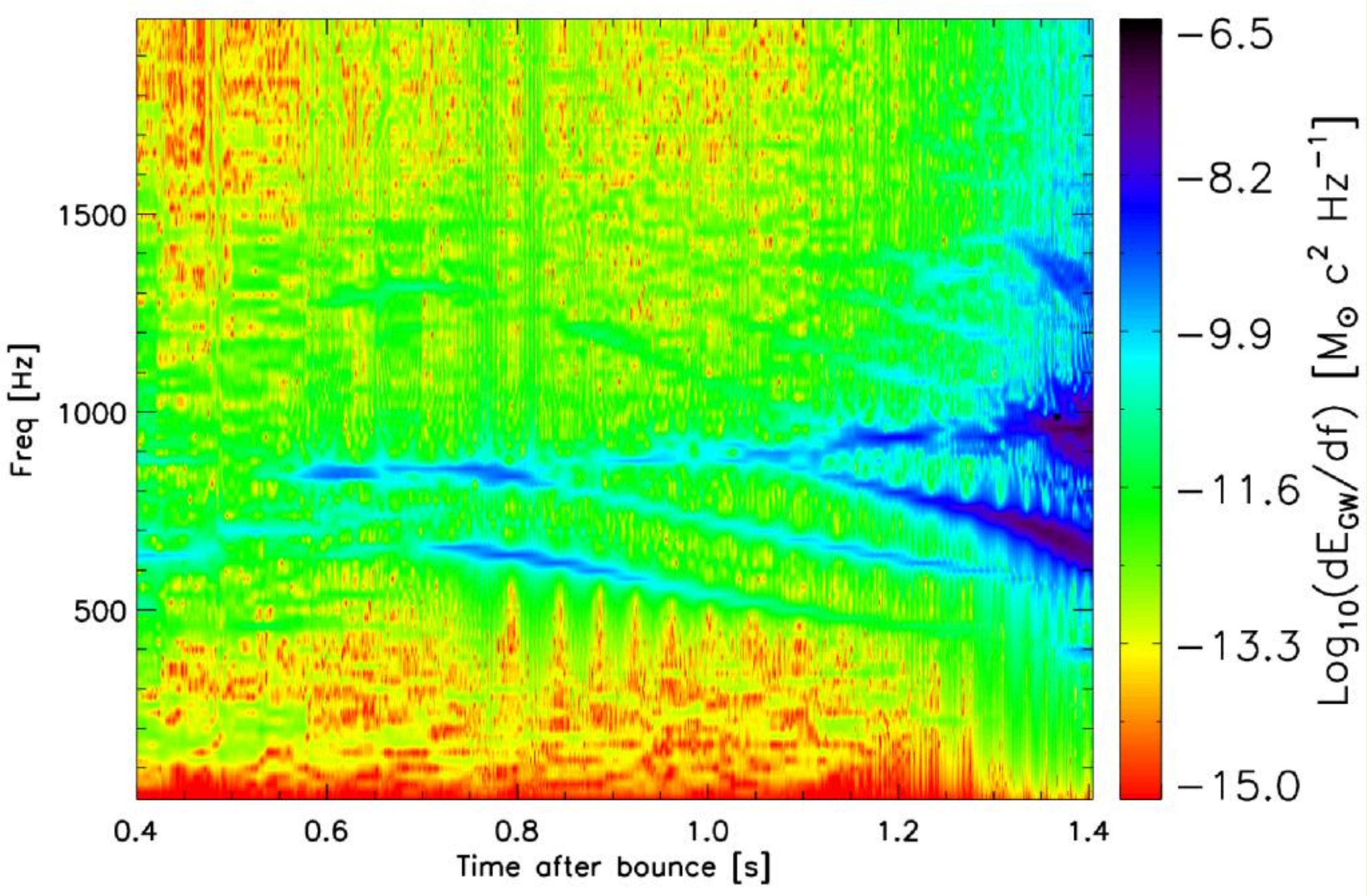


GW Spectra and LIGO Sensitivity



- $E_{GW} \sim 10^{-8} — 10^{-6}\ M_\odot c^2$, one model $8 \times 10^{-5}\ M_\odot c^2$.
- Progenitor mass (= accretion rate) dependence.

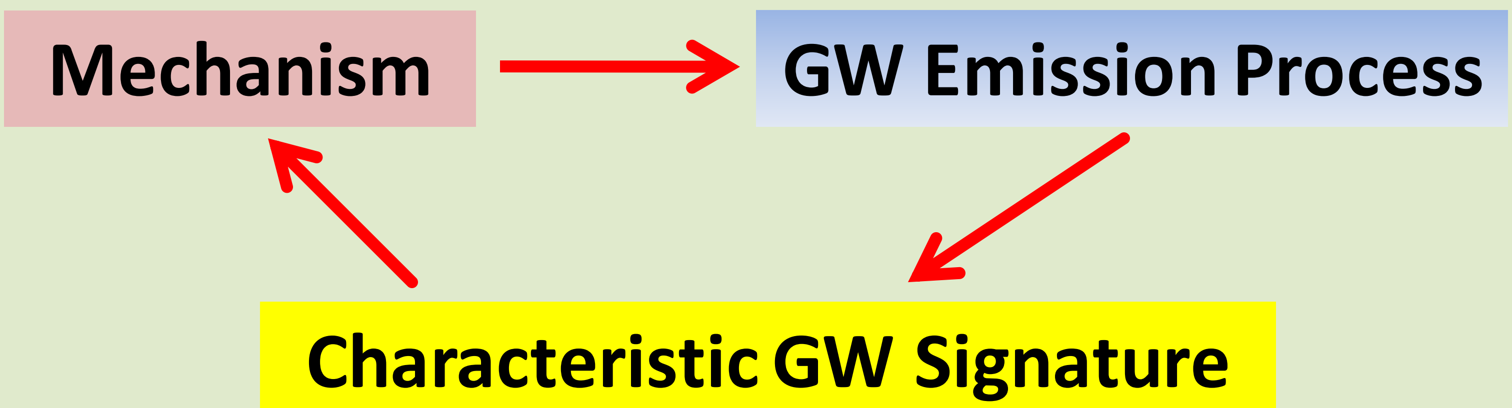
Time-Frequency Analysis of the GW Power Spectrum



Models s15.0WHW02

Putting Things Together:

GWs as Indicators for the Core-Collapse Supernova Explosion Mechanism



GWs as Indicators for the SN Mechanism

Mechanism / Feature	MHD Mechanism	Acoustic Mechanism	Neutrino Mechanism
Progenitor Rotation	fast, $P_0 < 4$ s	none/slow	none/slow
Core Bounce GWs			
Convection/ SASI GWs			
Neutrino GWs			
Rotational 3D Instability GWs			
PNS g-mode GWs			

GWs as Indicators for the SN Mechanism

Mechanism / Feature	MHD Mechanism	Acoustic Mechanism	Neutrino Mechanism
Progenitor Rotation	**fast, $P_0 < 4$ s**	**none/slow**	**none/slow**
Core Bounce GWs	**strong**		
Convection/ SASI GWs	none/weak		
Neutrino GWs	large h, low energy		
Rotational 3D Instability GWs	**strong, though competition with MRI**		
PNS g-mode GWs	none		

GWs as Indicators for the SN Mechanism

Mechanism / Feature	MHD Mechanism	Acoustic Mechanism	Neutrino Mechanism
Progenitor Rotation	**fast, $P_0 < 4$ s**	**none/slow**	**none/slow**
Core Bounce GWs	**strong**	none/weak	
Convection/ SASI GWs	none/weak	moderate	
Neutrino GWs	large h, low energy	moderate h, low energy	
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- Galactic SN necessary with LIGO I, Advanced LIGO: Local Group
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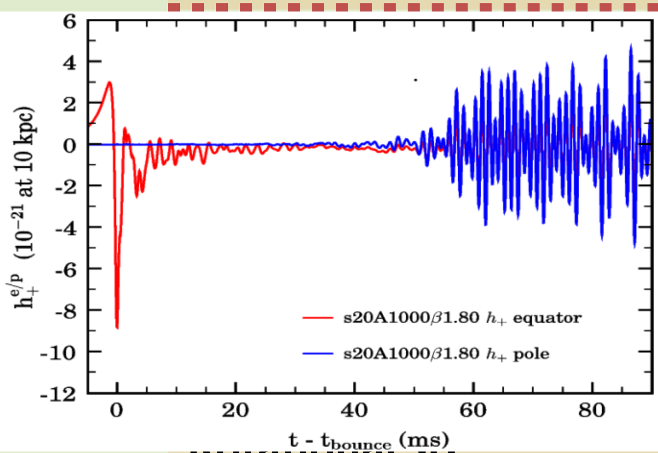

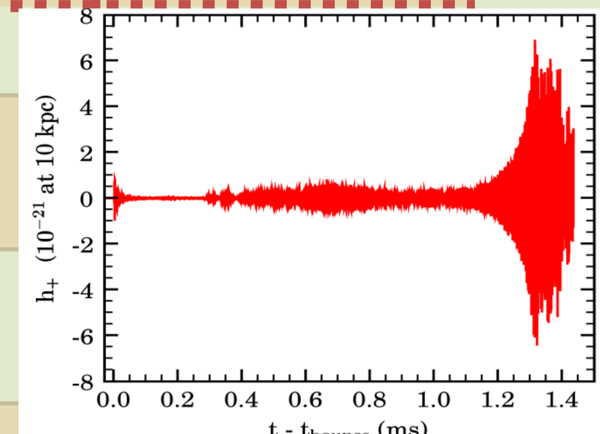

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The Sad Truth
or
Supernova Rates and The Reach of LIGO.

Core-Collapse Supernova Rates

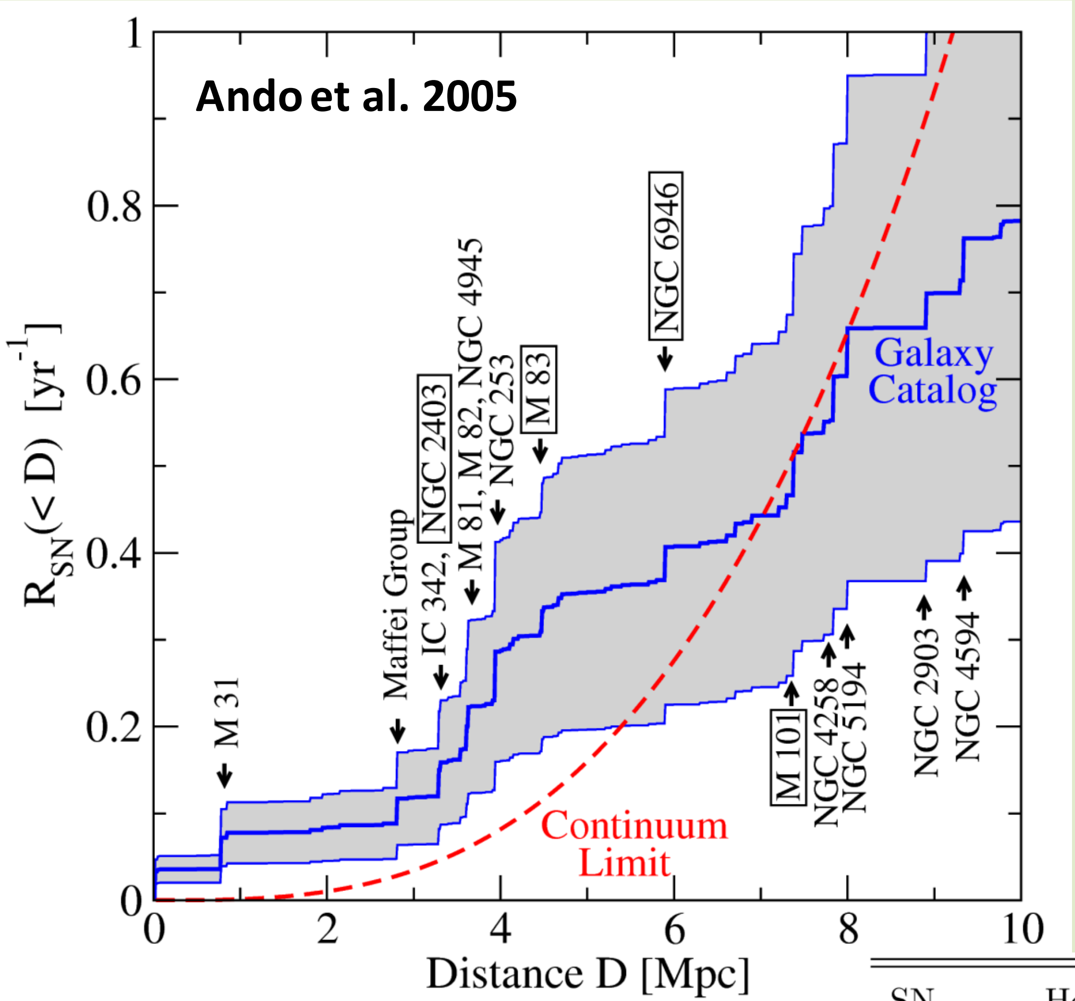
- Local group of galaxies: V $\sim$ 30 Mpc^3
  - Milky Way, Andromeda (M31), Triangulum (M33) + $\sim$30 small galaxies/satellite galaxies (incl. SMC & LMC).

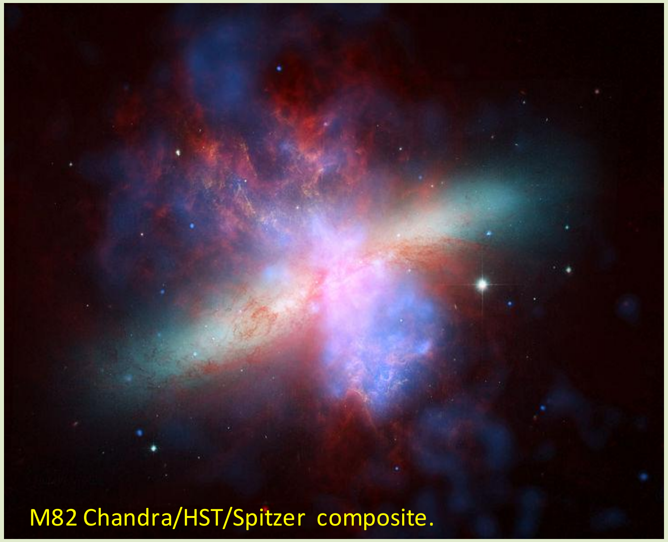
Galaxy	Distance (kpc)	Core-Collapse SN Rate $(100\ \text{yr})^{-1}$
Milky Way	0–$\sim$15	0.50–2.50
LMC	$\sim$50	0.10 – 0.50
SMC	$\sim$60	0.06 – 0.12
M31	$\sim$770	0.20 – 1.20
M33	$\sim$840	0.16 – 0.68
IC 10	$\sim$750	0.05 –0.11
IC 1613	$\sim$770	$\sim$0.04
NGC 6822	$\sim$520	$\sim$0.04

Compiled from long list of references, e.g. Cappellaro et al., den Bergh & Tammann.

- Local group: worst case 1 SN in 90 years, best case 1 SN in 20 years.
- Most local group events with $\sim$100 kpc from Earth.
- Next jump in rate around M82 at 3.5 Mpc.

Nearby Core-Collapse Supernovae





M82 Chandra/HST/Spitzer composite.

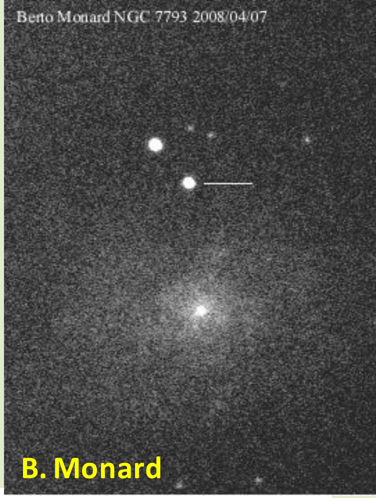
M31 (Andromeda) Spitzer.

Core-collapse SNe within 5 Mpc since the beginning of LIGO operations:

[Ott 2008 in prep.]

SN	Host Galaxy	Date	Type	Distance
2008bk	NGC 7793	20080325 [132]	II-P	~ 3.9 [133]
2005af	NGC 4945	20050208 [134]	II-P	~ 3.6 [133]
2004dj	NGC 2403	20040731 [135]	II-P	~ 3.3 [133]
2004am	M 82	20040305 [136]	II-P	~ 3.5 [137]
2002kg	NGC 2403	20021026 [138]	IIn	~ 3.3 [133]

SN 2008bk



- SN 2008bk (type II-p) discovered on 03/25/08. Core collapse between 02/15 and 03/05.
- LIGO L1 & H1 and VIRGO down for upgrades. LIGO H2 and GEO600 in Astrowatch mode.

Process	Model	LIGO2 4 km	LIGO L1/H1	LIGO H2	GEO600	VIRGO
Rotating Collapse	s11A2O13 [20]	0.124	0.008	0.005	0.001	0.009
& Bounce	s20A2O09 [20]	0.130	0.008	0.006	< 0.001	0.010
	s40A3O12 [20]	0.214	0.024	0.013	< 0.001	0.018
Rotational Instability	s20A2B4 [44, 52]	0.319	0.021	0.014	0.003	0.022
	s20A2B4 (×5) [44, 52]	0.713	0.047	0.031	0.007	0.049
PNS g-modes	s11.2 [21]	0.147	0.006	0.005	0.002	0.009
	s15.0 [21]	0.454	0.021	0.015	0.006	0.027
	s25.0 [21]	0.612	0.029	0.020	0.007	0.037
	s25.0 (×2)[21]	0.866	0.041	0.029	0.009	0.052
	s25WW [22]	5.331	0.217	0.151	0.057	0.328

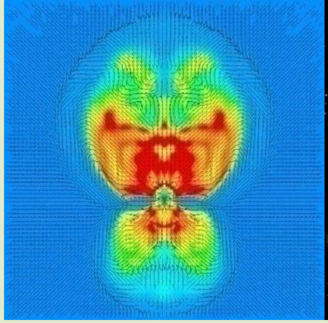
$$S/N = \sqrt{\int_0^\infty d\ln f \, \frac{h_{\mathrm{char}}^2}{h_{\mathrm{rms}}^2}}$$

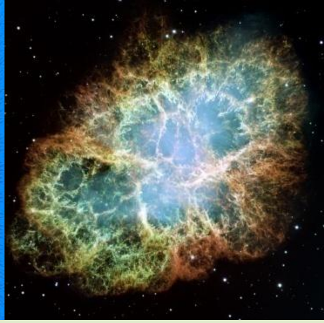
[Ott 2008]

Thanks:
Erik Katsavounidis &
Michael Landry

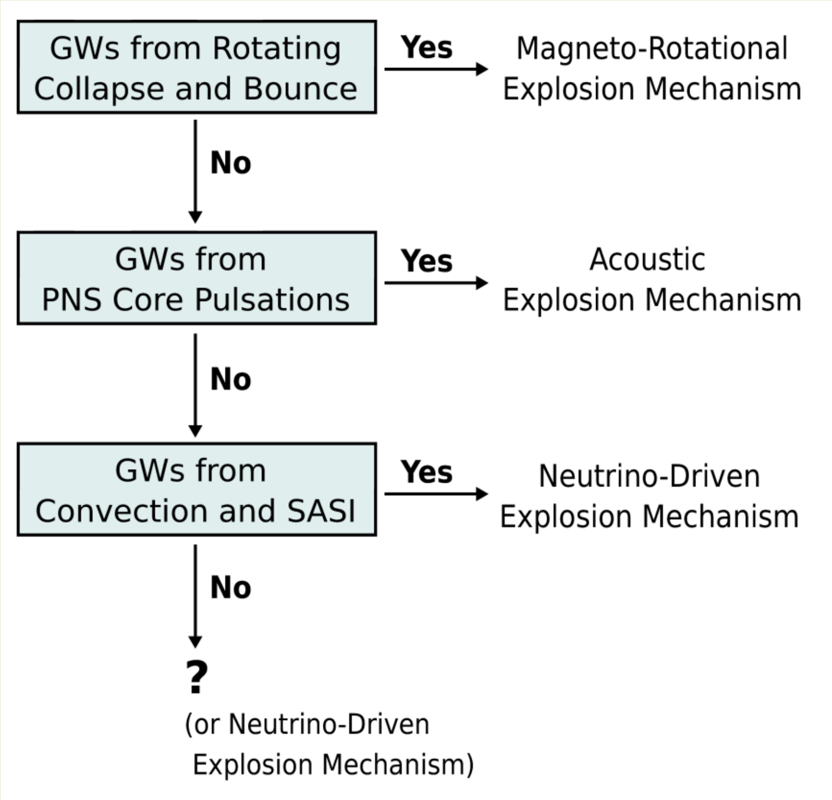
- H2 & GEO600 should not have seen anything. Burst-search underway.
- Even LIGO 2 would have had trouble seeing a core-collapse SN at 4 Mpc.

Summary & Conclusions





- There are at least 3 ways in which simulations manage to blow up massive stars.
- Mechanisms sufficiently different to allow a schematic "decision diagram" based on GW observations:



- Gravitational waves from a galactic/SMC/LMC SN may help constrain the explosion mechanism. More distant SNe can help set upper limits.
- Rotating collapse/bounce waveforms becoming robust; other emission processes need more & better modeling.