Stellar Collapse, Core-Collapse Supernovae and Gravitational Waves

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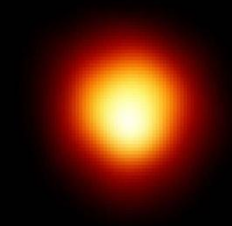
Plan of this Talk

- Introduction: The Core-Collapse Supernova Problem
- Supernova Mechanisms
  - Neutrino Mechanism
  - MHD/Magnetorotational Mechanism
  - Acoustic Mechanism
- **Remarks on Black Hole Formation**
- **Gravitational Waves from Stellar Collapse, Core-Collapse Supernovae and Protoneutron Stars:**
  - GW emission mechanisms.
  - How to probe the core-collapse supernova explosion mechanism with GWs.

Betelgeuse as seen by the HST, D $\approx$ 200 pc

Rigel, D $\approx$240 pc



Betelgeuse as seen by the HST, D $\approx$ 200 pc

Rigel, D $\approx$240 pc

SN1987A, LMC, D $\approx$ 51.4 kpc
Progenitor: BSG Sanduleak -69° 220a, 18 M_{SUN}

- < 1 SN/40 years in the Milky Way
- < 2-3 SN/100 years in the Local Group
- **> 1 SN/2 years at D ~ 3-5 Mpc.**

The Core-Collapse Scenario

- $M_{ZAMS} \geq 7$—$10\ M_{Sun}$
- Nuclear fusion up to O/Ne or iron-group nuclei.
- O/Ne or Iron core: electron degenerate, Chandrasekhar-mass object; $P \approx K\rho^{4/3} + P_{\rm thermal}$
- Effective Chandrasekhar mass:

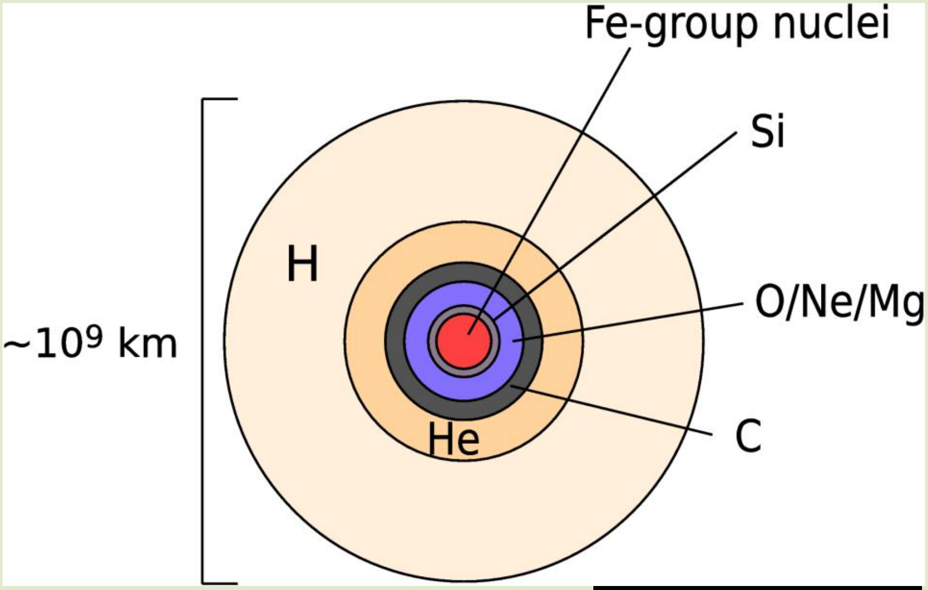
$$M_{\rm Ch} \approx 5.38\, Y_e^2 \left[1 + \frac{s_e^2}{\pi k_{\rm B} Y_e}\right] M_\odot$$

~1.4 – 2 M_{SUN}.

- Onset of gravitational collapse when pushed over effective M_{Ch}:

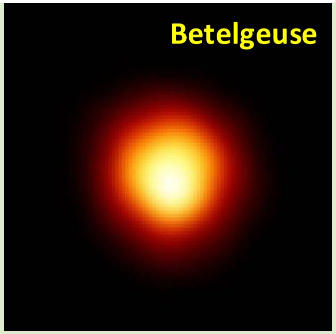
$$e^- + p \overset{(W)}{\rightarrow} \nu_e + n$$

$$\gamma + {}^{56}_{26}\mathrm{Fe} \rightleftharpoons 13\alpha + 4n$$



- Conditions in the core at collapse:

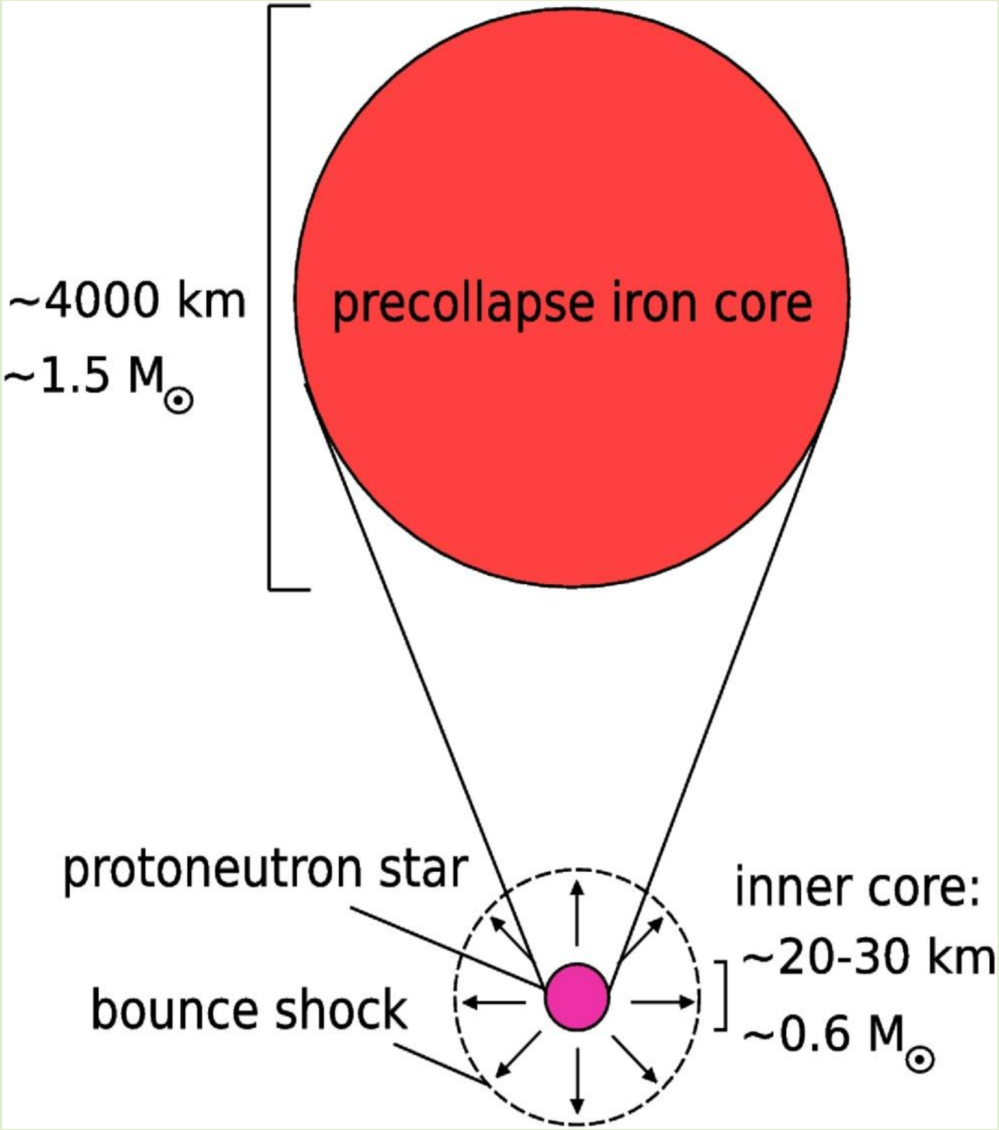
$\rho_c \approx 10^{10}$ g/cm^3
$T \approx 0.6 - 0.5$ MeV
$Y_e \approx 0.43 - 0.48$



Collapse and Bounce

- Collapse separates iron core into homologously ($v \propto r$) collapsing **inner core** and supersonically collapsing **outer core**.
- EOS stiffens at ρ_{nuc}: Core rebounds ("core bounce"); hydrodynamic bounce shock.
- Shock loses kinetic energy to **dissociation** + **neutrinos**: -> **Shock stalls**.

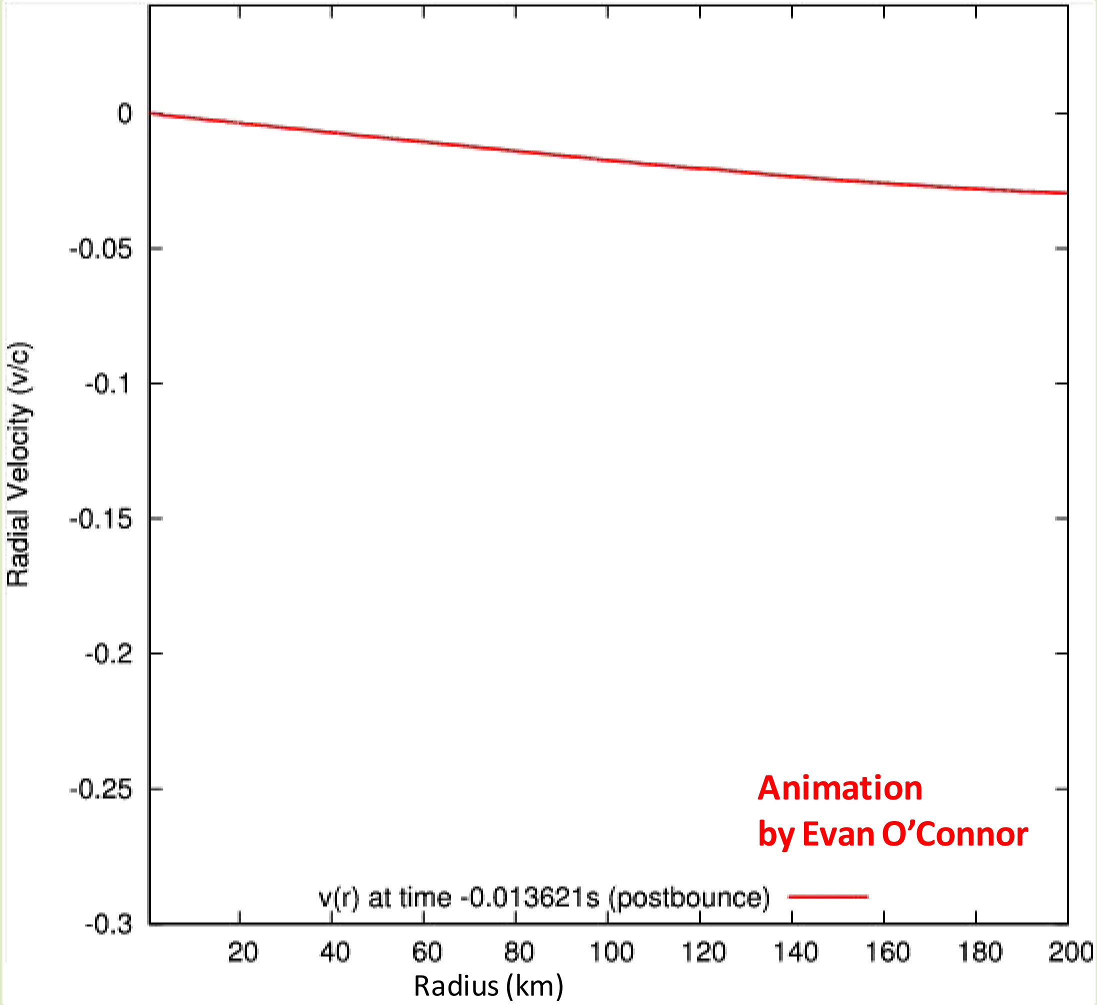
$\rho_c \approx 3 \times 10^{14}$ g/cm^3
$T \approx 5 - 10$ MeV
$s \approx 1 - 2\ k_B$/baryon
$Y_e \approx 0.25 - 0.30$
$M_{PNS} \approx 0.6\ M_{SUN}$



The Supernova Problem

E_{Grav} = 300 [B]ethe (3 x 10^{53} erg)
$E_{Explosion}$ = 1 B
$E_{Neutrinos}$ = 99% E_{Grav} ≈ 15% $M_{SUN}c^2$

Any explosion mechanism must tap the gravitational energy reservoir and convert the necessary fraction into energy of the explosion.



- Shock always stalls (no 'prompt' hydrodynamic explosions).
- Shock **revival** and SN explosion or **collapse to BH** (collapsar/GRB?).
- **What is the mechanism of shock revival?**

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Introduced by:

Mechanism	Introduced by
Neutrino Mechanism	[Colgate & White 1966, Arnett 1966, Wilson 1985, Bethe & Wilson 1985]
Magnetorotational Mechanism	[LeBlanc & Wilson 1970, Bisnovatyi-Kogan et al. 1976, Meier et al. 1976, Symbalisty 1984]
Acoustic Mechanism	[proposed by Burrows et al. 2006, 2007; not (yet?) confirmed by other groups/codes]

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The Neutrino Mechanism

[Wilson 1985, Bethe & Wilson 1985; recent reviews: Kotake et al. 2006, Janka et al. 2007]

- Neutrino cooling: $Q_\nu^- \propto T^6$
- Neutrino heating: $Q_\nu^+ \propto L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$
- **Neutrino mechanism**: Based on subtle imbalance between neutrino **heating** and **cooling** in the postshock region.

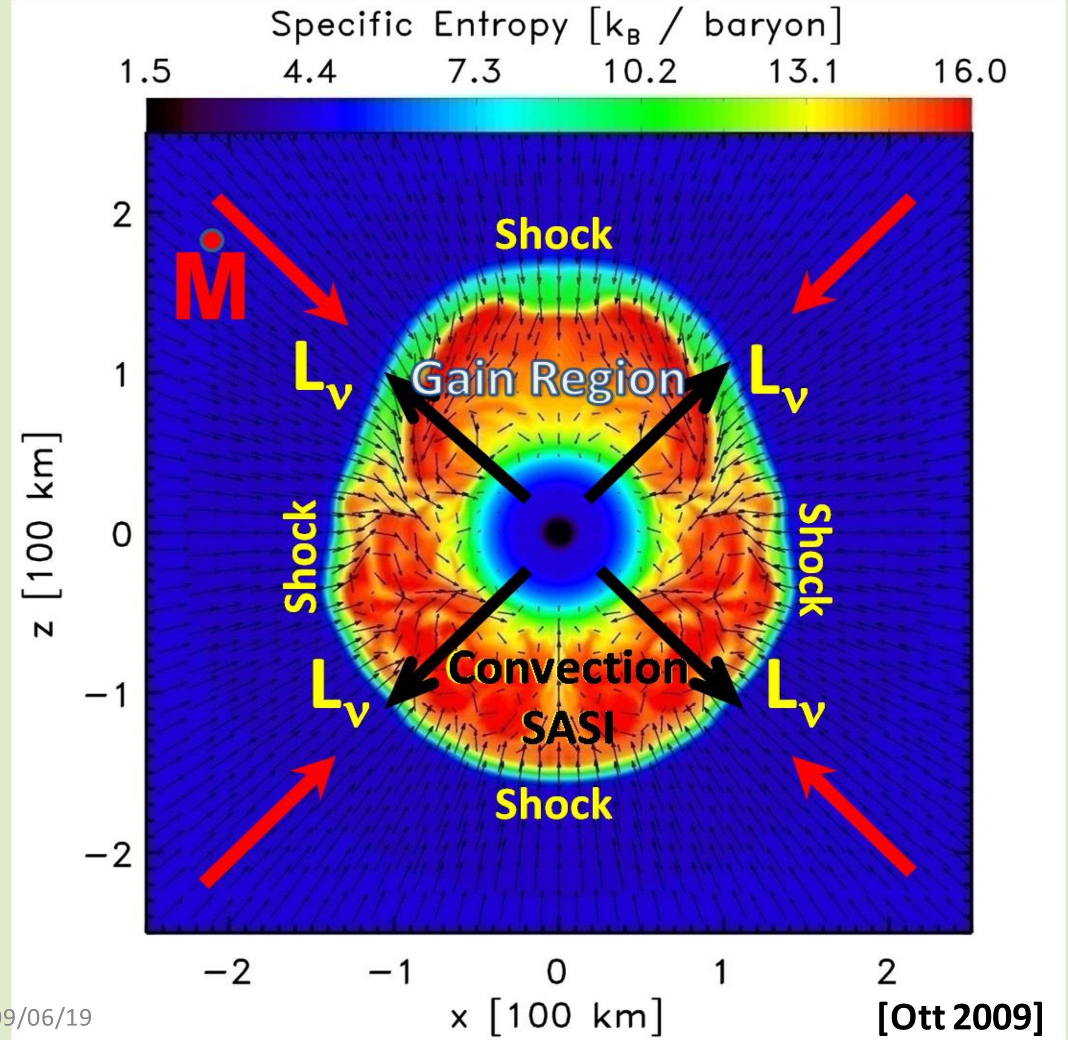
Net heating where:

$$Q_\nu^+ > Q_\nu^-$$

Problem: **Fails to explode massive stars in spherical symmetry.**

[Thompson et al. 2003, Rampp & Janka 2002, Liebendörfer et al. 2002,2005]

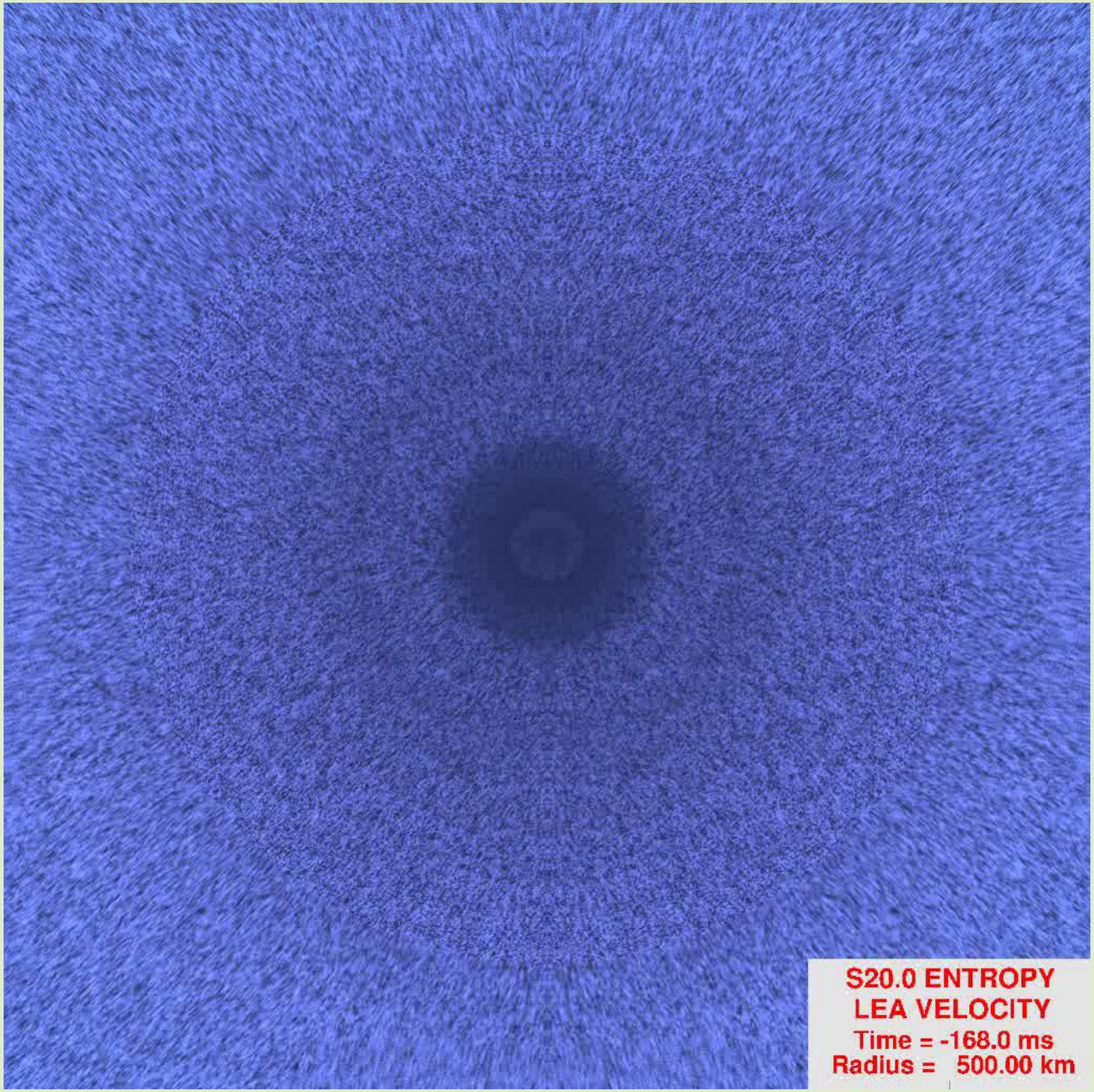
Breaking of spherical symmetry is a key ingredient of the supernova mechanism!



[Ott 2009]

Standing Accretion Shock Instability

[Blondin et al. '03,'06; Foglizzo et al. '06, Scheck et al. '06, '07, Burrows et al. '06, '07,
Kotake et al. '07, '09, Iwakami et al. '08, '09]



Advective-acoustic cycle drives shock instability.

Seen in simulations by all groups!

Status of the Neutrino Mechanism

- Works for low-mass massive stars in spherical symmetry (1D): O-Ne cores with ZAMS M≤ 9 M_{SUN}. [Kitaura et al. 2006, Burrows 1988, Burrows et al. 2007c]
- **Dessart et al. '06,'07**: 2D works in the case of accretion-induced collapse (AIC) of White Dwarfs to Neutron Stars.
- **Marek & Janka 2009**: 2D + soft equation of state (EOS) + pseudo-general-relativistic (GR) potential + ray-by-ray neutrino transport. **-> late, weak explosion in 11.2 and 15 M_{SUN} stars.**
- **Mezzacappa, Bruenn et al. [unpublished, private communication]**: 2D + soft EOS + pseudo-GR potential + ray-by-ray MGFLD neutrino transport. **-> early, strong explosions** (in disagreement with Marek & Janka?)
- **Ott et al. 2008: Outcome insensitive to neutrino transport details, but no neutrino-driven explosions in best VULCAN/2D simulations.**

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

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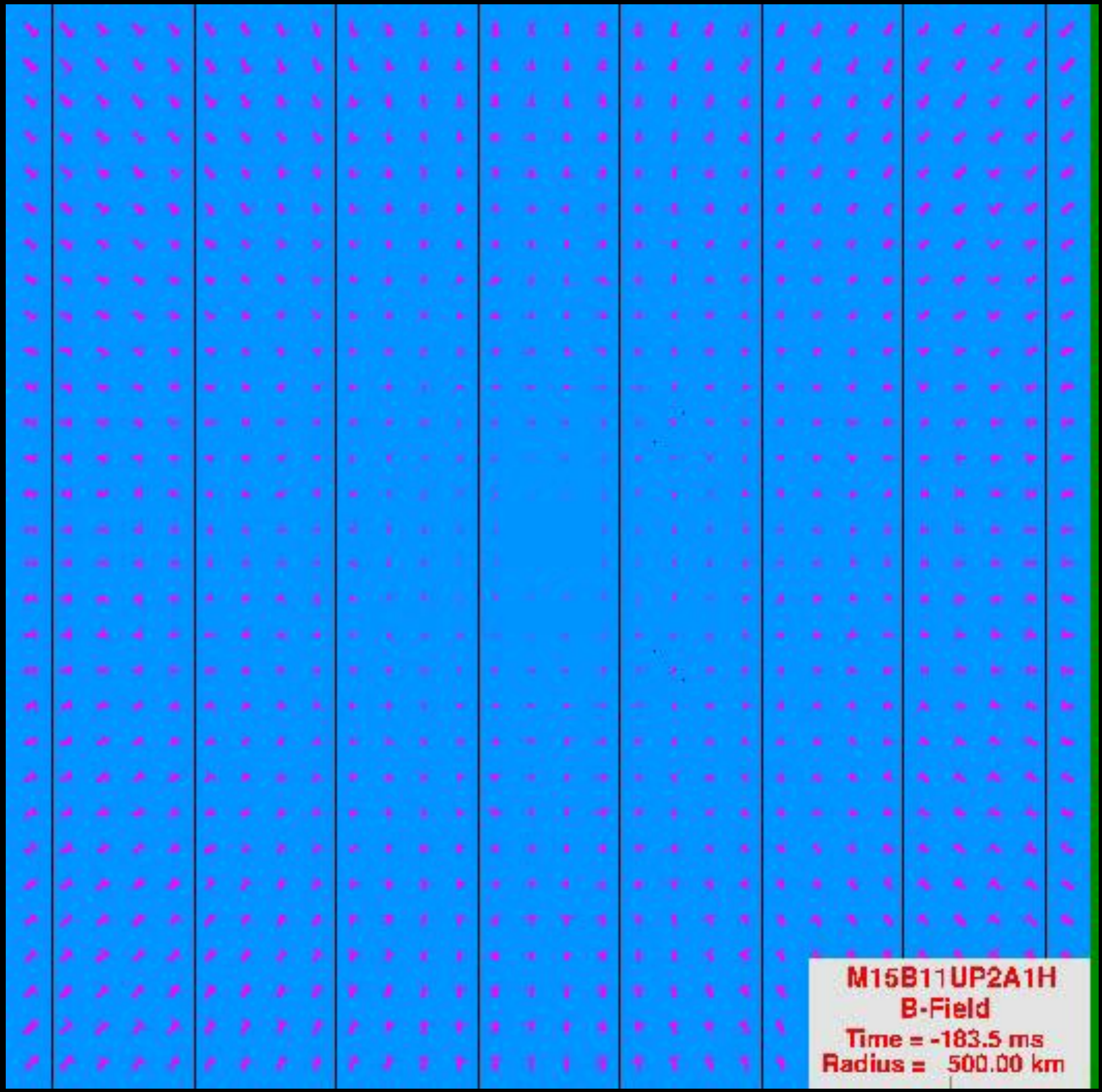
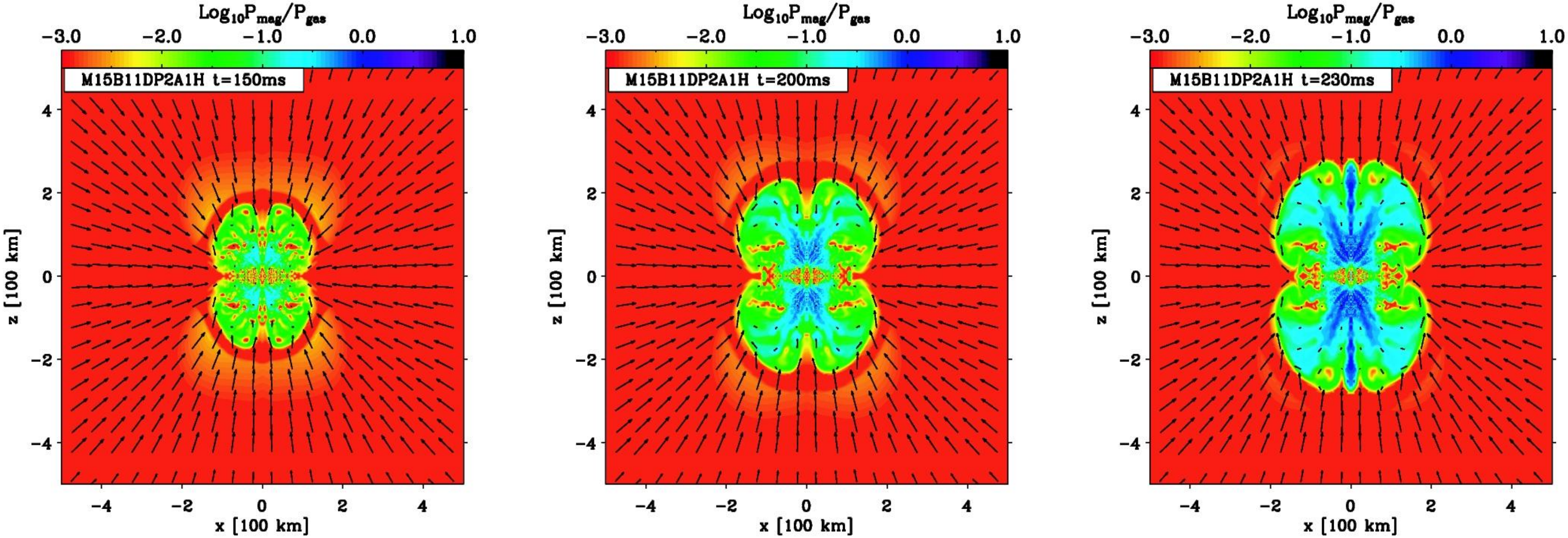
MHD-driven Explosions

[e.g., Burrows et al. 2007, Dessart et al. 2008, Kotake et al. 2004, Yamada & Sawai 2004, Sawai et al. 2008, Takiwaki et al. 2009]

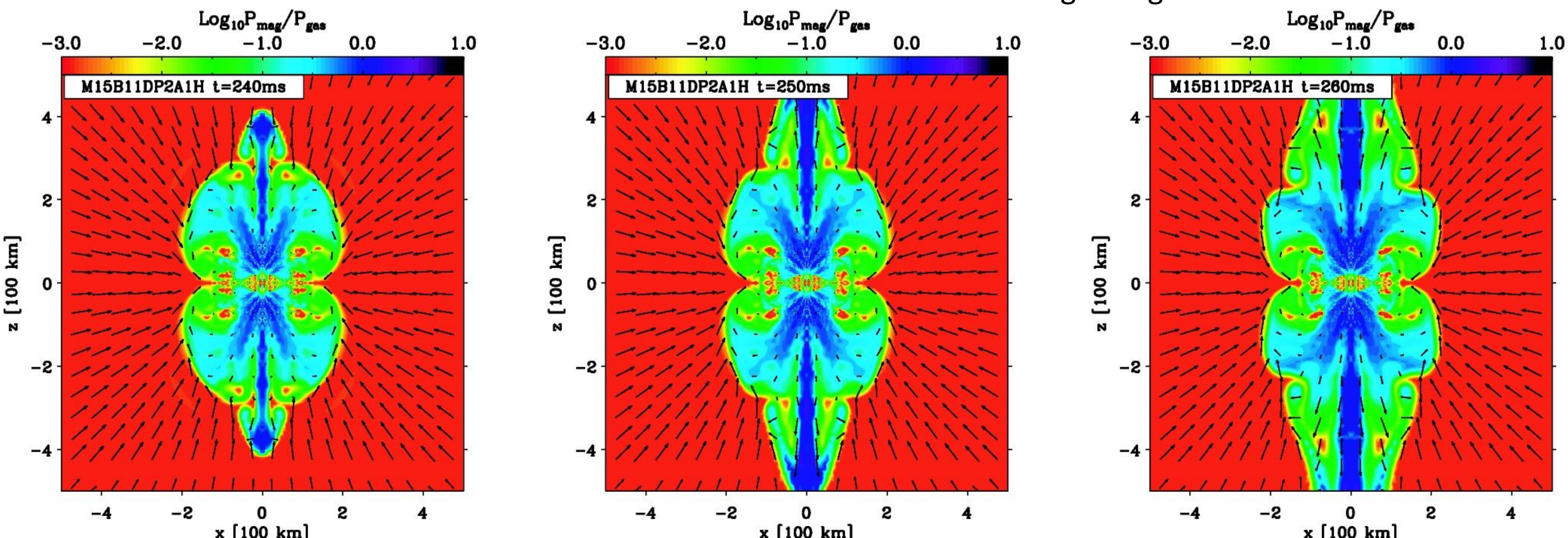
- **Rapid rotation**:
  P_0 < 4-6 s
  -> millisecond PNS
- PNS rotational energy: ~10 B
- Amplification of B fields up to equipartition:
  - compression
  - dynamos
  - magneto-rotational instability (MRI)
- Jet-driven outflows.
- MHD-driven explosion may be GRB precursor.



VULCAN 2D R-MHD code, Livne et al. 2007, Burrows et al. 2007.

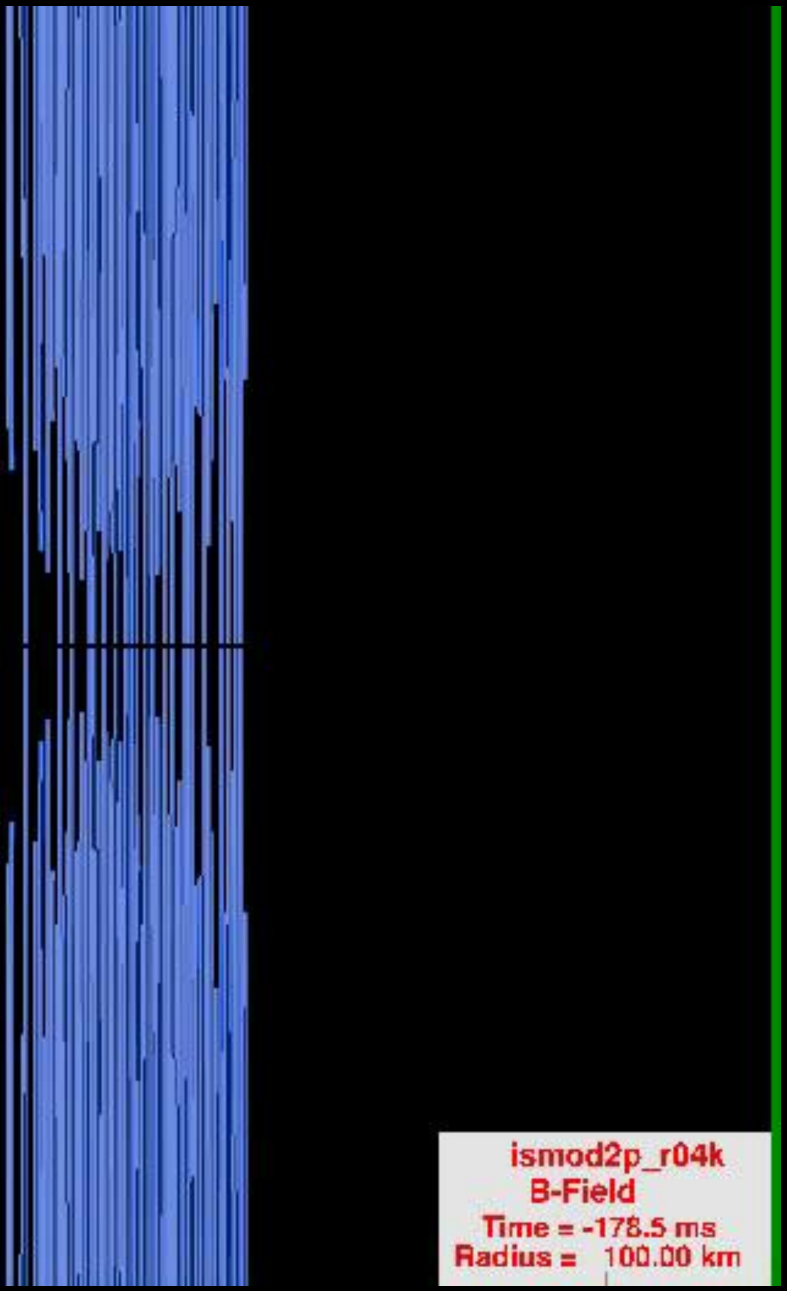


MHD jet/explosion launched when $P_{mag} / P_{gas} \sim 1$



Newtonian
Radiation-MHD
Simulations with
VULCAN/2D

Magnetic field lines in
M15B11UP2A1H of
Burrows, Dessart,
Livne, Ott, Murphy '07.



Features/Limitations of the Magnetorotational Mechanism

[Burrows et al. 2007]

- Jet powers up to 10 B/s (10^{52} erg/s).
- **Simultaneous explosion and accretion**.
- **Hypernova** energies (> 10 B) attainable.
- MHD mechanism inefficient for cores with precollapse P_0 > 4 s, but stellar evolution + NS birth spin estimates: **P_0 > 30 s in most cores**.

  [Heger et al. 2005, Ott et al. 2006]
- MHD explosion — a GRB precursor?
- Limitations: Resolution does not allow to capture MRI in VULCAN/2D; Simulations 2D and Newtonian.

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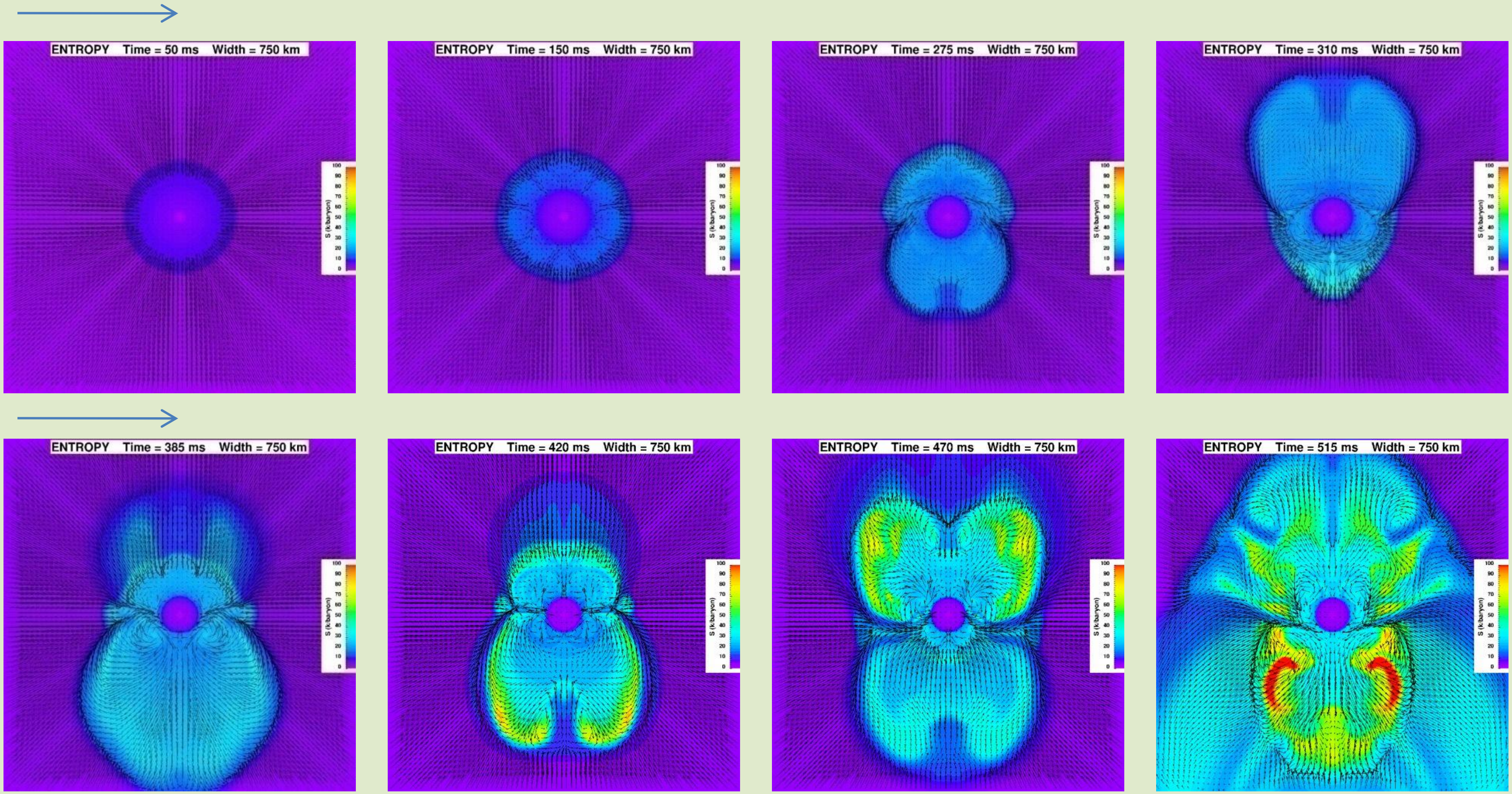
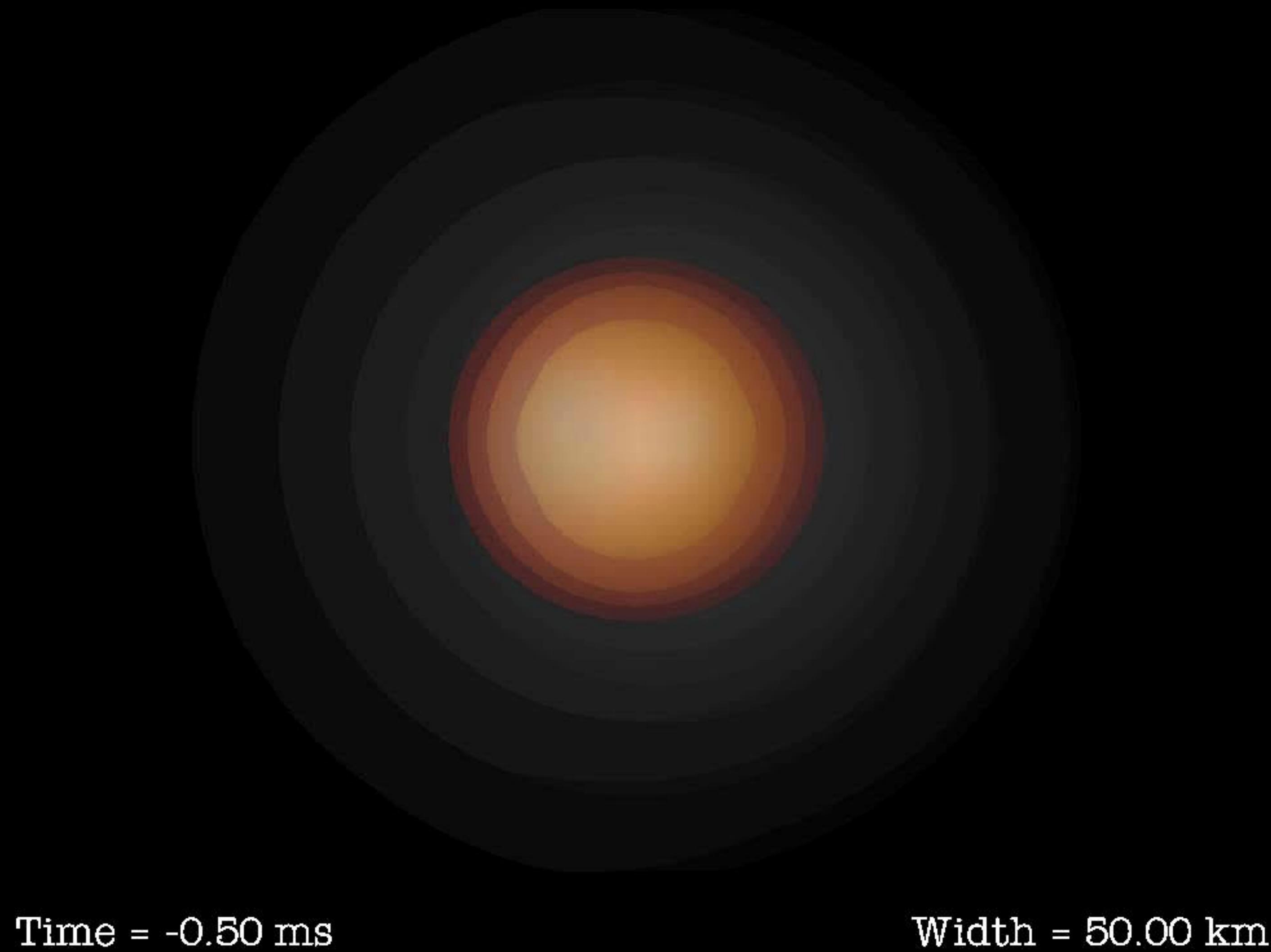
Setting the Stage: SASI

[e.g., Burrows et al. 2006, 2007bc, Ott et al. 2006]



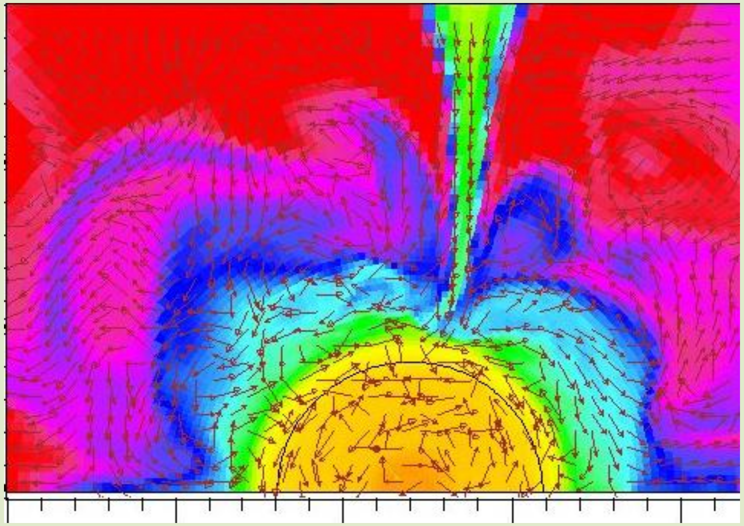


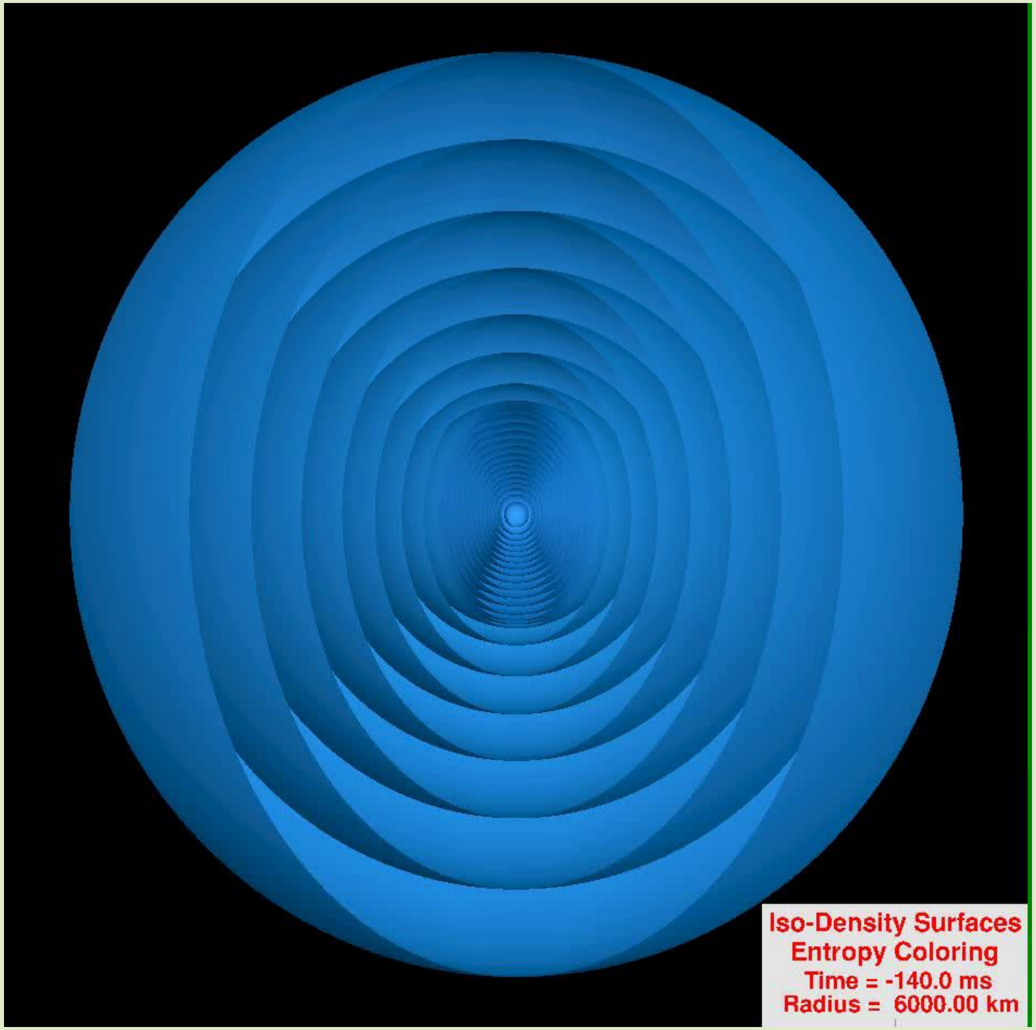
PNS core oscillations, Burrows et al. 2006, 2007; Ott et al. 2006

Acoustic Mechanism

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

- SASI-modulated supersonic accretion streams and SASI generated turbulence excite lowest-order (l=1) g-mode in the PNS. f ≈ 300 Hz.



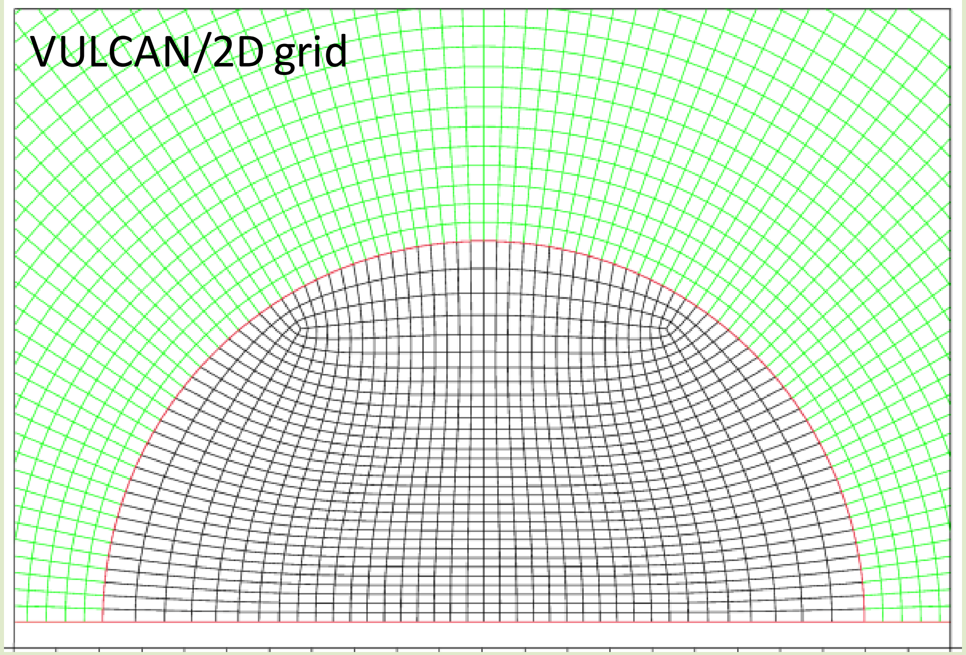


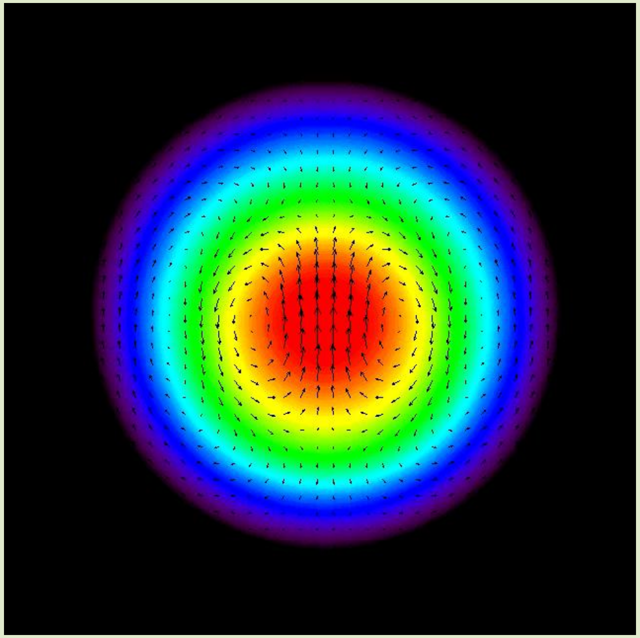
- g-modes reach large amplitudes ~500 ms —1 s after bounce.
- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.
- ~1 B explosions at late times.
- (1) hard to simulate; unconfirmed, (2) **possible parametric instability, limiting mode amplitudes.** [Weinberg & Quatert'08]

Testing the Acoustic Mechanism

- So far no independent confirmation of the acoustic mechanism.
- However: unstable physical g-modes PNS shown to exist.

  [Ferrari et al. 2003, 2007; Yoshida et al. 2007]
- Key questions:
  - Do g-mode reach amplitudes as high as seen in our calculations?
  - Can the neutrino mechanism be made to work generically?
  - Effects of GR and 3D?
- Fundamental prerequisite for non-linear numerical tests of g-mode excitation: Grid must be singularity free & allow change of the inner core's geometric



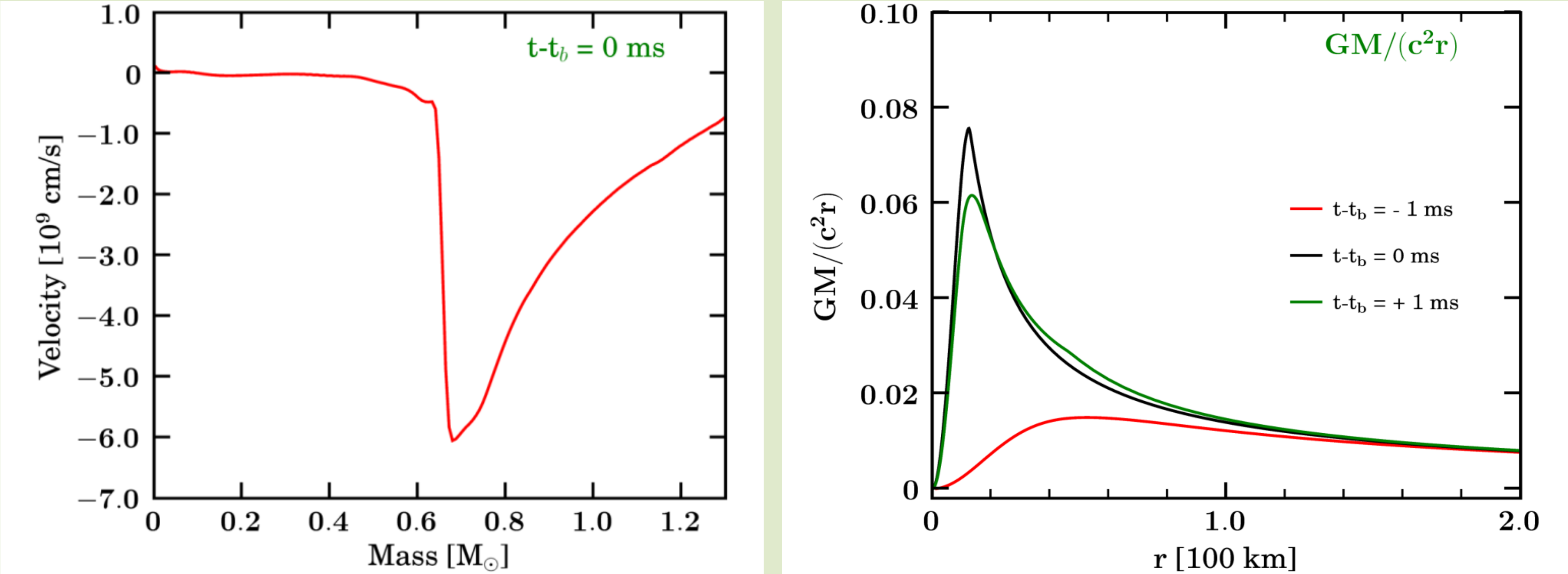


A Few Words on
Black Hole Formation

Black Hole Formation in Stellar Collapse

[O'Connor, Ott & Phinney in preparation]

1) There is no direct/prompt BH formation:



- Generic: $M_{IC} = M_{PNS}$ at bounce ≈ 0.5 – 0.7 M_{SUN}. **Set by nuclear physics, electron capture and rotation**.
- Inner core easily stabilized by stiff core of the nuclear force (+ nucleon degeneracy).

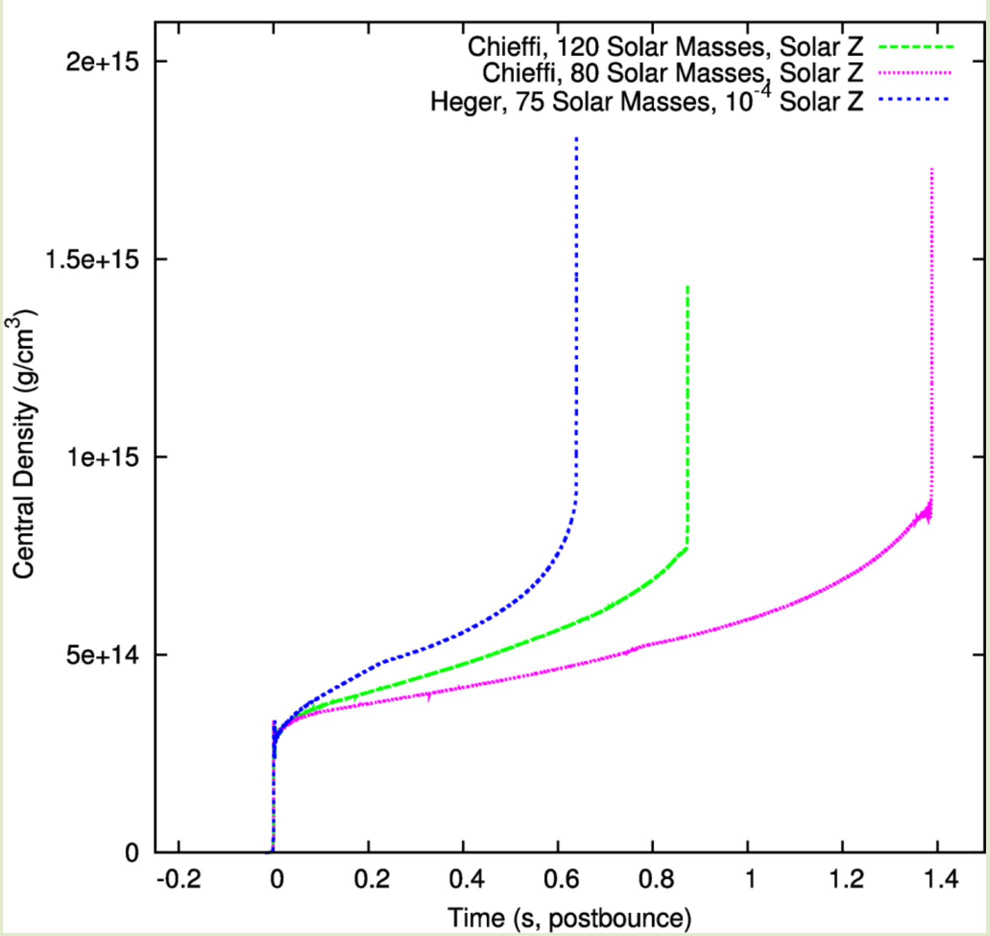
Black Hole Formation in Stellar Collapse

[O'Connor, Ott & Phinney in preparation]

1) There is no direct/prompt BH formation.

2) Route 1 to a BH: ***Collapsar Type I*** [Heger et al. 2003]

- Explosion fails.
- BH forms on accretion timescale. τ_{BH} determined by
  (1) Stiffness of the nuclear EOS.
  (2) Accretion rate
  <- progenitor structure.

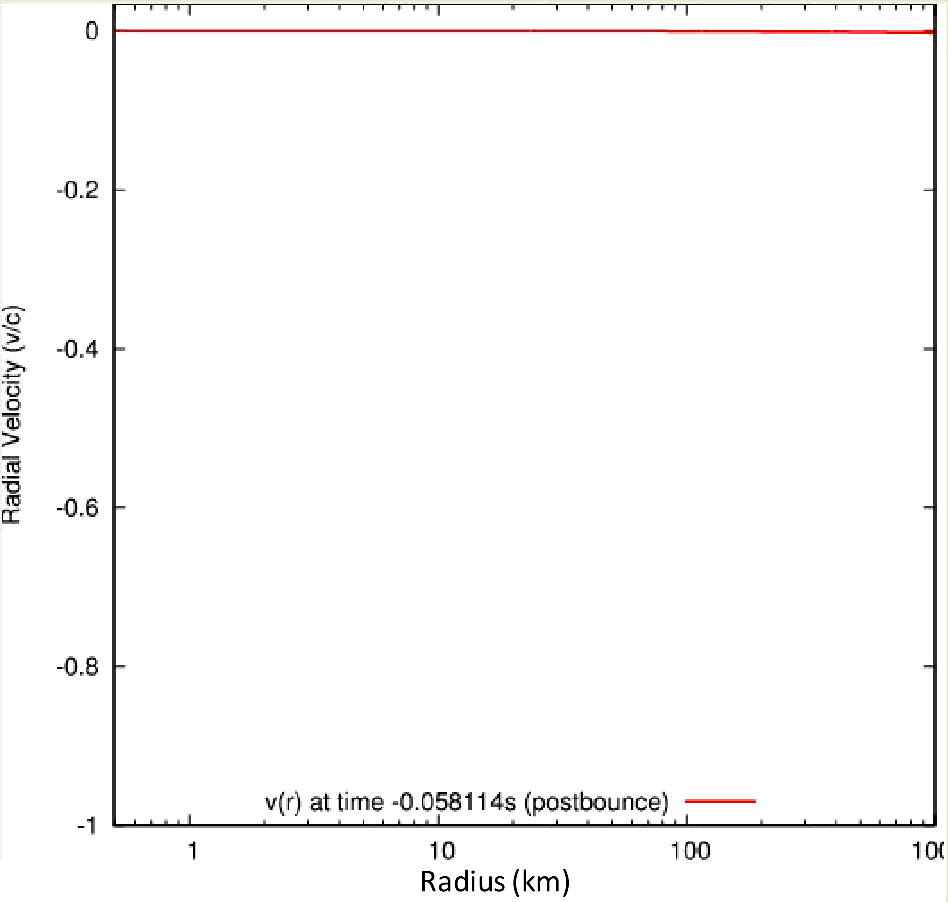


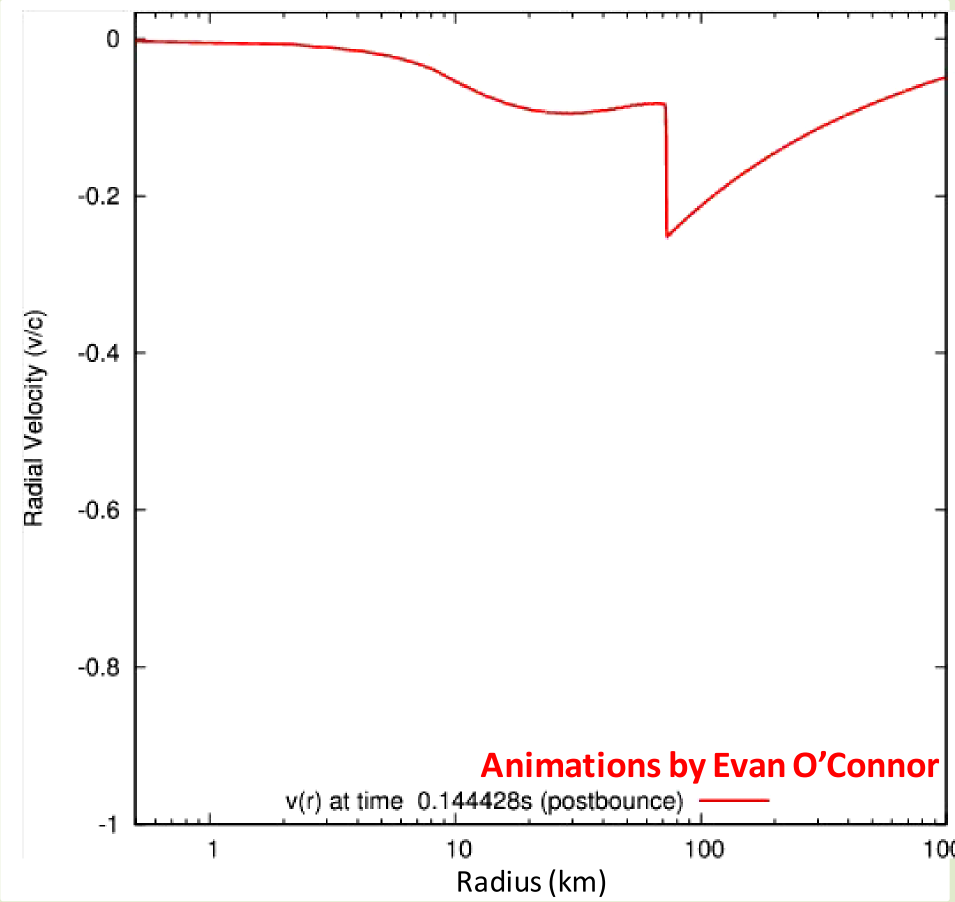
3) Route 2 to a BH: ***Collapsar Type II***

- Weak explosion, subsequent fall-back accretion. [Zhang & Woosley 2008]

Simulations of Black Hole Formation in Failing Core-Collapse Supernovae

[O'Connor, Ott & Phinney in preparation, see also Sumiyoshi et al. 2006, 2007, 2008, Fischer et al. 2009]



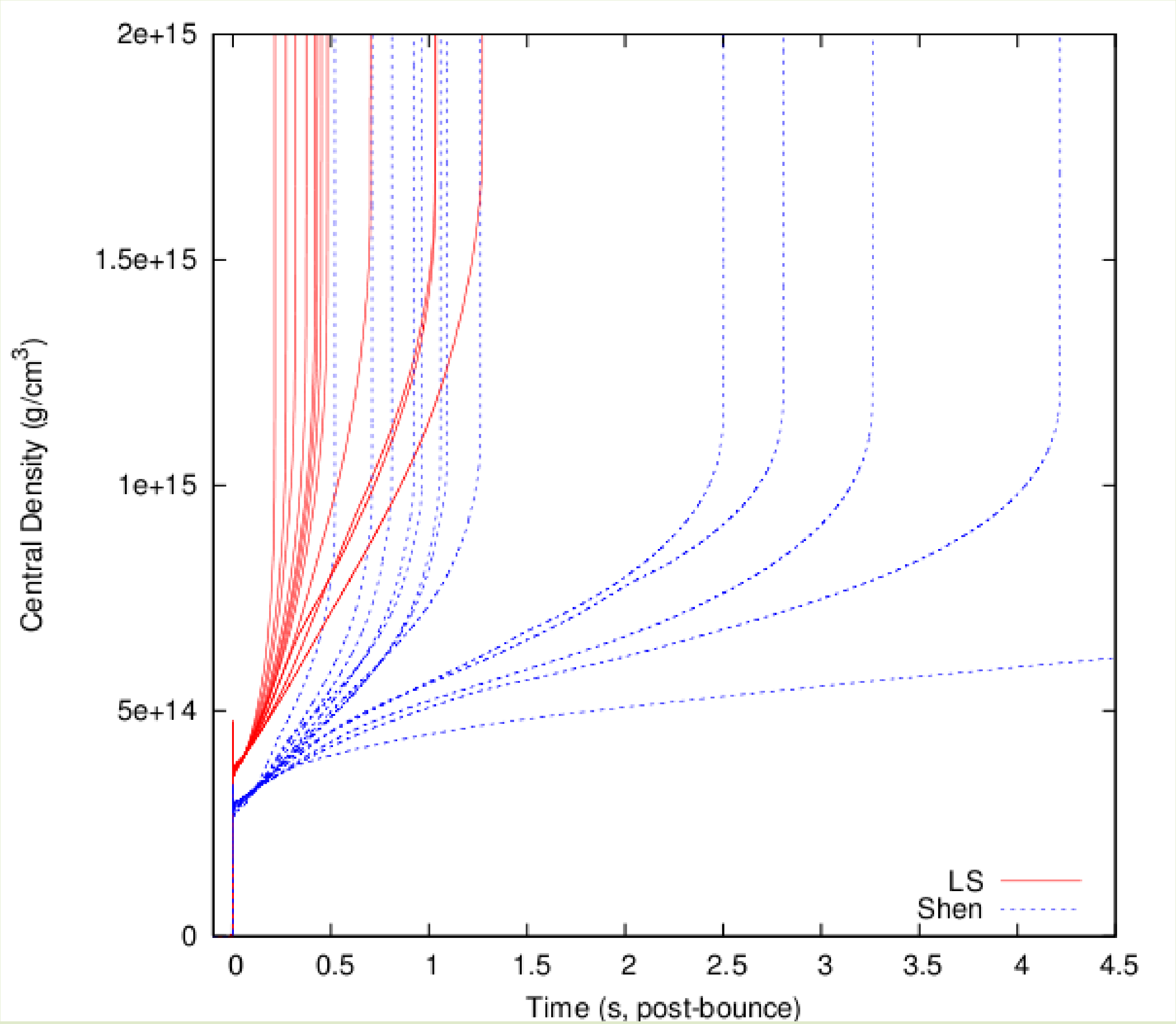


- **Parameter study underway in 1D**: Dependence on progenitor structure/mass, metallicity, nuclear EOS stiffness, neutrino heating.

Simulations of Black Hole Formation in Failing Core-Collapse Supernovae

[O'Connor, Ott & Phinney in preparation, see also Sumiyoshi et al. 2006, 2007, 2008, Fischer et al. 2009, Sekiguchi & Shibata 2005, 2008]

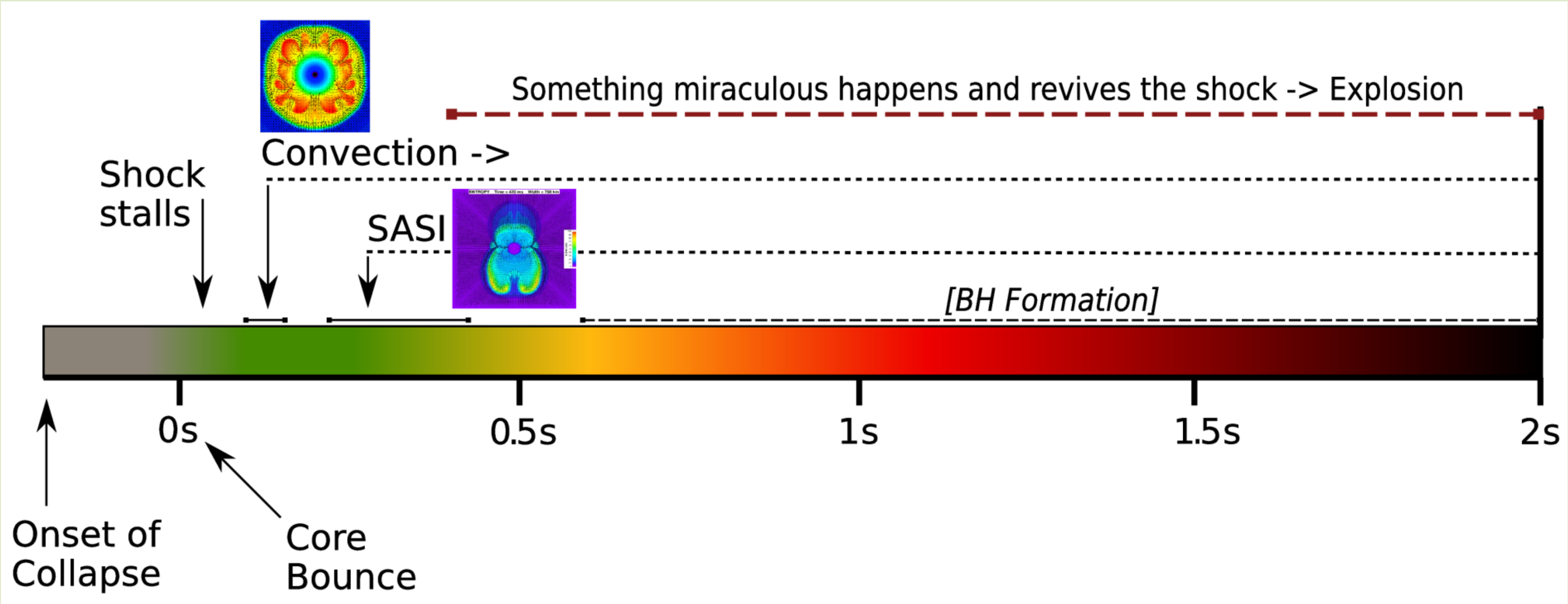
- **Some preliminary results:**



Gravitational Waves from Stellar Collapse, Core-Collapse Supernovae and Protoneutron Stars

[Ott 2009a , Class. Quant. Grav. and Ott 2009b, arXiv:0905.2797]

A SN Theorist's GW Wishlist



- **Explosion mechanism** and its multi-D nature.
- Finite-temperature nuclear EOS.
- PNS structure and evolution to NS.
- PNS/NS magnetic fields.
- PNS rotation; birth spin of NSs.
- Black hole formation.

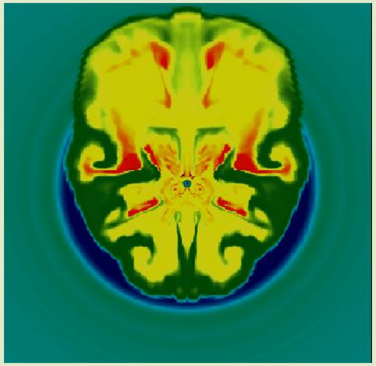
- Progenitor physics:
  - Nature: AIC, O/Ne, or Iron core.
  - Structure, rotational configuration.
  - Precollapse asphericities.

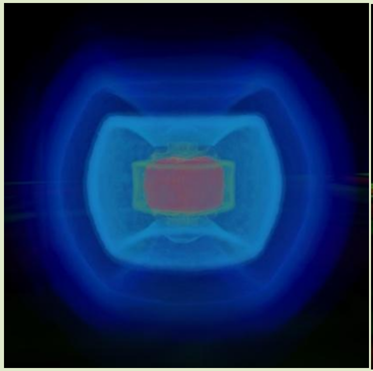
GW Emission Processes in Core-Collapse SNe

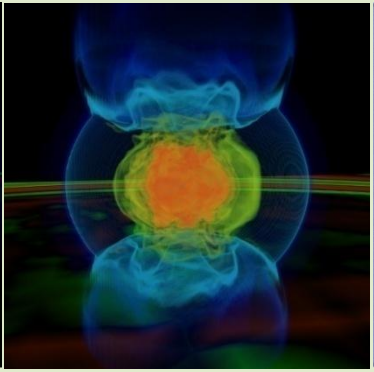
[Reviews: Kotake et al. 2006, Ott 2009]

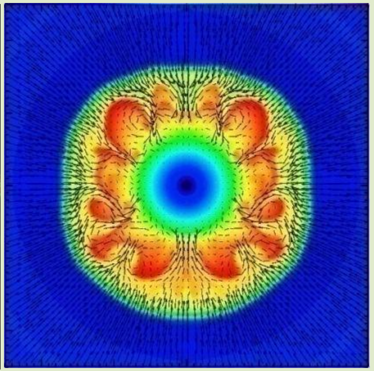
- Rotating core collapse and core bounce
- Dynamical rotational 3D instabilities
- Postbounce convection and SASI
- Protoneutron star core pulsations
- BH formation
- Anisotropic neutrino emission
- Aspherical outflows
- Magnetic stresses

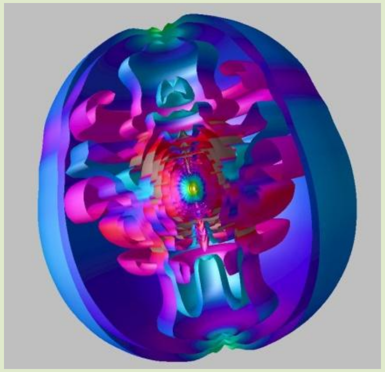
Bursts with "Memory"

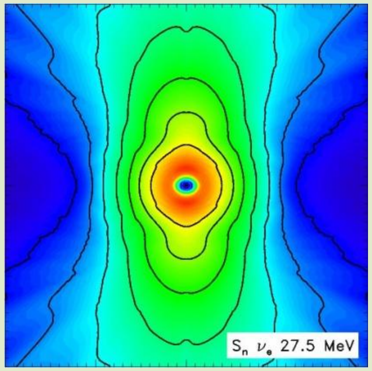








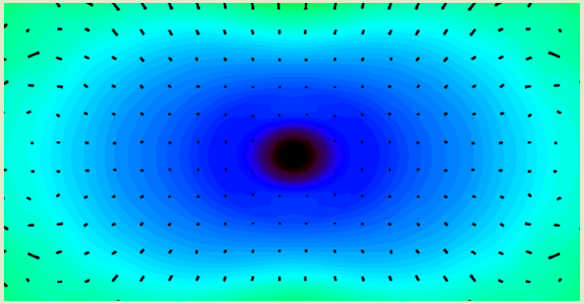




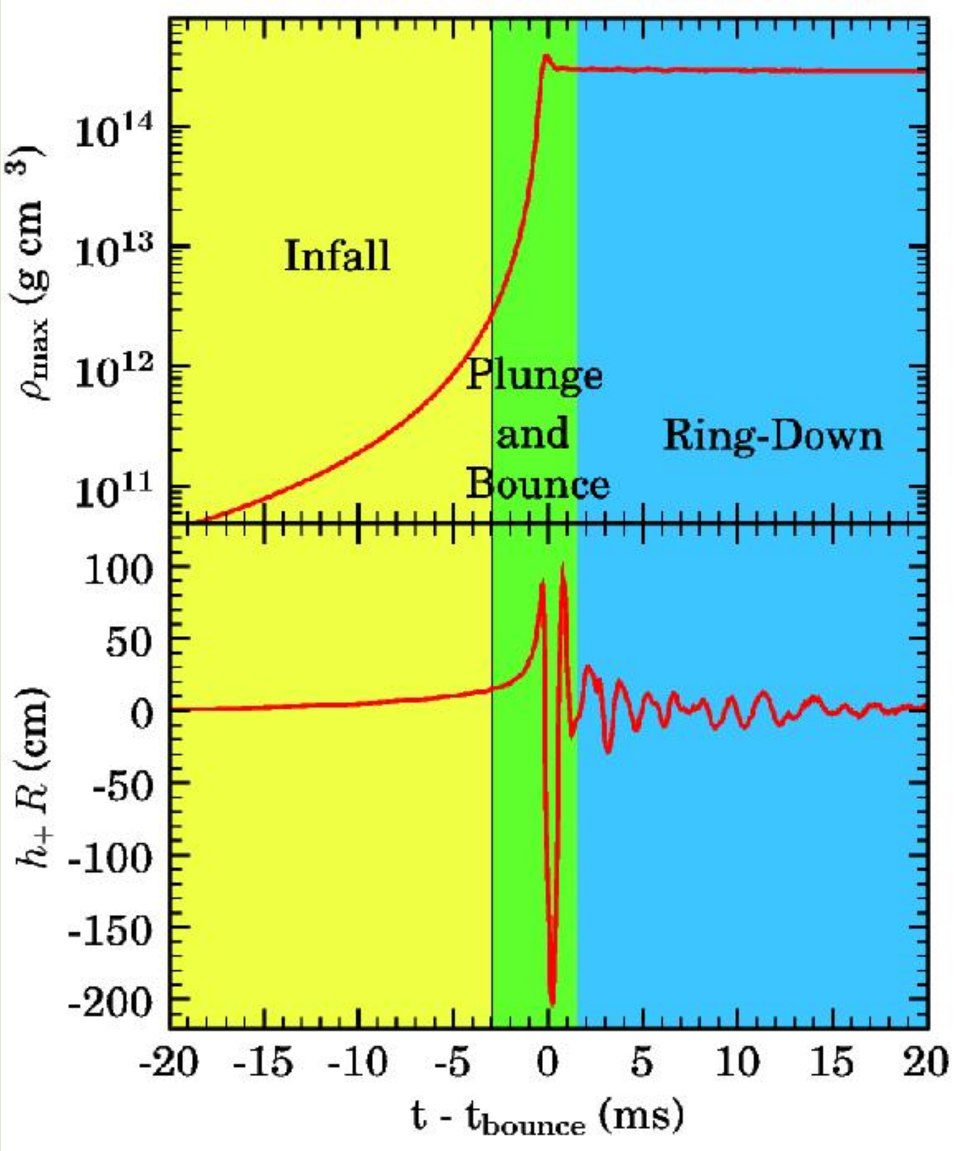
GWs from Rotating Core Collapse & Bounce

[Ott et al. 2004, Kotake et al. 2003, 2004, Dimmelmeier et al. 2008, Dimmelmeier et al. 2007, Ott et al. 2007 etc.]

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



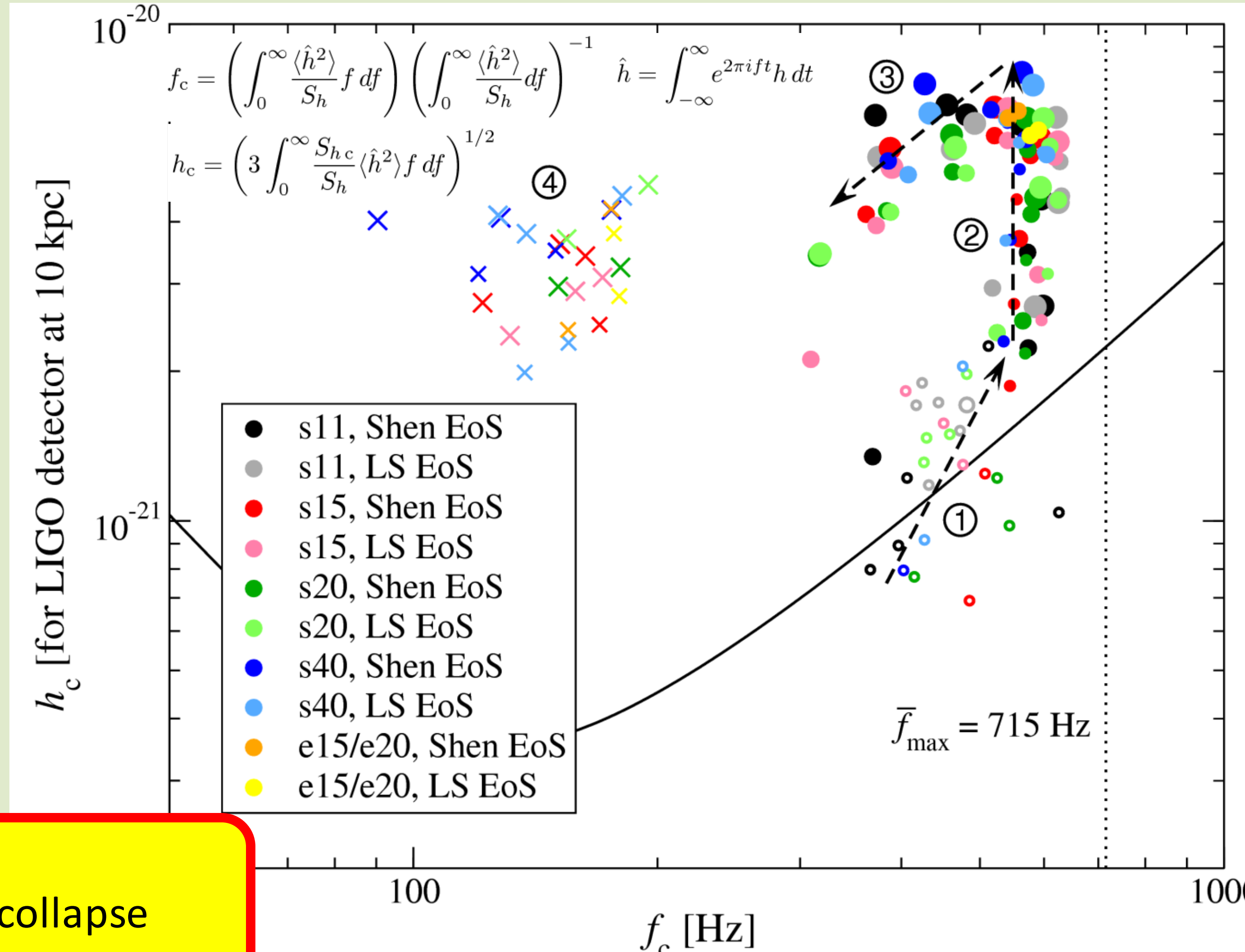
- At core bounce: Very large accelerations -> rapidly changing mass quadrupole moment.
- Most extensively studied GW emission in core collapse
- **Always axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + **Gravity** + **Stiffening of EOS**.
- MHD effects: only for extreme precollapse magnetization. [Kotake et al. '04, Obergaulinger et al.'05, '06]



New Extended 2D GR Model Set

[**Dimmelmeier, Ott, Marek, and Janka 2008**, 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.



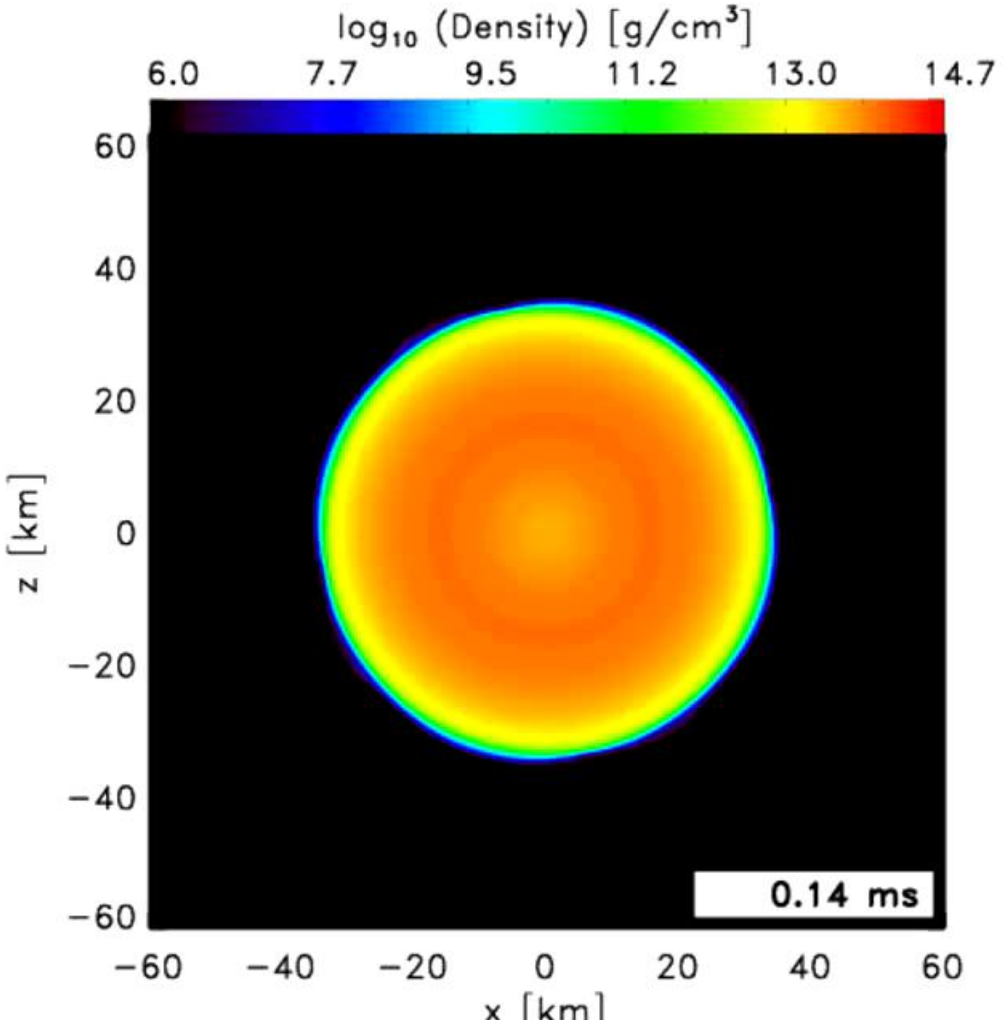
1) slow rotation, pressure-dominated bounce, prompt convection
2) moderately-rapid rotation, pressure-dominated bounce
3) rapid rotation, pressure-dominated, rotation-influenced bounce
4) single centrifugal bounce.

Results

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

PNS Spin and Rotational Instabilities

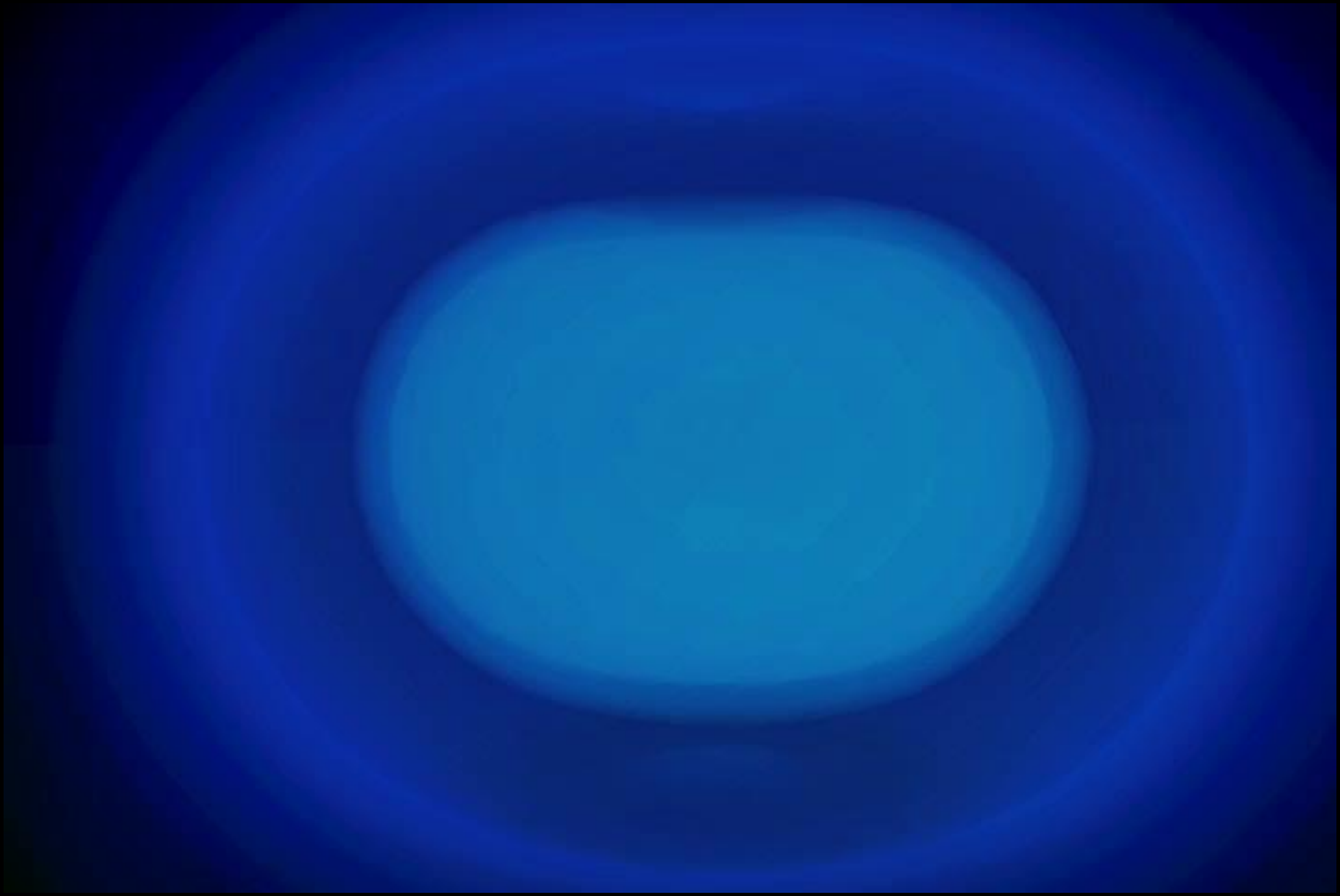
[Dimmelmeier et al. 2008, Ott et al. 2007, Ott et al. 2006]



[Ott et al. 2009 in prep.]

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

Rapid Rotation and Nonaxisymmetric Dynamics



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

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(imφ). m=2 "bar-modes"
  $(T/|W|)_{\mathrm{dynamical}} = 0.27$, $(T/|W|)_{\mathrm{secular}} \approx 0.14$. [e.g., Chandrasekhar 1969]
  Numbers hold roughly in GR and moderate differential rotation.
  [e.g., Baiotti et al. 2007]
- **Can a real PNS reach such high T/|W|?**

PNS Spin and Rotational Instabilities

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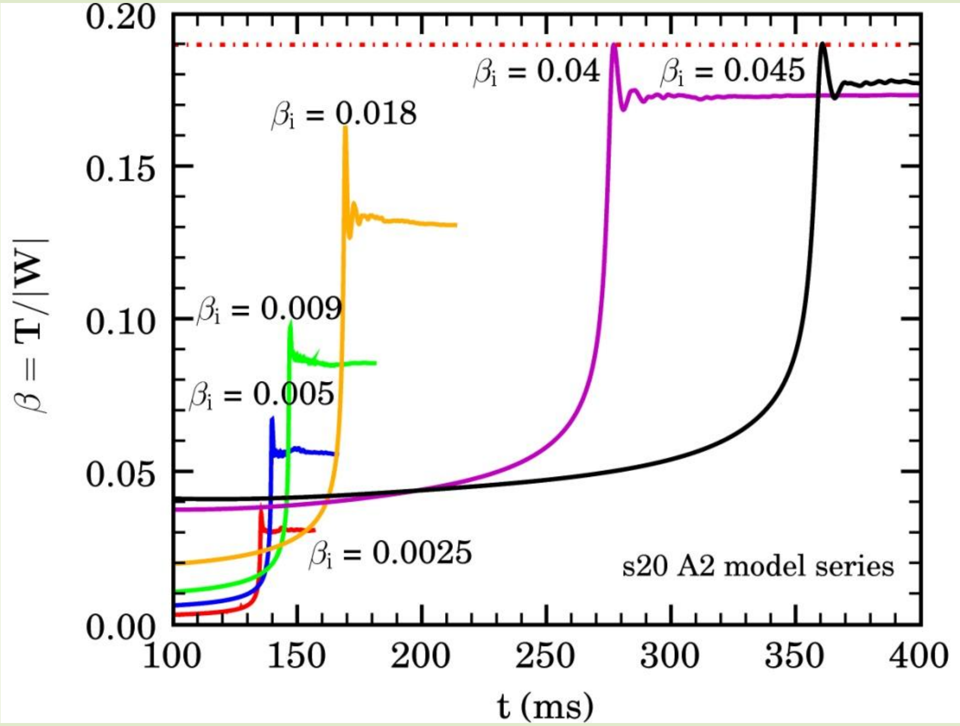
- **Can a real PNS reach such high T/|W|?**



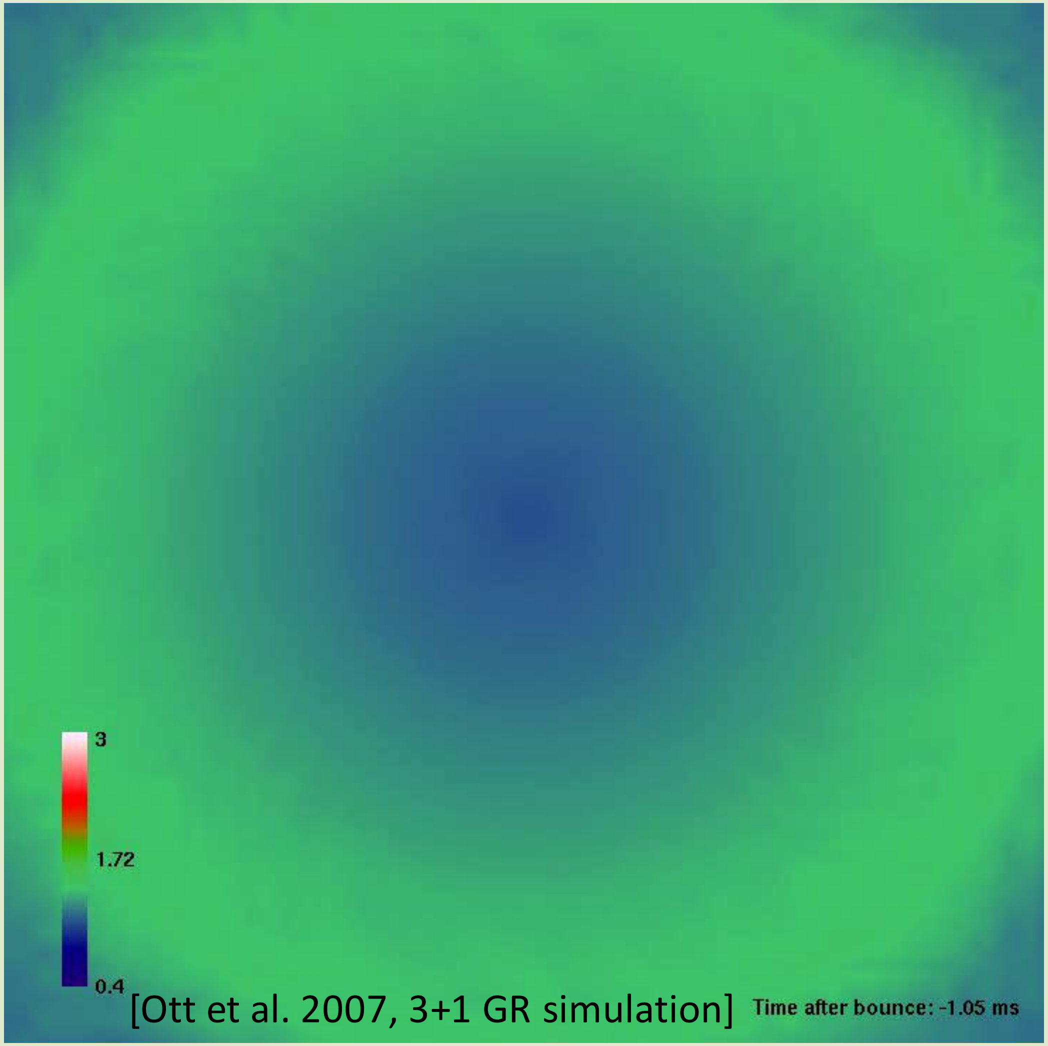
- Direct numerical simulation: **No** – collapsing cores hit rotational barrier.
  [Ott et al. PRL 2007 & CQG 2007, **Dimmelmeier et al. 2008**]
- Critical T/|W| (secular/ dynamical) attainable during PNS cooling.
- B-fields: rapid spindown (?)

Low-T/|W| Rotational Instability

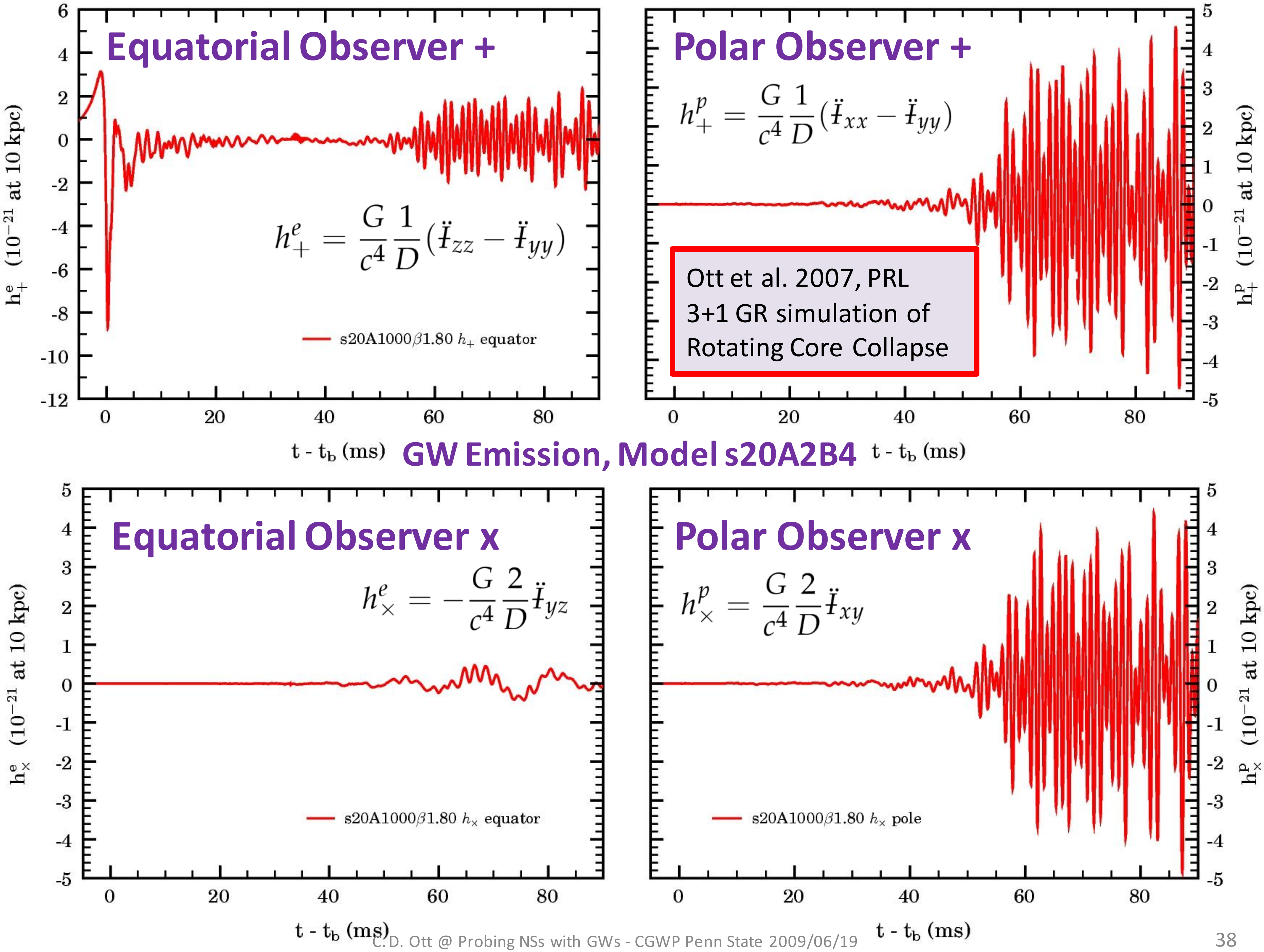
- Dynamical rotational instability at low T/|W|.

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

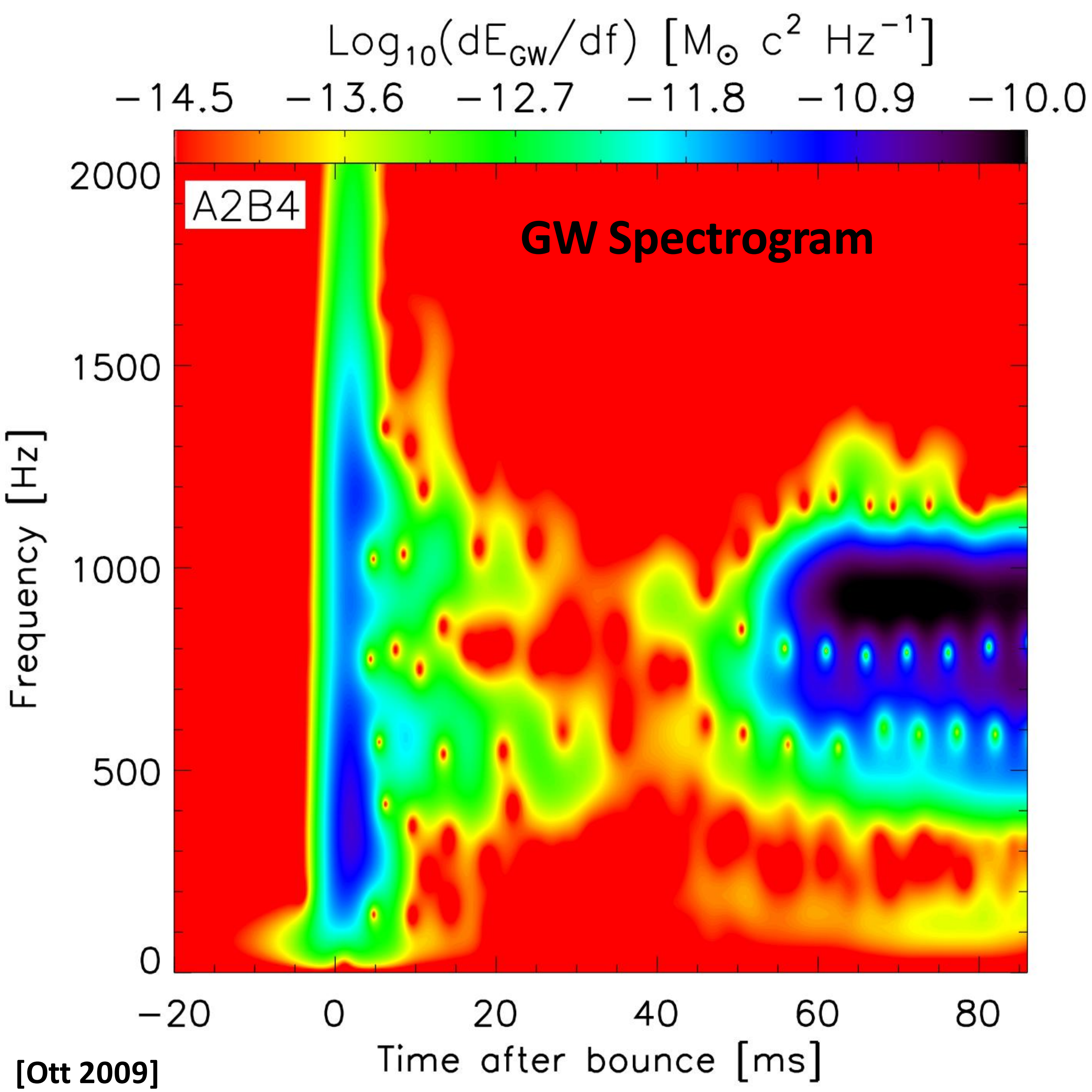
- Dominant m=1 mode; m={2,3} modes mixed in (radial & temporal variation).
- Mechanism:
  Corotation instability
  Resonance of unstable mode with background fluid at corotation point(s).
- Spiral density waves – relationship to accretion and galactic disks?
  -> angular momentum transport.



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



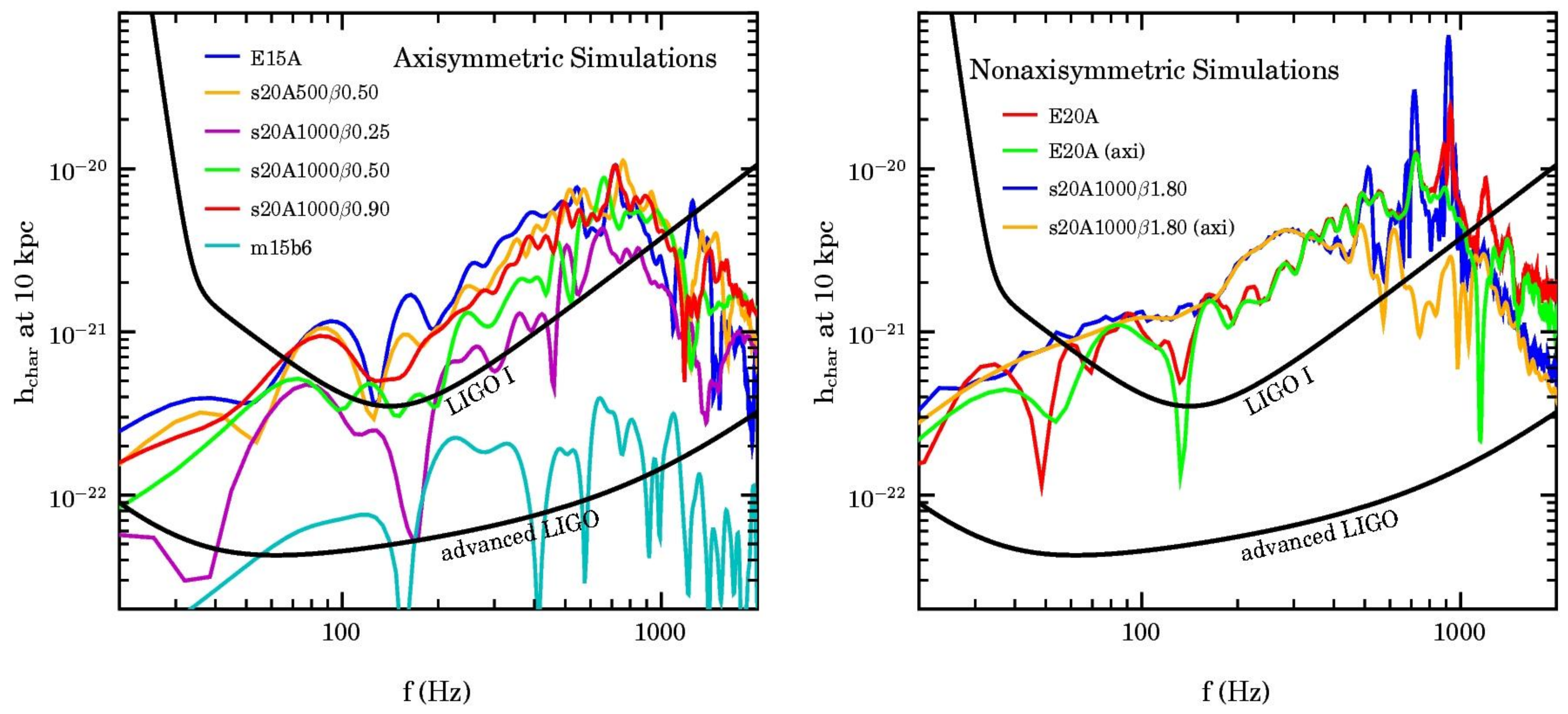
Equatorial Observer +
$h^e_+ = \frac{G}{c^4}\frac{1}{D}(\ddot{I}_{zz} - \ddot{I}_{yy})$
s20A1000β1.80 h_+ equator
Polar Observer +
$h^p_+ = \frac{G}{c^4}\frac{1}{D}(\ddot{I}_{xx} - \ddot{I}_{yy})$
Ott et al. 2007, PRL
3+1 GR simulation of
Rotating Core Collapse
GW Emission, Model s20A2B4
Equatorial Observer x
$h^e_\times = -\frac{G}{c^4}\frac{2}{D}\ddot{I}_{yz}$
s20A1000β1.80 $h_\times$ equator
Polar Observer x
$h^p_\times = \frac{G}{c^4}\frac{2}{D}\ddot{I}_{xy}$
s20A1000β1.80 $h_\times$ pole
h^e_+ (10^{-21} at 10 kpc)
h^p_+ (10^{-21} at 10 kpc)
$h^e_\times$ (10^{-21} at 10 kpc)
$h^p_\times$ (10^{-21} at 10 kpc)
t - t$_b$ (ms)



Log10(dEGW/df) [M⊙ c² Hz⁻¹]
−14.5
−13.6
−12.7
−11.8
−10.9
−10.0
A2B4
GW Spectrogram
Frequency [Hz]
2000
1500
1000
500
0
−20
0
20
40
60
80
Time after bounce [ms]
[Ott 2009]

GW Emission vs. Detector Noise

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



- 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 and SASI

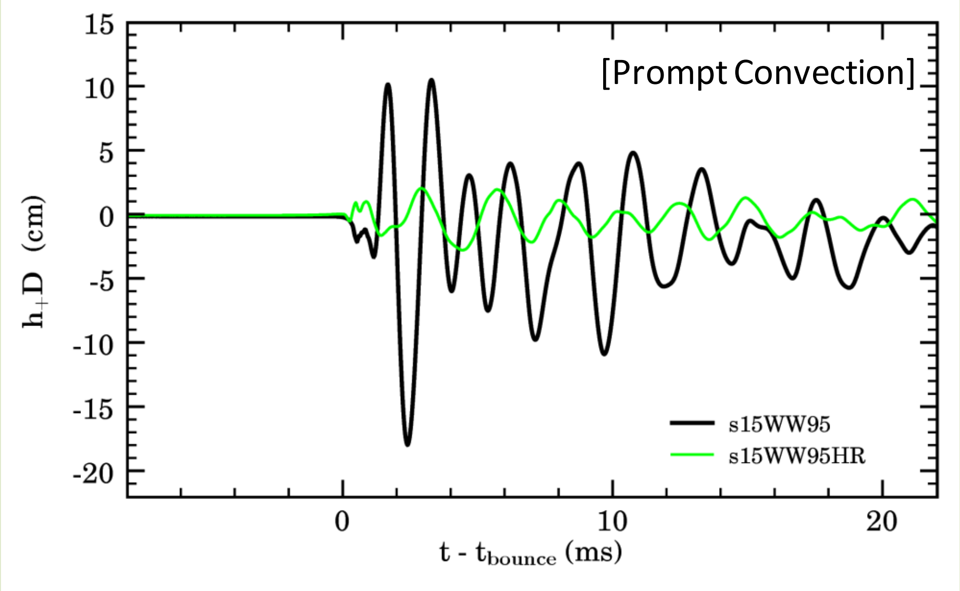
(Most) Calculations performed with the axisymmetric Newtonian VULCAN/2D radiation-(magneto)hydrodynamics code.

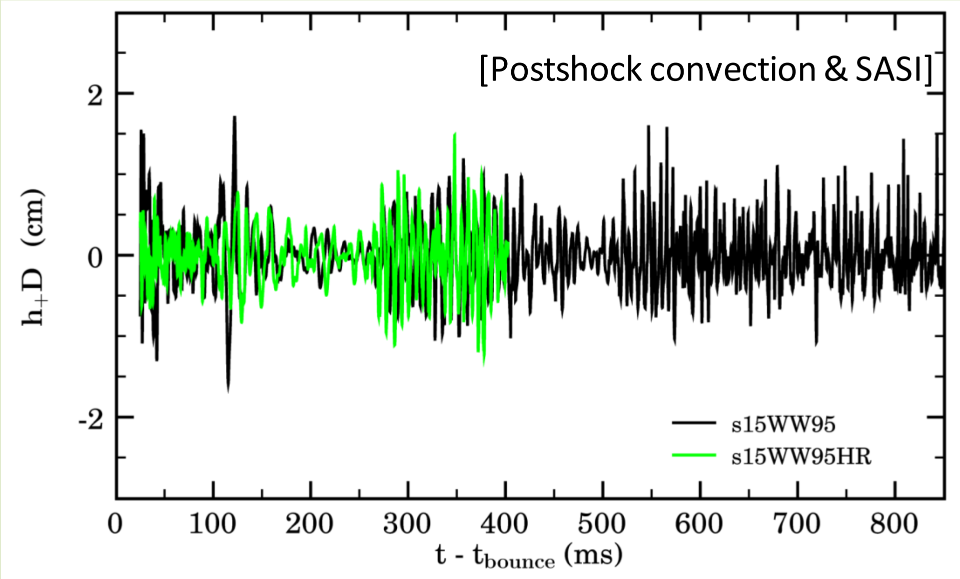
[Livne et al. ‘93, ‘04, ‘07, Burrow et al. ‘06, ‘07abc, Dessart et al. ‘06,ab ’07, Ott et al. ‘06ab, ‘08]

Gravitational Waves from Convection & SASI

[Ott 2009, Marek et al. 2009, Kotake et al. 2007, 2009, Ott et al. 2006, Müller et al. 2004, Janka & Müller 1997]

- **Prompt postbounce convection**.
- Neutrino-driven convection & SASI in postshock region.
- **Lepton-gradient driven convection inside the PNS**.
- SASI modifies/distorts convection, leads to enhanced accretion.
- **Turbulence/convection/SASI are "stochastic" sources of GWs; impossible to template**.





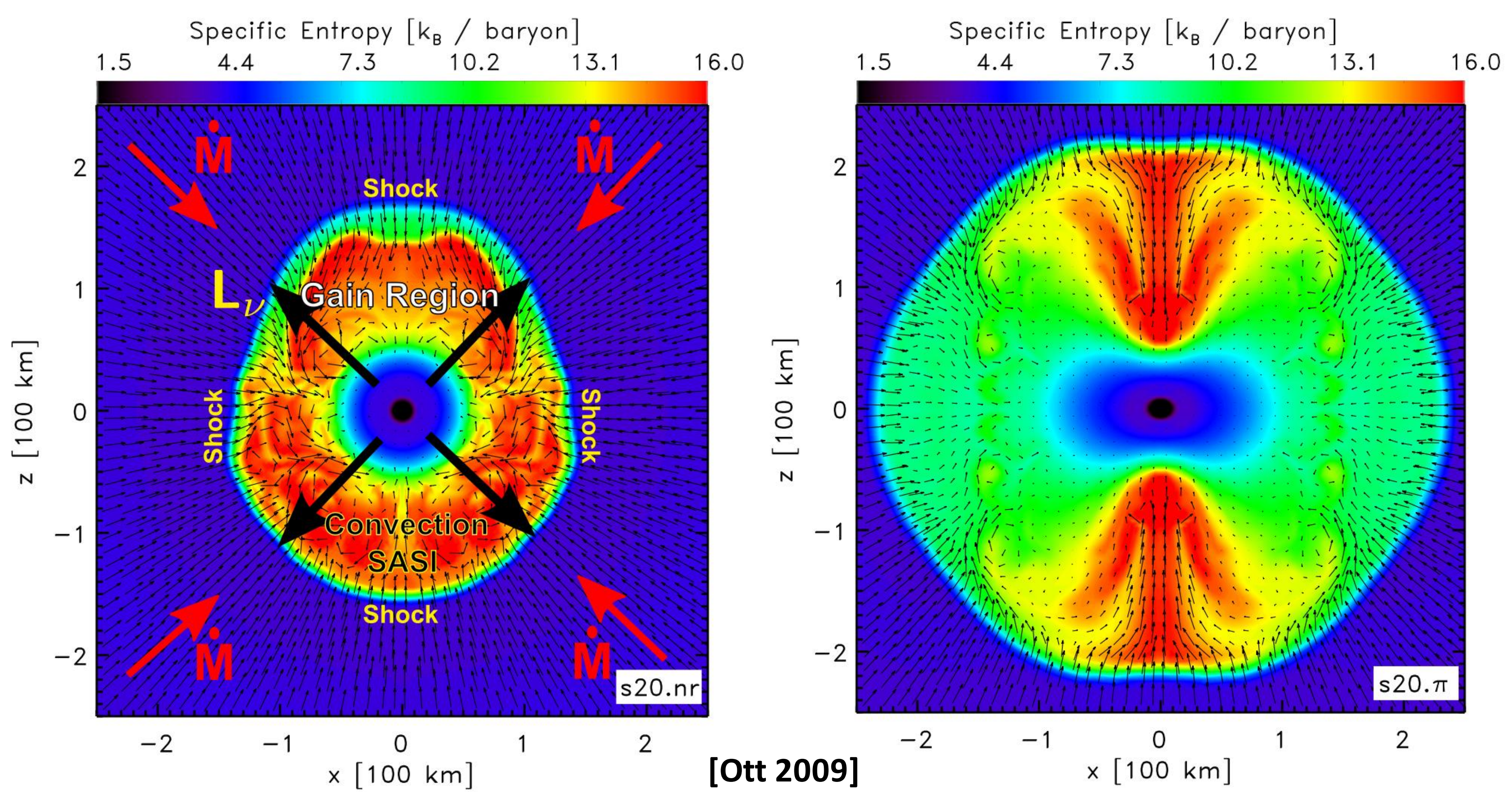
Convection in Postbounce Supernova Cores

[Ott 2009, Marek et al. 2009, Kotake et al. 2007, 2009, Ott et al. 2006, Müller et al. 2004, Janka & Müller 1997]

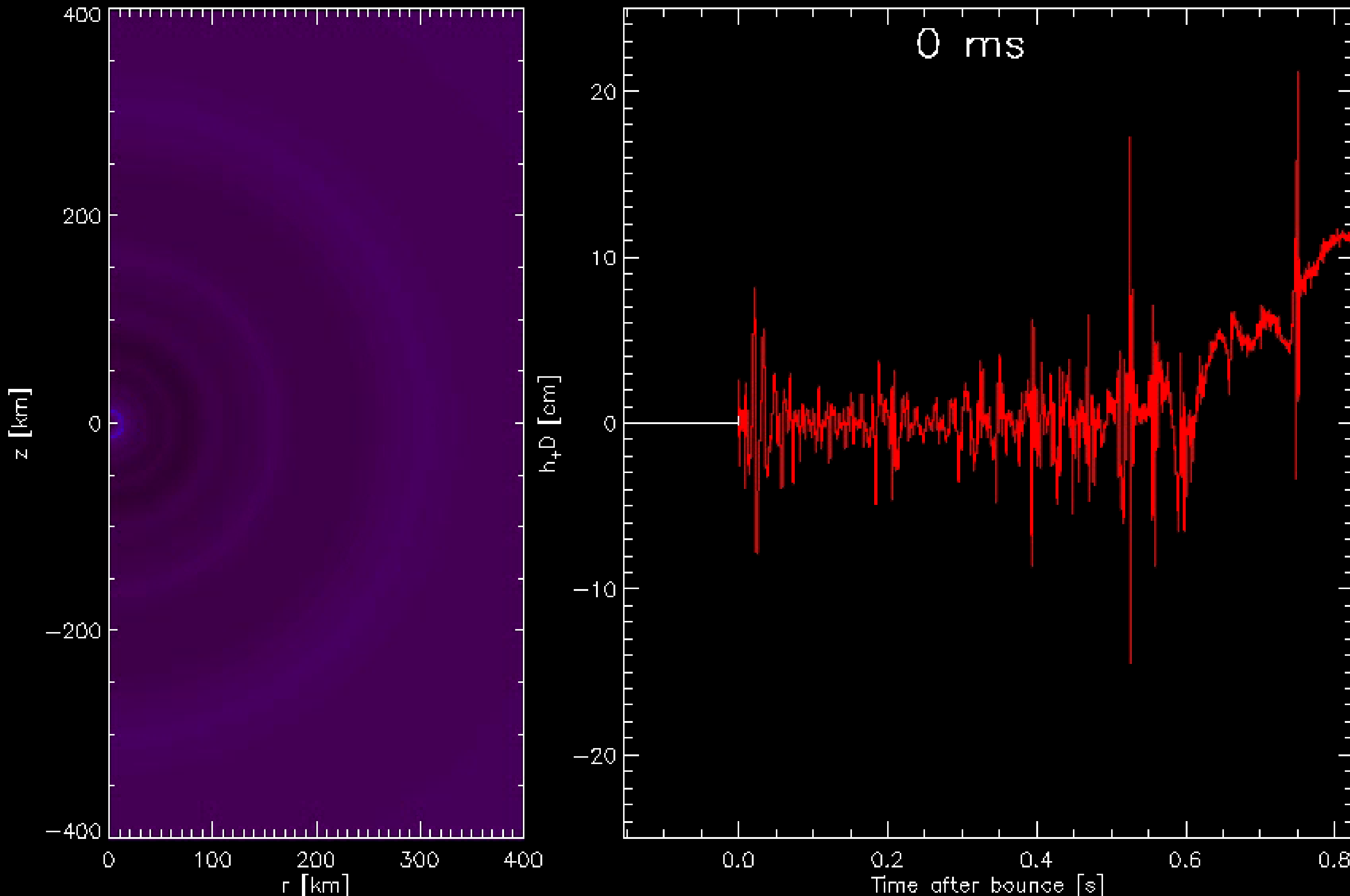
- Solberg-Høiland criterion for instability:

$$N^2 + \frac{1}{r^3}\frac{d}{dr}j^2 < 0 \qquad j = \Omega r^2 \qquad N^2 = \frac{g}{p\gamma}\left(\frac{\partial p}{\partial s}\bigg|_{\rho,Y_l}\frac{ds}{dr} + \frac{\partial p}{\partial Y_l}\bigg|_{\rho,s}\frac{dY_l}{dr}\right)$$

-> rotation generally damps convection! (Brunt-Väisäla Frequency)



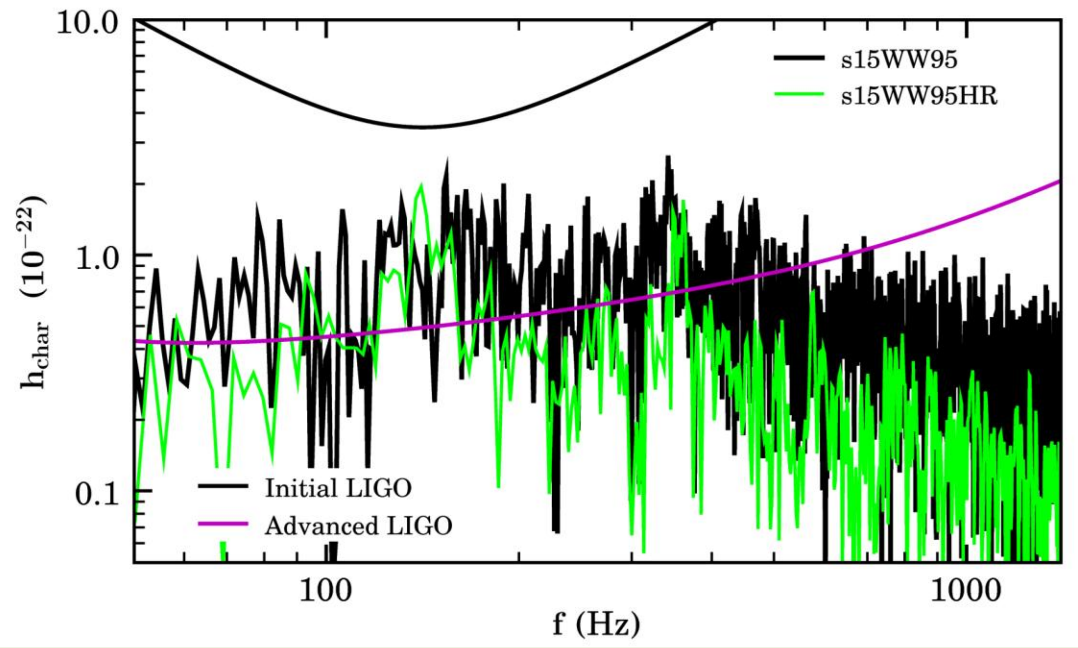
[Ott 2009]



[Murphy, Ott and Burrows 2009 (in preparation)]

Convection & SASI (cont'd)

[Ott '09, see also Kotake et al. '07, '09, Marek et al. 2009]



$$h_{\rm char} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\rm GW}}{df}}$$

Process	Typical $\|h\|$ (at 10 kpc)	Typical f (Hz)	Duration Δt (ms)	$E_{\rm GW}$ $(10^{-10} M_{\odot} c^2)$	Limiting Factors or Processes
Prompt Convection	$10^{-23} - 10^{-21}$	$50 - 1000$	$0- \sim 30$	$\lesssim 0.01 - 10$	Seed perturbations, entropy/lepton gradient, rotation
	(Emission characteristics depend on seed perturbations.)				
PNS Convection	$2 - 5 \times 10^{-23}$	$300 - 1500$	500 – several 1000	$\lesssim 1.3(\frac{\Delta t}{1s})$	rotation, BH formation, strong PNS g-modes
Neutrino-driven Convection and SASI	$10^{-23} - 10^{-22}$ (peaks up to 10^{-21})	$100 - 800$	$100- \gtrsim 1000$	$\gtrsim 0.01(\frac{\Delta t}{100ms})$ $\lesssim 15(\frac{\Delta t}{100ms})$	rotation, explosion, BH formation

Switching Gears:

GWs emitted by

Anisotropic Neutrino Emission and Large-Scale Asymmetries

(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]

GWs from Anisotropic Neutrino Emission

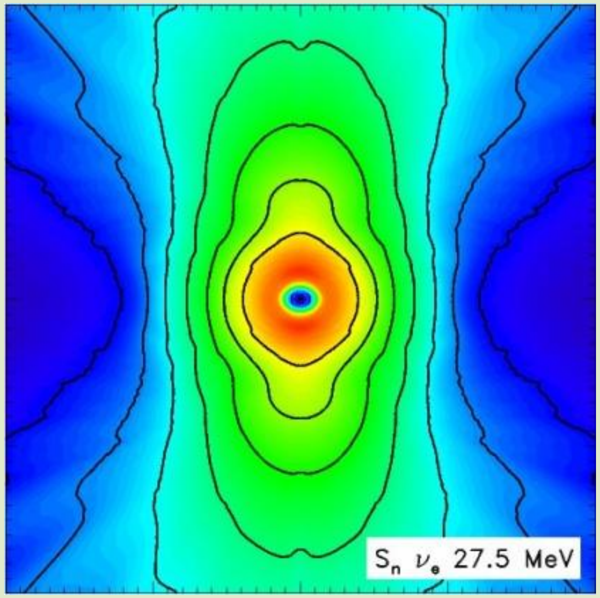
[Epstein 1978, Burrows & Hayes 1996, Janka & Müller 1997, Müller et al. 2004, Ott 2009, Kotake et al. 2007, 2009]

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

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

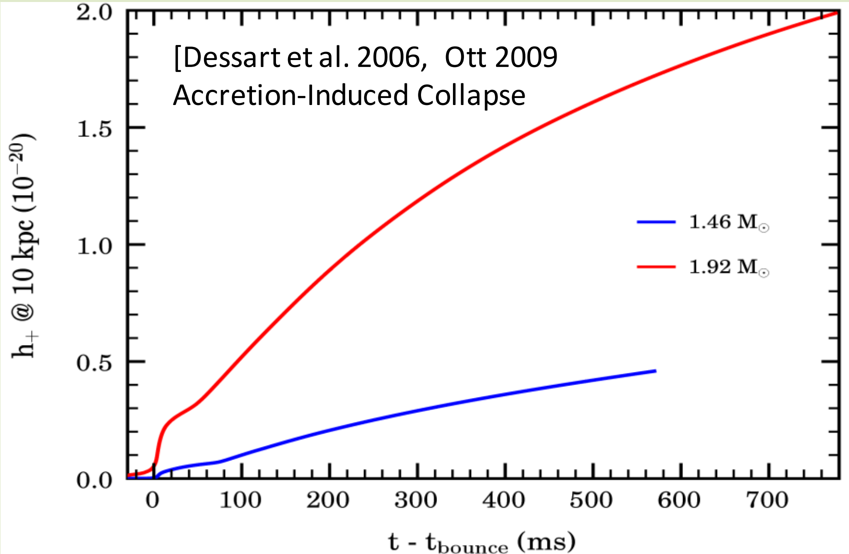
$$\alpha(t) = \frac{1}{L_\nu(t)}\int_{4\pi}\Psi(\vartheta',\varphi')\frac{dL_\nu(\vec{\Omega}',t)}{d\Omega'}d\Omega'$$

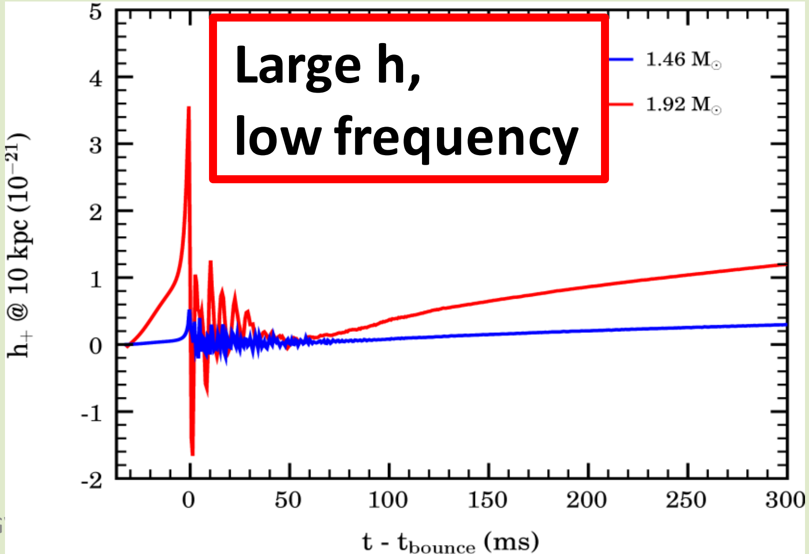
GW "Memory"



[Ott et al. 2008]

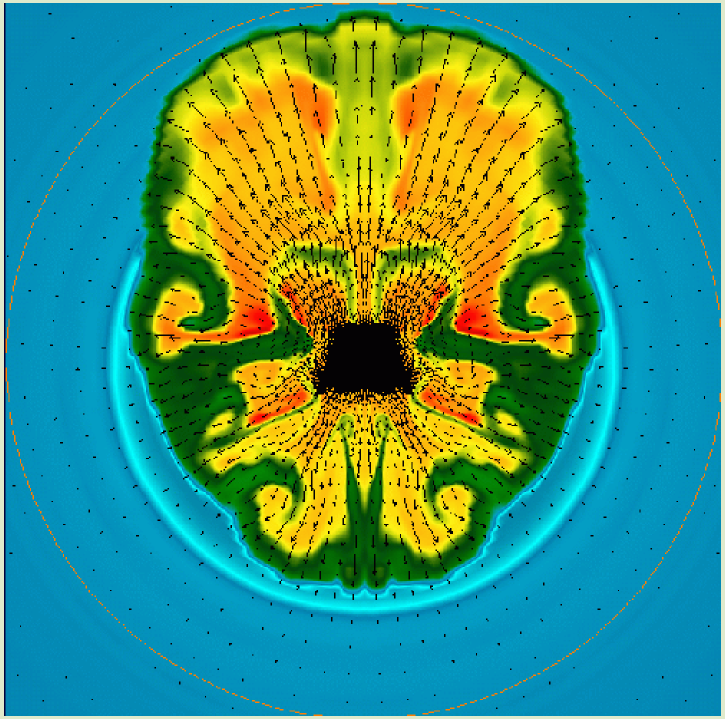
- Anisotropic neutrino emission in core-collapse SNe:
  - **Convective overturn & SASI**
  - **Rapid rotation**
  - **Large-scale asymmetries**

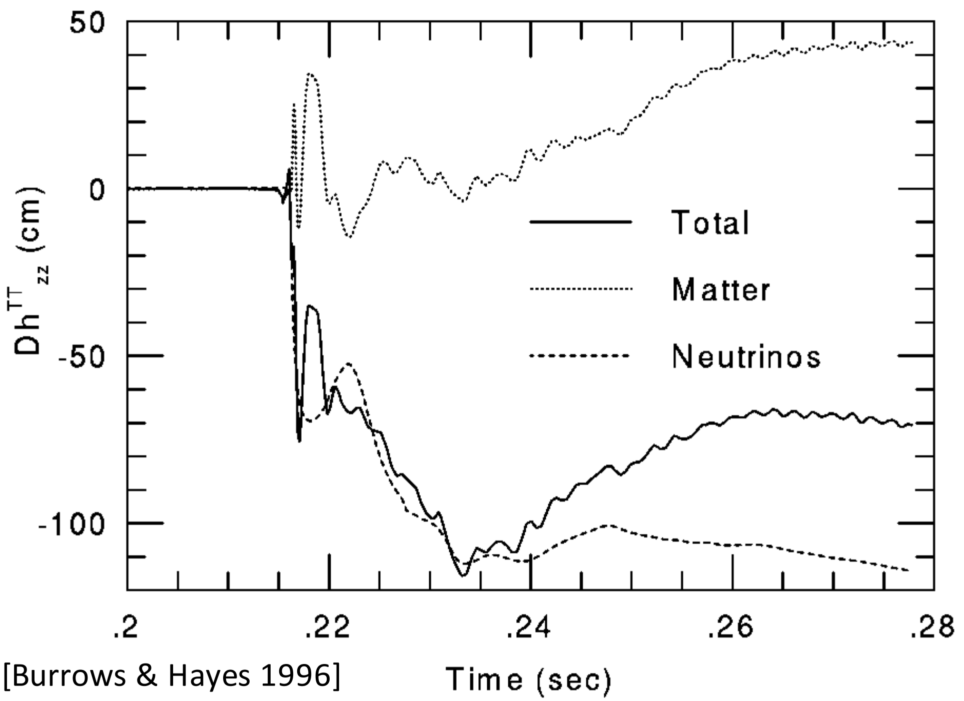




GWs from Aspherical Outflows

[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.

Switching gears again:

GWs emitted by

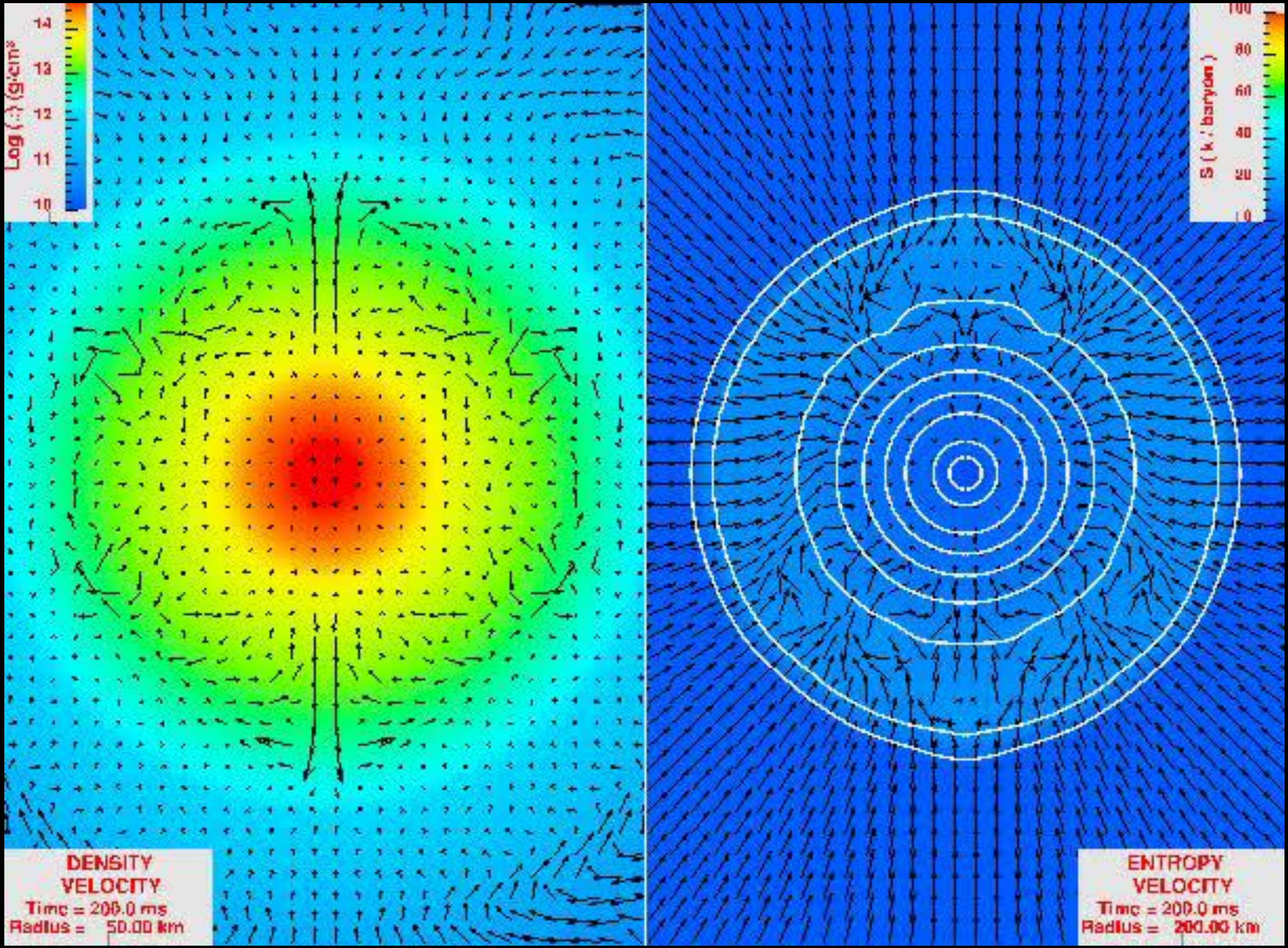
Protoneutron Star g-Mode Pulsations

(in the context of the 'Acoustic Mechanism'
Burrows et al. 2006, 2007, Ott et al. 2006)

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]

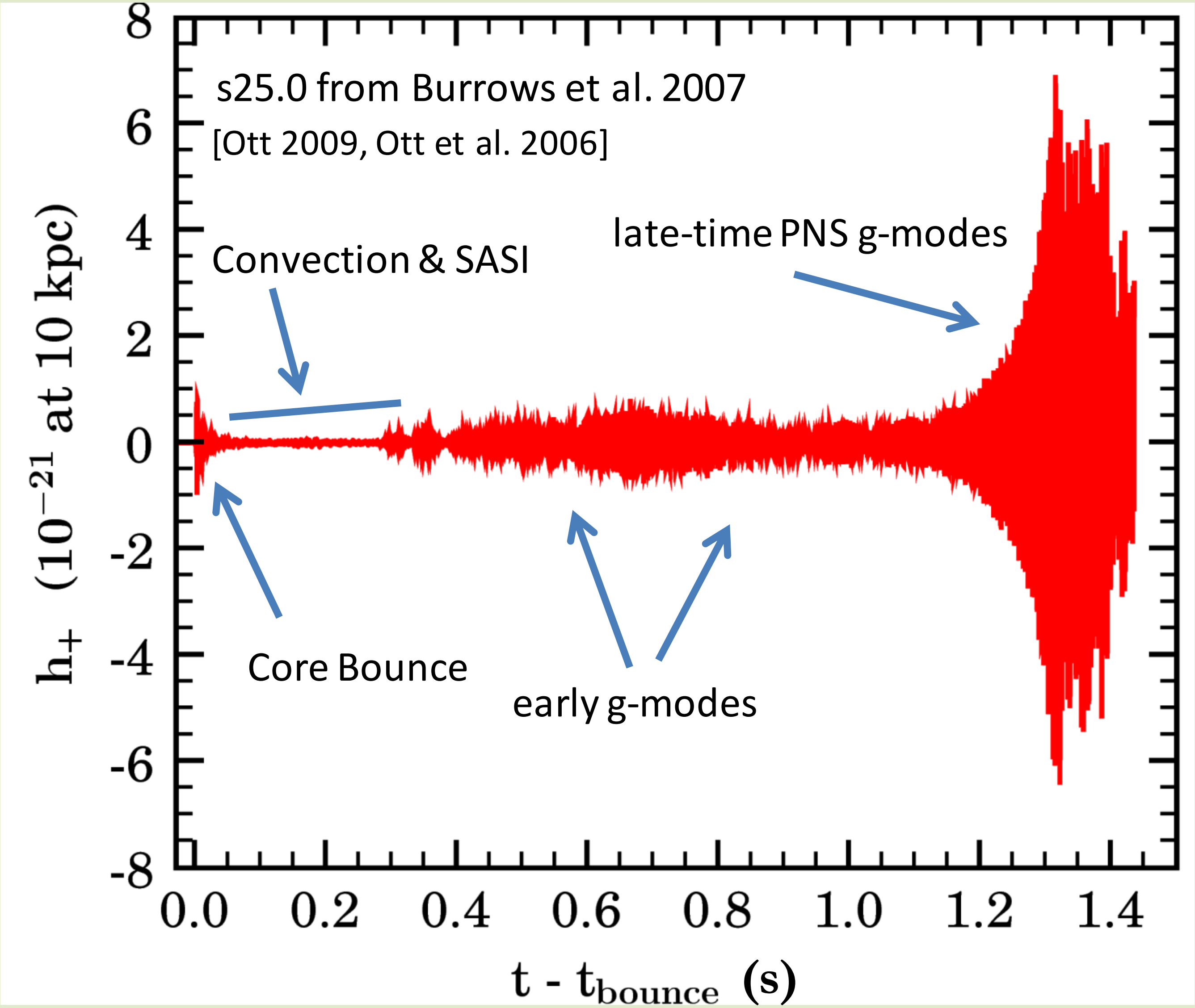
PNS g-modes and the Acoustic Mechanism



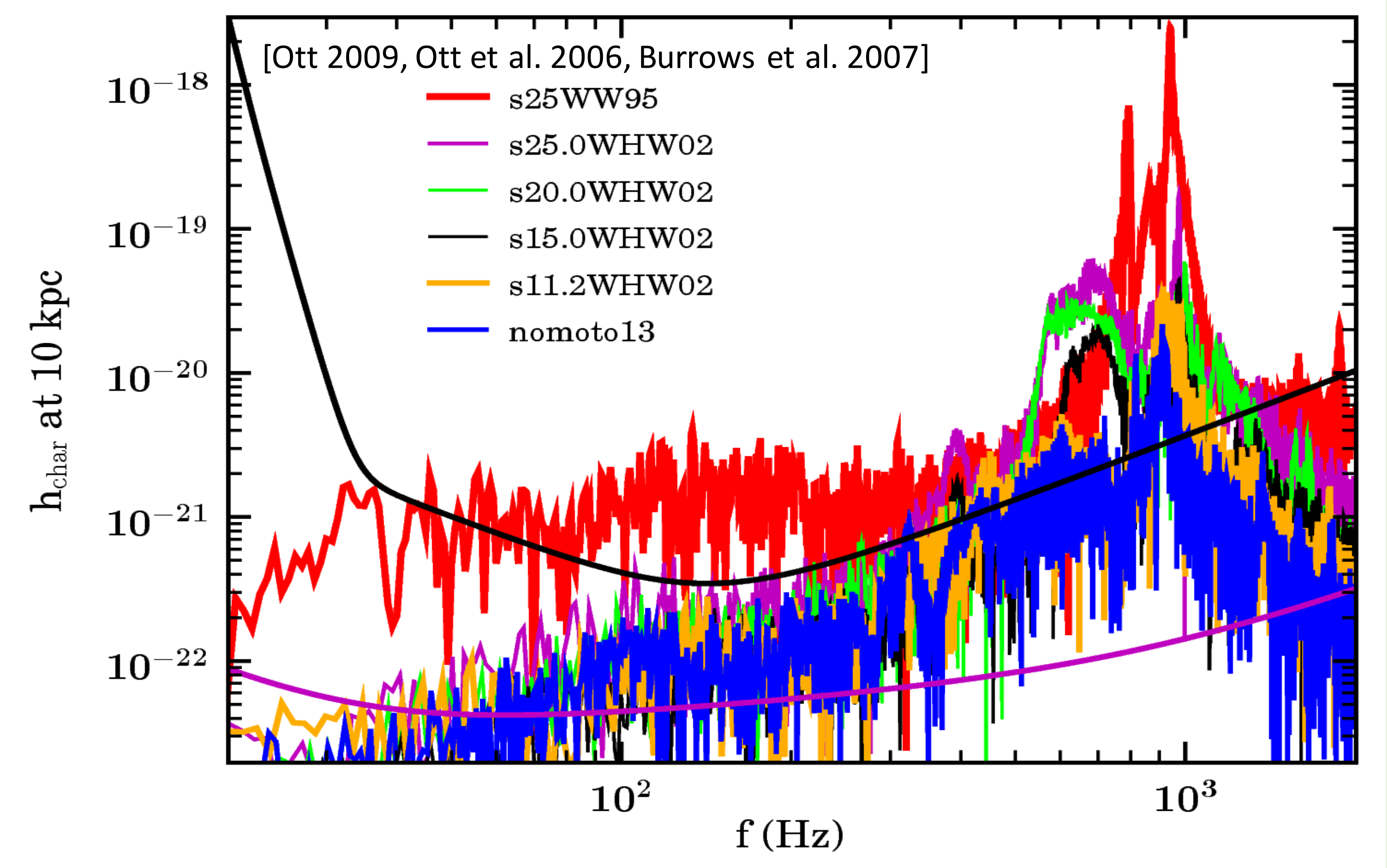
[Burrows et al. 2006, 2007b/c, Ott et al. 2006]

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

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

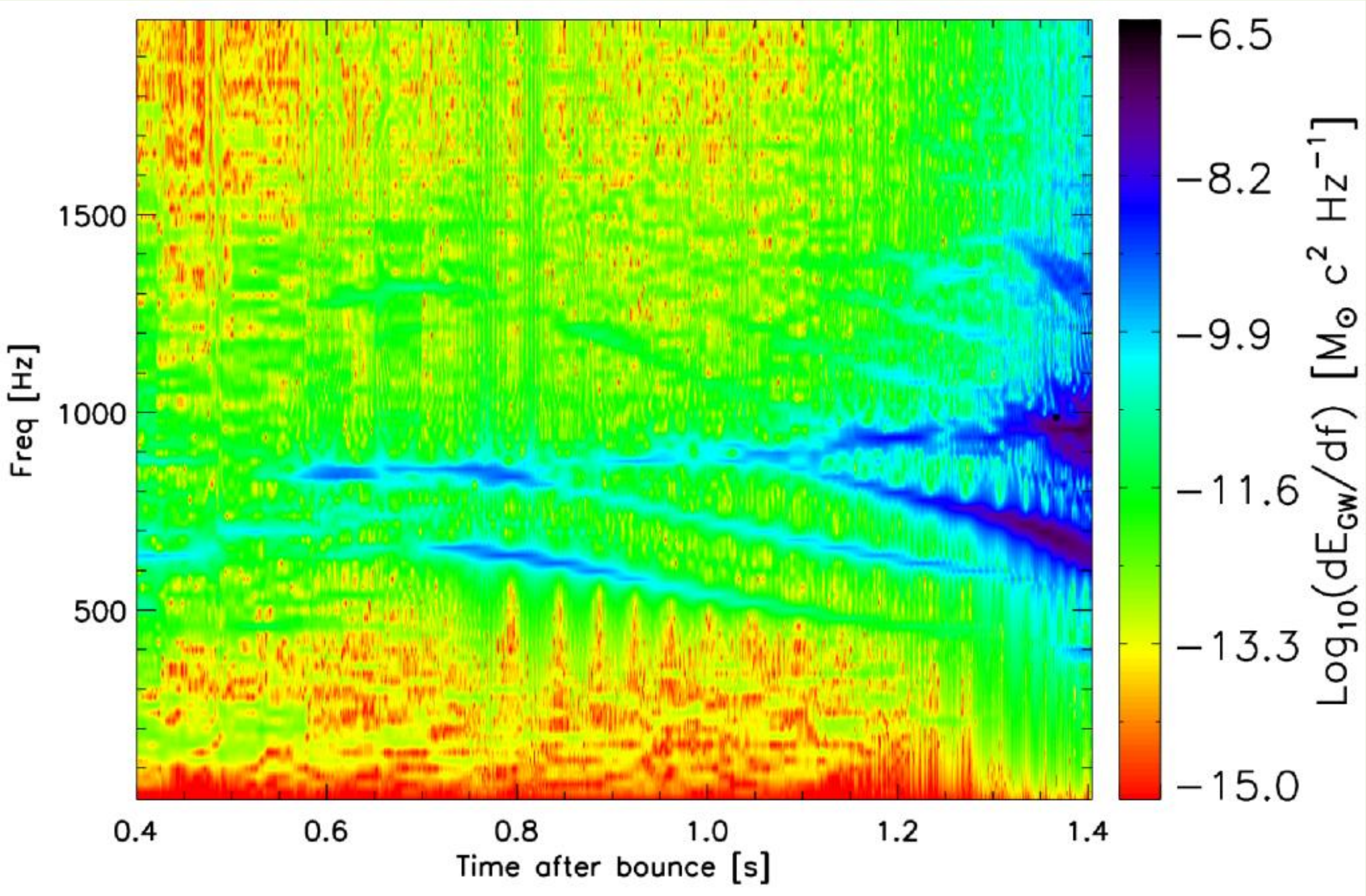


GW Spectra and LIGO Sensitivity



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

Time-Frequency Analysis of the GW Power Spectrum



Models s15.0WHW02

Can we use GWs as Indicators for the Core-Collapse Supernova Explosion Mechanism?

[Ott 2009, arXiv:0905.2797]

Mechanism → **GW Emission Process** → **Characteristic GW Signature** → **Mechanism**

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

[Ott 2009, arXiv:0905.2797 and CQG Topical Review]

Neutrino Mechanism

Magnetorotational Mechanism

Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

[Ott 2009, arXiv:0905.2797 and CQG Topical Review]

Dominant GW Emission Process(es)

Mechanism	Dominant GW Emission Process(es)
Neutrino Mechanism	→ Convection and SASI.
Magnetorotational Mechanism	
Acoustic Mechanism	

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

[Ott 2009, arXiv:0905.2797 and CQG Topical Review]

Dominant GW Emission Process(es)

Neutrino Mechanism	→	Convection and SASI.
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism		

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

[Ott 2009, arXiv:0905.2797 and CQG Topical Review]

Dominant GW Emission Process(es)

Neutrino Mechanism	→	Convection and SASI.
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism	→	PNS pulsations.

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

[Ott 2009, arXiv:0905.2797 and CQG Topical Review]

Dominant GW Emission Process(es)

Neutrino Mechanism →	Convection and SASI.
Magnetorotational Mechanism →	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism →	PNS pulsations.

-> Very clear mapping between explosion mechanism and GW signature.

Some Observational Aspects

Core-Collapse Supernova Rates

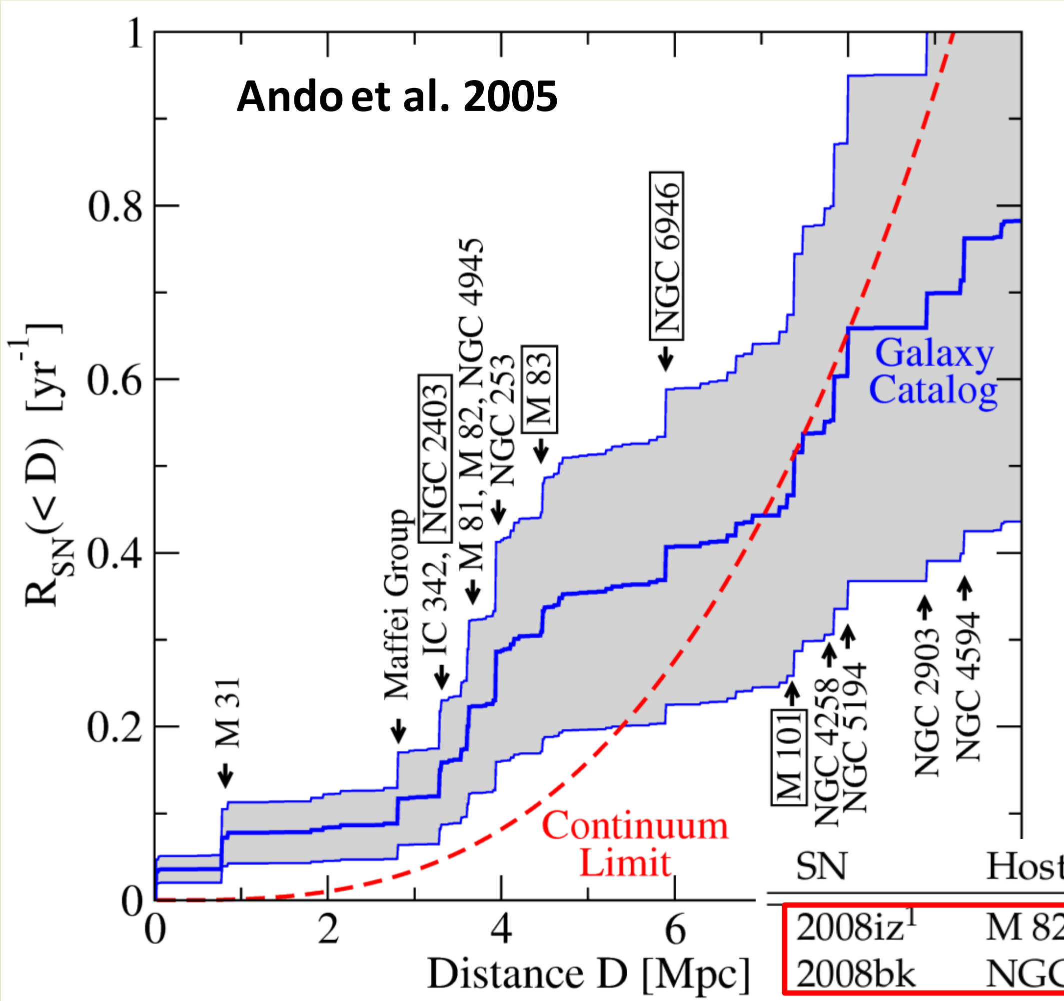
- Local group of galaxies: V $\sim$ 30 Mpc^3
  - Milky Way, Andromeda (M31), Triangulum (M33) + $\sim$30 small galaxies/satellite galaxies (incl. SMC & LMC).

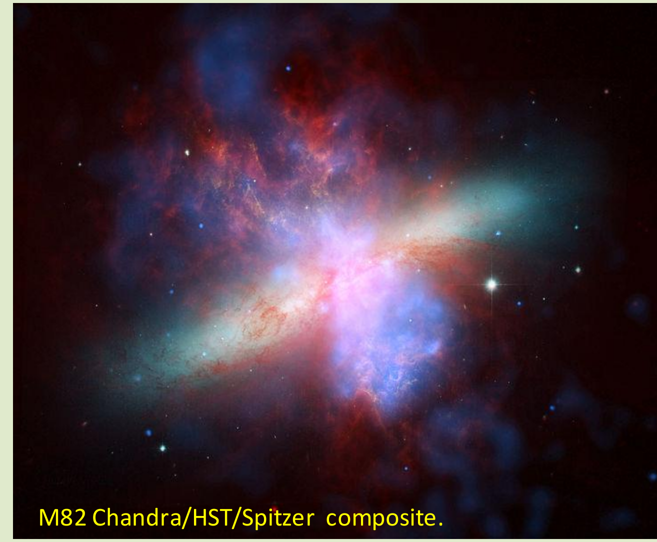
Galaxy	Distance (kpc)	Core-Collapse SN Rate $(100\ \mathrm{yr})^{-1}$
Milky Way	0–$\sim$15	0.50–2.50
LMC	$\sim$50	0.10 – 0.50
SMC	$\sim$60	0.06 – 0.12
M31	$\sim$770	0.20 – 1.20
M33	$\sim$840	0.16 – 0.68
IC 10	$\sim$750	0.05 –0.11
IC 1613	$\sim$770	$\sim$0.04
NGC 6822	$\sim$520	$\sim$0.04

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.

Nearby Core-Collapse Supernovae




M82 Chandra/HST/Spitzer composite.

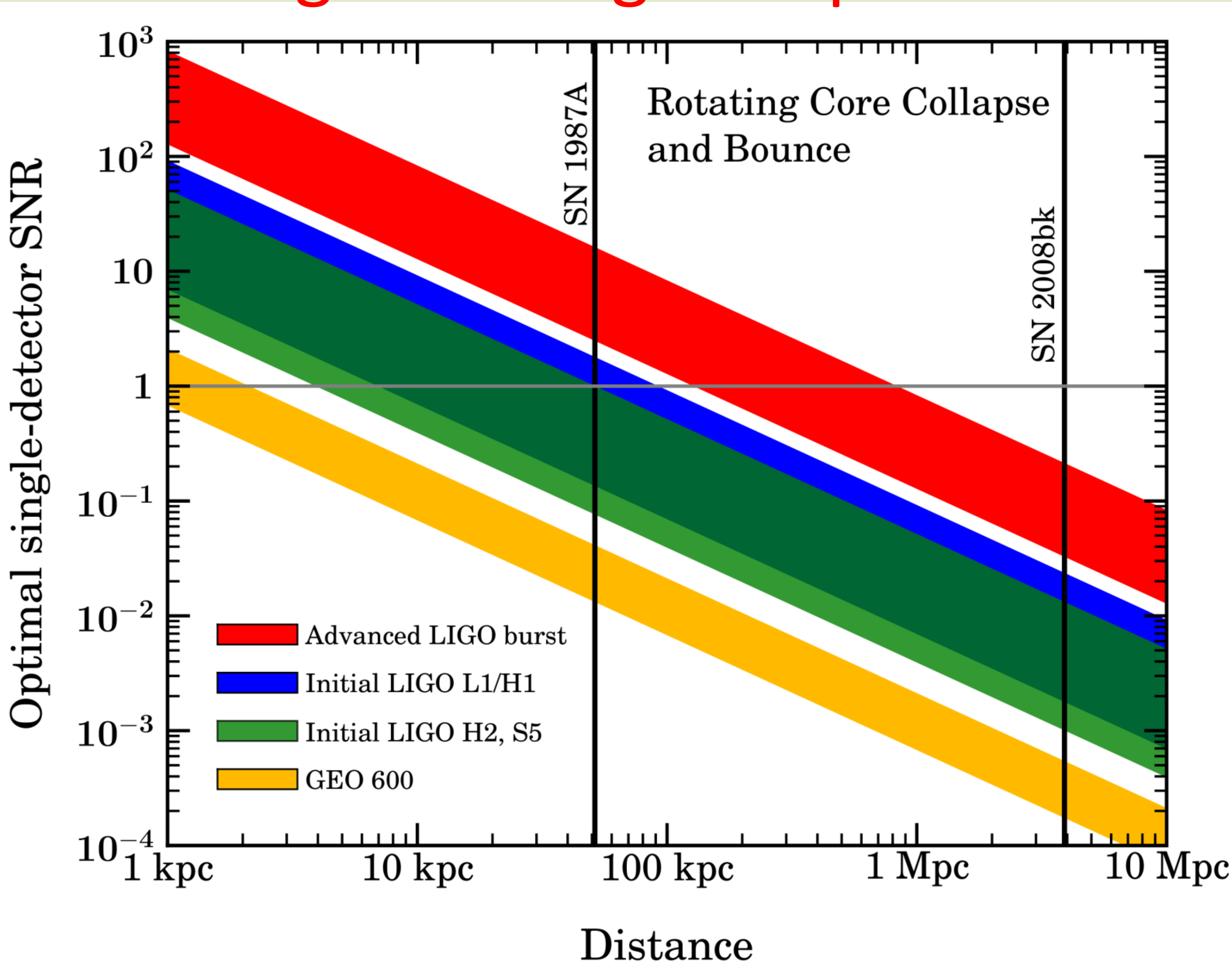
Core-collapse SNe within 5 Mpc since the beginning of LIGO operations:

SN	Host Galaxy	Date	Type	Distance
2008iz[1]	M 82	20090515 [2]	II	~ 3.5 [3]
2008bk	NGC 7793	20080325 [4]	II-P	~ 3.9 [5]
2005af	NGC 4945	20050208 [6]	II-P	~ 3.6 [5]
2004dj	NGC 2403	20040731 [7]	II-P	~ 3.3 [5]
2004am	M 82	20040305 [8]	II-P	~ 3.5 [3]
2002kg	NGC 2403	20021026 [9]	IIn	~ 3.3 [5]

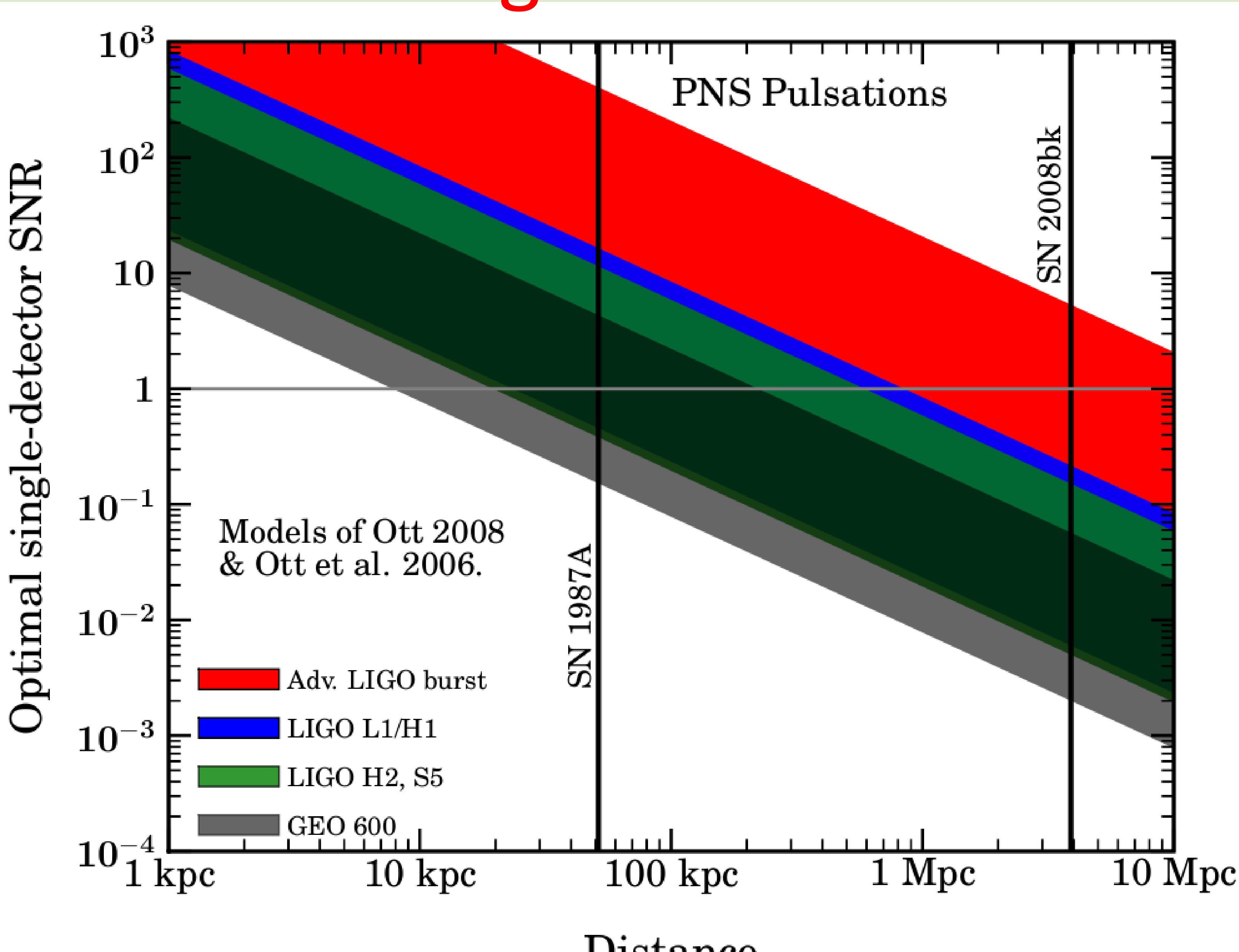
[1] Radio supernova, not observed in the optical. Explosion in late January 2008.


M31 (Andromeda) Spitzer.

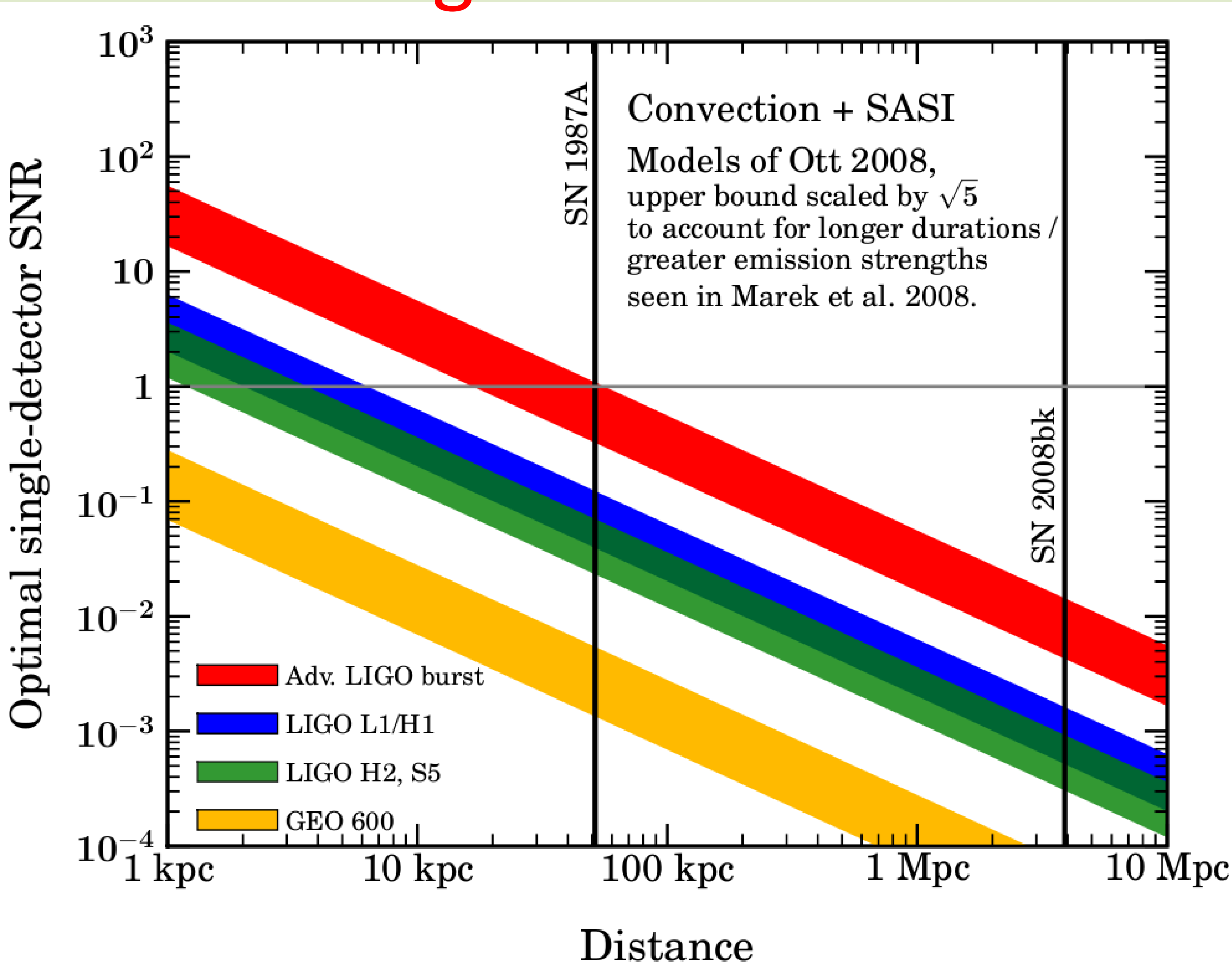
SNR Scaling: Rotating Collapse & Bounce



SNR Scaling: PNS Pulsations



SNR Scaling: Convection & SASI



Summary and Remarks

- Multi-D core-collapse SN simulations are maturing -> 3 potential explosion mechanisms: **ν**, **MHD**, **acoustic**
- **The GW signature of the 3 considered mechanisms is likely to be mutually exclusive**.
- **Galactic core-collapse SN would allow to constrain SN mechanism.**

- Problem: Galactic SN rate: 1 in ~40 years.
  Local group: 2 in ~40 years.

  -> Need to go out to 3-5 Mpc where rate jumps to 1 in ~2 years.
  Further problem: adv. LIGO not sufficiently sensitive:
- **Need more adv. LIGO sensitivity from ~500 to ~1000 Hz.**
- Status of the modeling of GW emission processes:
  - Rotating collapse: getting robust. Convection, SASI: need 3D models.
  - All other mechanisms: need more simulations to understand systematics and emission characteristics.
  - **Are we missing something?**

Bonus: The Lowest-Mass Neutron Stars

- Observations: There are some NSs with $M < \sim 1.3\ M_{SUN}$.
  -> 4U1538-52: $0.9 \pm 0.2\ M_{SUN}$.
  -> B1756-2251: $1.2 \pm 0.01\ M_{SUN}$.
  -> J1141-6545: $1.3 \pm 0.01\ M_{SUN}$.

- Factors determining the NS mass:
  - Nuclear physics, electron capture (progenitor entropy), rotation during collapse -> size of the inner core at bounce: $0.45 - 0.75\ M_{SUN}$.
  - Time between core bounce and explosion. Accretion rate: $O(1\ M_{SUN}/s)$.
  - Fallback after explosion (perhaps $\sim 0.1\ M_{SUN}$ and more).

- Most likely progenitors:
  - AIC: Accretion induced collapse of (super-Chandrasekhar) O/Ne WD
  - Collapse of O/Ne core of evolved low-mass massive star $\sim$6-8 M_{SUN}.

- Some AIC results:
  - Dessart et al. 2006: 2 models simulated; $1.30\ M_{SUN}$ and $1.39\ M_{SUN}$.
  - Abdikamalov et al. 2009: large GR model set. $0.9 - 1.1\ M_{SUN}$.

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Daniele Malesani (Dark Cosmology Centre/NBI)
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