Happy Birthday SN1987A!!!

Supernova 1987A, Large Magellanic Cloud, D $\approx$ 160000 lightyears
Progenitor Star: Blue Supergiant Sanduleak -69° 220a, 18 M_{SUN}

Simulations of Stellar Collapse, Core-Collapse Supernovae, and the Formation of Stellar-Mass Black Holes

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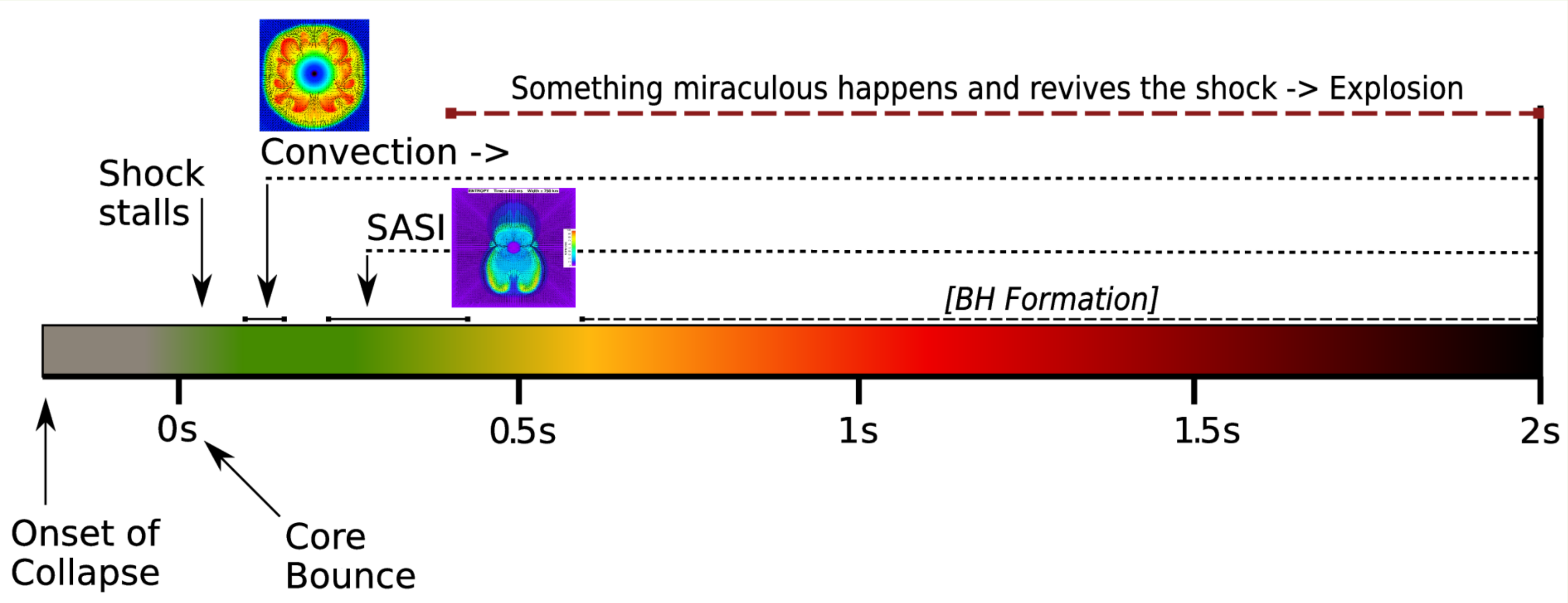
JIGSAW 2010, TIFR, Mumbai

Plan of this Talk

- Introduction and an Aside on the SN EOS
- Core-Collapse Supernova Mechanisms
- 2D Angle-Dependent Neutrino Radiation-Hydrodynamics CCSN Simulations
- Observables of the CCSN Mechanism: Gravitational Waves and Neutrinos
- Failing Core-Collapse Supernovae and The Formation of Stellar-Mass Black Holes
- *Bonus*: Spectral swap in a 1D CCSN model

Core Collapse Timeline



- Energy reservoir: few x 10^{53} erg (100 B)
- Explosion energy: ~1 B
- Time frame for explosion: ~0.3 – 2.0 s after bounce.
- BH formation at baryonic PNS mass ≥ 1.8 – 2.5 M_{SUN}.

The Supernova (Simulation) EOS

- At high temperatures ($T > 0.5$ MeV) and densities:
  Nuclear Statistical Equilibrium (NSE) -> EOS function of (ρ, T, Y_e) alone.
- Pressure contributions by: electrons, photons, baryons.
- Core-collapse supernova simulations require robust EOS that covers:
  ρ: $\sim 10^4 - 10^{15}$ g/cm^3, T: 0.01 – 100 MeV, Y_e: 0 – 0.6.
  Tabulated EOS with high density of points required for performance and thermodynamic consistency.
- **Two general approaches**:
  1) "First Principles": Many-body theory/(rel.)Hartree-Fock (mean-field) calculations:
     Hillebrandt & Wolf 1985, H. Shen et al. 1998.
  2) Phenomenological: Compressible liquid droplet model
     Lattimer & Swesty 1991 (LSEOS).
- Key parameters governing stiffness: Nuclear symmetry energy S_v and incompressiblity modulus K_0.
- In case you are interested: http://www.stellarcollapse.org/microphysics provides tabulated versions of HShen and LSEOS.

Observed Neutron Star Masses

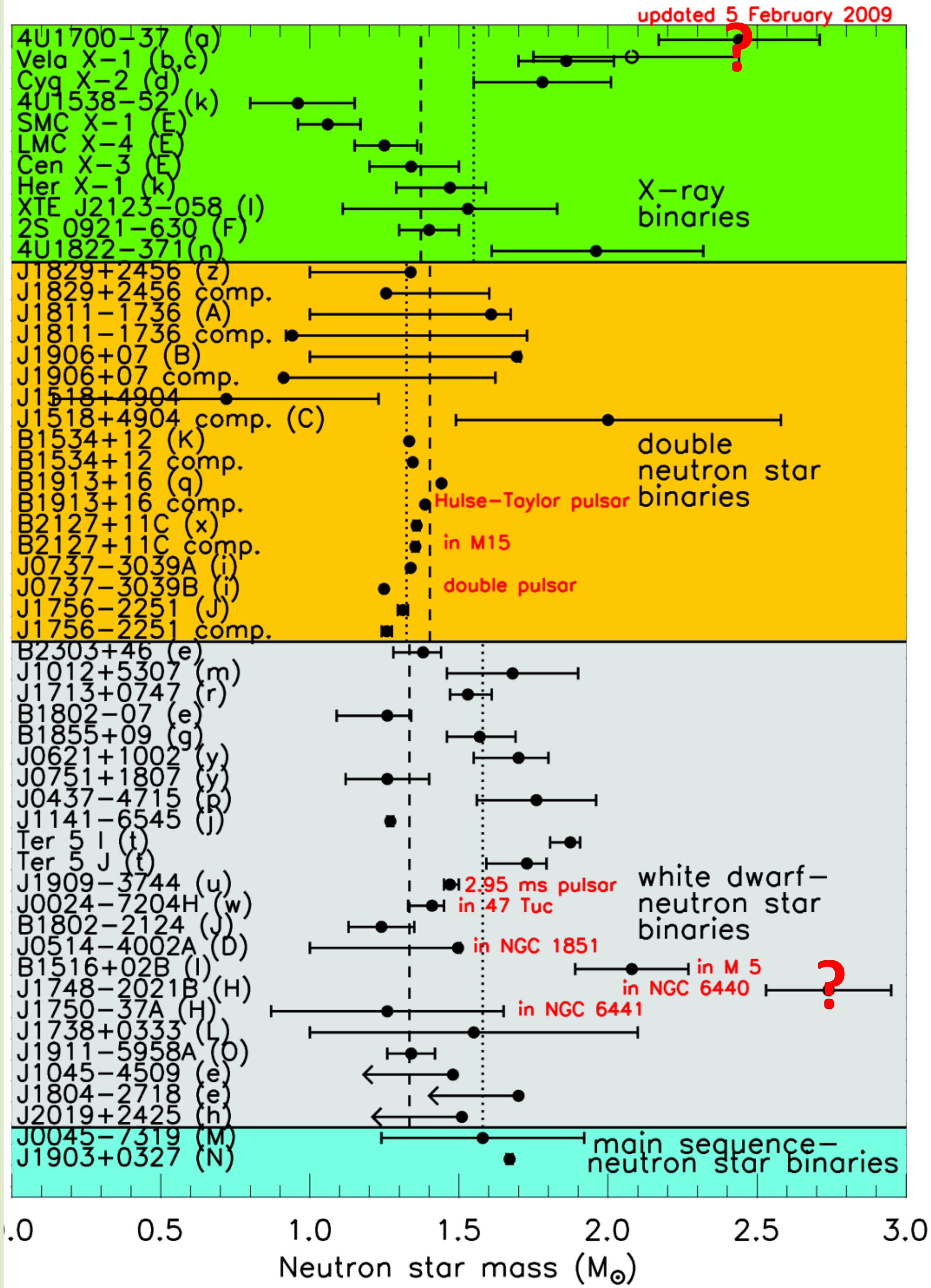
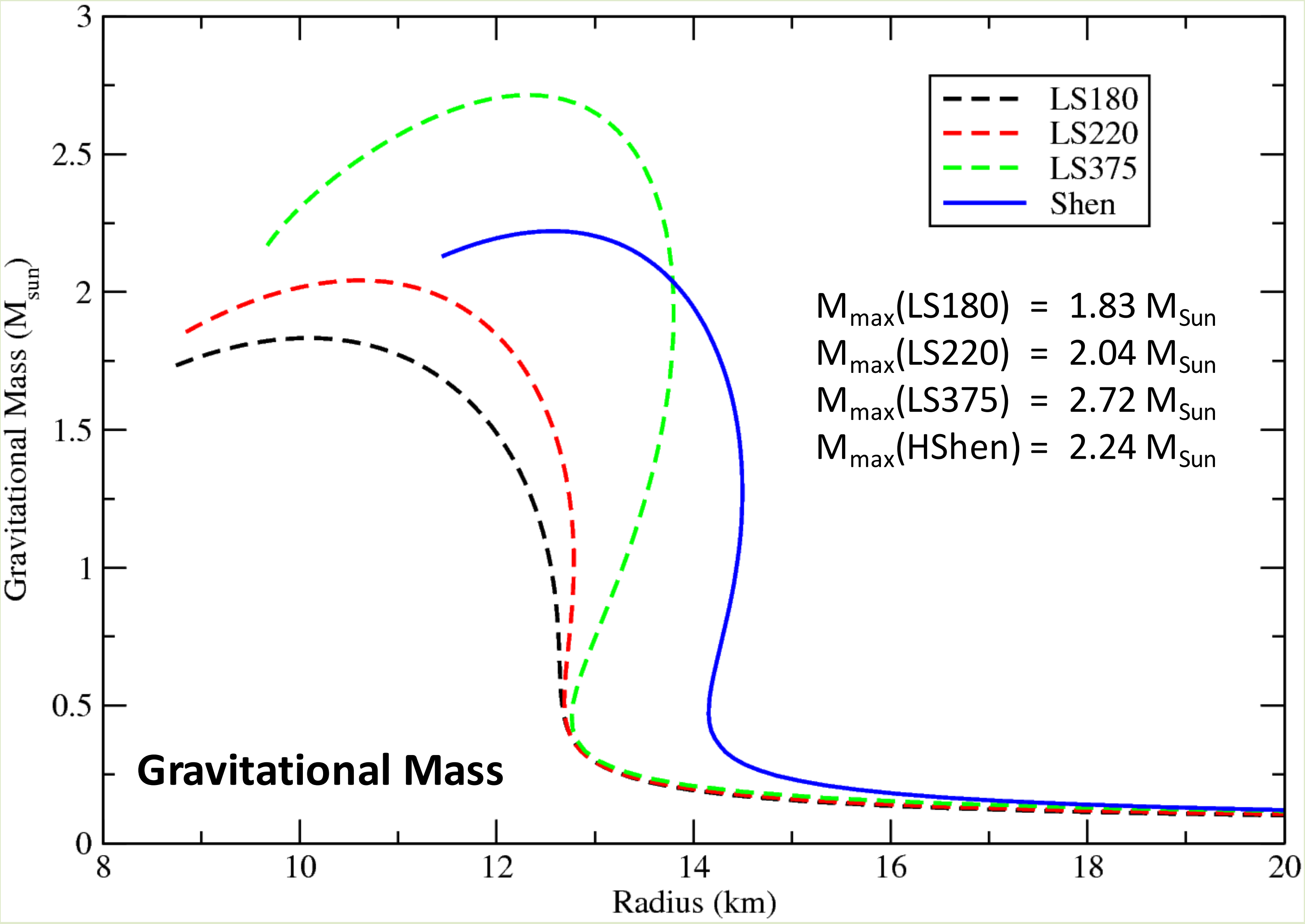
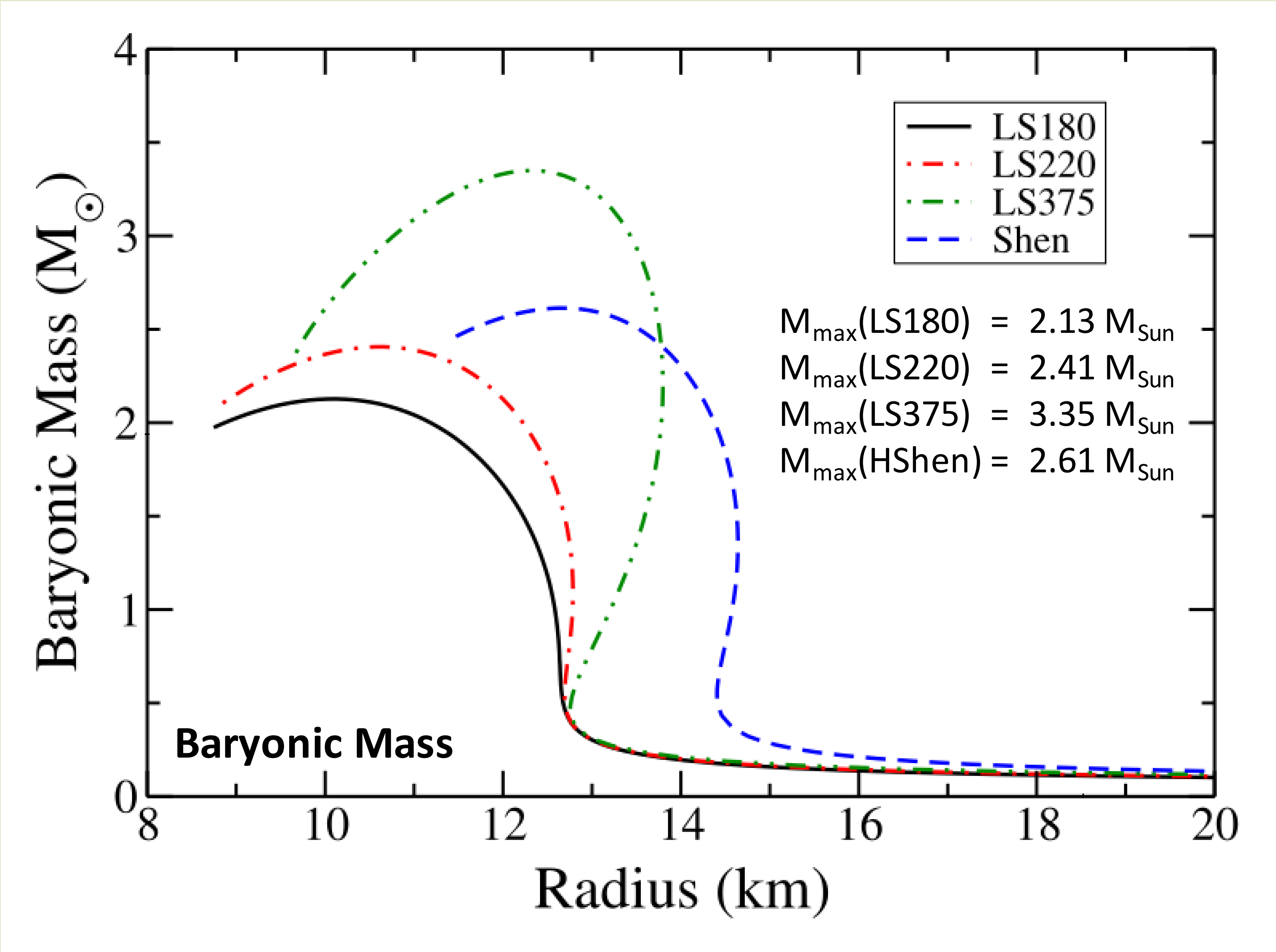


Table provided by Jim Lattimer

Neutron Star Masses (TOV, T=0.1 MeV, β equil.)



Neutron Star Masses (TOV, T=0.1 MeV, β equil.)



The Essence of Core-Collapse Supernova Explosion Mechanisms

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

Core-Collapse Supernova Mechanisms

Introduced by:

Mechanism	Introduced by
Neutrino Mechanism	[Colgate & White '66, Arnett '66, Wilson '85, Bethe & Wilson '85]
Magnetorotational Mechanism	[LeBlanc & Wilson '70, Bisnovatyi-Kogan et al. '76, Meier et al. '76, Symbalisty '84]
Acoustic Mechanism	[proposed by Burrows et al. '06, '07; not yet confirmed by other groups/codes]
Magneto-Viscous Mechanism	[Akiyama et al. '03, Thompson et al. '05]
Phase-Transition-Induced Mechanism	[Migdal et al. '71, Sagert et al. '09]

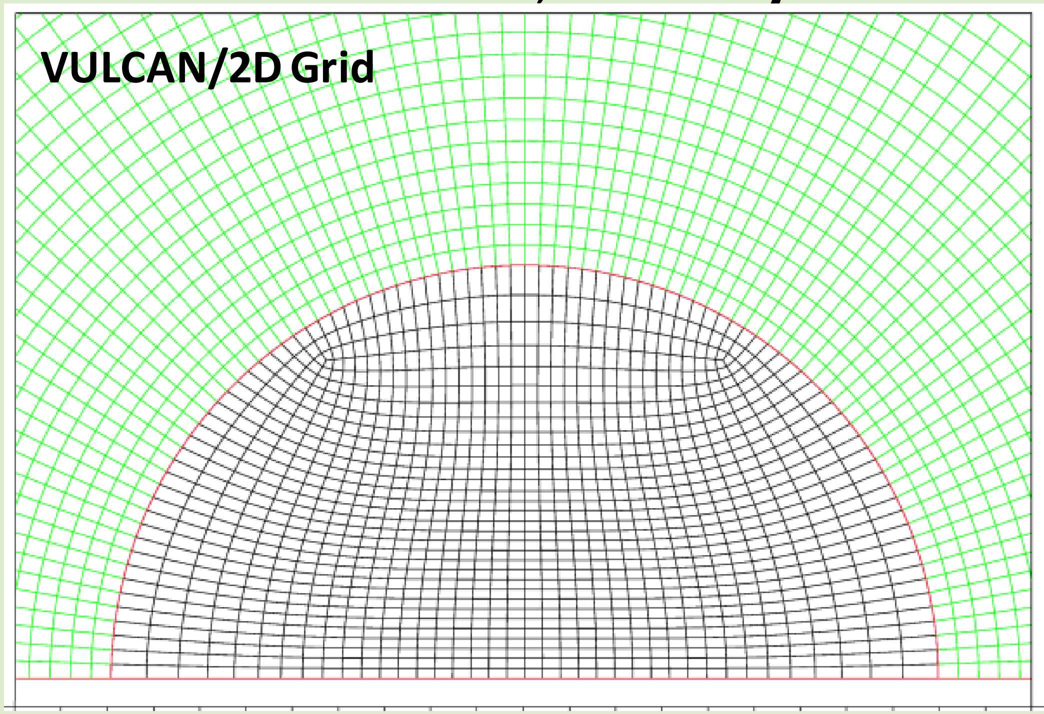
Core-Collapse Supernova Simulations of the Princeton (Jerusalem/Caltech/Marseille/Seattle) Group with VULCAN/2D

Adam Burrows (Princeton), Luc Dessart (Marseille), Eli Livne (Hebrew U),
Jeremiah Murphy (U Washington), Christian D. Ott (Caltech)

The VULCAN/2D Code

[Livne 1993, Livne et al. 2004, Livne et al. 2007, Burrows et al. 2007, **Ott et al. 2008**]

- **Axisymmetric Newtonian Magnetohydrodynamics** with rotation (2.5D).
- Unsplit 2nd order arbitrary Eulerian/Lagrangian (**ALE**) scheme.
- Newtonian gravity, logically cylindrical coordinates, **arbitrary mesh**.
- Radiation Transport:
  - **multi-group flux-lim. diff.** & **angle-dependent transport**.
  - Multiple energy groups, ν_e, $\bar{\nu}_e$, "ν_μ" species.
  - Slow-motion approximation.
- Multiple finite-temperature nuclear EOS options.
- Efficient parallelization in neutrino species/energy groups. Typical run size: 48–96 cores.



- Typical problem sizes: 50k zones x $\mathcal{O}(50)$ vars (MGFLD) x $\mathcal{O}(50)$ for angle-dep. transport.

Core-Collapse Supernova Mechanisms

Introduced by:

Neutrino Mechanism — [Colgate & White ‘66, Arnett ‘66, Wilson ‘85, Bethe & Wilson ‘85]

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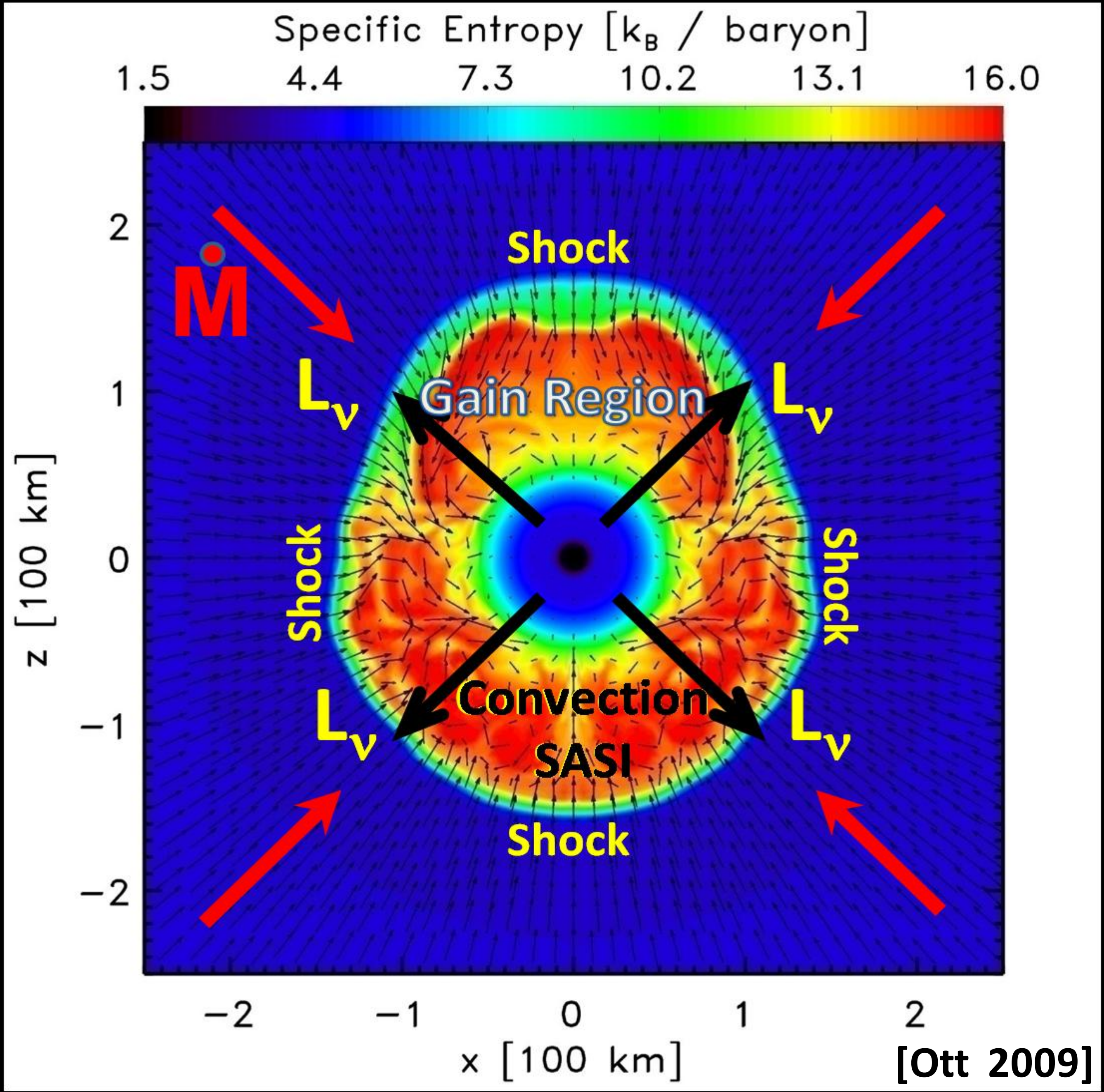
Neutrino Mechanism



[Ott 2009]

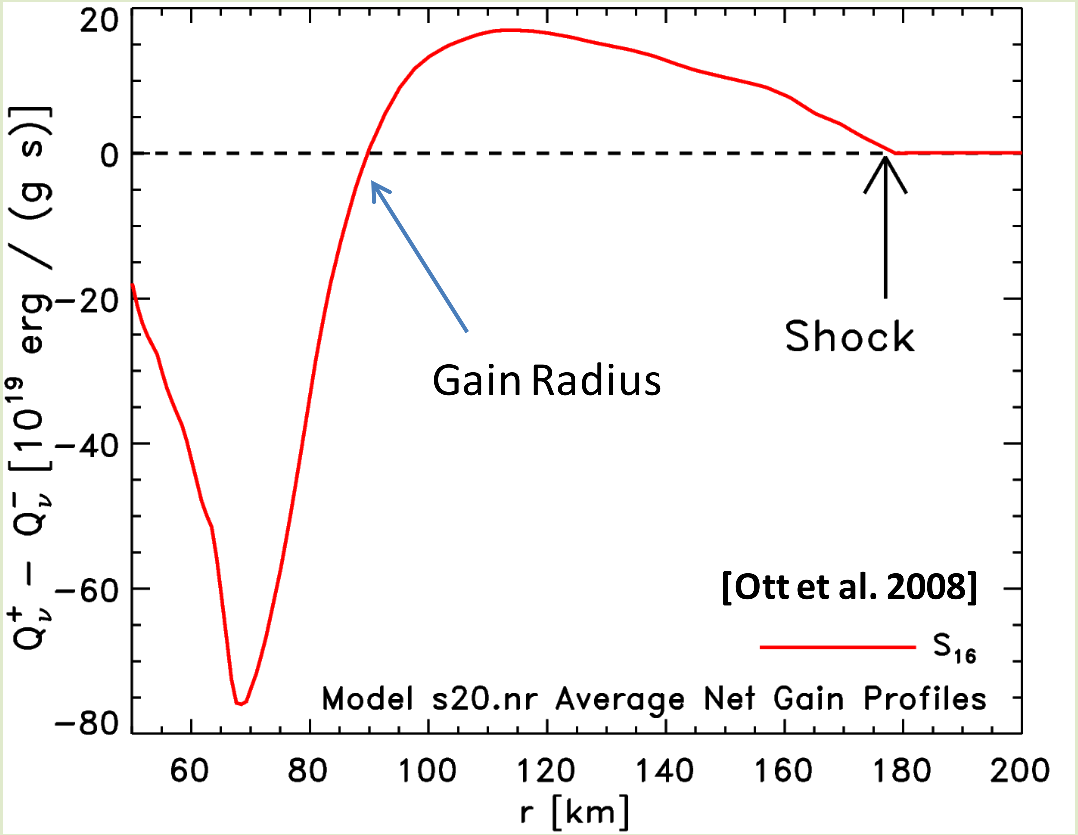
The Neutrino Mechanism

[Wilson 1985, Bethe & Wilson 1985; recent reviews: Kotake et al. 2006, Janka et al. 2007, Murphy & Burrows 2008]

- Neutrino cooling: $Q_\nu^- \propto T^6$
- Neutrino heating: $Q_\nu^+ \propto L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$

Net heating where:
$$Q_\nu^+ > Q_\nu^-$$

- **Neutrino mechanism**: Based on subtle imbalance between neutrino **heating** and **cooling** in the postshock region.



Problem:

Fails to explode massive stars in spherical symmetry.

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

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 et al. 2007c, Fischer et al. '09]
- **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.**

- **Bruenn, Mezzcappa, Messer et al. 2009** (conf. proceedings): 2D + soft EOS + pseudo-GR potential + ray-by-ray MGFLD neutrino transport. **-> early, strong explosions** (disagreement with Marek & Janka?)

- **Ott et al. 2008: No neutrino-driven explosions in angle-dependent VULCAN/2D simulations (but: Shen EOS, Newtonian gravity).**

Core-Collapse Supernova Mechanisms

Introduced by:

Neutrino Mechanism — [Colgate & White '66, Arnett '66, Wilson '85, Bethe & Wilson '85]

→ **Magnetorotational Mechanism** — [LeBlanc & Wilson '70, Bisnovatyi-Kogan et al. '76, Meier et al. '76, Symbalisty '84]

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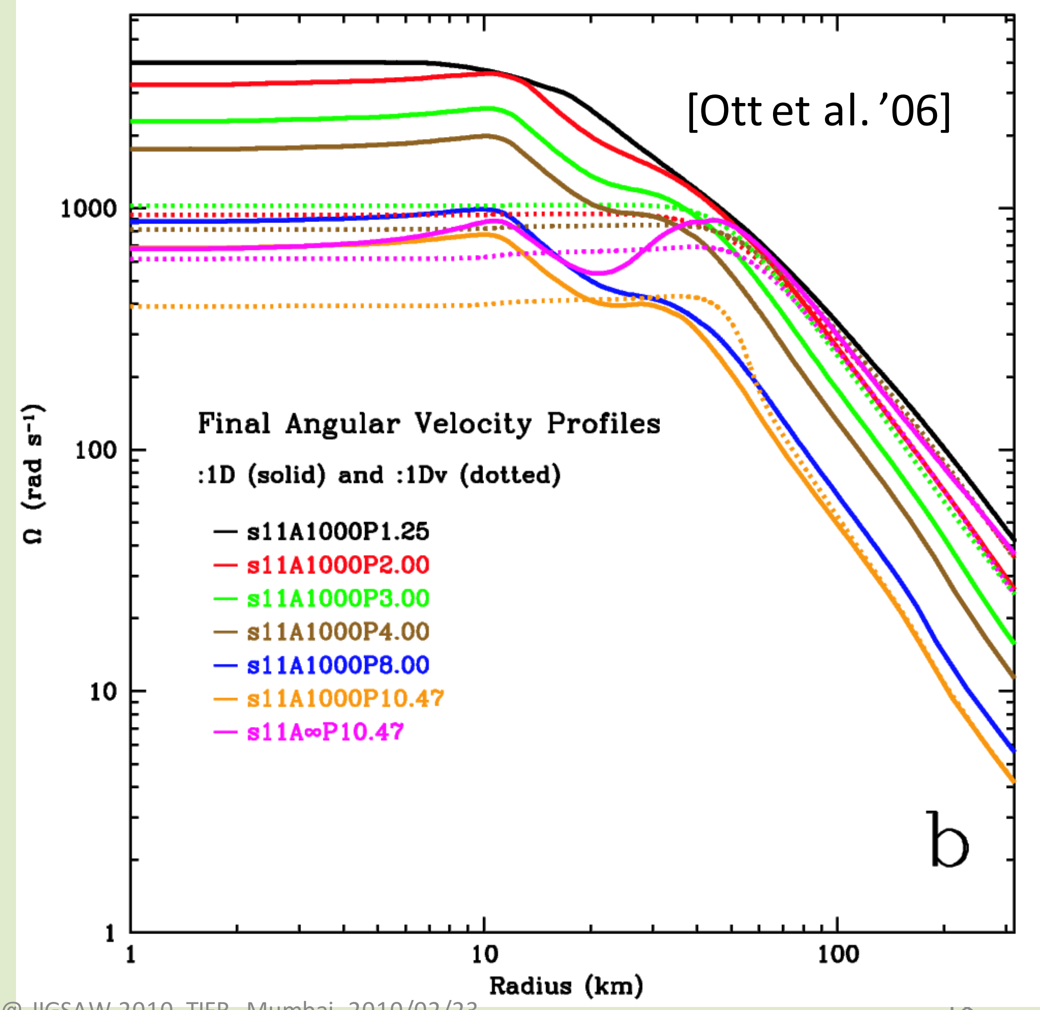
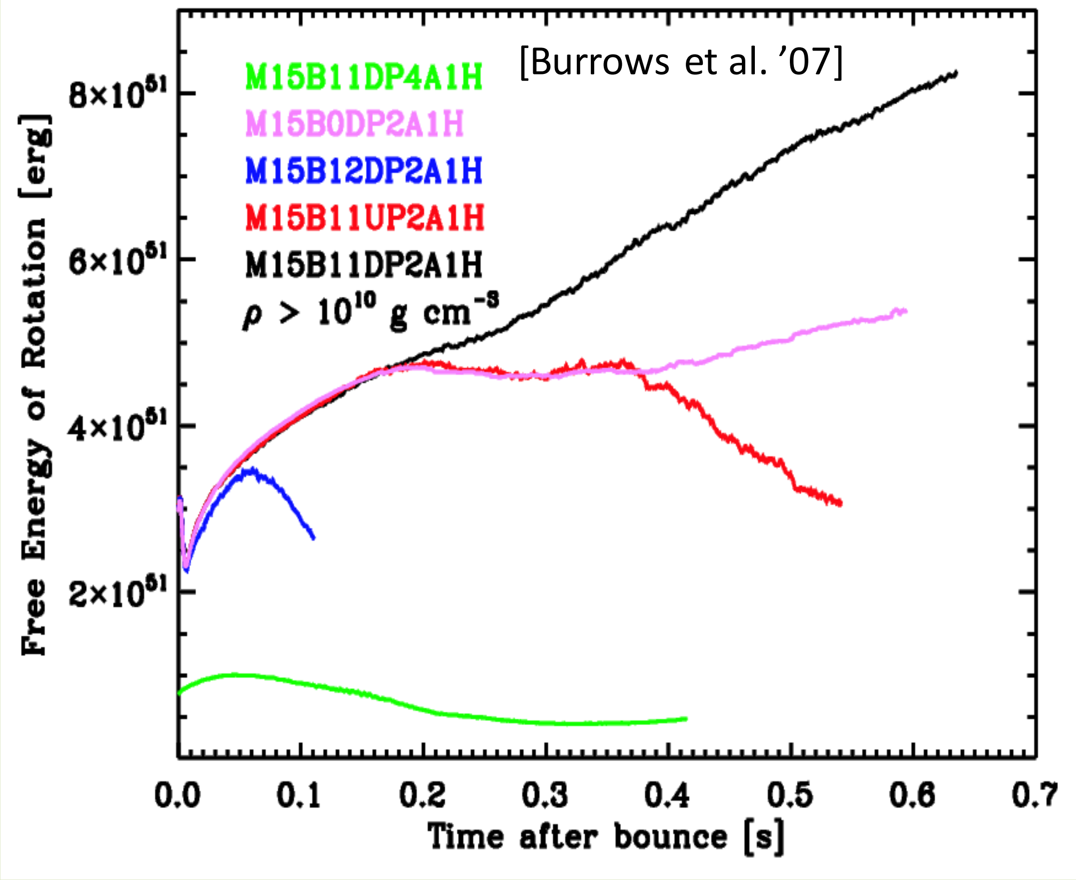
Free Energy of Differential Rotation

- Lowest energy state of rotating body at fixed angular momentum is solid body rotation.
- **Differential rotation is a natural consequence of rotating collapse.**



Free Energy of Differential Rotation

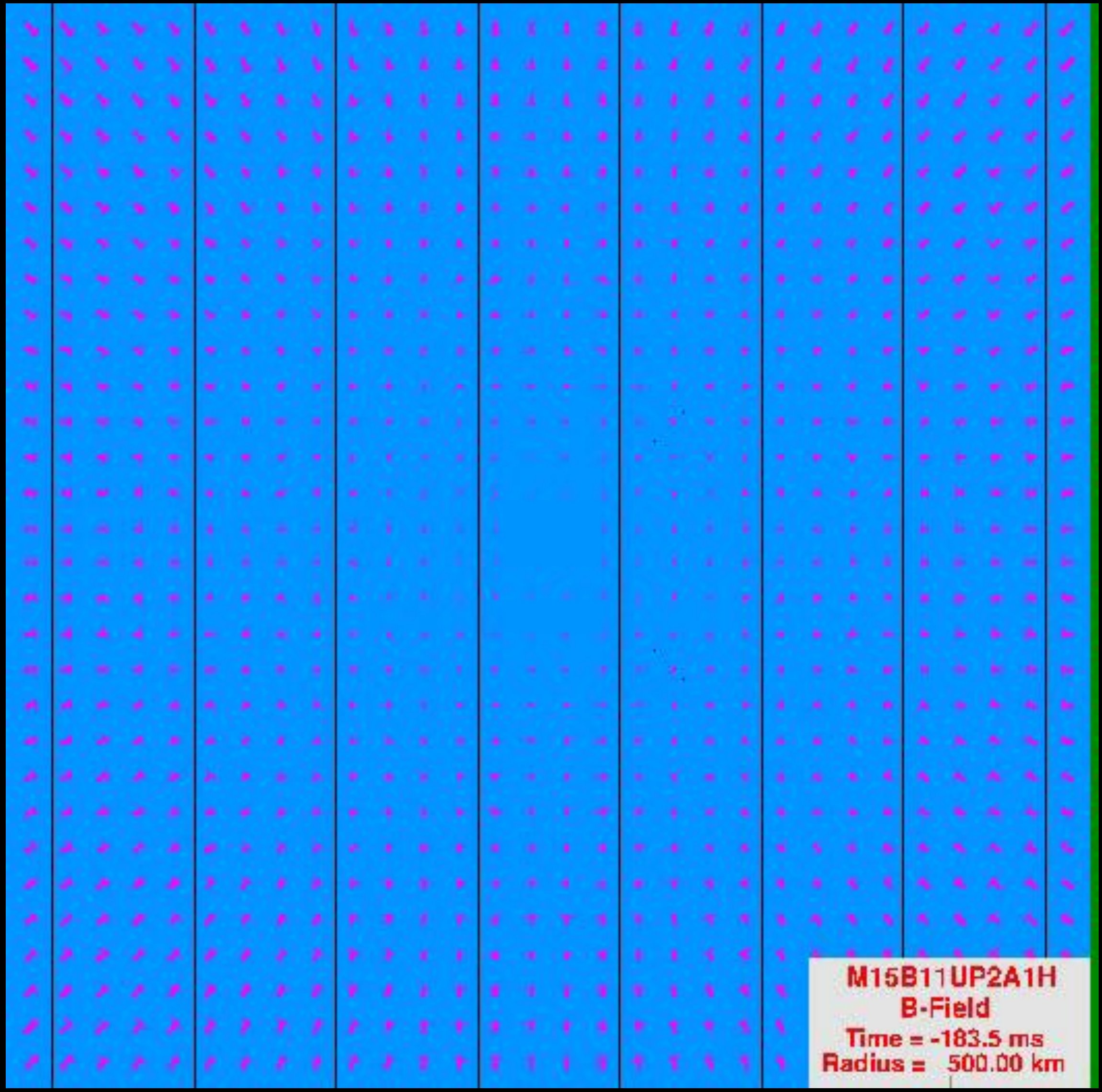
- Lowest energy state of rotating body at fixed angular momentum is solid body rotation.
- **Differential rotation is a natural consequence of rotating collapse.**
- **-> "free energy" of differential rotation can be tapped by process(es) operating on rotational shear dΩ/dr.**
  - Ω-dynamo (winding)
  - Magnetorotational Instability. (MRI)
- Precollapse central iron-core periods < 4 s needed to supply > 1 B explosion energy.
- Caveat: Vast majority of massive stars probably slow rotators with $P_{c,0}$ > 10 s [Ott et al. '06, Heger et al. '05].



MHD-driven Explosions

[e.g., Burrows et al. 2007, Dessart et al. 2008, Shibata et al. 2006, Kotake et al. 2004, Yamada & Sawai 2004]

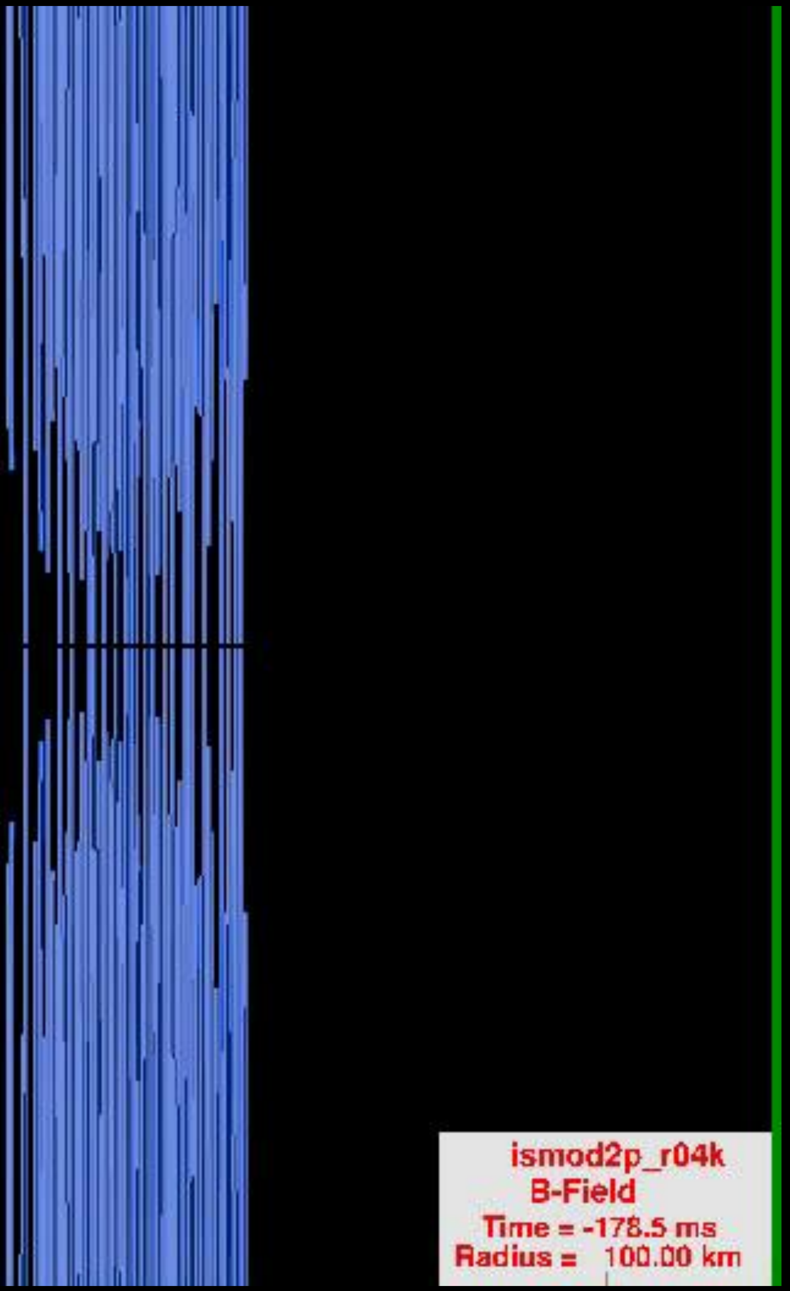
- **Rapid rotation**: P_0<4-6 s -> millisecond PNS
- PNS rotational energy: ~10 B = 10^{52} erg
- Amplification of B fields up to equipartition:
  - compression
  - dynamos
  - magneto-rotational instability (MRI)
- BUT: MRI not resolved. Ansatz: Start with large progenitor field to get final field as if MRI worked.
- Jet-driven outflows.
- MHD-driven explosion may be GRB precursor.



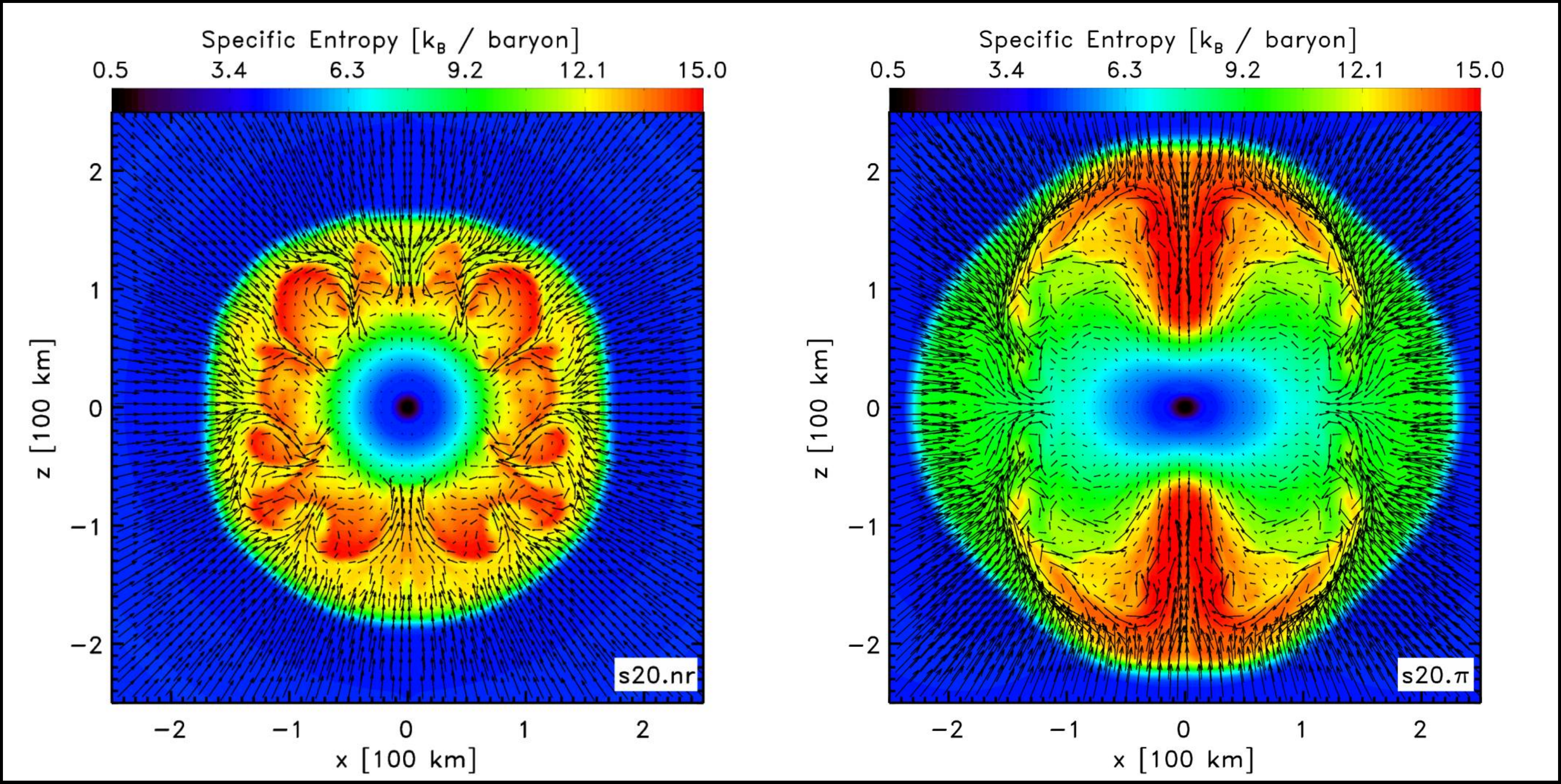
VULCAN 2D R-MHD code, Livne et al. 2007, Burrows et al. 2007.

Newtonian Radiation-MHD Simulations with VULCAN/2D

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



Another Twist: Rotation & Convection



$$N^2 + \frac{1}{r^3}\frac{d}{dr}j^2 < 0$$

$$j = \Omega r^2$$

$$N^2 = \frac{g}{p\gamma}\left(\left.\frac{\partial p}{\partial s}\right|_{\rho,Y_l}\frac{ds}{dr} + \left.\frac{\partial p}{\partial Y_l}\right|_{\rho,s}\frac{dY_l}{dr}\right)$$

Core-Collapse Supernova Mechanisms

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Magneto-Viscous Mechanism

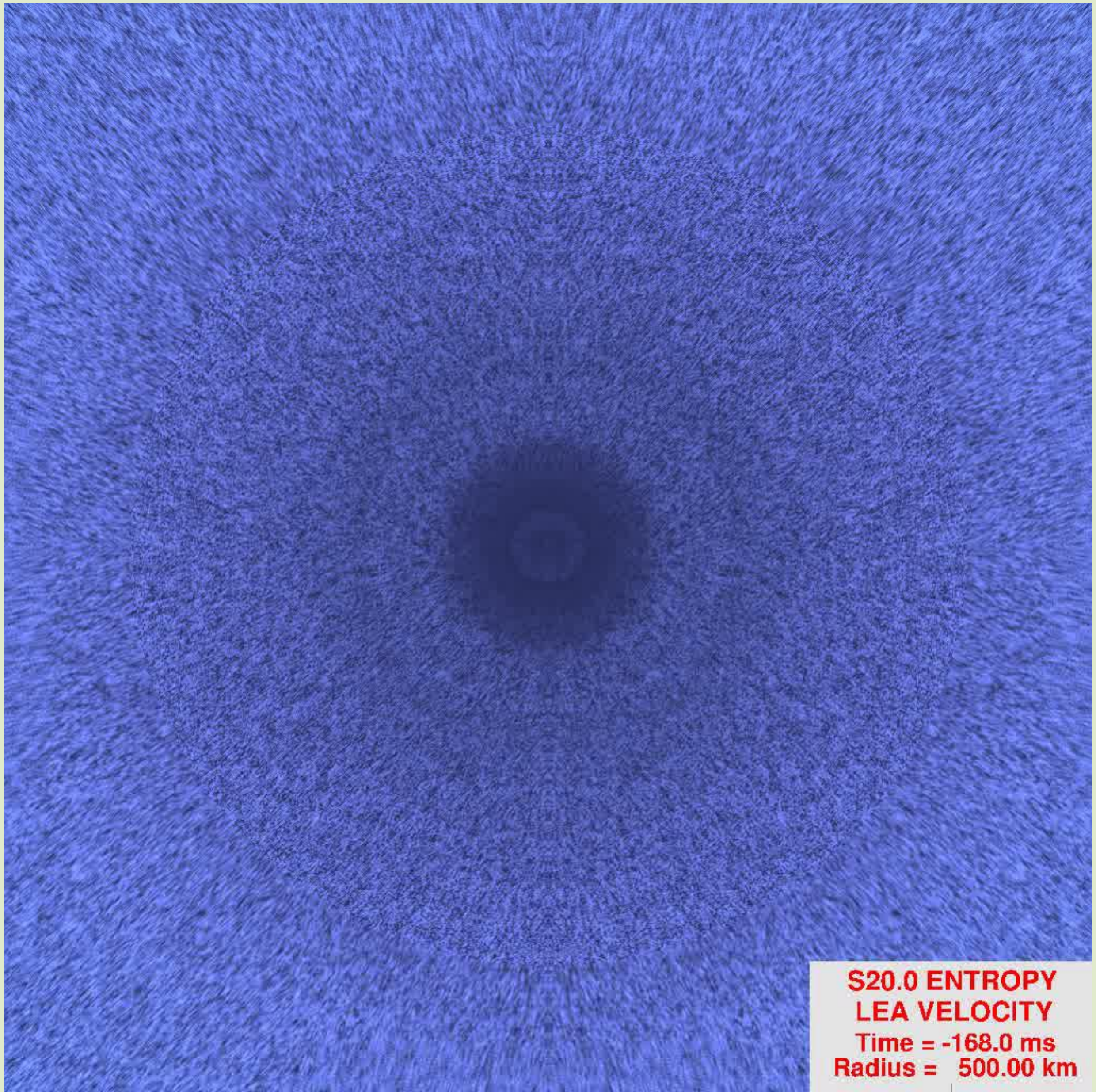
[Akiyama et al. ‘03, Thompson et al. ‘05]

Phase-Transition-Induced Mechanism

[Migdal et al. ’71, Sagert et al. ‘09]

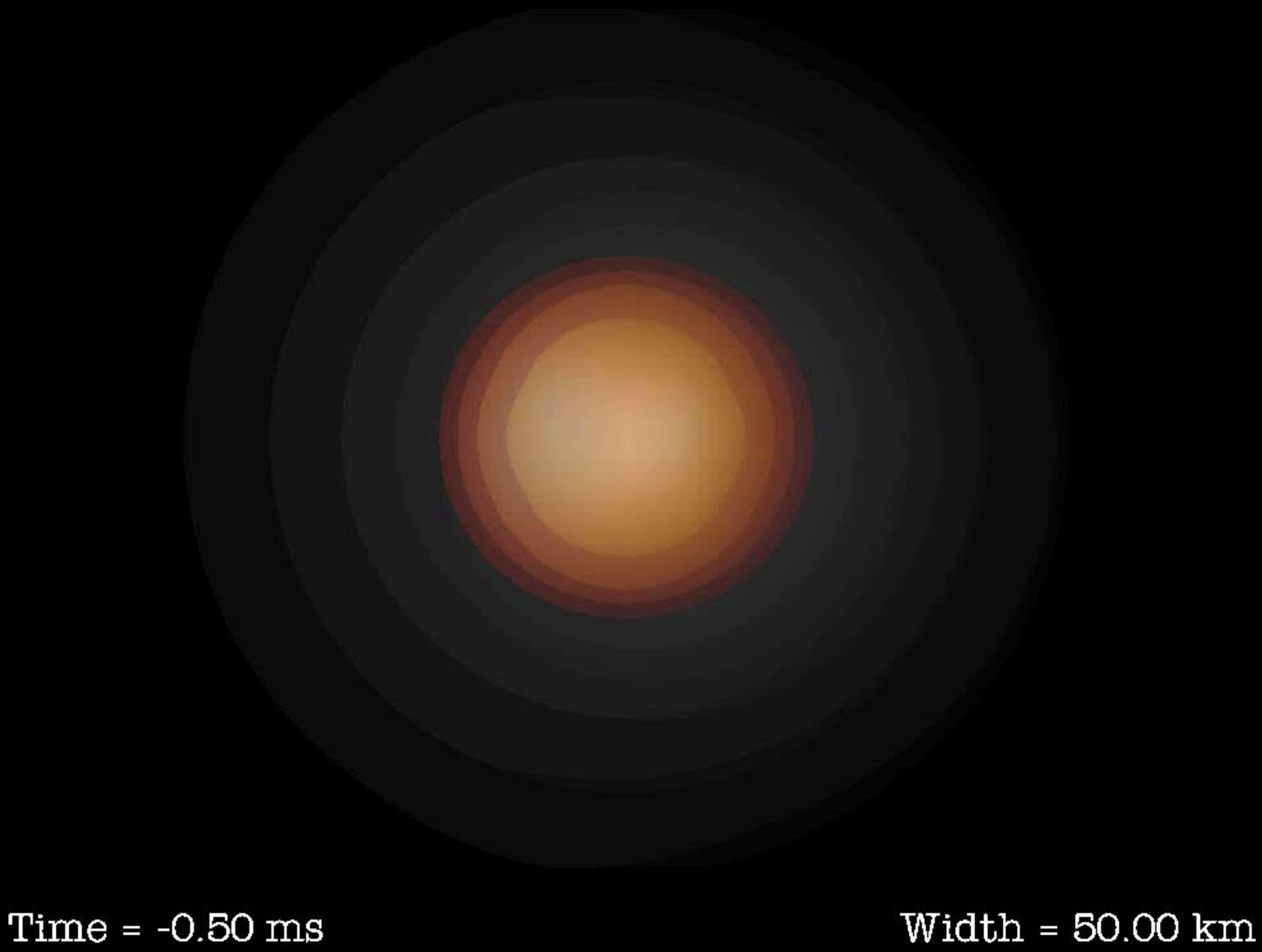
Standing Accretion Shock Instability

[e.g., Blondin et al. 2003,2006; Foglizzo et al. 2006, Scheck et al. 2006, 2007, Burrows et al. 2006, 2007]



Advective-acoustic cycle drives shock instability.

Seen in simulations by all groups!

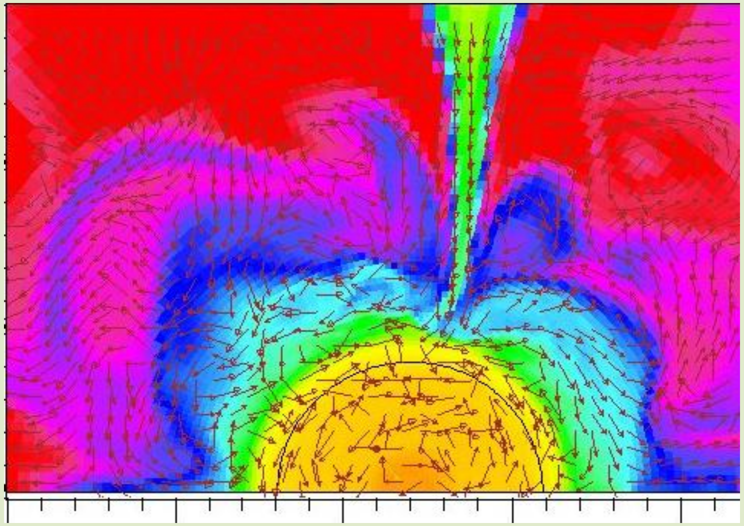


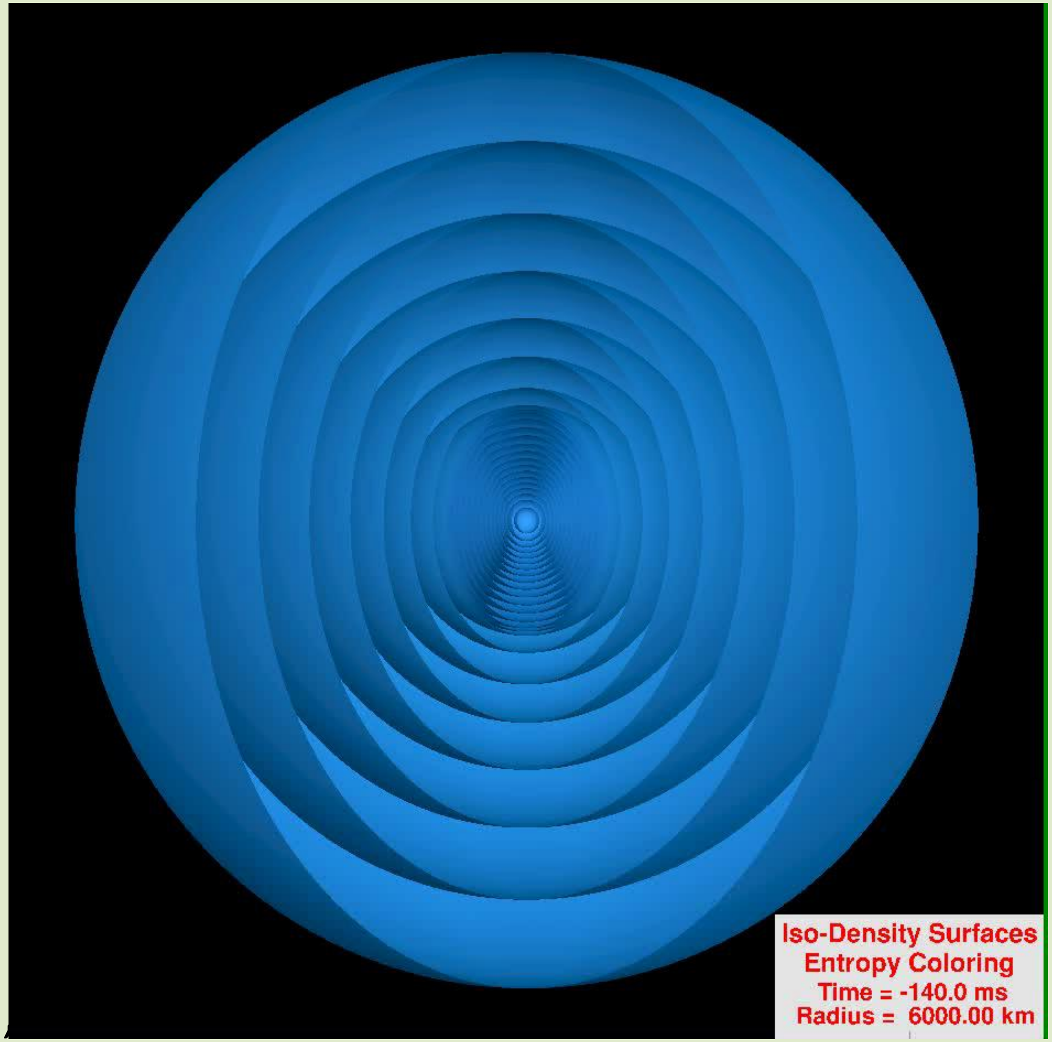
PNS core oscillations, Burrows et al. 2006, 2007; Ott et al. 2006

Acoustic Mechanism

[Burrows, Livne, Dessart, Ott, Murphy 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.



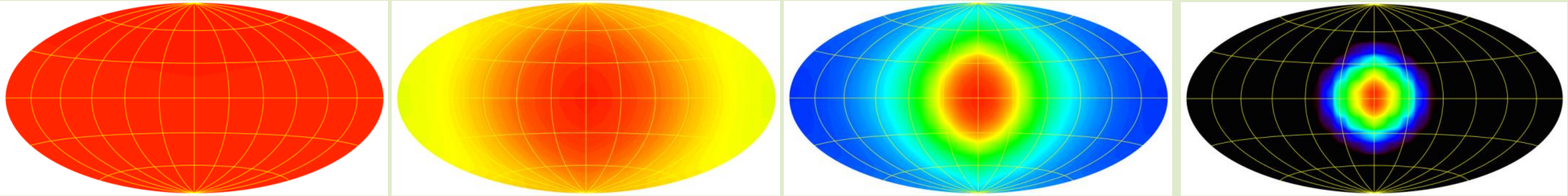


- g-modes reach large amplitudes ~500 ms —1 s after bounce.
- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.
- ~1 B explosions at late times.
- (1) hard to simulate; unconfirmed, (2) possible parametric instability, limiting mode amplitudes. [Weinberg & Quatert'08]

2D Angle-Dependent Neutrino Radiation-Hydrodynamics Core-Collapse Supernova Simulations

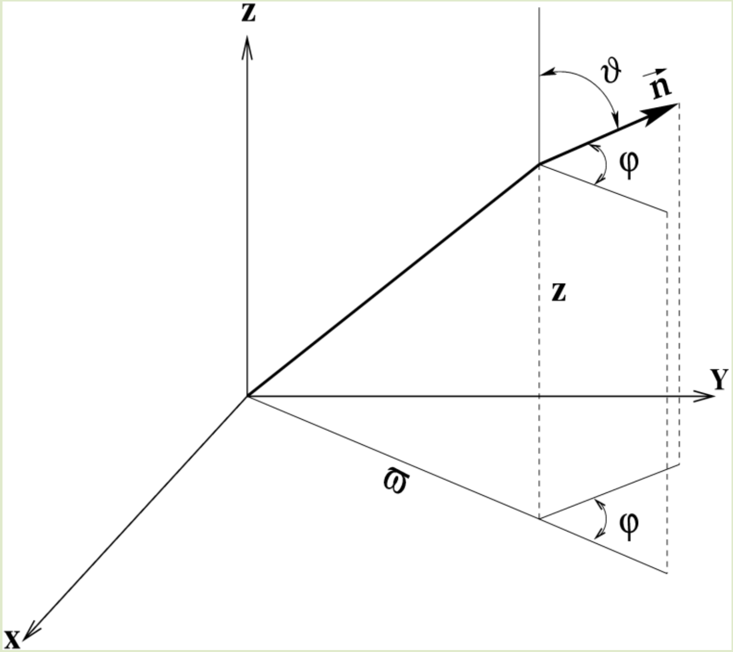
Ott et al. 2008, ApJ

with Adam Burrows (Princeton), Luc Dessart (Marseille), and Eli Livne (Hebrew University, Jerusalem)



The First 2D Angle-Dependent Neutrino-RHD Simulations

[Livne et al. 2004, **Ott et al. 2008, Ott et al. 2009**]



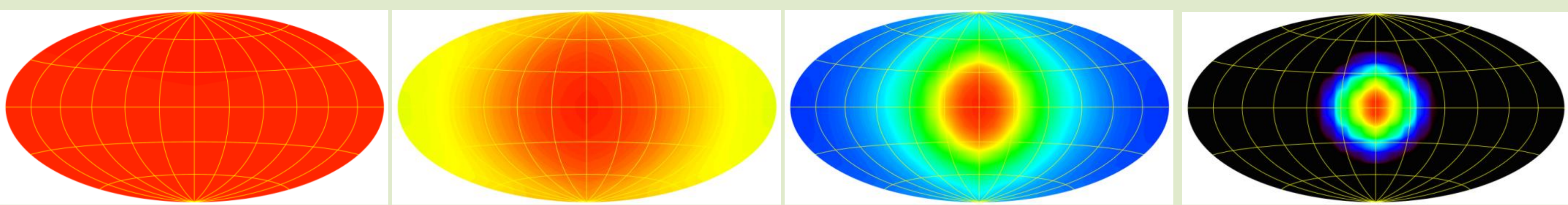
- Method of short-characteristics S_n
  [e.g. Castor 2004]
- Evolution of the specific intensity.

$$\frac{1}{c}\frac{\partial I(\vec{r},\vec{n},\epsilon_\nu)}{\partial t} + \vec{n}\,\vec{\nabla} I(\vec{r},\vec{n},\epsilon_\nu) = \Xi[I(\vec{r},\vec{n},\epsilon_\nu),\rho,T,Y_e]$$

$$J = \frac{1}{4\pi}\oint I d\Omega \qquad \vec{H} = \frac{1}{4\pi}\oint \vec{n} I d\Omega \qquad \mathbf{K} = \frac{1}{4\pi}\oint \vec{n}\cdot\vec{n}\, I d\Omega$$

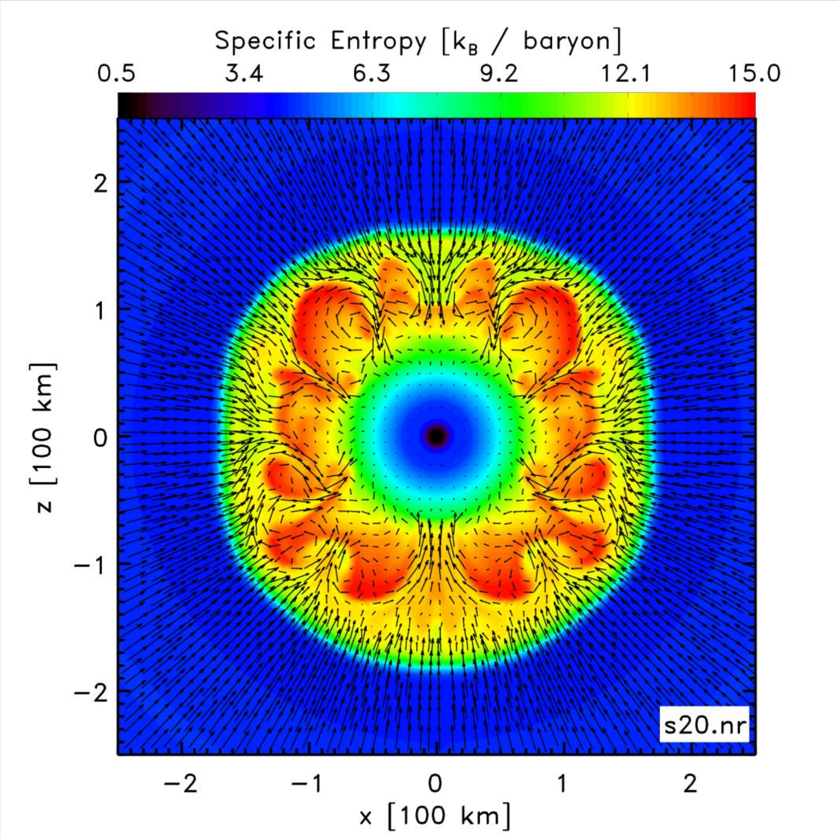
- 5D: 2D spatial,
  3D (ϵ, θ, ϕ) momentum space.

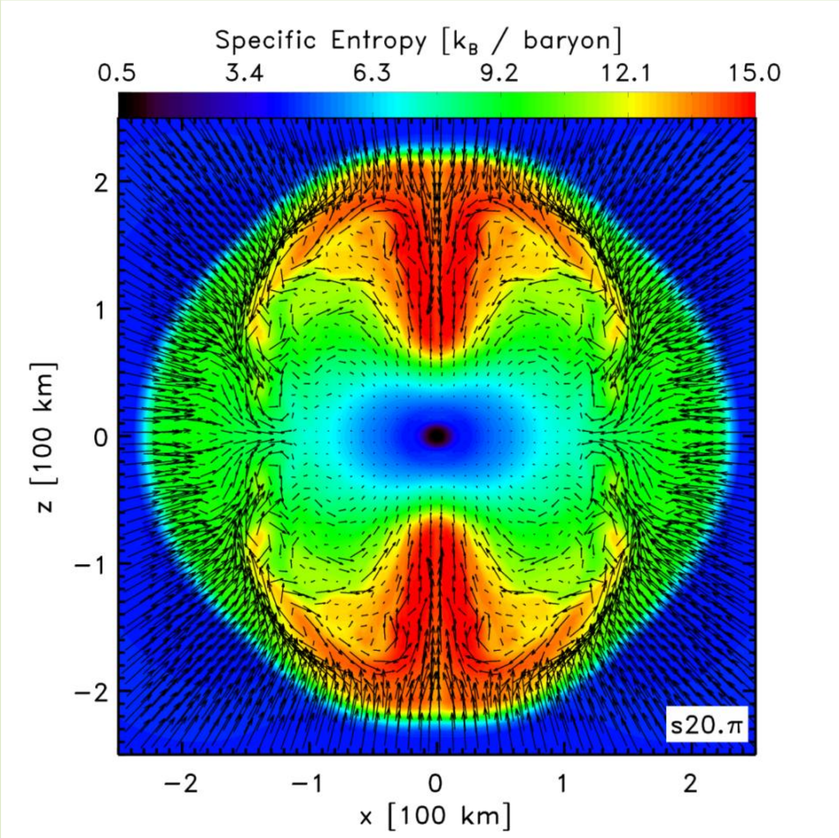
- At high optical depths: matching to diffusion approximation.
- Comparison with multi-group flux-limited diffusion approximation.



30 km 60 km 120 km 240 km

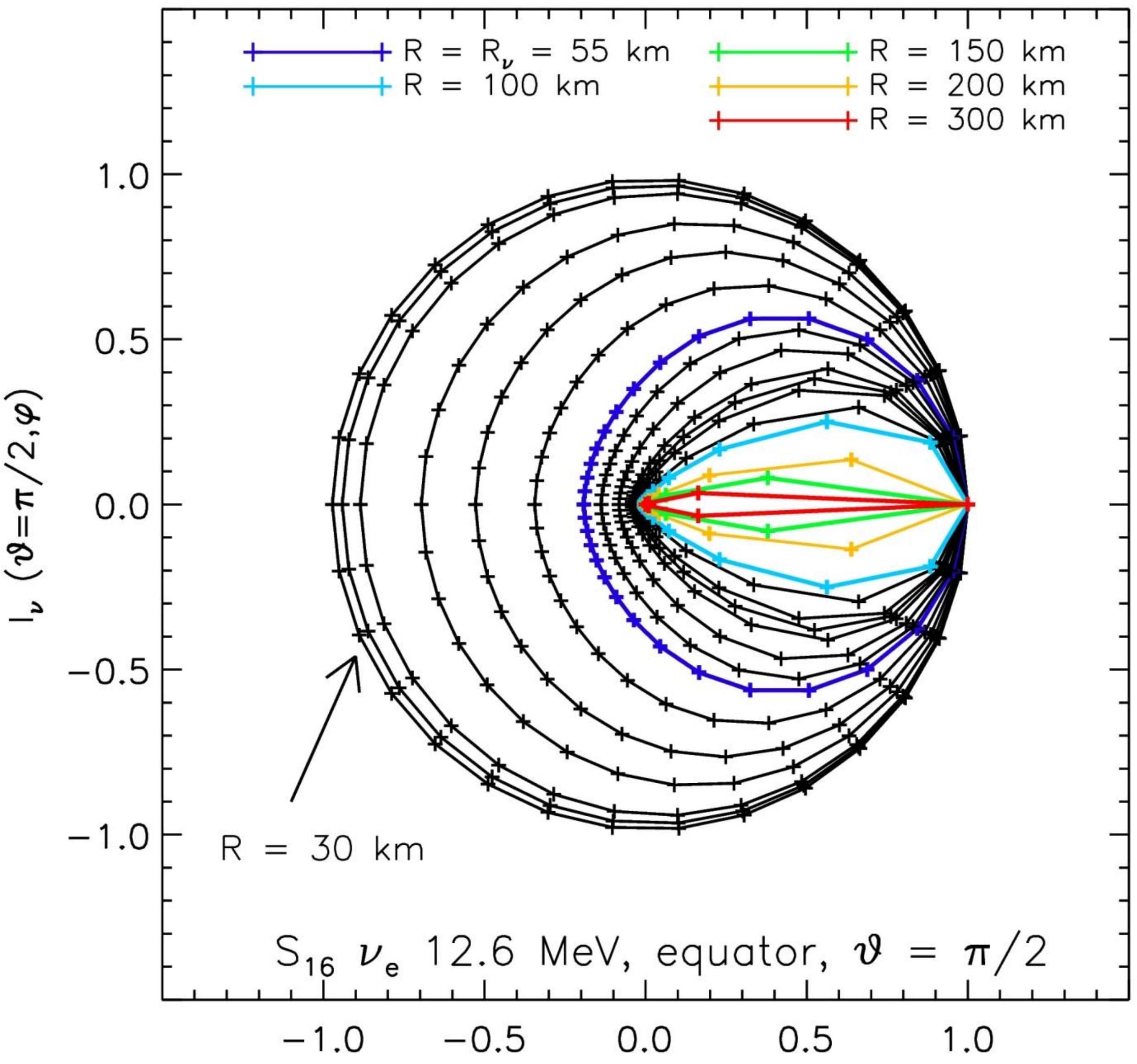
Postbounce SN Models:

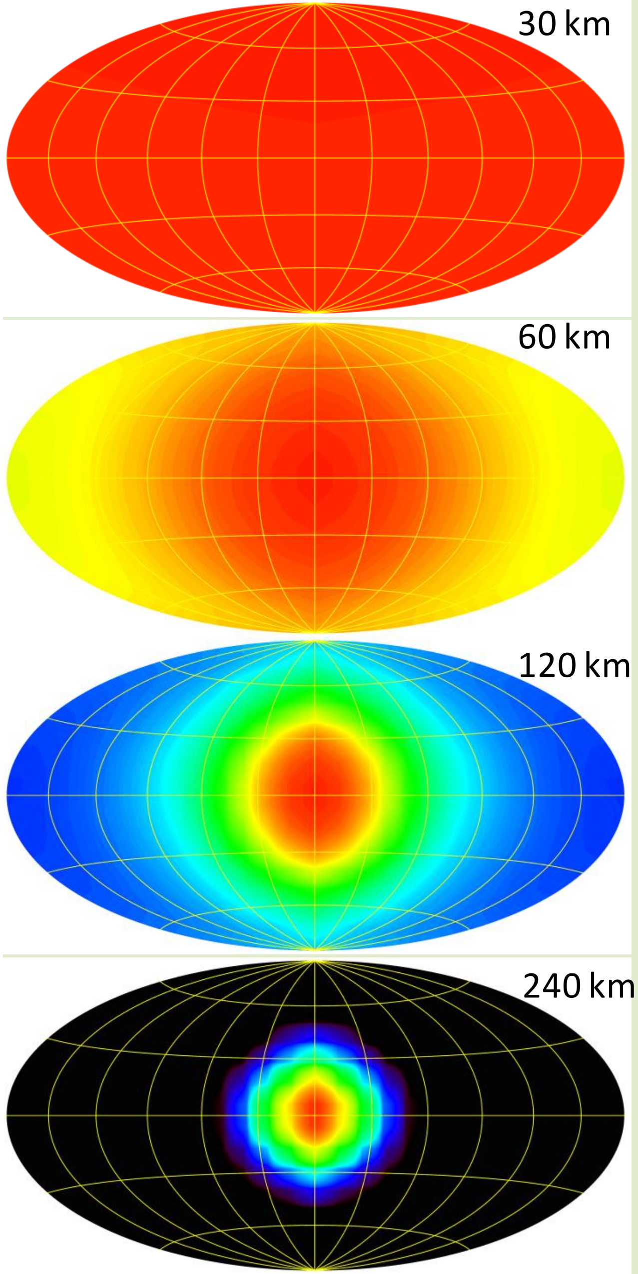




- 20-solar mass star of Woosley, Heger & Weaver 2002. Shen EOS.
- Nonrotating (s20.nr) and rotating model (s20.π, precollapse central P_0 = 2 s, Ω_0 = π rad/s).
- Evolved to 160 ms postbounce with MGFLD, then stationary-state S_n solution.
- Steady-State solutions with S_8,S_{12},S_{16} -> 40,92,162 total angular zones.
- Long-term (~400 ms) time-dependent calculations with S_8.

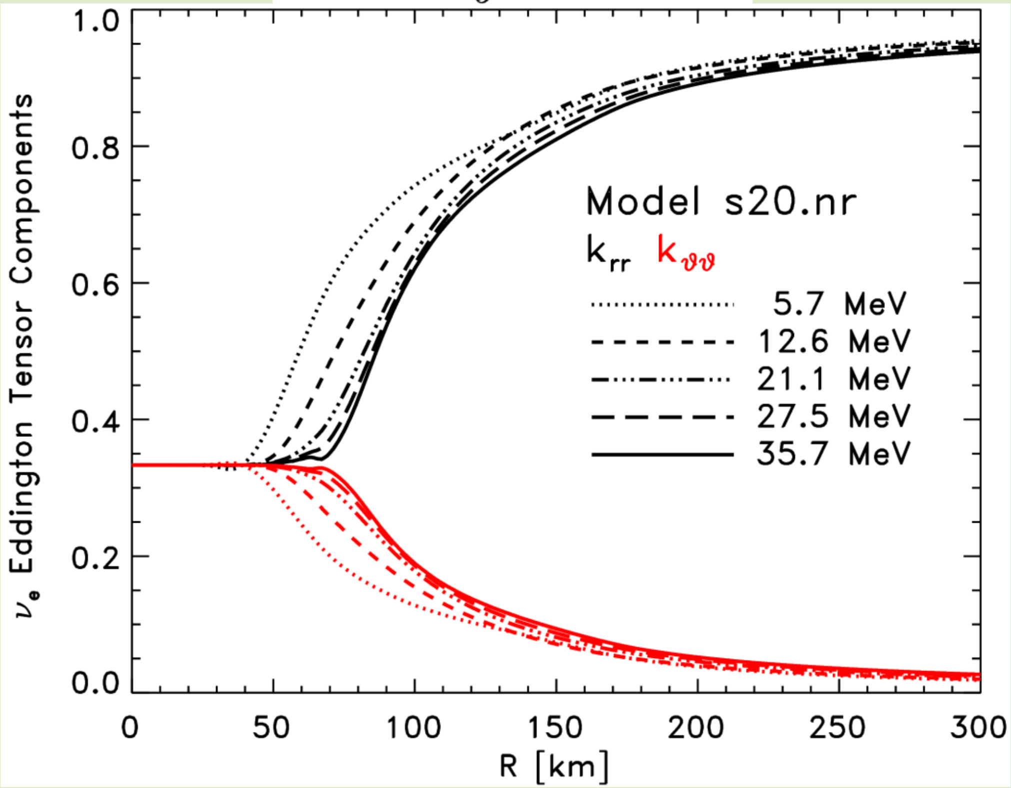
The Radiation Field





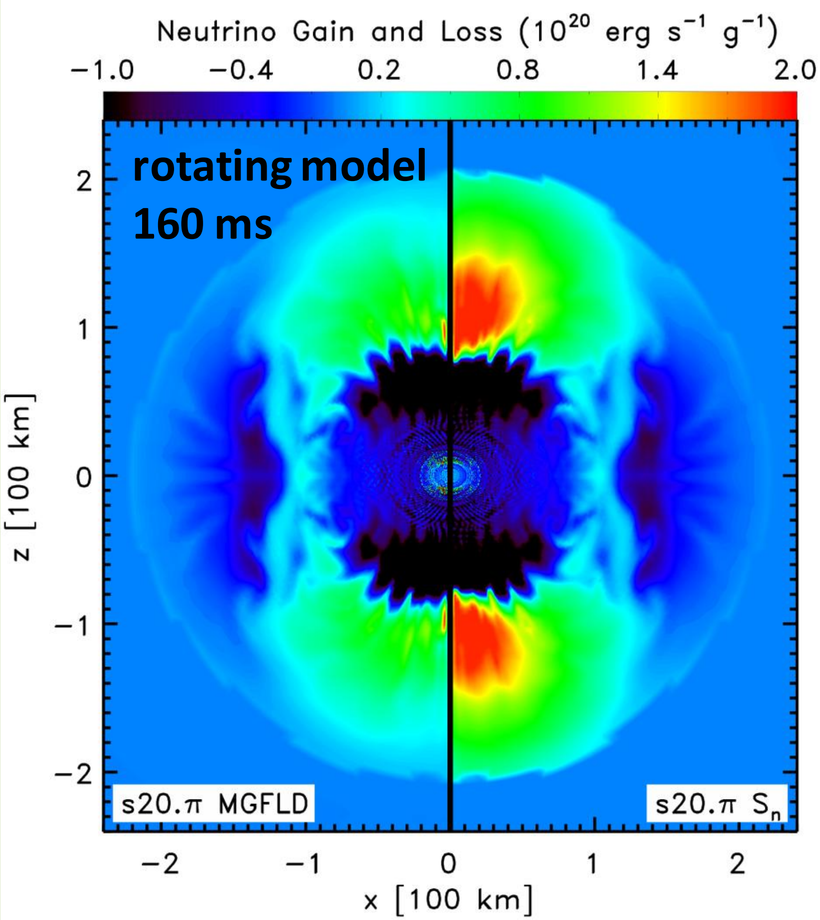
Eddington Tensor Components

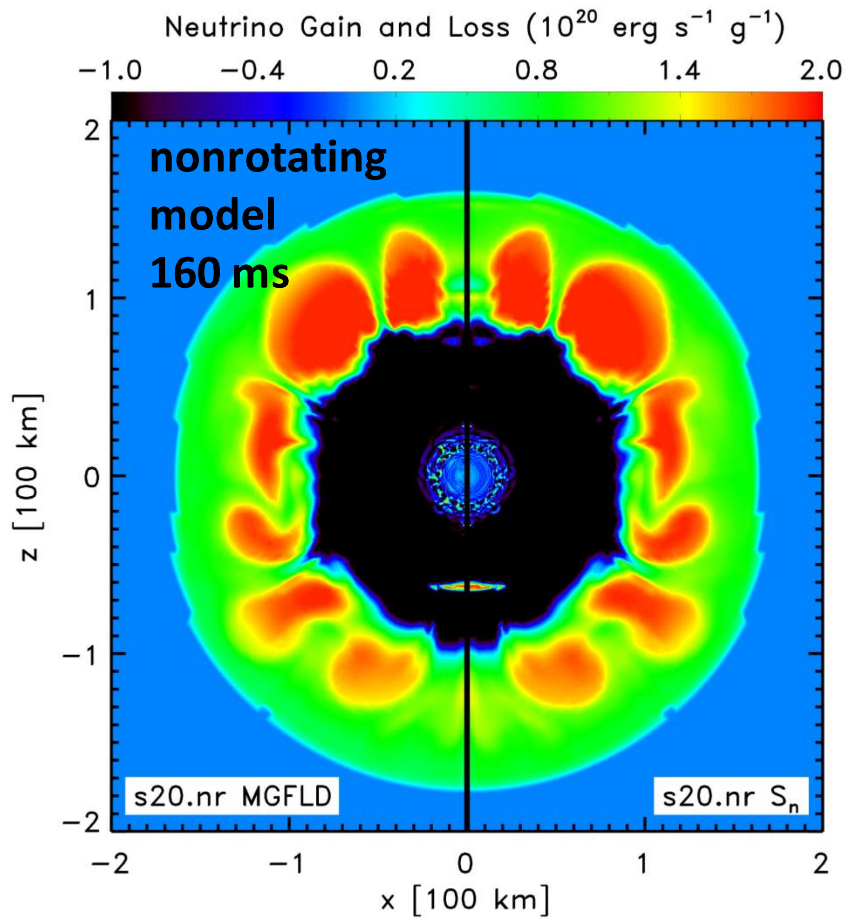
$$\mathbf{K} = \frac{1}{4\pi} \oint \vec{n} \cdot \vec{n} \, I \, d\Omega$$



- In axisymmetry and without velocity dependence: 4 independent components (3 diagonal, 1 off-diagonal).
  (note: 1D/Ray-by-Ray -> only one "Eddington factor")
- Here: spherical coordinates; off-diagonal term $K_{r\vartheta}$ small (<1%).

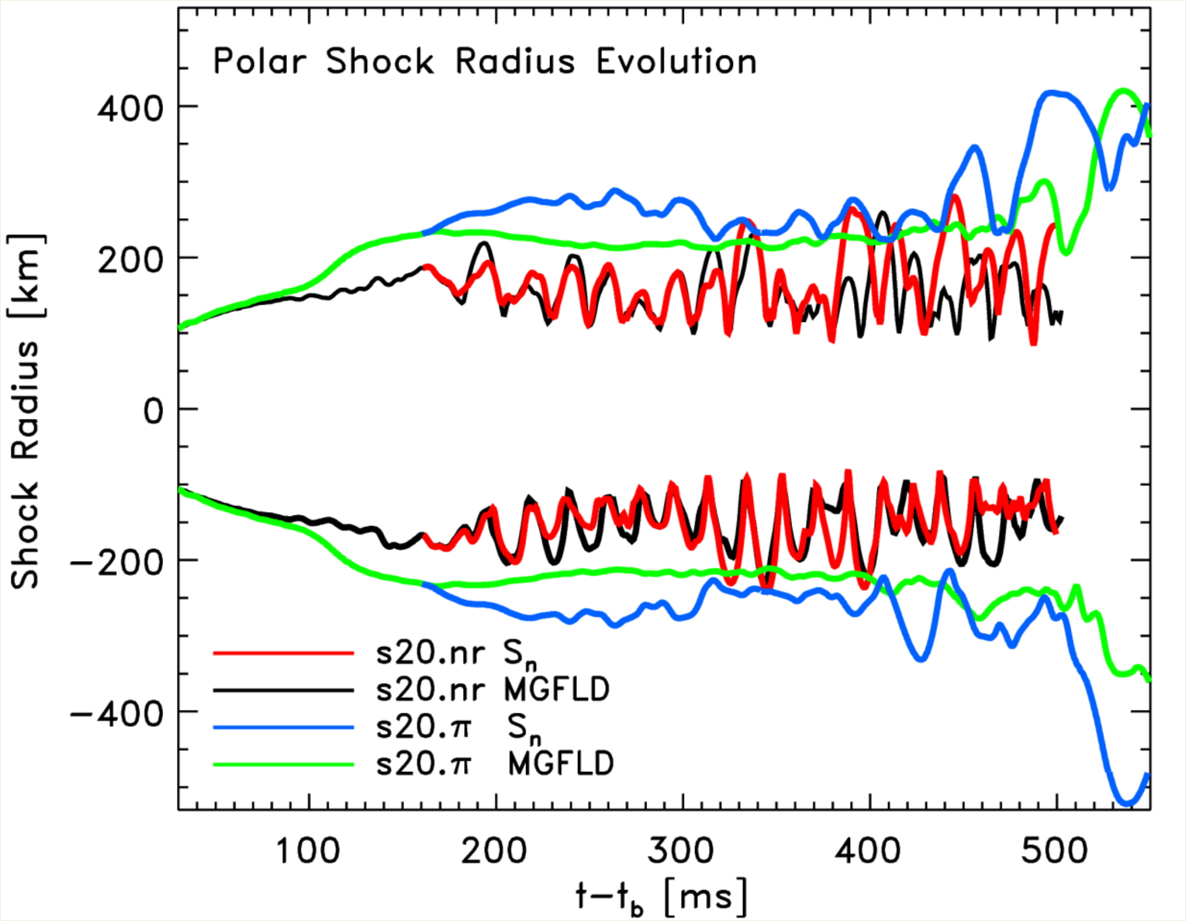
Comparing S_n with MGFLD [Ott et al. 2008]





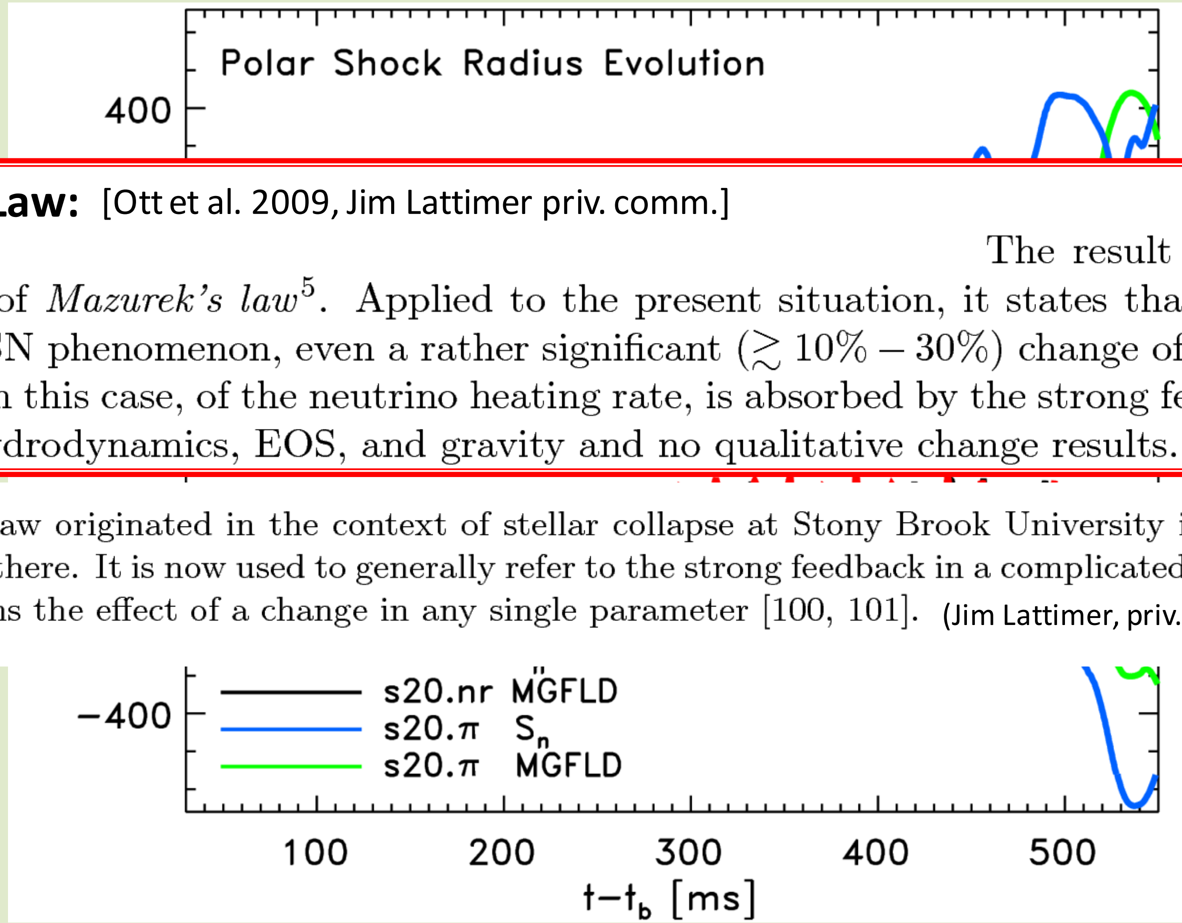
- Improved, angle-dependent transport leads to greater heating (10-30%), larger shock radii / greater excursions.
- Model appears to "settle" at new quasi-equilibrium.
- **But: No signs of explosion.**

Shock Radii



- S_n leads to *somewhat* larger shock radii / greater excursions.
- Pronounced initial polar shock expansion in s20.π.
  Model appears to “settle” at new quasi-equilibrium.
- No sign of explosion.
- s20.π develops SASI at late times, faster/stronger in S_n variant.

Shock Radii



Mazurek's Law: [Ott et al. 2009, Jim Lattimer priv. comm.]

The result of this study is an example of *Mazurek's law*[5]. Applied to the present situation, it states that in the tightly-coupled CCSN phenomenon, even a rather significant ($\gtrsim 10\% - 30\%$) change of the postbounce conditions, in this case, of the neutrino heating rate, is absorbed by the strong feedback between radiation, hydrodynamics, EOS, and gravity and no qualitative change results.

[5] Mazurek's law originated in the context of stellar collapse at Stony Brook University in the 1980's when Ted Mazurek was there. It is now used to generally refer to the strong feedback in a complicated astrophysical situation which dampens the effect of a change in any single parameter [100, 101]. (Jim Lattimer, priv. comm.)

- S_n leads to *somewhat* larger shock radii / greater excursions.
- Pronounced initial polar shock expansion in s20.π.
  Model appears to "settle" at new quasi-equilibrium.
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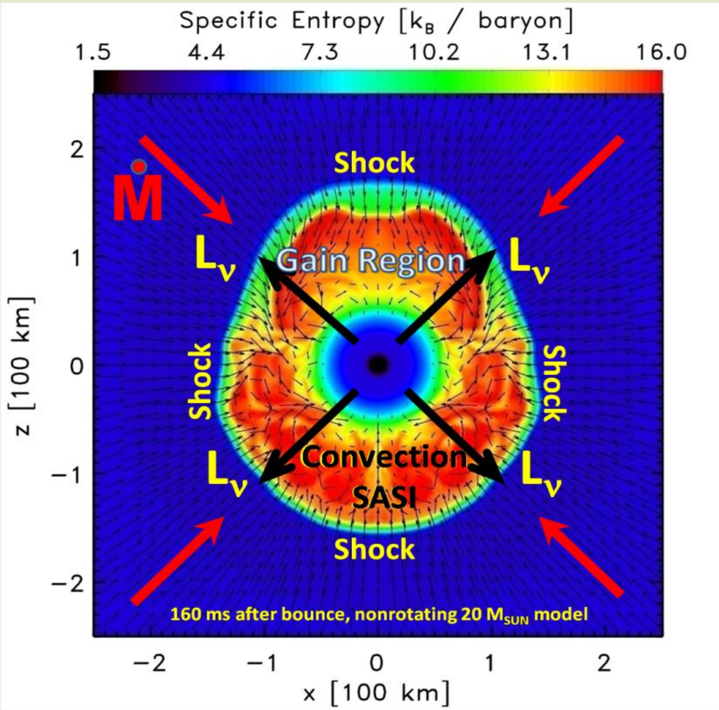
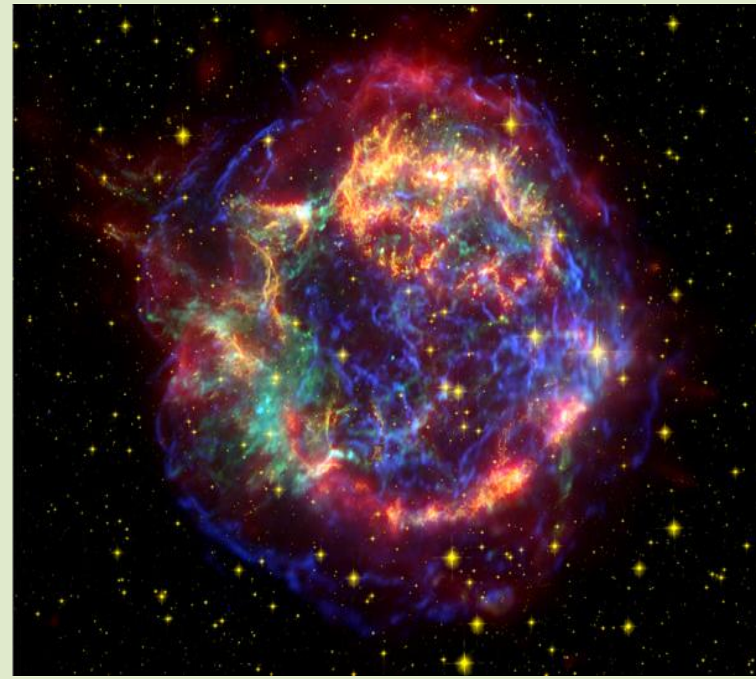
Observing the Explosion Mechanism



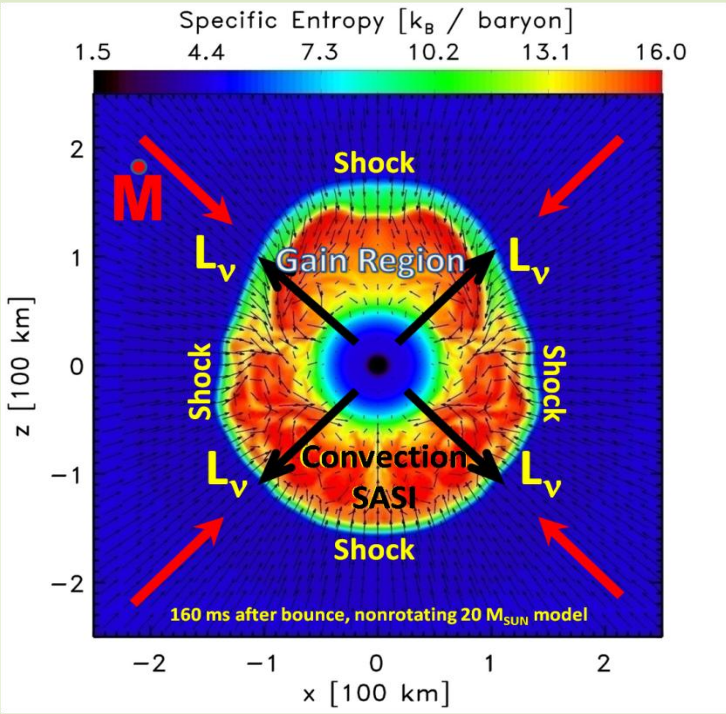


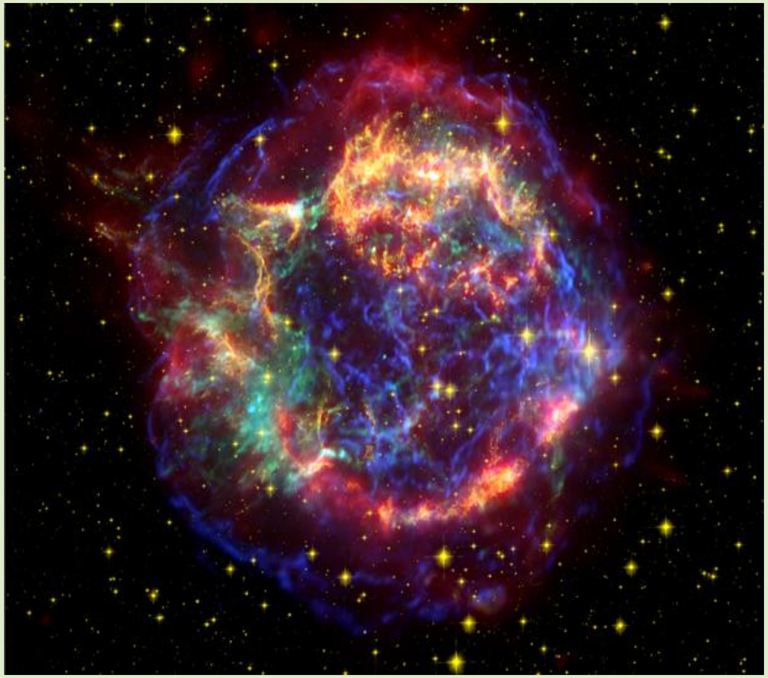
Secondary Observables

Classical Observational Astronomy:

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

Observing the Explosion Mechanism





Chandra

Neutrino and Gravitational Wave Astronomy

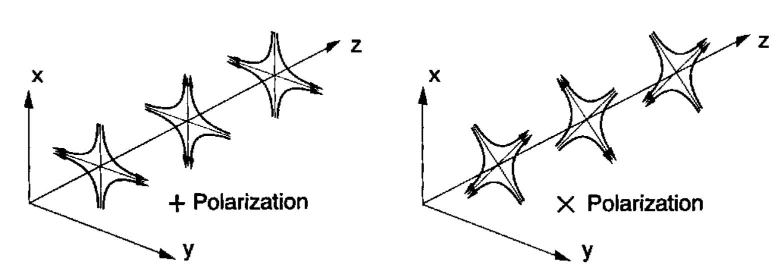
- Direct "live" information from the supernova engine.
- **Gravitational Waves: Directly linked to the ubiquitous multi-D dynamics in the postshock region and in the PNS.**

Primary Observables

Gravitational Waves

- Einstein equations in linear limit: Inhomogeneous wave equations -> Gravitational Waves.
- 2 polarizations:

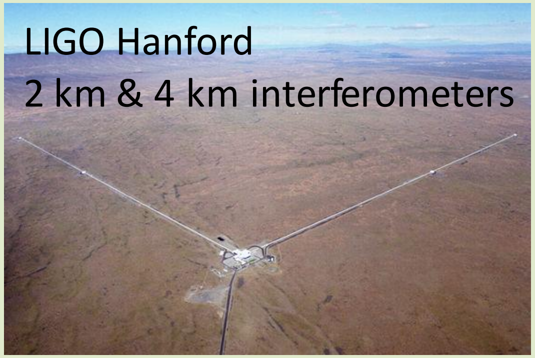
$$\mathbf{h} = h_+ \mathbf{e}_+ + h_\times \mathbf{e}_-$$



- Emission: GWs are of leading order quadrupole waves. Emitted by accelerated aspherical bulk-mass motions. "Weak-field", "slow-motion" limit:

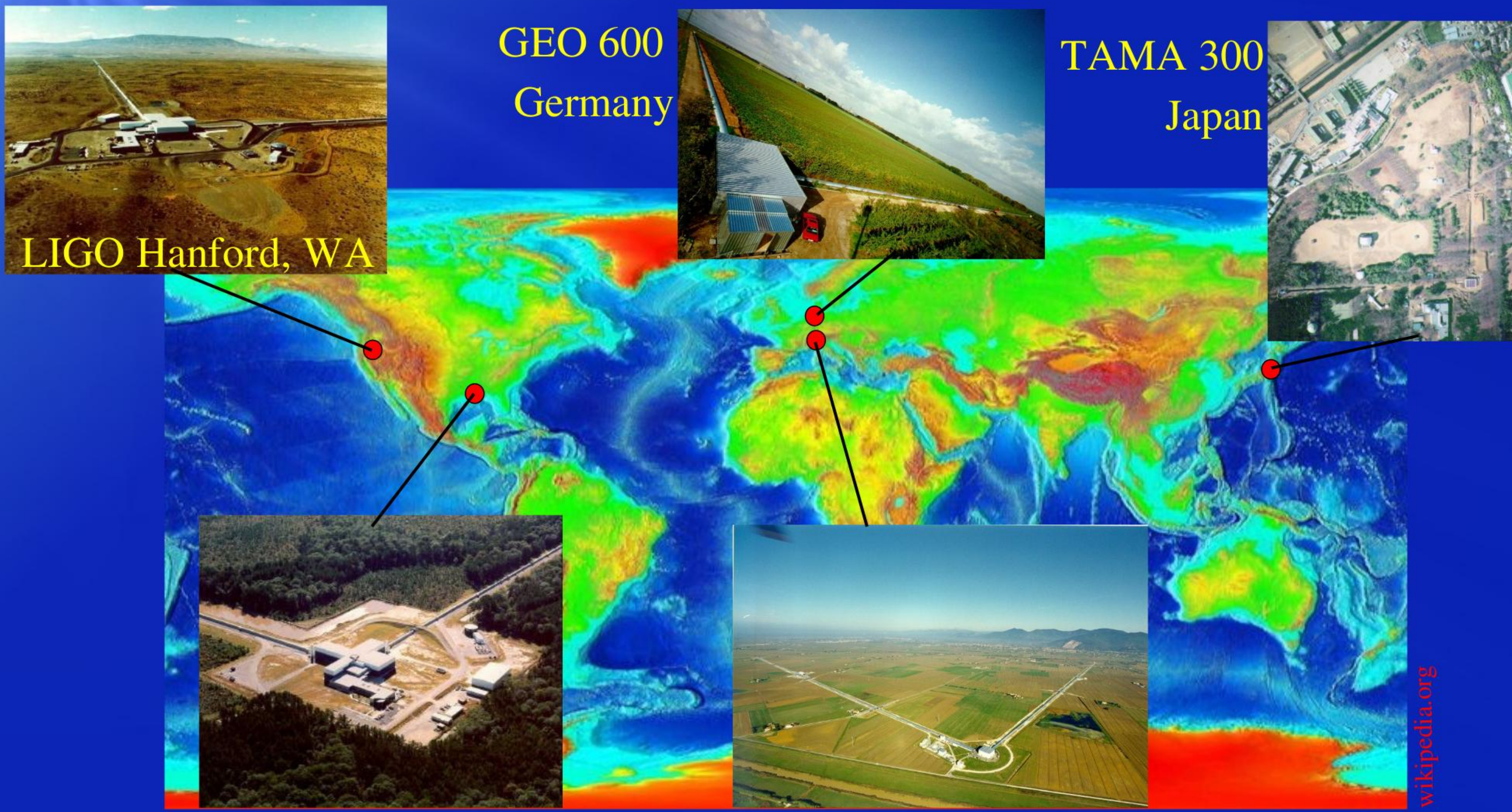
$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t-\frac{|\vec{x}|}{c})\right]^{TT}$$

- GWs are weak and couple weakly to matter. **Good**: Little absorption/scattering **Bad**: Very difficult to observe.
- Observation:
  Need to measure rel. displacements < $\mathbf{10^{-20}}$.
  - Interferometers: LIGOs, LISA
  - Resonant mass detectors.



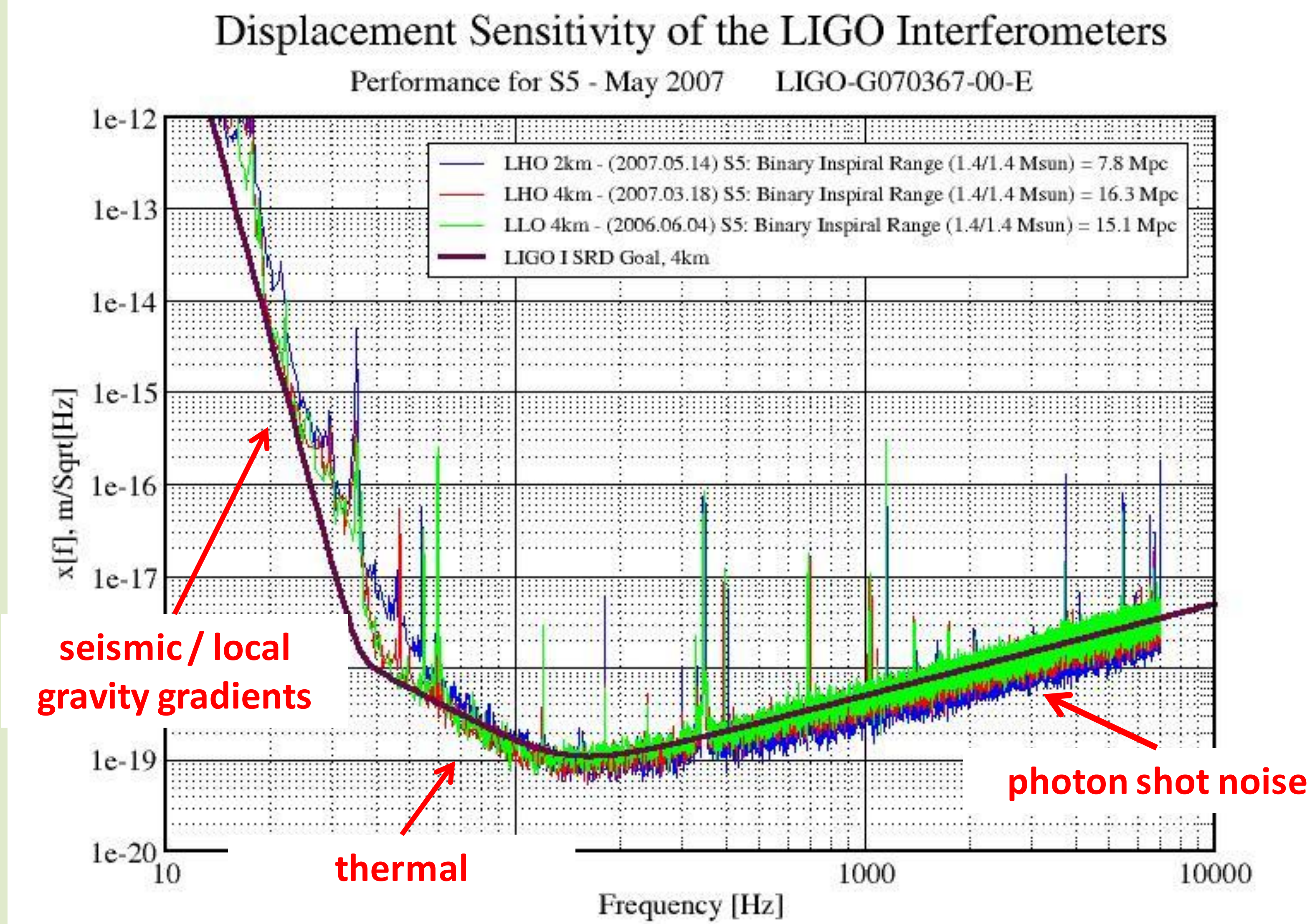
Gravitational Wave Astronomy

International Network of LIGOs



Currently taking data!

Gravitational Wave Detection



-> **Enhanced** versions of LIGO and VIRGO currently taking data!

Gravitational-Wave Signatures of Core-Collapse Supernova Mechanisms

[Ott '08, '09, Classical & Quantum Gravity]

Still to be addressed / work in progress: Neutrino Signatures of Core-Collapse Supernova Mechanisms

Blowing up Massive Stars: Core-Collapse SN Mechanisms

Neutrino Mechanism

Magnetorotational Mechanism

Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant Multi-D Dynamics and GW Emission Processes

Neutrino Mechanism

Magnetorotational Mechanism

Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant Multi-D Dynamics and GW Emission Processes

Neutrino Mechanism → Convection and SASI.

Magnetorotational Mechanism

Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant Multi-D Dynamics and GW Emission Processes

Neutrino Mechanism → Convection and SASI.

Magnetorotational Mechanism → Rotating core collapse & bounce, PNS rotational instabilities.

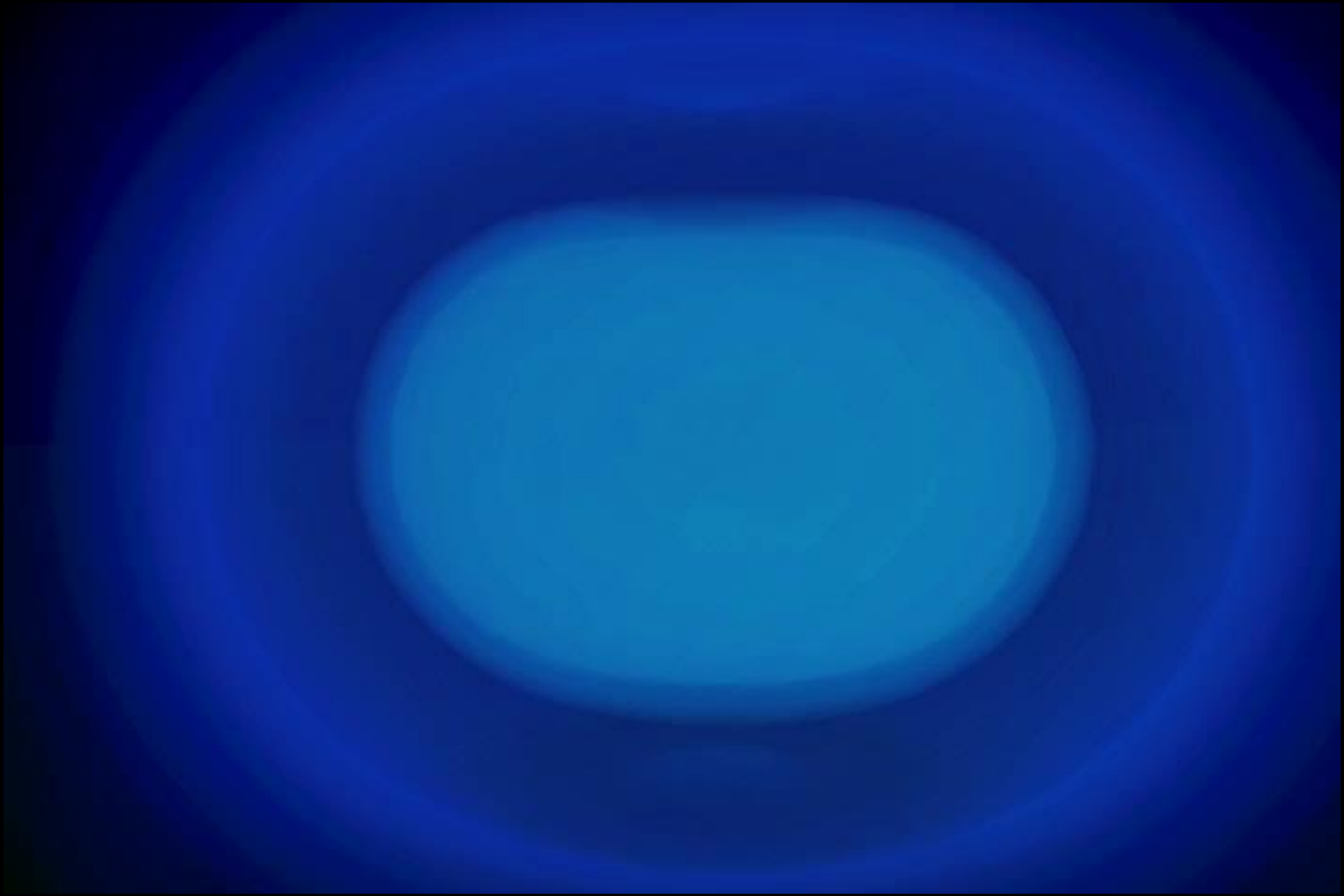
Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant Multi-D Dynamics and GW Emission Processes

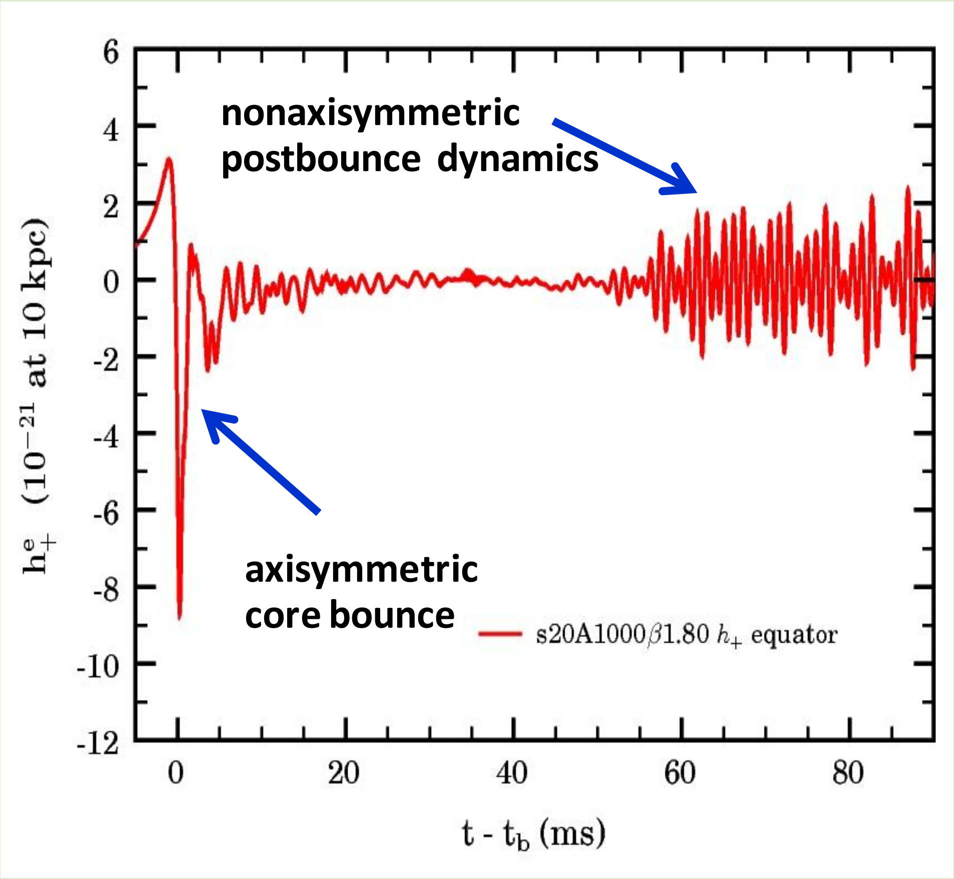
Mechanism		Dominant Multi-D Dynamics and GW Emission Processes
Neutrino Mechanism	→	Convection and SASI.
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism	→	PNS pulsations.

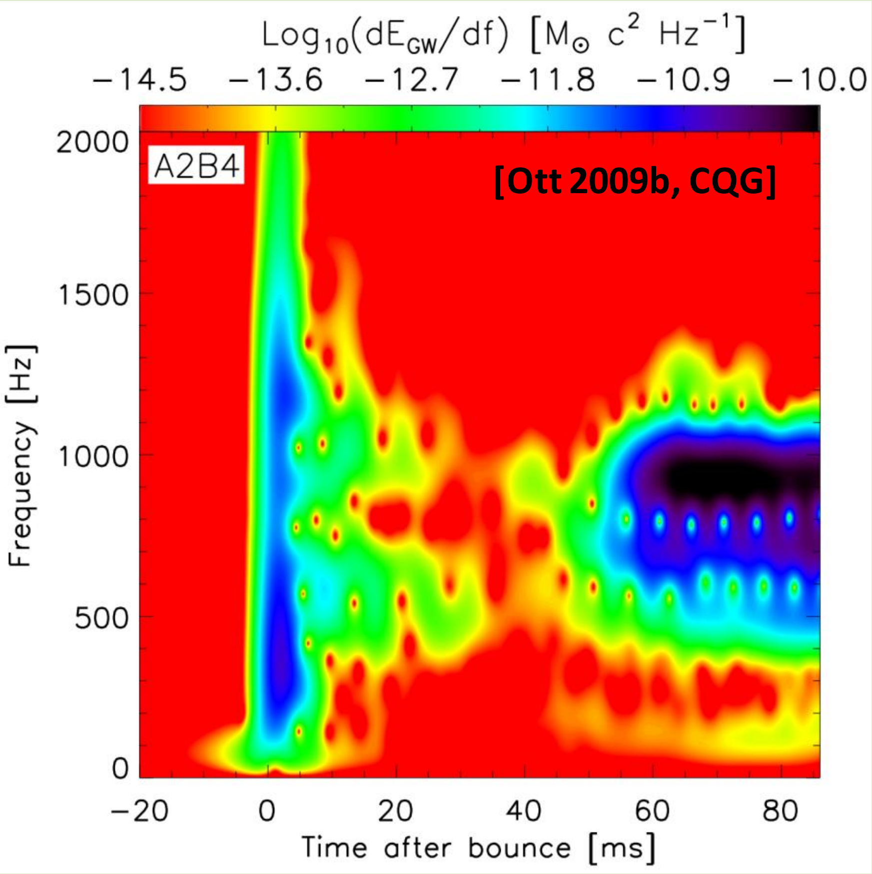
Rapidly Rotating Stellar Collapse in 3+1 GR

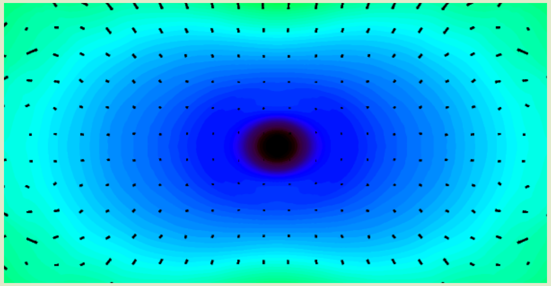


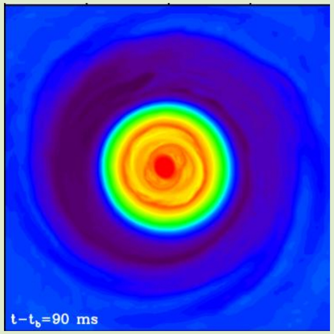
3D GR simulation Ott et al., rendition by R. Kähler, Zuse Institute, Berlin

GWs from Rotating Collapse & Rotational Instability



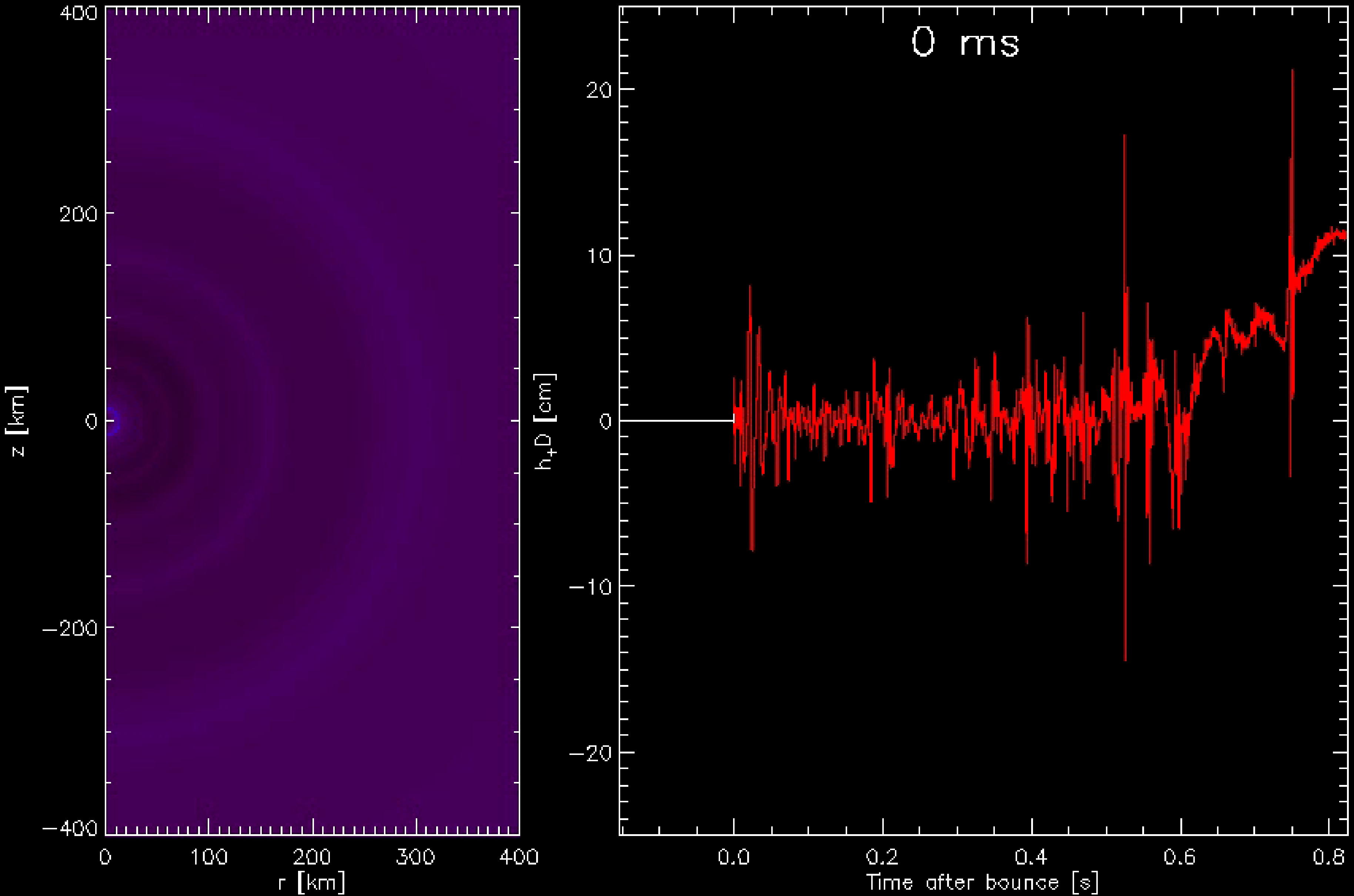






See:
Ott et al. '07,
Ott '09a,b
Scheidegger et al. '08, '09

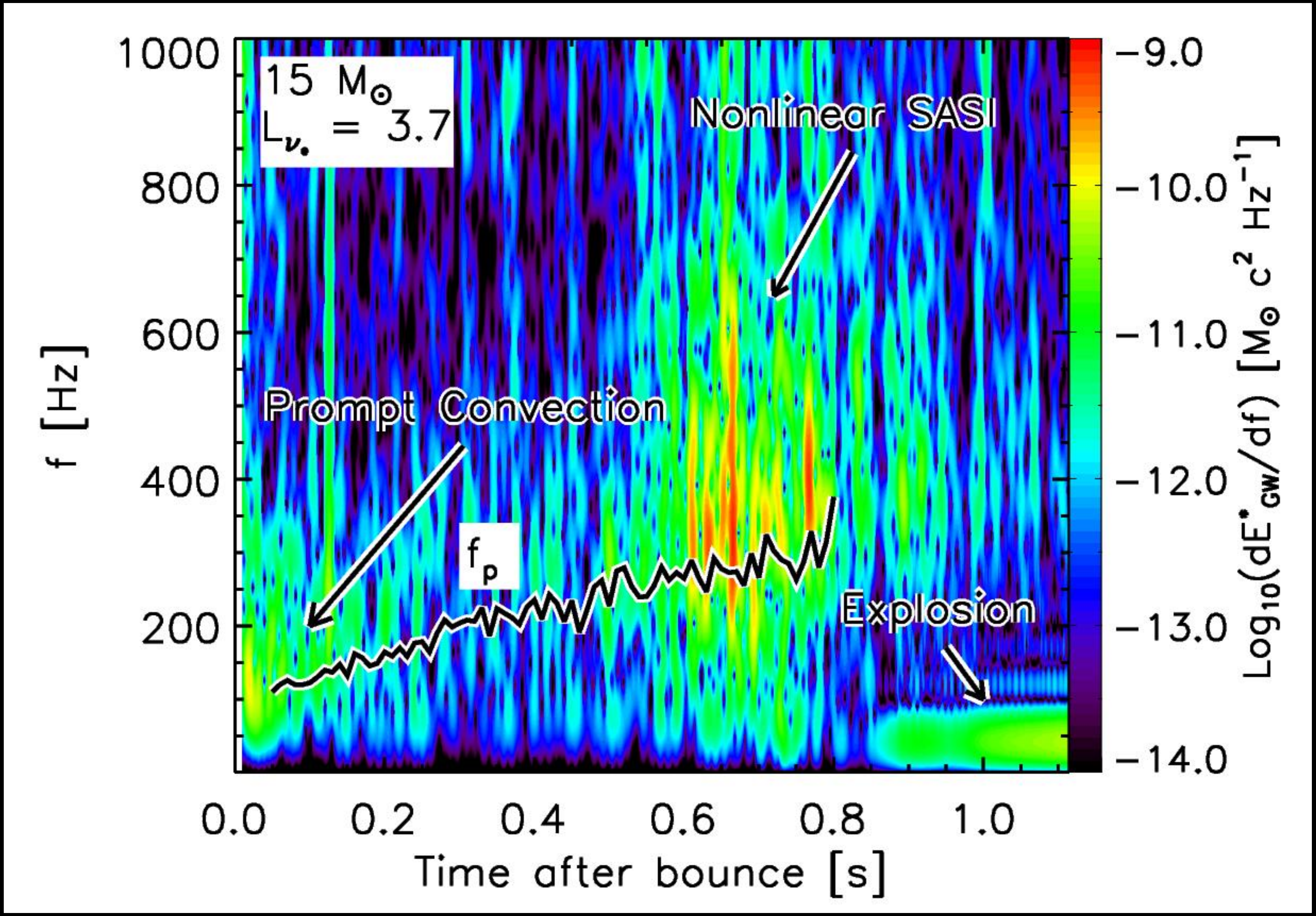
The GW Signature of Convection and SASI



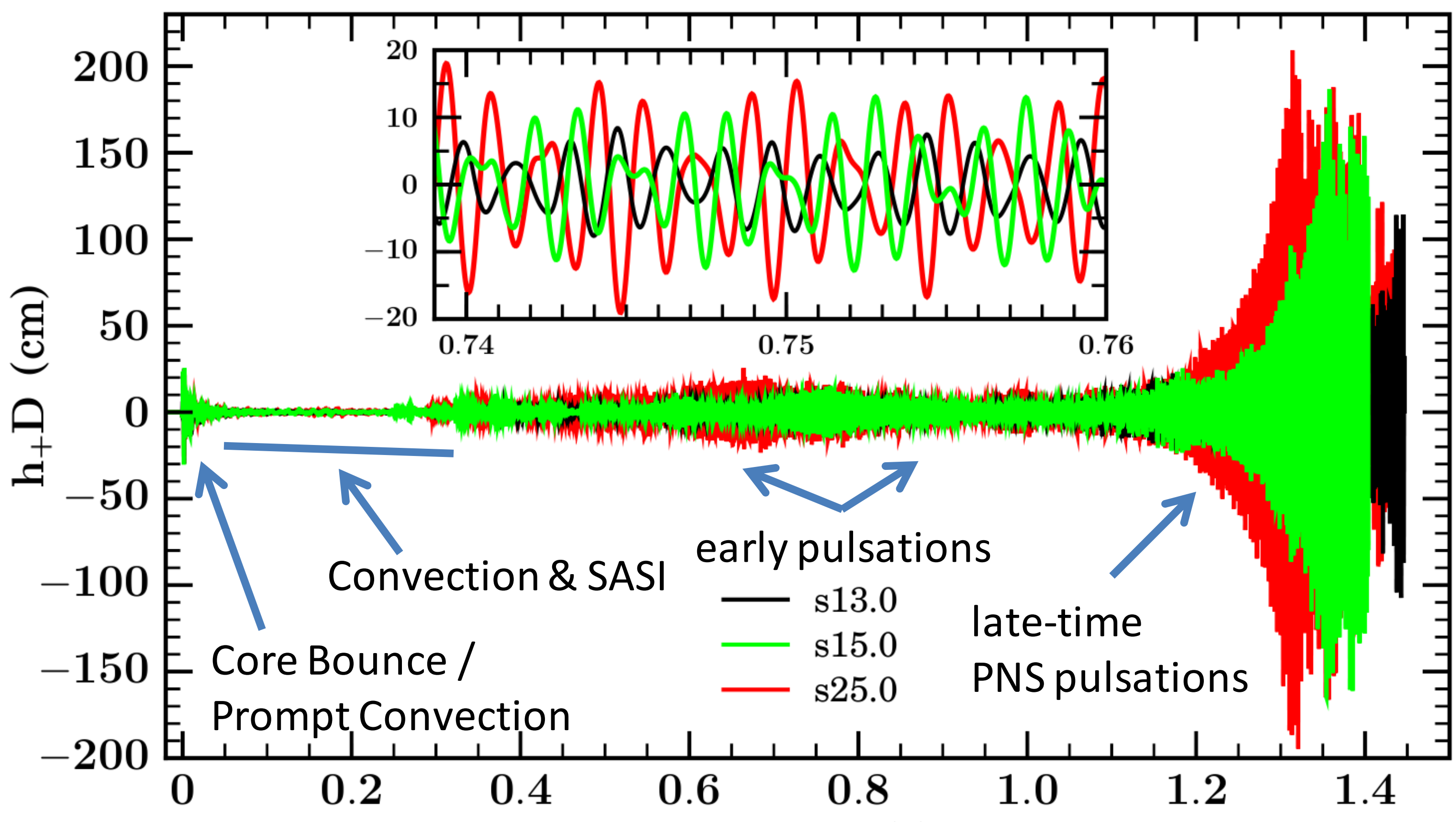
[Murphy, Ott and Burrows 2009]

Convection/SASI GW Time-Frequency Evolution

[Murphy, Ott & Burrows 2009]

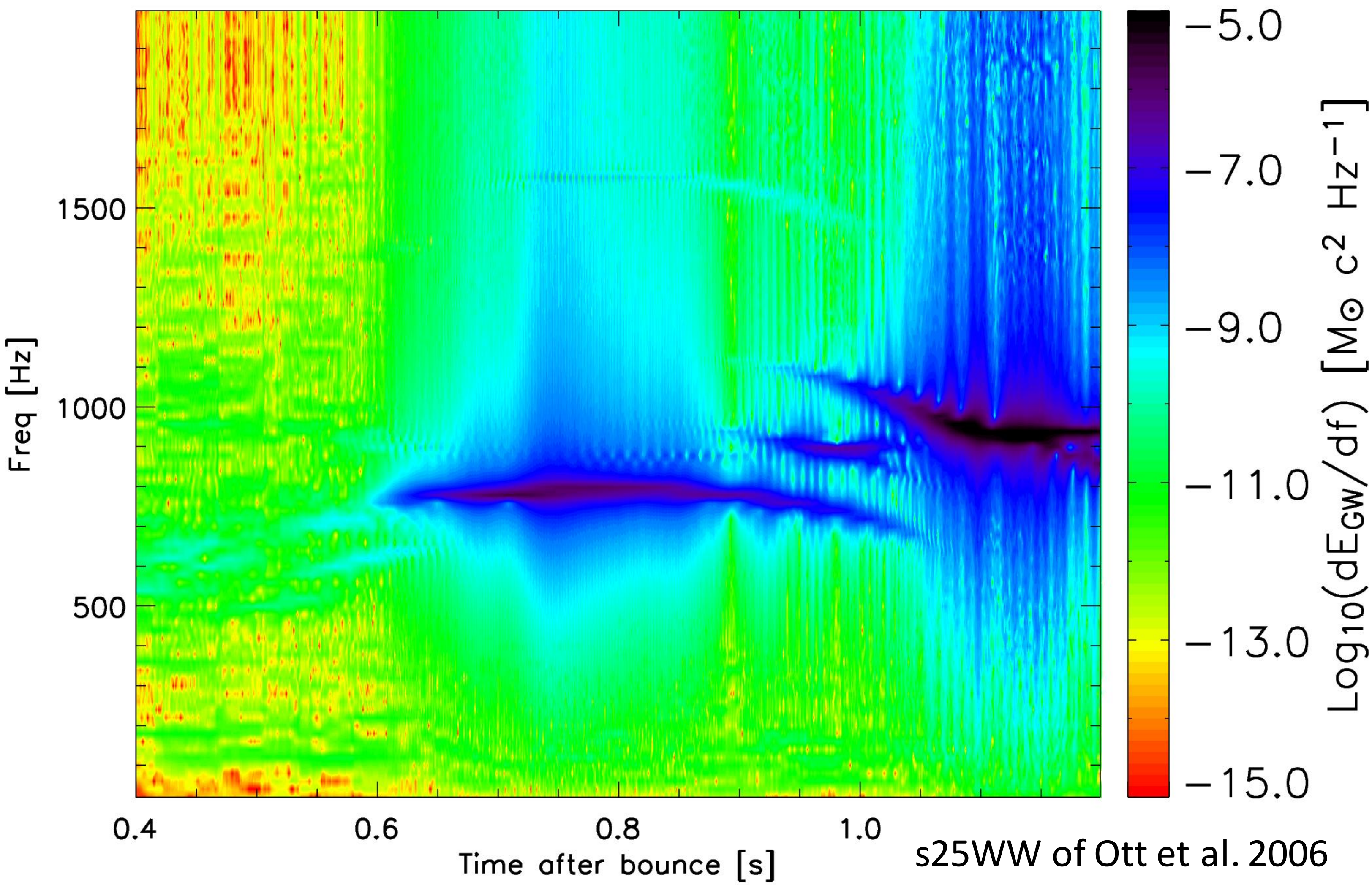


GWs from PNS Core Pulsations in the Context of the Acoustic Mechanism



[Ott 2009ab, Ott et al. 2006]

PNS Pulsations: GW T-F Evolution



s25WW of Ott et al. 2006

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant Multi-D Dynamics and GW Emission Processes

Mechanism		Dominant Multi-D Dynamics and GW Emission Processes
Neutrino Mechanism	→	Convection and SASI.
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism	→	PNS pulsations.

-> Ott CQG 26, 204015 (2009):

-> Clear mapping between explosion mechanism and GW signature.

Adding Neutrinos to the Mix: (work in progress)

Potential Neutrino Signature

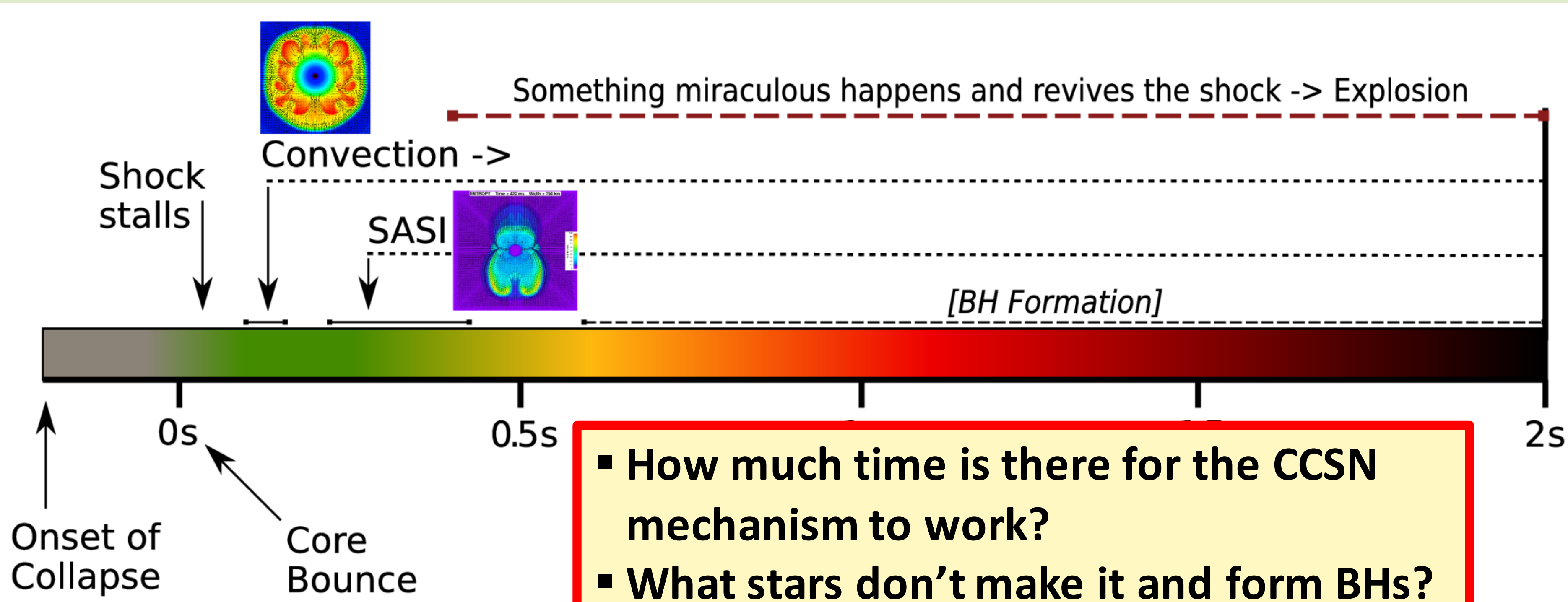
Mechanism	Potential Neutrino Signature
Neutrino Mechanism	High-frequency variations of $L_{\nu\ (e,ebar)}$
Magnetorotational Mechanism	Very soft spectrum along equator, Very hard spectrum along poles.
Acoustic Mechanism	High-frequency variations of L_ν, including ν_x . Long delay to explosion (> 0.8-1 s).

Key: Use combined neutrino/GW information to break observational degeneracies.

The Formation of **Black Holes** in Failing Core-Collapse Supernovae

with **Evan O'Connor** (Caltech), Uli Sperhake (Caltech),
and **Erik Schnetter** (LSU), Peter Diener (LSU) ,
Frank Löffler (LSU), Adam Burrows (Princeton)

Core Collapse Timeline



- **How much time is there for the CCSN mechanism to work?**
- **What stars don't make it and form BHs?**
- **What stars explode, but make BHs by fallback accretion?**
- **What is the connection to GRBs.**
- To date: No systematic studies that take full CCSN physics into account, but see work by Fryer et al., Sumiyoshi et al., Fischer et al.

- Energy reservoir: few x 10^{53} erg (100 B)
- Explosion energy: ~1 B
-
-

Simulations of BH Formation

- Published work:
  1D: Lagrangian GR radiation-hydro, very few detailed models.
  [Sumiyoshi et al. '06, '07, '08; Fischer et al. 2009]
  2D/3D: Polytropic/Gamma-Law models; collapse of isolated NS or collapsing polytropes. No microphysics/neutrinos.
  [Baiotti et al., Shibata & Sekiguchi]

- **Our new approach**: [O'Connor & Ott 2009, Ott et al. 2010 (in prep.)]
  - Goals: (1) Study systematics of BH formation in the limiting case of spherical symmetry.
    (2) Develop efficient microphysics technology/approximations for multi-D simulations.
    (3) Study long-term postbounce evolution, BH formation, and late-time evolution in 3D GR using the Cactus Framework.
    -> 5 year NSF PetaApps award PetaCactus (LSU/Caltech/Princeton)

GR1D

- **GR1D**: ***Open-Source 1.5D GR hydrodynamics code.*** [O'Connor & Ott 2009]
- Available from http://www.stellarcollapse.org .
- **Radial-gauge, polar-slicing** (-> Schwarzschild-like coordinates).

$$ds^2 = -\alpha(r,t)^2 dt^2 + X(r,t)^2 dr^2 + r^2 d\Omega^2$$

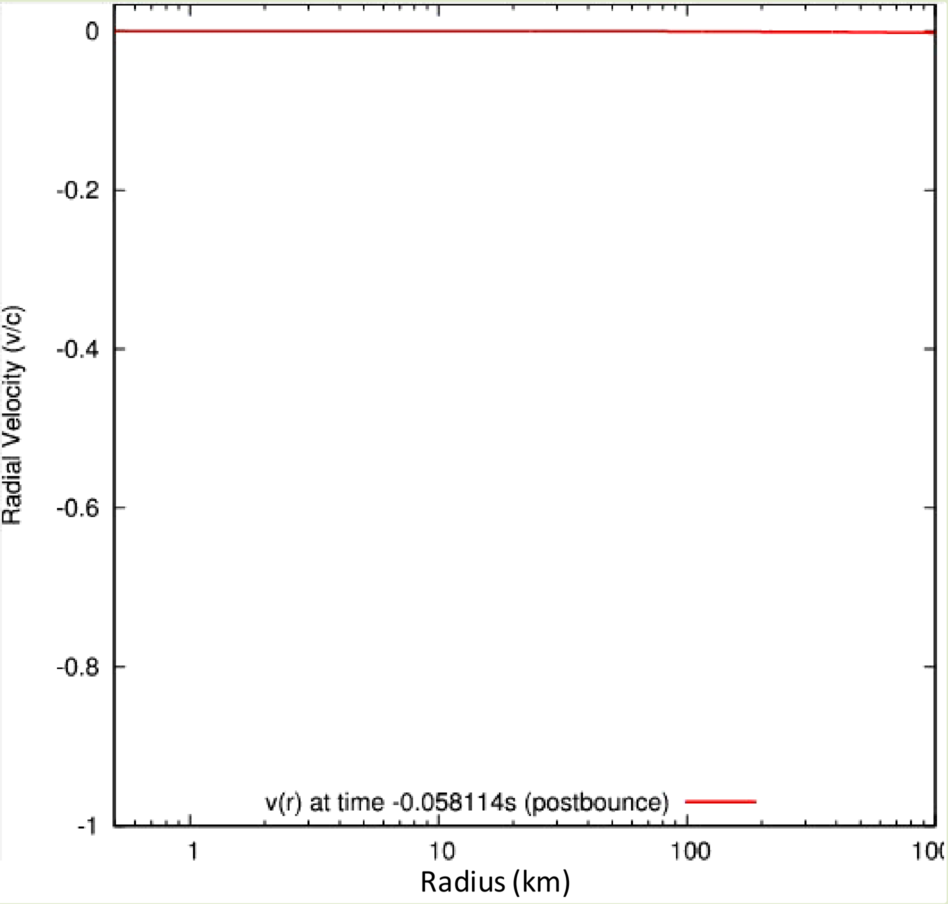
$$\alpha(r,t) = \exp[\phi(r,t)], \quad X(r,t) = \left(1 - \frac{2m(r,t)}{r}\right)^{-1/2}$$

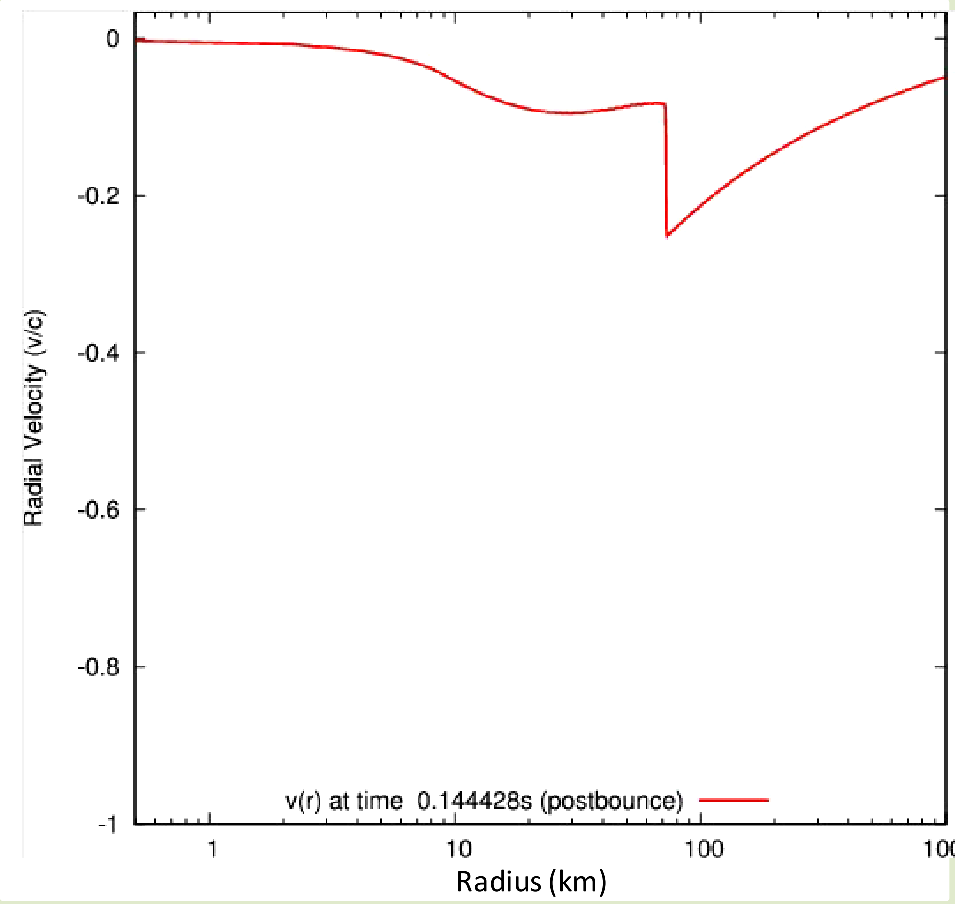
$$\phi(r,t) = \int_0^r X^2 \left[\frac{m(r',t)}{r'^2} + 4\pi r'(P + \rho h X^2 u^{r'} u^{r'})\right] dr' + \phi_0$$

- Shellular rotation (hence, 1.5D).
- High-resolution shock-capturing hydro, PPM reconstruction, HLLE solver.
- Multiple finite-temperature microphysical EOS: H. Shen et al. 1998, Lattimer & Swesty 1991 with K={180,220,375} MeV. EOS tables available in HDF5 format on http://www.stellarcollapse.org .
- 3-flavor, energy-averaged (gray) neutrino leakage and approximate neutrino heating.

Example: Black Hole Formation in Failing Core-Collapse Supernovae

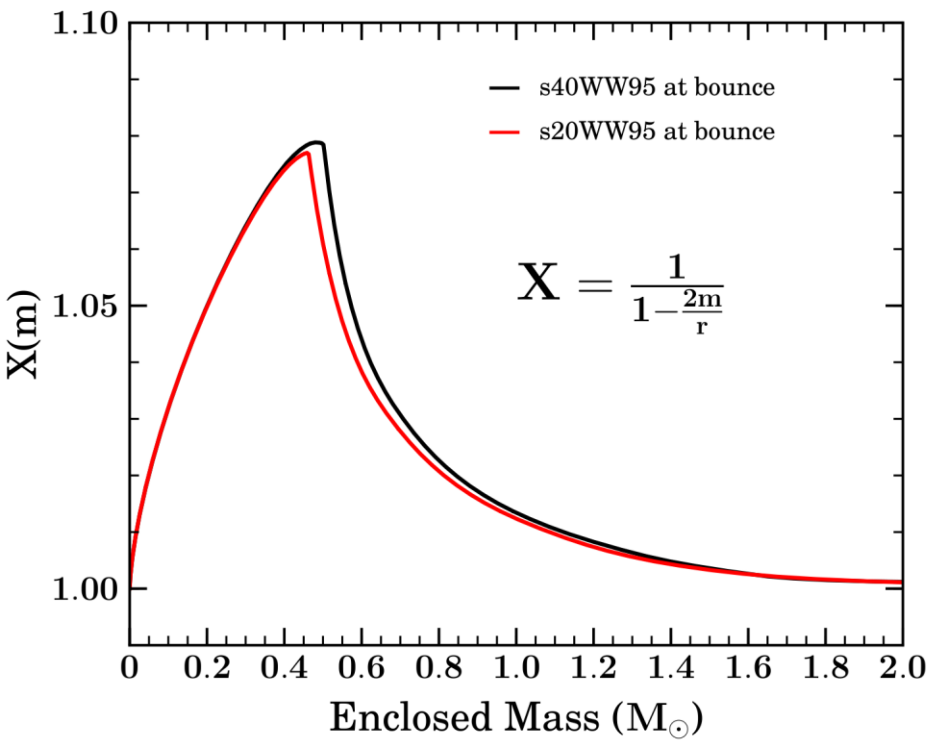
[O'Connor & Ott 2009, see also Sumiyoshi et al. 2006, 2007, 2008, Fischer et al. 2009]

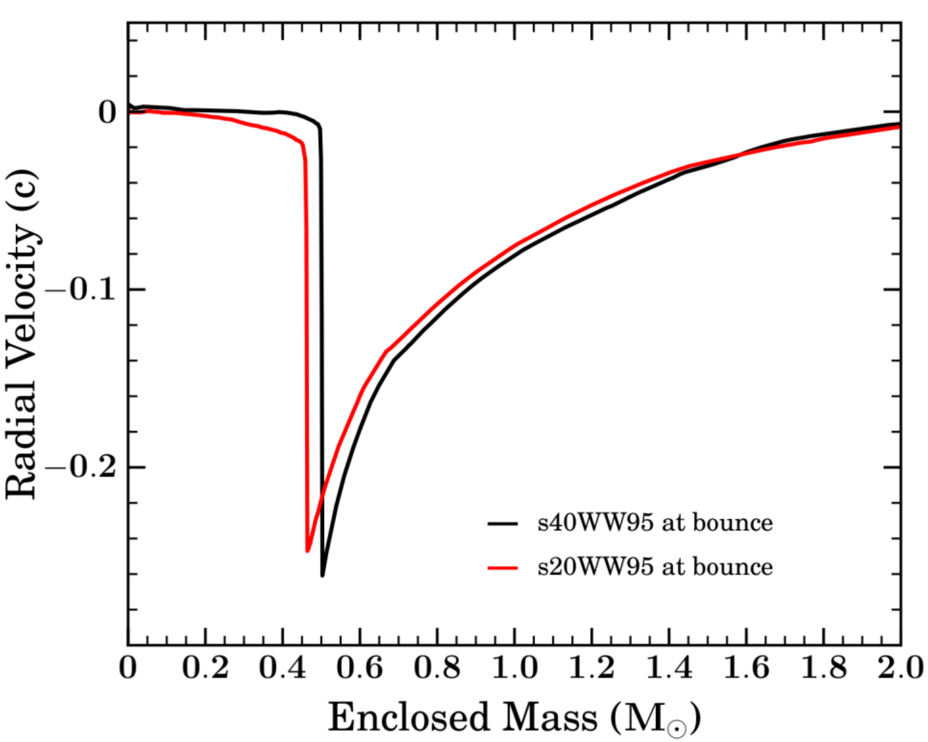




Animations by Evan O'Connor

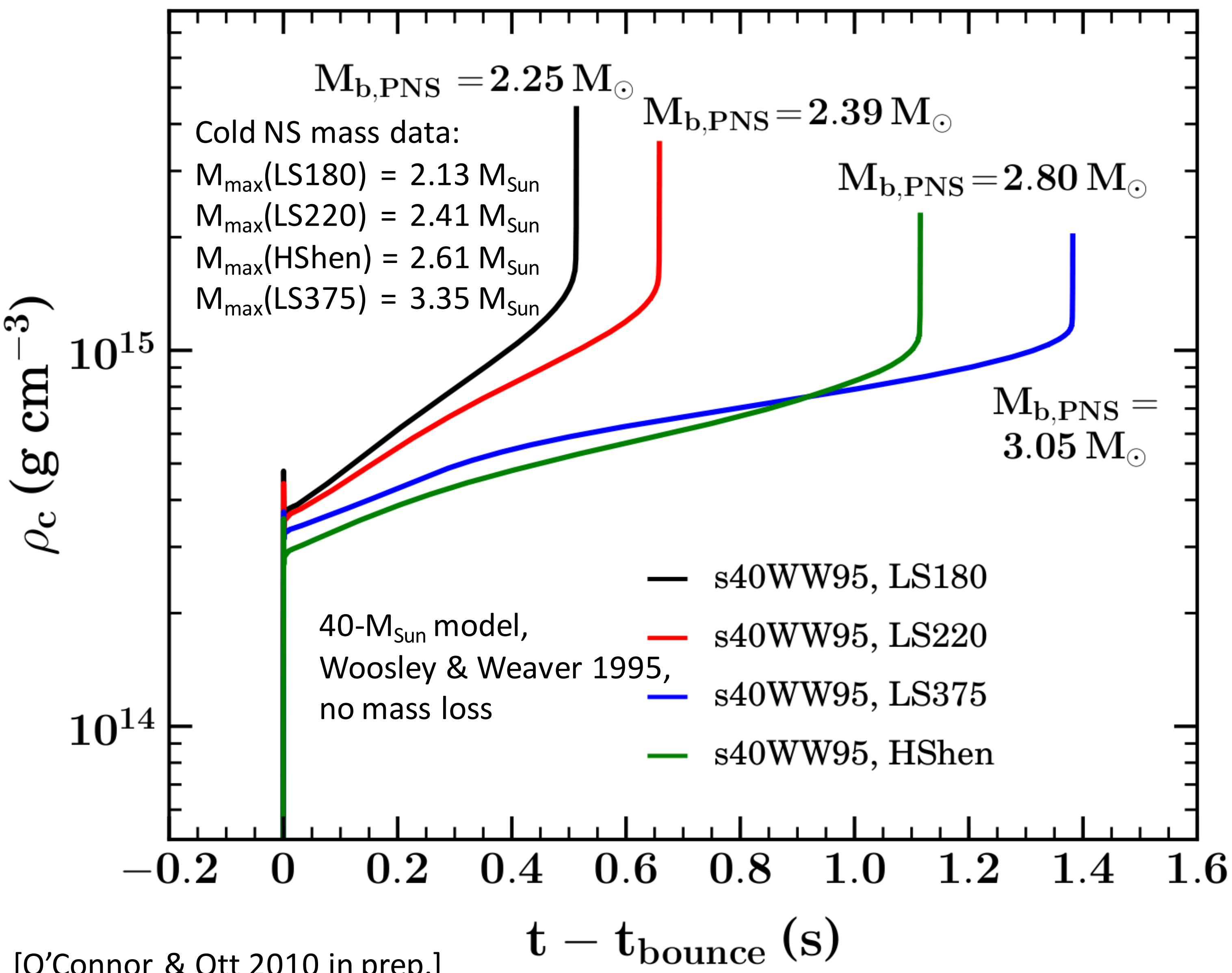
There Is No Direct BH Formation!





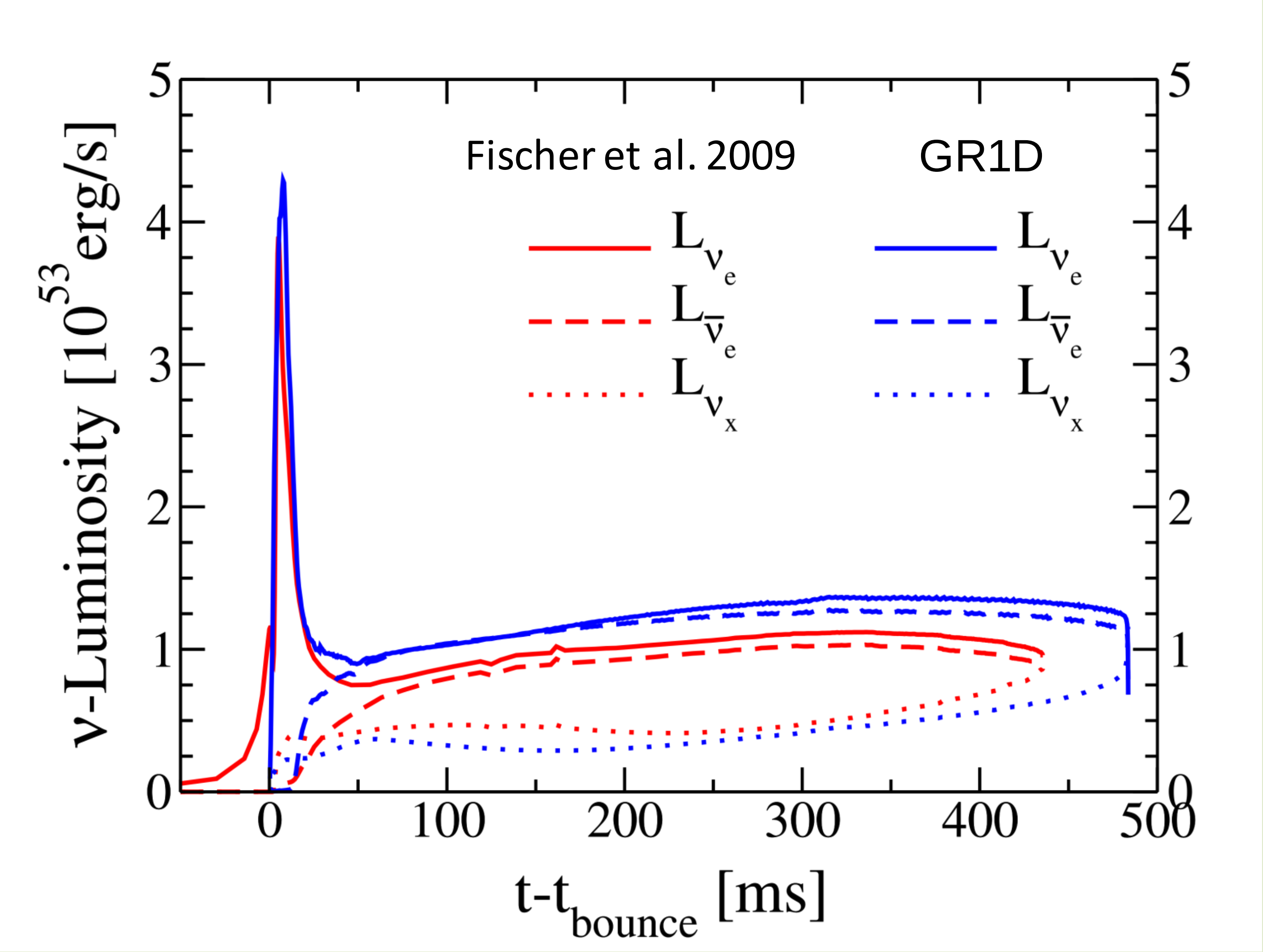
- Generic: $M_{IC} = M_{PNS}$ at bounce ≈ 0.4 – 0.7 M_{Sun}. **Set by nuclear physics, electron capture and general collapse hydrodynamics**.
- Inner core easily stabilized by stiff core of the nuclear force + nucleon degeneracy. Exception: Very massive stars, M > ~100 M_{Sun}
- **All 'ordinary' massive stars undergo a PNS phase before BH formation**.

Equation of State Dependence



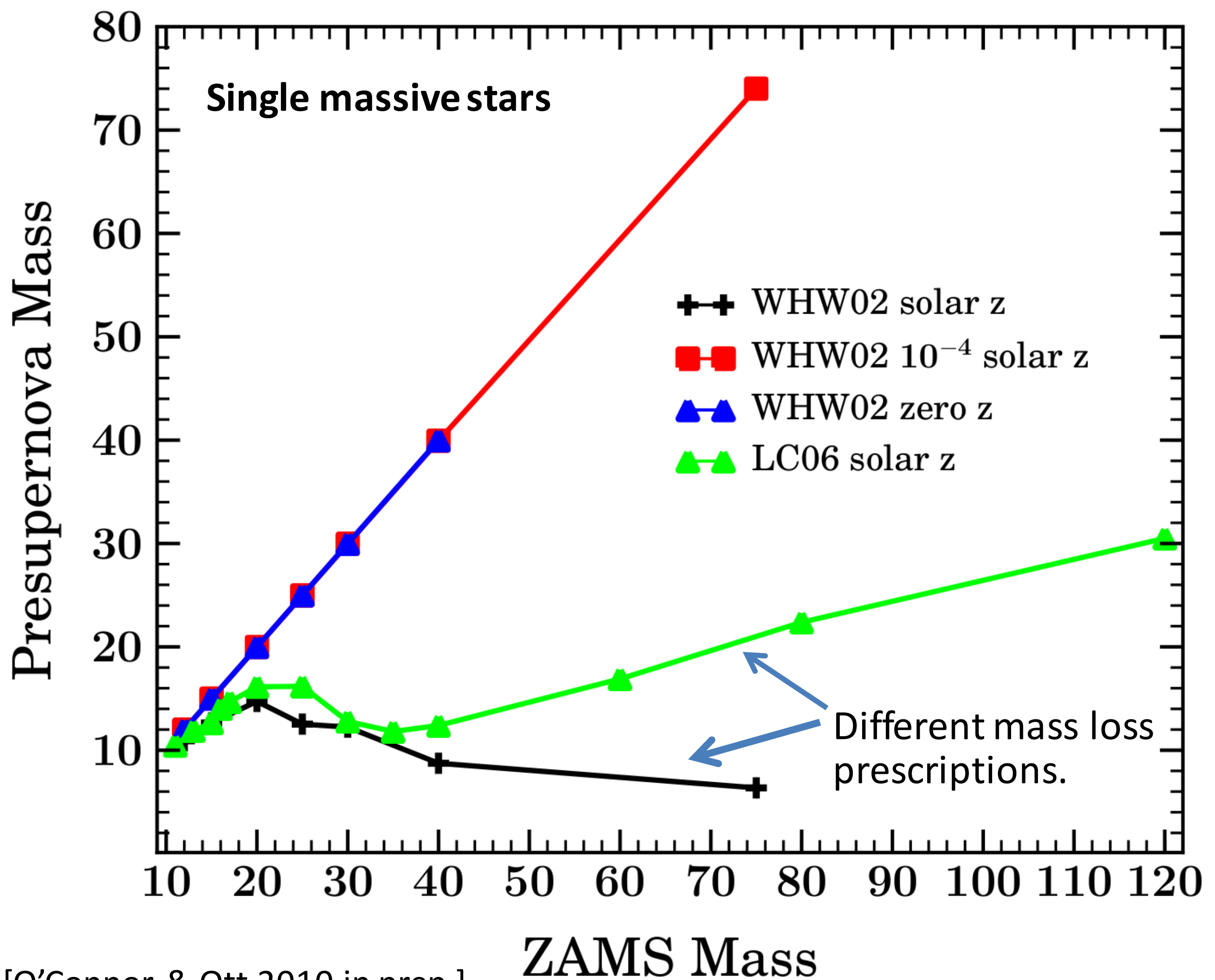
[O'Connor & Ott 2010 in prep.]

Comparison with Full Transport



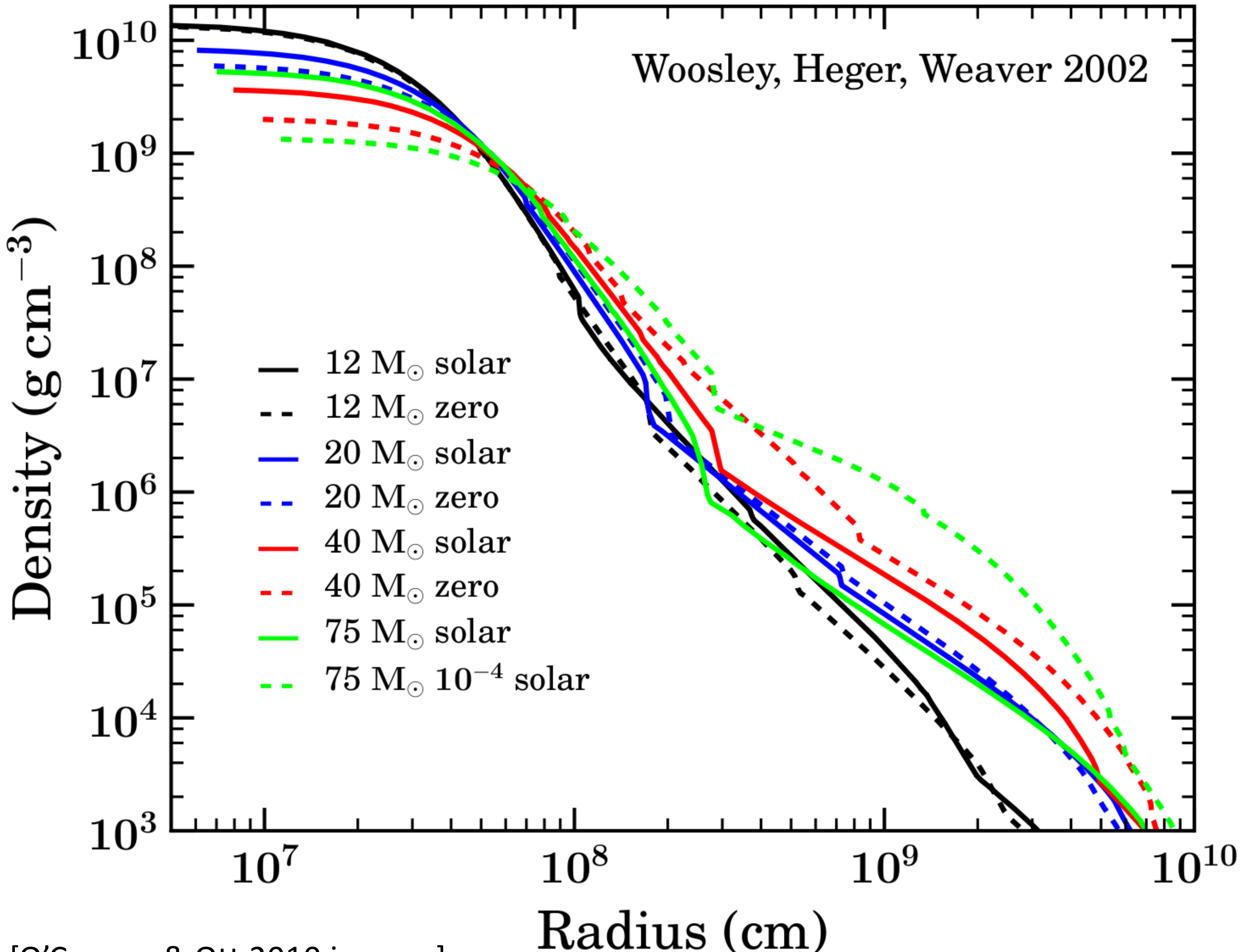
- GR1D reproduces full transport to 25% in terms of Lnu and to 10% in terms of the time of BH formation, but is roughly 10 times faster. -> allows for parameter study.

Precollapse Stellar Structure



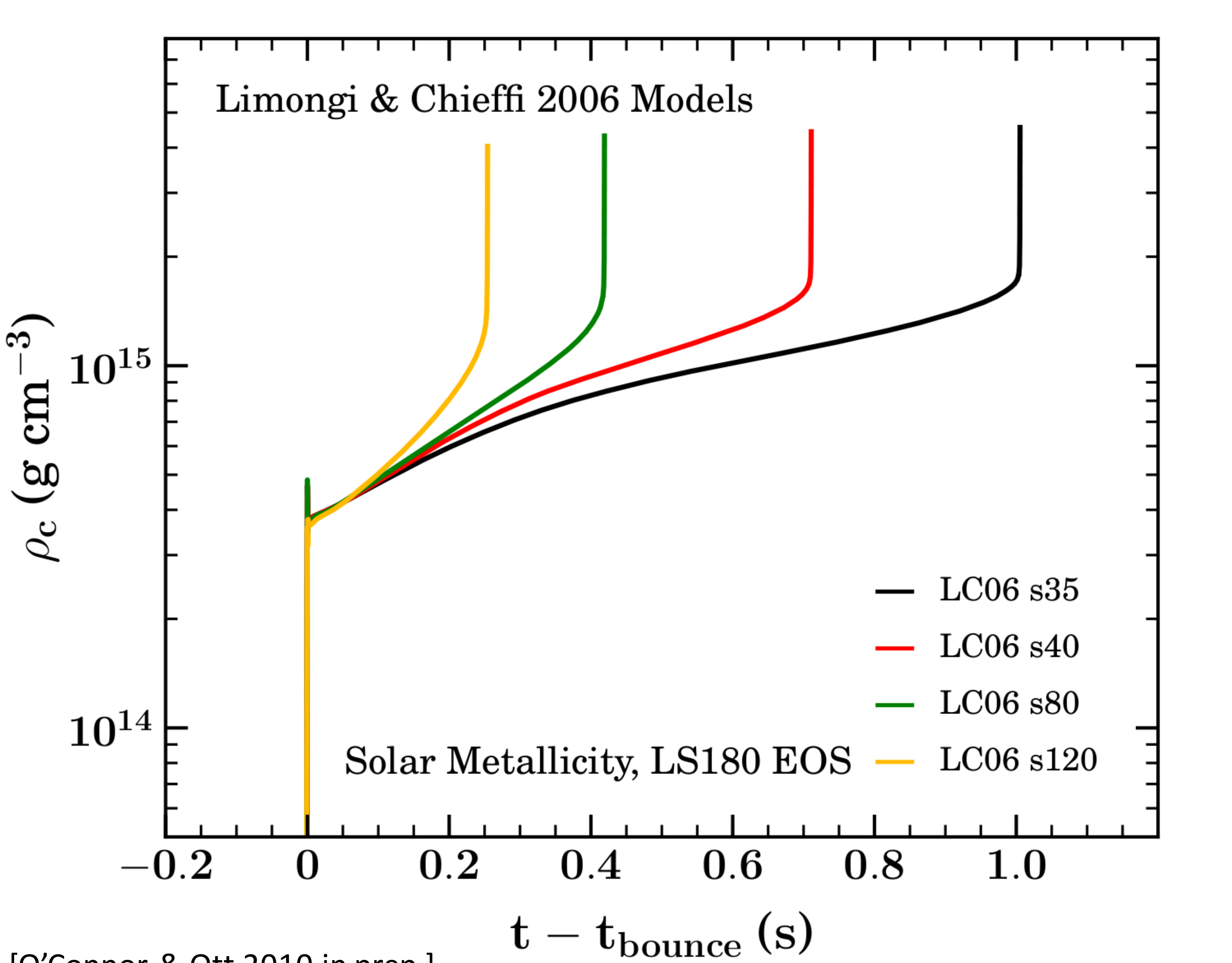
[O'Connor & Ott 2010 in prep.]

Precollapse Stellar Structure



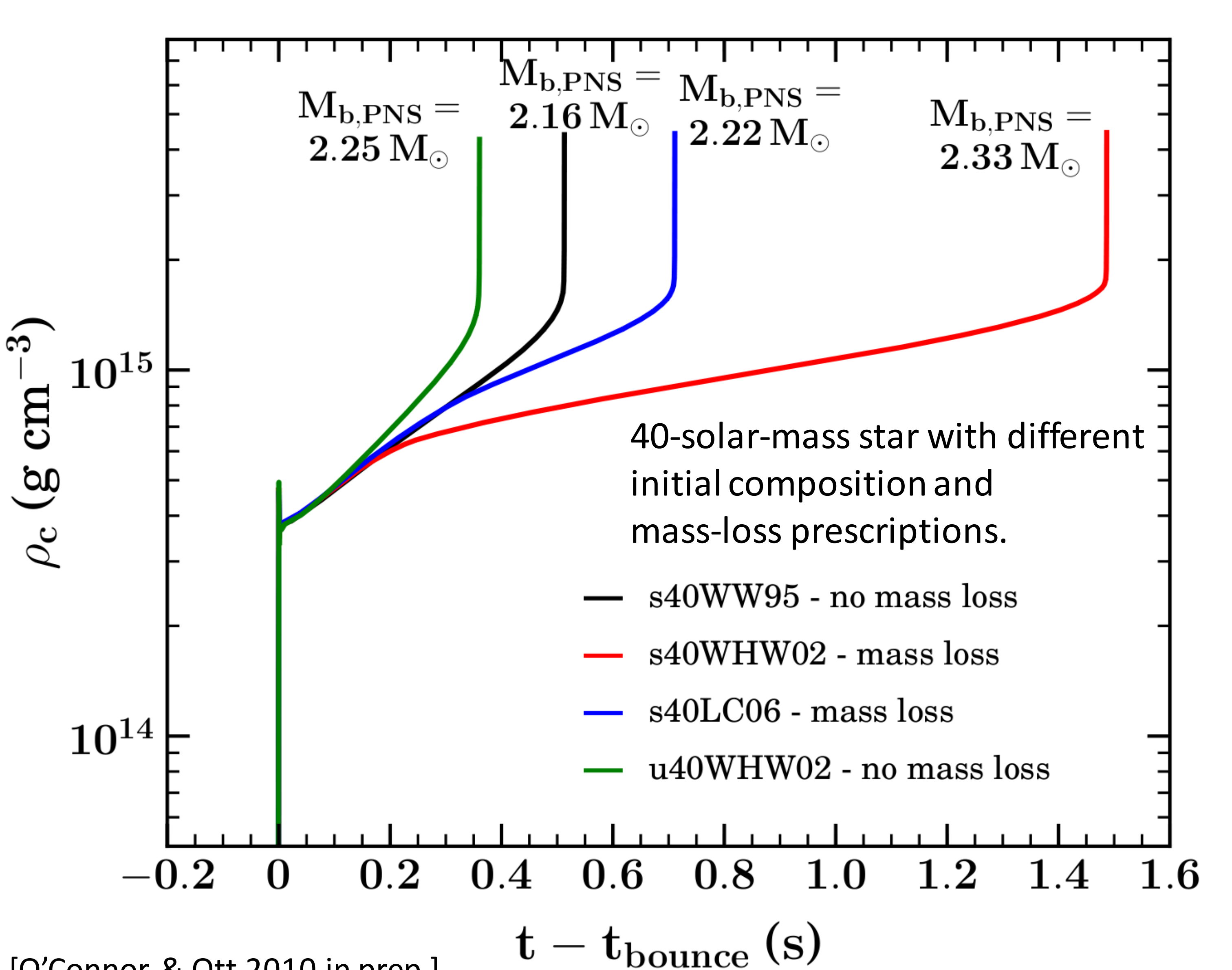
[O'Connor & Ott 2010 in prep.]

Variations in ZAMS Mass



[O'Connor & Ott 2010 in prep.]

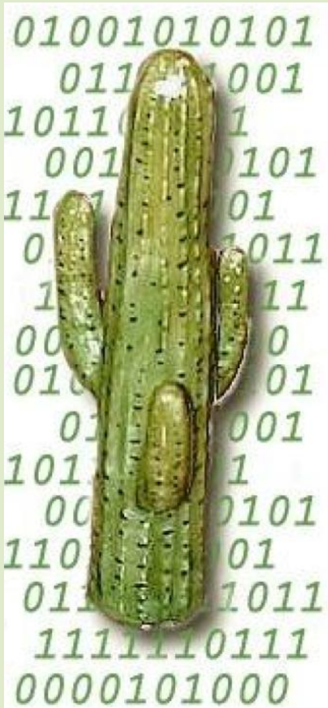
Metallicity / Mass Loss



[O'Connor & Ott 2010 in prep.]

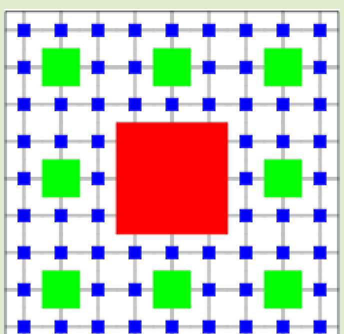
on to 3D ...

Computational Framework



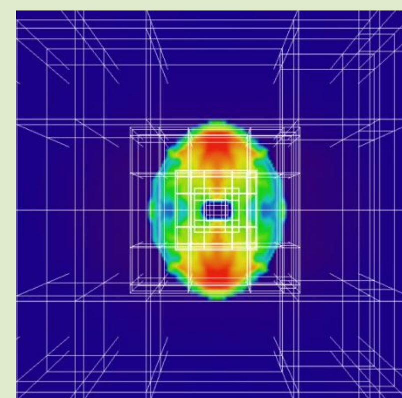
Cactus [http://www.cactuscode.org]

- **Open-source** software framework for HPC, developed at the **Center for Computation & Technology** at LSU.
- Includes tools for code development, dynamic simulation control, data analysis, visualization, data handling (HDF5).
- Manage increased complexity with high-level abstractions, e.g. for inter-node communication, multi-core parallelism, I/O
- Active user community since 1998 in numerical relativity, fluid dynamics, and quantum gravity.



Carpet [http://www.carpetcode.org]

- **Open-source** driver for Adaptive Mesh Refinement (AMR) and multi-block systems.
- Developed by Erik Schnetter (LSU).
- Full vertex-centered and cell-centered Berger-Oliger AMR with sub-cycling in time.

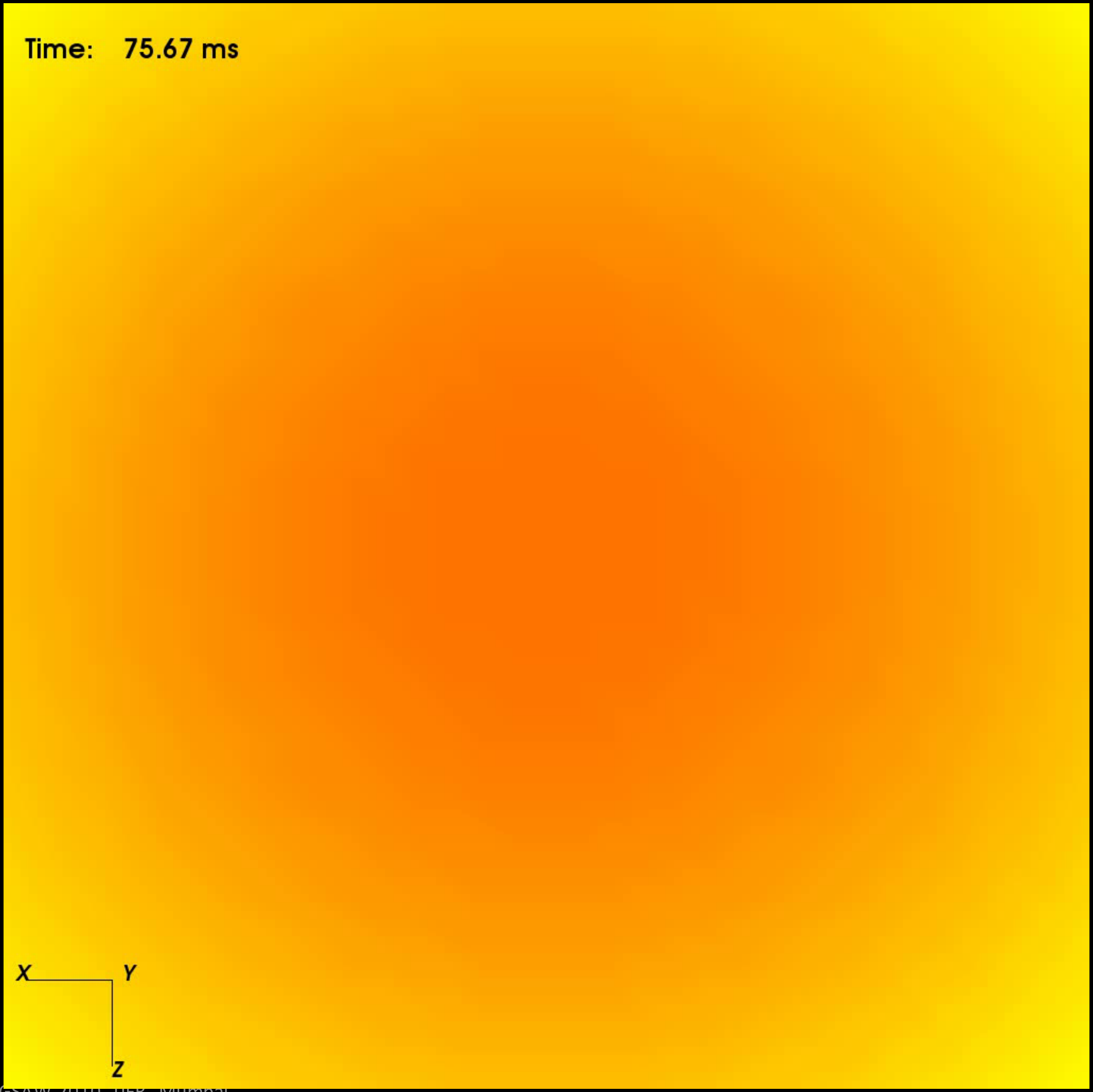


Spacetime Evolution: **McLachlan**

- **State-of-the-art Einstein solver**, high-order finite differencing (up to 8th)
- Code is automatically generated with the ***Kranc*** package via Mathematica (equations contain ~5000 terms).
- Optimized for hybrid OpenMP/MPI.
- Developed in NSF-funded CIGR/XiRel collaboration (LSU, GA Tech, RIT, Caltech), available as **open source**. [Brown et al. 2007, 2009]

MHD, Microphysics & Neutrinos: **Zelmani GR Core-Collapse Package**

- High-resolution Shock-Capturing hydrodynamics with PPM reconstruction based on the **open-source** GRHD code **Whisky/Avanti**. Extension to GRMHD in development.
- Multiple finite-temperature nuclear EOS options. Neutrino leakage and heating scheme [O'Connor & Ott '09].


Time: 75.67 ms
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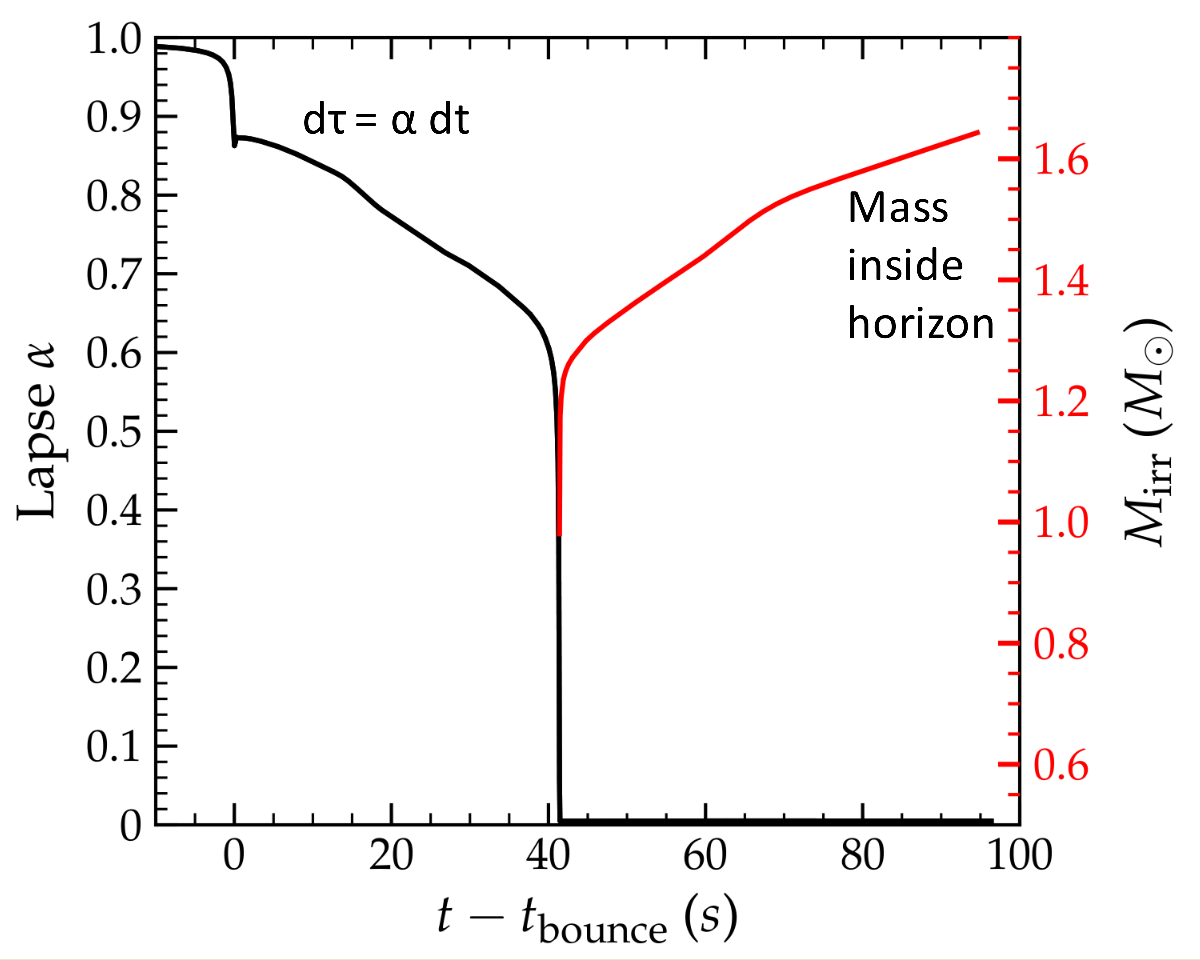
What this just was... [Ott et al. 2010 in prep.]

- Exploratory calculation: 3D, but restricted to octant.
  - 40-solar-mass Woosley & Weaver 1995 progenitor.
  - Simplified hybrid EOS: Piecewise polytrope with thermal component, $\Gamma_1 = 1.30$, $\Gamma_2 = 2.00$, $\Gamma_{th} = 1.30$. Mimics stiffening of EOS & effects of dissociation and deleptonization.
  - Moderate rotation, $\Omega_0 = 1$ rad/s.
  - 11 levels of MR, using hydro excision.
  - More realistic 3D models running right now.



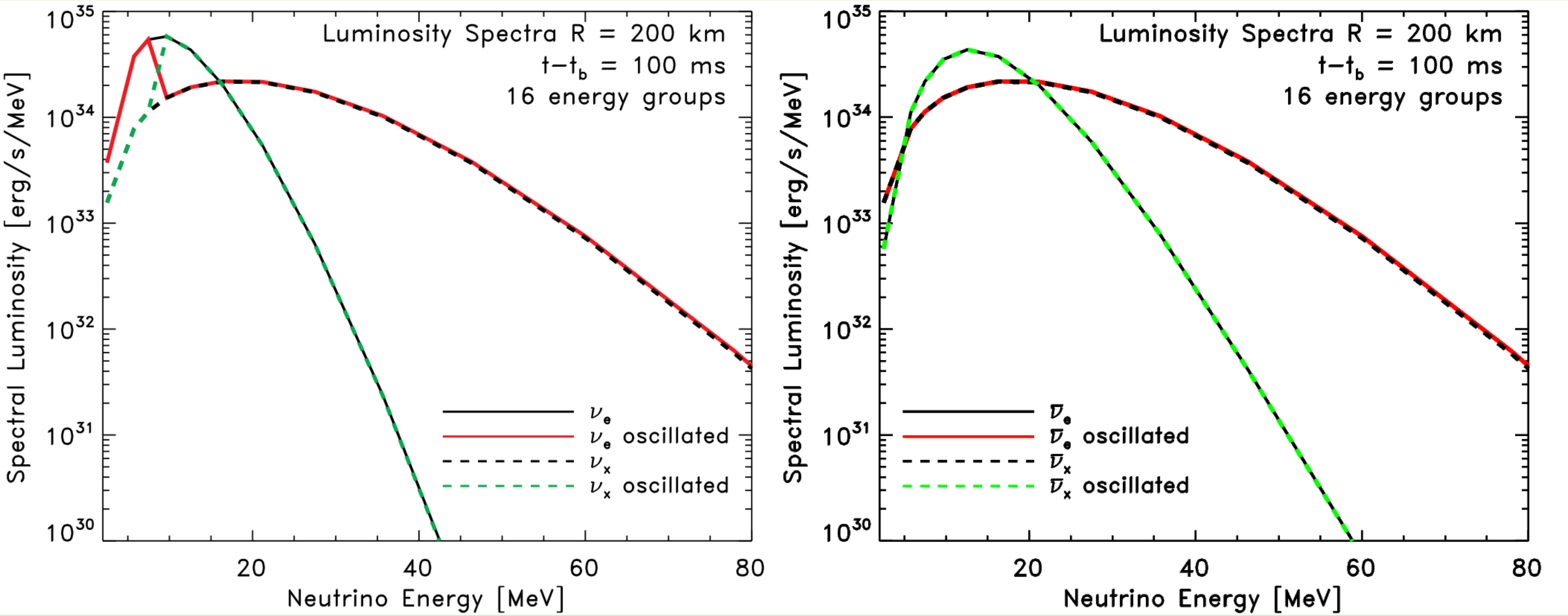
Bonus Slides

Faking it:

An Ad-Hoc Test of the Effect of
Self-Induced Flavor Oscillations
on Core-Collapse Supernova Dynamics

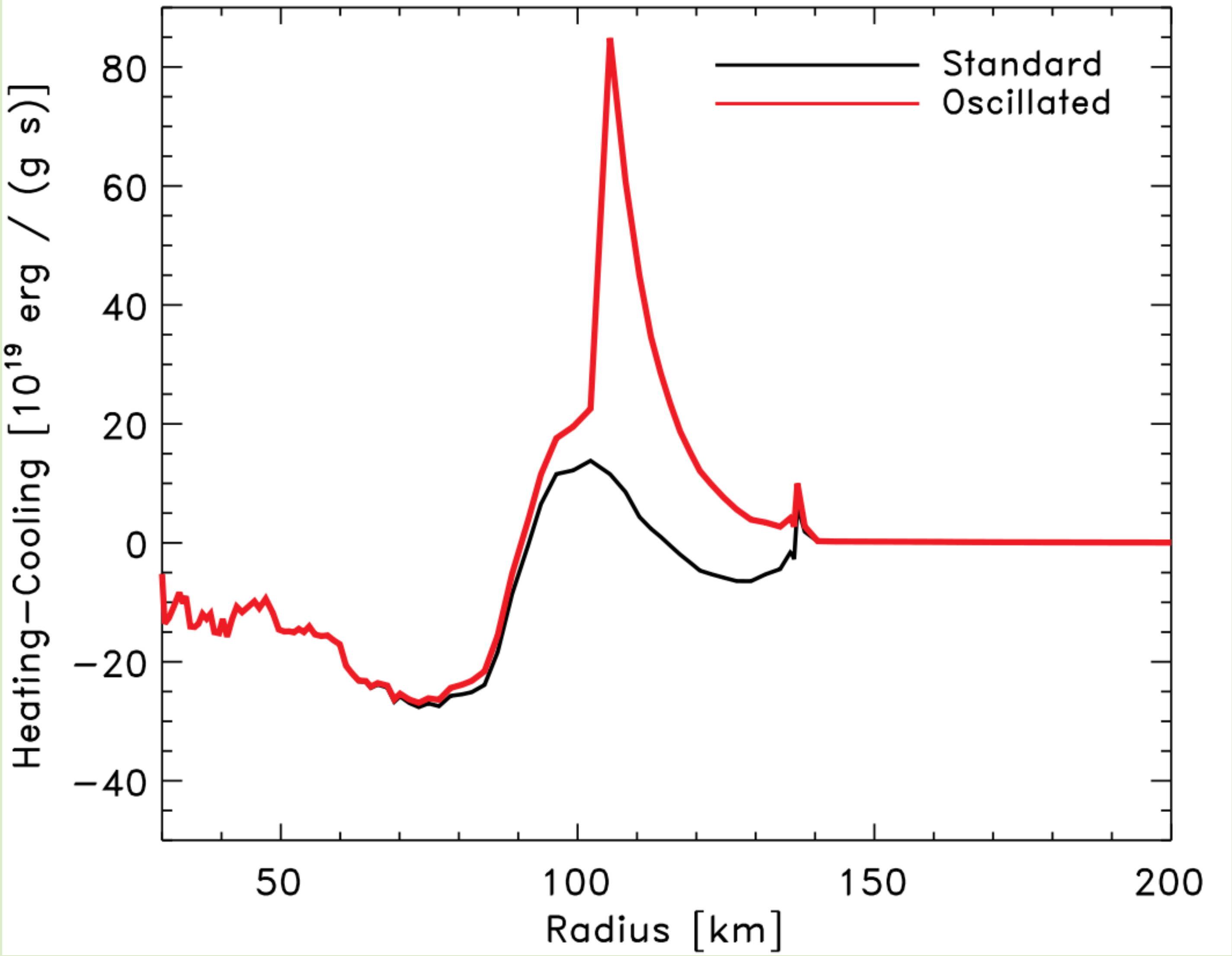
Ott et al. 2010 in preparation

Setup



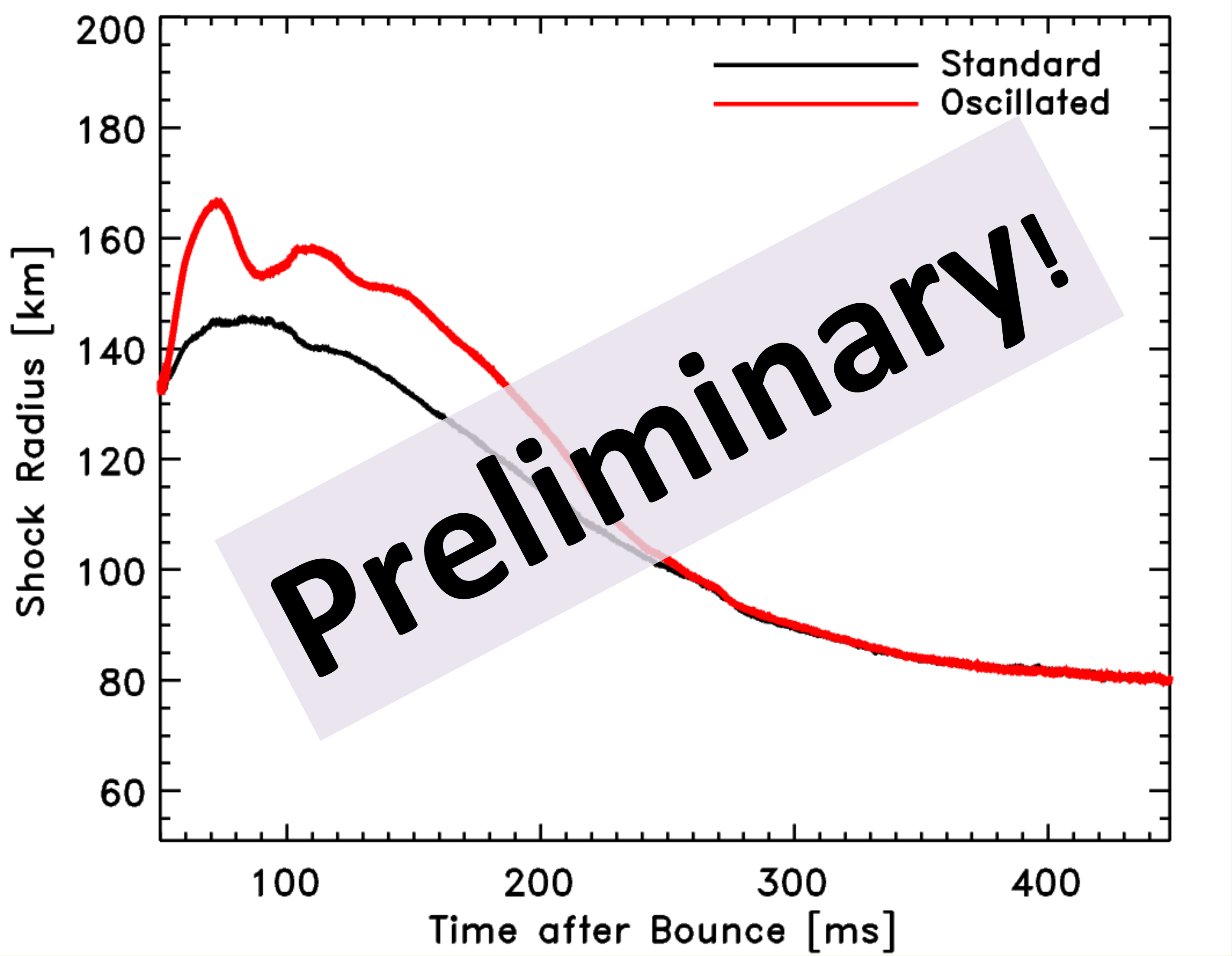
- Following Fogli et al. '07, '08.
- IH, split at 7 MeV (electron neutrinos), 2 MeV (antis)
- 12 solar mass progenitor, 100 ms after core bounce. Code: 1D Version of VULCAN/2D.
- Assume: Ad-hoc spectral swap manifest at R = 90 km.

Result



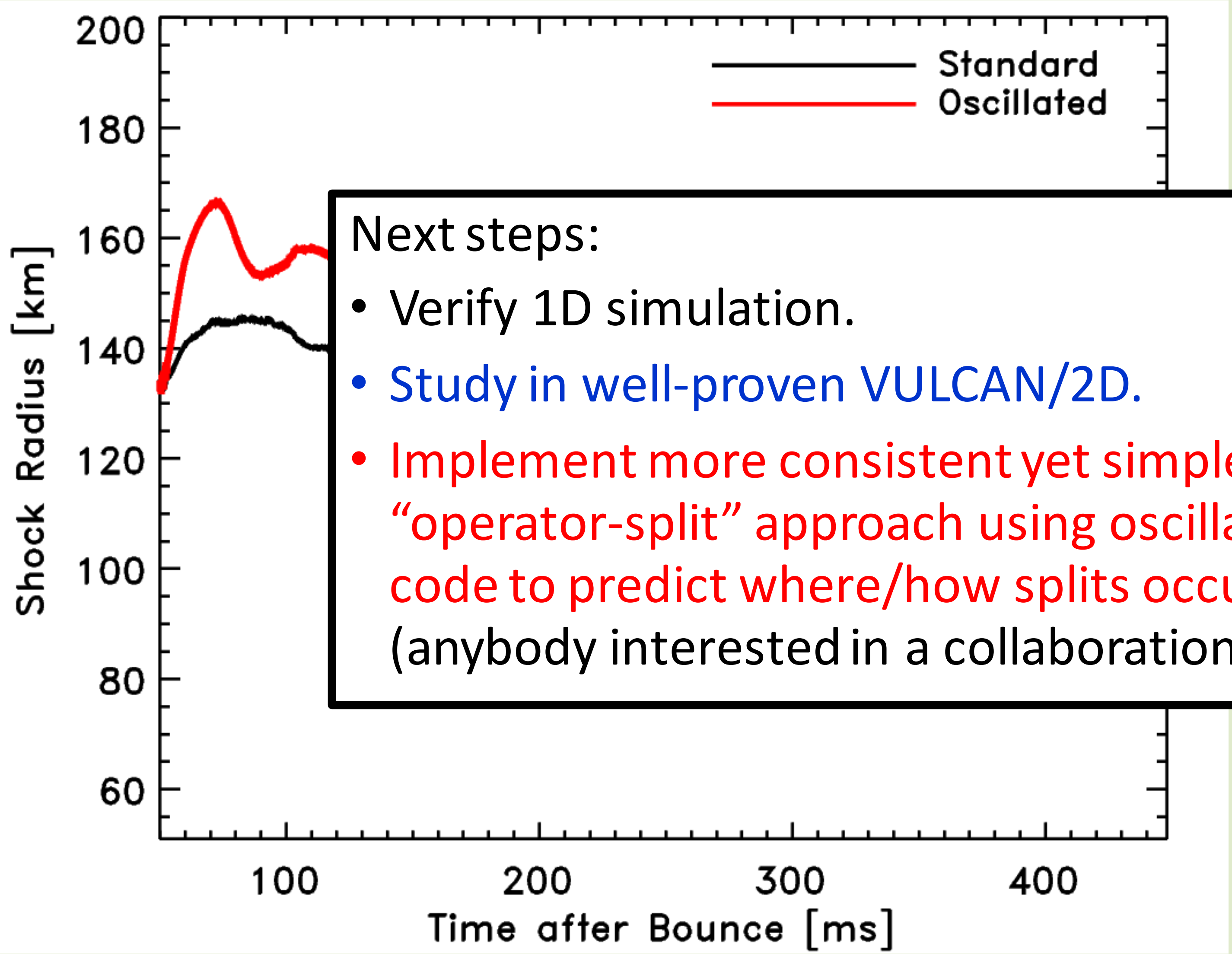
- Huge increase in instantaneous heating rate.

Dynamical Impact



- Another case of Mazurek's law? Still checking simulation...

Dynamical Impact



Next steps:

- Verify 1D simulation.
- Study in well-proven VULCAN/2D.
- Implement more consistent yet simple "operator-split" approach using oscillation code to predict where/how splits occur (anybody interested in a collaboration?).

- Another case of Mazurek's law? Still checking simulation...

Summary

- Multi-D core-collapse supernova simulations are maturing
  -> 3 potential explosion mechanisms:
  neutrino, **magnetorotational**, **acoustic**
- **The gravitational-wave signature of the 3 considered mechanisms is likely to be mutually exclusive**. Neutrinos will help as well.
- **Galactic core-collapse SN would allow to constrain SN mechanism.**

- Ordinary massive stars don't collapse directly to BHs.
  There is always a protoneutron star phase of 0.2 to multiple seconds.
- **First 3D models of BH formation in failing CCSNe -- more realistic models to come soon.**

- First (very preliminary) results on the potential dynamical impact of self-induced neutrino oscillations on the CCSN mechanism.

Supplemental Slides

Understanding the Core-Collapse SN Mechanism

- Core-Collapse Supernova Physics:

Fully coupled!

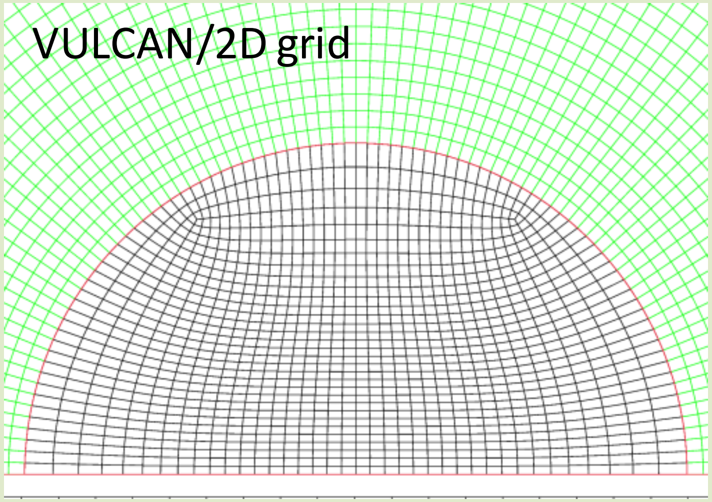
Magneto-Hydrodynamics / Plasma Physics	→	Dynamics of the stellar fluid.
General Relativity	→	Gravity
Nuclear and Neutrino Physics	→	Nuclear EOS, nuclear reactions & ν interactions.
Transport Theory	→	Neutrino transport.

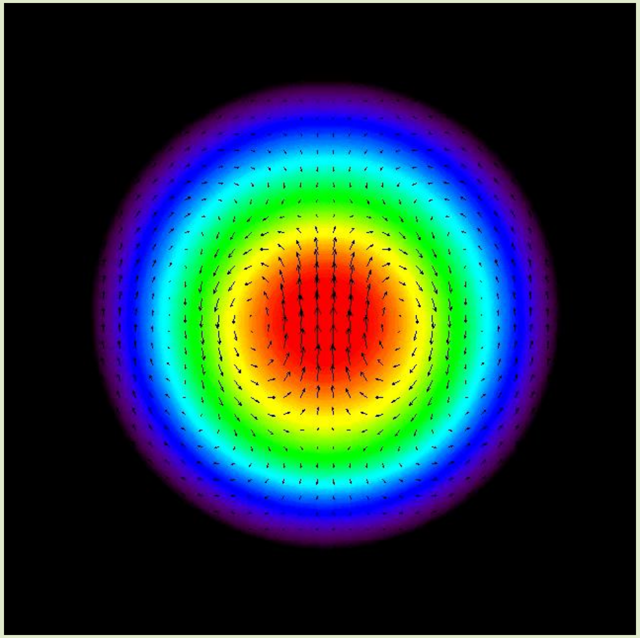
- Additional Complication: **The Multi-D Nature of the Beast**
  - Rotation, **fluid instabilities** (convection, turbulence, advective-acoustic, rotational), **MHD dynamos**, precollapse multi-D perturbations.
    -> **Need multi-D (ideally 3D) treatment.**

- Route of Attack: **Computational Modeling**
  - First 1D computations in the late 1960's: **Colgate & White, Arnett, Wilson**
  - Best current simulations still 1D.
  - **Good 2D Models (with various approximations [Gravity/Transport]).**
  - **First 3D Models.**

Testing the Acoustic Mechanism

- So far no independent confirmation of the acoustic mechanism.
- Overstable physical g-modes PNS shown to exist. [Ferrari et al. 2003, 2007; Yoshida et al. 2007]
- Questions:
  - Do modes reach amplitudes as high as seen in our calculations?
  - Effects of GR and 3D?
- Fundamental prerequisite for non-linear numerical tests of mode excitation: Grid must be singularity free & allow change of the core's geometric center.
- Marek & Janka '09:
  Modes shown to exist, but don't reach high amplitudes. But: (1) Amplitudes become high only at t > 0.6 - 0.8 s (not simulated),
  (2) MJ09 grid not singularity free.
  -> Acoustic Mech. not yet numerically ruled out.






Time: 119.33 ms
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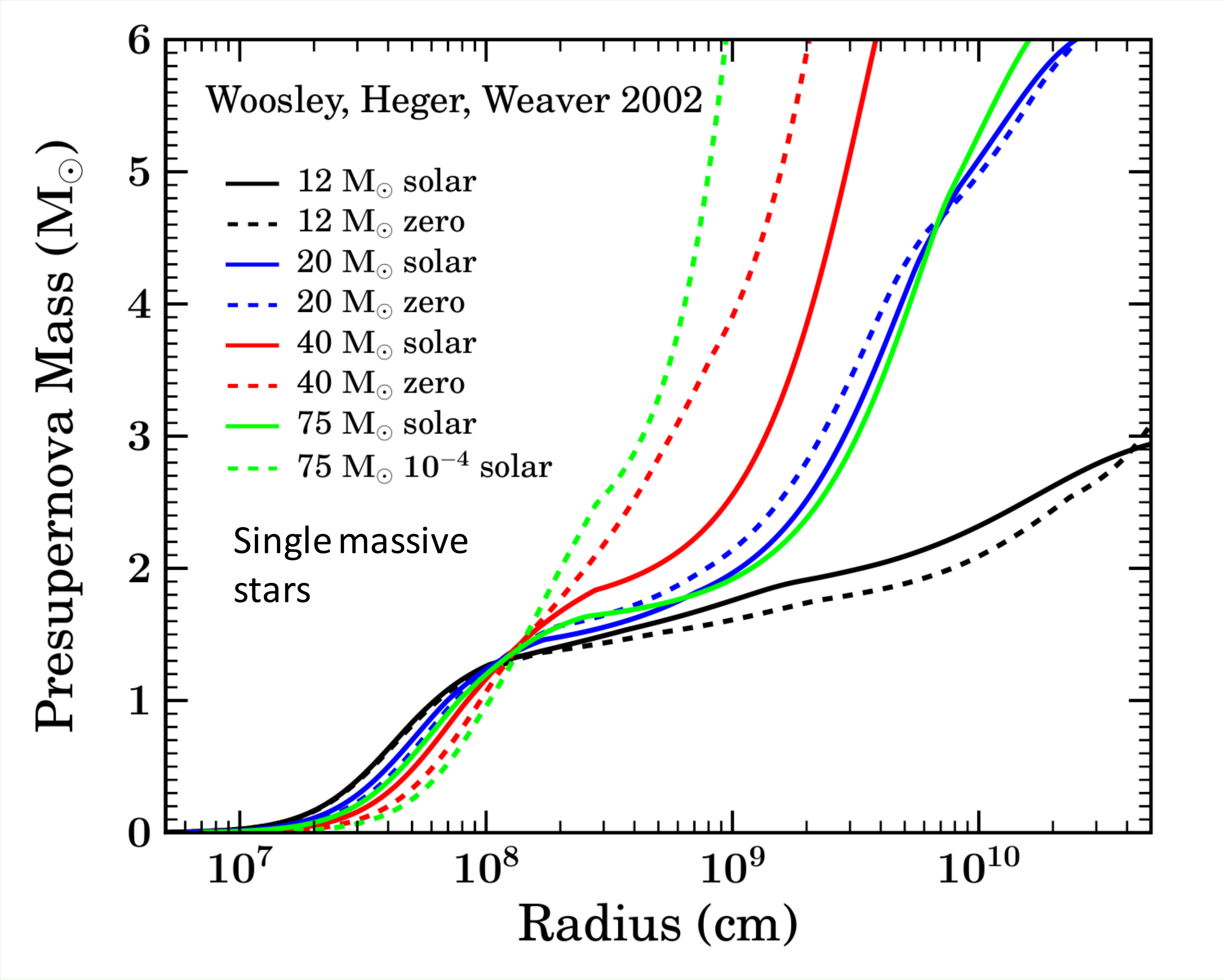
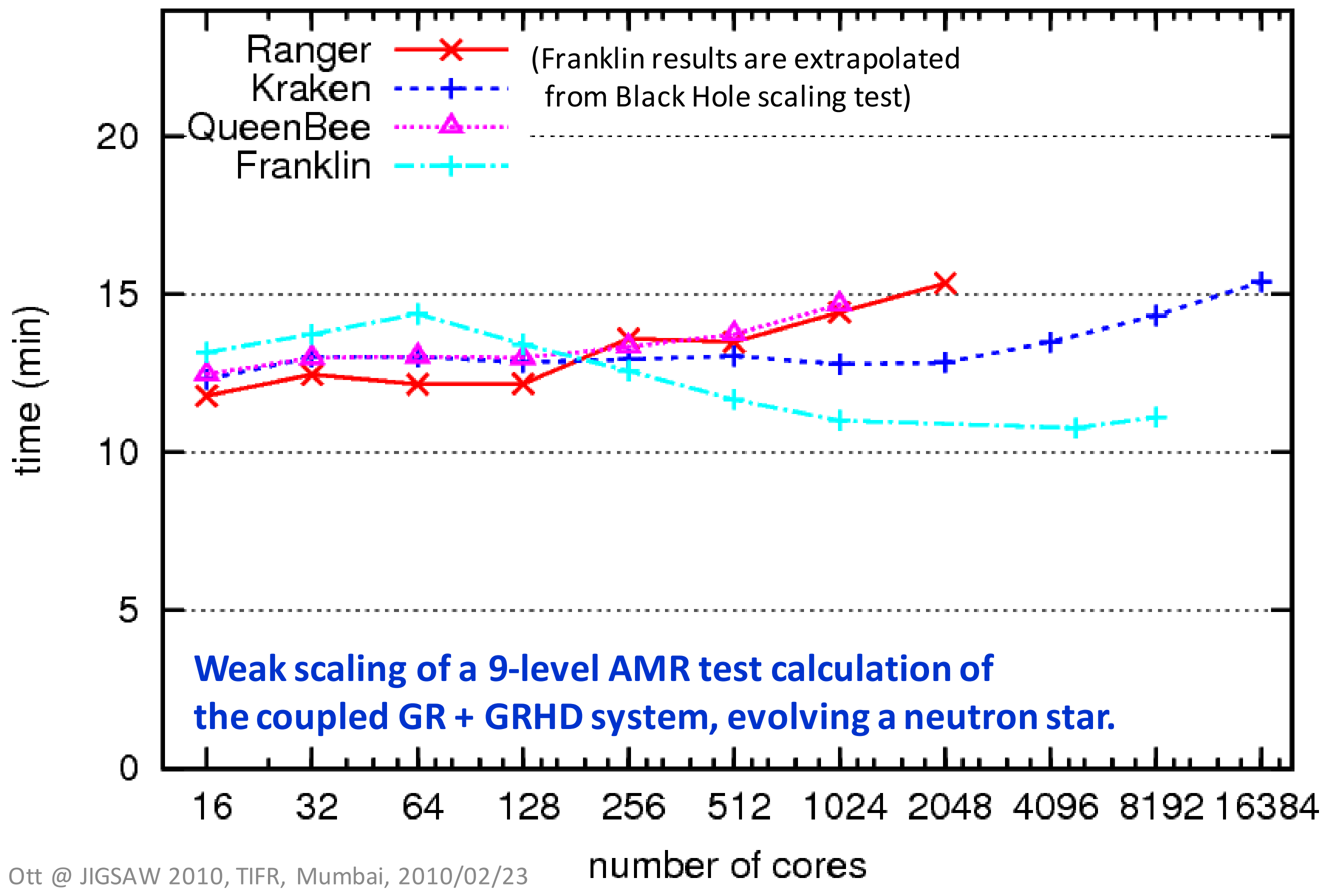
Precollapse Stellar Structure



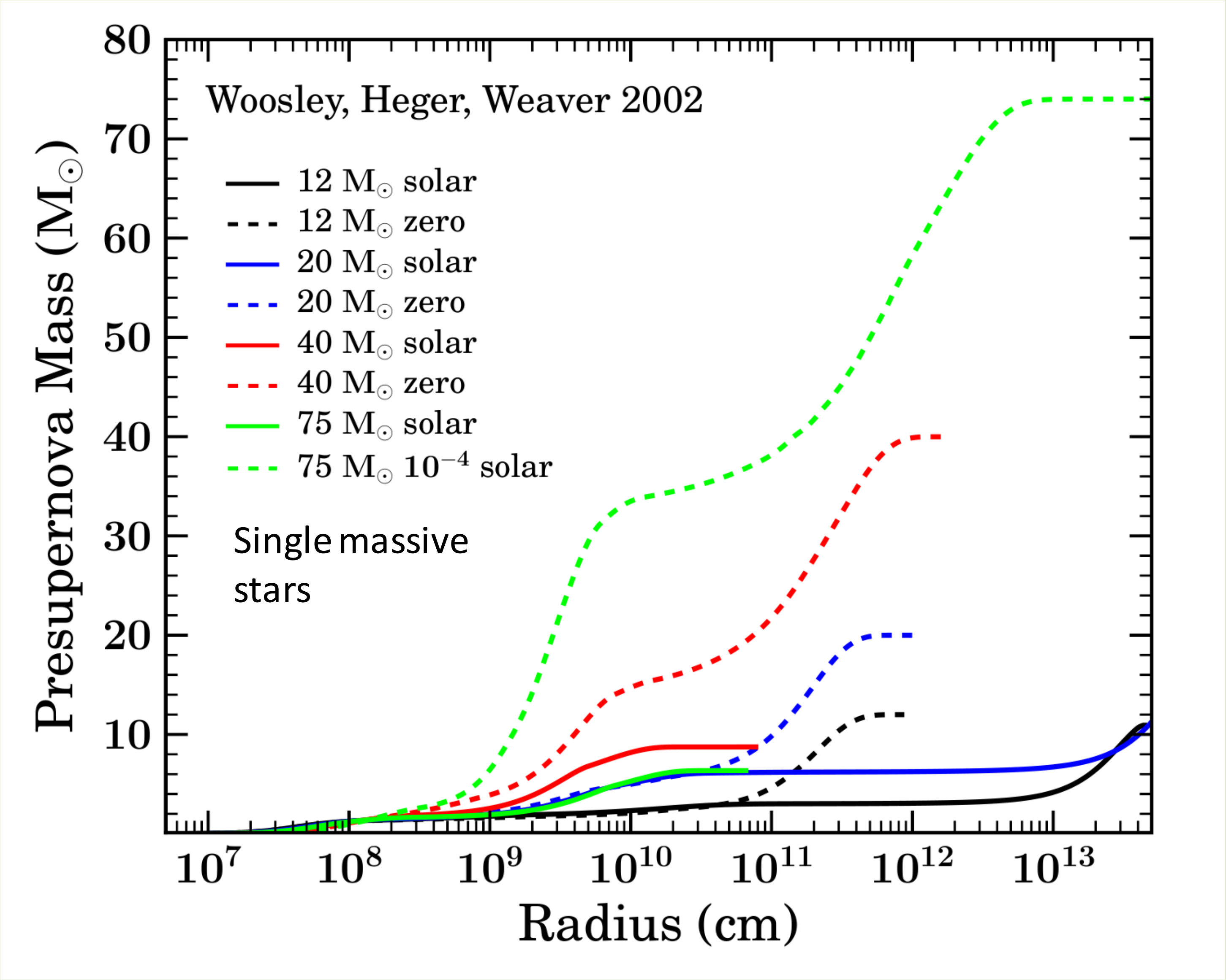
Computational Cost & Scaling

[Based on GR+GRHD]

- 9 levels of refinement, each 400^3 zones, 400 3D grid functions -> Memory footprint > ~**2 TB** (including inter-process buffers)
- 1 single-zone update: 50 kflop; total timesteps: ~1 M (fine grid). -> ~**1500 Petaflops**. Factor 5-10 larger with radiation transport.



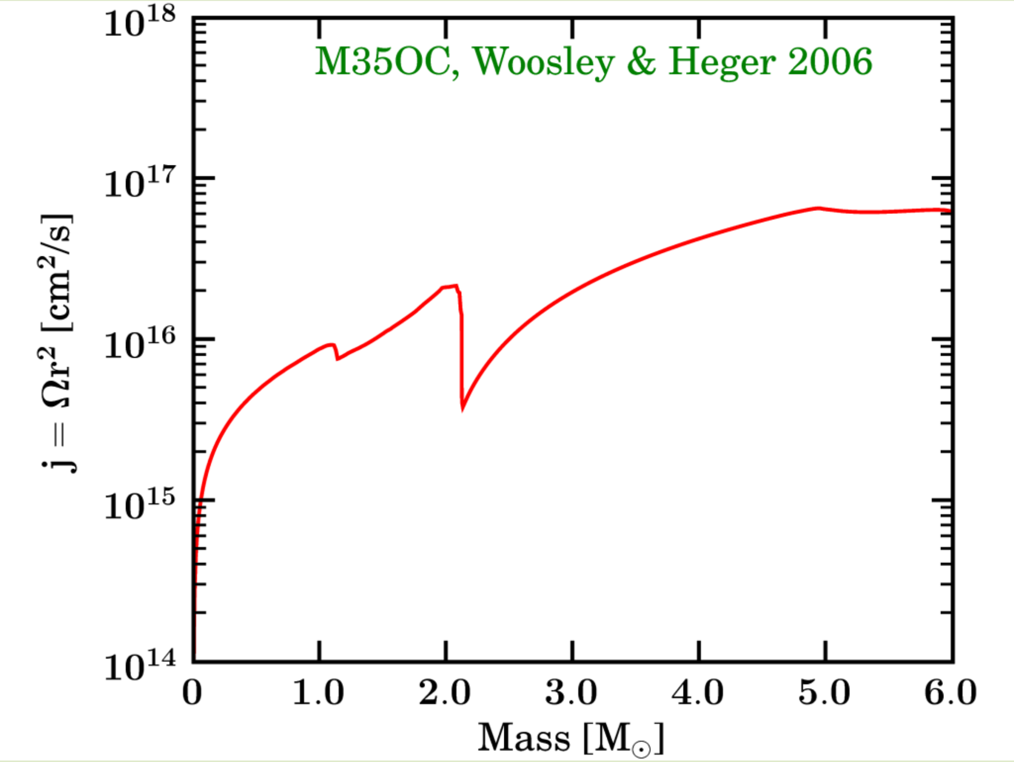
Precollapse Stellar Structure



Testing GRB Progenitors

[Dessart, Burrows, Livne, Ott, Murphy, ApJL 2008]

- Necessary specific angular momentum to make a disk around a maximally spinning Kerr BH:
  $j > \sim 1.5 \times 10^{16}\ (M_{BH}/3M_{SUN})\ cm^2/s$.
  -> need rapidly rotating progenitor star.

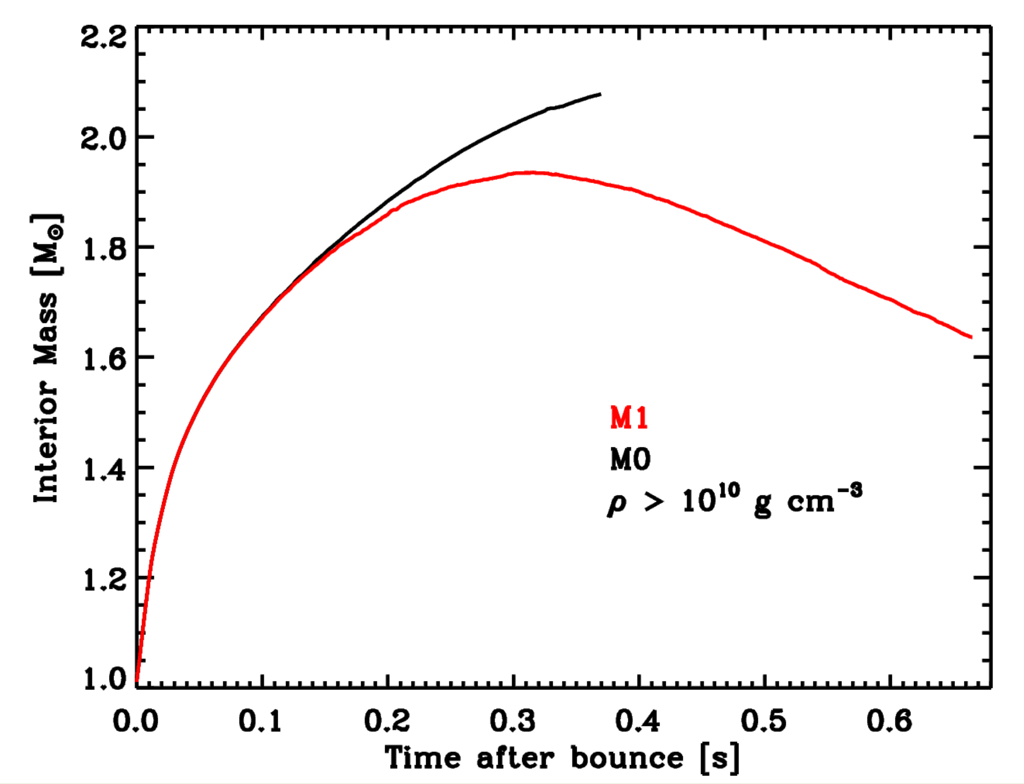


- Basic question:
  Can rapid rotation + MHD inhibit BH formation and a GRB?
  -> Newtonian MHD simulations with VULCAN/2D.

Testing GRB Progenitors

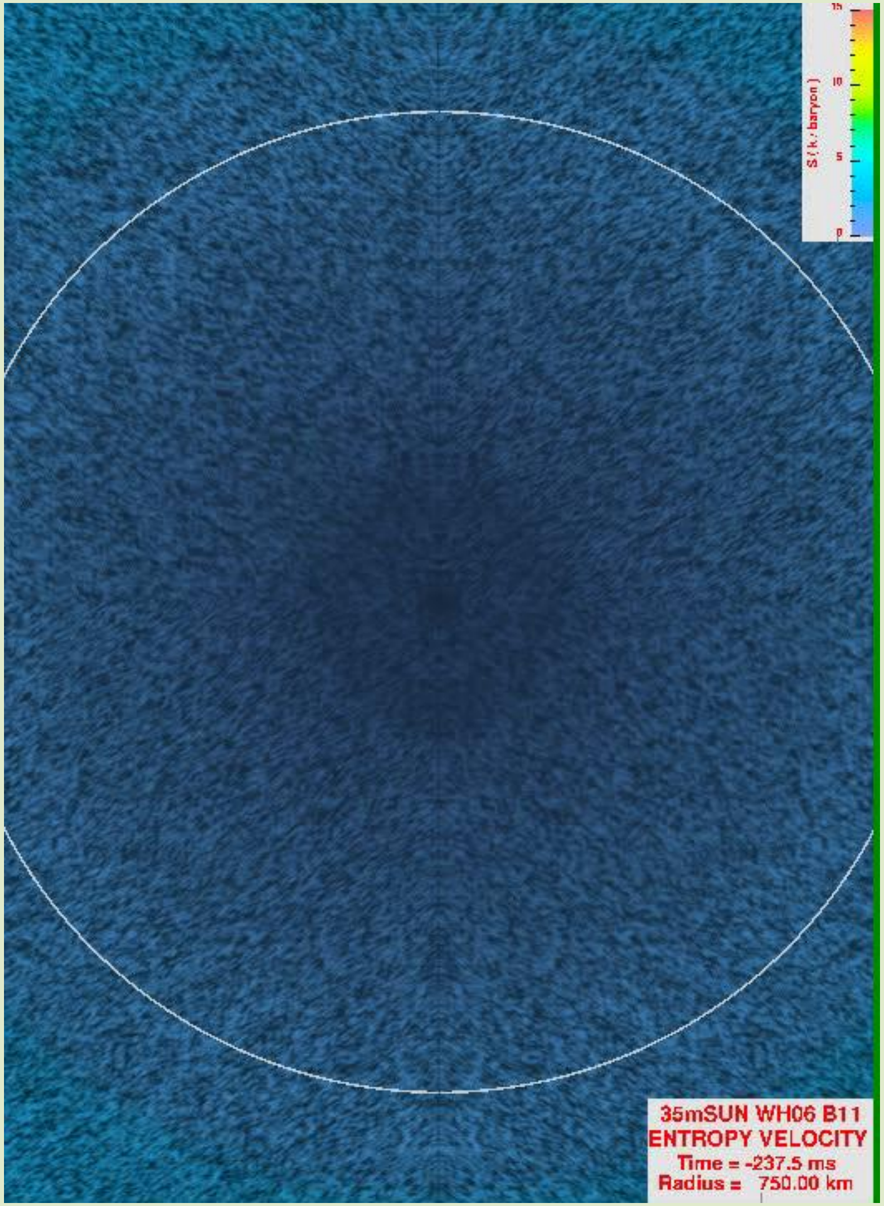
[Dessart, Burrows, Livne, Ott, Murphy, ApJL 2008]

- Model 35OC from Woosley & Heger 2006; original precollapse rotational configuration.
- Initial B-field: Two models
  M0: 2 x 10^{10} G toroidal, 8 x 10^{11} G poloidal (progenitor model)
  M1: 2 x 10^{10} G toroidal, 4 x 10^{12} G poloidal.



Testing GRB Progenitors

[Dessart, Burrows, Livne, Ott, Murphy, ApJL 2008]



- Rapid rotation + MHD can inhibit (or delay) BH formation in GRB progenitors.
- Standard Collapsar scenario may not work as straightforwardly as thought.