How Do Massive Stars Supernova? -

Core-Collapse Supernova Explosions: The Theoretical Challenge

Supported by:
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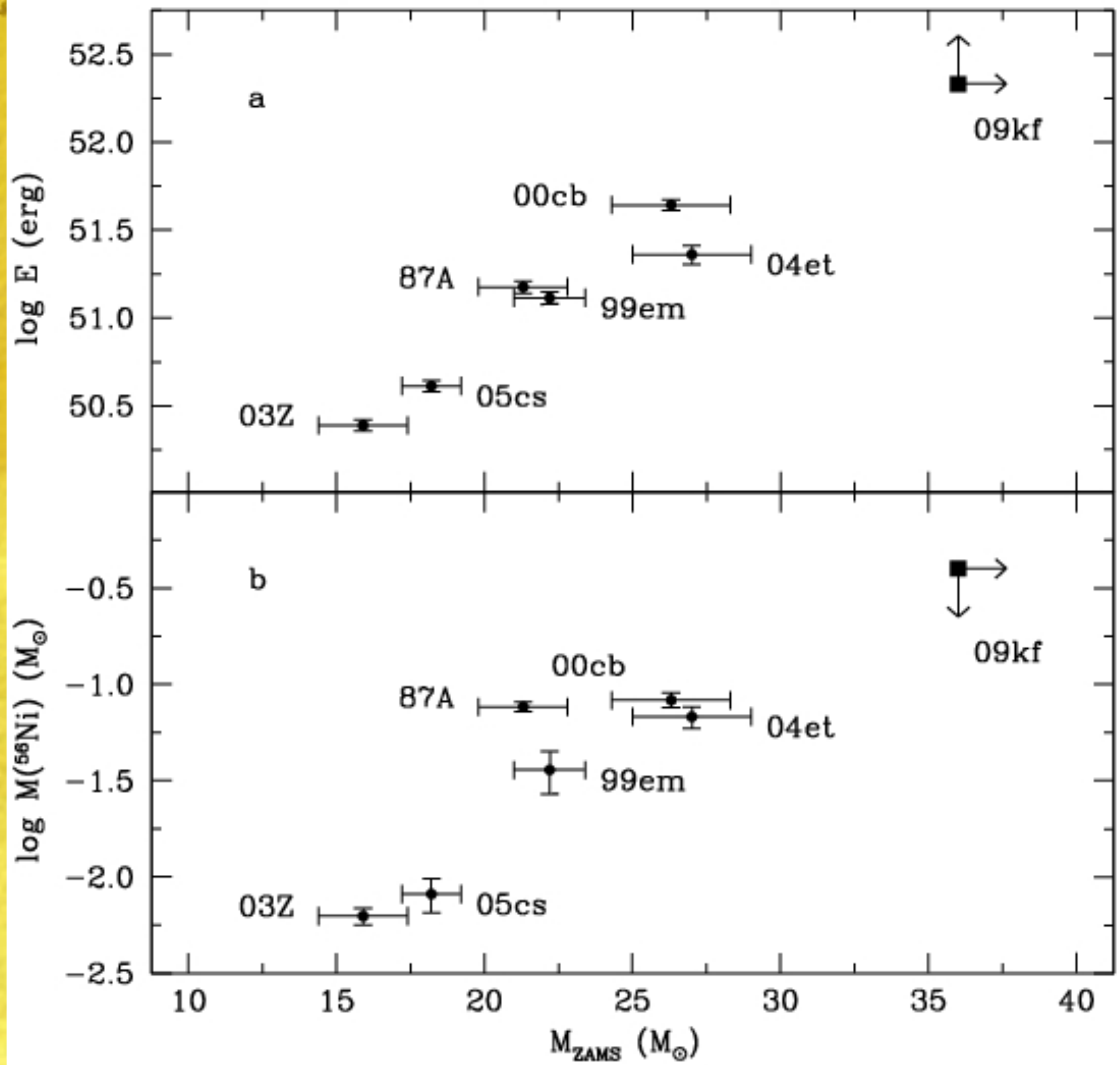
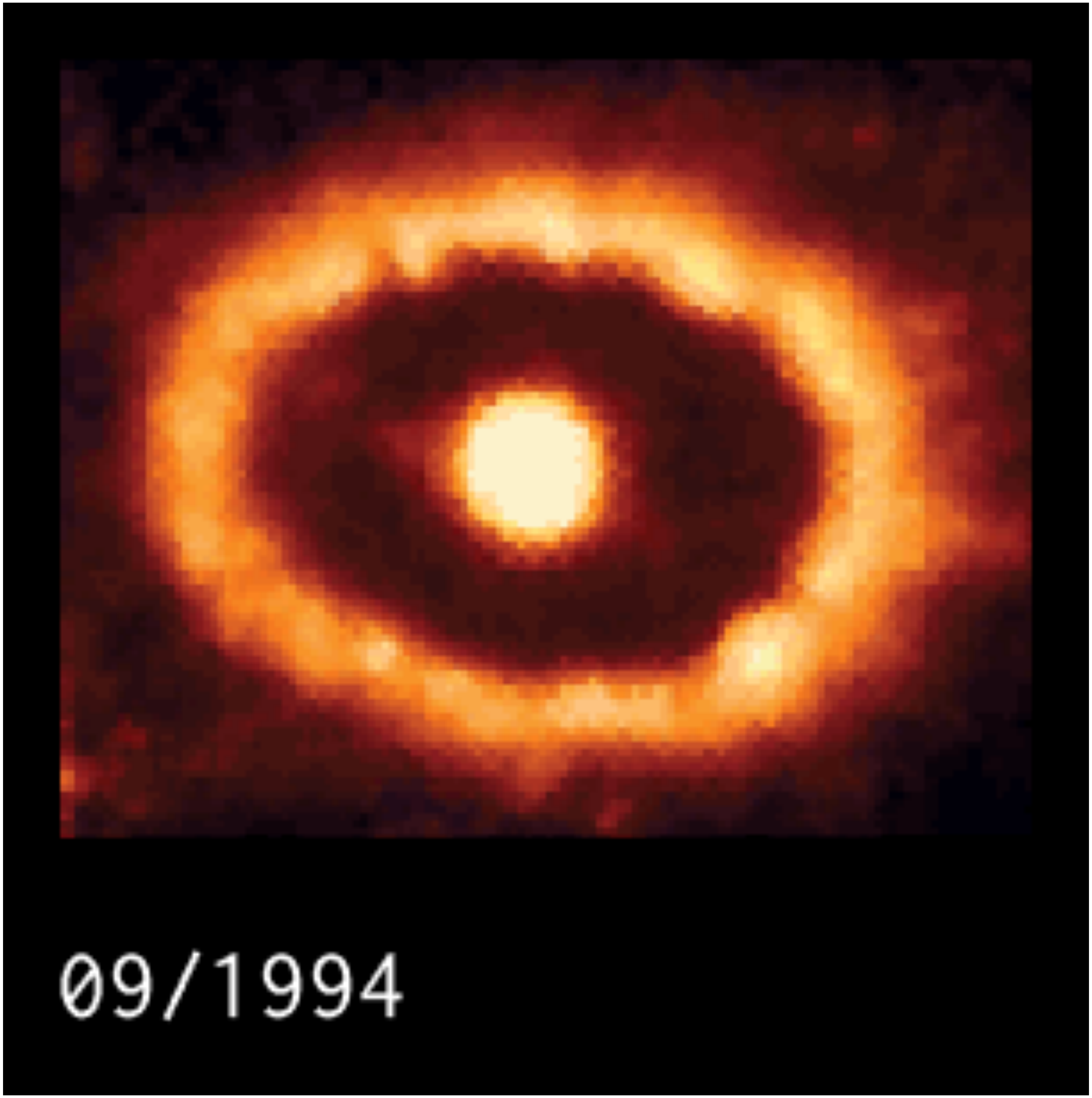
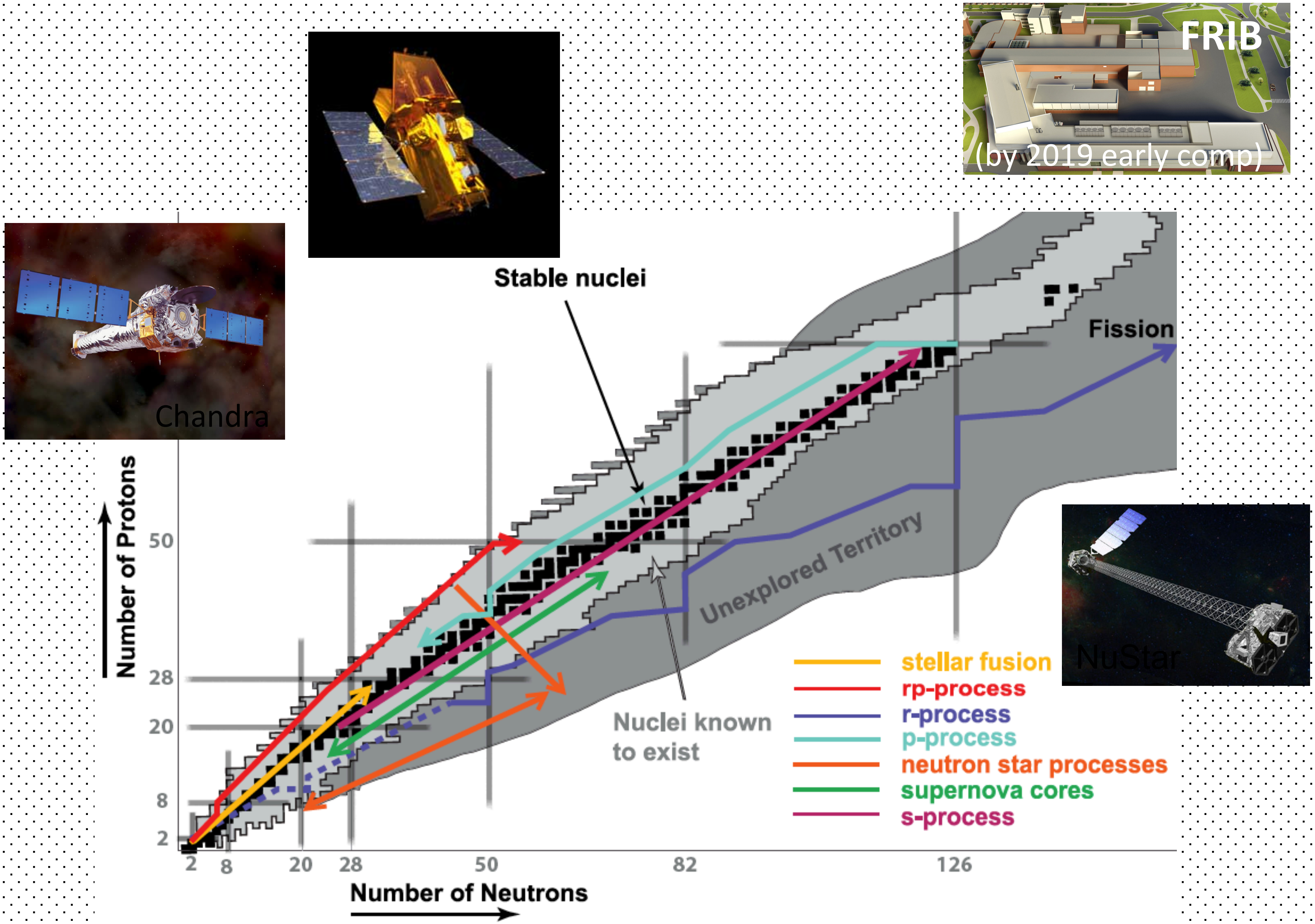
Explosion Energy and Nickel Mass vs. ZAMS Mass



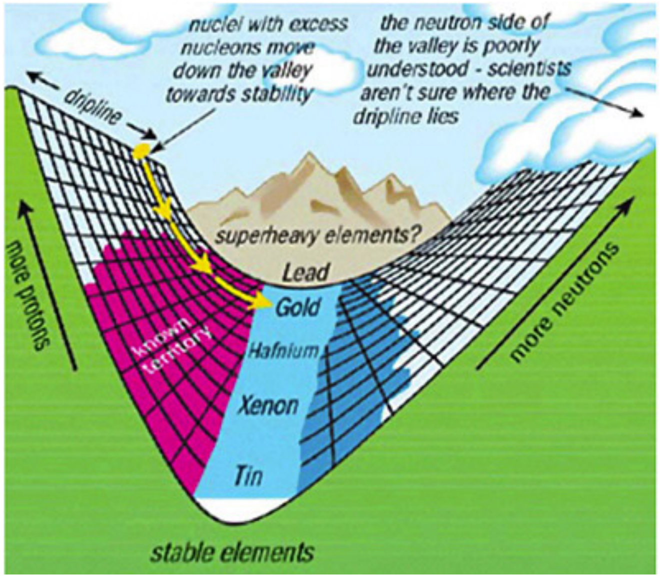
Utrobin & Chugai 2011


09/1994

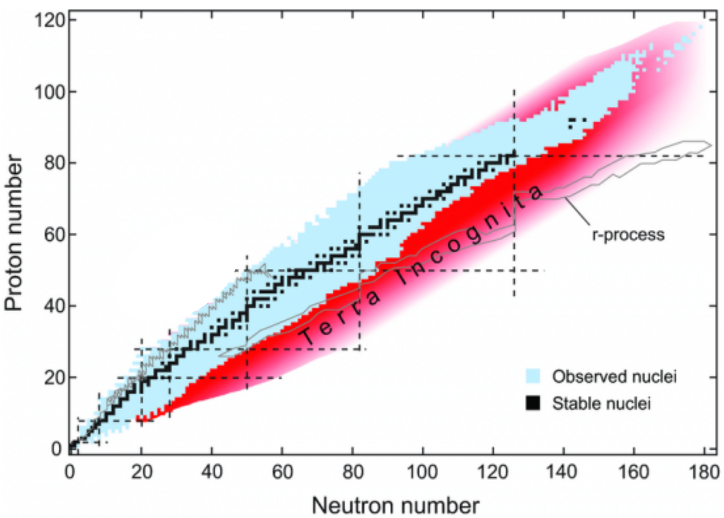
Nuclear Processes in the Cosmos

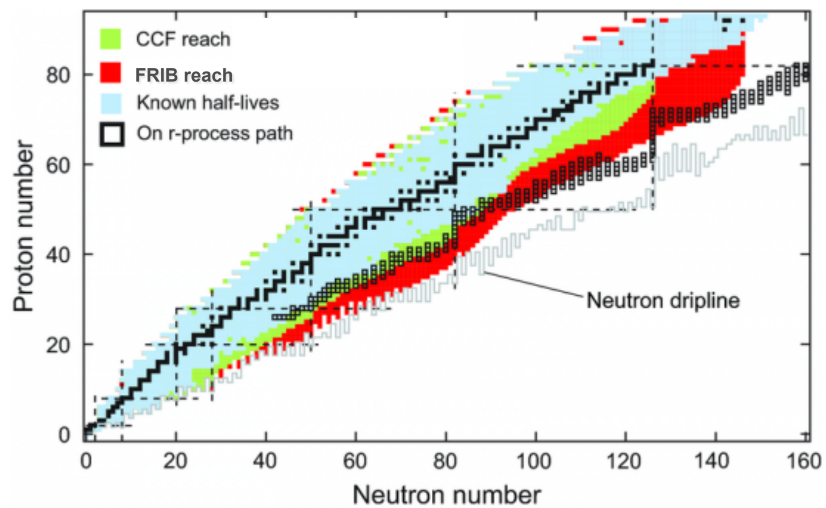


Reach of FRIB - Link to Nuclear Astrophysics

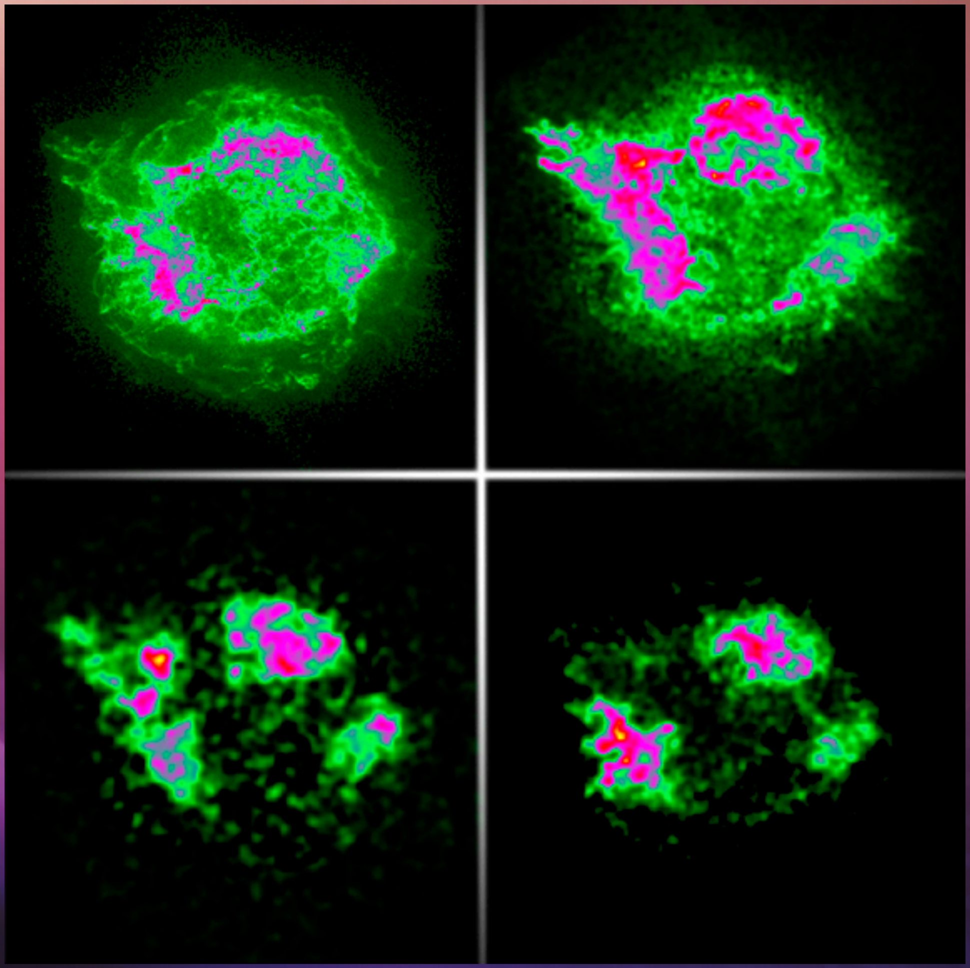


- Nuclear Masses & decay properties
- Neutron halos
- Disappearance of shell structure
- Emergence of new shapes,
- New collective modes of excitation
- Mapping the driplines
- Islands of stability





Observed Asymmetry

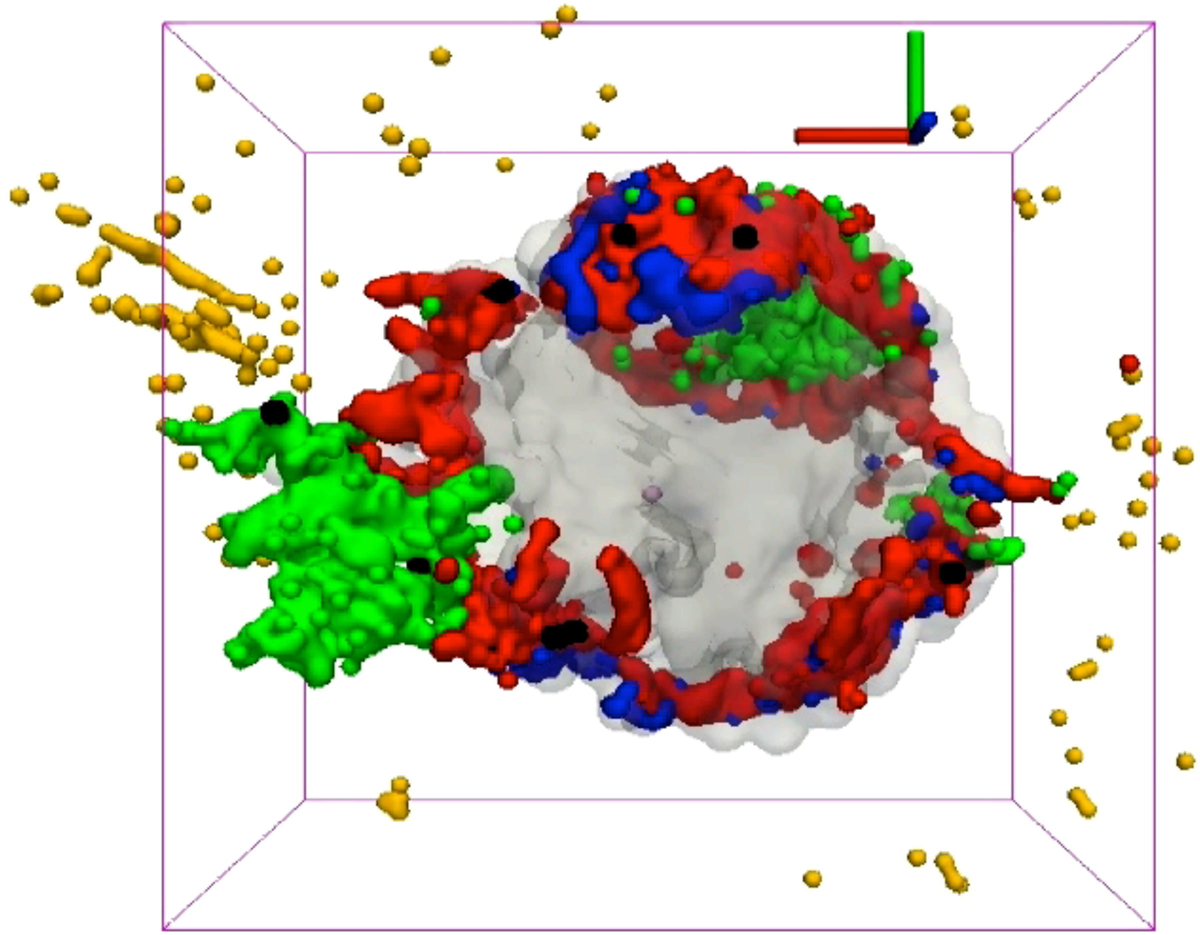


Cas A SN Remnant: Chandra

Cas A Remnant

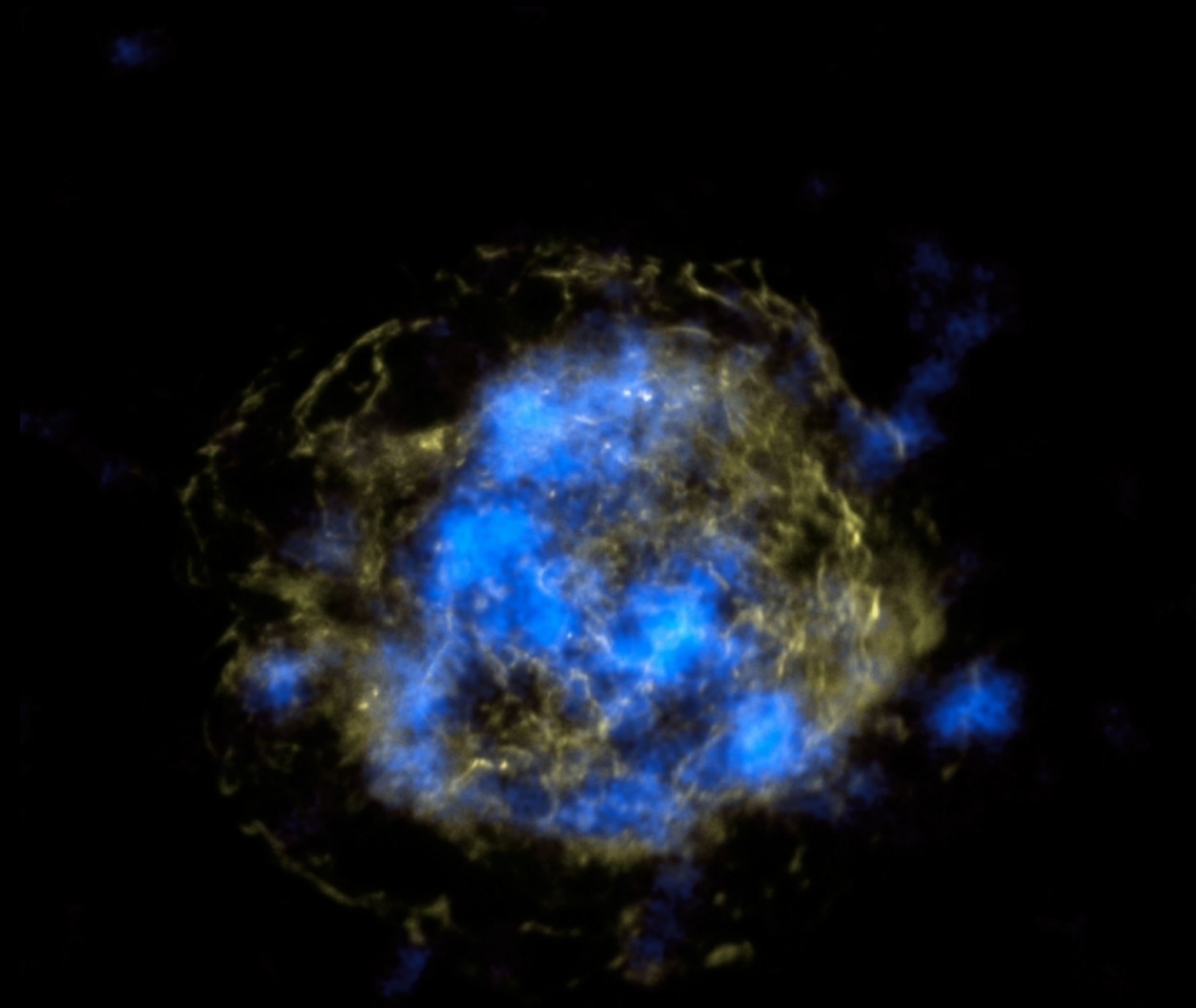
Fe

Si



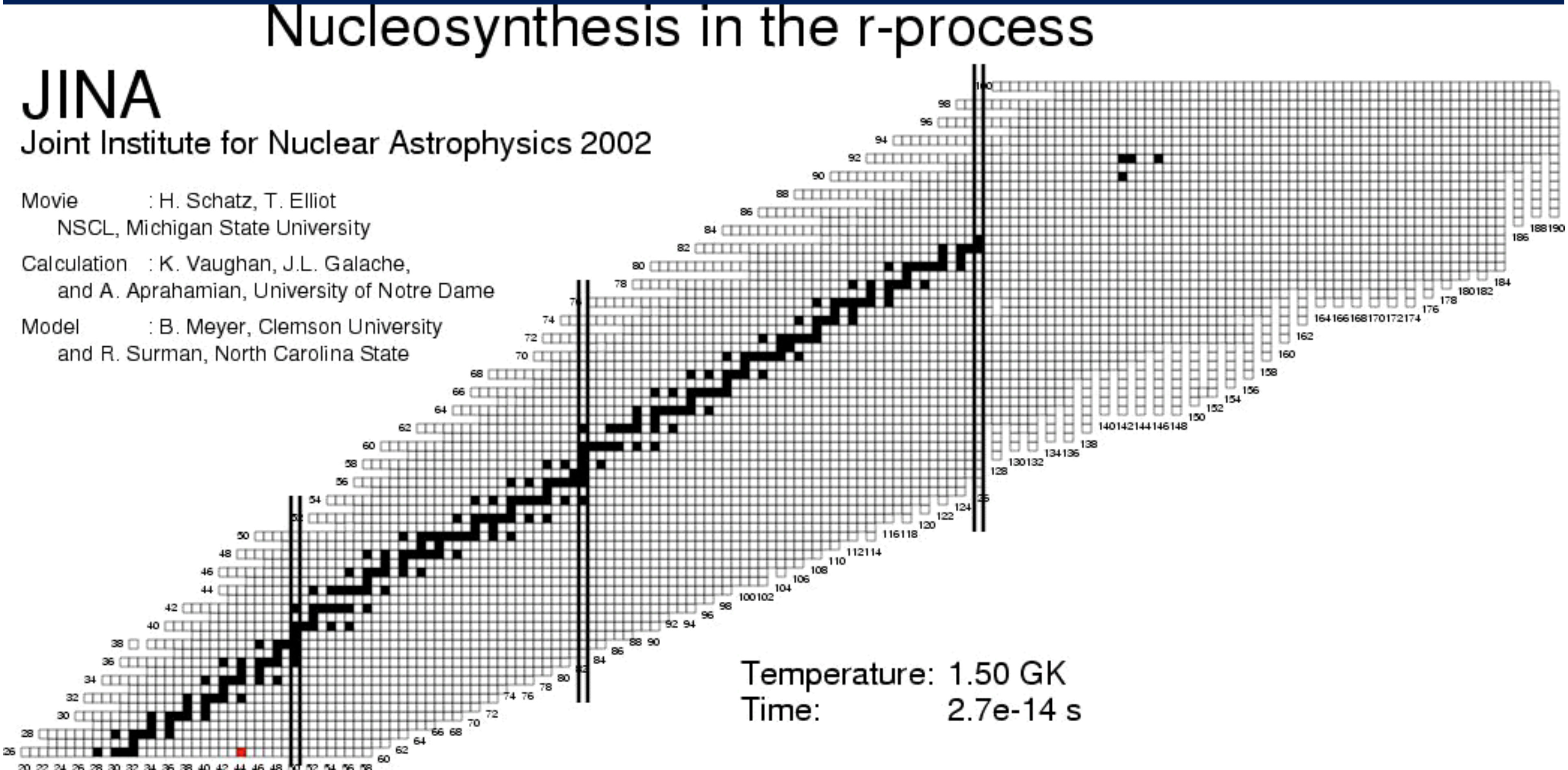
DeLaney et al. 2010

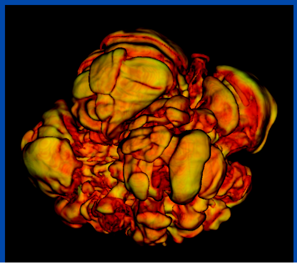
Cas A Remnant in ^{44}Ti

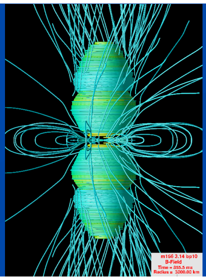


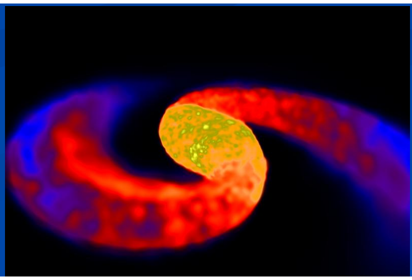
Radioactive Titanium (blue)

R-Process Nucleosynthesis









"R-process" Nucleosynthesis?

No natural site for 2^{nd} or 3^{rd} Peak in CCSNe (~ Solar Metallicity)?

Mechanisms of Explosion

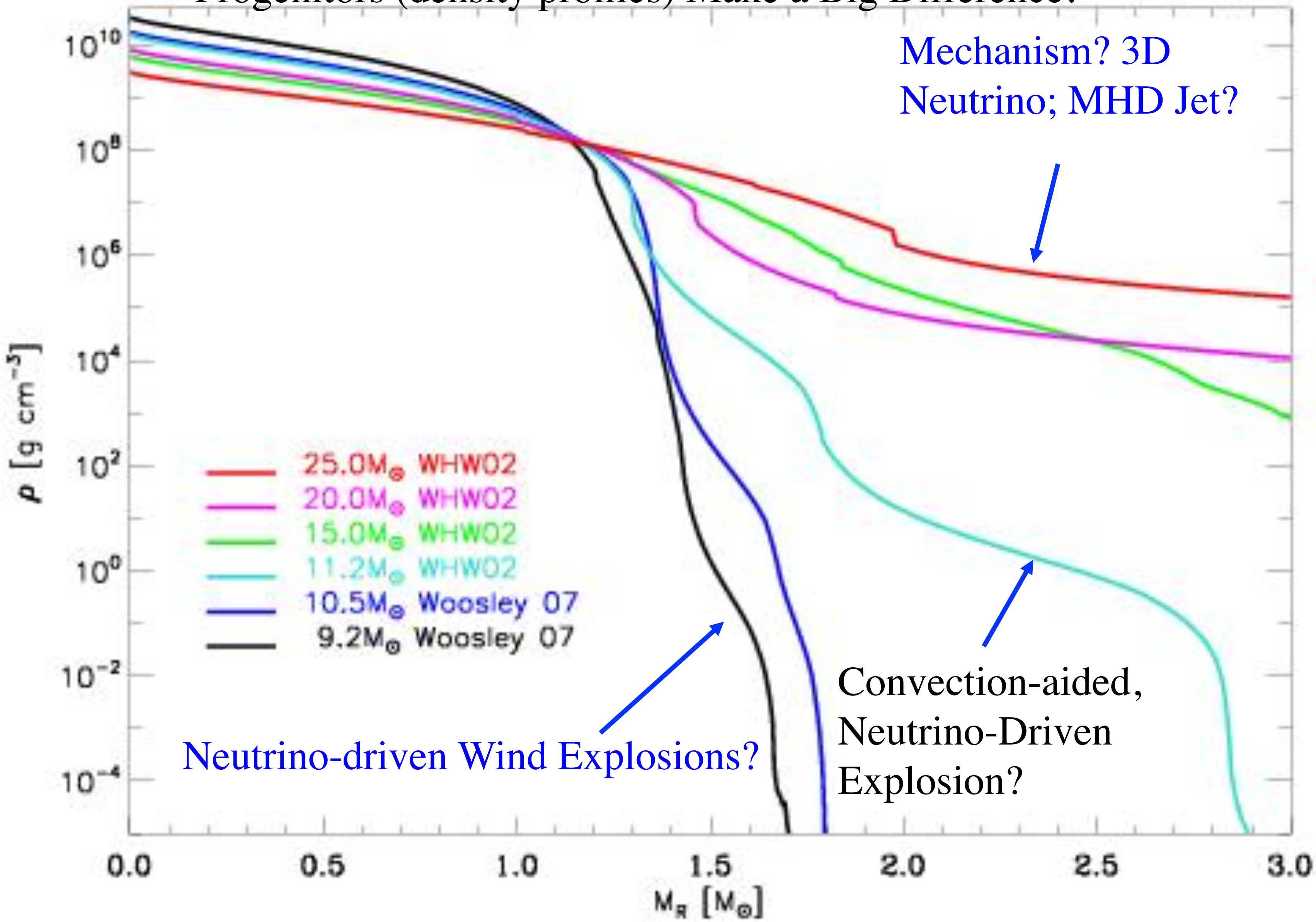
- Direct Hydrodynamic Mechanism: always fails
- Neutrino-Driven Wind Mechanism, ~1D; Low-mass progenitors
- 2D Convection Neutrino-driven (circa 1995-2009)
  ("SASI" not a mechanism, but a shock instability)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf
- MHD/Rapid Rotation - "Hypernovae"?
- Acoustic Power/Core-oscillation Mechanism? (Aborted if neutrino mechanism works earlier; Weinberg & Quataert ?)
- 3D "Convection" Neutrino-driven Mechanism

Important Ingredients/Physics

- Progenitor Models (and initial perturbations?)
- Multi-D Hydrodynamics (3D)
- Multi-D Neutrino Transport (multi-D) (most challenging aspect)
- Instabilities - Neutrino-Driven Convection (+ SASI?)
- Neutrino Processes - Cross sections, emissivities, etc. (at high densities?)
- General Relativity (May & White; Schwartz; Bruenn et al.; Mueller et al.; Kotake et al.)
- Rotation!

Density Profiles of Supernova Progenitor Cores

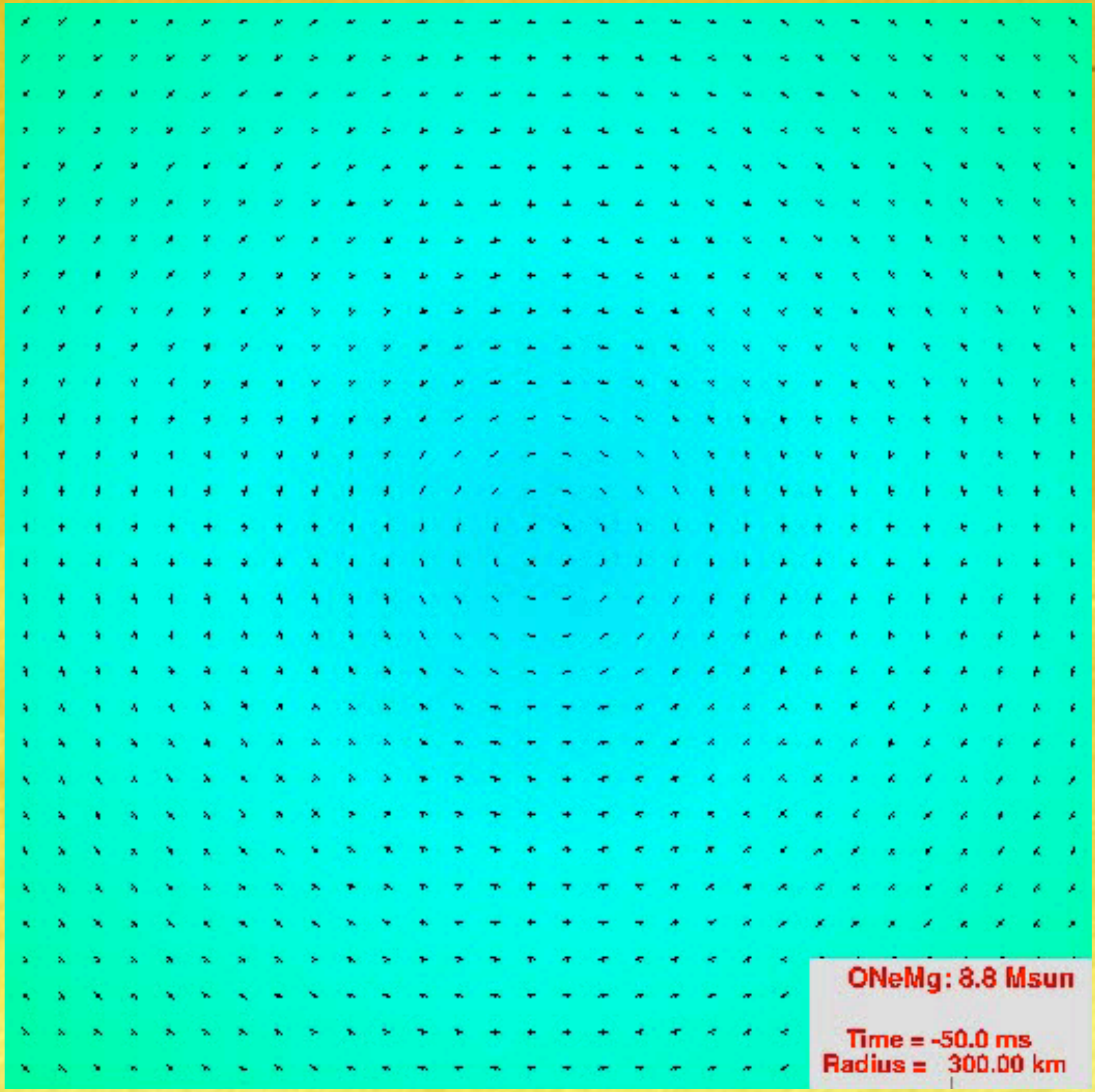
Progenitors (density profiles) Make a Big Difference!



8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion

First shown by Kitaura et al. 2006

Burrows, Dessart, & Livne 2007



SN 2009md;

SN 1997D:

Low Energy Explosion

NOTE WIND THAT FOLLOWS

VULCAN/2D Multi-Group,Multi-Angle, Time-dependent Boltzmann/Hydro (6D)

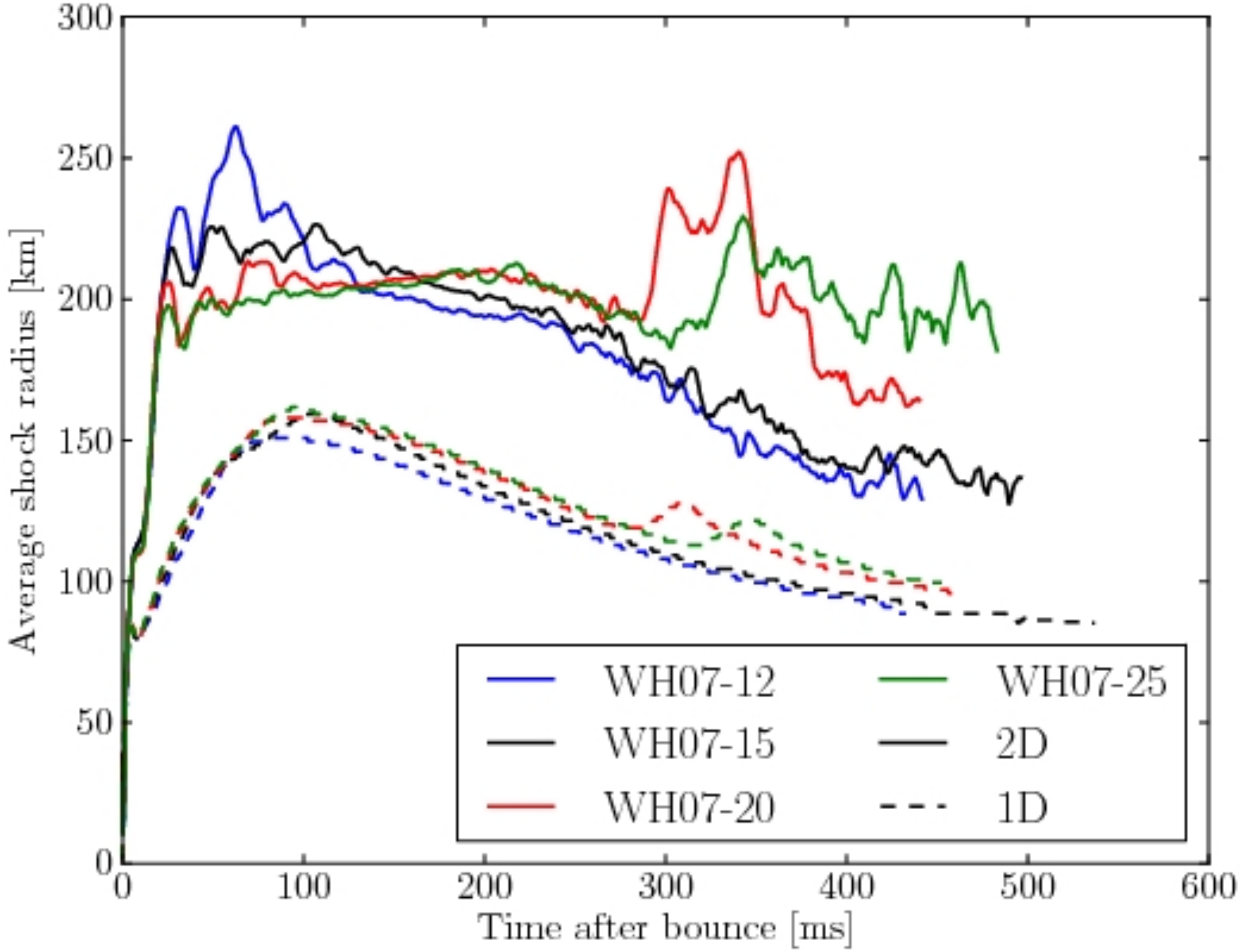
- One of only two codes (CASTRO and VULCAN) with multi-D transport used in supernova theory
- Arbitrary Lagrangian-Eulerian (ALE); remapping
- 6 - dimensional (1(time) + 2(space) + 2(angles) + 1(energy-group))
- Moving Mesh, Arbitrary Grid; Core motion (kicks?)
- 2D multi-group, multi-angle, S_n (~150 angles), time-dependent, implicit transport - Ott et al. 2009
- 2D MGFLD, rotating version (quite fast)
- Poisson gravity solver
- Axially-symmetric; Rotation
- MHD version ("2.5D") - div B = 0 to machine accuracy; torques
- Flux-conservative; smooth matching to diffusion limit
- Parallelized in energy groups; almost perfect parallelism
- Livne, Burrows et al. (2004,2007a)
- Burrows et al. (2006,2007b), Ott et al. (2005,2008); Dessart et al. 2005ab,2006

CASTRO - 3D AMR, Multi-Group Radiation-Hydrodynamic Supernova Code

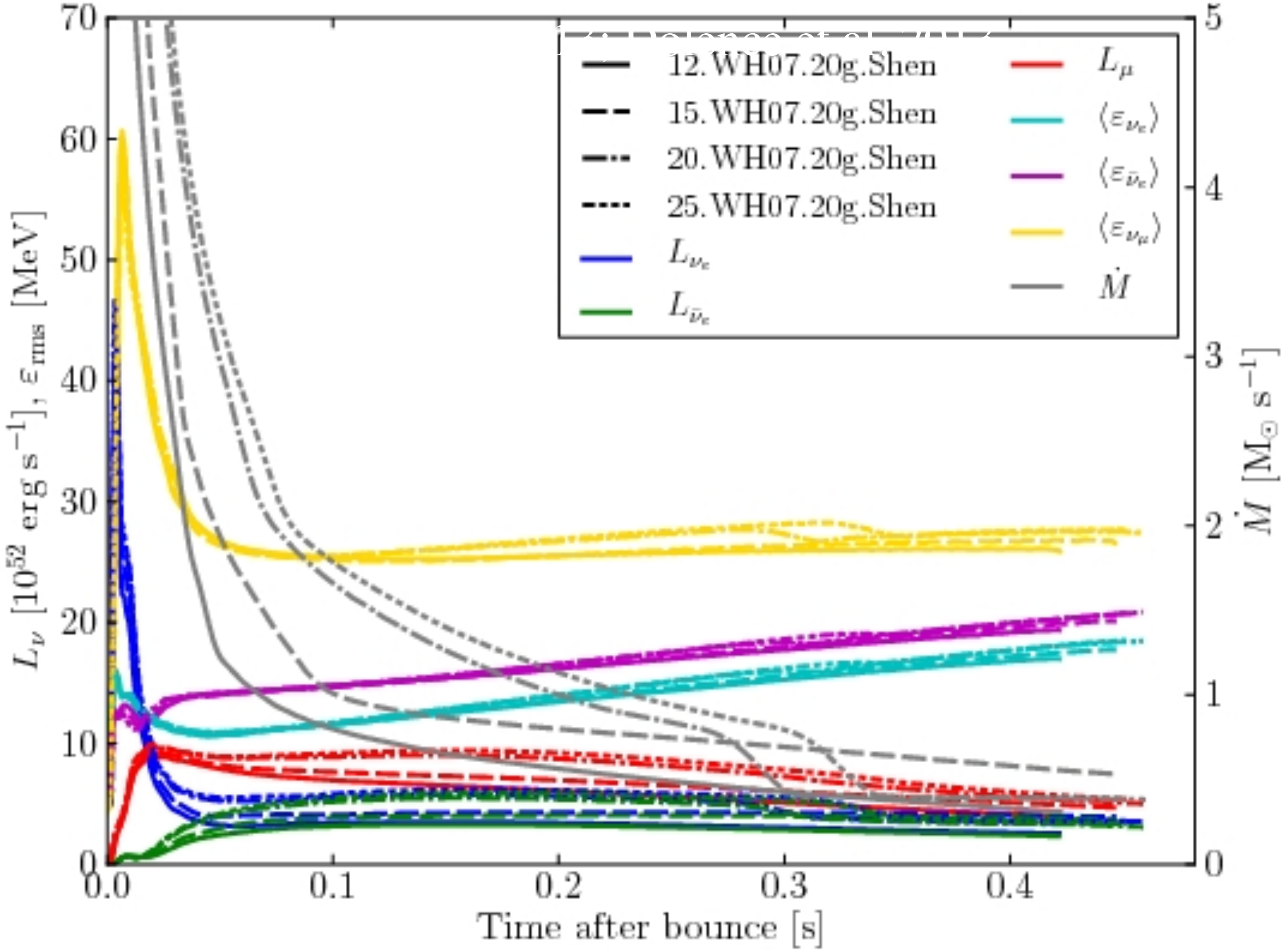
- 2nd-order, Eulerian, unsplit, compressible hydro
- PPM and piecewise-linear methodologies
- Multi-grid Poisson solver for gravity
- Multi-component advection scheme with reactions
- Adaptive Mesh Refinement (AMR) - flow control, memory management, grid generation
- Block-structured hierarchical grids
- Subcycles in time (multiple timestepping - coarse, fine)
- Sophisticated synchronization algorithm
- BoxLib software infrastructure, with functionality for serial distributed and shared memory architectures
- 1D (cartestian, cylindrical, spherical); 2D (Cartesian, cylindrical); 3D (Cartesian)
- Transport is a conservative implementation with v/c terms and inelastic scattering
- Uses scalable linear solvers (e.g., hypre) with high-performance preconditioners that feature parallel multi-grid and Krylov-based iterative methods - challenging!
- Developers: John Bell, Ann Almgren, Weiqun Zhang, Louis Howell, Adam Burrows, Jason Nordhaus - LBNL, LLNL, Princeton

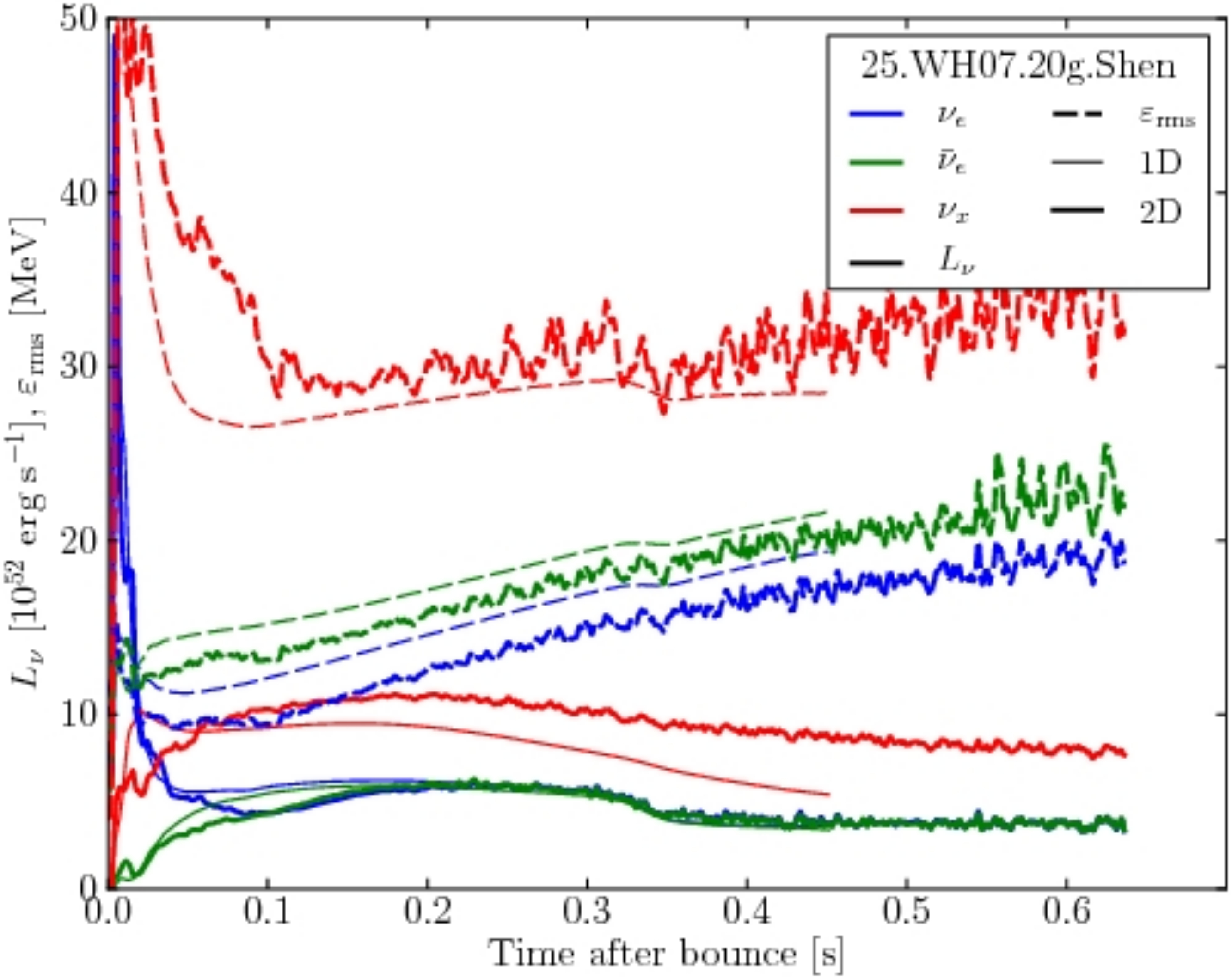
2D, 1D (CASTRO): MGFLD with multi-D Transport (no ray-by-ray)

Burrows et al. 2013; Dolence et al. 2014

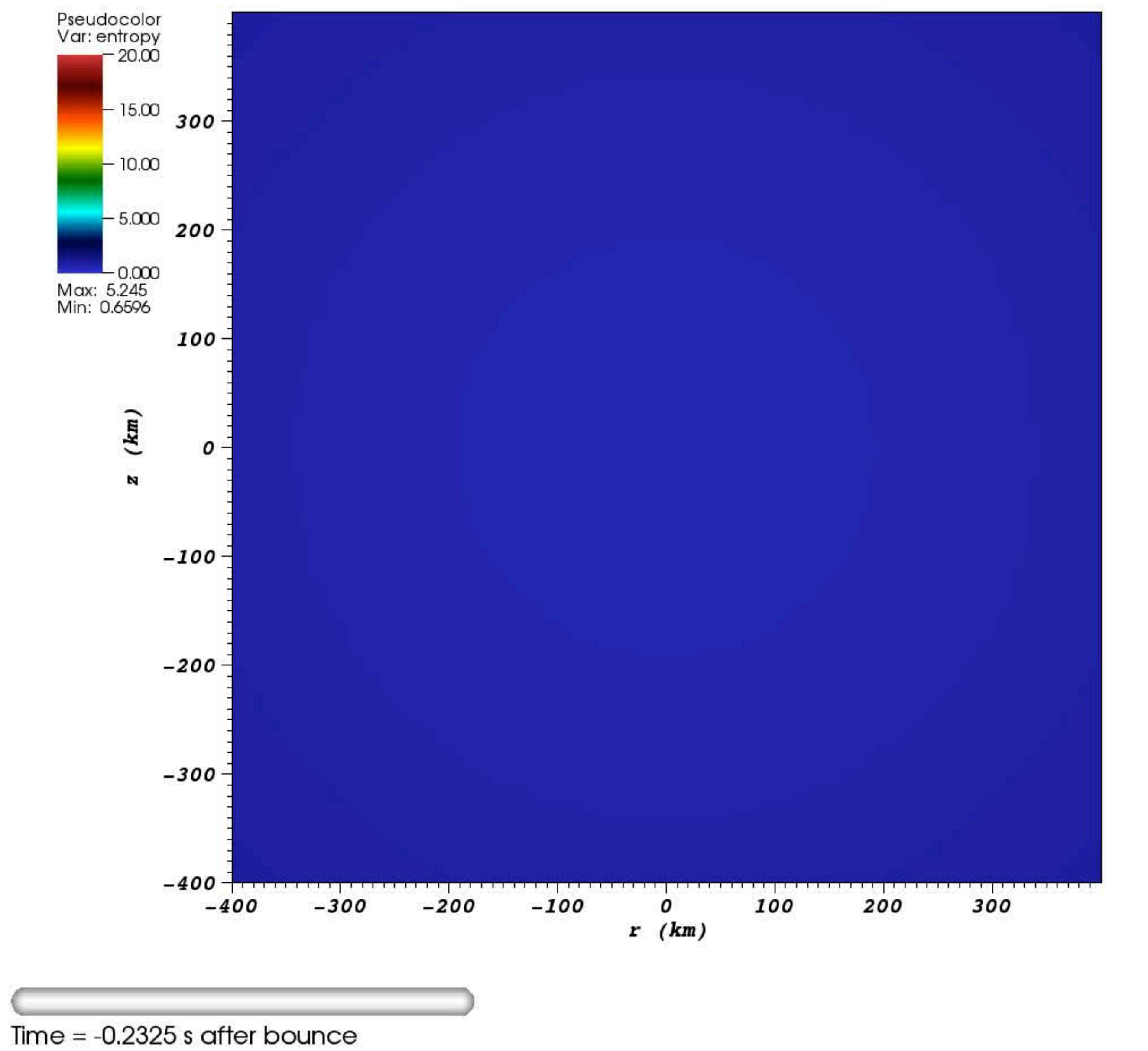


Average shock radius [km]
Time after bounce [ms]
0
50
100
150
200
250
300
0
100
200
300
400
500
600
WH07-12
WH07-15
WH07-20
WH07-25
2D
1D


12.WH07.20g.Shen
15.WH07.20g.Shen
20.WH07.20g.Shen
25.WH07.20g.Shen
L_{ν_e}
$L_{\bar{\nu}_e}$
L_μ
$\langle \varepsilon_{\nu_e} \rangle$
$\langle \varepsilon_{\bar{\nu}_e} \rangle$
$\langle \varepsilon_{\nu_\mu} \rangle$
$\dot{M}$
L_ν [10^{52} erg s^{-1}], $\varepsilon_{\rm rms}$ [MeV]
$\dot{M}$ [M$_\odot$ s^{-1}]
Time after bounce [s]

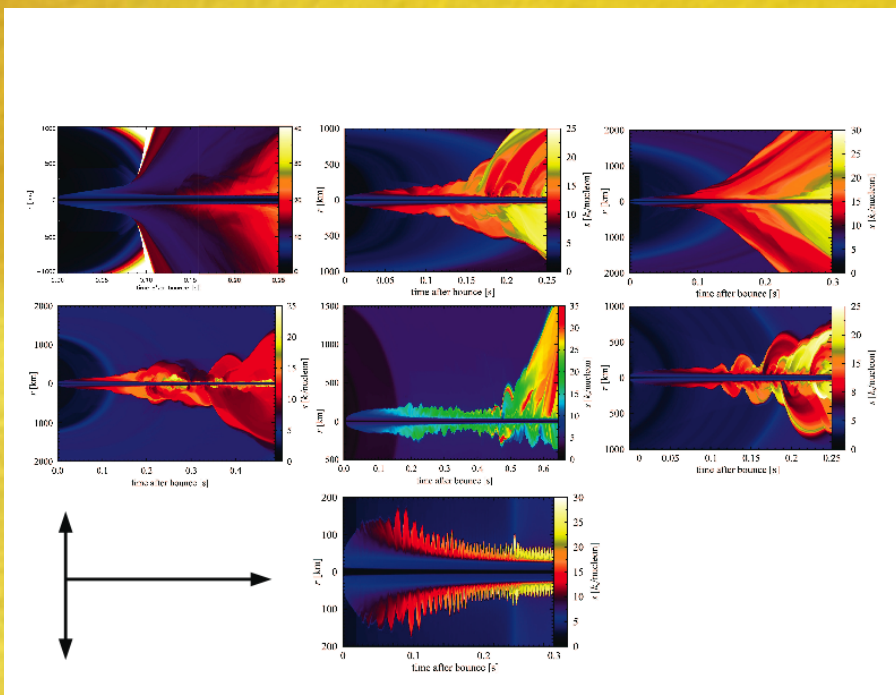


25.WH07.20g.Shen
ν_e
$\bar{\nu}_e$
ν_x
L_ν
$\varepsilon_{\rm rms}$
1D
2D
L_ν [10^{52} erg s^{-1}], $\varepsilon_{\rm rms}$ [MeV]
Time after bounce [s]

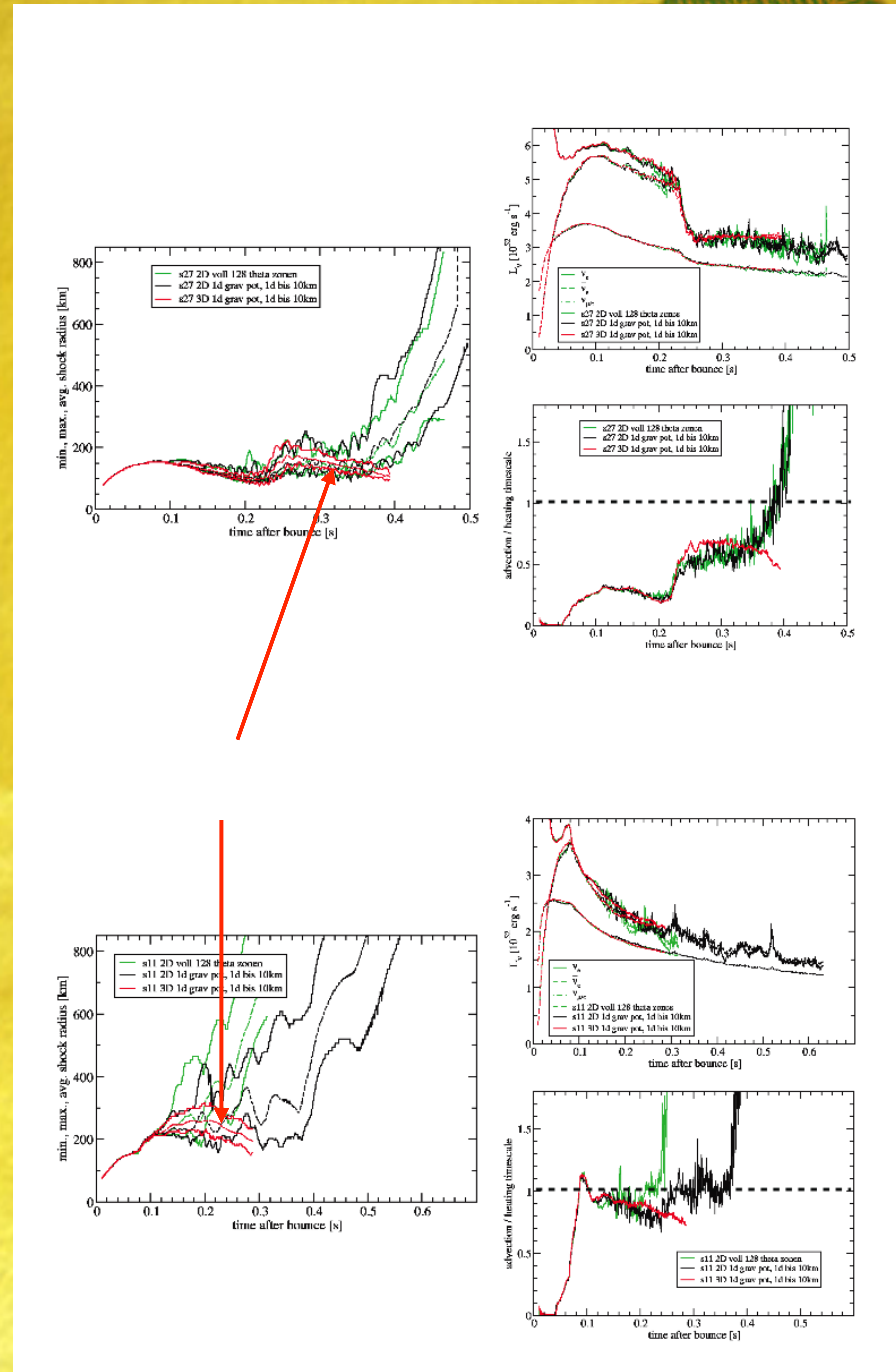


25 solar mass (WH 2007) 2D (Castro): MGFLD with multi-D Transport

Janka et al.



3D not exploding, when 2D did??



Neutrino Mechanism Confusion?

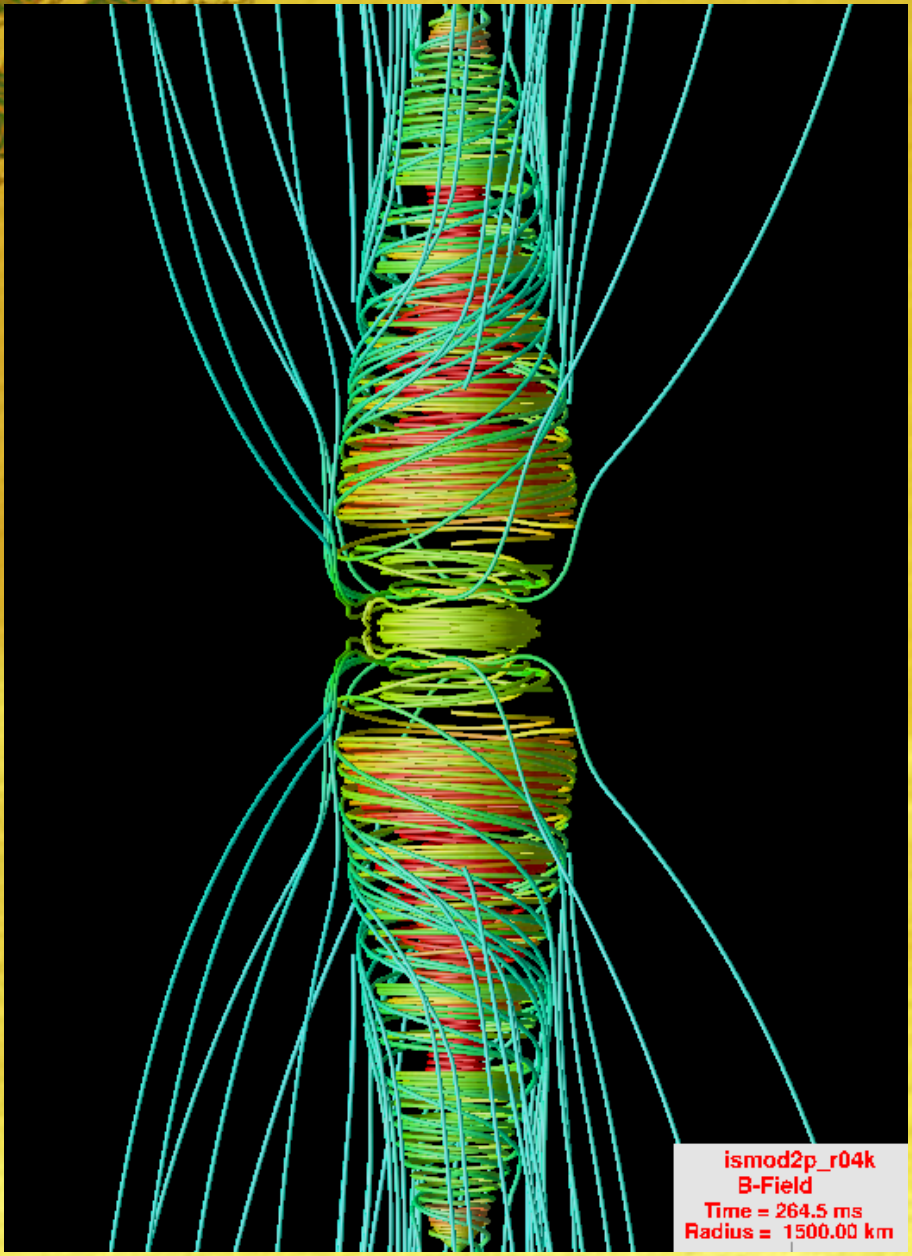
- 2D explosions compromised by Axial Sloshing ("SASI"), which is not much in evidence in (non-rotating) 3D simulations
- 2D: Groups do not agree qualitatively or quantitatively
- When models explode, explosion is marginal and get very different energies
- Compromised by "ray-by-ray" approximations employed by some?
- 3D not reproducing explosions seen in 2D
- Is something missing?

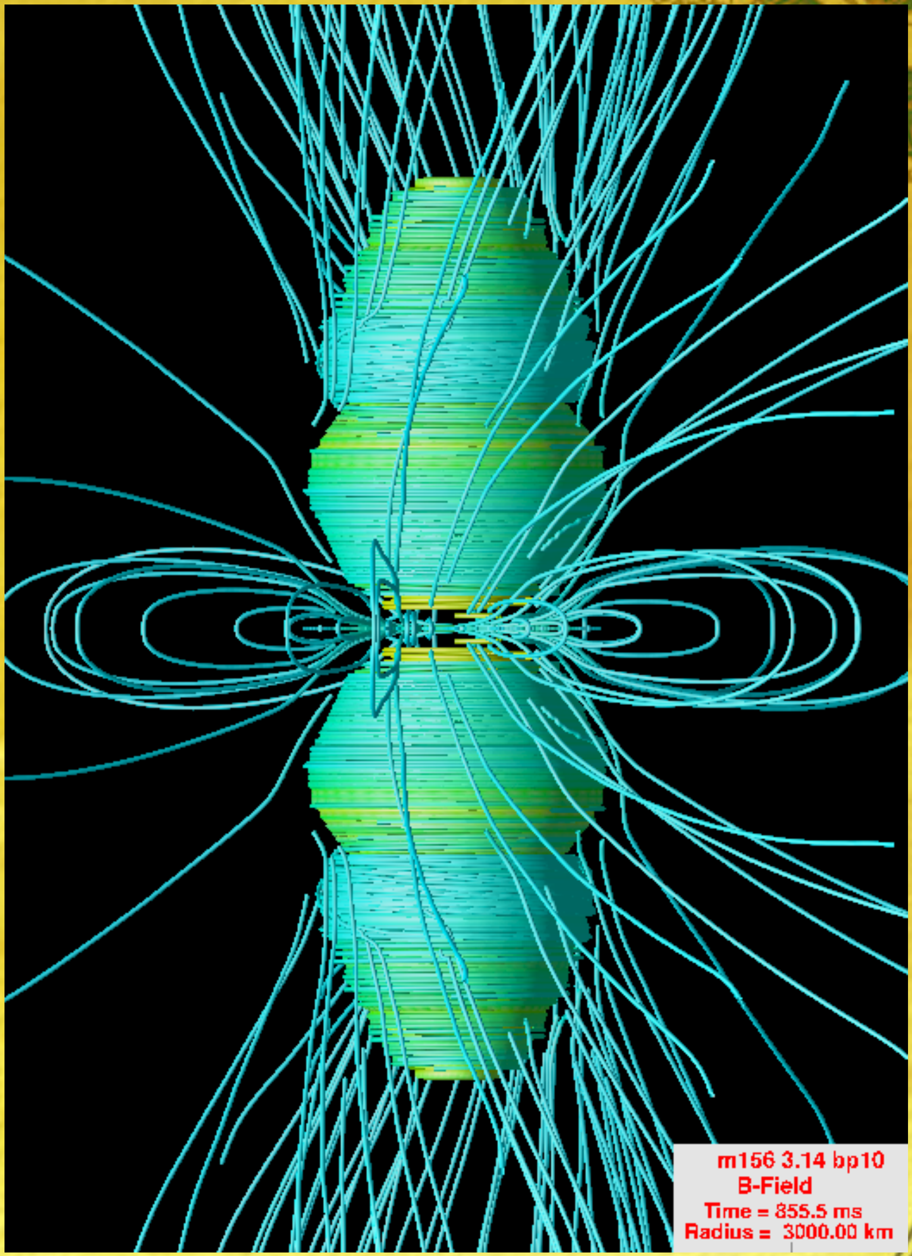
MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation Required

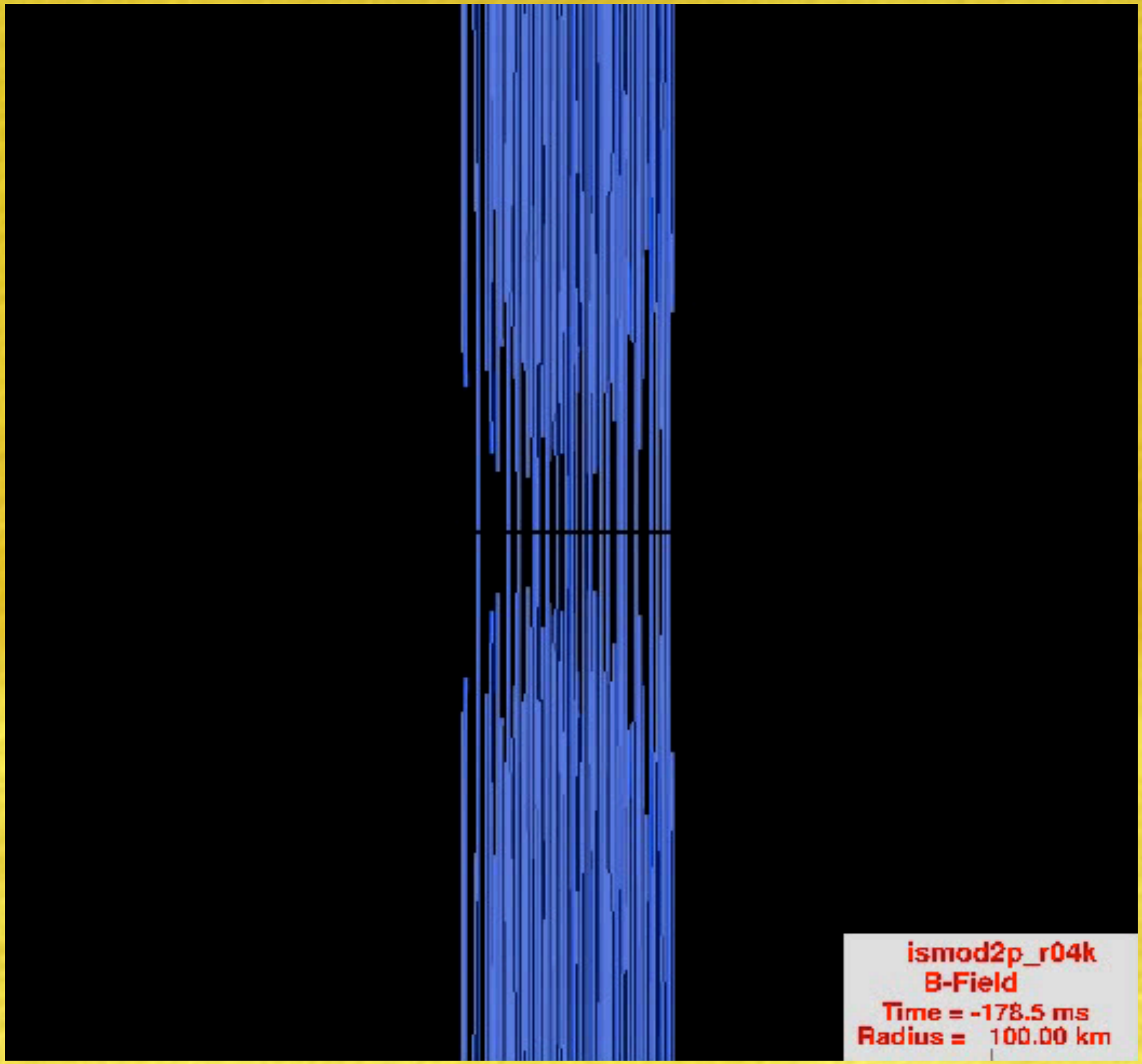
Hypernovae! (connections with GRBs)

Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007, 2008

Rotation Winding, the MRI and B-field Stress effects


ismod2p_r04k
B-Field
Time = 264.5 ms
Radius = 1500.00 km


m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km



The only multi-group “2 1/2”-D Radiation-Magneto-Hydrodynamic (RMHD) simulations of Core-Collapse Supernovae performed (Burrows et al. 2007)

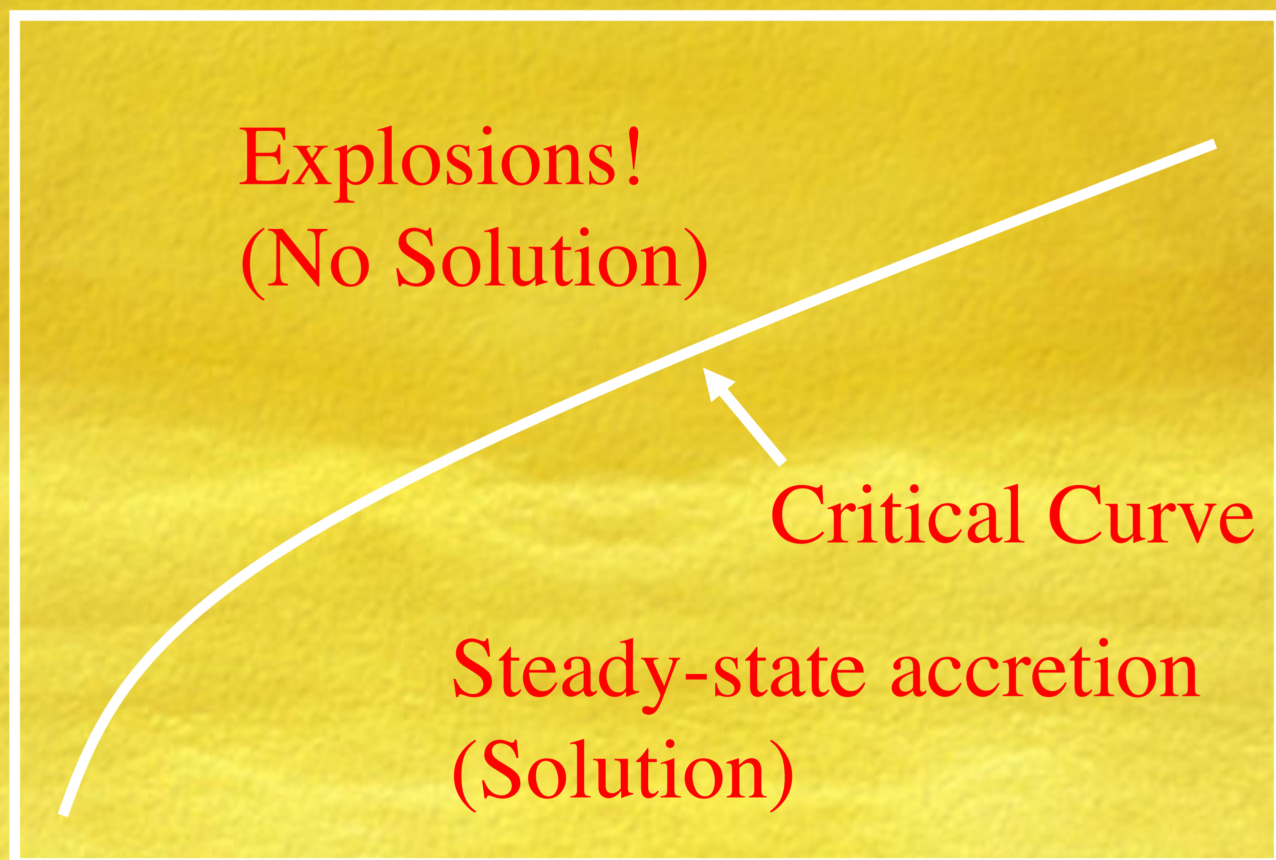
The Generic Neutrino Heating Mechanism - Multi-D Crucial

The Pause that Refreshes?

Burrows & Goshy '93; Murphy & Burrows 2008

Critical Condition for Neutrino Mechanism: Dimension-dependent

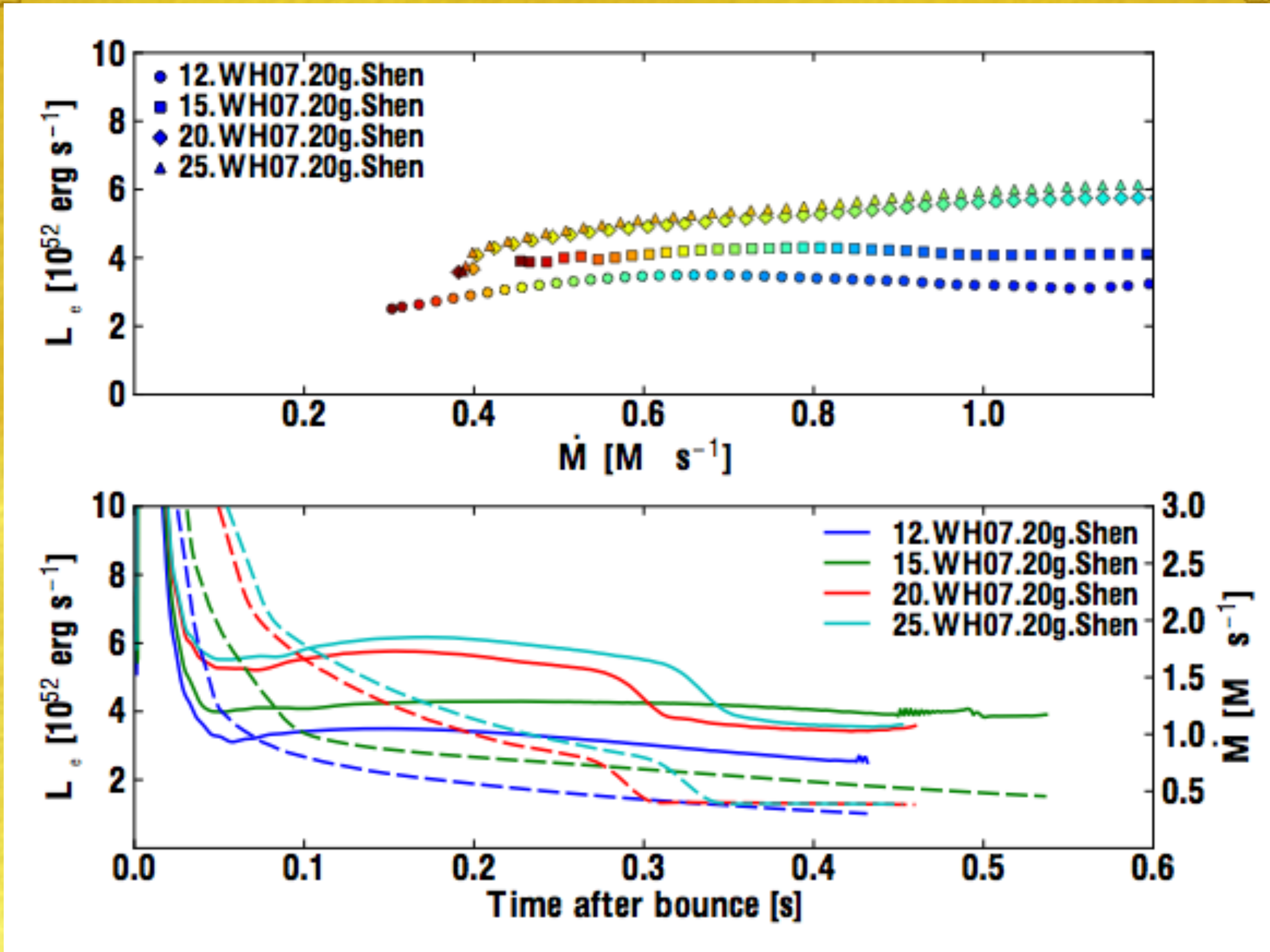
$L_{\nu e}$



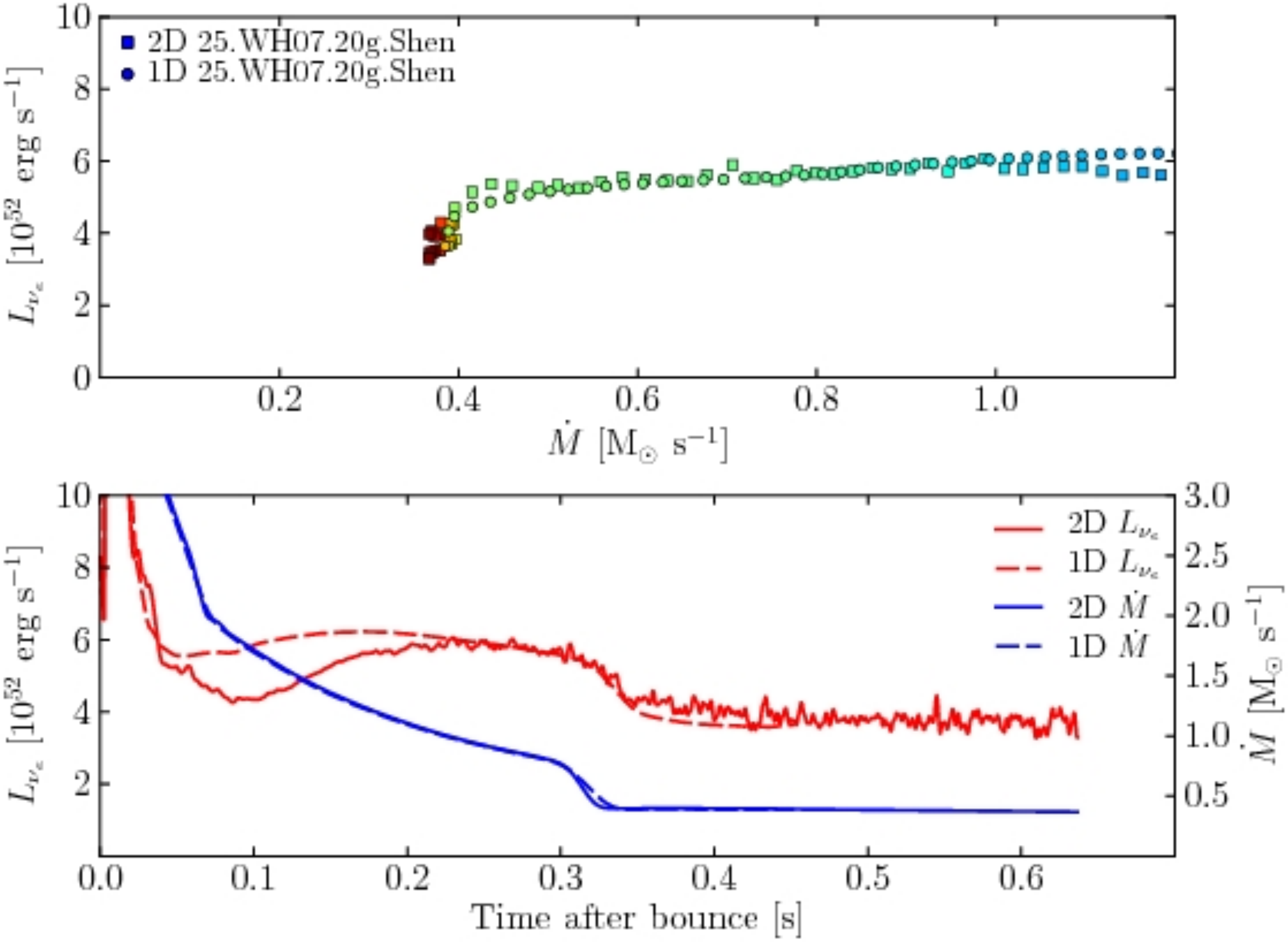
$\dot{M}$ "equivalent" to $\tau_{adv} \sim \tau_{heat}$ condition

L_ν vs. Accretion Rate Parameter Study

Burrows et al. 2013; Dolence et al. 2014

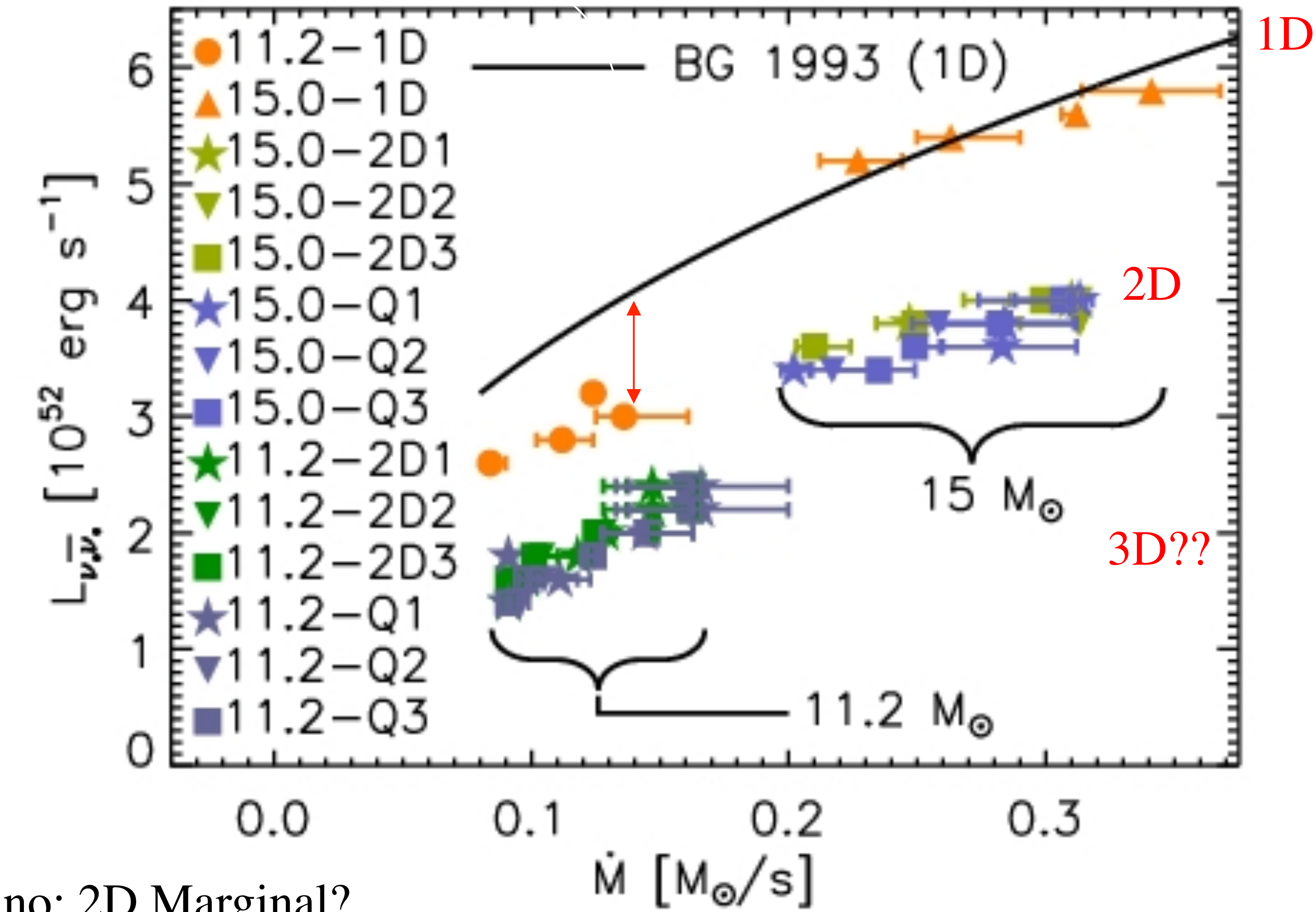


Burrows et al. 2013; Dolence et al. 2013



Critical Curve for Neutrino Mechanism: 1D versus 2D

Different mass cores

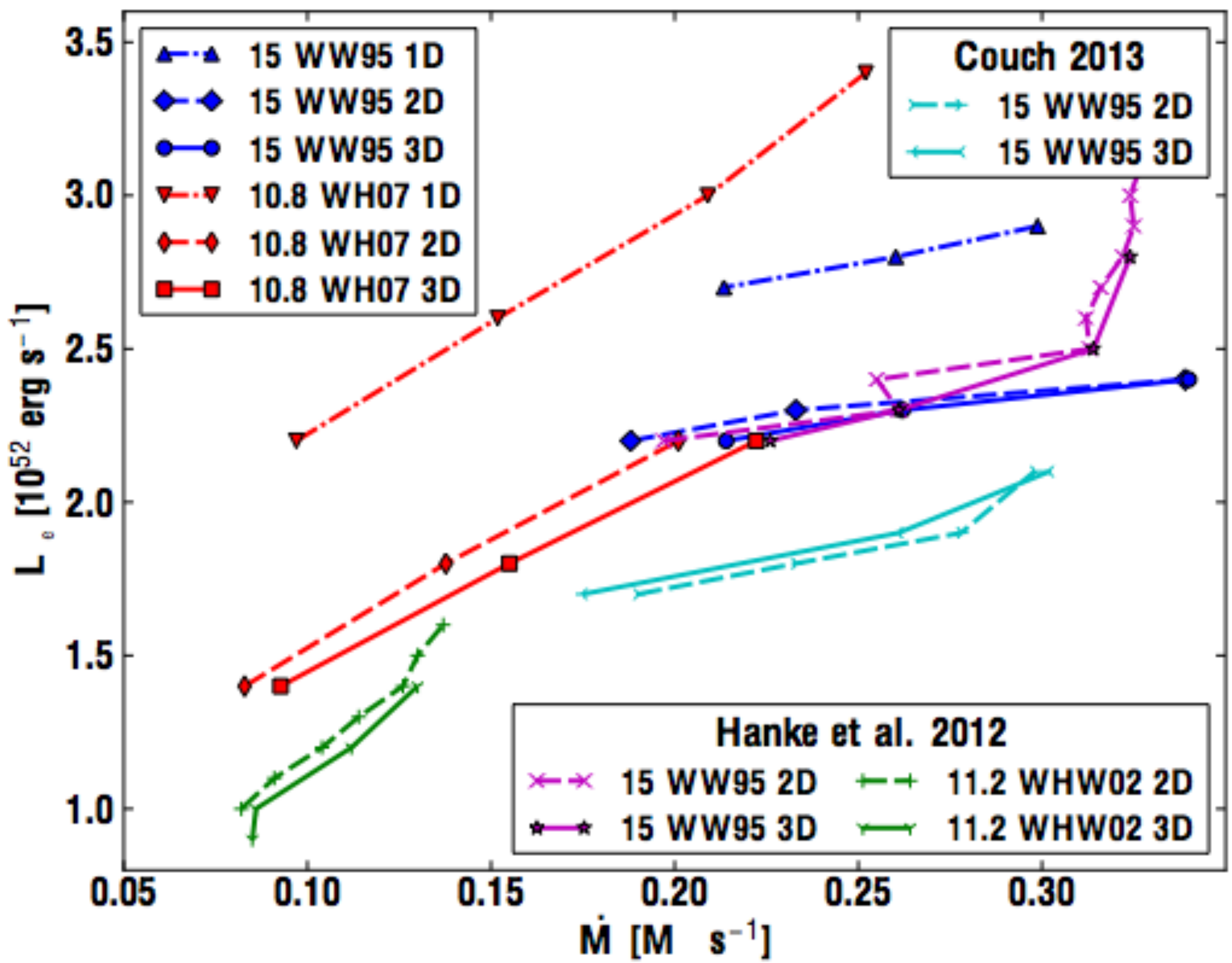


1D no; 2D Marginal?

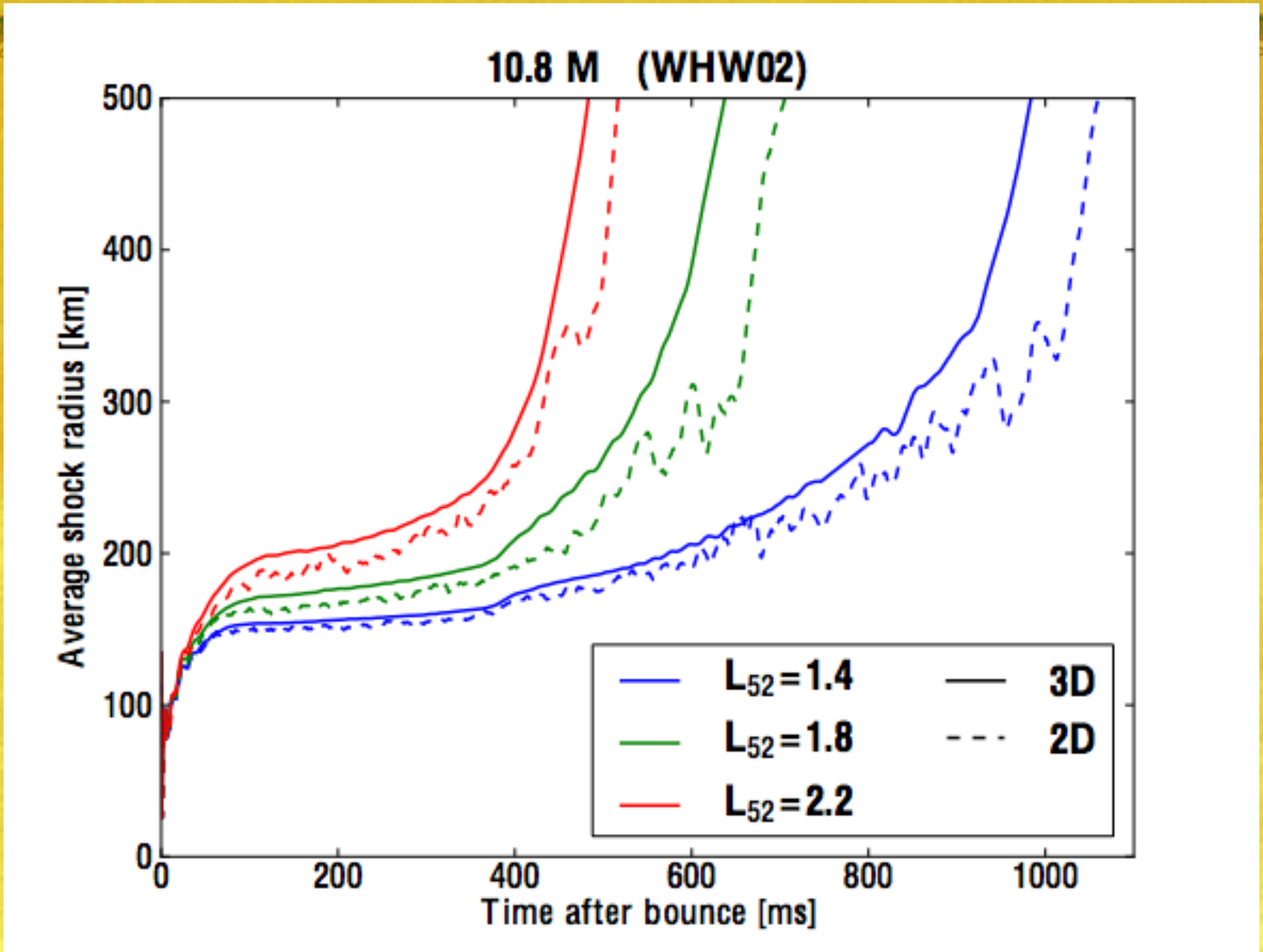
Murphy & Burrows 2008

How do the critical luminosities differ between 1D, 2D, and 3D?

Critical Curve(s)



Mean Radius Evolution in 3D and 2D: 10.8 Solar Mass

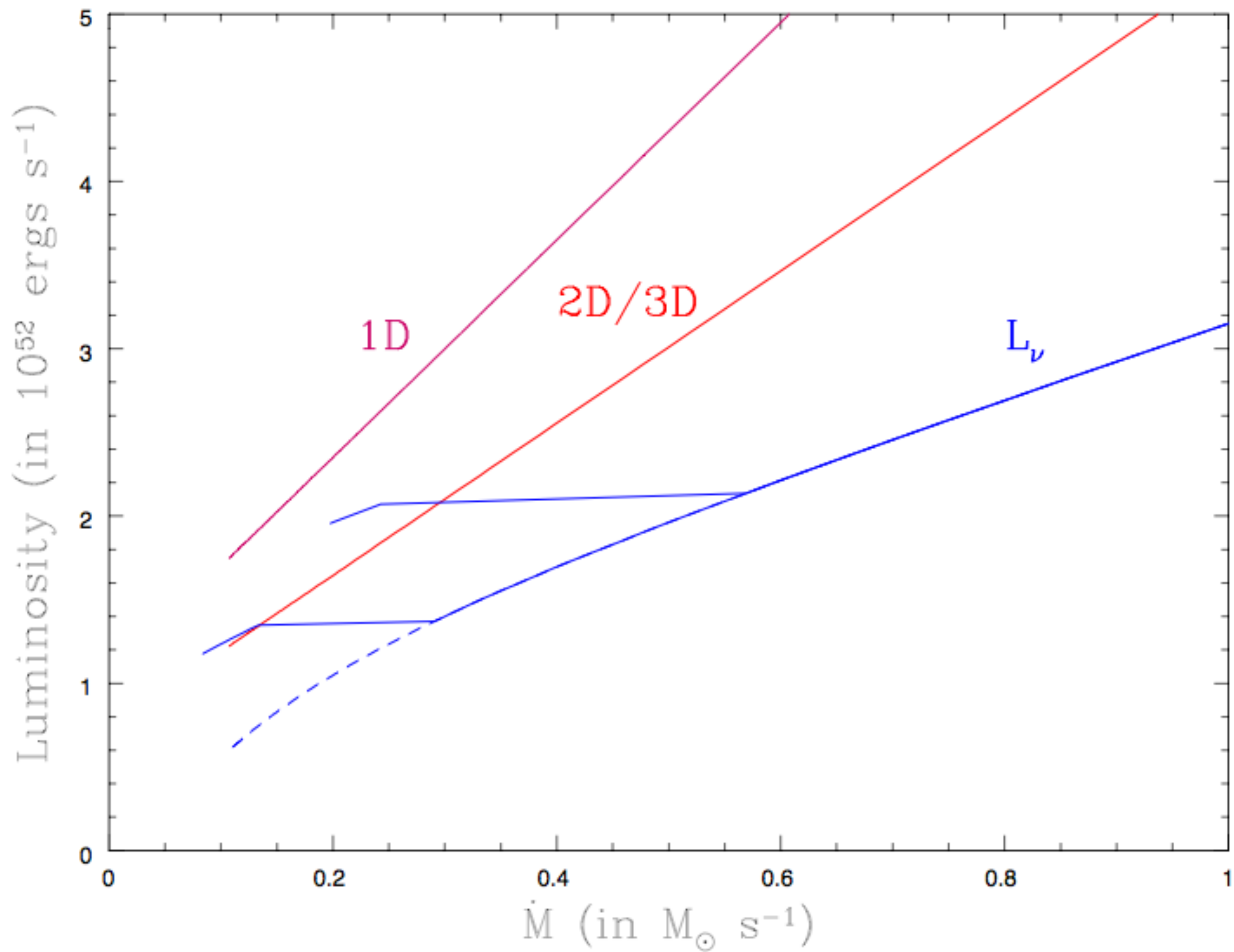


Explosions are Earlier in 3D

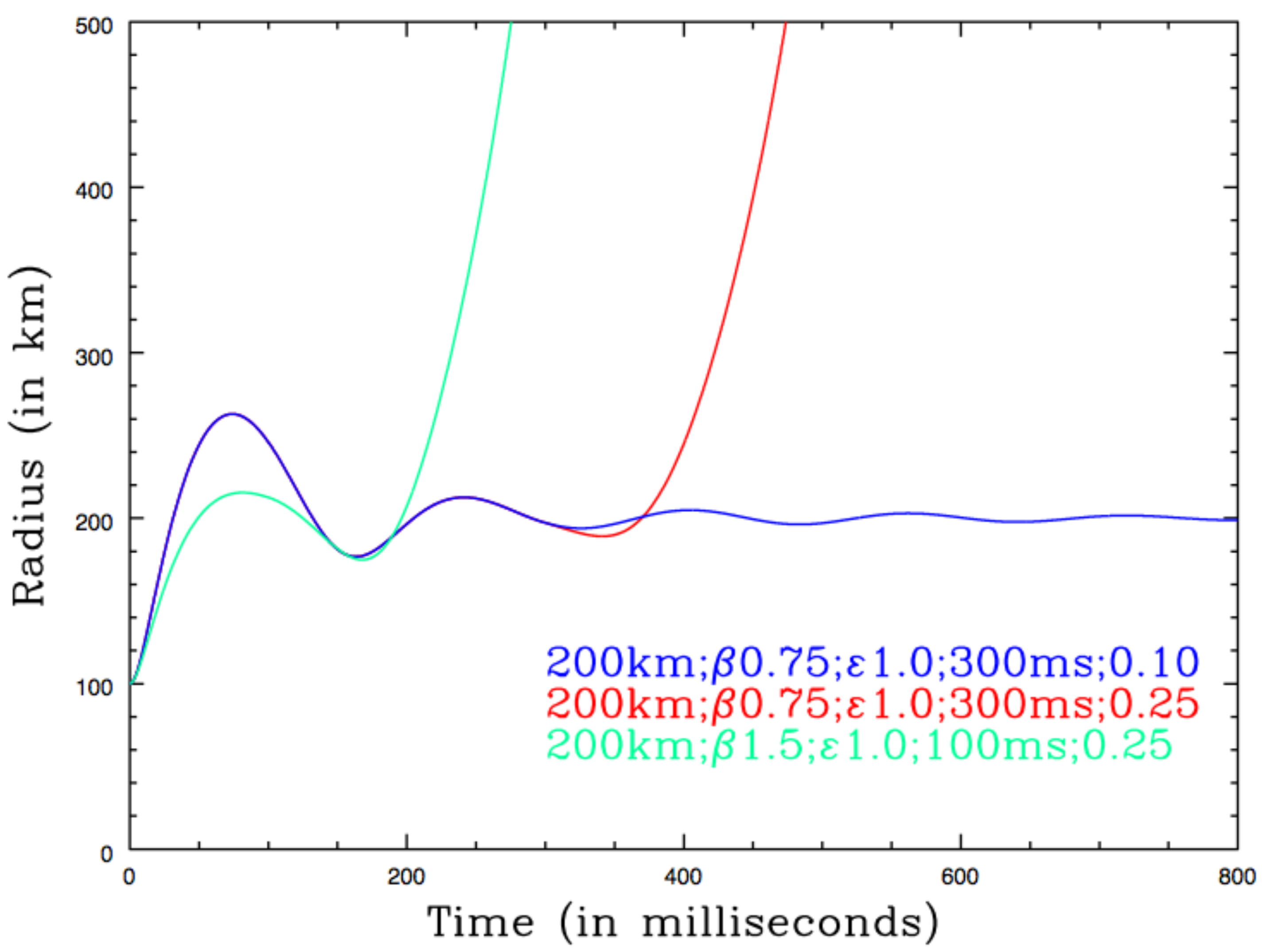
$$\begin{aligned}
\frac{d^2R}{dt^2} + 2\beta\lambda\frac{dR}{dt} &= \varepsilon\lambda_{adv}^2\big(R_{\rm E}(L,\dot{M}) - R\big)\ , \\
\frac{d(L - L_c(t))}{dt} &= \lambda_{adv}\big(L_A(\dot{M}) + L_c(t) - L\big)\ , \\
\lambda &\sim \frac{1}{\tau_{adv}}\Big(1 - \frac{L}{L_{cr}(\dot{M})}\Big)\ ,
\end{aligned}$$

$$\dot{M} = f(t)$$

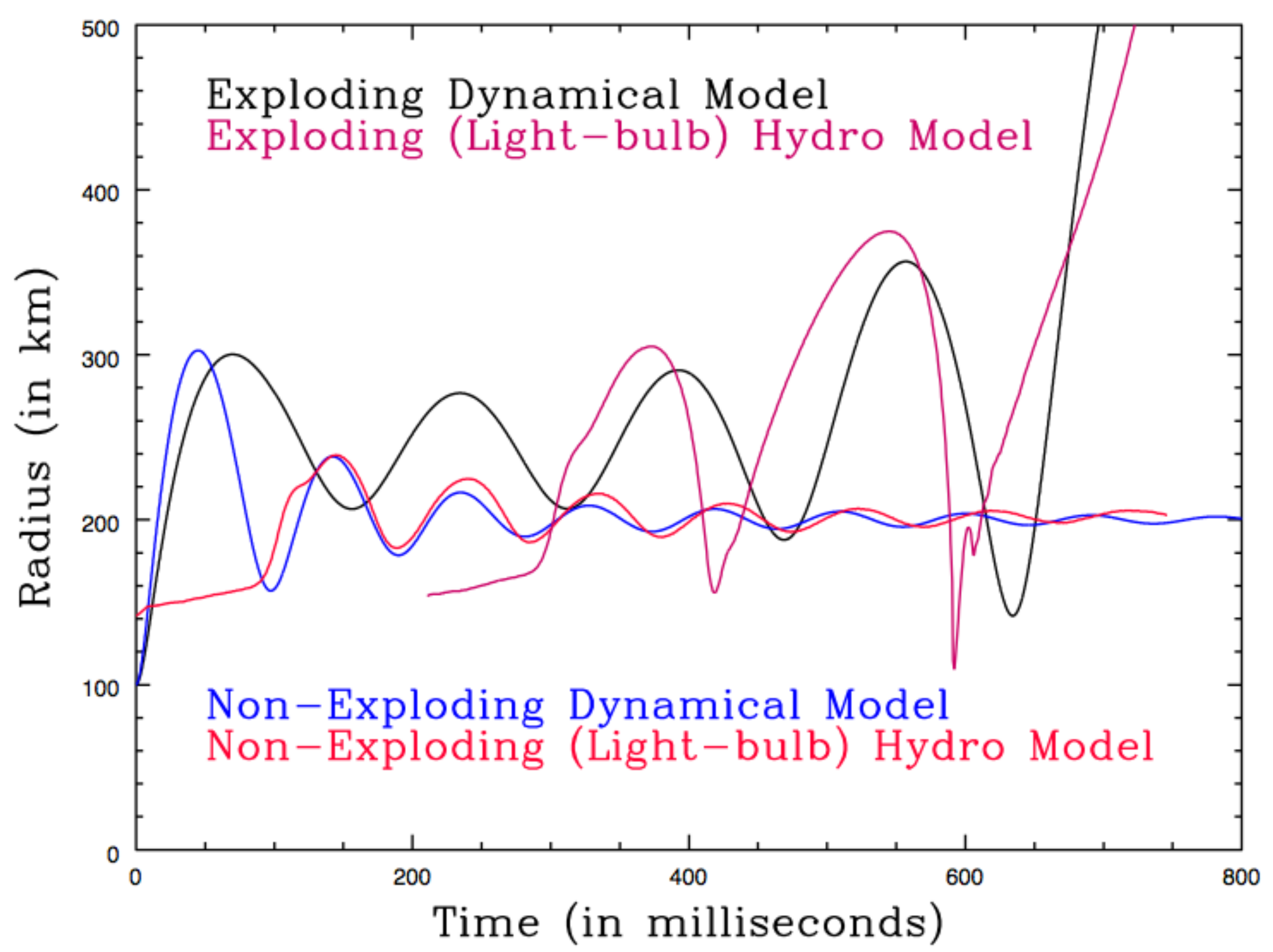
Critical Curve Intersection by Abrupt Change in Accretion Rate?



Simplified Dynamical Model of Shock Evolution with Abrupt Change in Accretion Rate



Comparison of Dynamical Model Results with Hydrodynamic Models



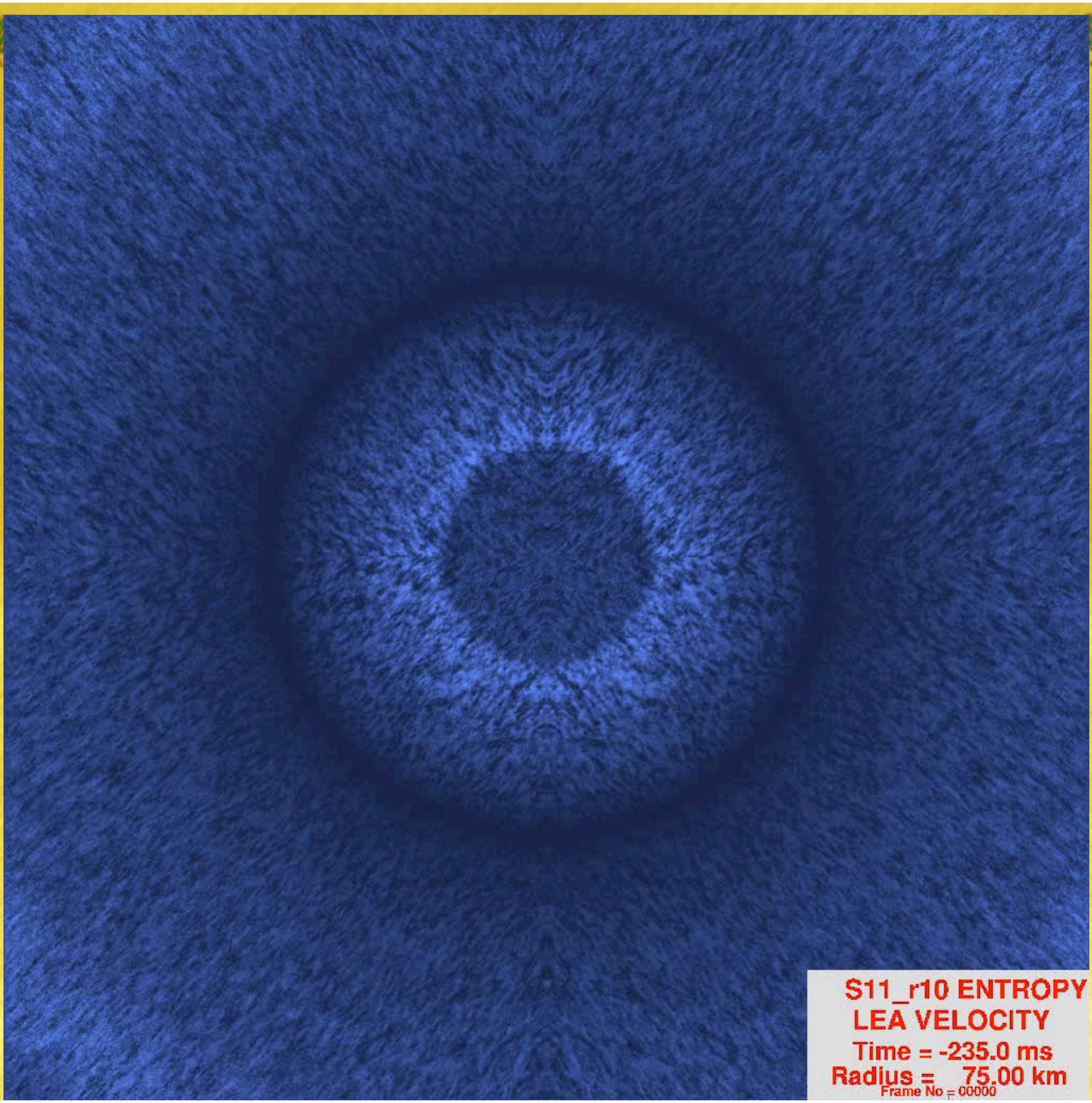
"Protoneutron Star Convection"

Ledoux (S/Y_e ?) and/or Doubly-Diffusive Convection?

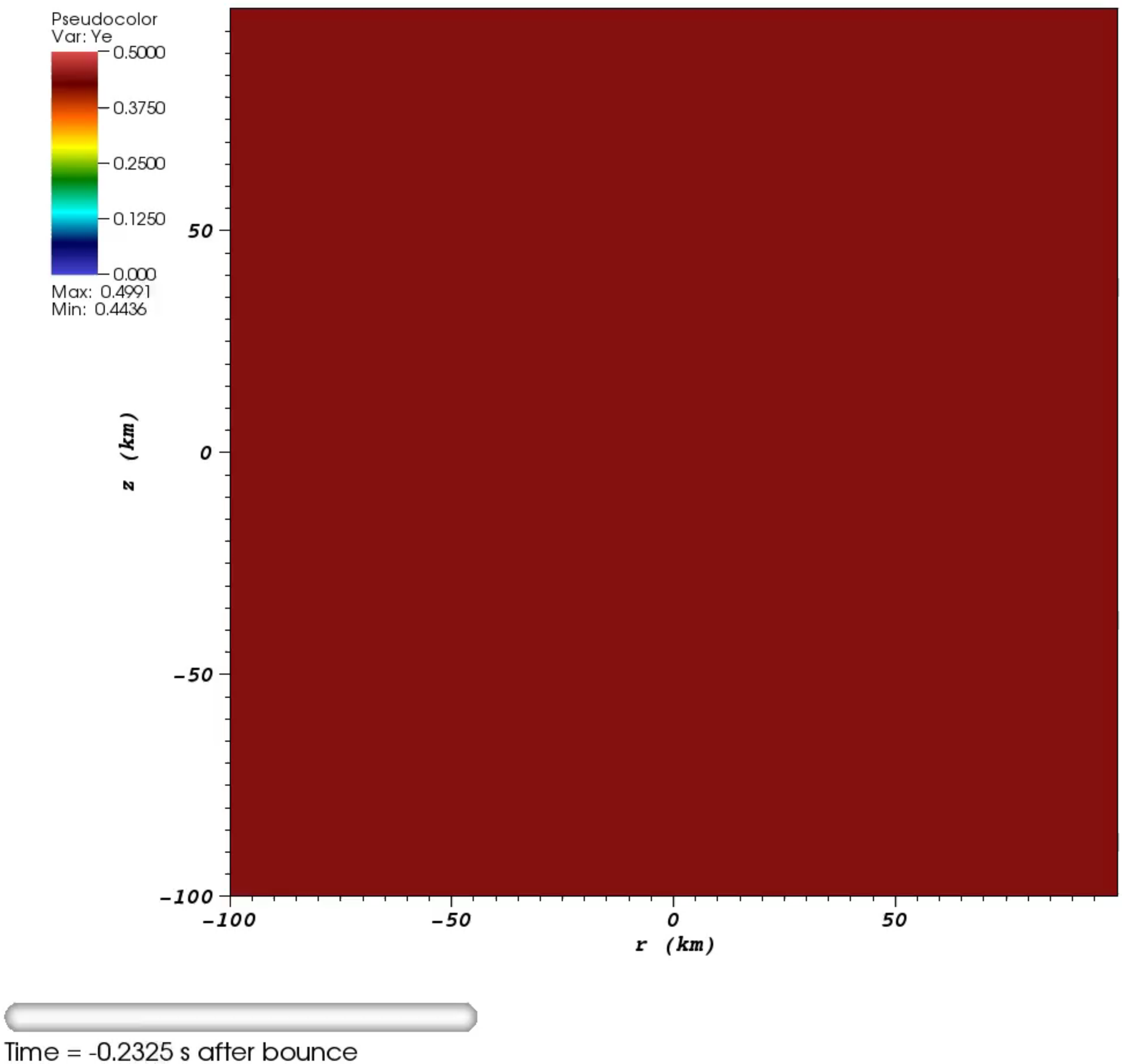
Can it Boost the Driving Neutrino Luminosities?

(Wilson 1985; Wilson & Mayle 1988)

Study by Dessart et al. 2006



S11_r10 ENTROPY
LEA VELOCITY
Time = -235.0 ms
Radius = 75.00 km
Frame No = 00000



Pseudocolor
Var: Ye
0.5000
0.3750
0.2500
0.1250
0.000
Max: 0.4991
Min: 0.4436
z (km)
50
0
−50
−100
−100
−50
0
50
r (km)
Time = -0.2325 s after bounce

A Tale of Two Instabilities:

Neutrino-driven Convection (Buoyancy) versus the Sanding Accretion-Shock Instability ("SASI")

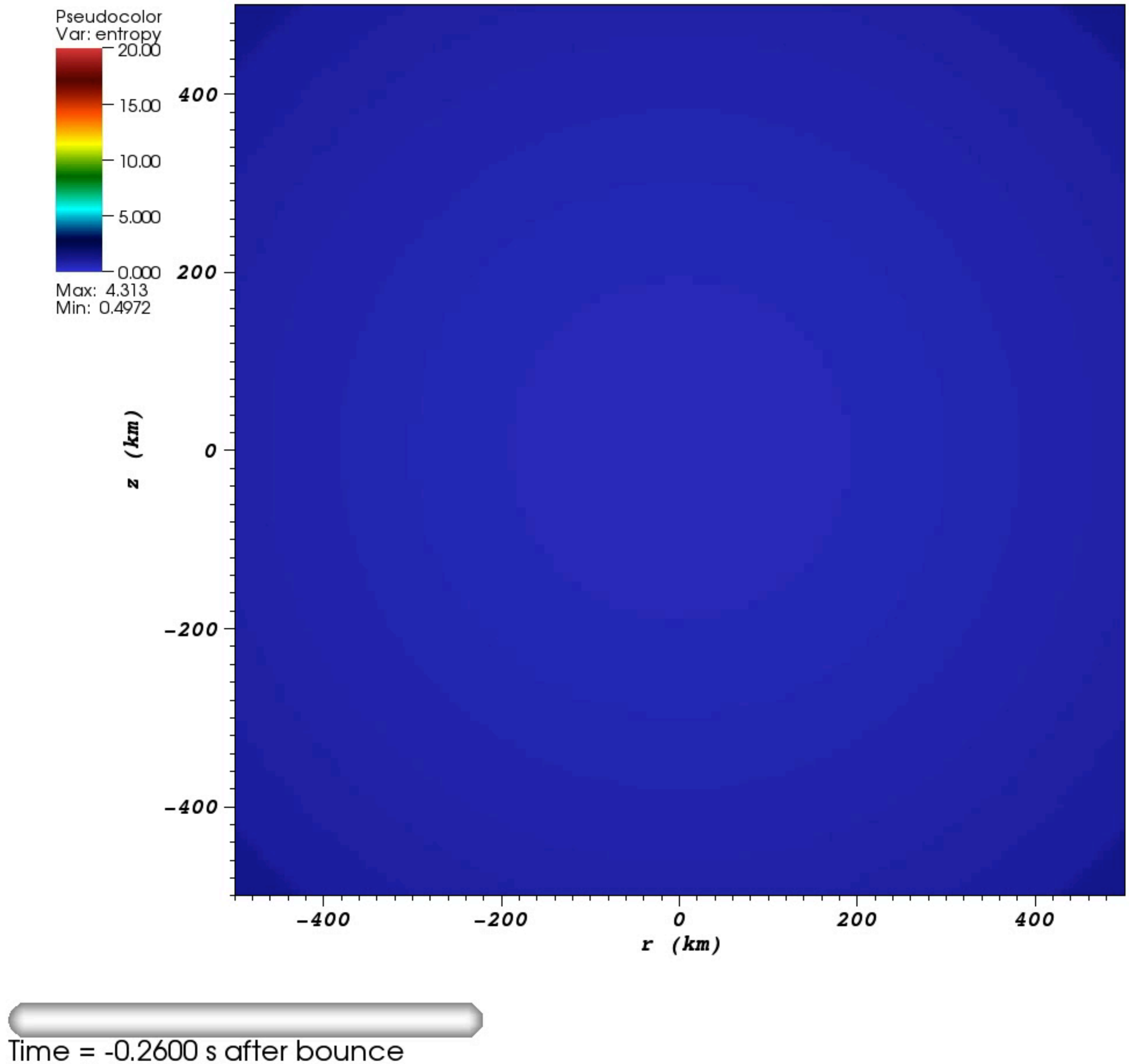
CASTRO - 1D, 2D, 3D

Hydro, plus simple transport Results

2D:2.3

"Inverse" Energy Cascade in 2D -

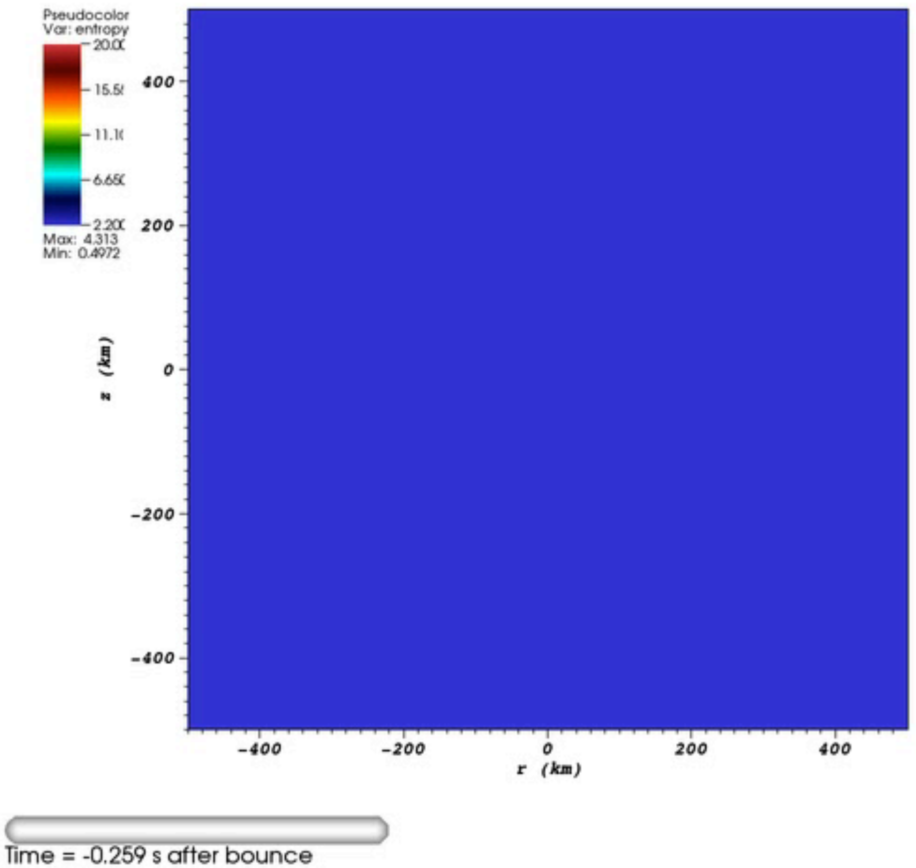
Buoyancy-Driven Convection has (anomalously) a lot of large-scale power - Often confused for the SASI

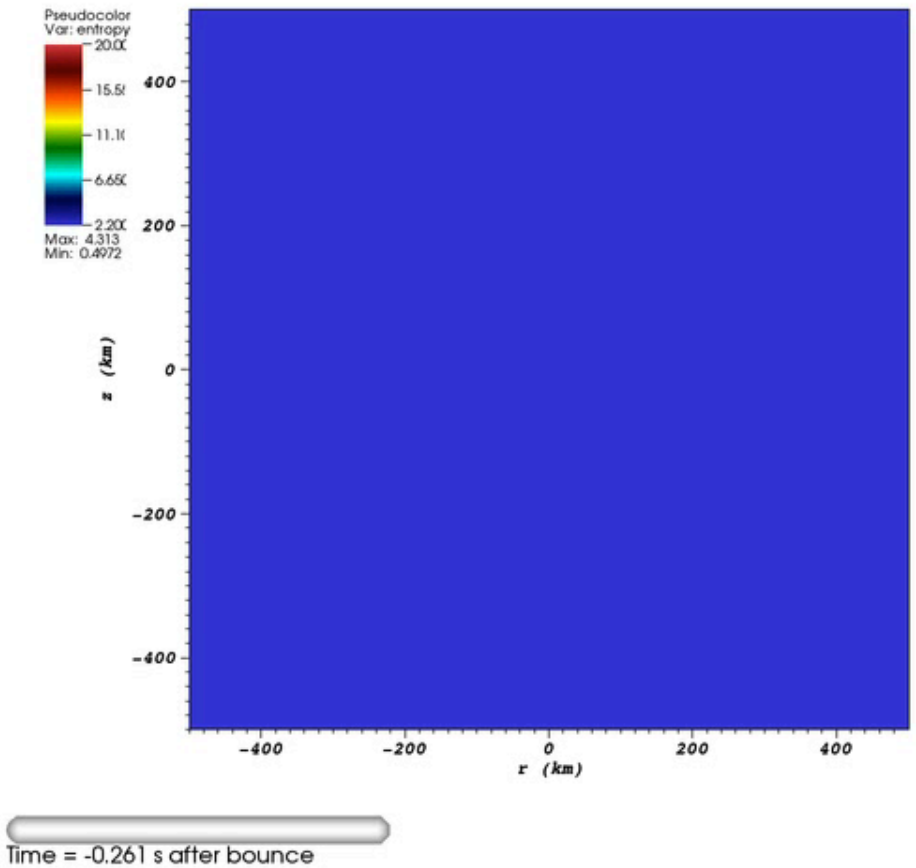


Comparison - with and without Neutrinos

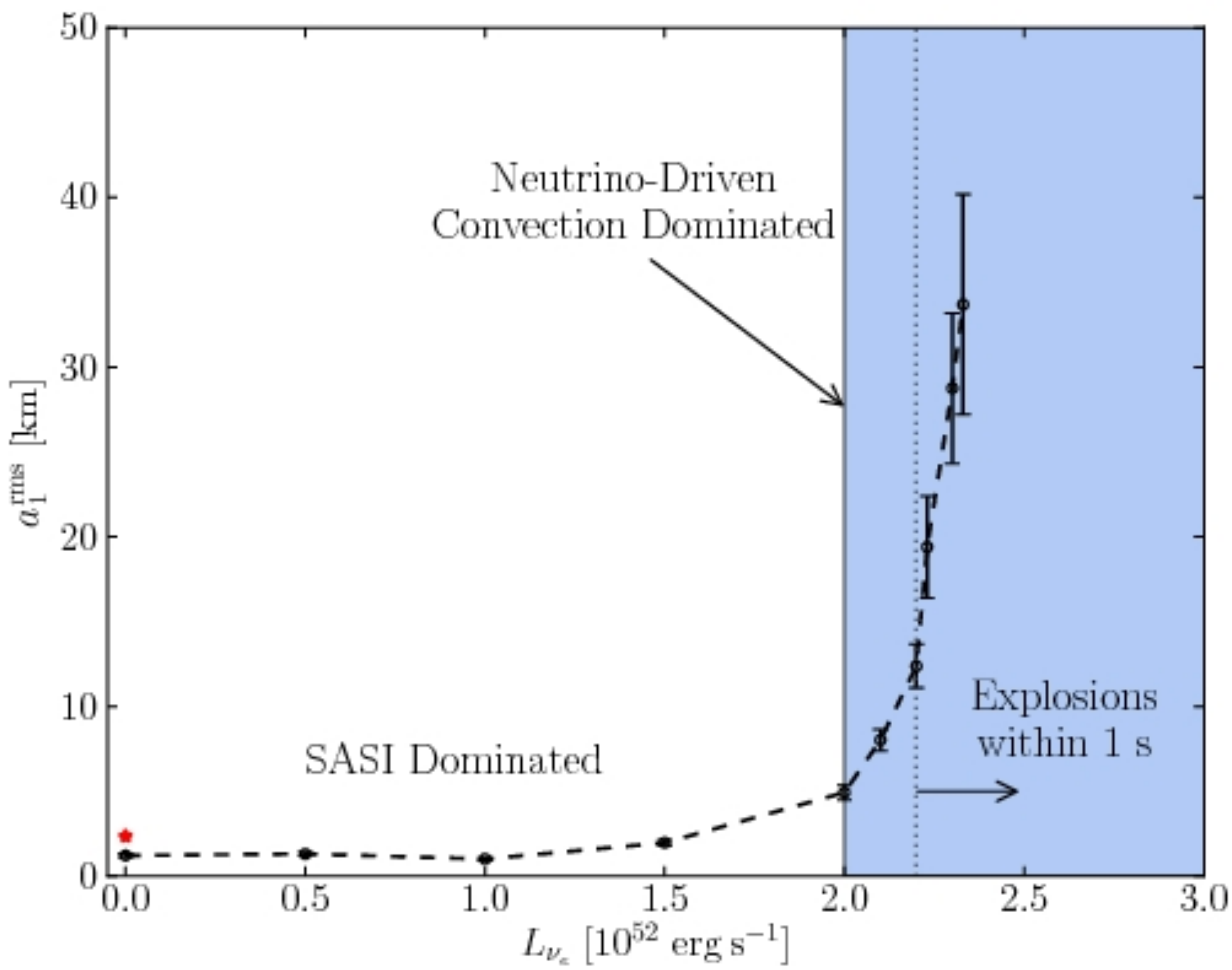
Neutrino-driven (Buoyancy) Convection - Crucial

SASI generally Subdominant





Dipolar Amplitudes versus Driving Luminosity

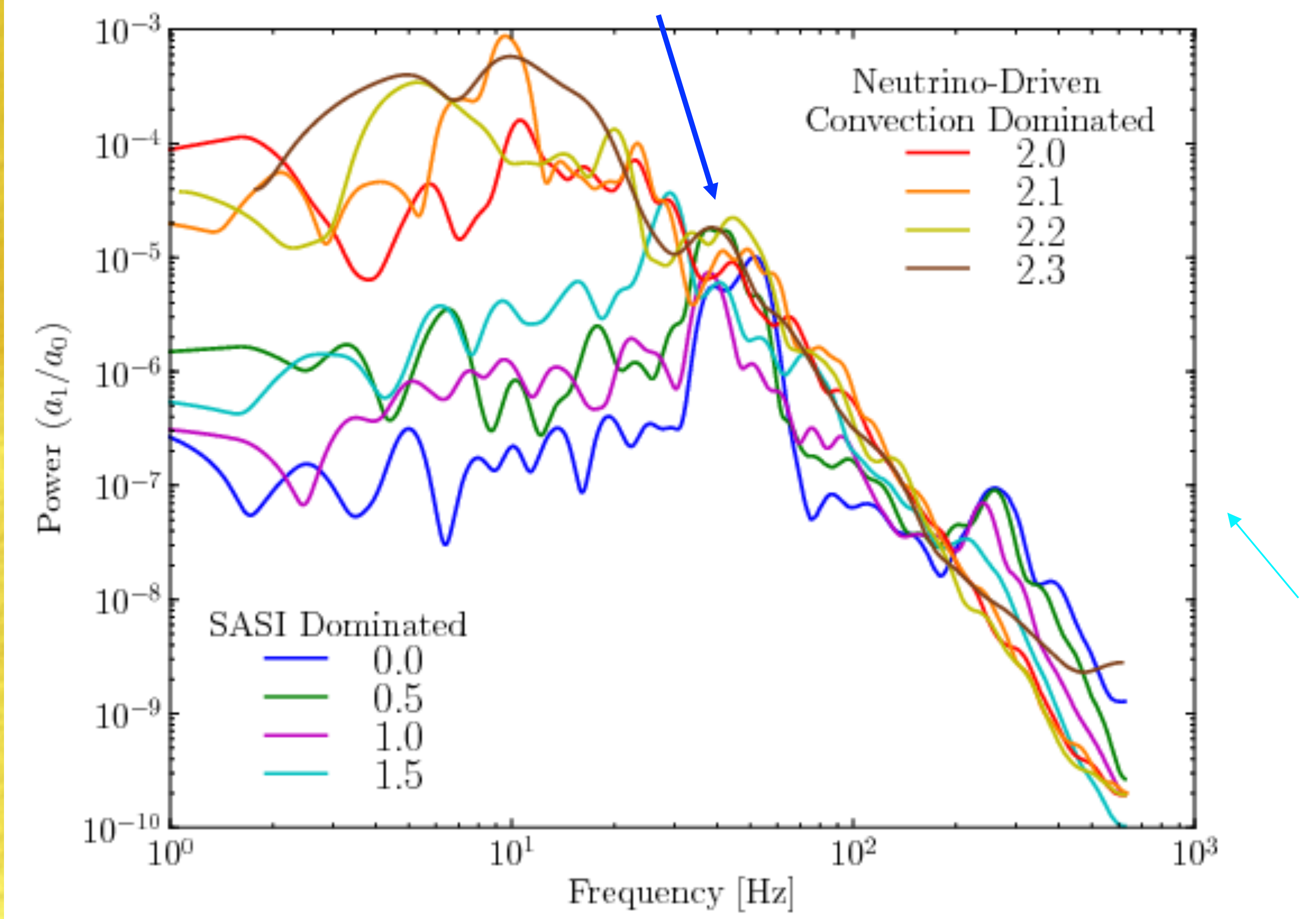


Burrows, et al. 2012; See also Couch & O'Connor 2013

SASI is subdominant for all neutrino-driven explosions

Shock Surface Power Spectrum versus Driving Luminosity

x100



Neutrino-driven Buoyancy, not SASI

See also Fernandez et al. 2013)

“When Neutrinos Drive the Explosion, Neutrinos Drive the Turbulence”

The “SASI” is Less Relevant (or is Sub-Dominant) in Neutrino-Driven Supernovae

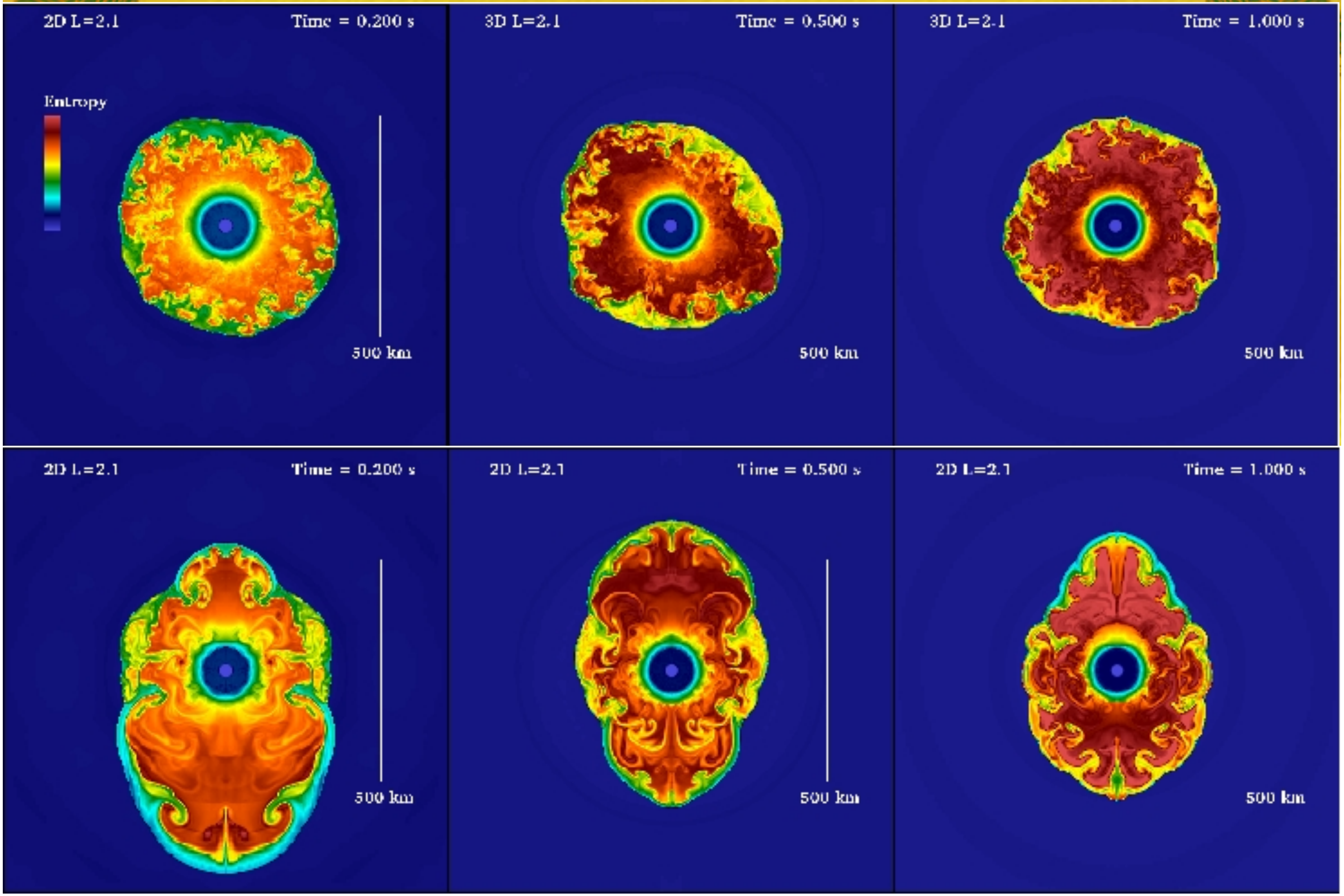
Confusing in 2D Buoyancy-Driven Convection with the SASI

- In 2D, convection (inverse) cascades to large scales and small spherical harmonic order (l)
- The SASI favors small angular orders l (=1 (dipolar), 2) ⟶ Confusion
- Misled by the notion that convection is a small-scale, large-l phenomenon, some said large-scale, small l, motions couldn't be convection - small $\Delta R/R$
- However, large $\Delta R/R$ convection favors small l, larger scales
- Computationally limited to 2D, the wrong intuitions were developed
- Nature is 3D - cascade is to small scales, but SASI is still large scale (as in 2D) - not much in evidence in 3D

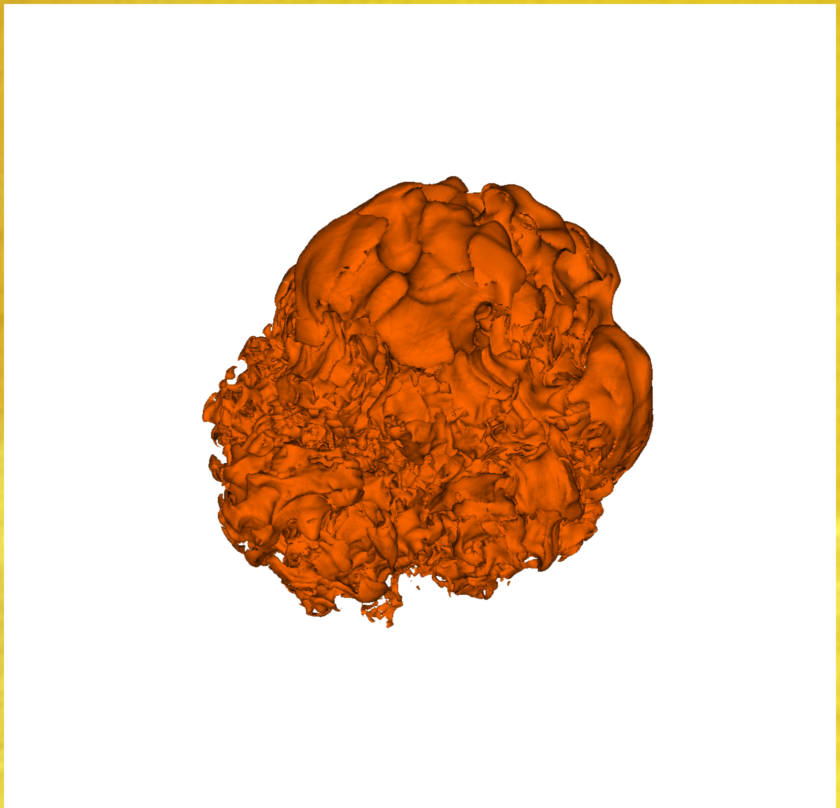
Character of 3D Turbulence Qualitatively Different than that in 2D

Amplitudes of Dipolar ("Sloshing") Modes much Smaller in 3D

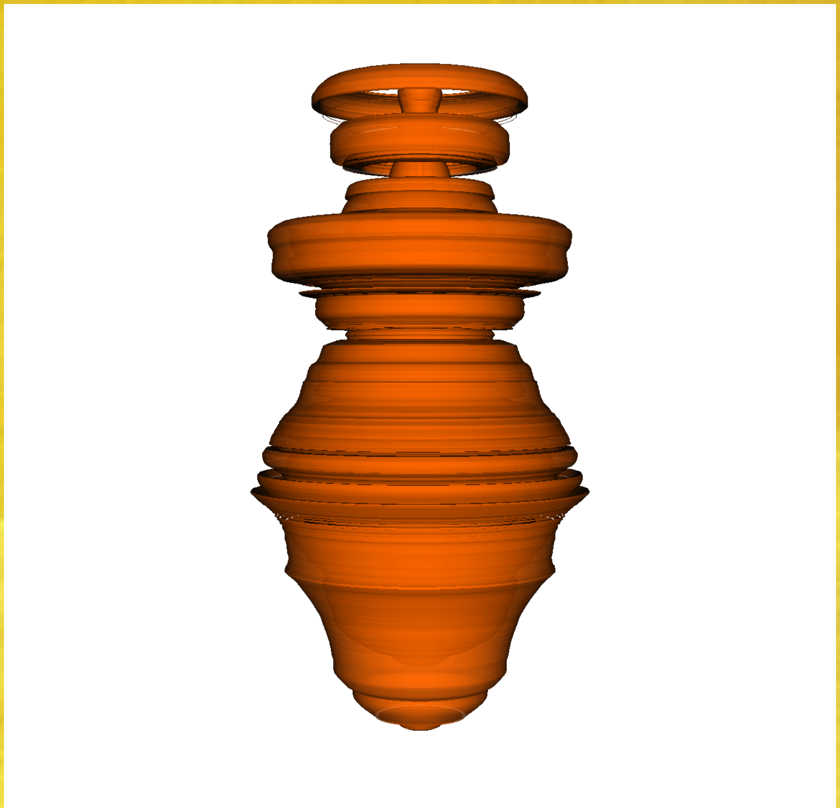
Comparison of 2D with 3D



3D

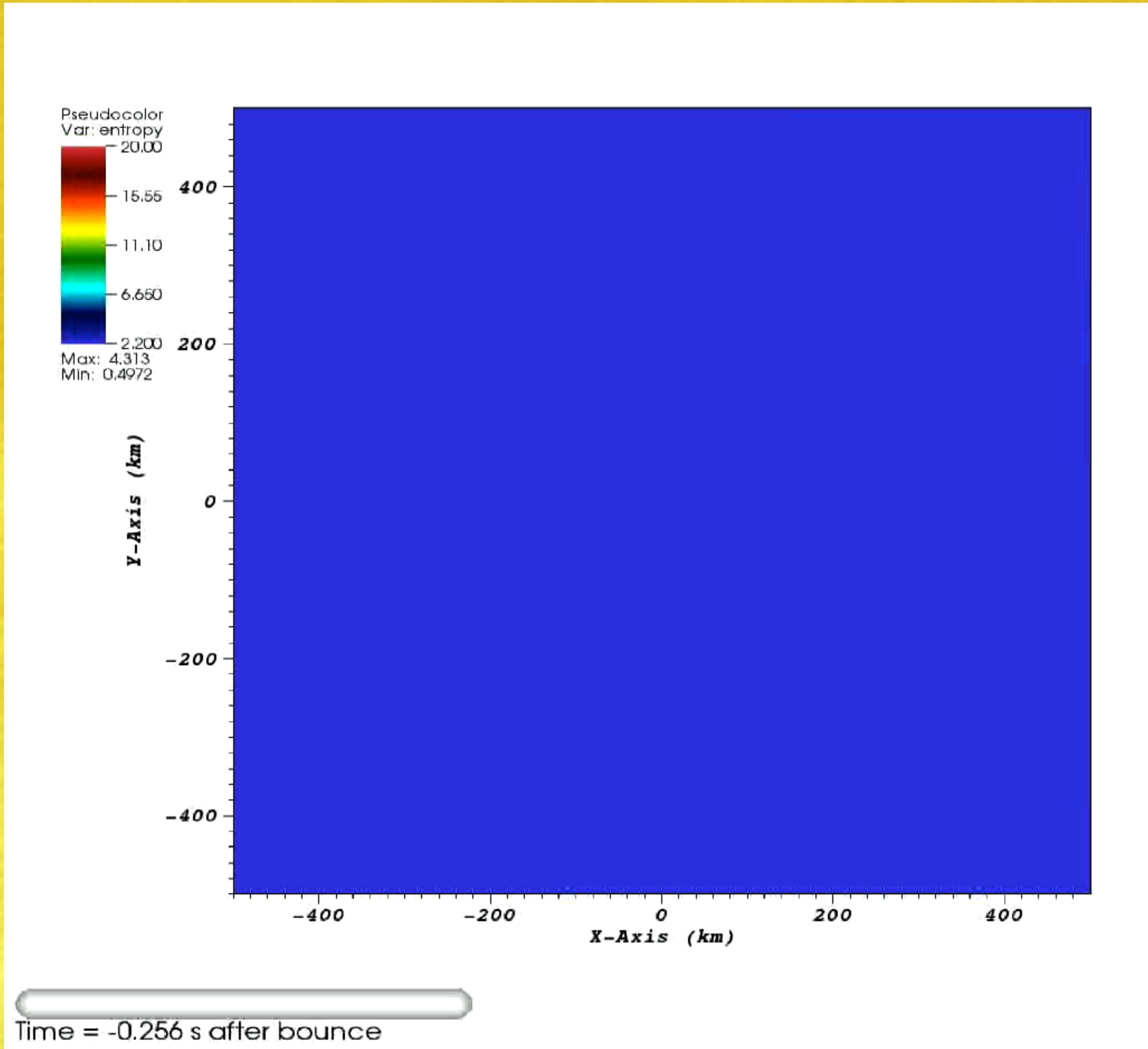


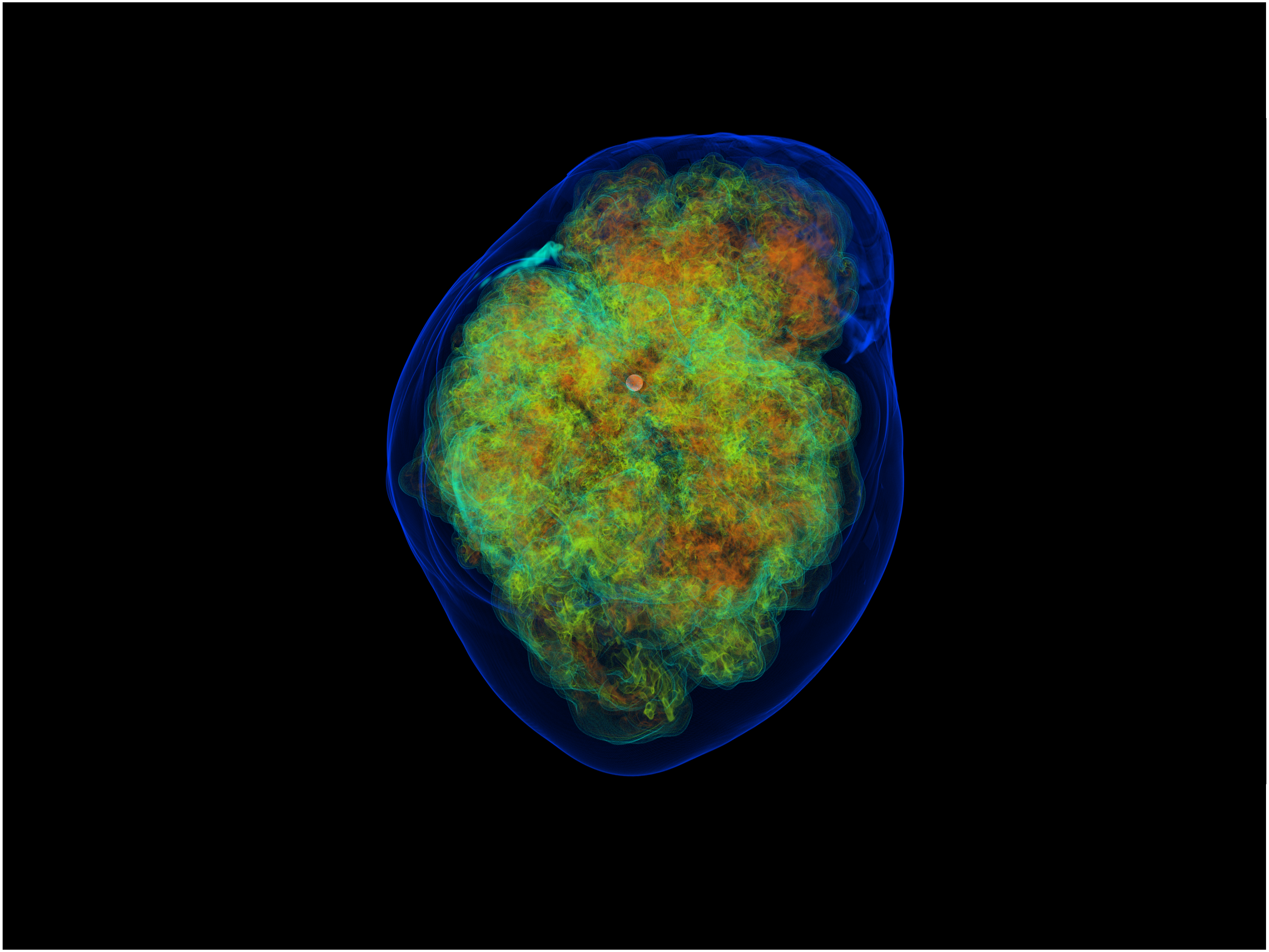
2D



Couch 2012

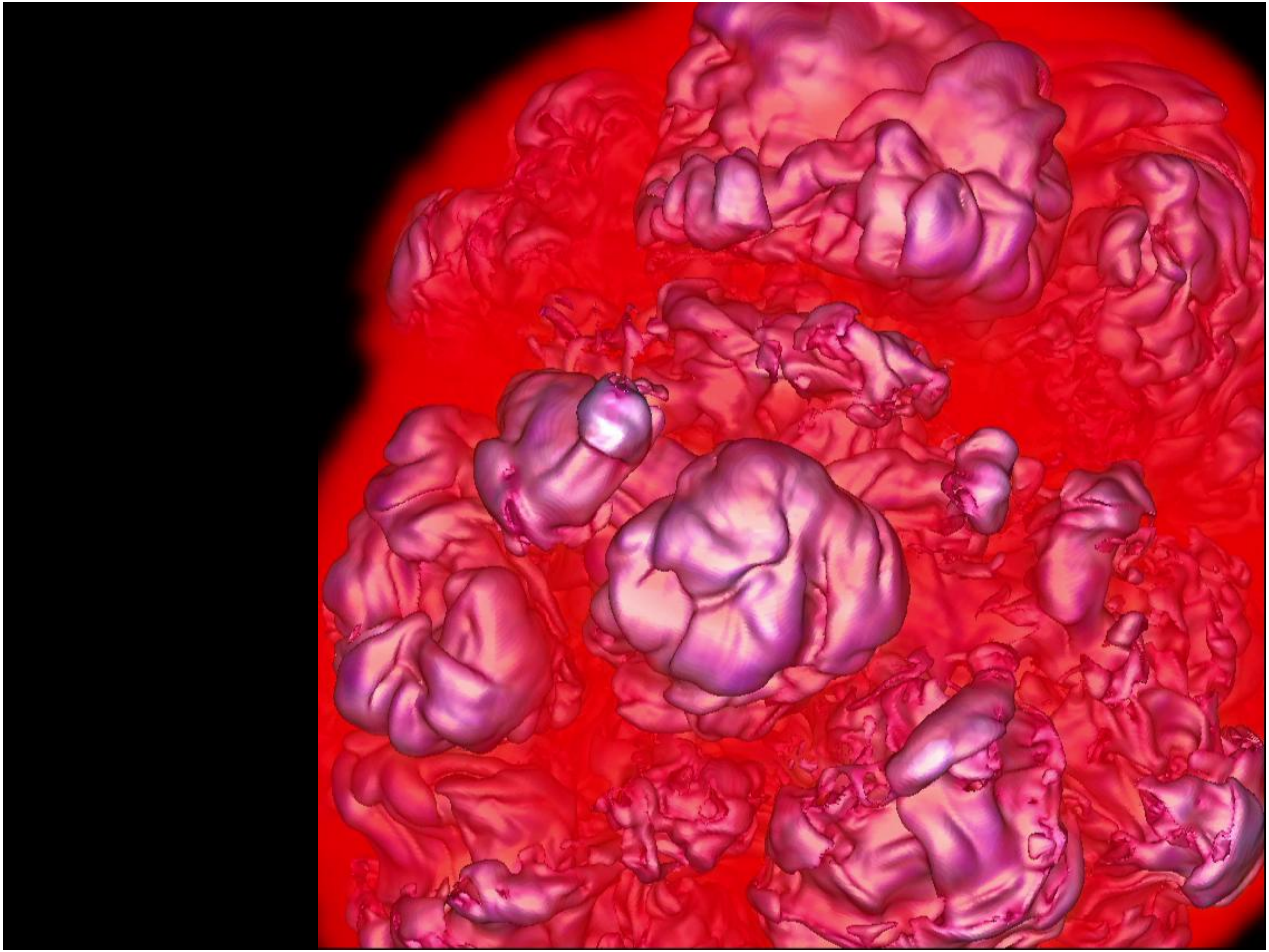
Character of 3D turbulence and Explosion Very Different from those in 2D

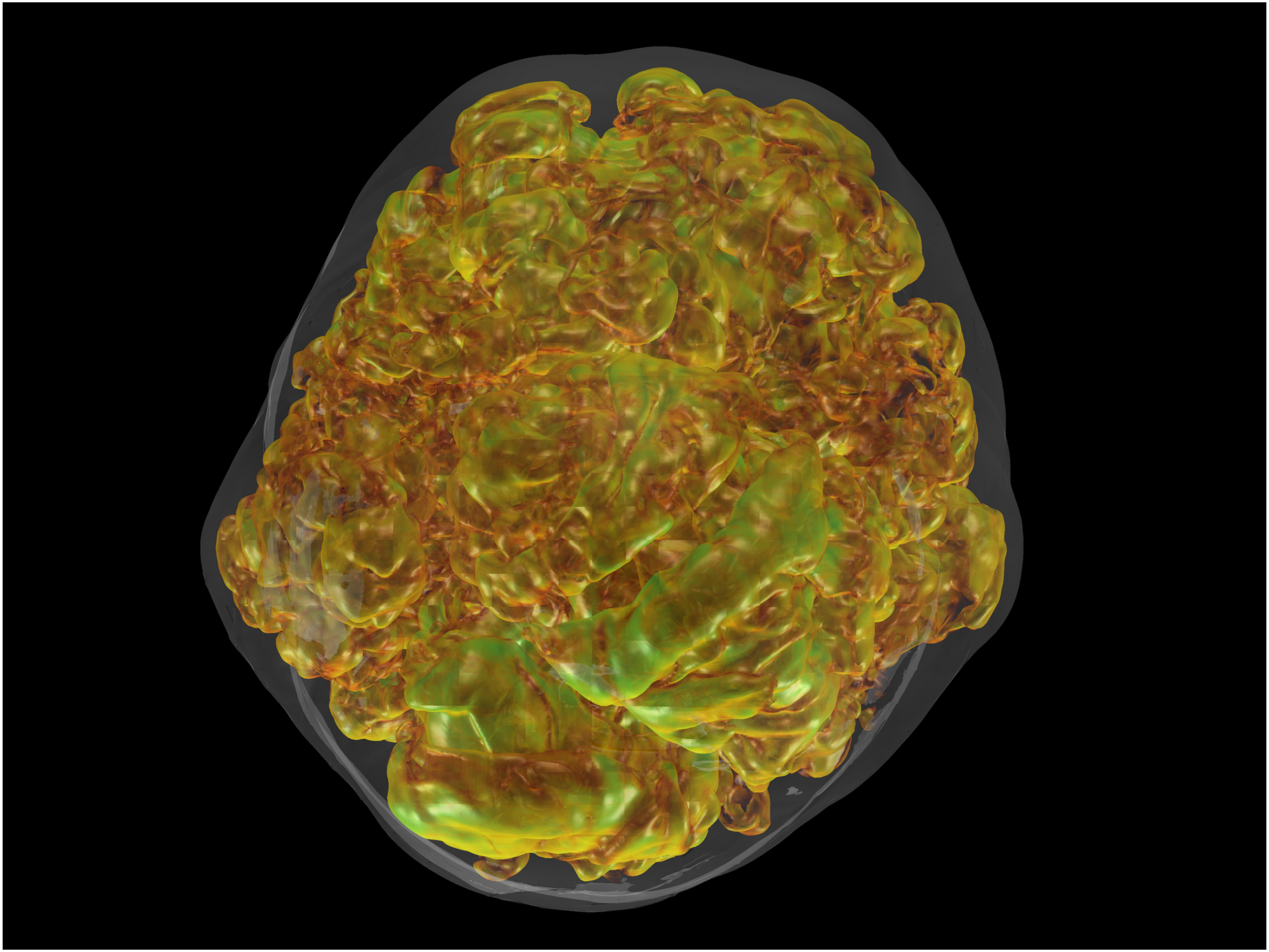


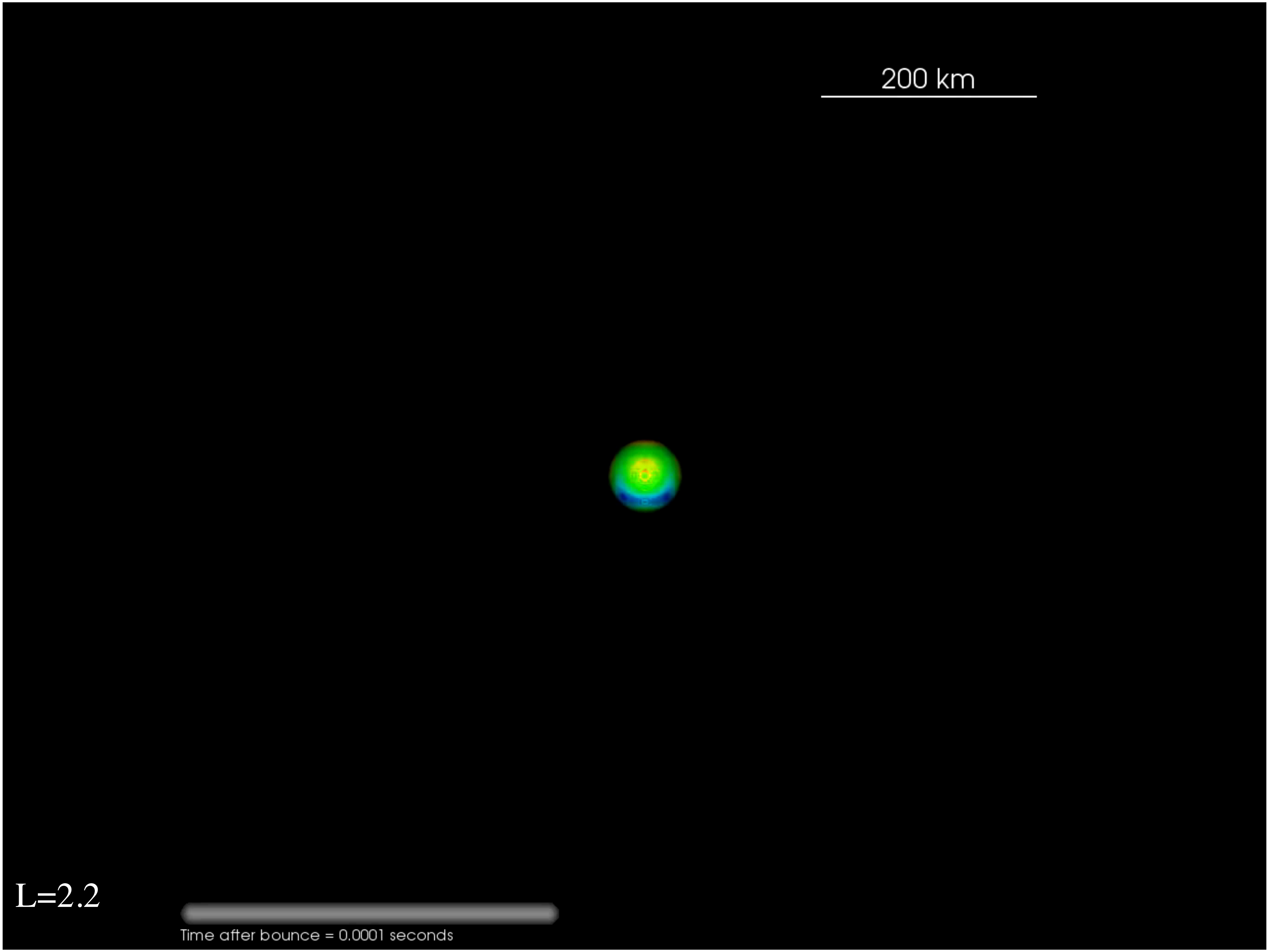


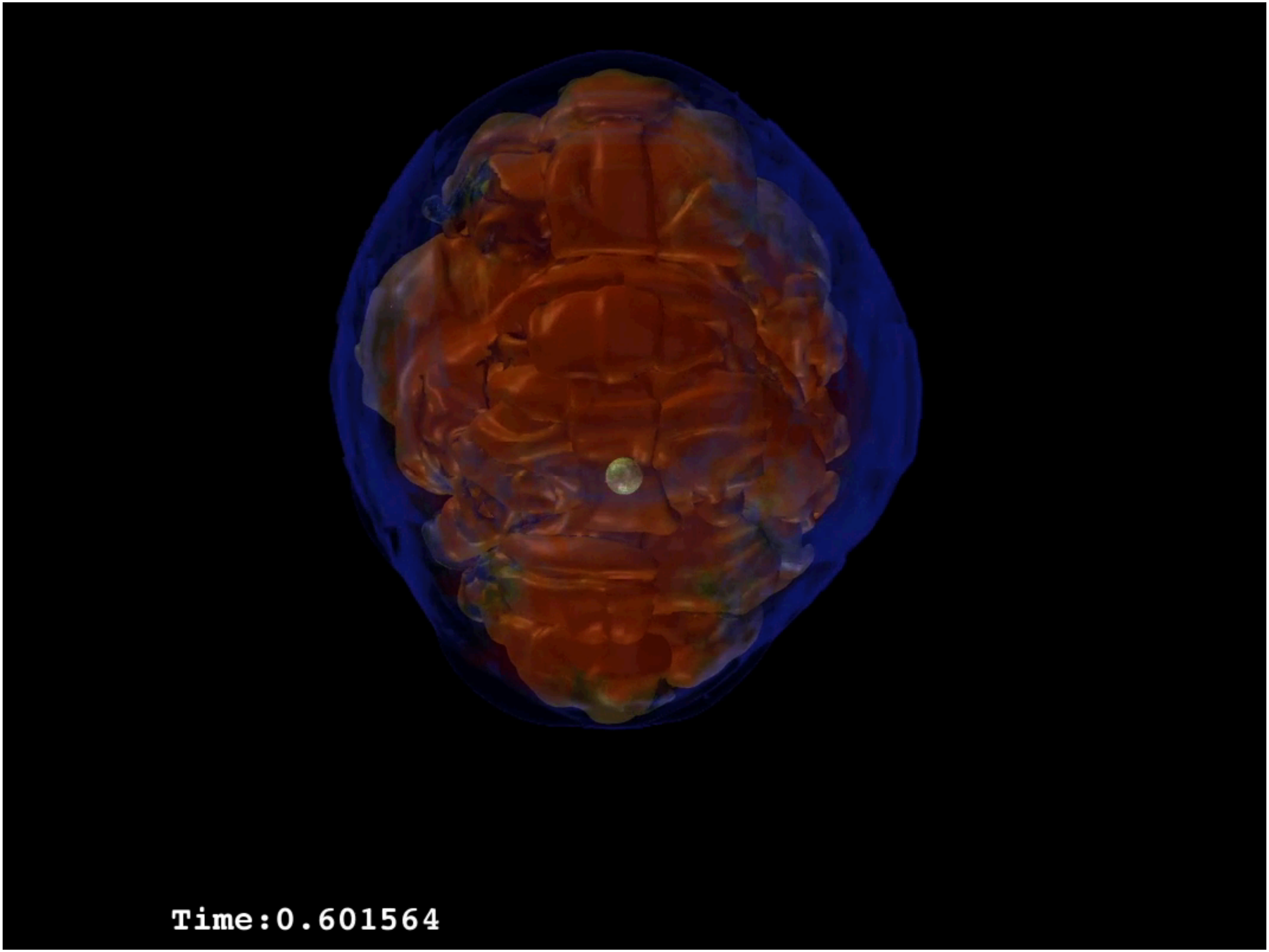
Bubble(s) lead (and lead to) Explosion

(Dolence et al. 2013)






200 km
L=2.2
Time after bounce = 0.0001 seconds


Time:0.601564

Dimensional Dependence of:

1) Dwell time in Gain region

2) Turbulent Pressures (!)

3) Cooling rate interior to Gain Radius

4) Unstable Mode order (l)

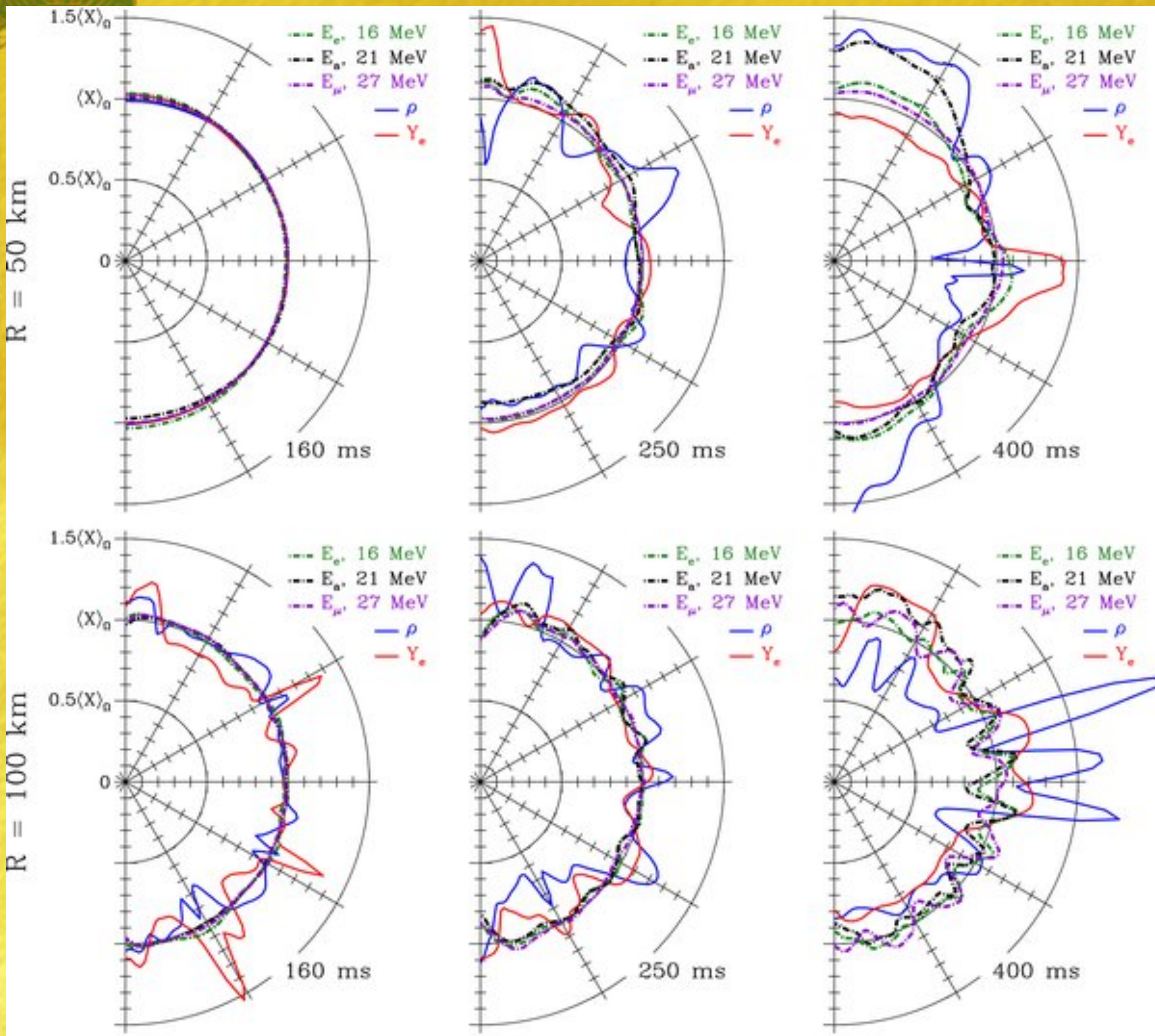
5) Delay to Explosion (!)

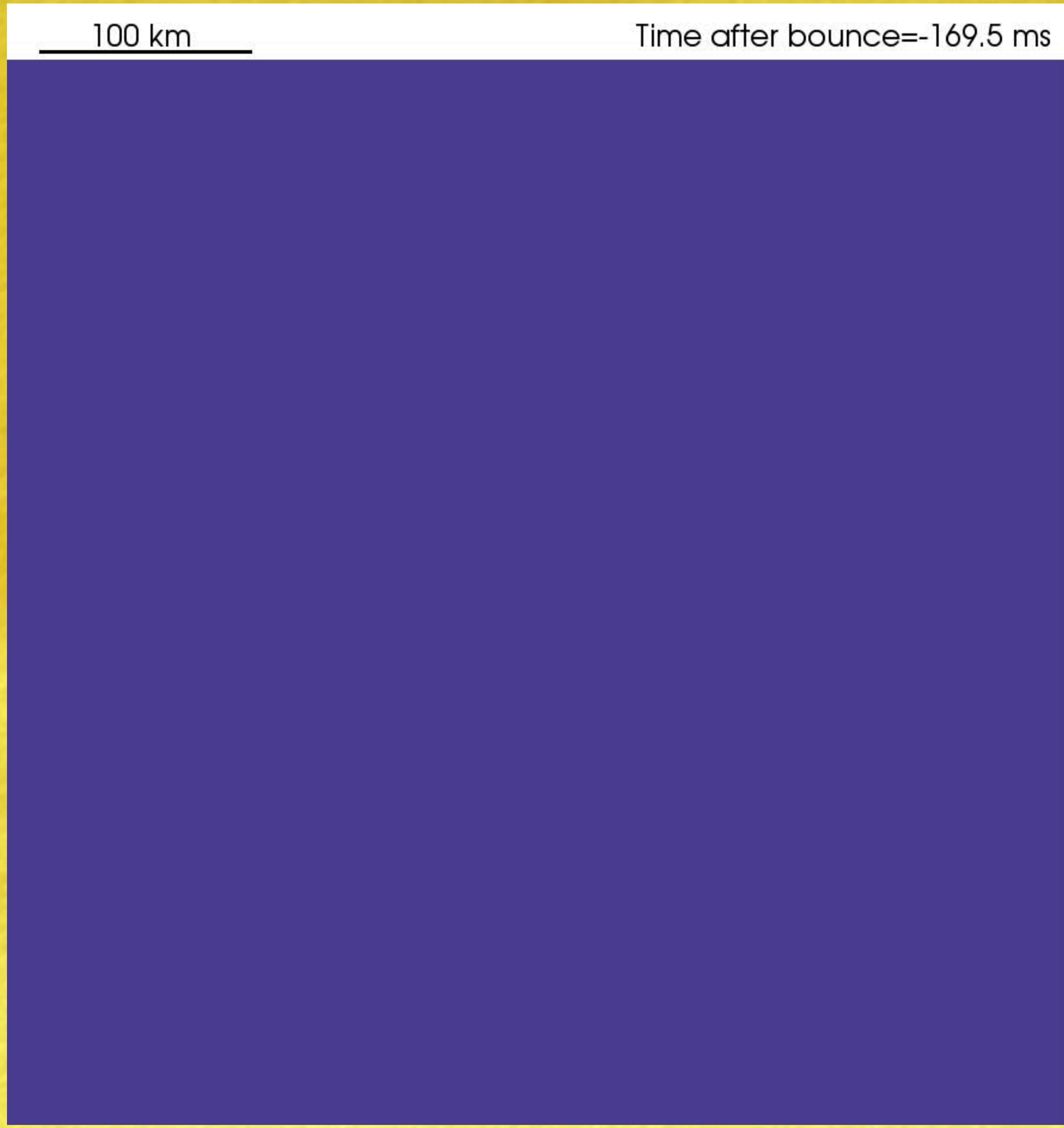
Possible Problems with "Ray-by-ray" Pseudo-Transport

Ray-by-ray May Exaggerate Angular and Temporal Variation in Neutrino Fluxes and Heating

- In 2D, the artificial sloshing along the axis (identified by some with the SASI) might facilitate explosion
- "Ray-by-ray" heating rate correlates too strongly with axial motion
- Real Multi-D transport smoothes angular variation of matter sources
- Needs to be tested (but has not been)

Brandt et al. 2011 - Multi-Angle, Multi-Group, 2D Transport

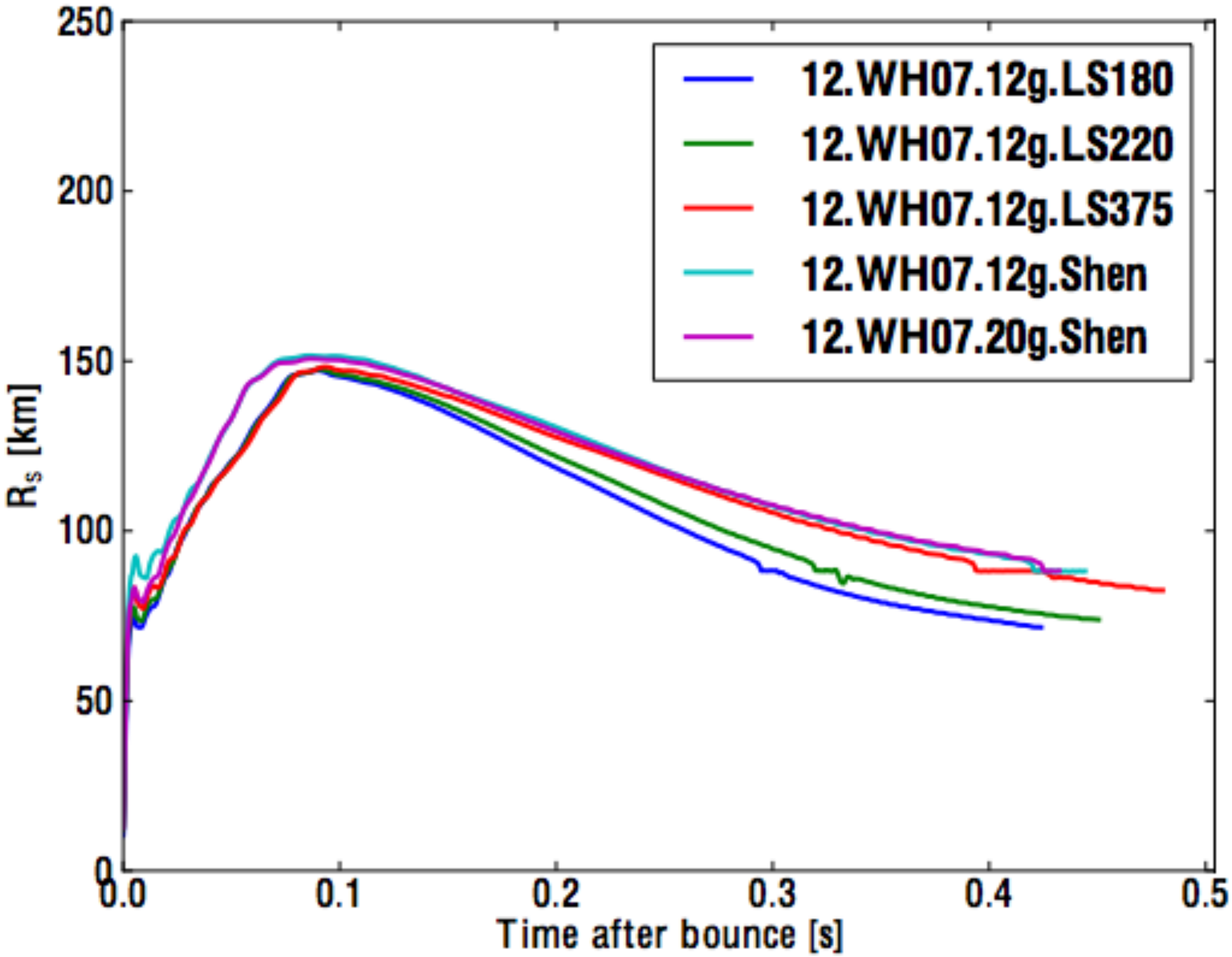




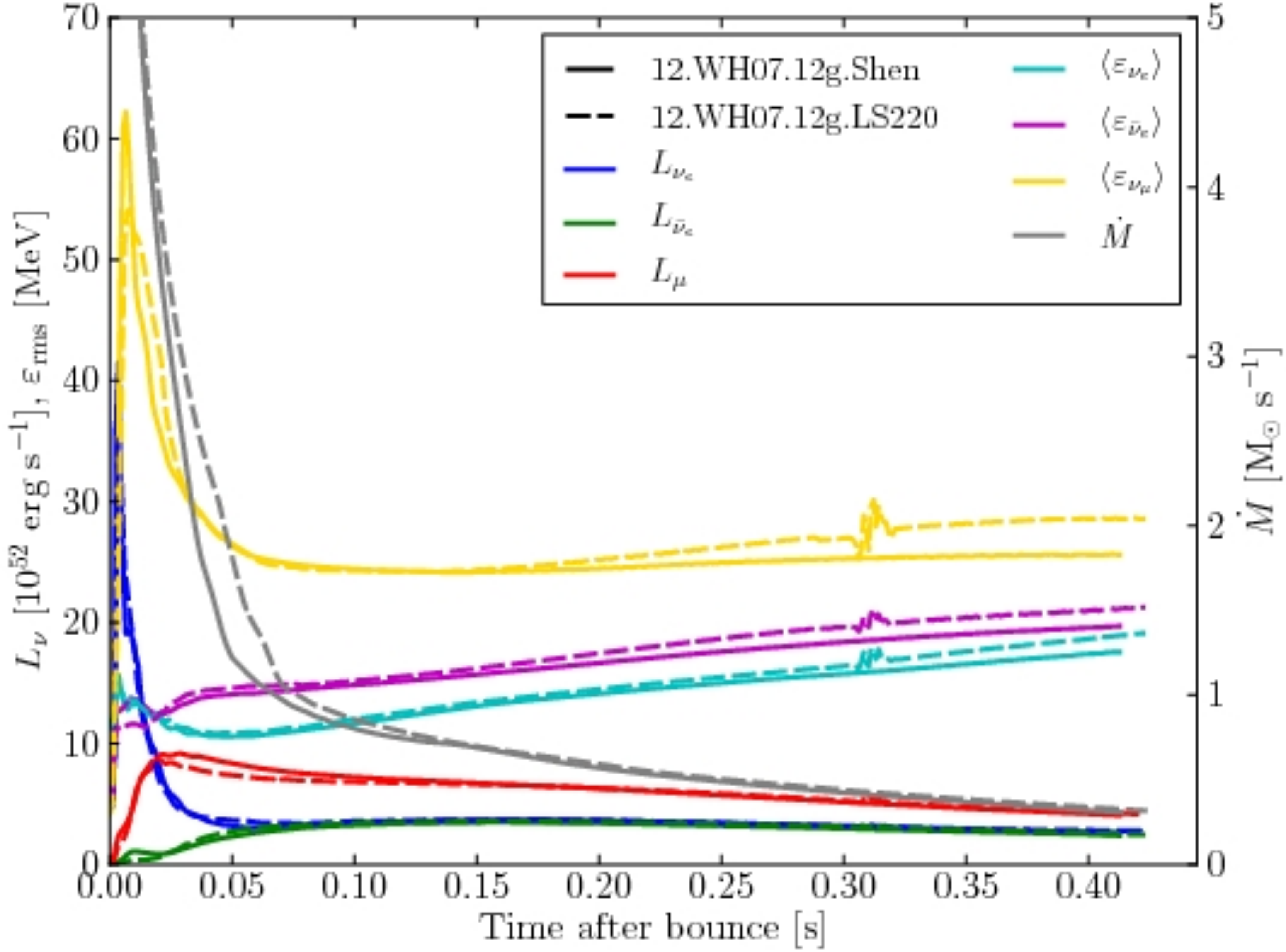
2D (Castro): MGFLD with multi-D Transport (no ray-by-ray)

Different EOSs

Different Equations of State: 1D Examples

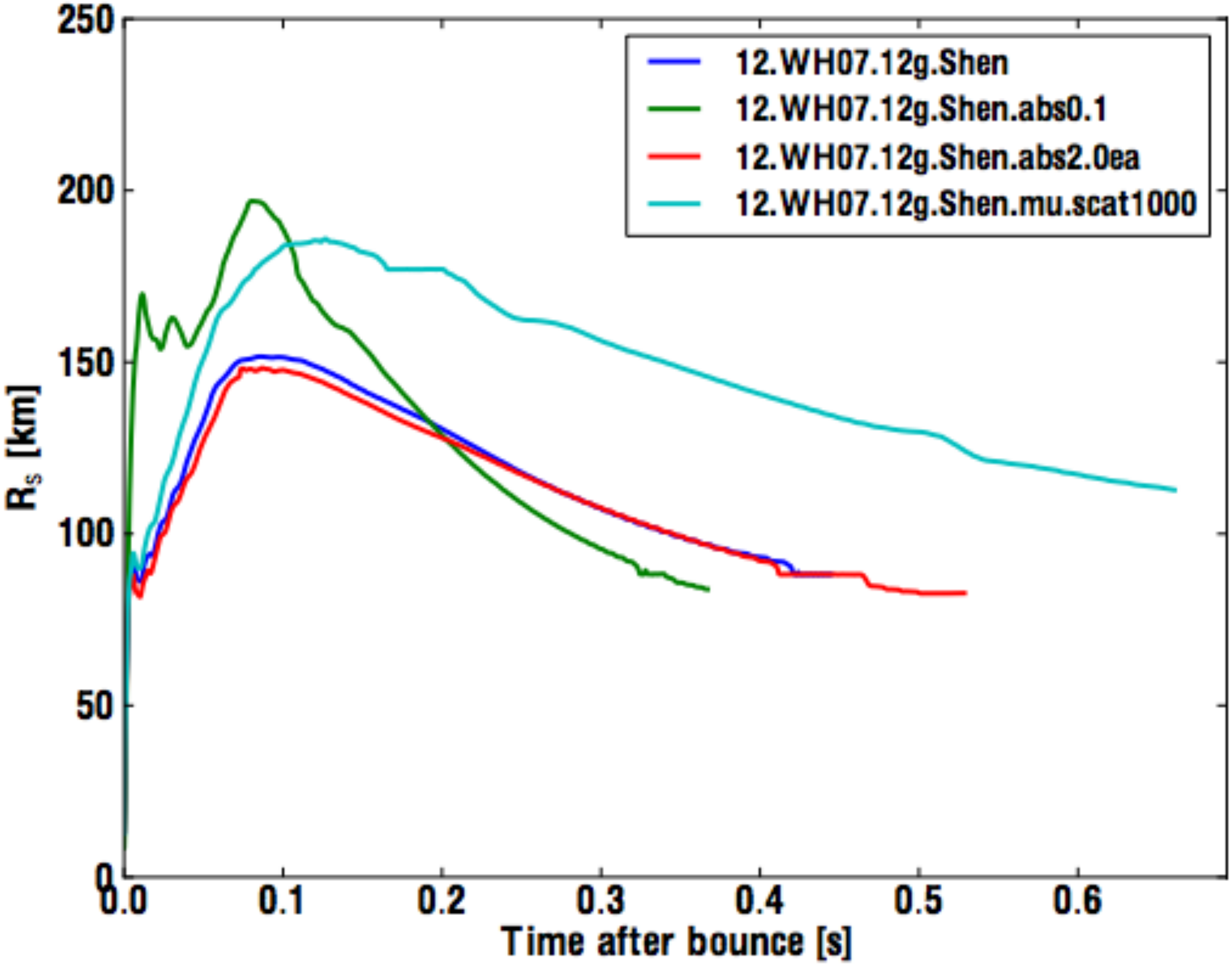


Shen versus LS 220: 1D Example



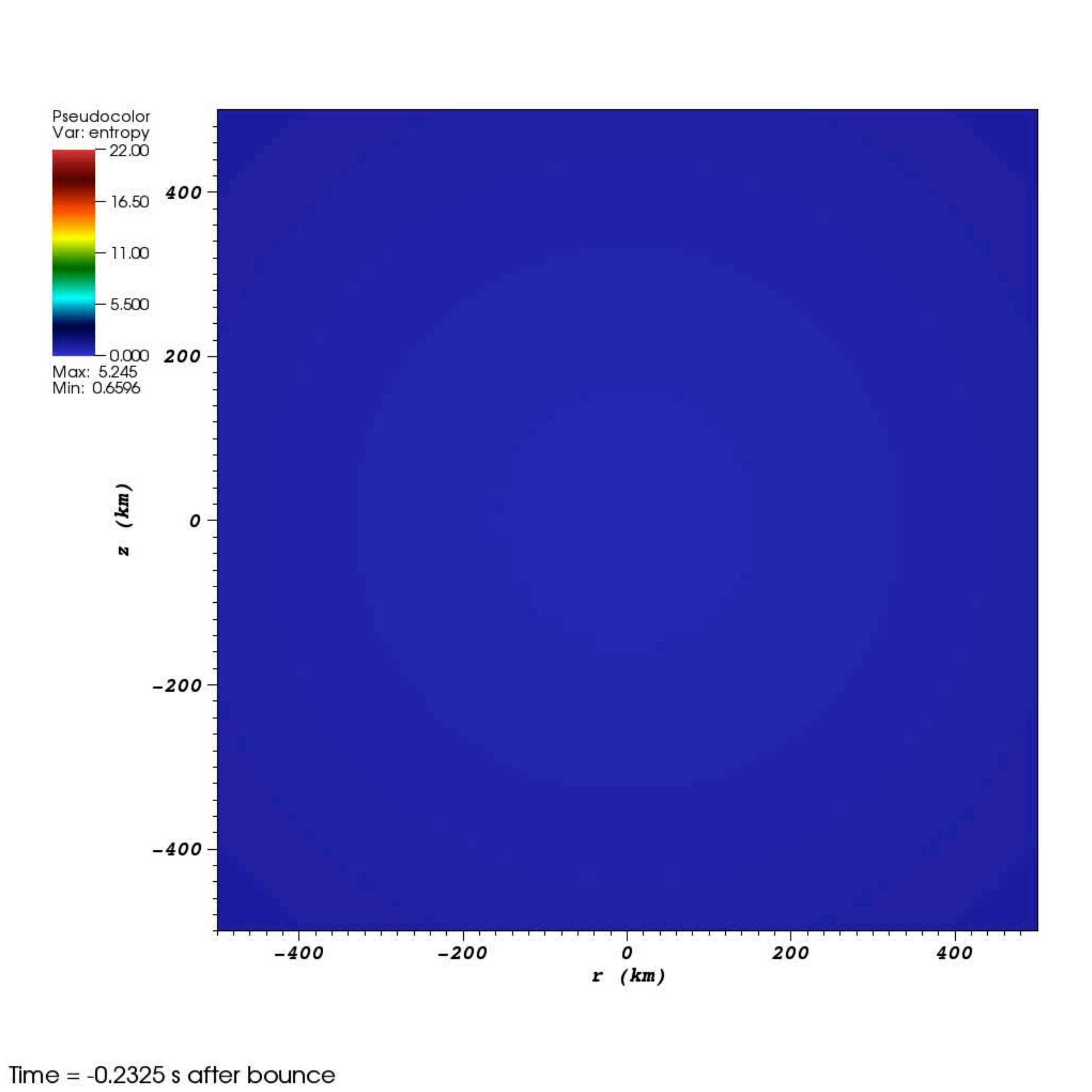
The Effects of Drastic Changes in Neutrino Opacities - FEEDBACKS

Drastic Changes in Neutrino Opacities: 1D Examples



Pre-Collapse Perturbations

See also Couch & Ott 2013



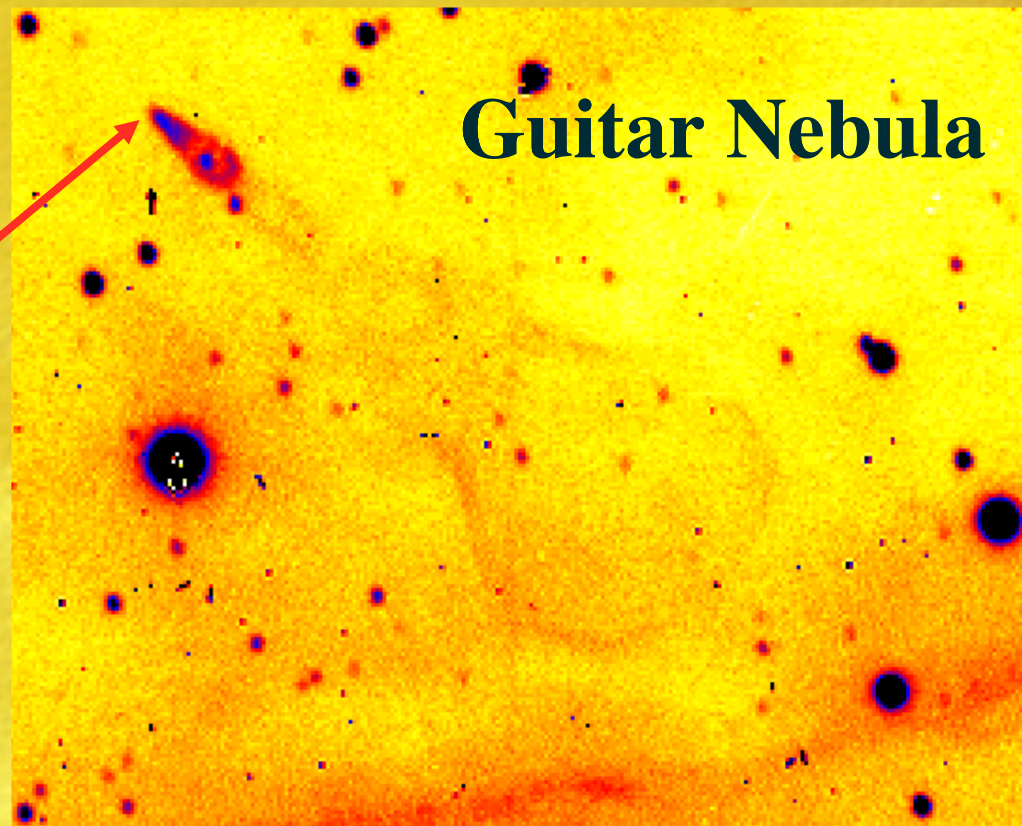
25 solar mass (WH 2007) 2D (Castro): MGFLD with multi-D Transport, with Shelf (!)

Pulsar Kicks

- Hydrodynamic Mechanism Seems Natural - "Simple" Recoil
- Net Neutrino momentum component may be small
- No need for exotic mechanisms (Harrison-Tademaru, parity violation, B-fields, ….)

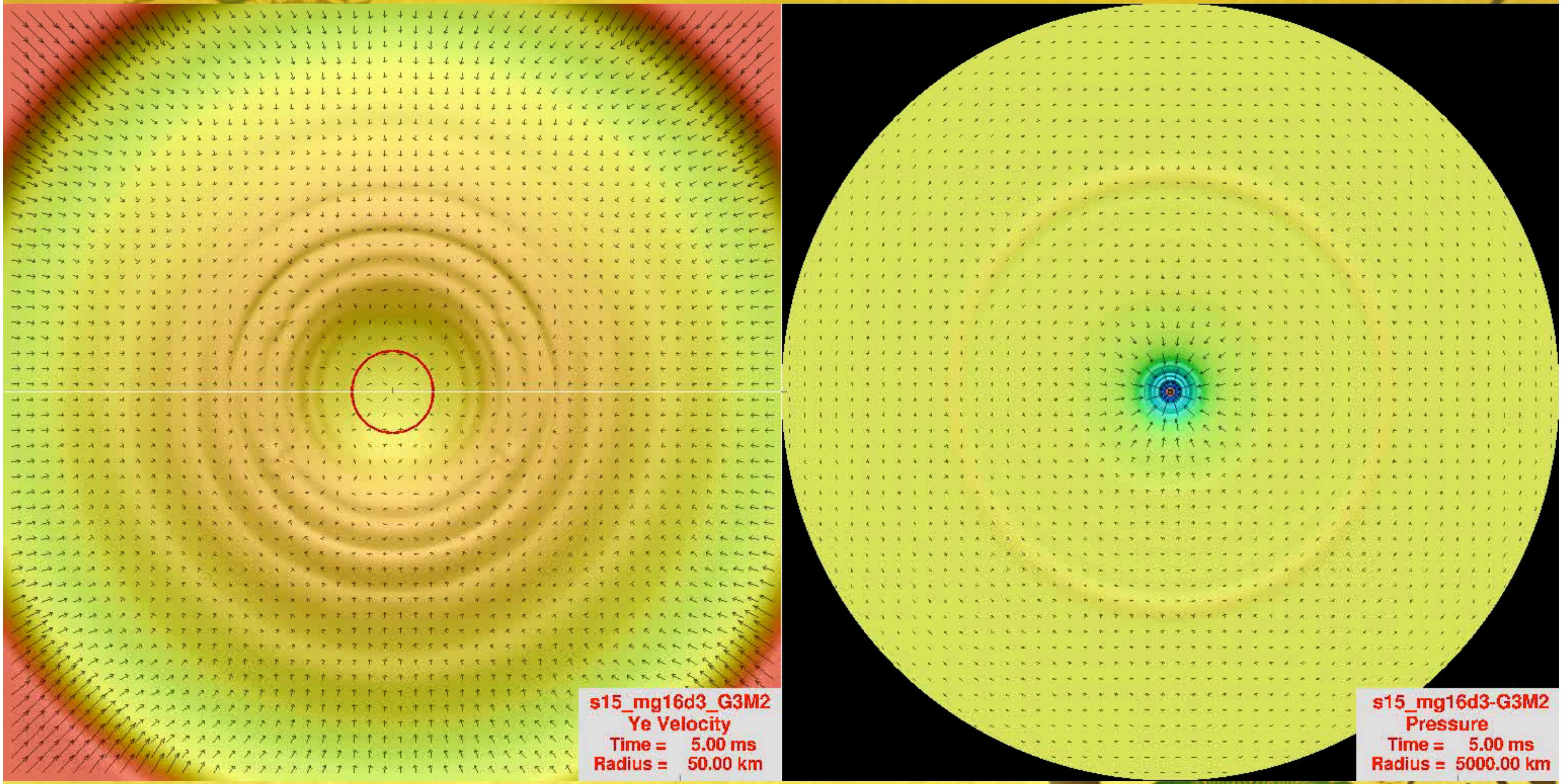
Pulsar Recoil: A Generic Feature

<u>Pulsar Kicks:</u>
Pulsar B2224+65
and Bow Shock
$V \geq 1000$ km s^{-1}



Cordes, Romani, Lundgren '93

The Origin of Pulsar Kicks in Hydrodynamic (and neutrino?) Recoil



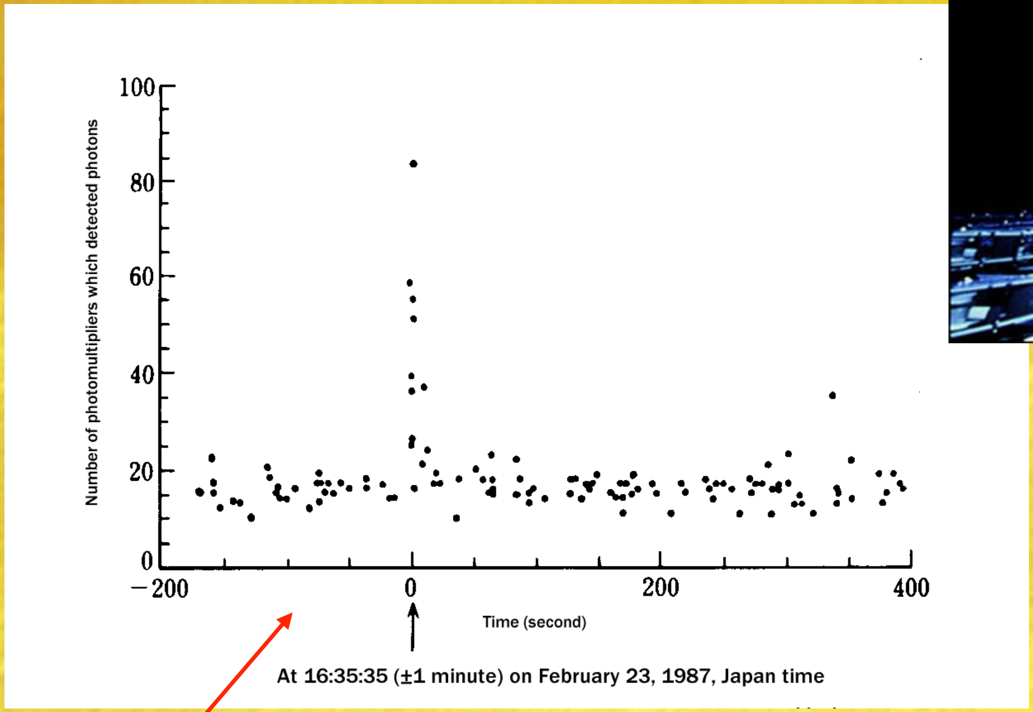
Nordhaus, Burrows, & Ott 2010

Acceleration ~ 500 km/s^2

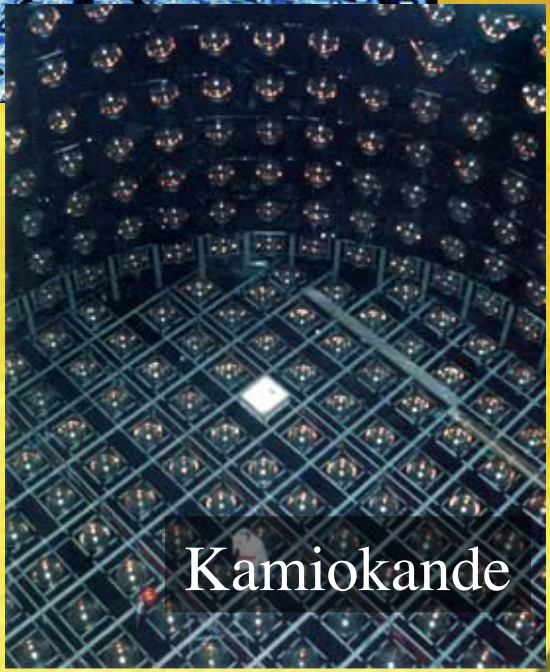
See also pioneering work of Scheck et al., for an extensive suite of related simulations

Neutrino Bursts/Signatures

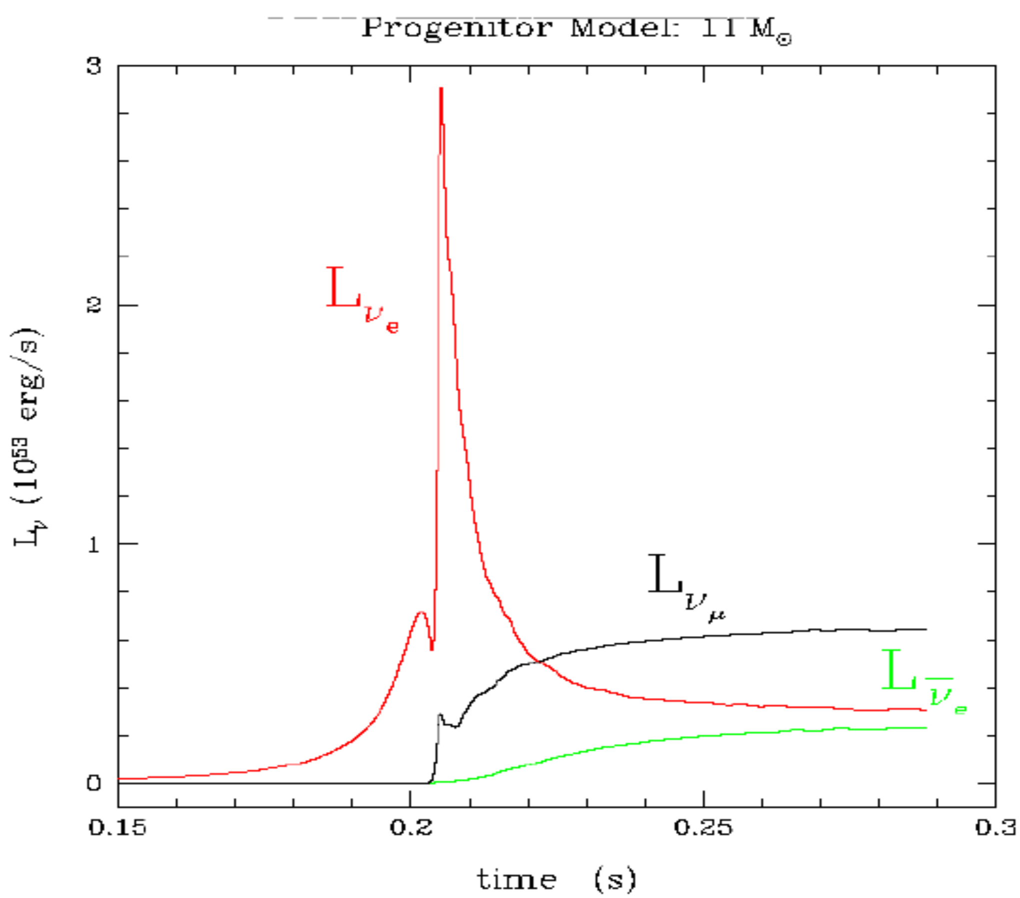
Core-Collapse Neutrinos Detected

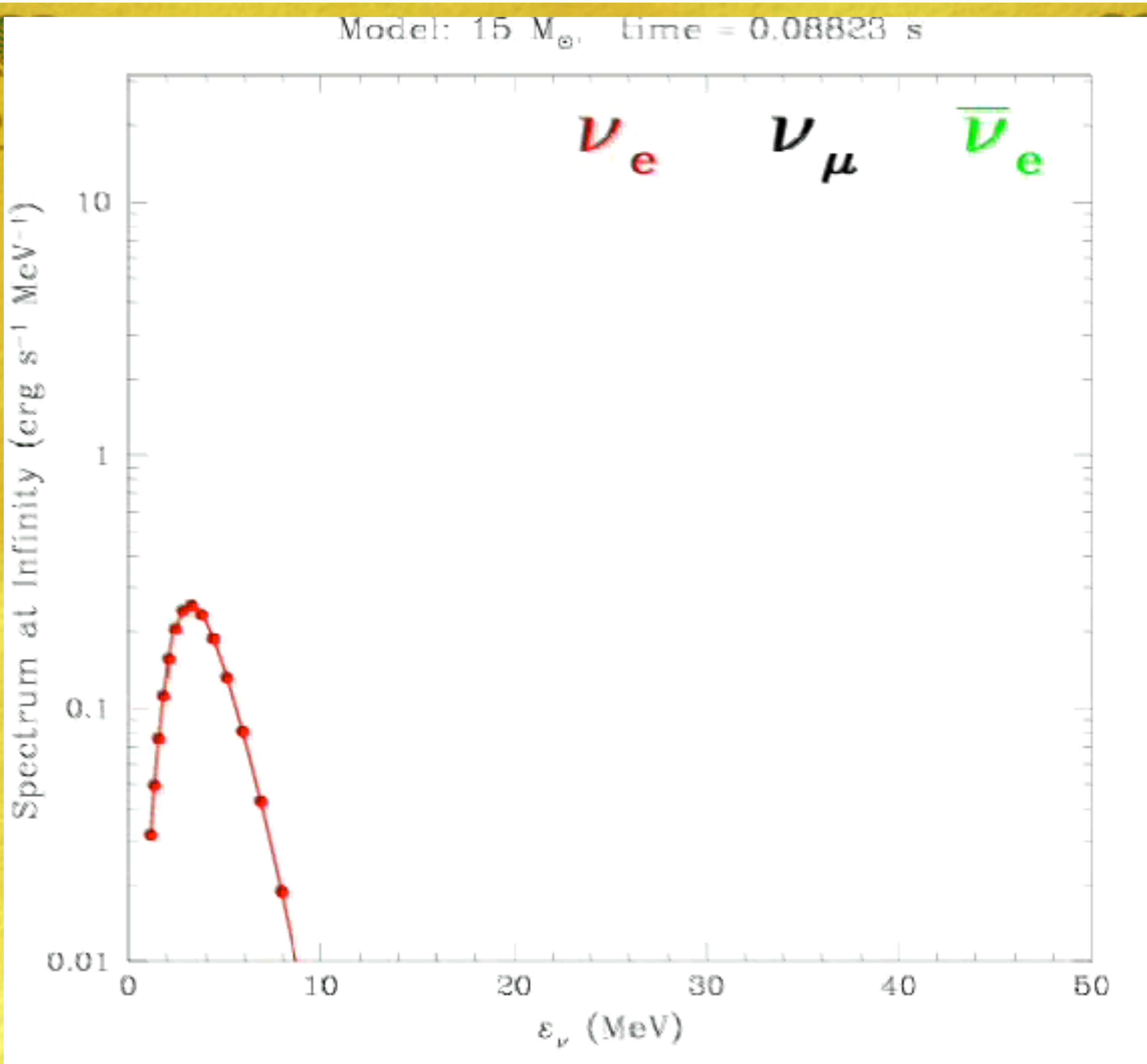


Kamioka II



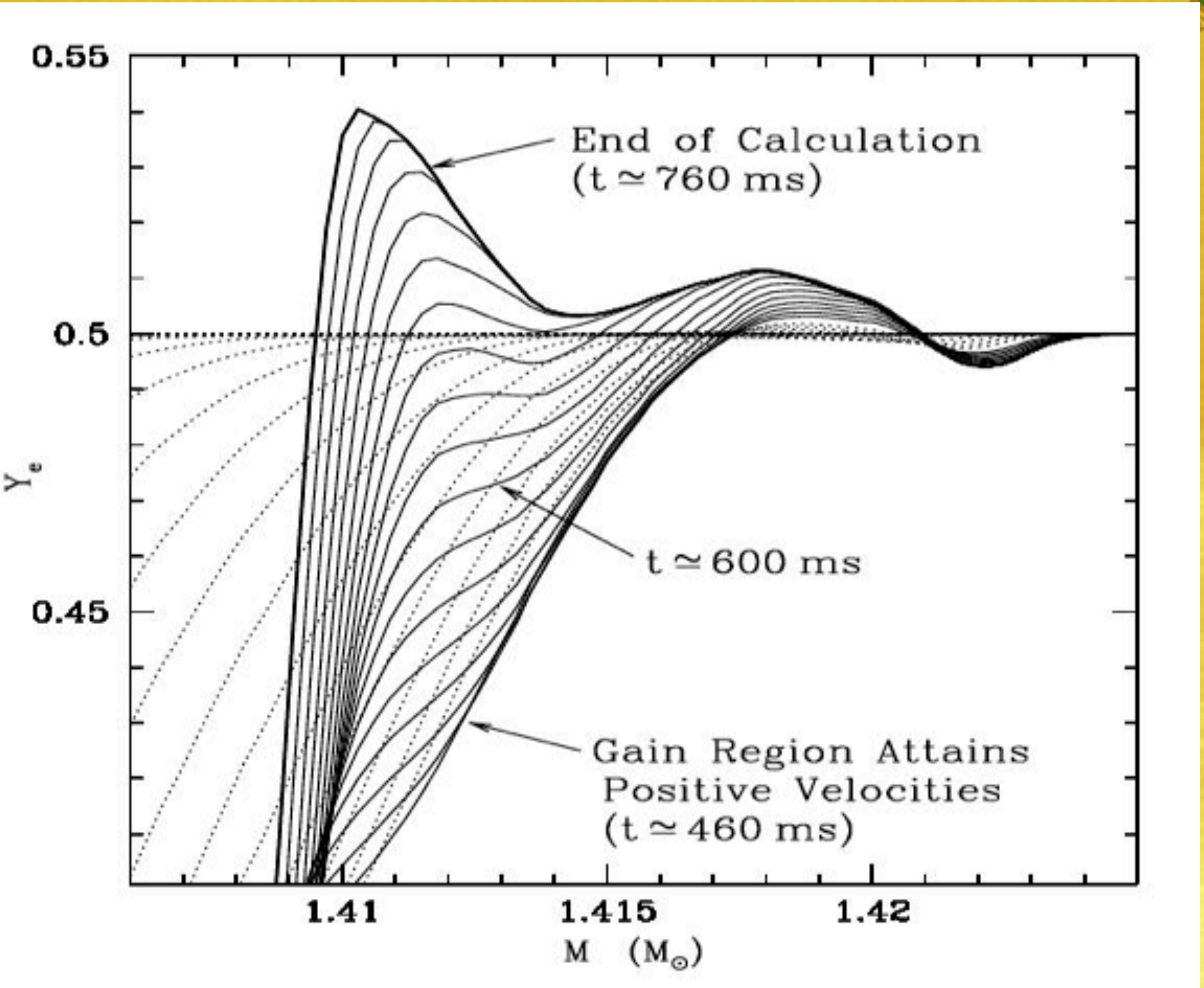
Breakout Burst of Neutrinos: Precision Boltzmann Transfer





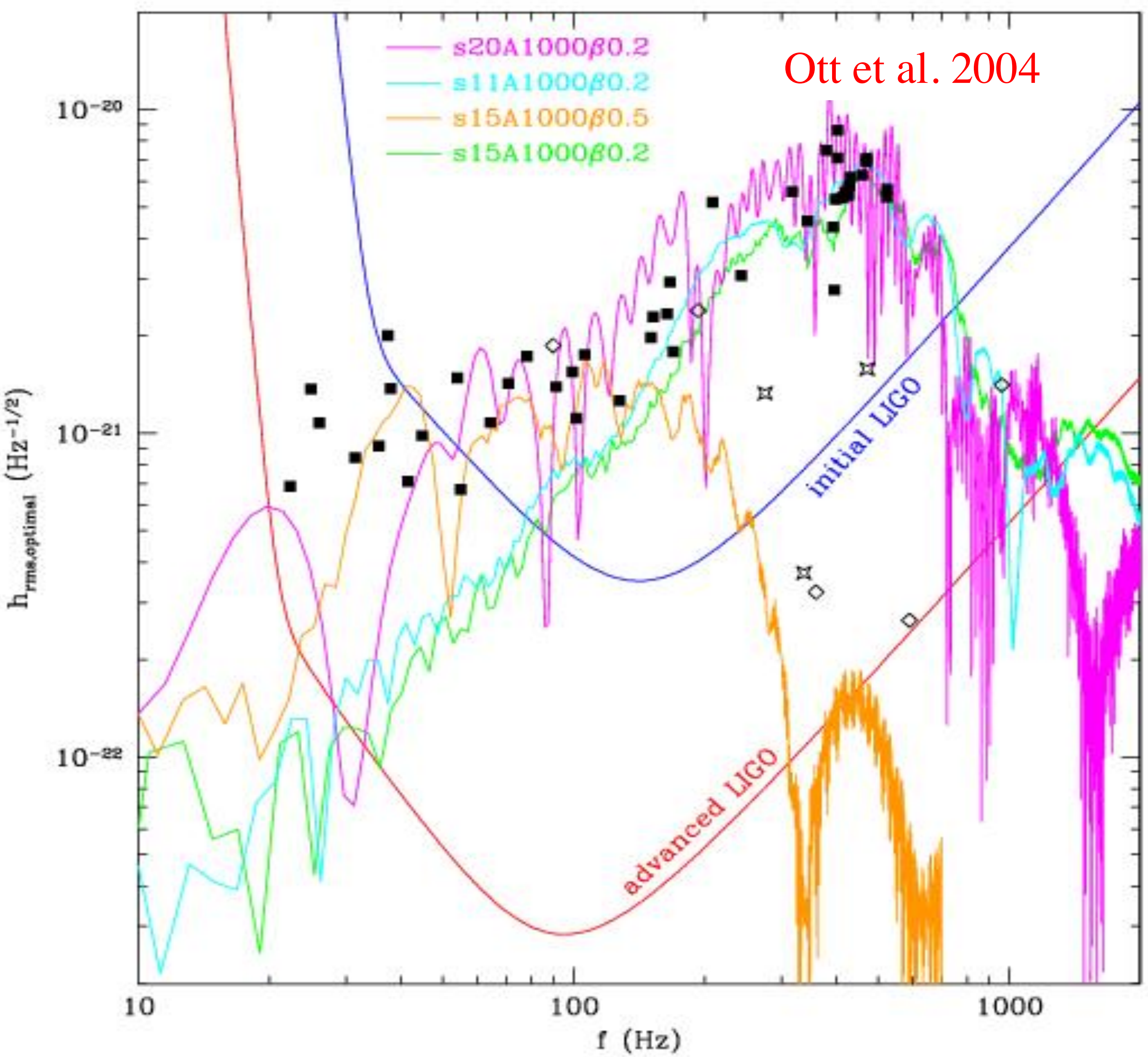
Model: 15 $M_\odot$, time = 0.08823 s
ν_e
ν_μ
$\bar{\nu}_e$
Spectrum at Infinity (erg s^{-1} MeV^{-1})
10
1
0.1
0.01
0
10
20
30
40
50
ε_ν (MeV)

Ejecting Some $Y_e > 0.5$ Material

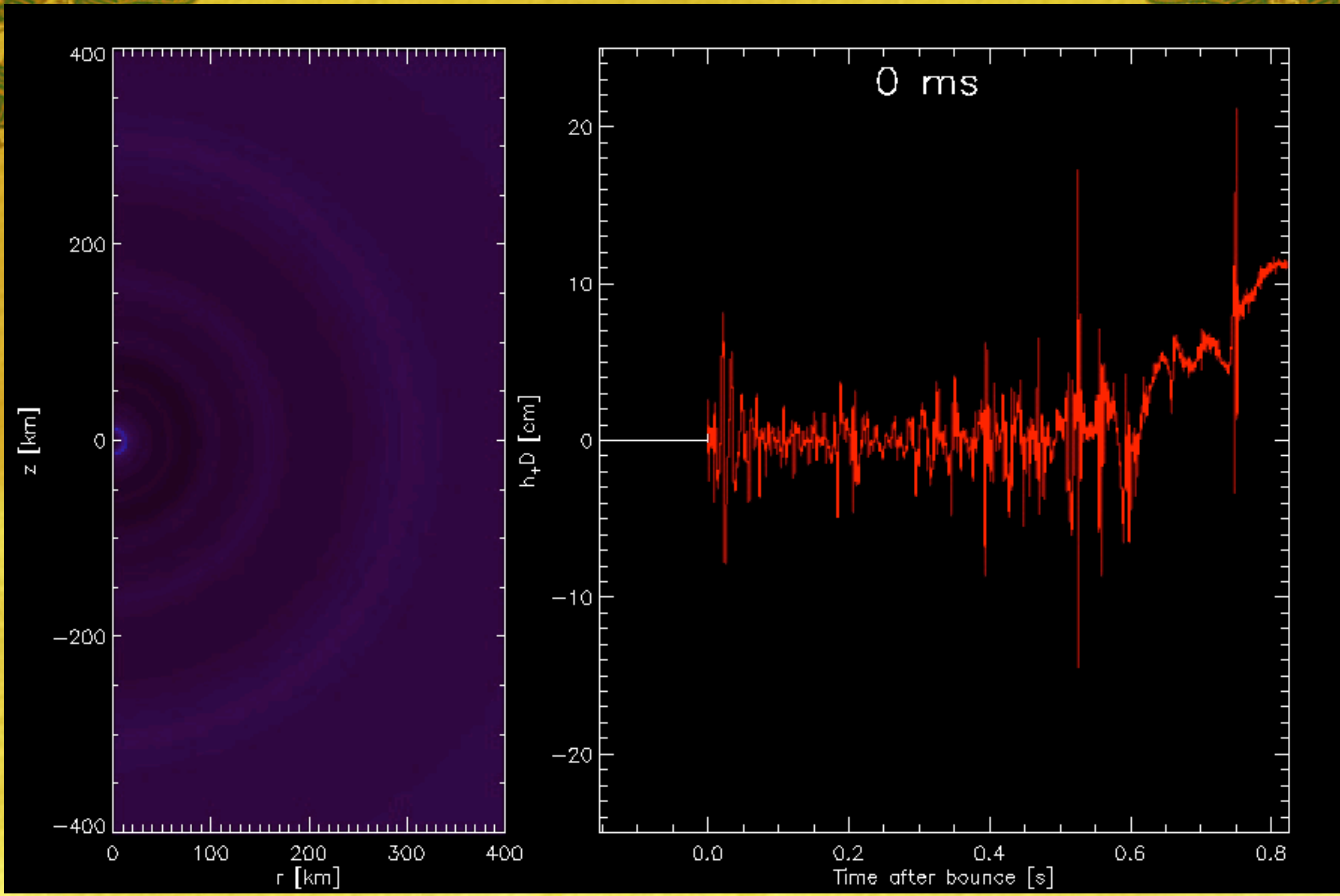


Gravitational Radiation from Supernovae

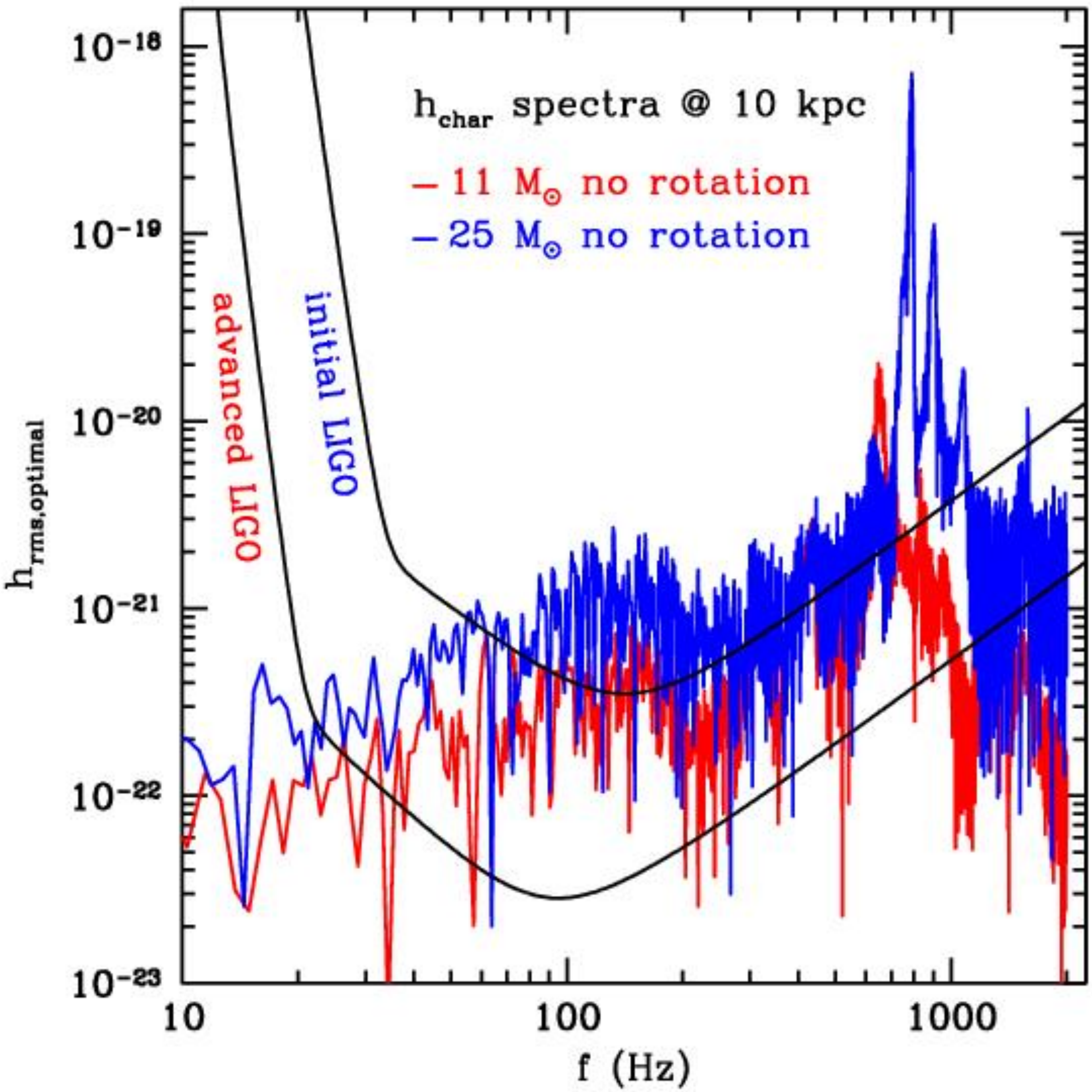
Ott et al. (2004,2006)



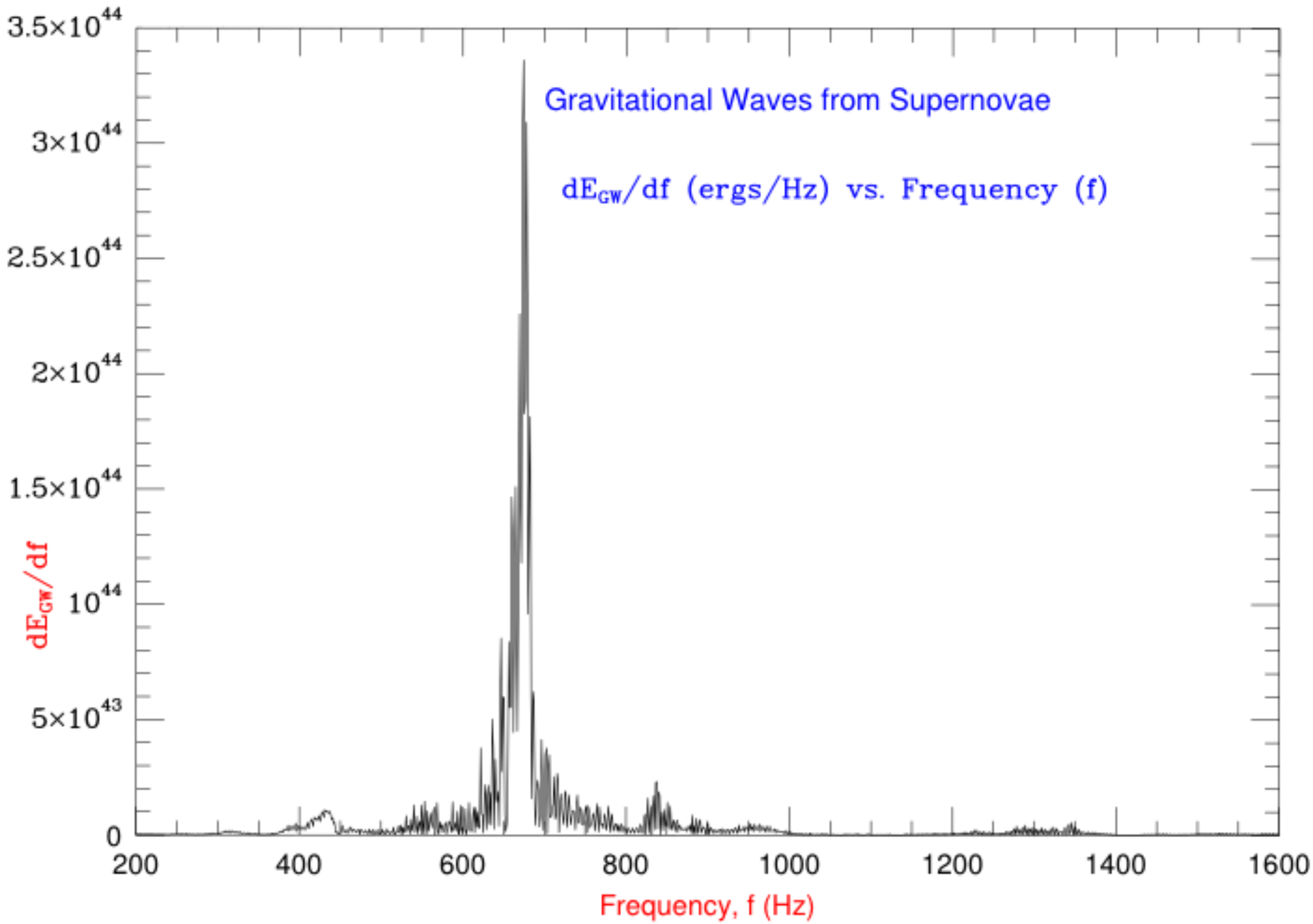
Ott et al. 2004
s20A1000β0.2
s11A1000β0.2
s15A1000β0.5
s15A1000β0.2
initial LIGO
advanced LIGO
$h_{rms,optimal}$ $(Hz^{-1/2})$
f (Hz)
10^{-20}
10^{-21}
10^{-22}
10
100
1000



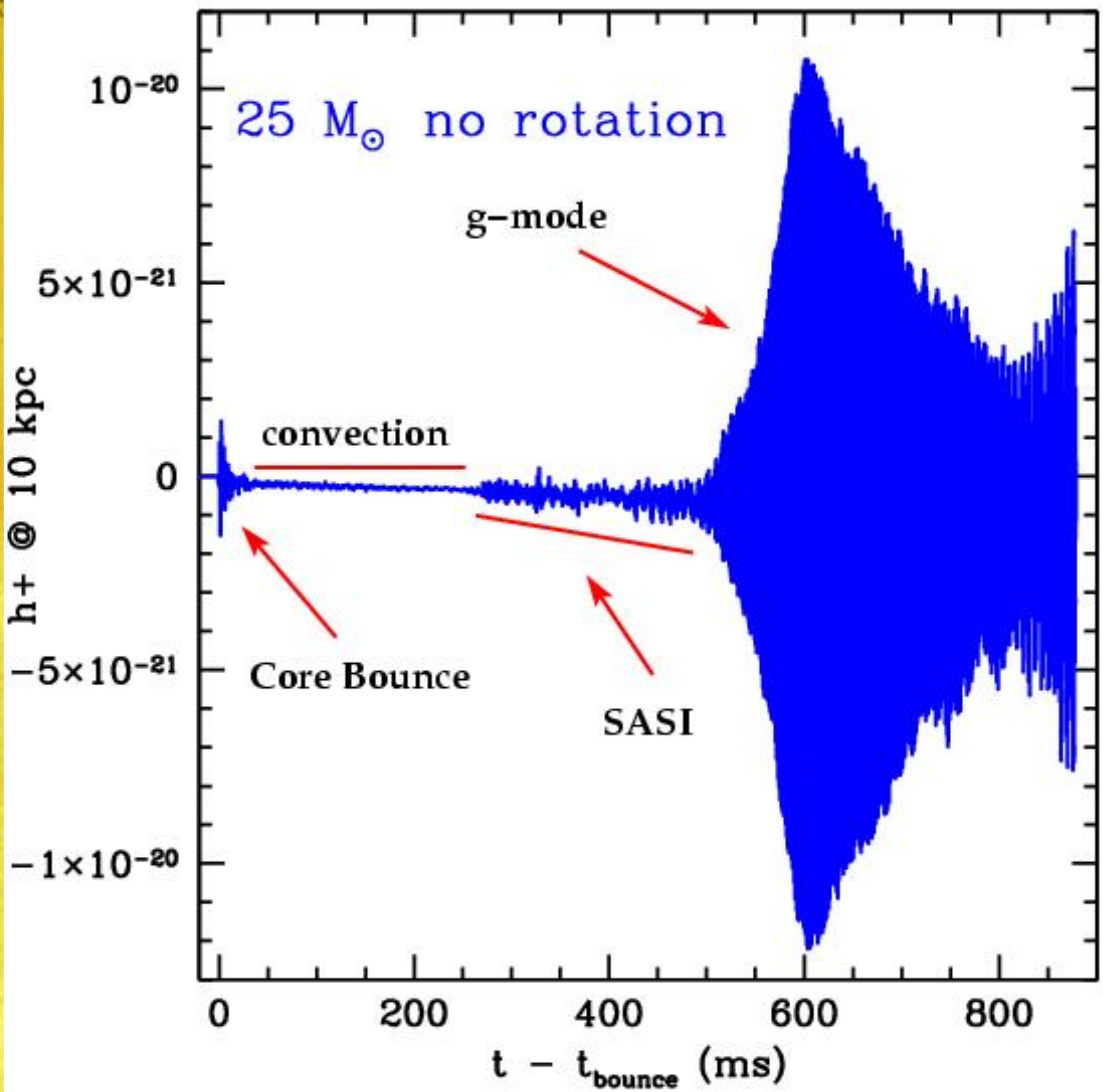
Murphy et al. 2009



h_char spectra @ 10 kpc
– 11 M☉ no rotation
– 25 M☉ no rotation
advanced LIGO
initial LIGO
h_rms,optimal
f (Hz)
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10
100
1000

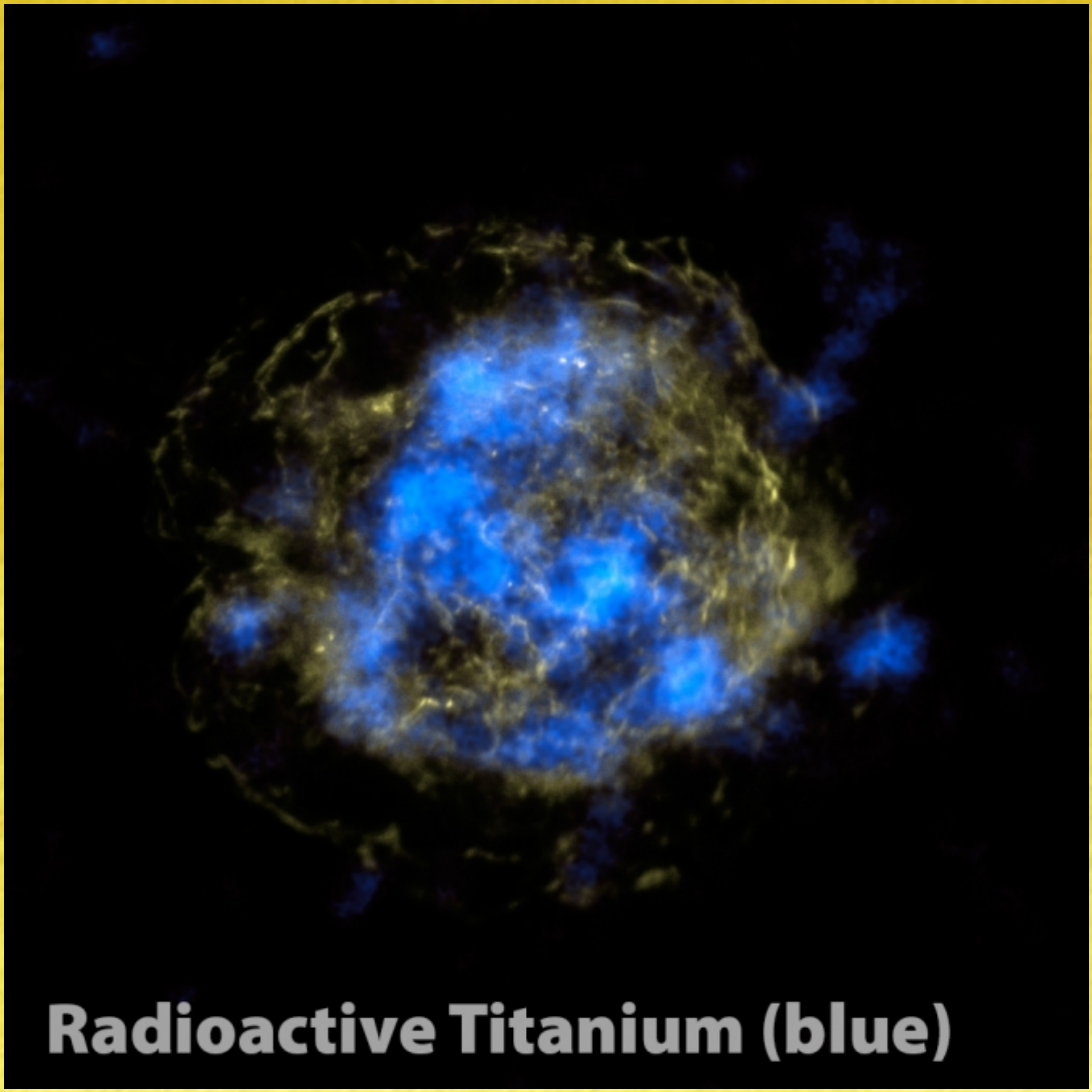


Gravitational Waves from Supernovae
dE_GW/df (ergs/Hz) vs. Frequency (f)
3.5×10^44
3×10^44
2.5×10^44
2×10^44
1.5×10^44
10^44
5×10^43
0
dE_GW/df
200
400
600
800
1000
1200
1400
1600
Frequency, f (Hz)



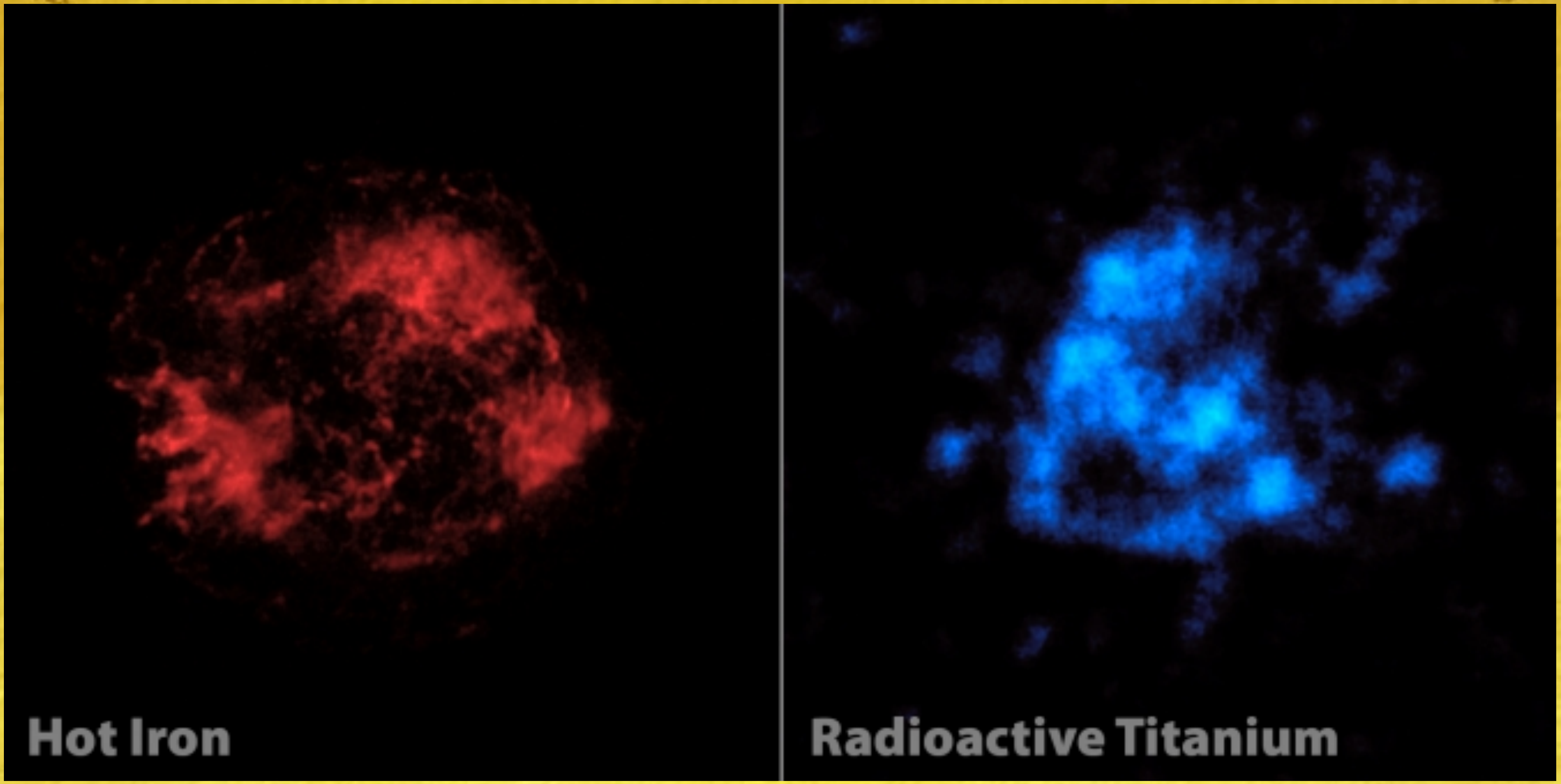
25 M☉ no rotation
g–mode
convection
Core Bounce
SASI
h+ @ 10 kpc
t – t_bounce (ms)
10^-20
5×10^-21
0
−5×10^-21
−1×10^-20
0
200
400
600
800

Cas A Remnant in ^{44}Ti



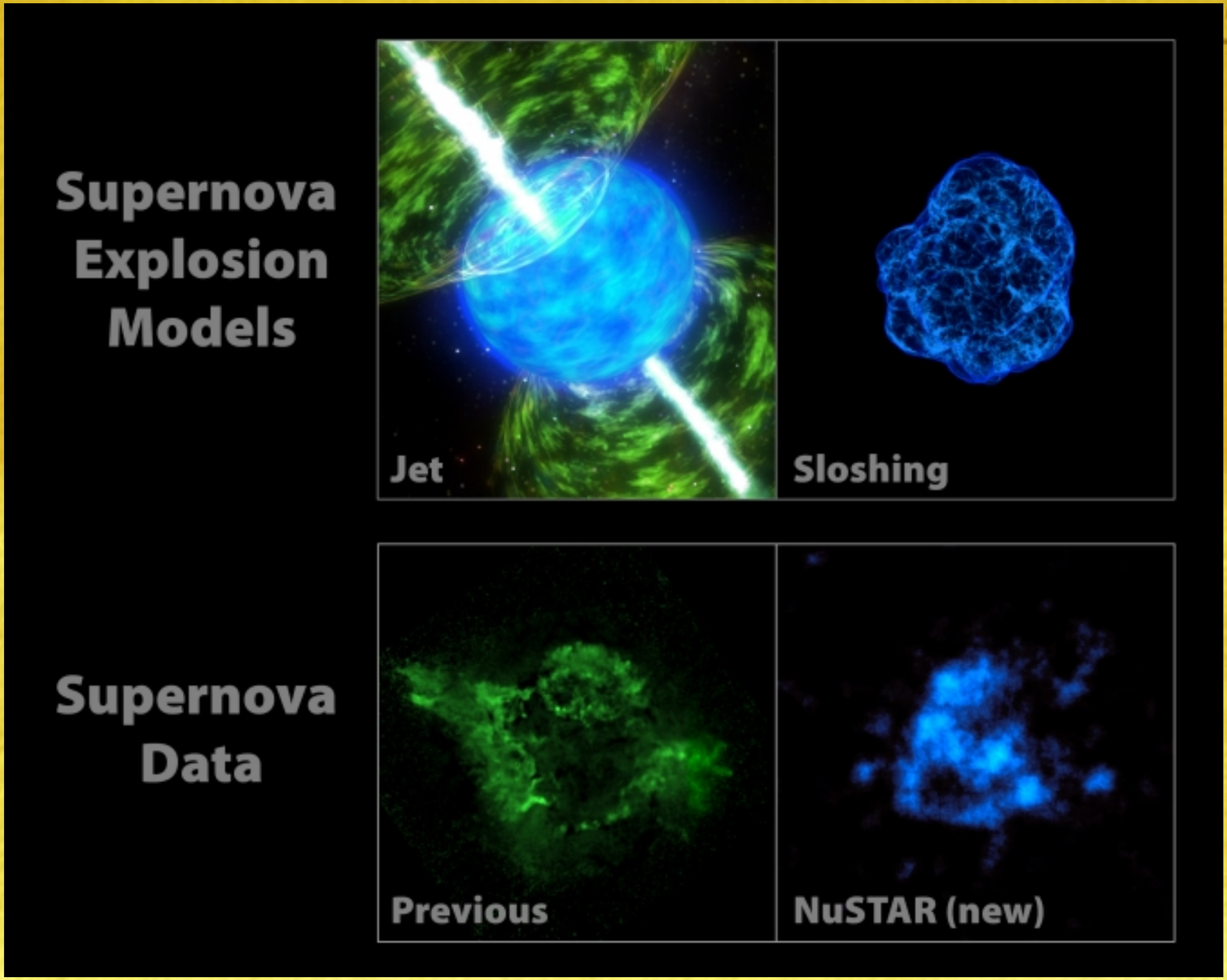
NuSTAR: Grefenstette et al. 2014

Cas A Remnant in ^{44}Ti

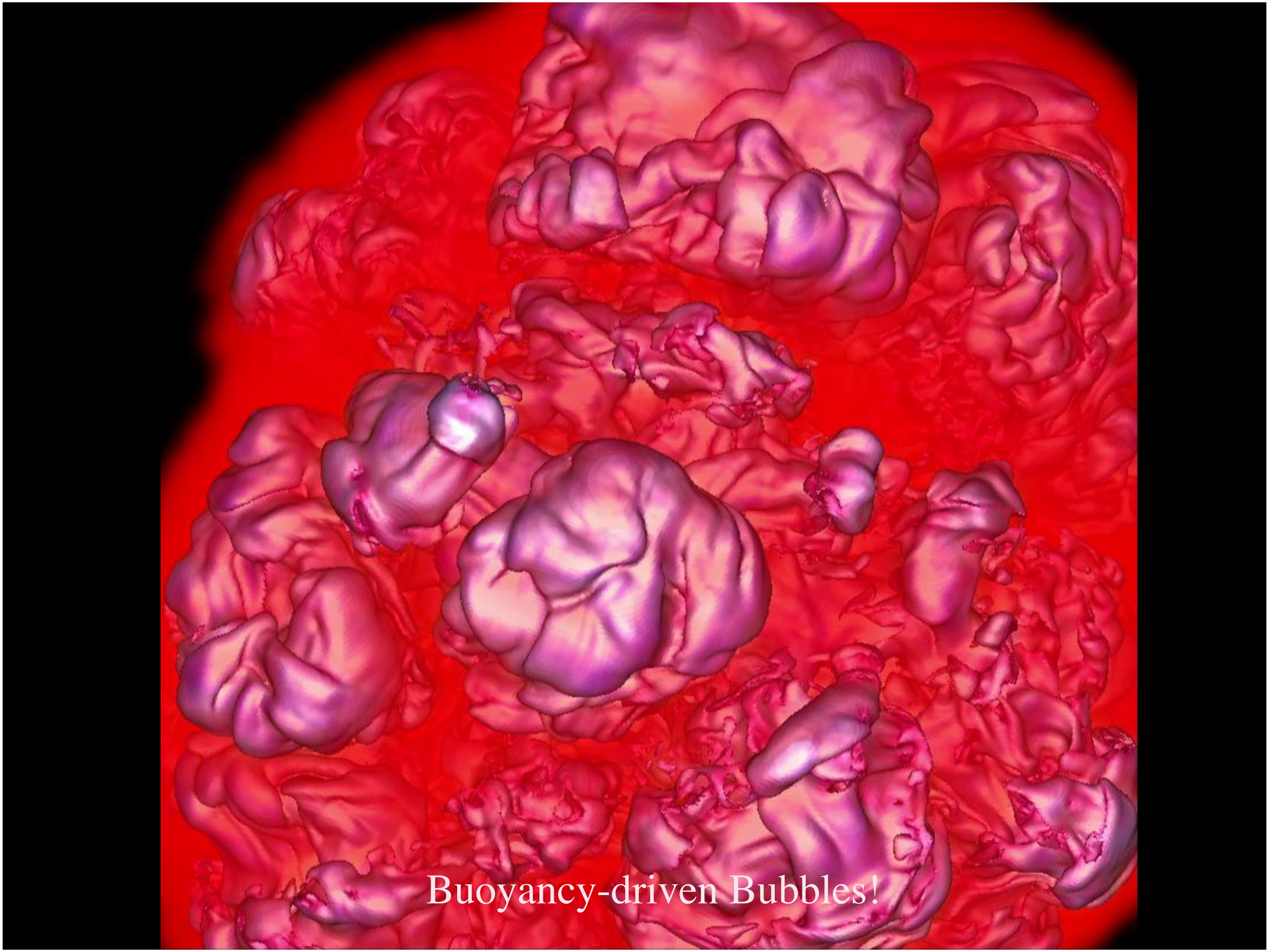


NuSTAR: Grefenstette et al. 2014

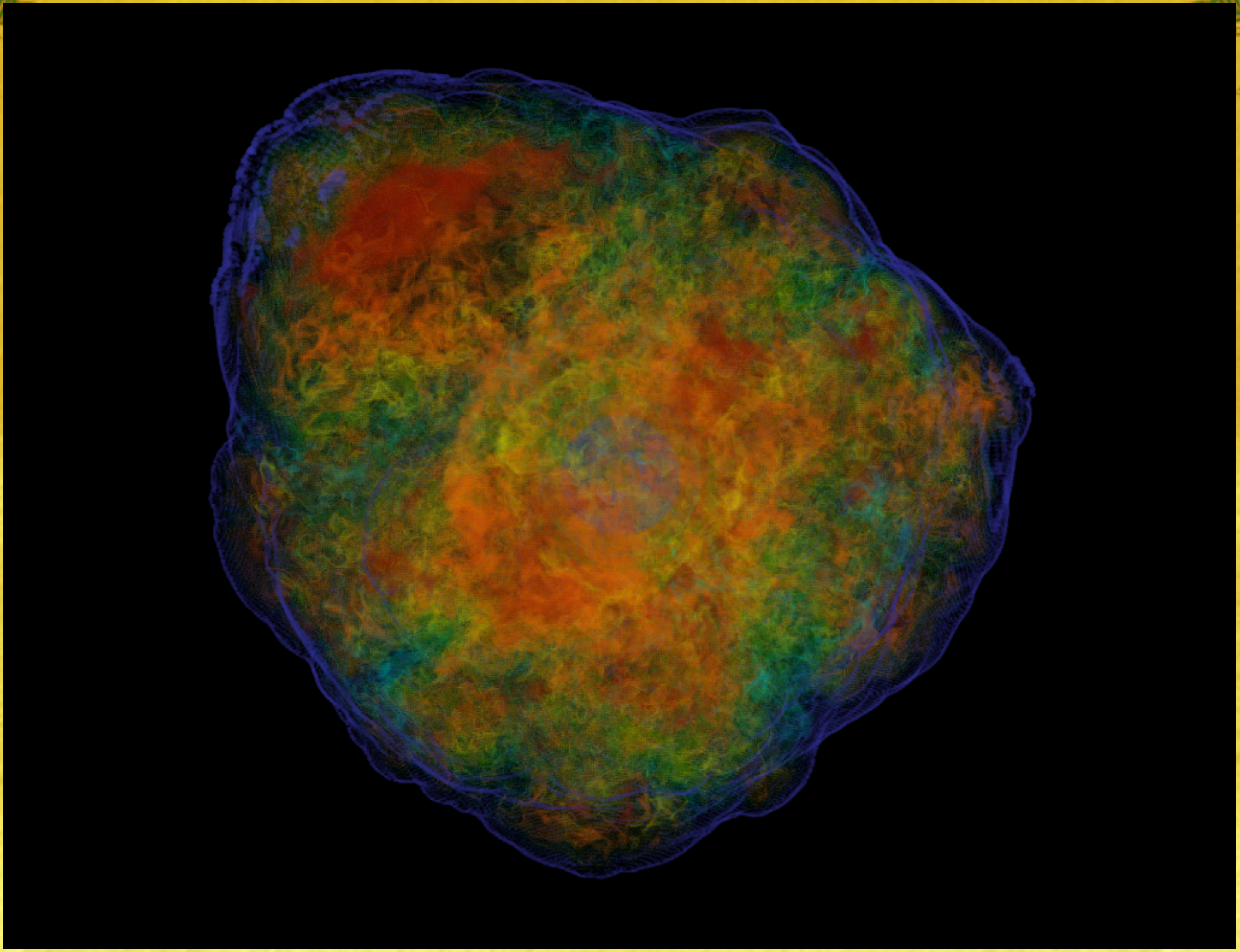
Cas A Remnant in ^{44}Ti



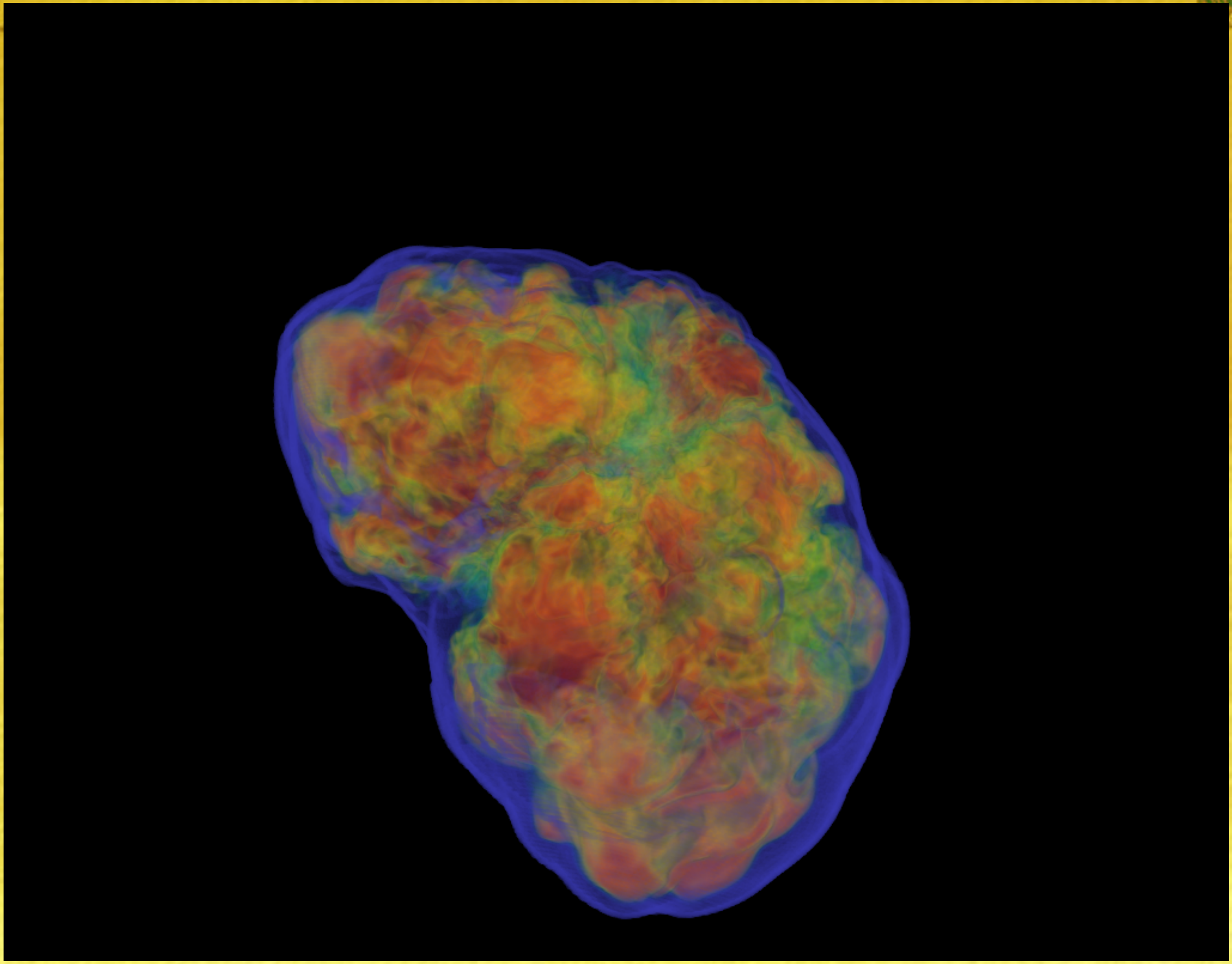
Grefenstette et al. 2014


Buoyancy-driven Bubbles!

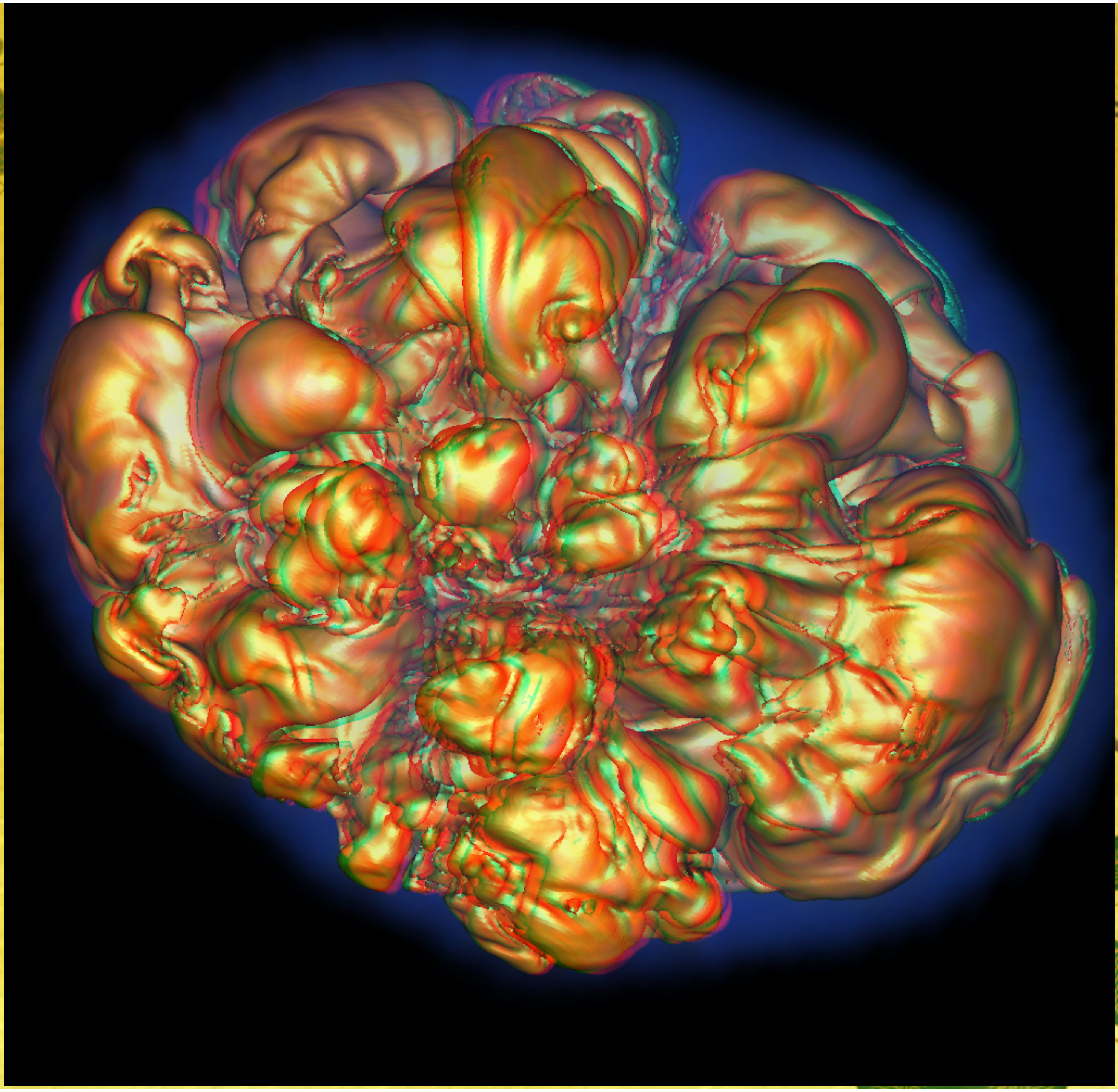
Burrows et al. 2012,2013: Generic 3D Ejecta Structures



Burrows et al. 2012,2013: Generic 3D Ejecta Structures



3D in 3D:



Core-Collapse Theory: A Status Summary

- "SASI" is not a mechanism
- Neutrino-driven convection > SASI (when object explodes to yield SN)
- "Ray-by-ray" may be problematic
- 3D different from 2D
- Multi-D is Key Enabler of explosion for (almost) all viable mechanisms
- Progenitor structure crucial (initial perturbations? -Density shelfs?)
- Whatever increases the steady-state post-bounce shock radius large is conducive to explosion
- Critical condition
- Input physics feedbacks can be severe - details?
- Neutrino Mechanism marginal/ambiguous in 2D; Need to go to 3D, but default 3D not exploding (Hanke et al. 2013)!?
- Rotation!!
- Is something missing?