Recent advances in core-collapse supernova theory

J. Nordhaus

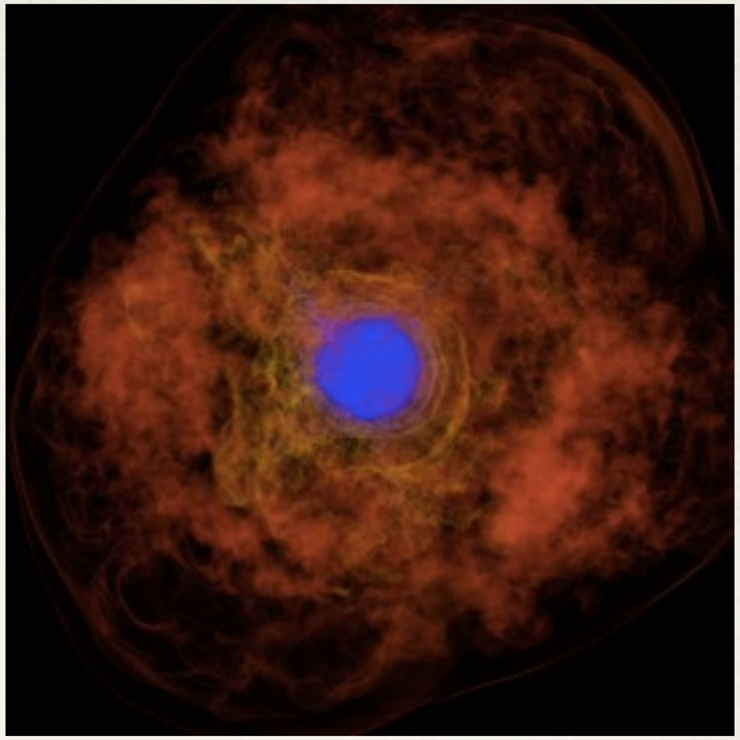
NSF Fellow - Rochester Institute of Technology

“Every passing hour brings the Solar System 43,000 miles closer to Globular Cluster M13 in Hercules - and still there are some misfits who insist there is no such thing as progress” - Ransom K. Fern

Kurt Vonnegut
The Sirens Of Titan

Contending Explosion Models:

- Neutrino Driven
- MHD Driven
- Acoustically Driven



The origin of neutron star kicks.

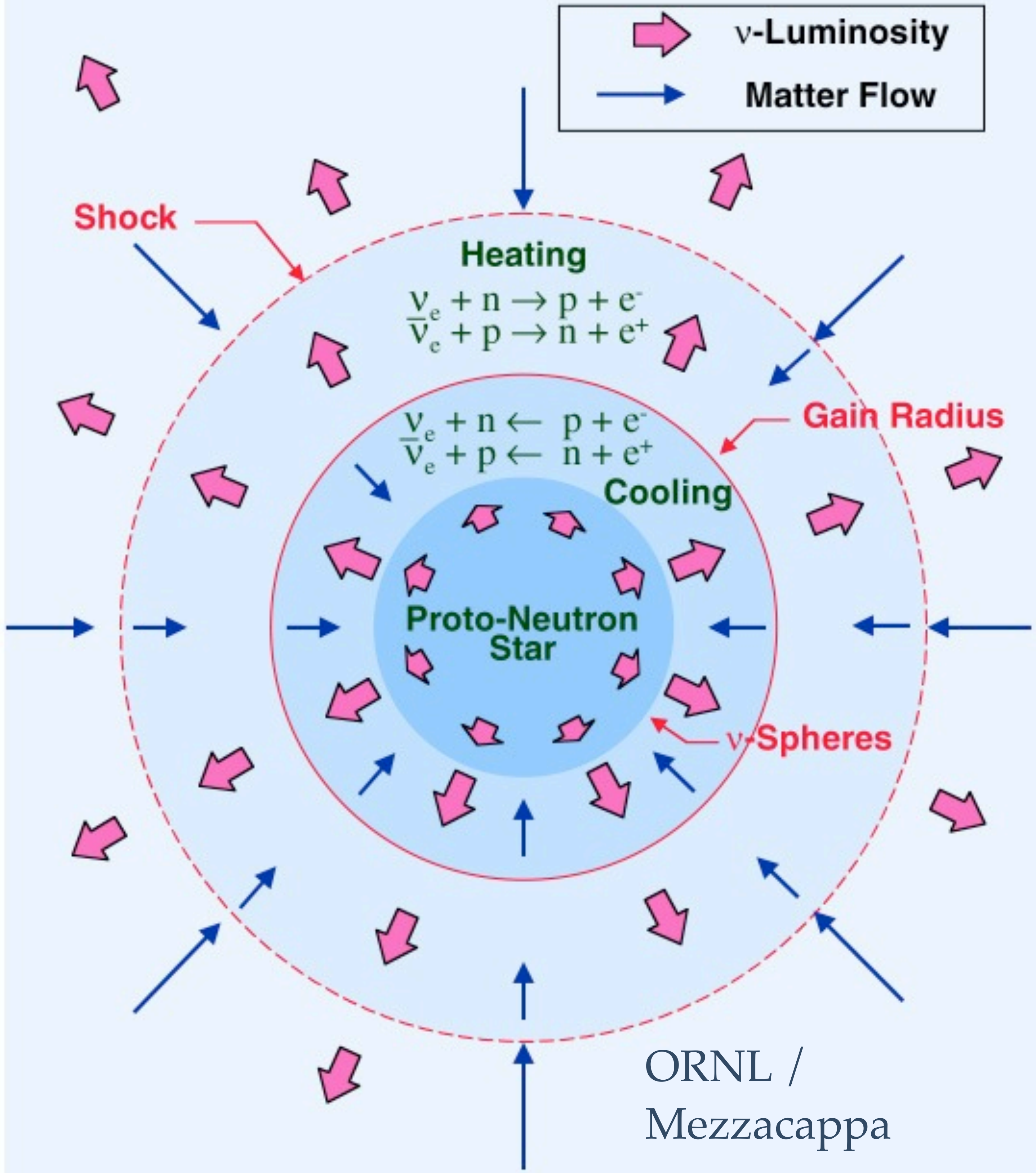
Multi-dimensional core collapse.

Pulsar spins from non-rotating progenitors.

Collaborators:

Princeton: E. Rantsiou, T. Brandt, A. Burrows
LBNL: A. Almgren
Caltech: C. Ott

Core collapse



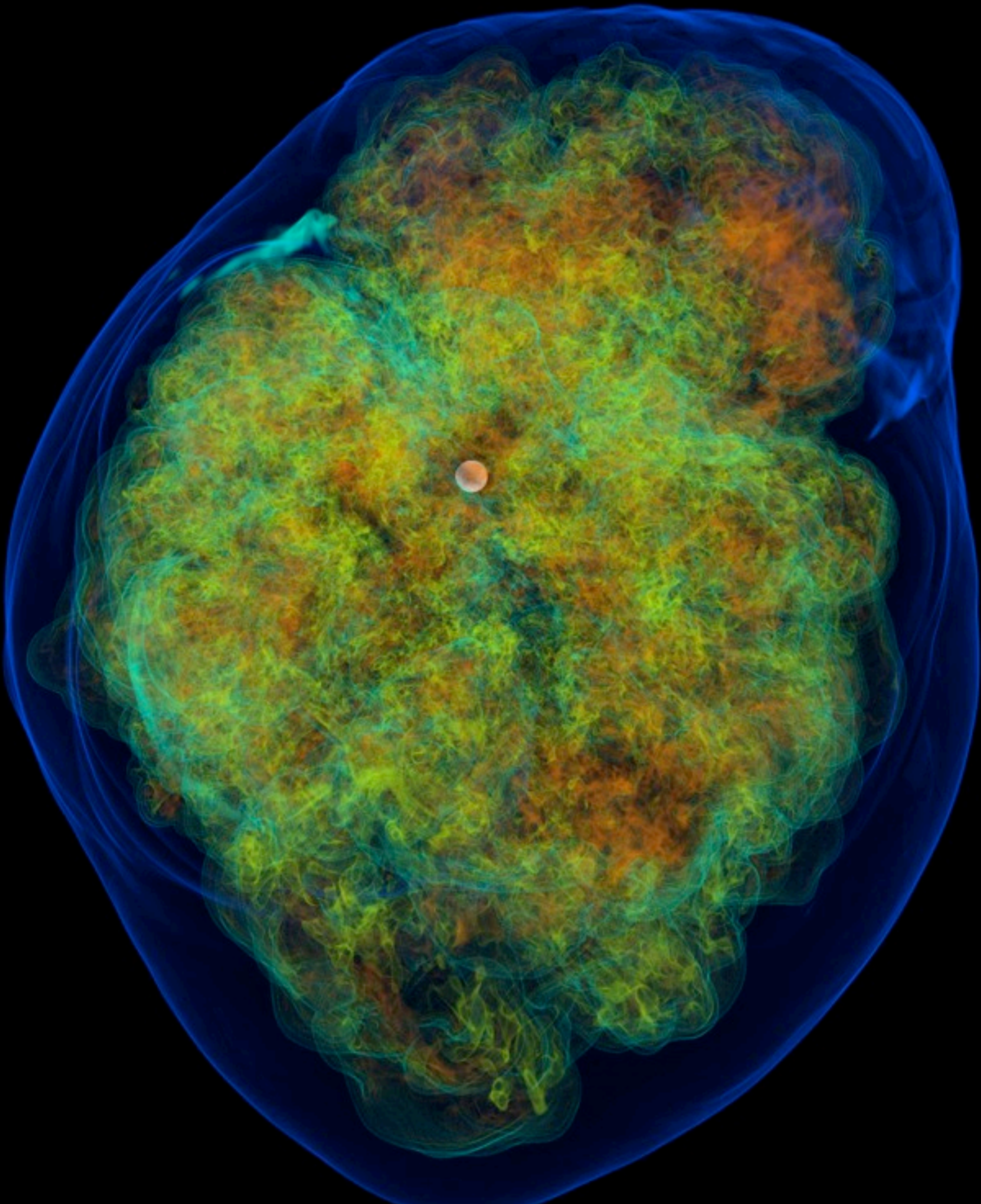
ORNL / Mezzacappa

Potentially Important Ingredients

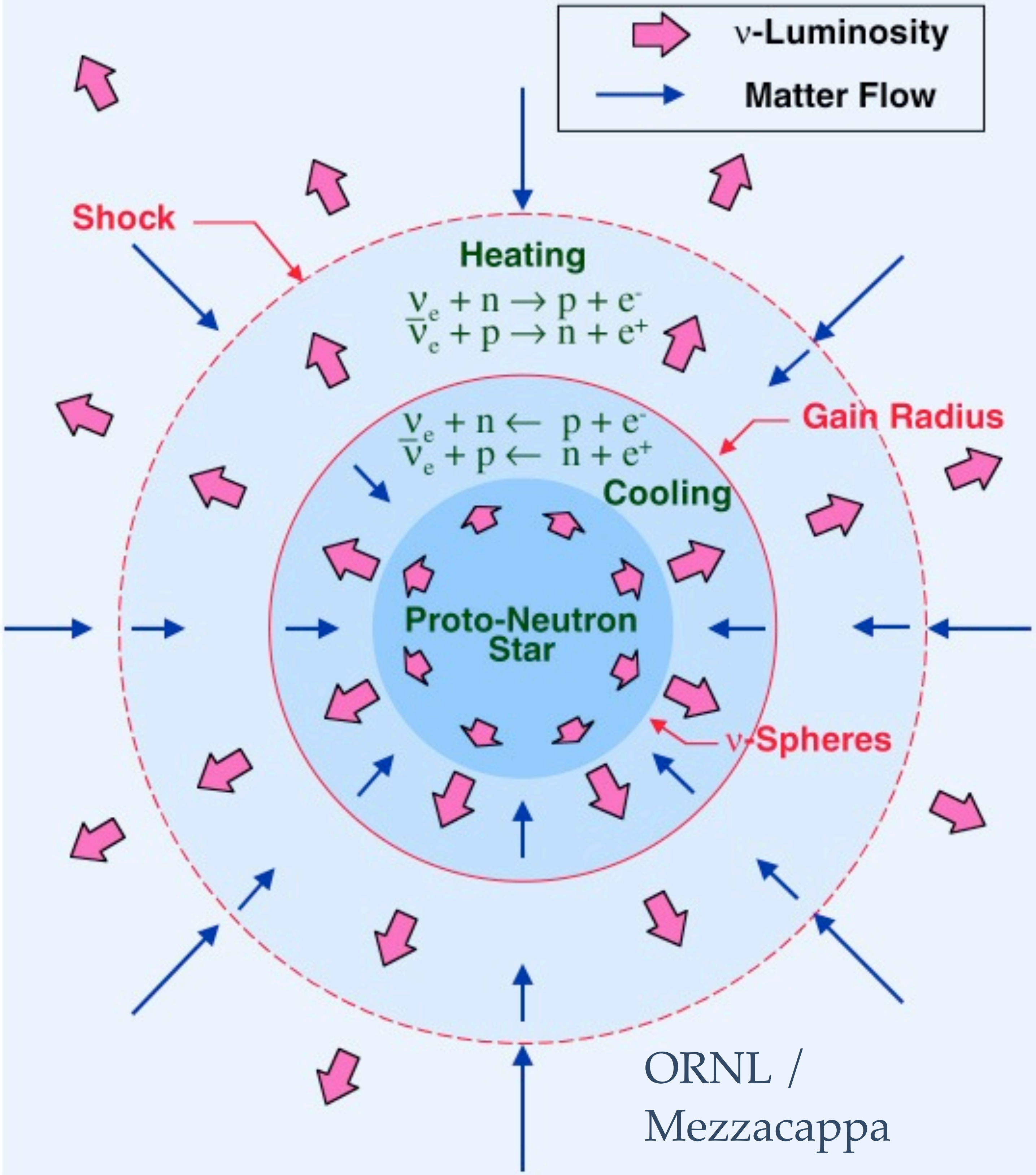
- Gravity
- Neutrino Heating
- Turbulence/Convection and Shock Instabilities
- Rotation
- Magnetic fields
- Nucleosynthesis
- General Relativity

Multi-dimensional effects important!

Goal: 3D models with sufficient realism that produce SN explosions



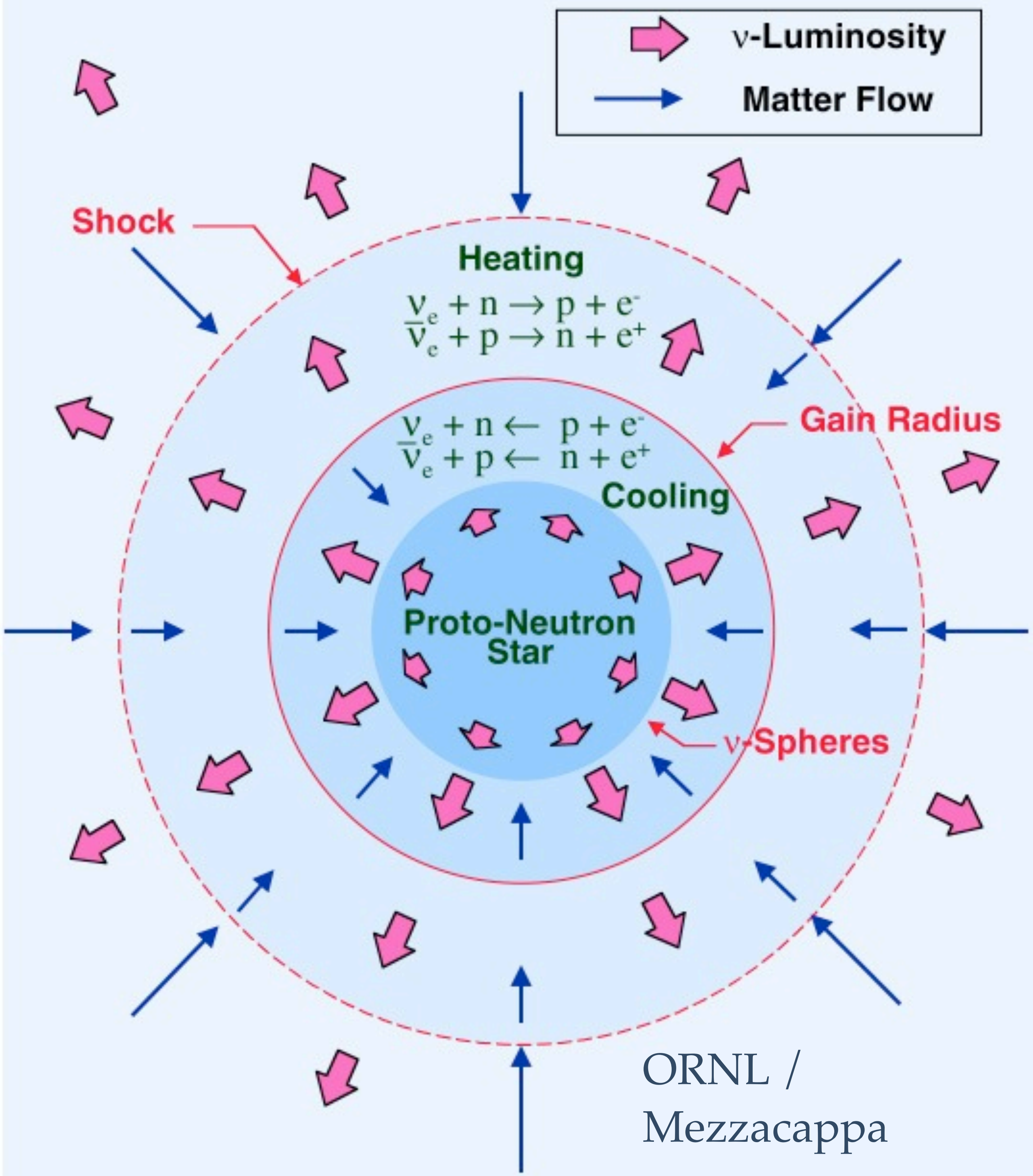
Core collapse



ORNL / Mezzacappa

Brief History

Core collapse

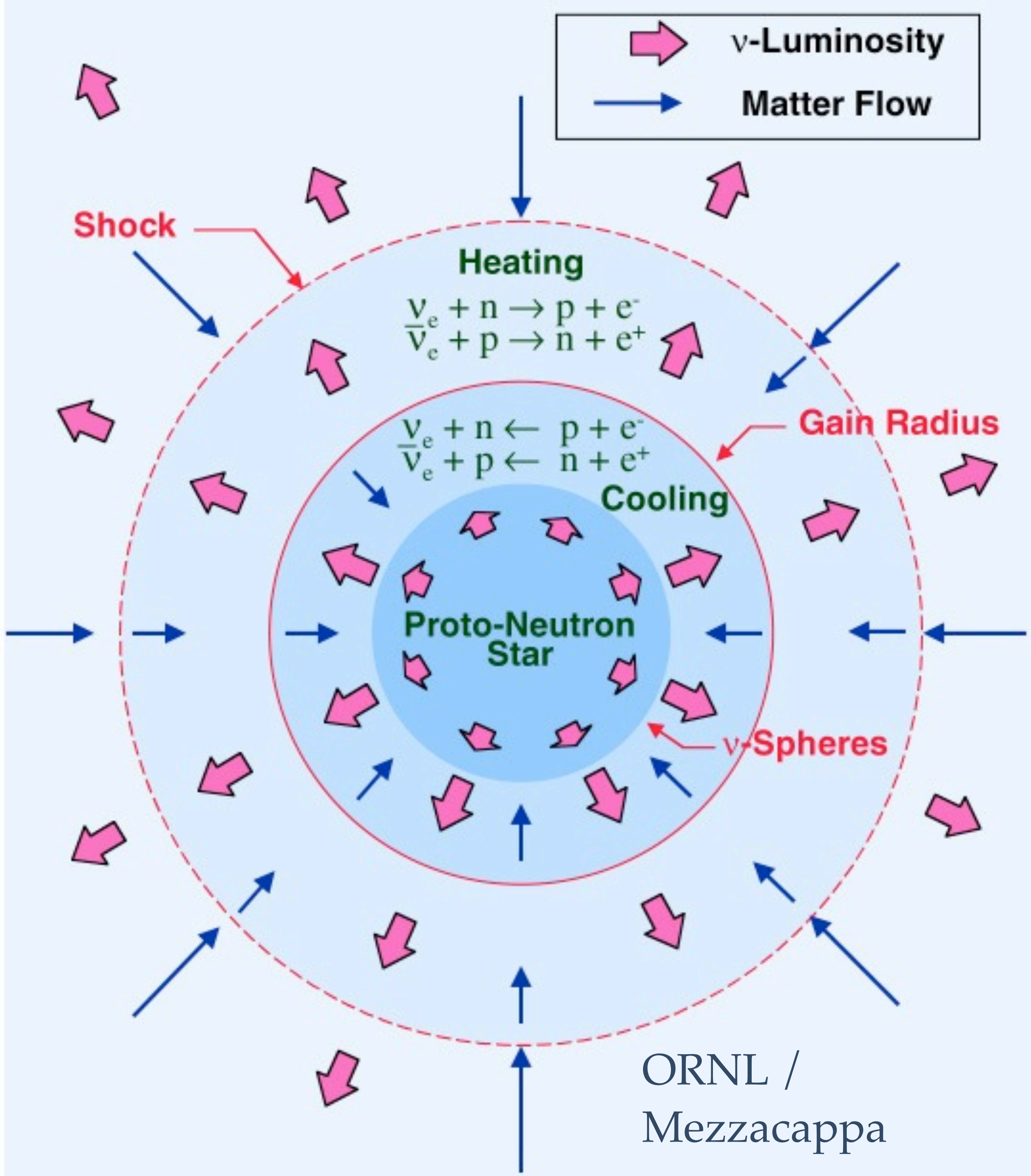


ORNL / Mezzacappa

Brief History

Direct Hydrodynamic Collapse
Colgate et al. 1961

Core collapse



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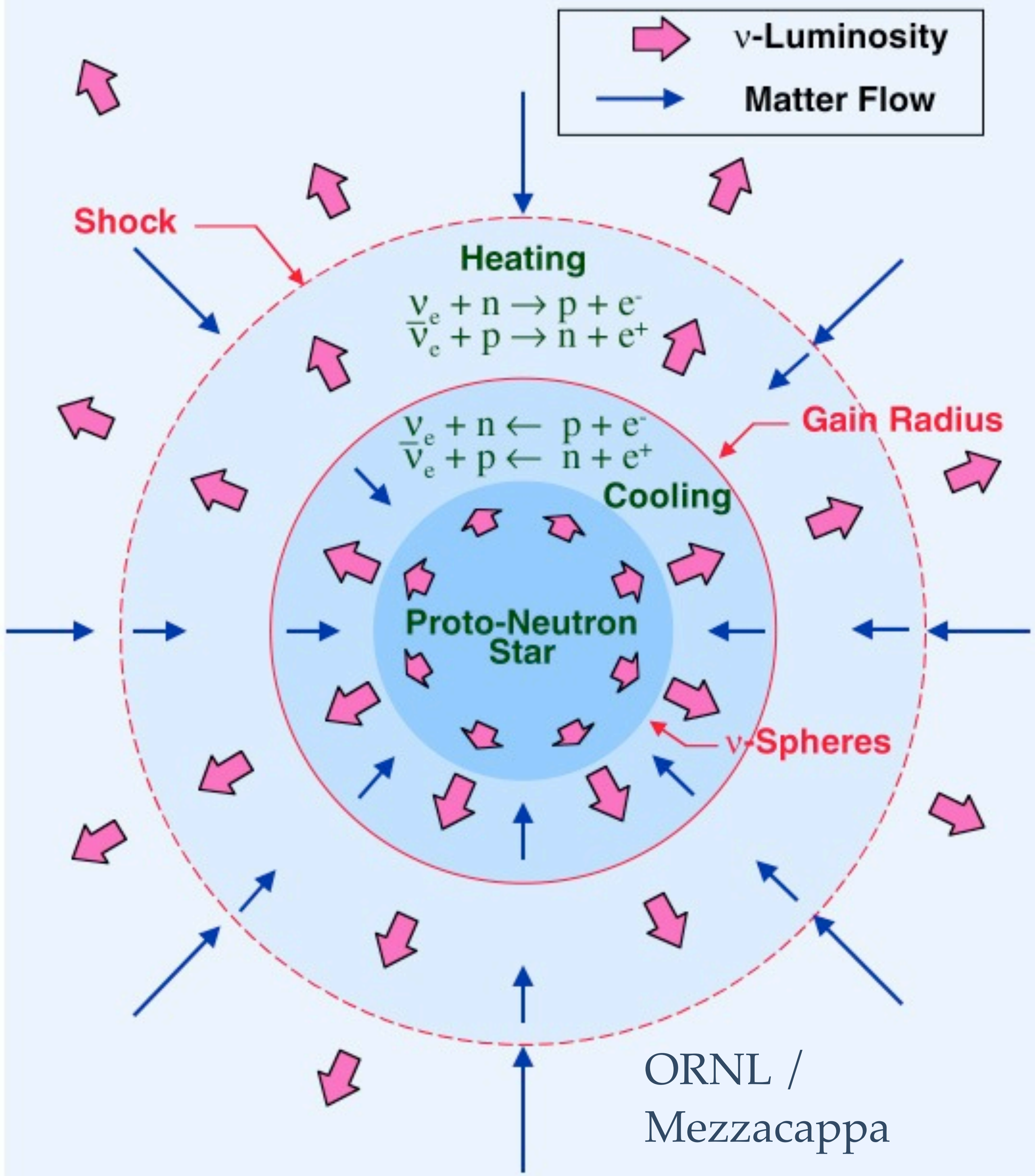
Direct Hydrodynamic Collapse
Colgate et al. 1961

Delayed Neutrino Mechanism
Colgate & White 1966; Arnett 1966; Wilson 1971

Core collapse



ORNL / Mezzacappa

Brief History

Direct Hydrodynamic Collapse
Colgate et al. 1961

Delayed Neutrino Mechanism
Colgate & White 1966; Arnett 1966; Wilson 1971

Current Status of Modern Simulations (from ~1995 - 2010):

Spherically Symmetric: Do not explode

Axisymmetric: Marginal explosions for a few cases

Three Dimensional: ???

Neutrino-driven explosion

Net neutrino deposition
in ``gain region"

Entropy →

2D axisymmetric
calculation

Low-mass progenitor,
low binding energy

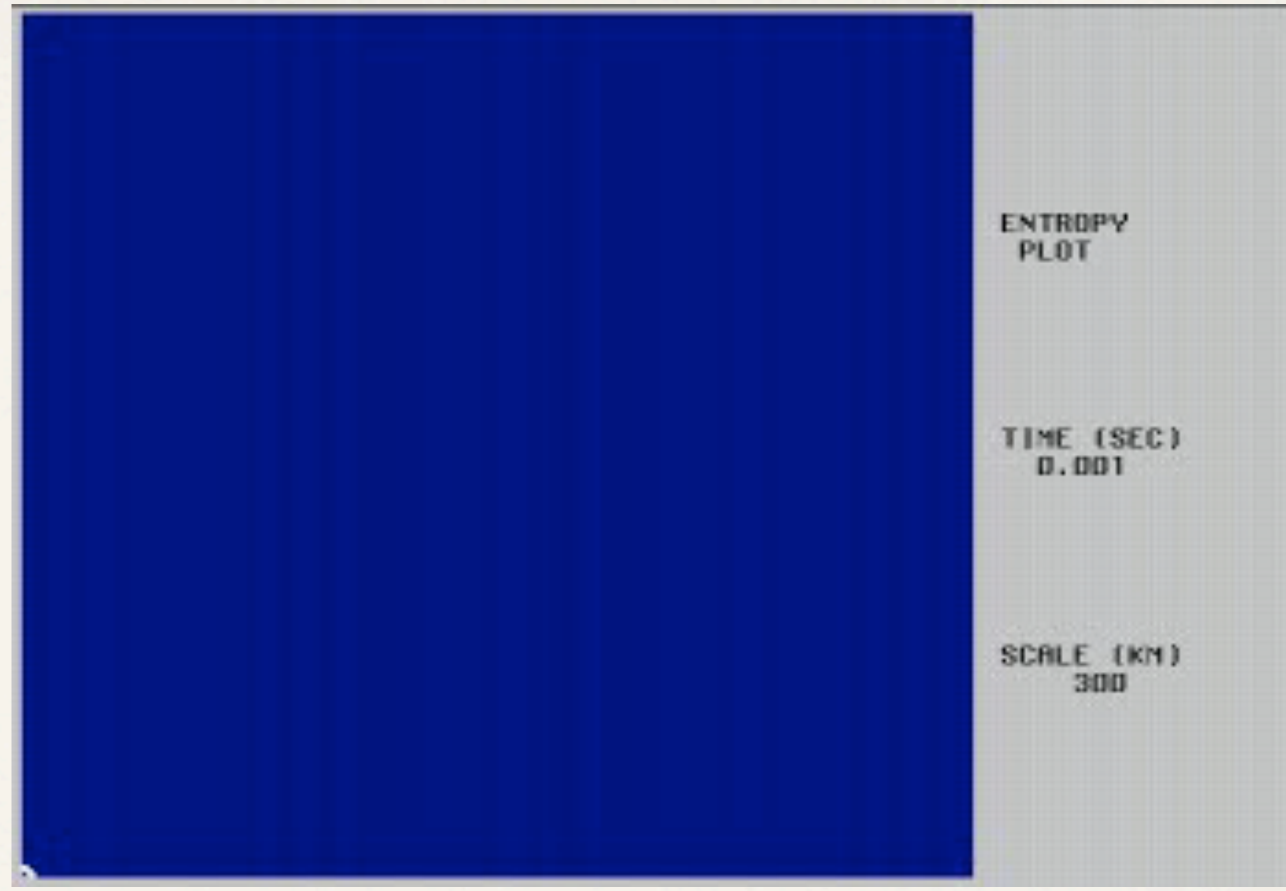
Electron fraction →

Neutrino-driven wind

Neutrino-driven explosion

Net neutrino deposition in ``gain region”

Entropy



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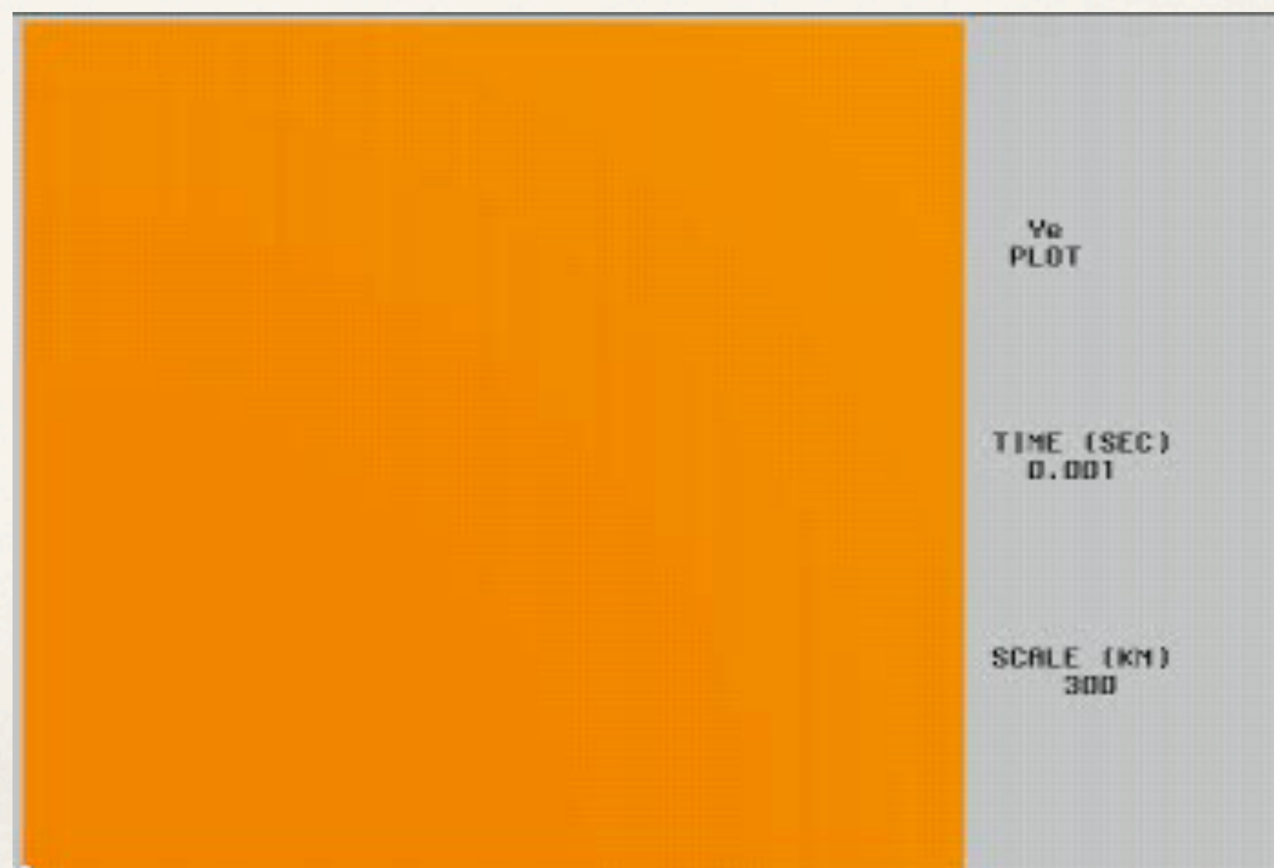


Neutrino-driven wind

MHD-driven explosion

Bipolar explosions

Requires rapid rotation

Initial core period < 2 s

← Linear winding only

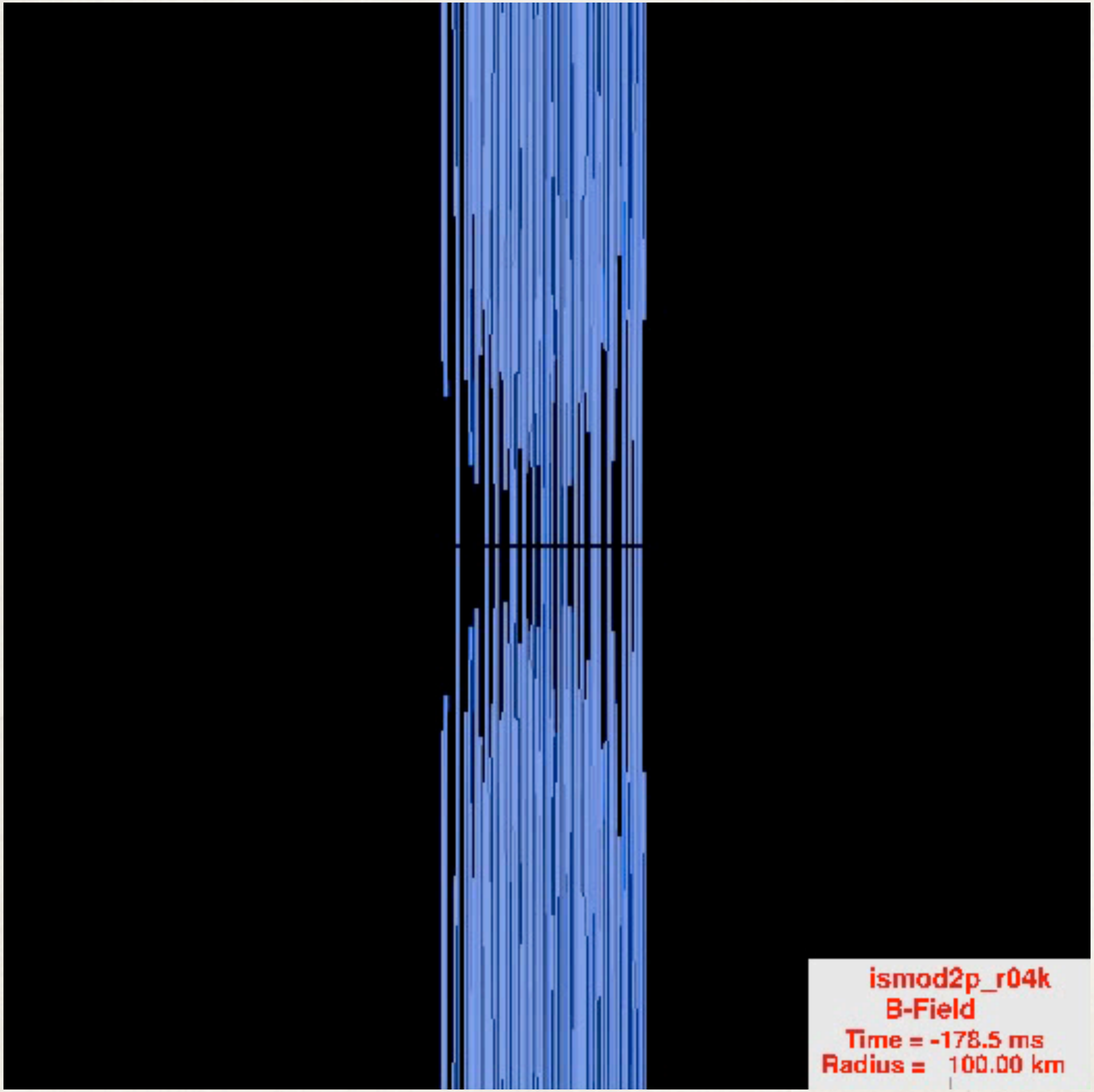
Burrows et al. 2007

Exponential B-field growth via dynamos/ MRI

Akiyama+ 2003

Blackman, Nordhaus & Thomas 2006

MHD-driven explosion



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Acoustically-driven explosion

Advective / acoustic

self-excited oscillator

primary core $l = 1$,
g-mode

late time explosions:
> 1 second

---

parametric
instability saturates
primary mode
power at $\sim 10^{48}$erg

Weinberg & Quataert 2008

Burrows et al. 2006

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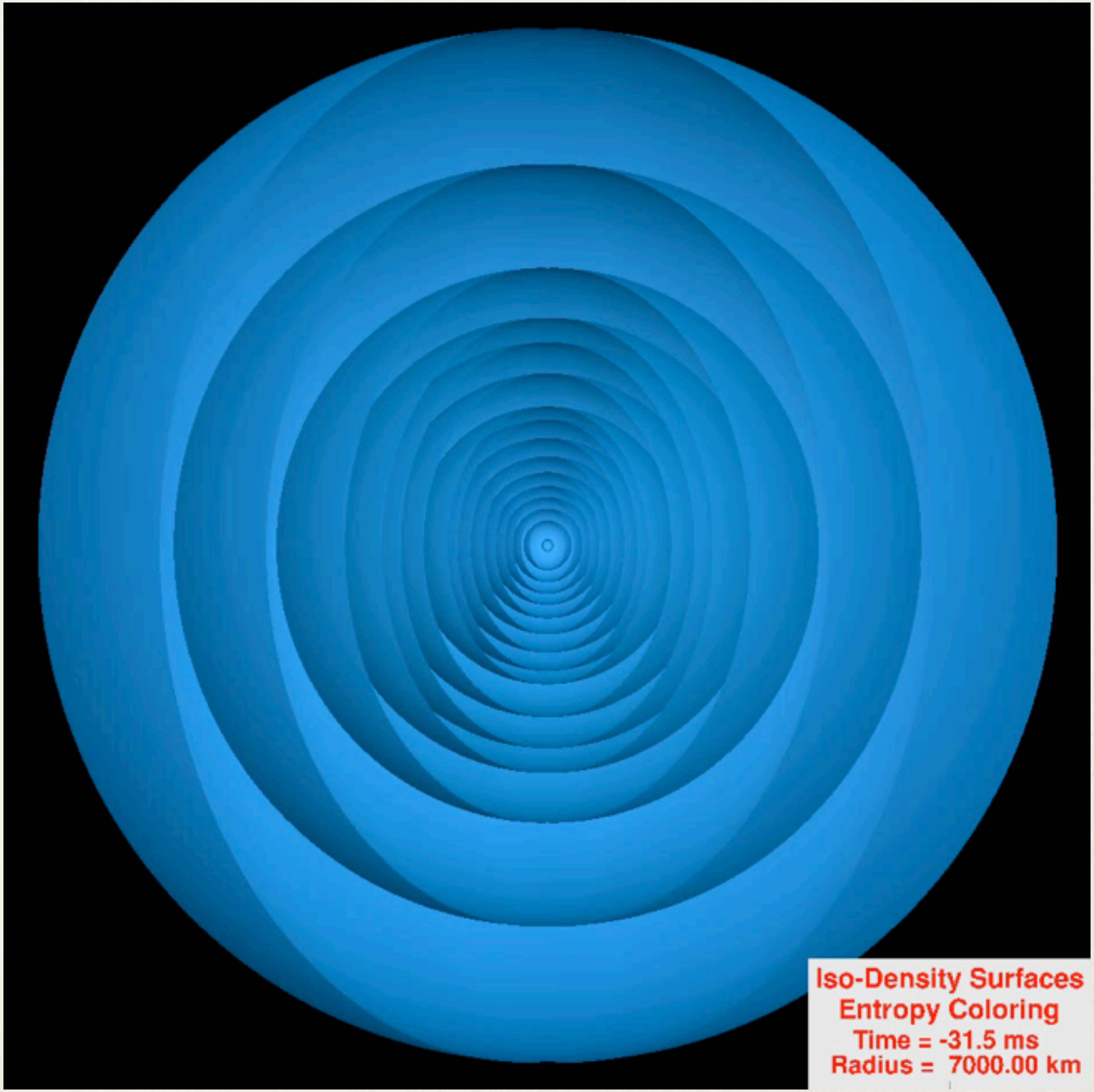
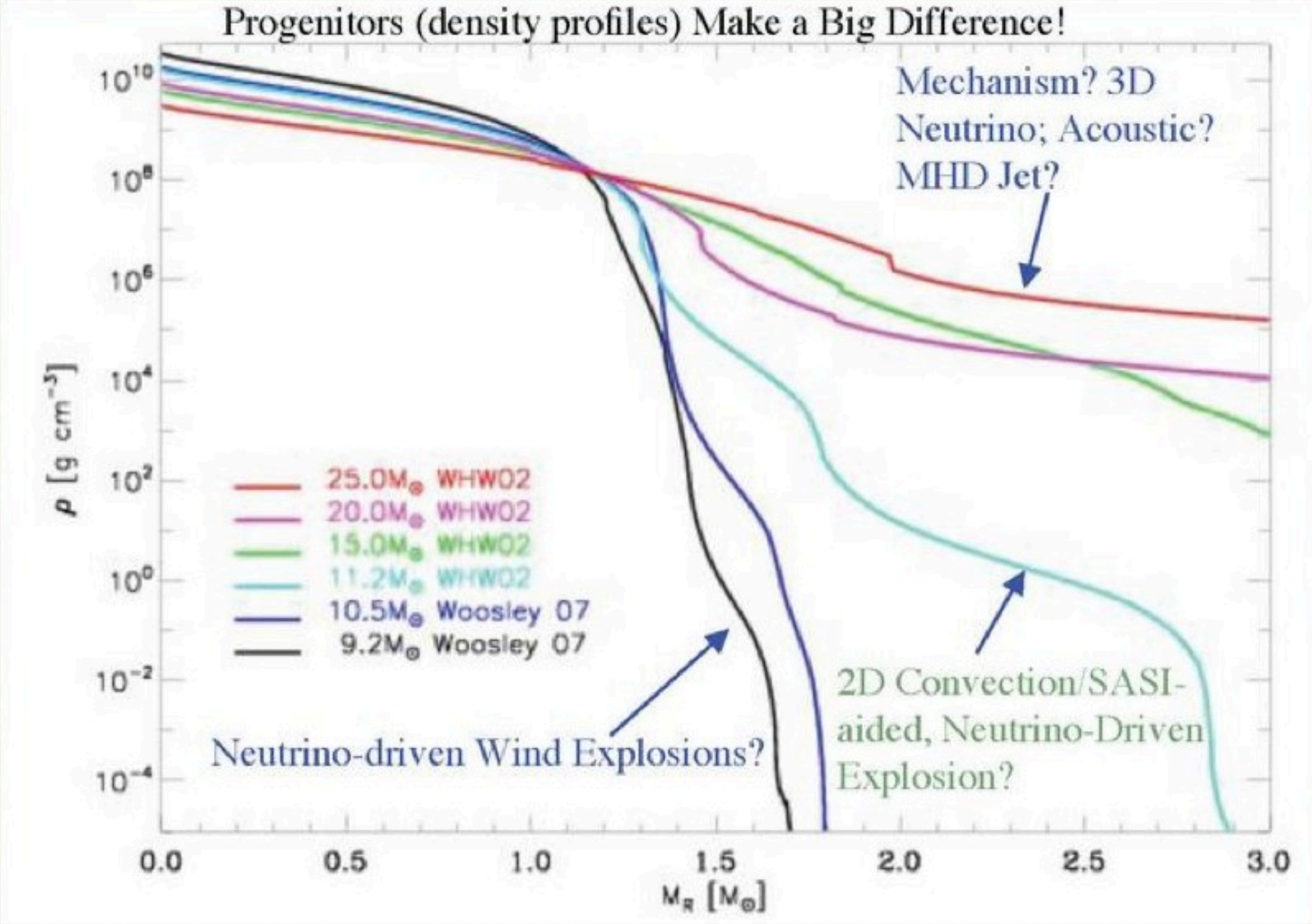


Burrows et al. 2006

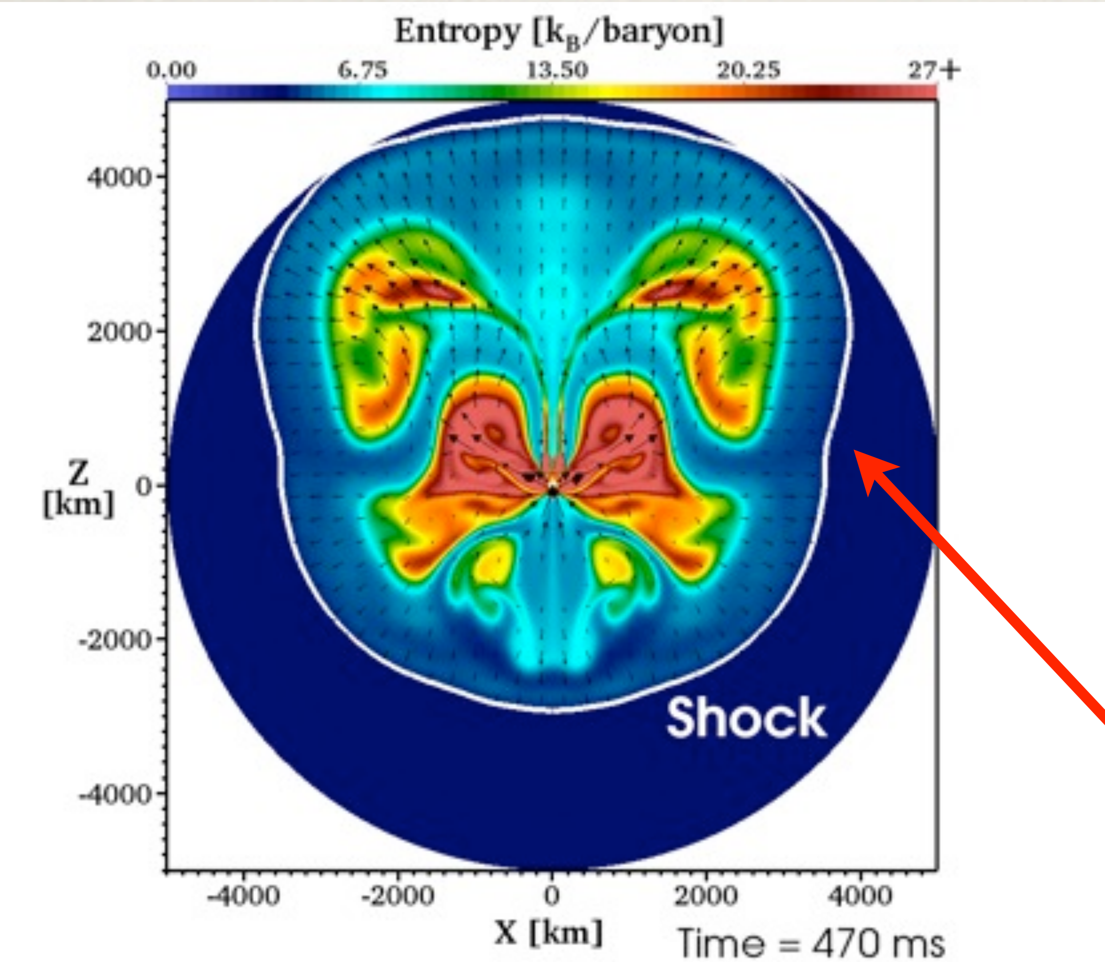


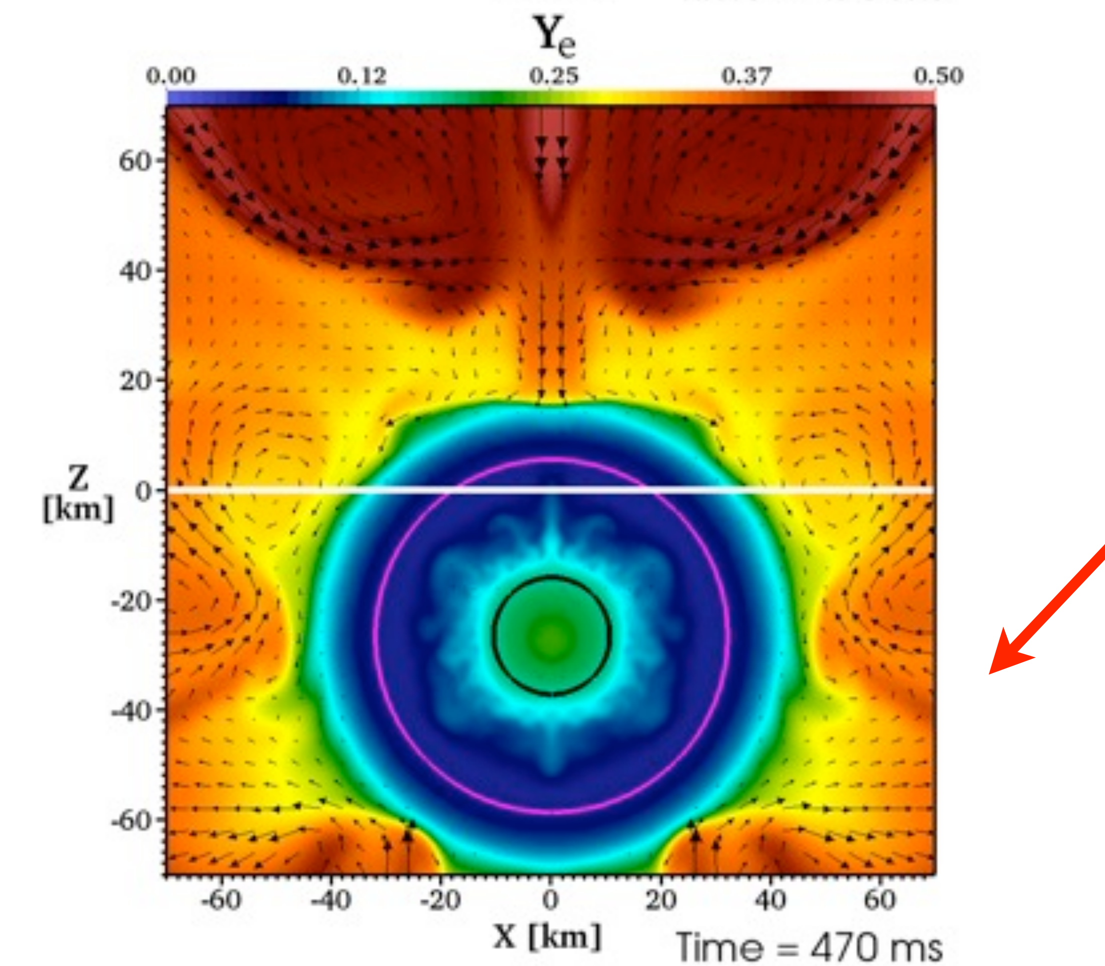
Progenitors (density profiles) Make a Big Difference!
Mechanism? 3D Neutrino; Acoustic? MHD Jet?
25.0M⊙ WHW02
20.0M⊙ WHW02
15.0M⊙ WHW02
11.2M⊙ WHW02
10.5M⊙ Woosley 07
9.2M⊙ Woosley 07
Neutrino-driven Wind Explosions?
2D Convection/SASI-aided, Neutrino-Driven Explosion?
ρ [g cm⁻³]
M_R [M⊙]

Recoil from Core Collapse

The Hydrodynamic Mechanism of Pulsar Kicks

Neutron Star Kicks I





Pulsar birth velocities typically 300 - 400 $\mathrm{km\ s^{-1}}$

VULCAN/2D - Rad-hydro simulation

Nordhaus et al. 2010a

Explosion primarily in +Z direction...

...leads to NS recoil in -Z direction

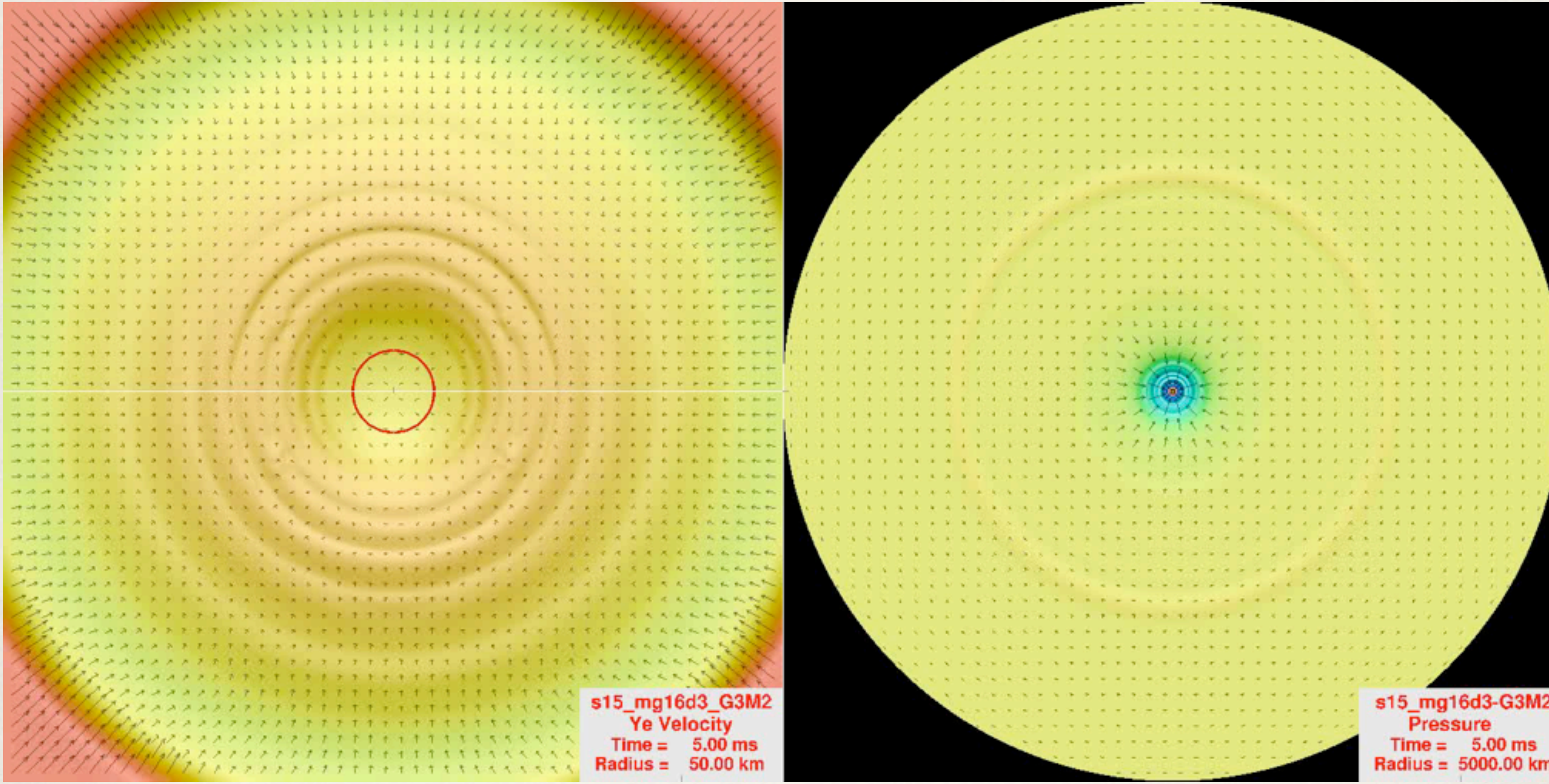
see also Scheck et al. 2006;

Wongwathanarat et al. 2010

Neutron Star Kicks II

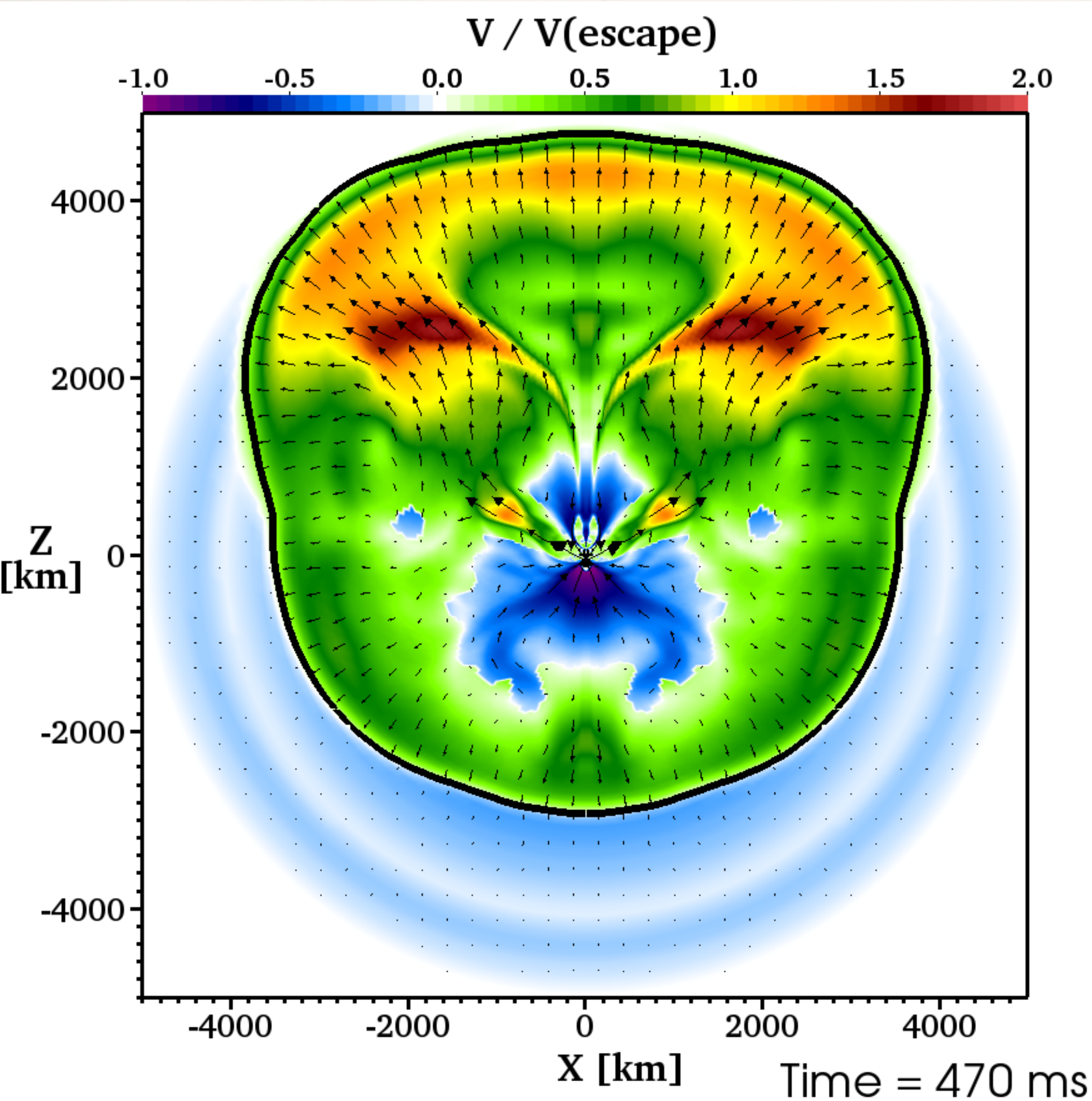
Nordhaus et al. 2010a

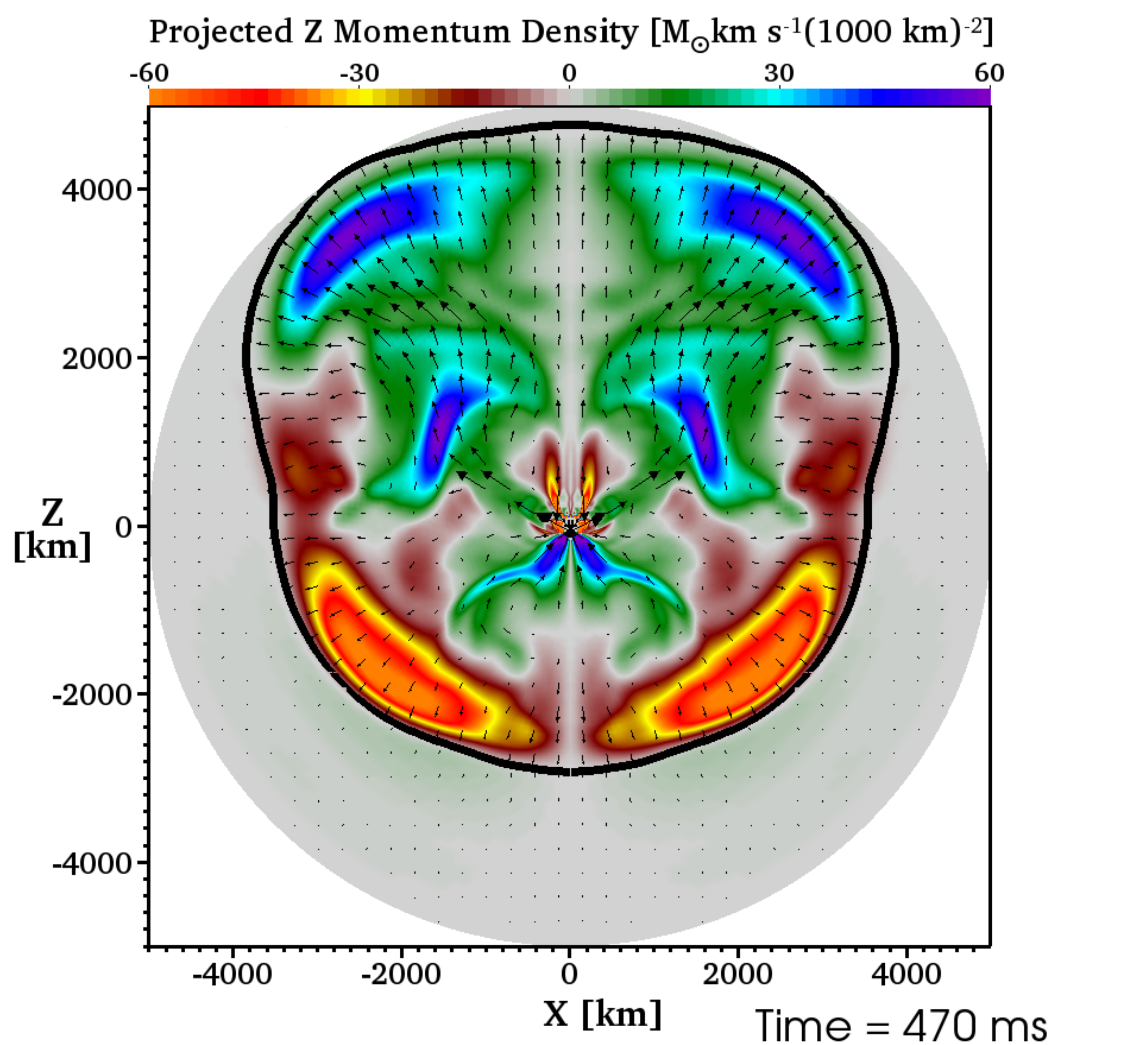
Neutron Star Kicks II



Nordhaus et al. 2010a

At the end of the simulation:





Location of shock is in black

Nordhaus et al. 2010a

Hydrodynamic Mechanism of Pulsar Kicks

Anisotropic neutrino emission (neutrino "rockets") not important for kicks!

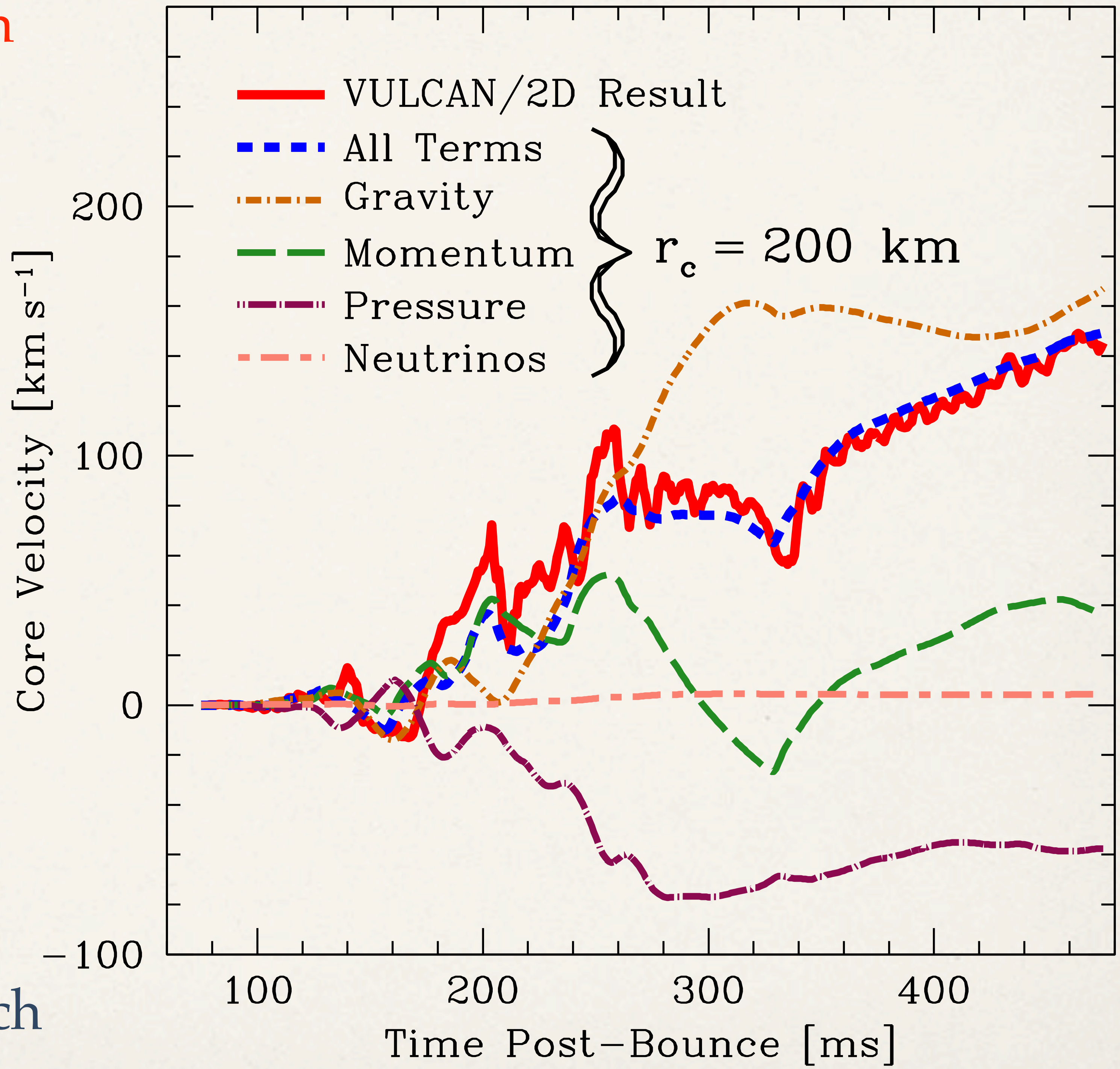
Gravitational tugboat effect is important.

At end of simulation:

$$v_{\rm NS} \sim 150 \;\; {\rm km\, s}^{-1}$$

$$a_{\rm NS} \sim 350 \;\; {\rm km \;\; s}^{-2}$$

Requires ~2-3 seconds to reach ballistic regime!



Nordhaus et al. 2010a

Radiation field is smooth...
... matter field is not.

Radiation field is smooth...
... matter field is not.

Hydrodynamic Origin of Pulsar Kicks

CASTRO - with neutrino heating/cooling scheme

Hydrodynamic Origin of Pulsar Kicks

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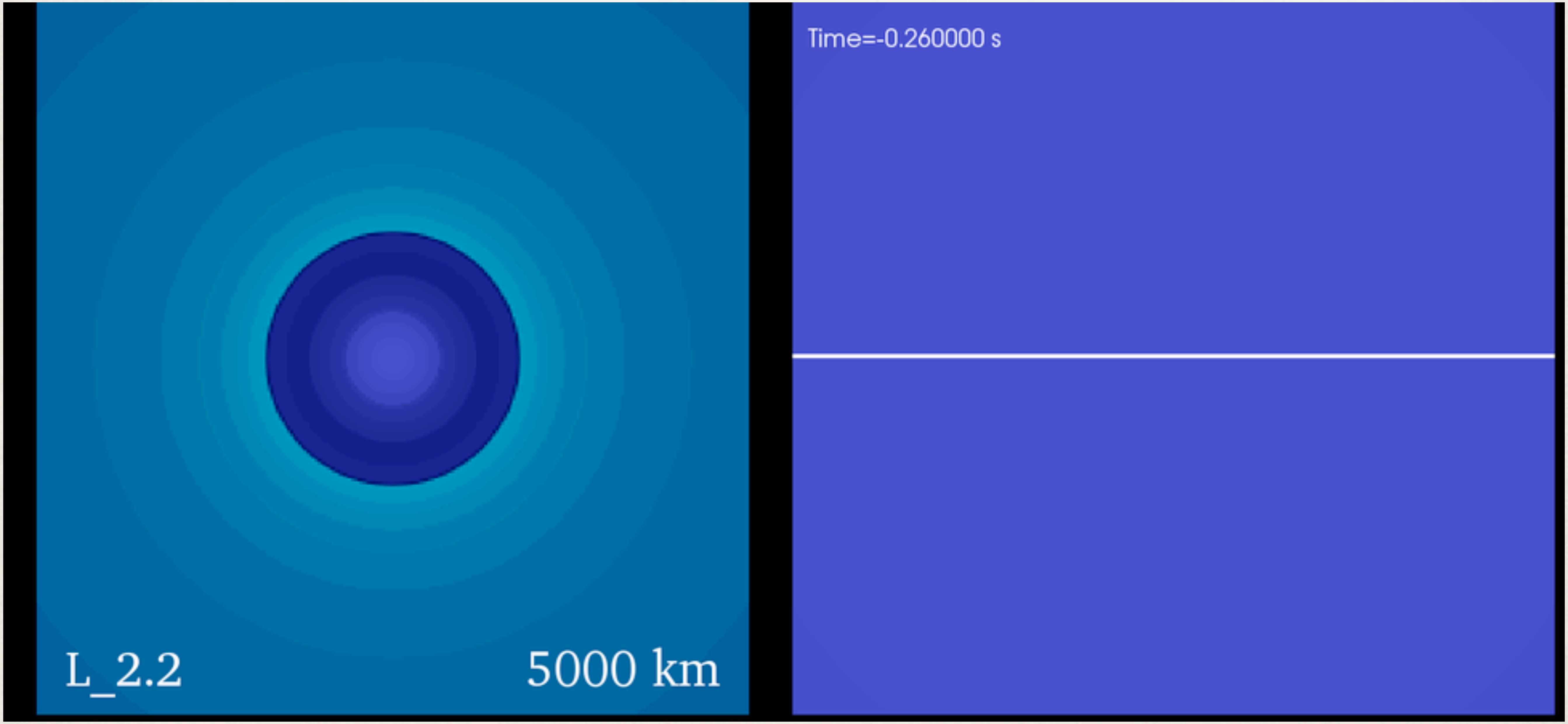
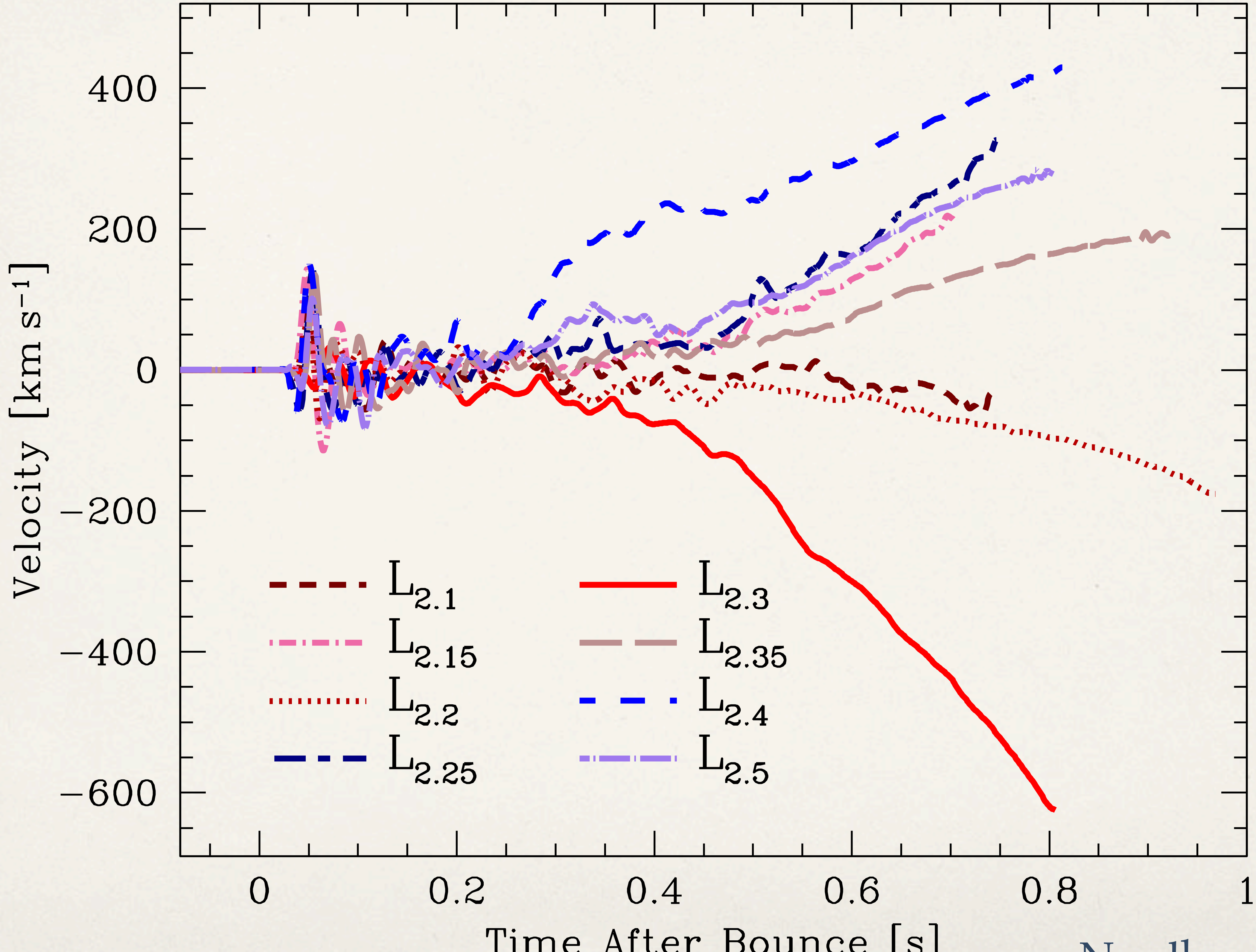
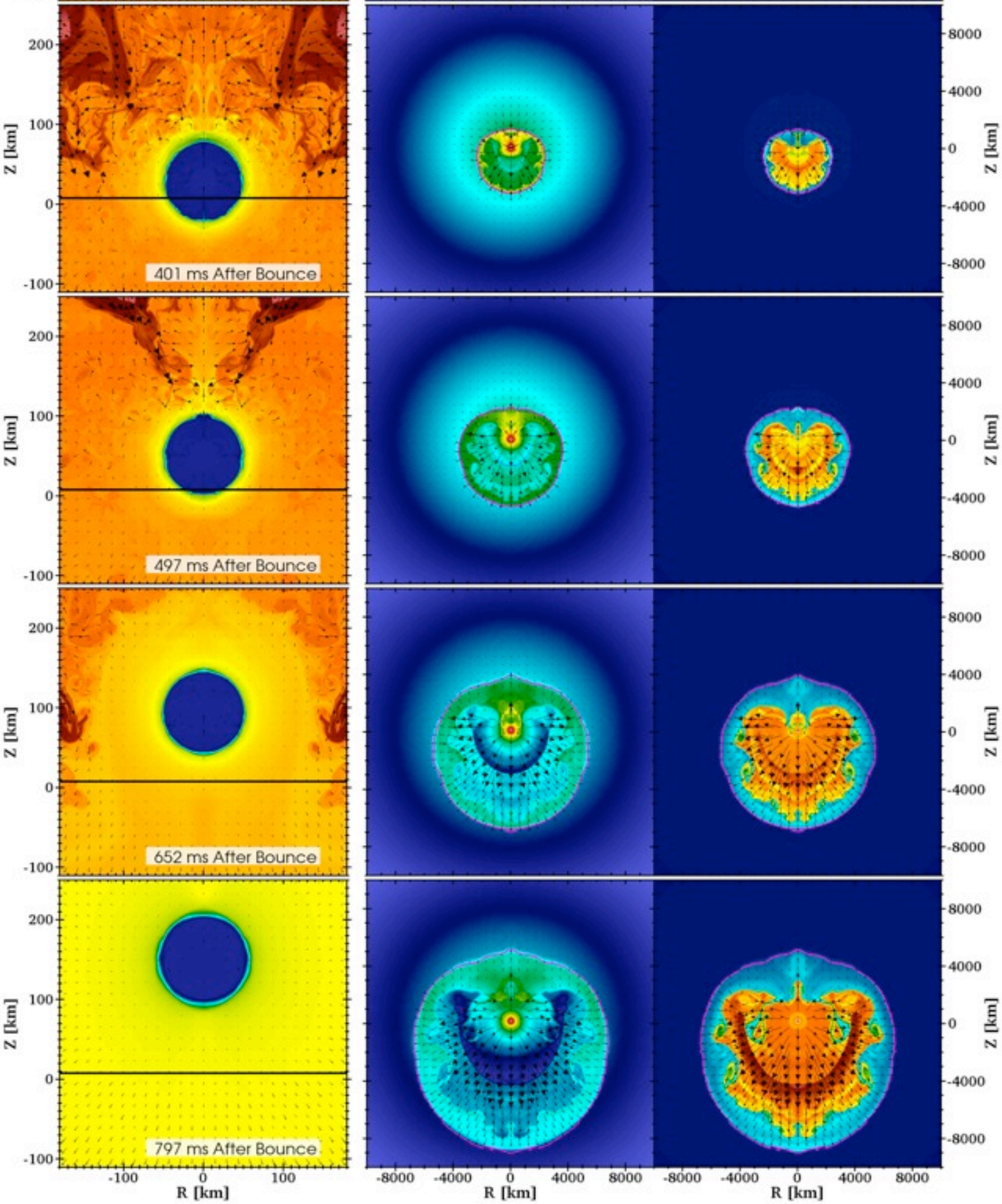


Hydrodynamic Origin of Pulsar Kicks



Nordhaus et al. 2012



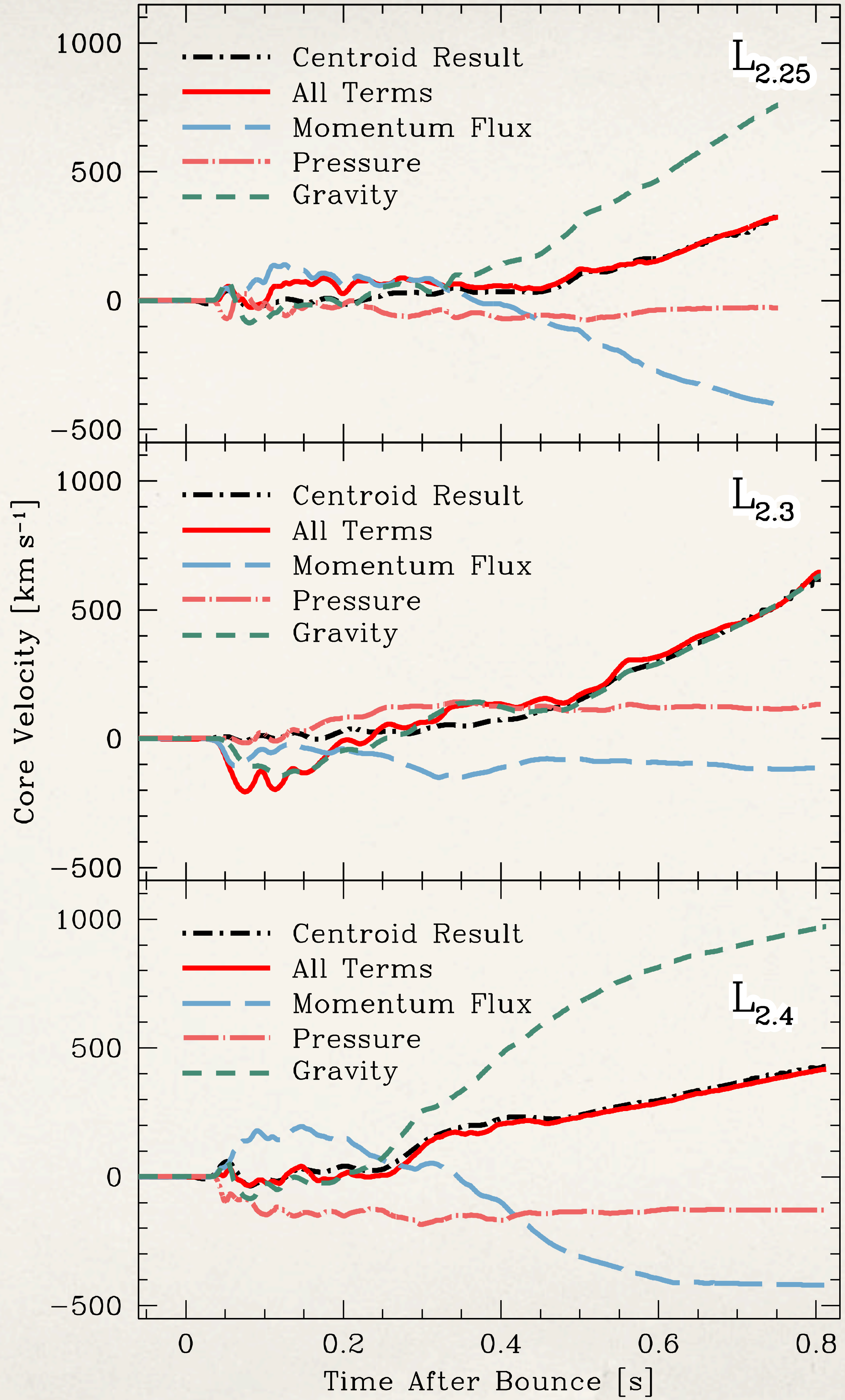
Pulsar Kicks

Gravitational effects are important.

With AMR can follow evolution farther in time.

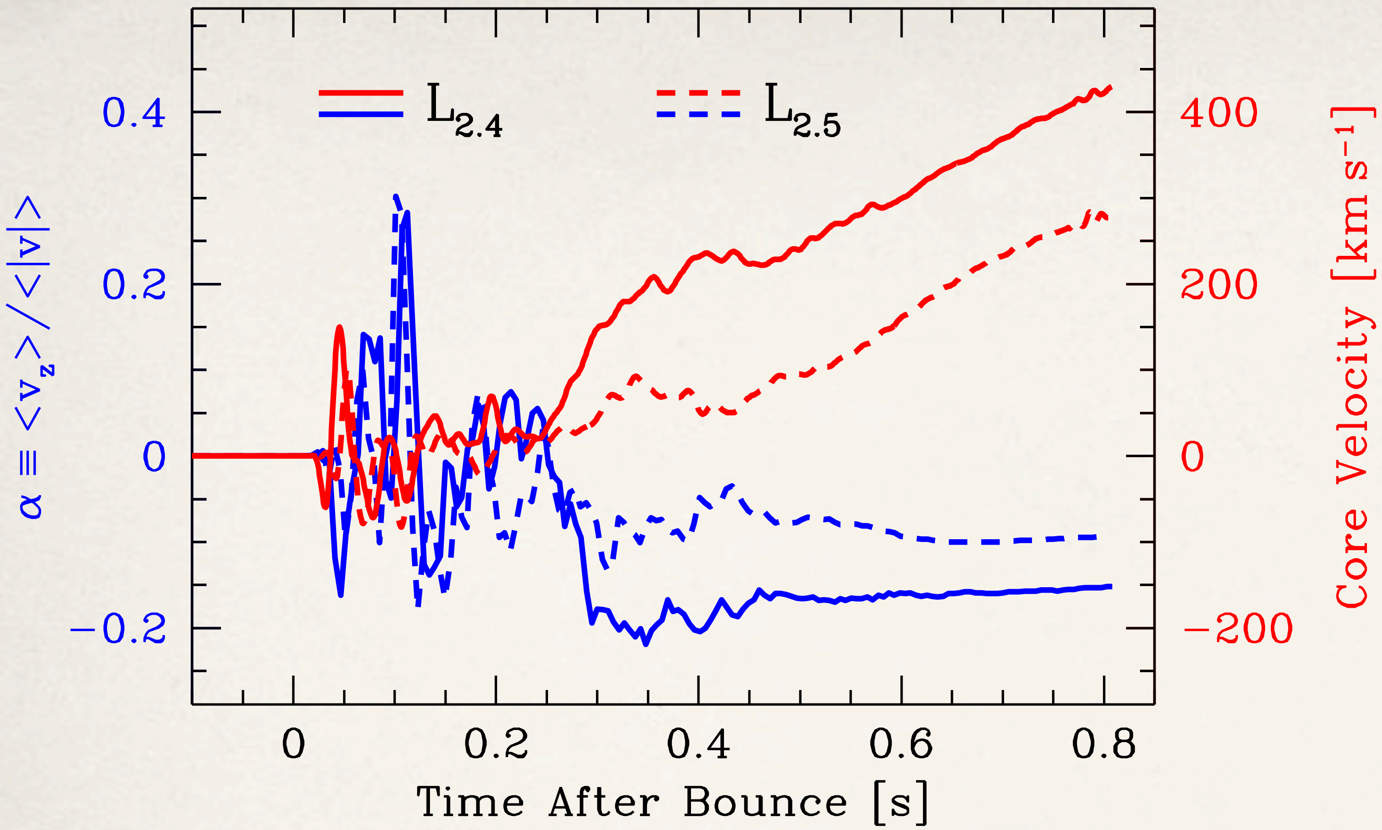
NS decoupled from surroundings

Nordhaus et al. 2012



At late times, gravity of the slow-moving ejecta dominates.

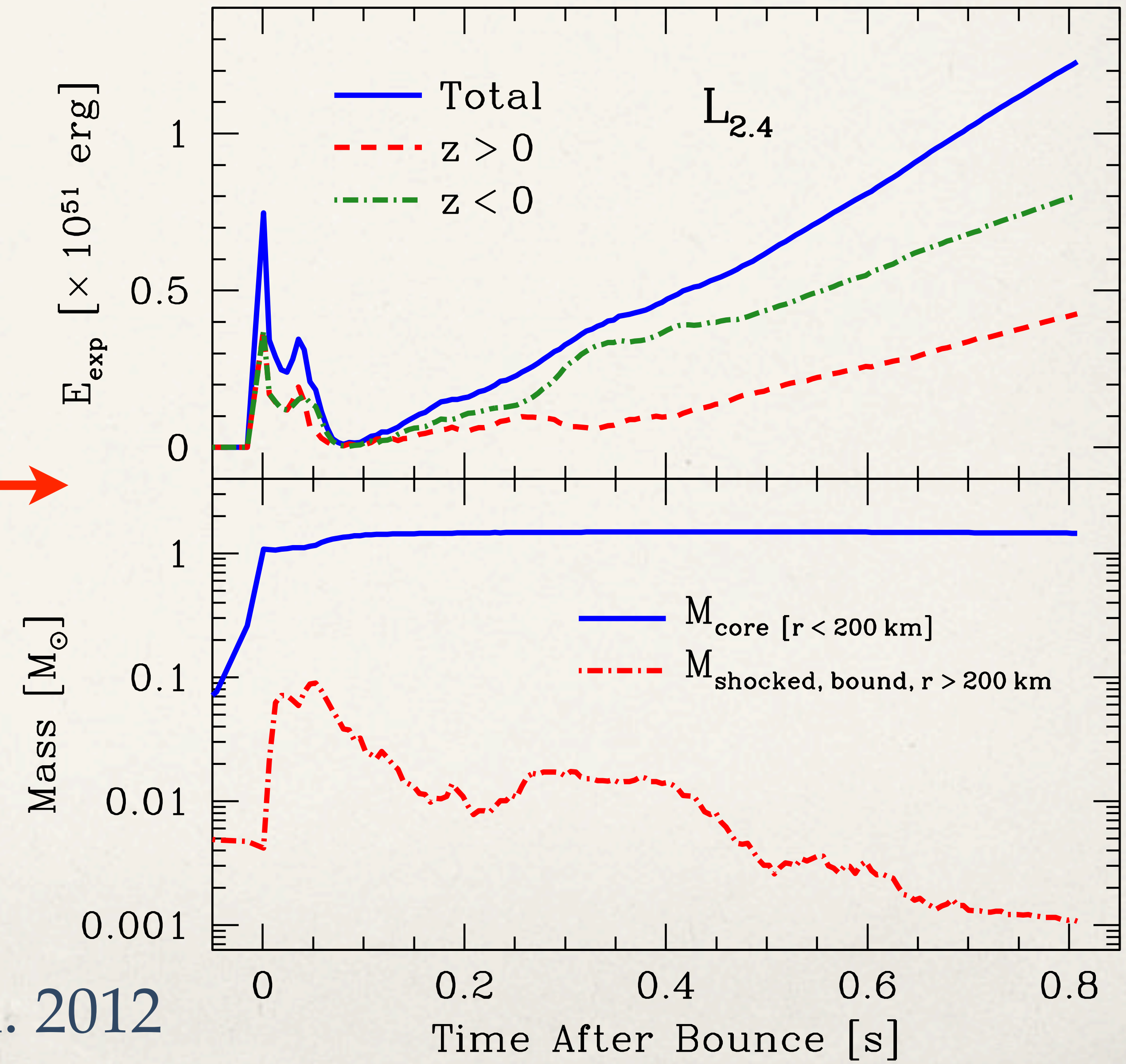
Nordhaus et al. 2012



The larger the degree of asymmetry, the larger the kick

Simulations achieve canonical supernova explosion energies.

Very little bound mass at end of the simulation.



Nordhaus et al. 2012

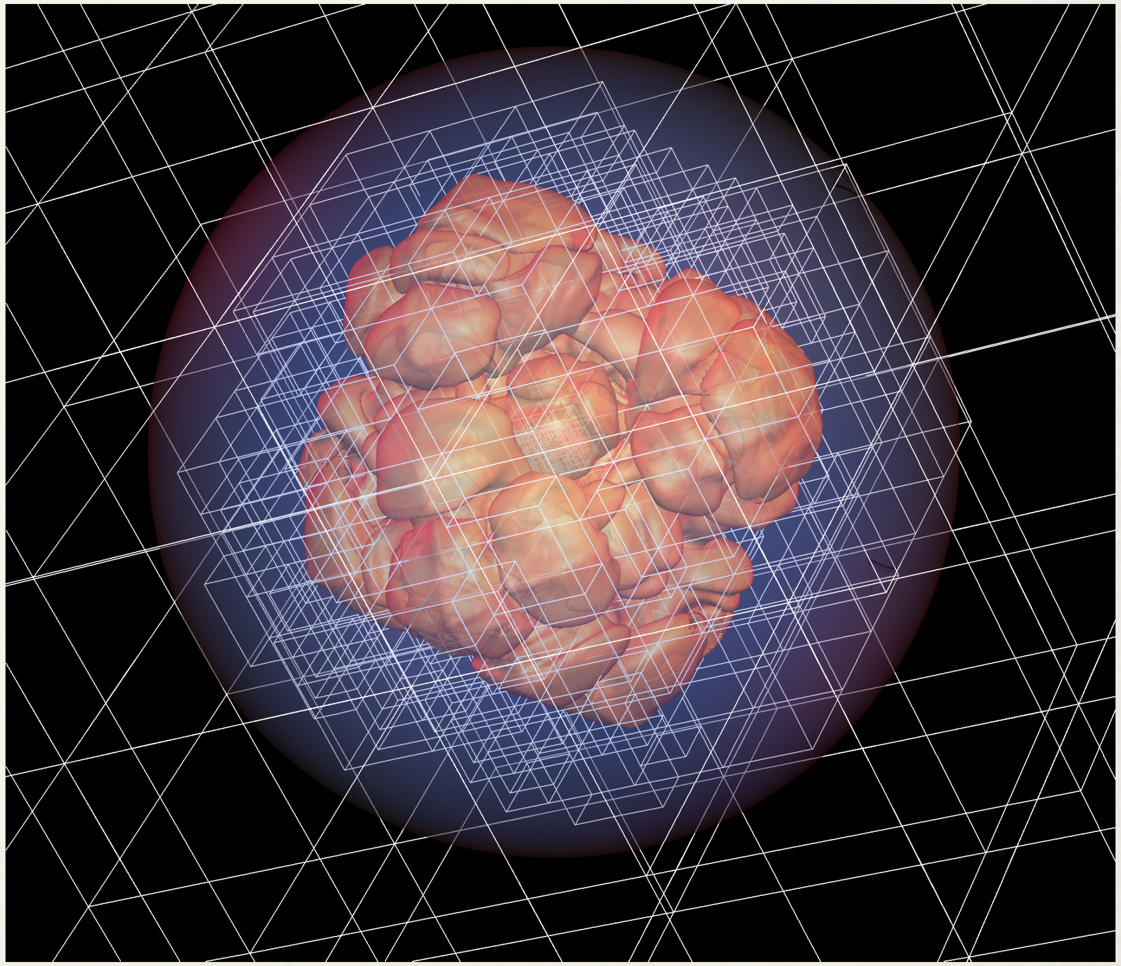
3D Core Collapse

Very different from 1D and 2D core collapse!

CASTRO: Compressible Astrophysics

- New multi-D radiation-hydrodynamics code
- Adaptive mesh refinement (AMR) with sub-cycling in time
- Advection: 2nd order, unsplit piecewise-linear or PPM
- Radiation: multi-group flux limited diffusion
- Gravity: Monopole or multi-grid Poisson solve
- Scales to over 200,000 cores!

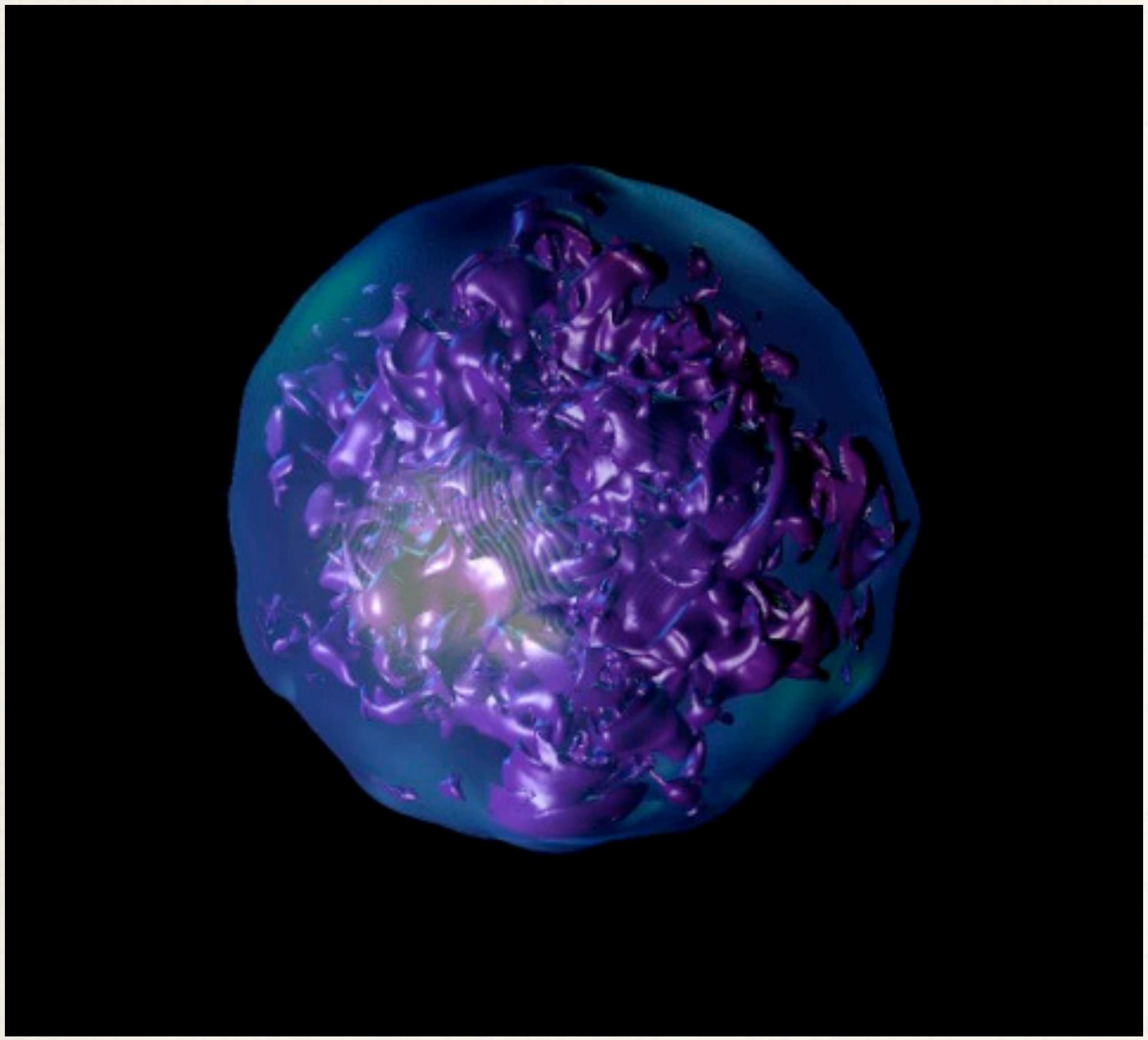
Team: Ann Almgren (LBL)
John Bell (LBL)
Louis Howell (LLNL)
Jason Nordhaus (Princeton)
Adam Burrows (Princeton)

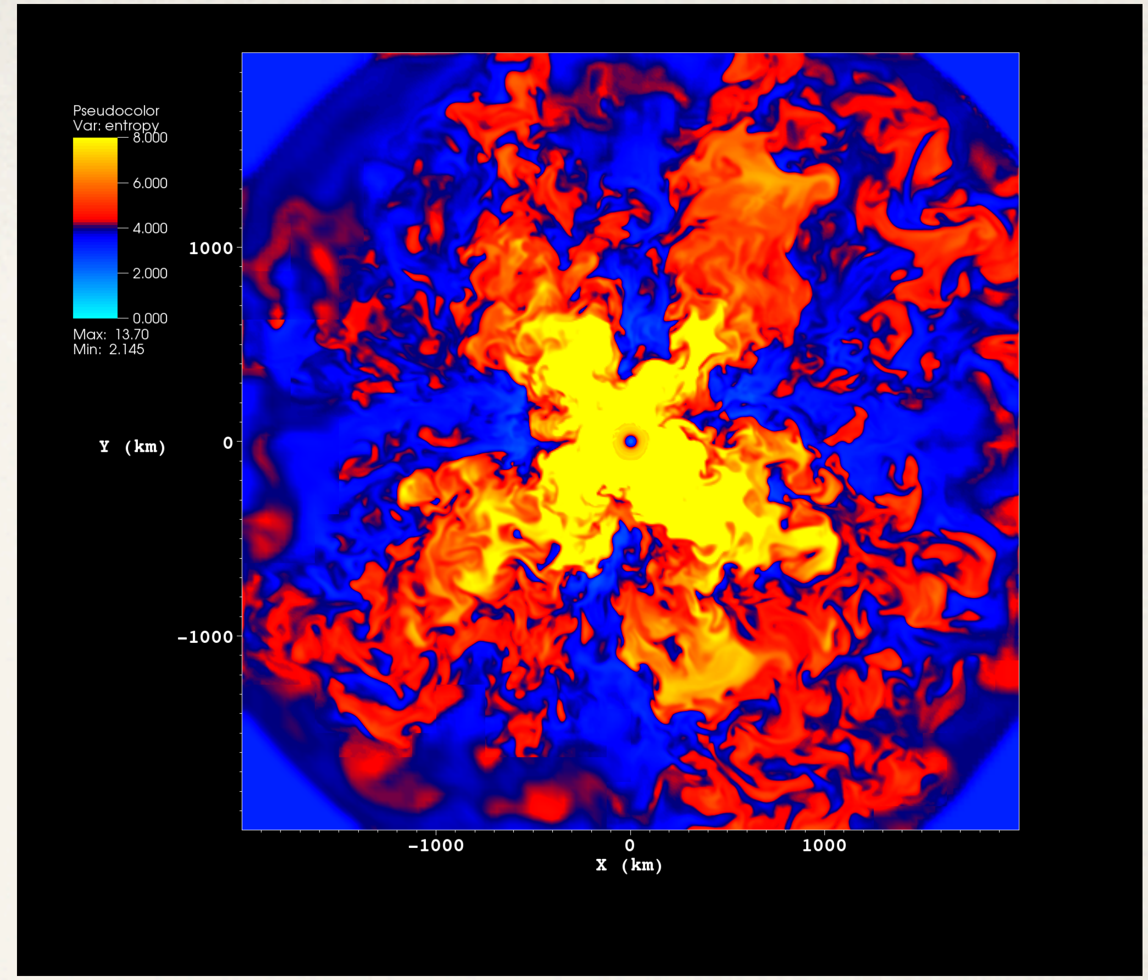


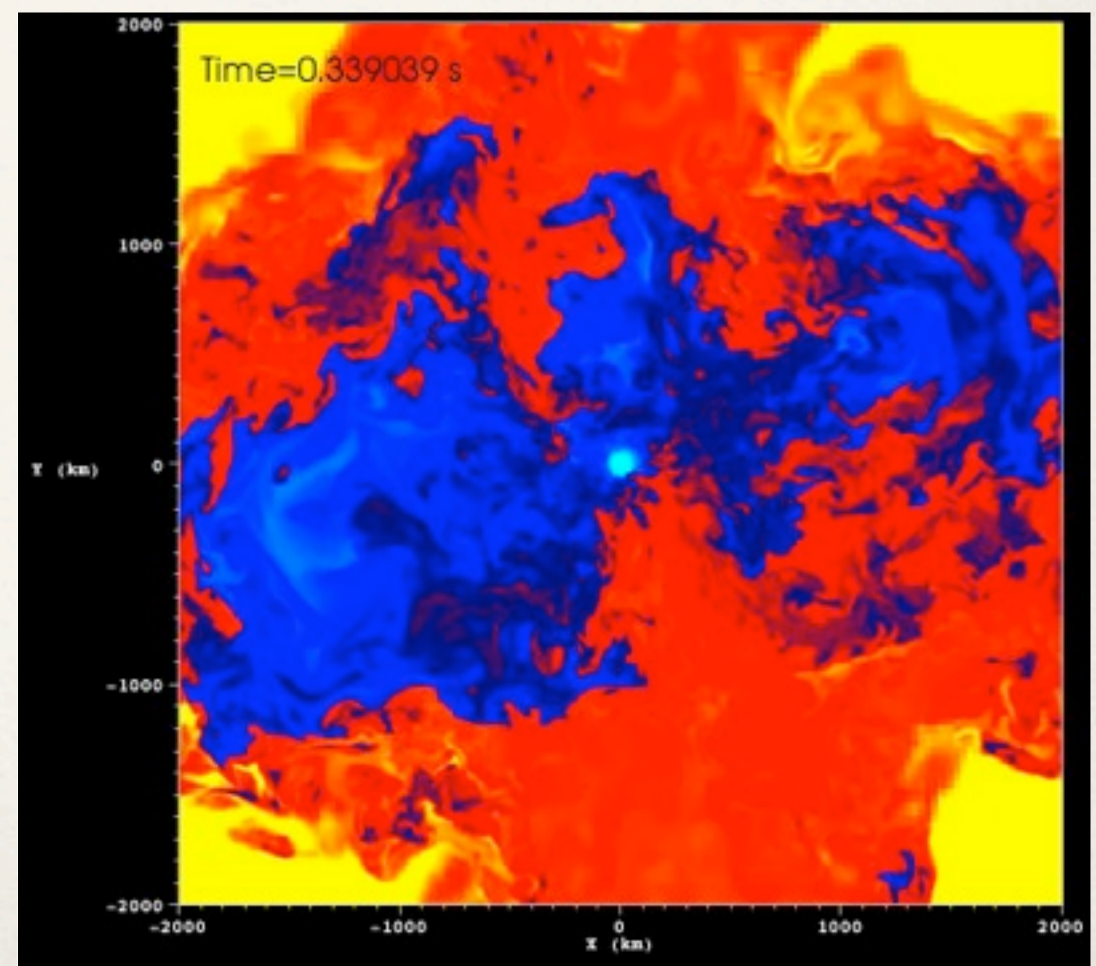
3D AMR block structure

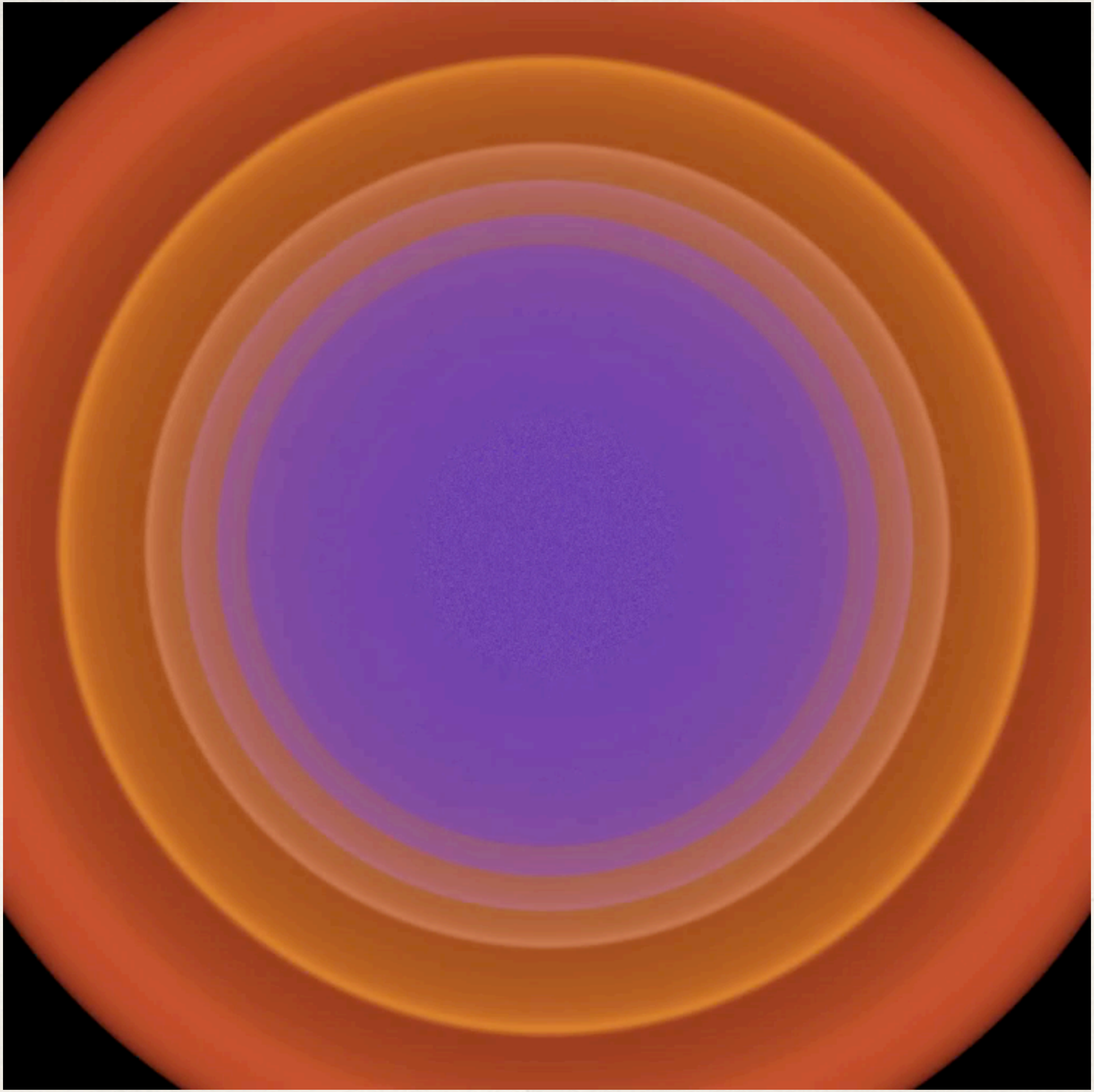
CASTRO

Simulations







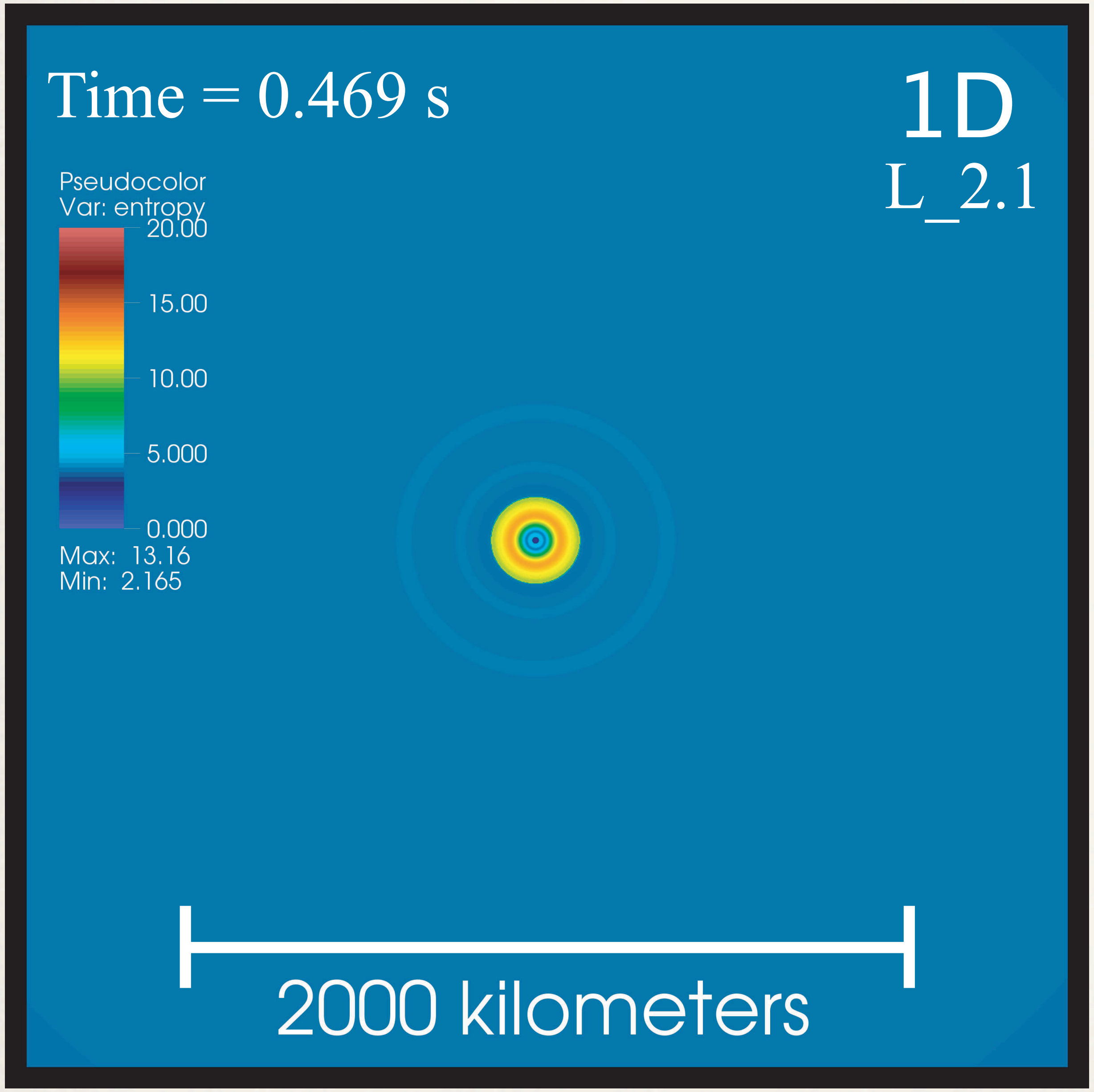


Spatial Dimension

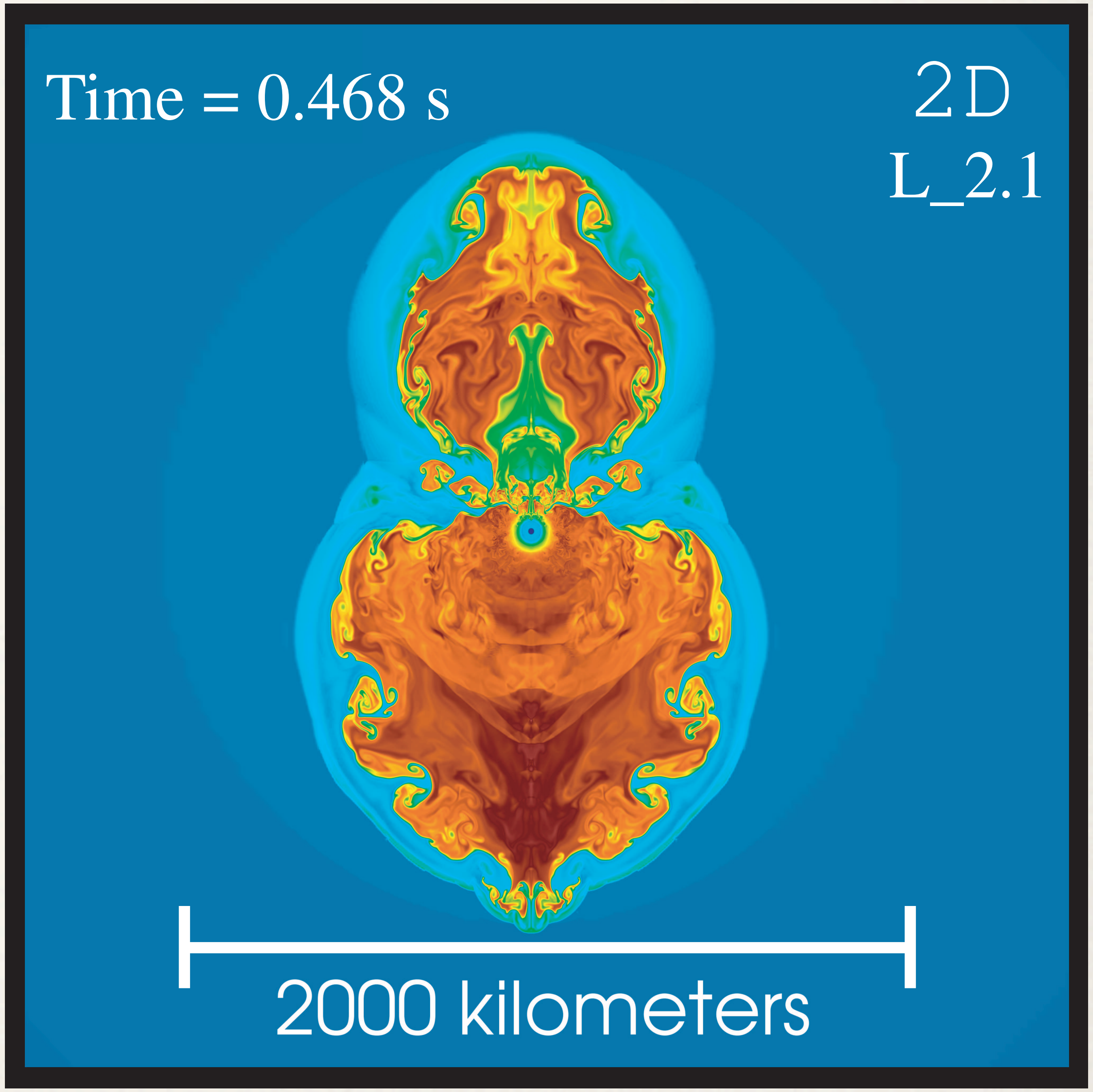
The key to the neutrino mechanism

Dimensional Dependence

Spherically Symmetric



Axisymmetric



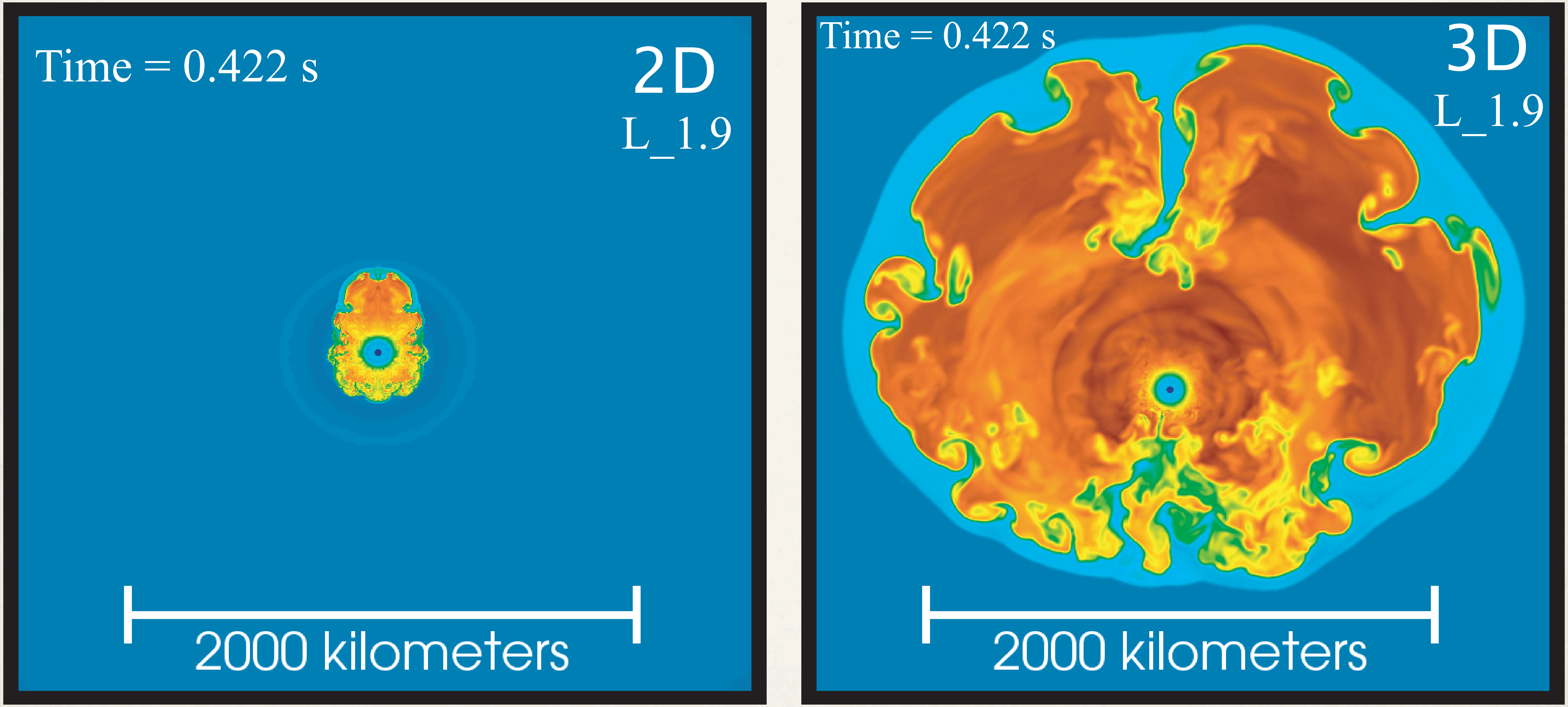
Nordhaus et al. 2010b

see also Burrows & Goshy 1993; Murphy & Burrows 2008

Dimensional Dependence

Axisymmetric

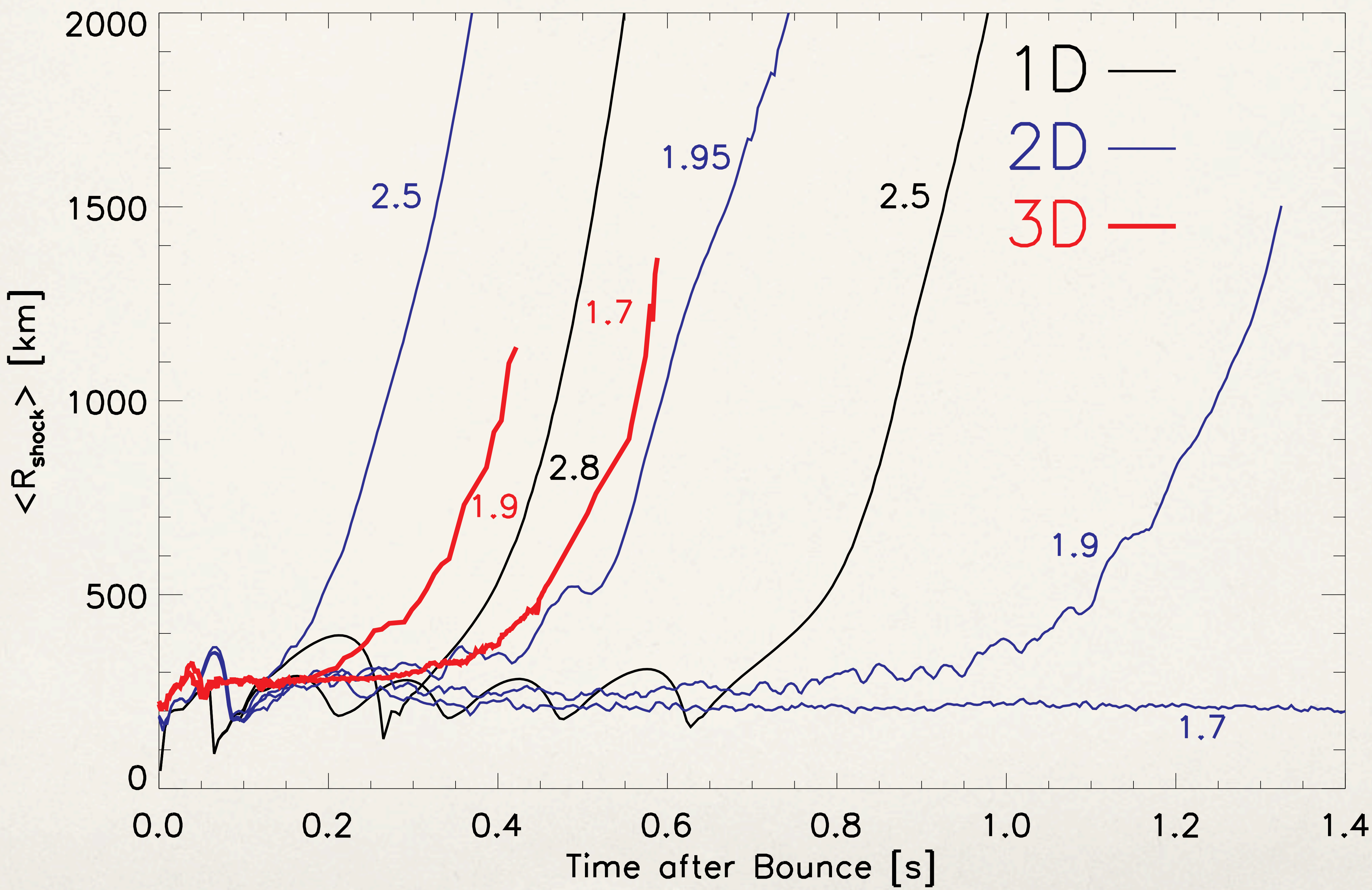
Three Dimensional



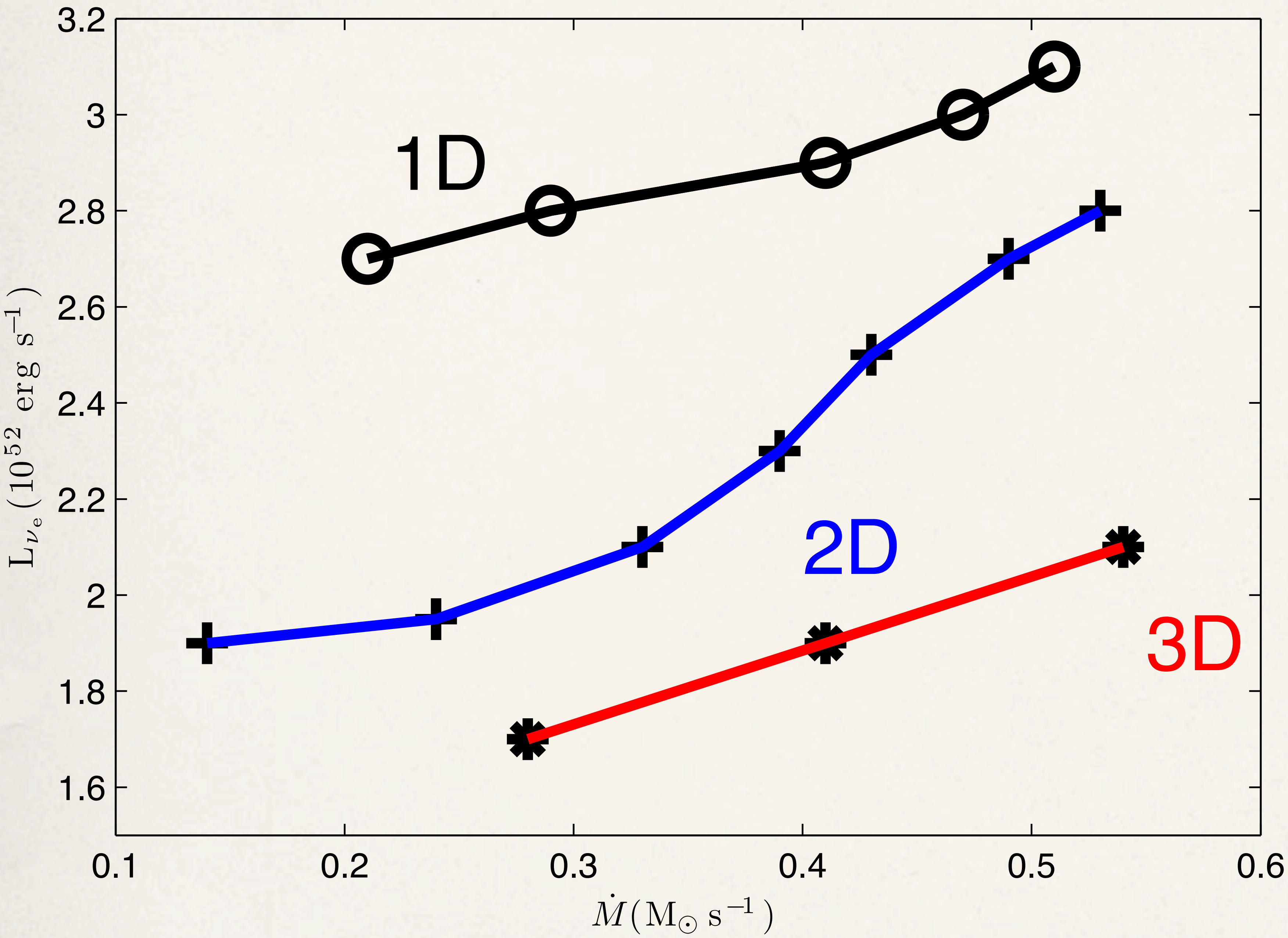
Nordhaus et al. 2010b

Average Shock Radii

Time of explosion is a strong function of dimension!



Critical Curve for Explosions



3D vs. 1D/2D

~50% easier to explode than 1D!

~25% easier to explode than 2D!

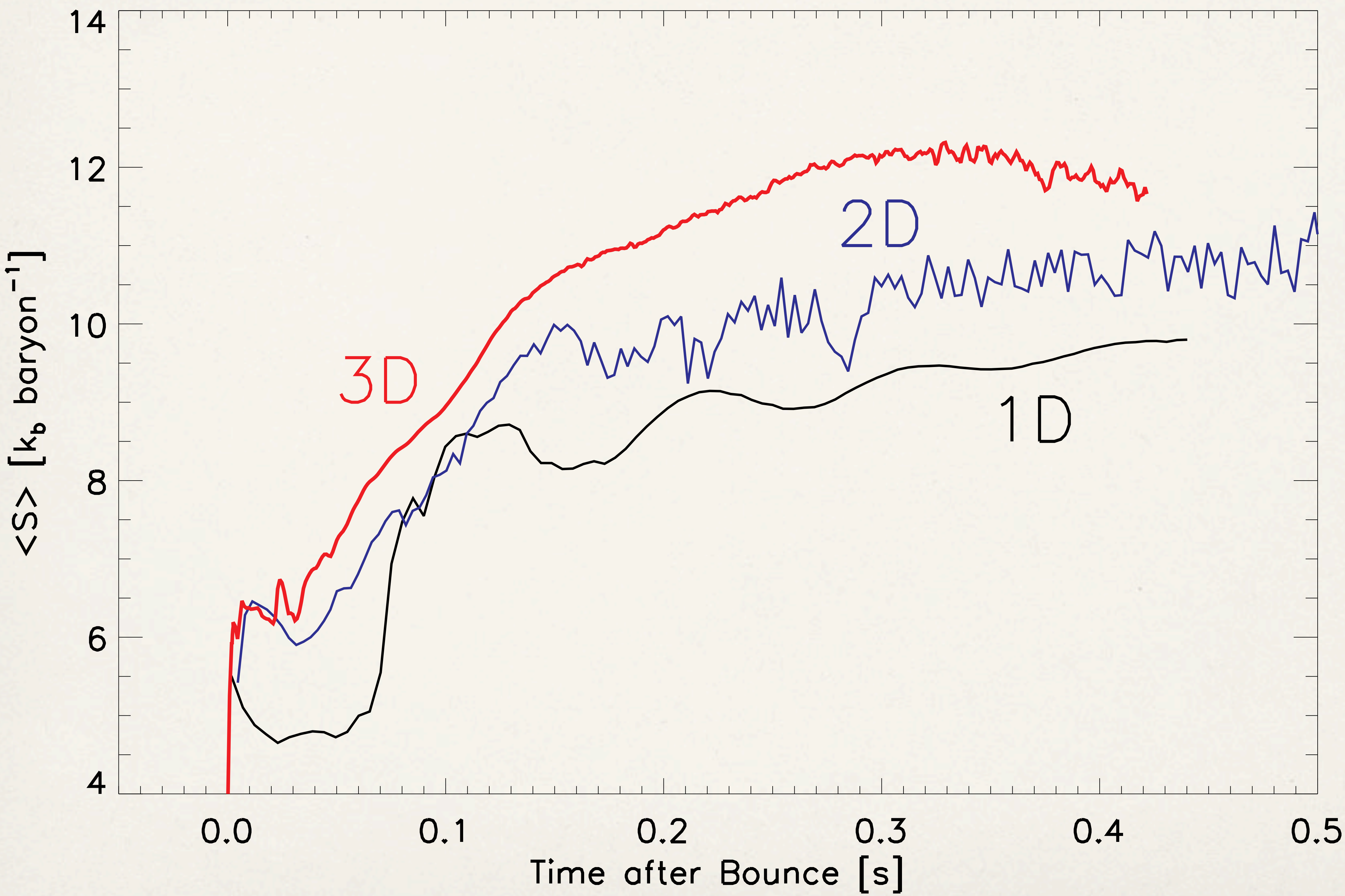
Bigger effect in magnitude than:

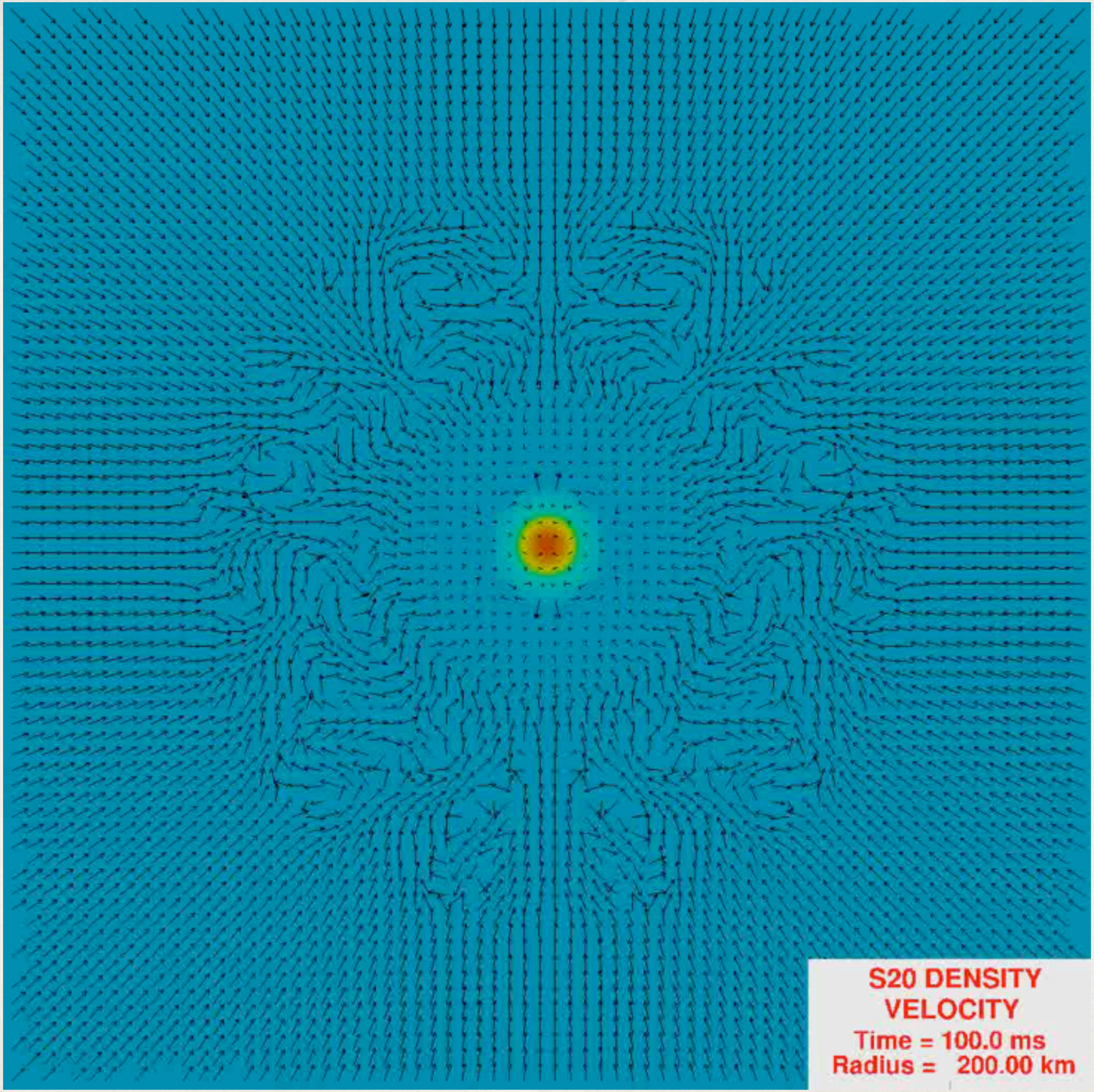
- inelastic scattering
- general relativity
- nuclear burning

Nordhaus et al. 2010b

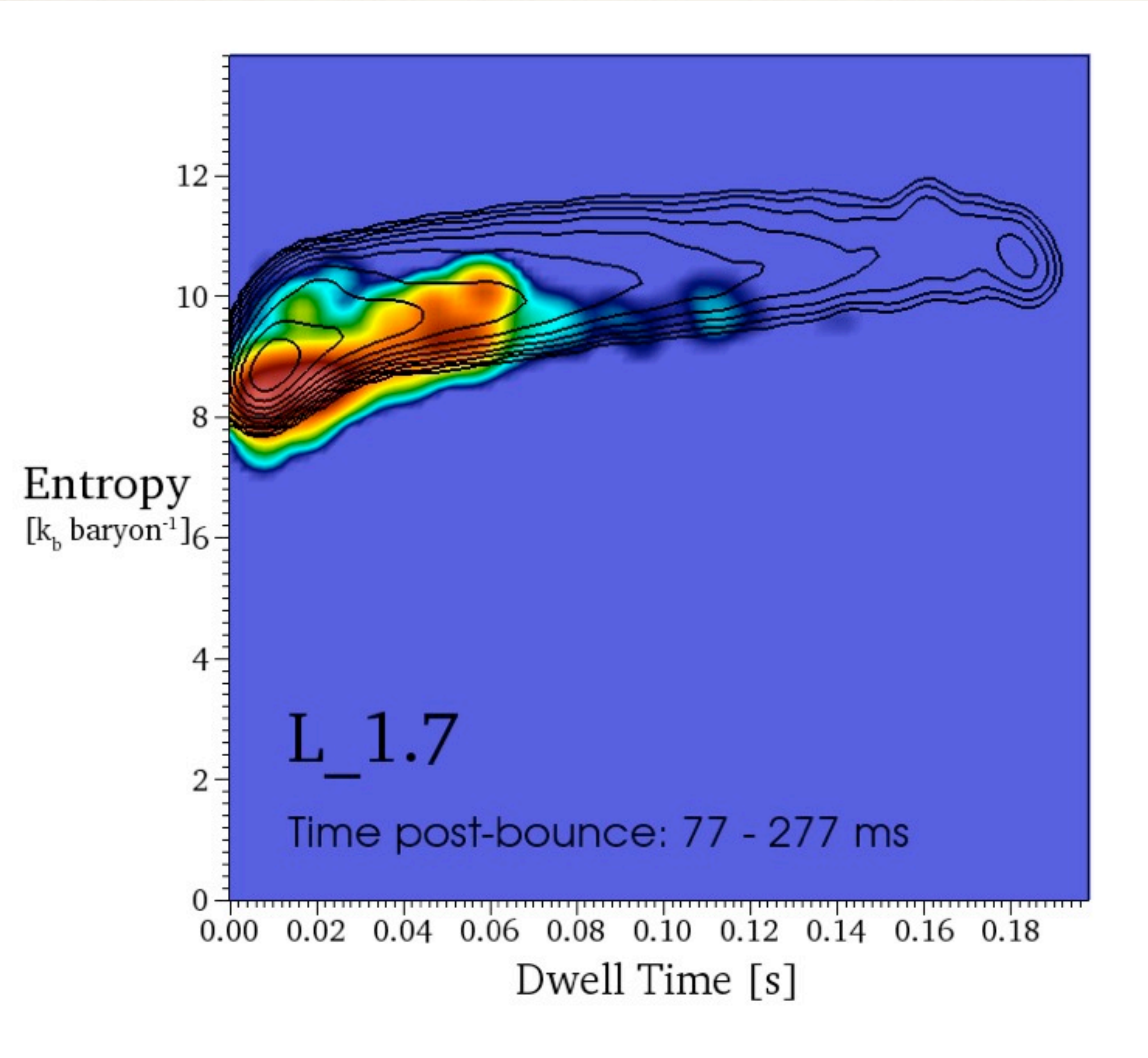
see also Burrows & Goshy 1993; Murphy & Burrows 2008

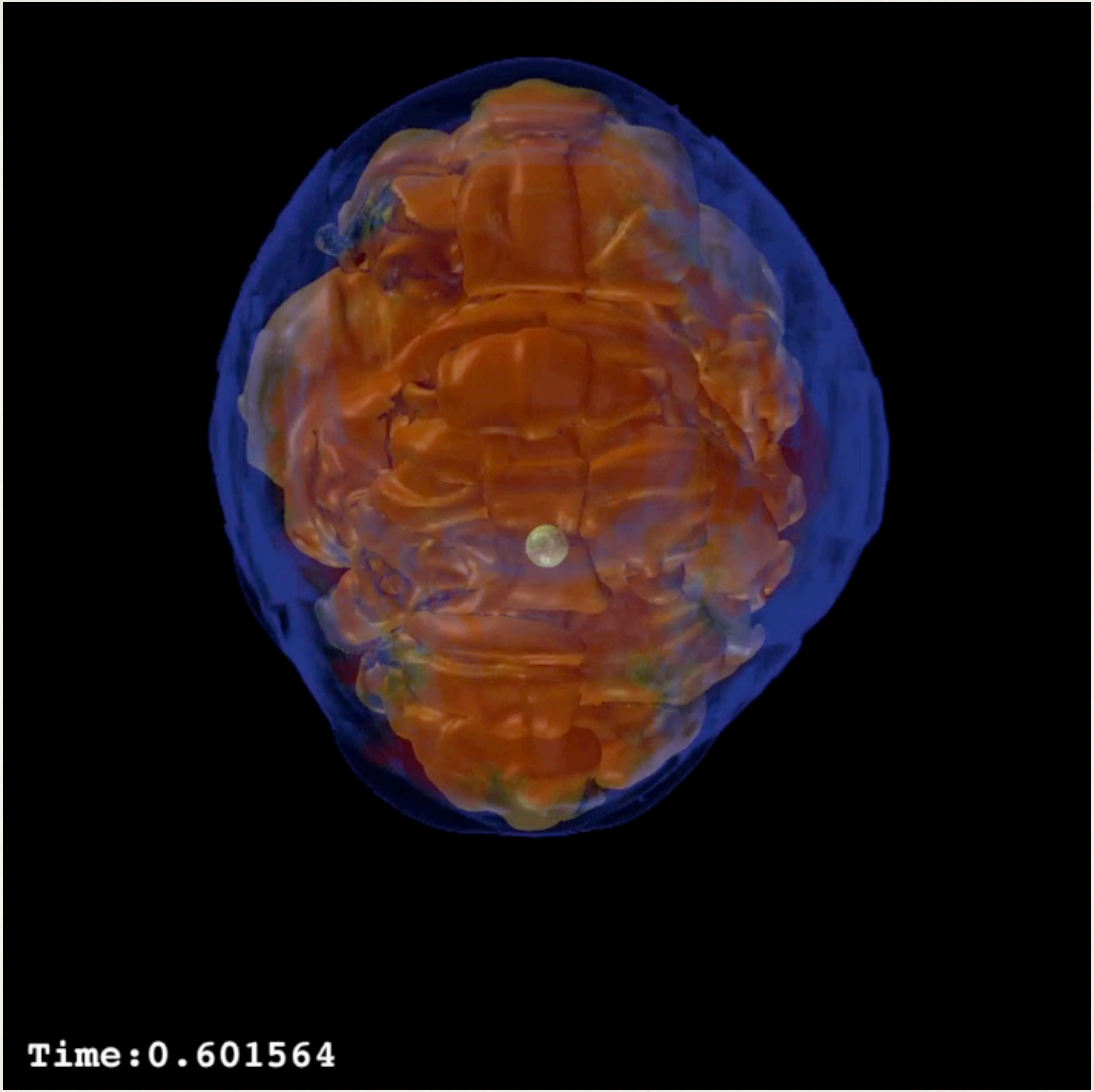
Higher Entropy and Longer Dwell Times




S20 DENSITY
VELOCITY
Time = 100.0 ms
Radius = 200.00 km

Dwell Time Distribution




Time:0.601564

Standing Accretion Shock Instability (SASI)

[redacted]

Axisymmetric

$\ell = 1$ mode
is dominant

Suggested as a fundamental characteristic of SN dynamics and way to spin-up pulsars;

Blondin & Mezzacappa 2007

Standing Accretion Shock Instability (SASI)

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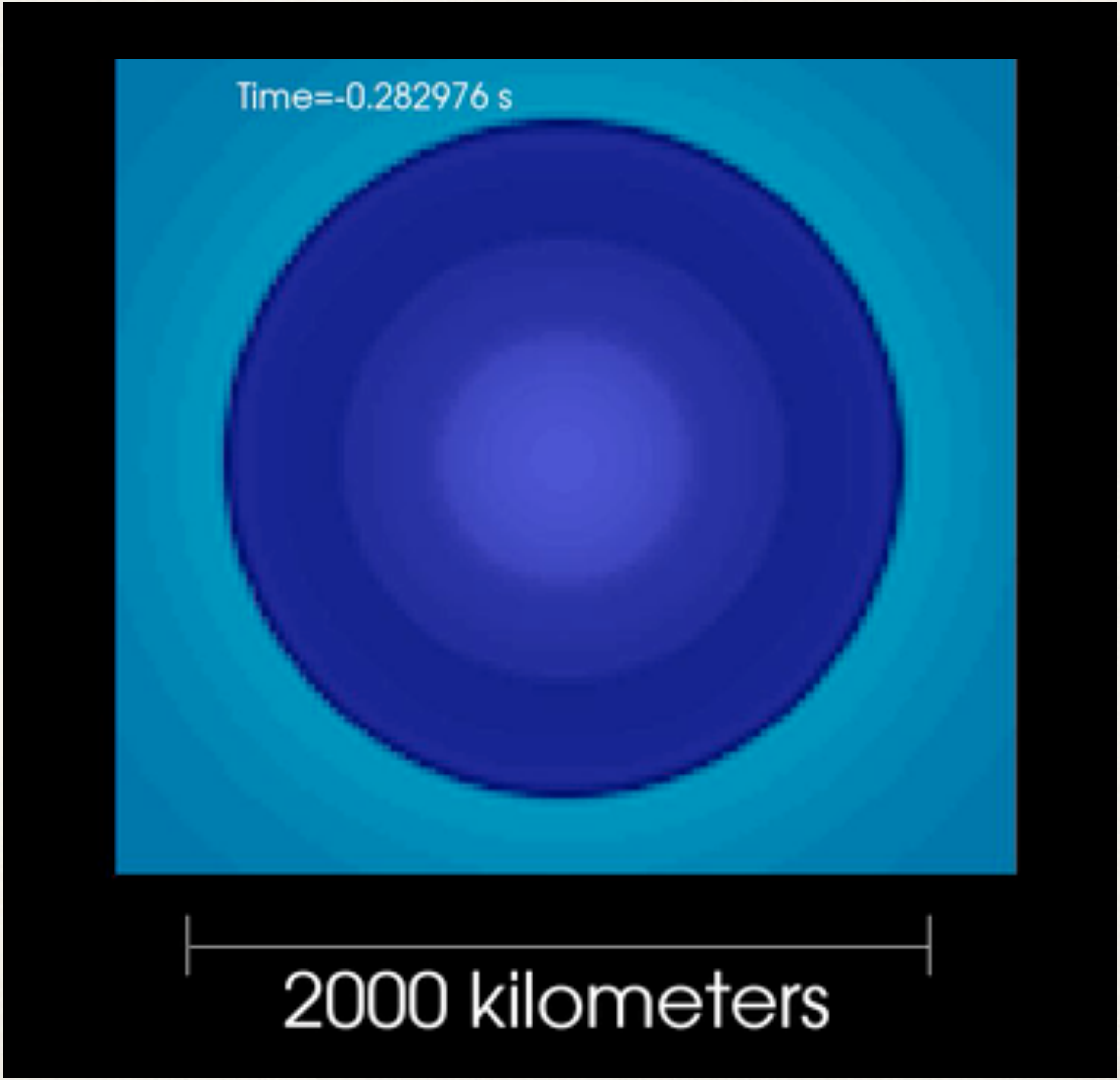
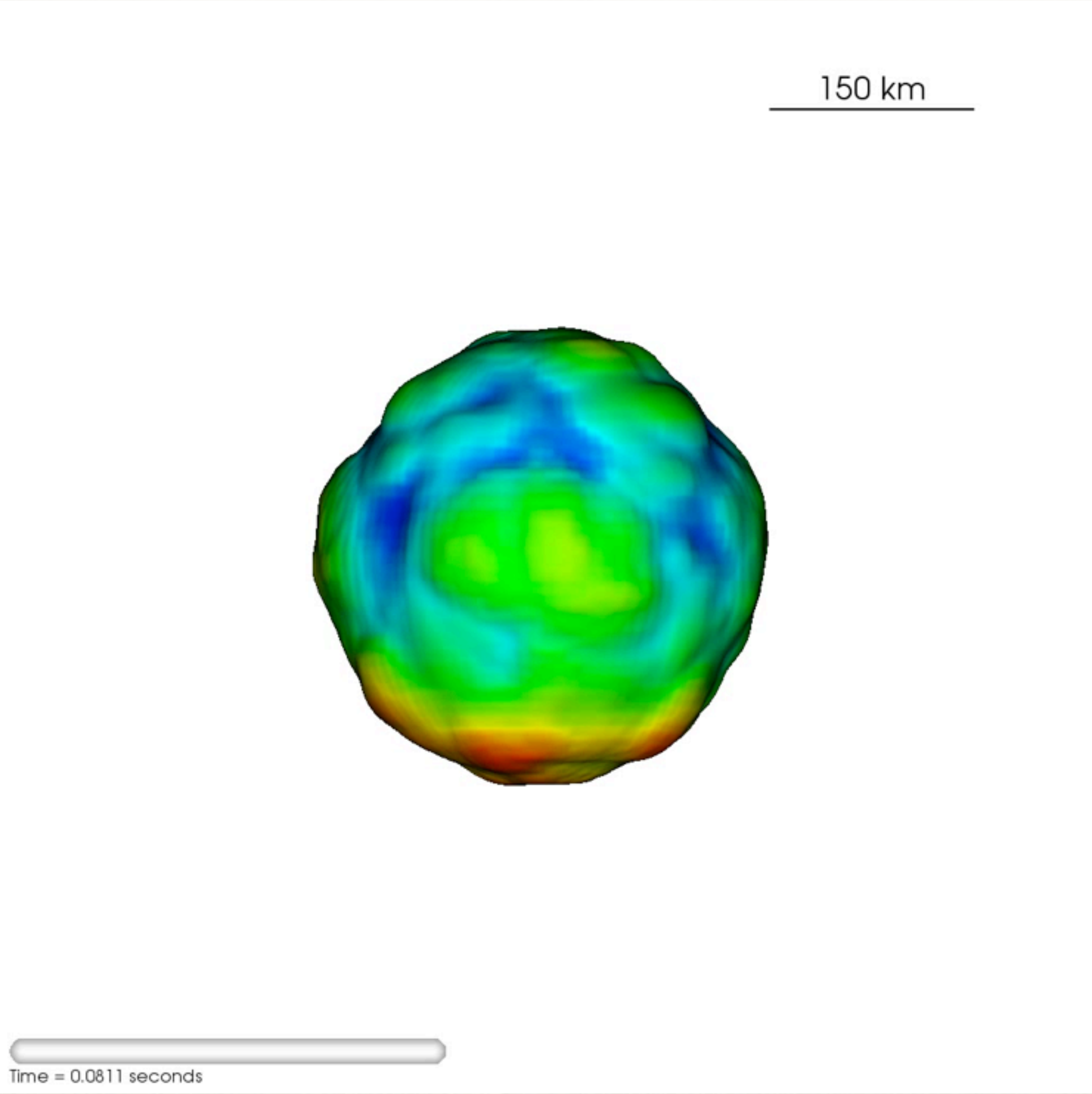
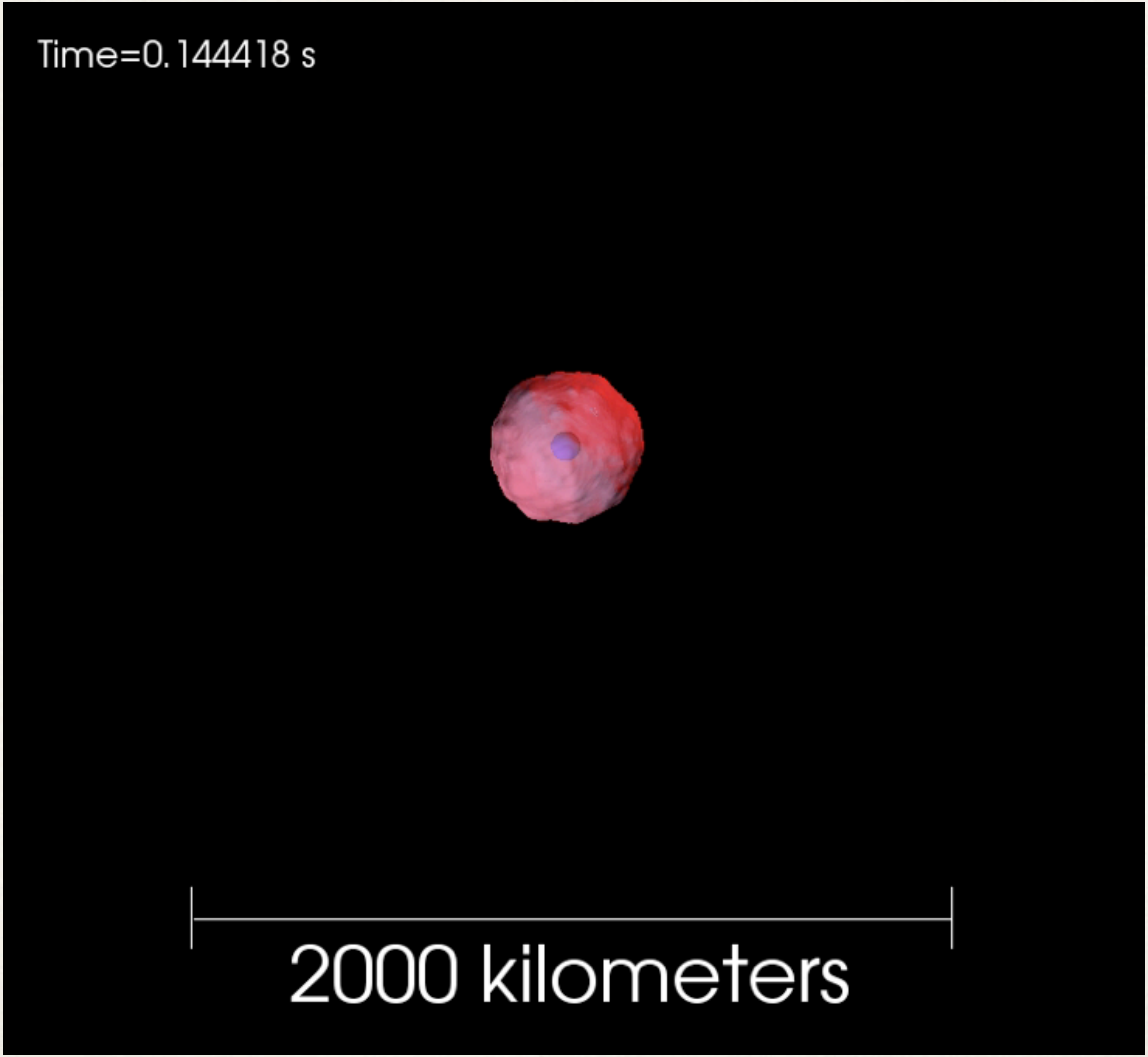



150 km
Time = 0.0811 seconds

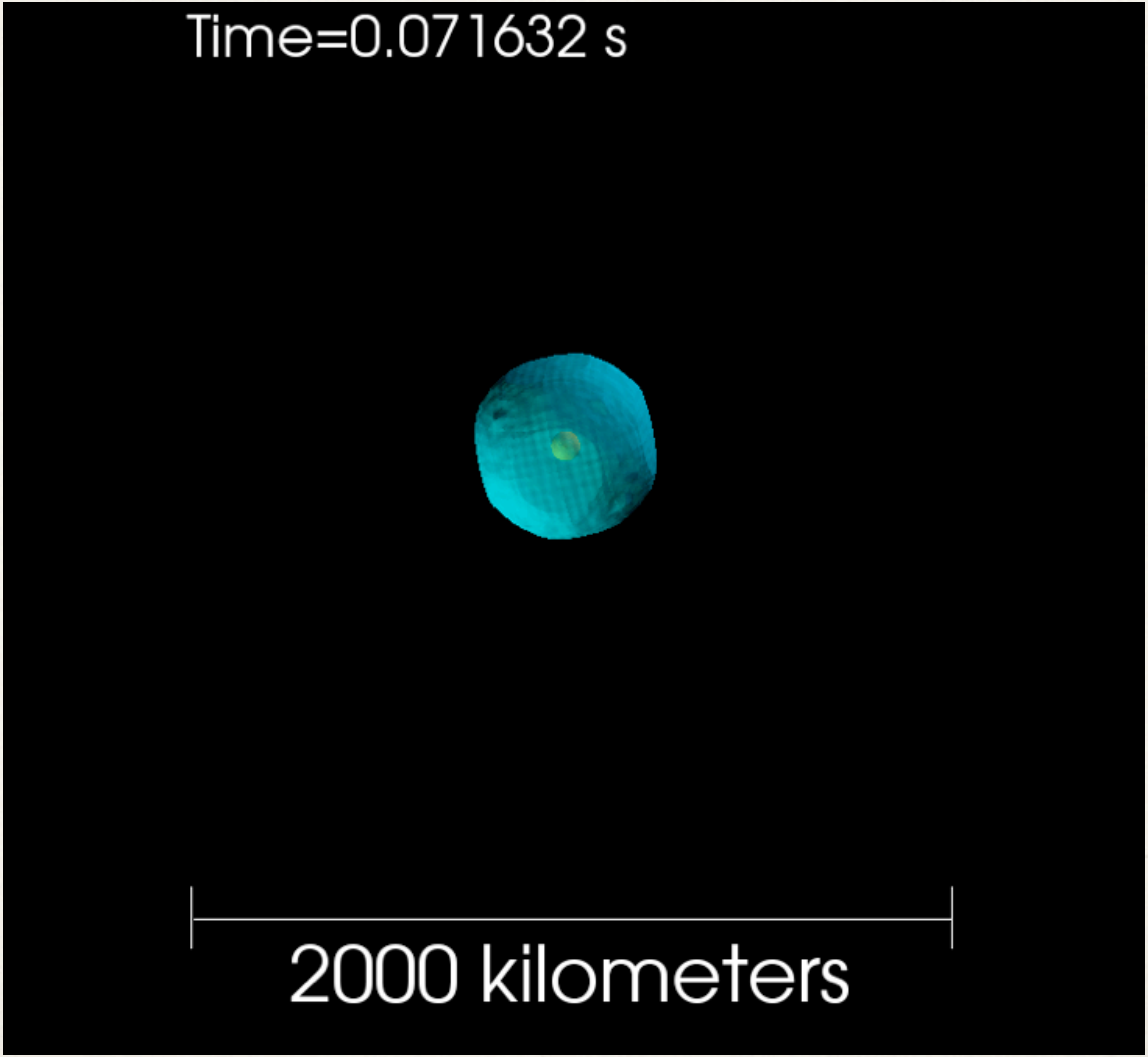
Non-Rotating Initial Model

Non-Rotating Initial Model



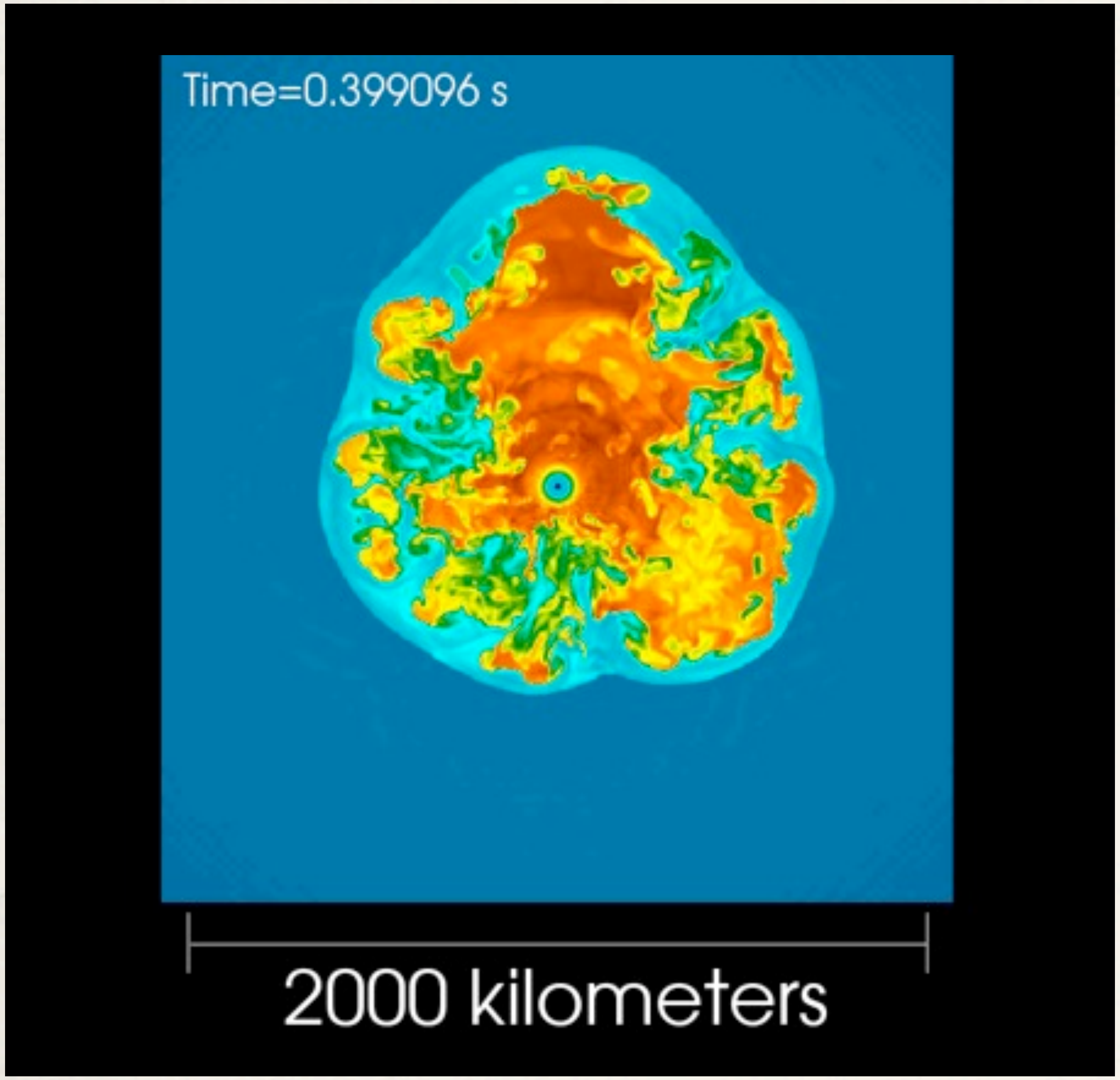
Rotating Initial Model

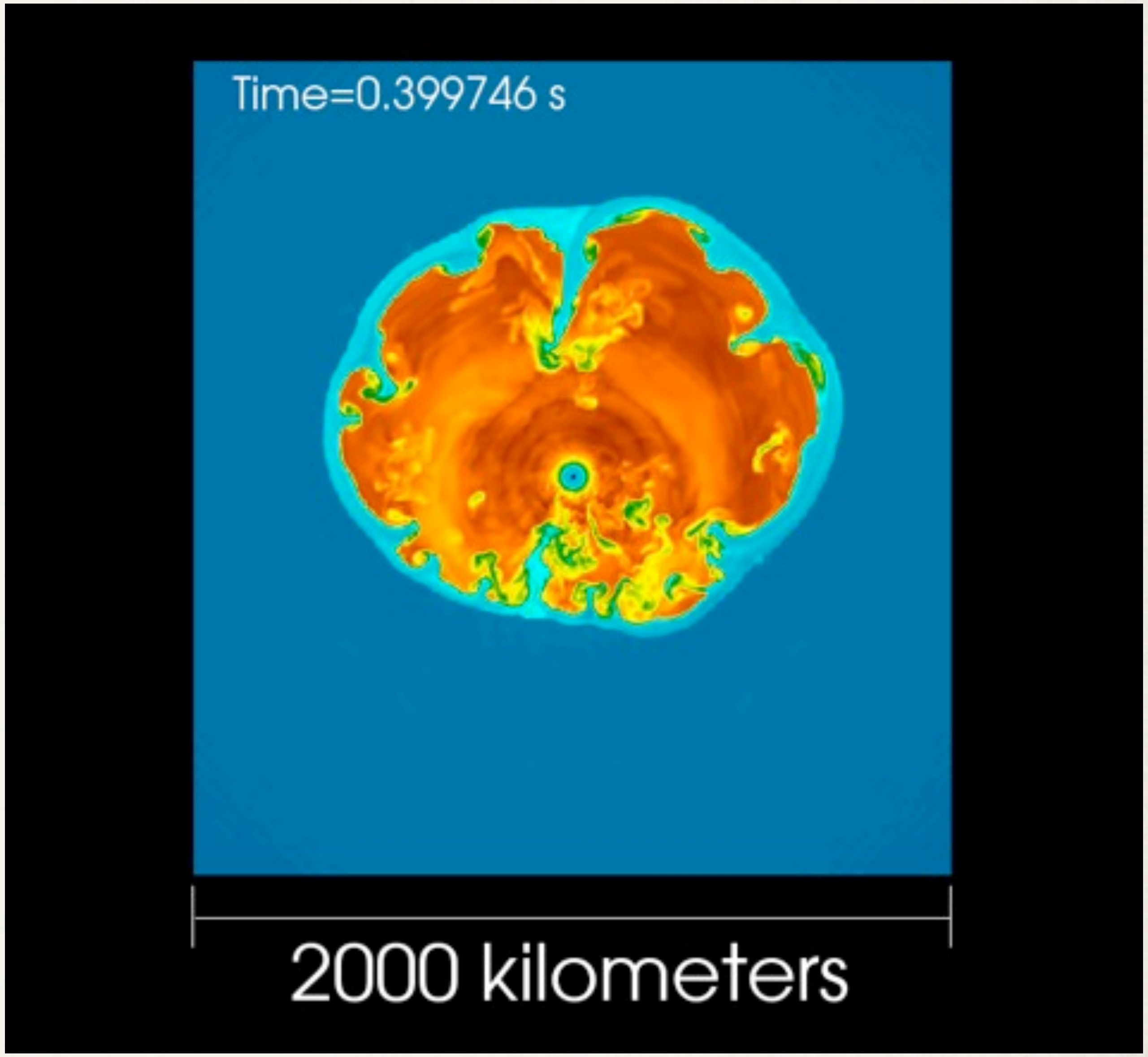
Rotating Initial Model



Rotating Initial Model

Non-Rotating Initial Model





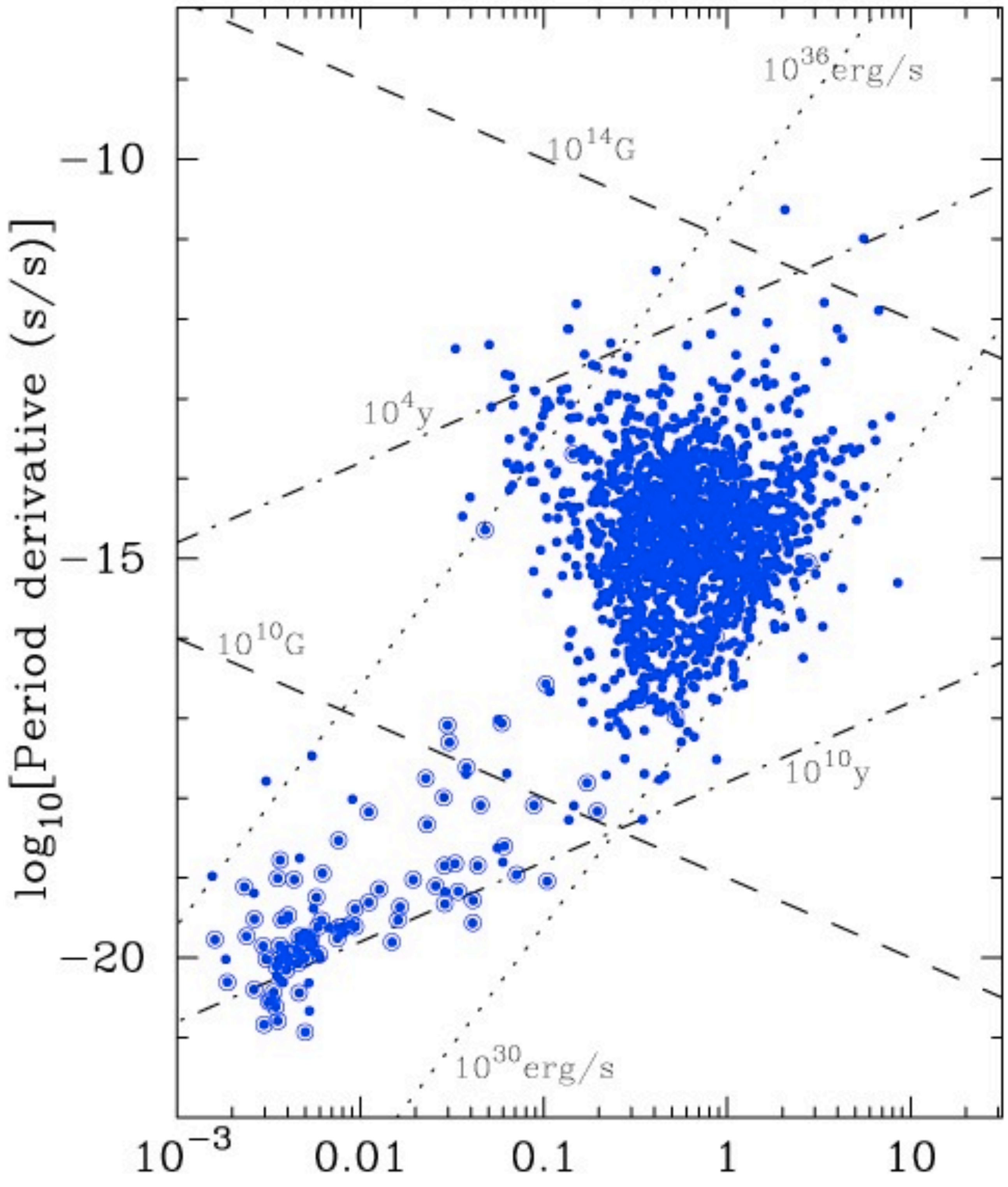
Explodes earlier and more mixing of ejecta

Initial rotation produces a preferred axis

Pulsar Spins

From instabilities during core collapse

Pulsar Spin Periods



Lorimer 2008

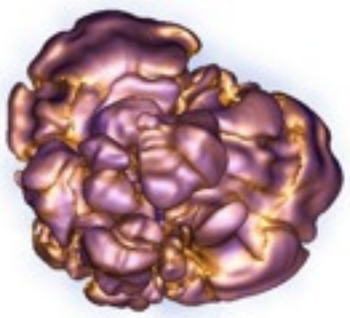
Suggested that core collapse could produce tens of ms birth spin periods from non-rotating progenitors.

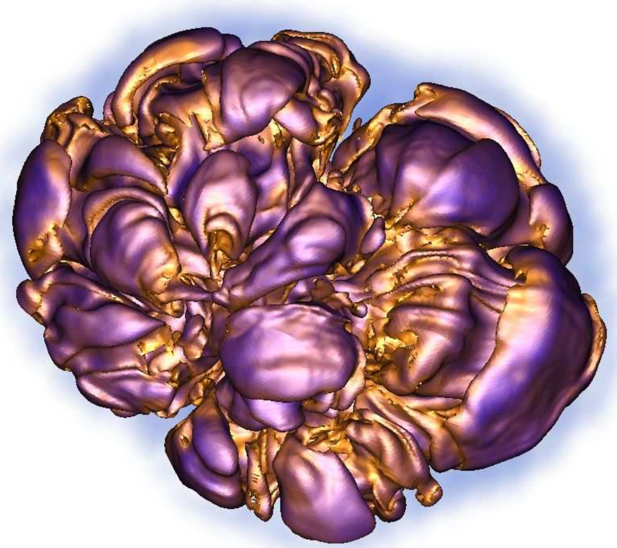
Blondin & Mezzcappa 2007
Blondin & Shaw 2007

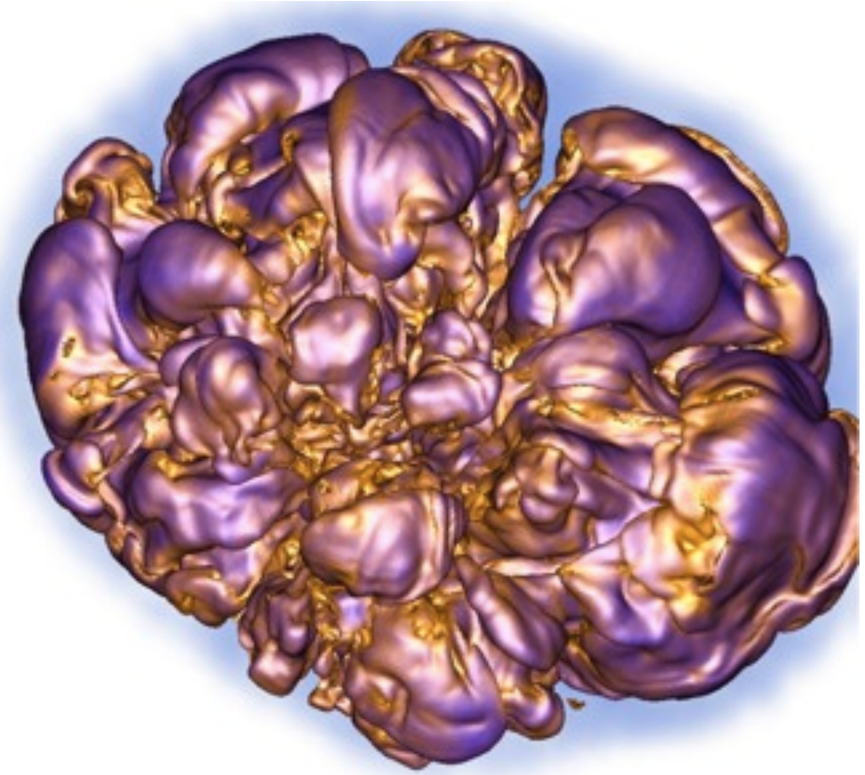
Initial simulations did not:

- follow collapse
- form the neutron star
- use a nuclear EOS
- explode

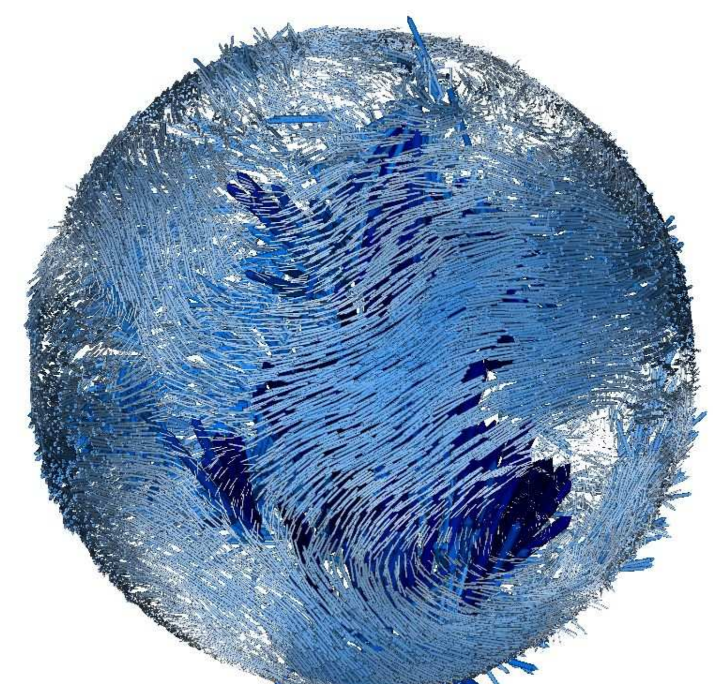
Time sequence



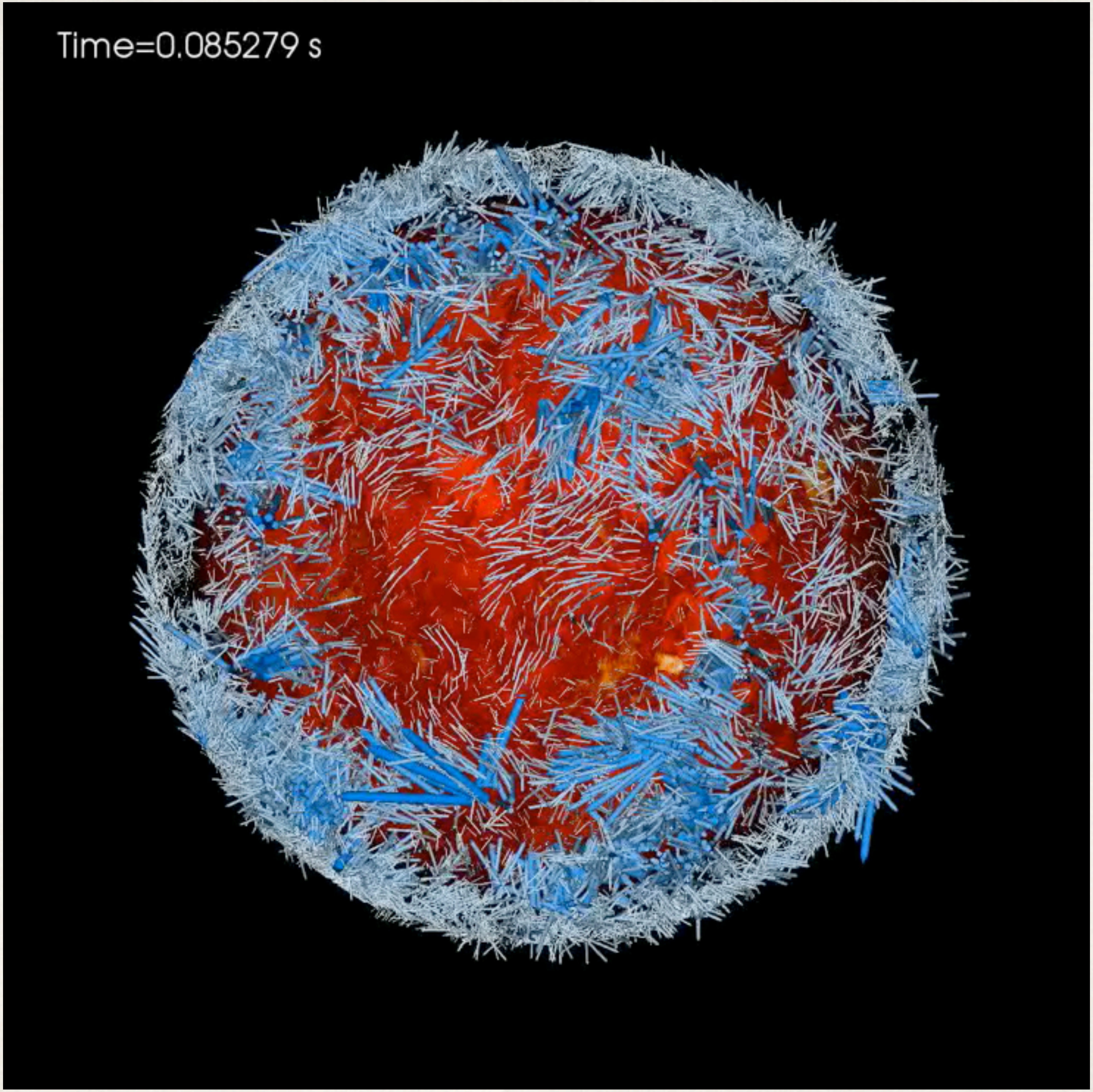




$15\,M_\odot$ progenitor, induced explosion

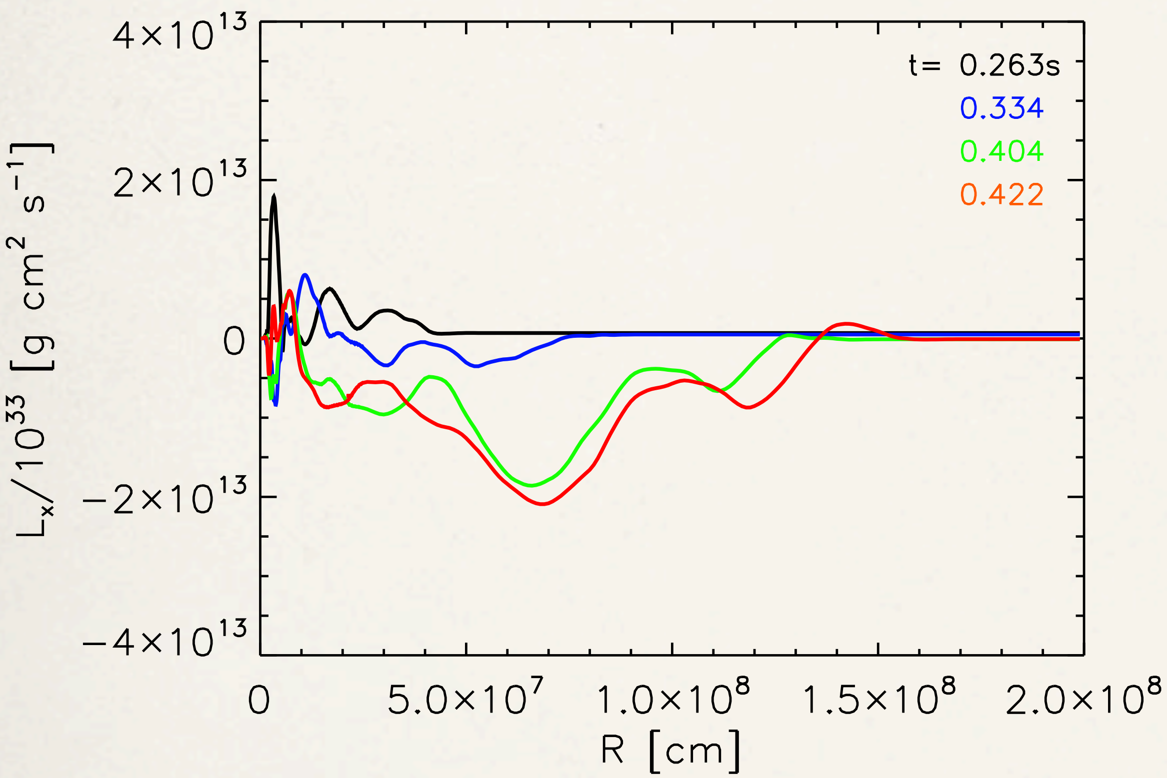


velocity vectors

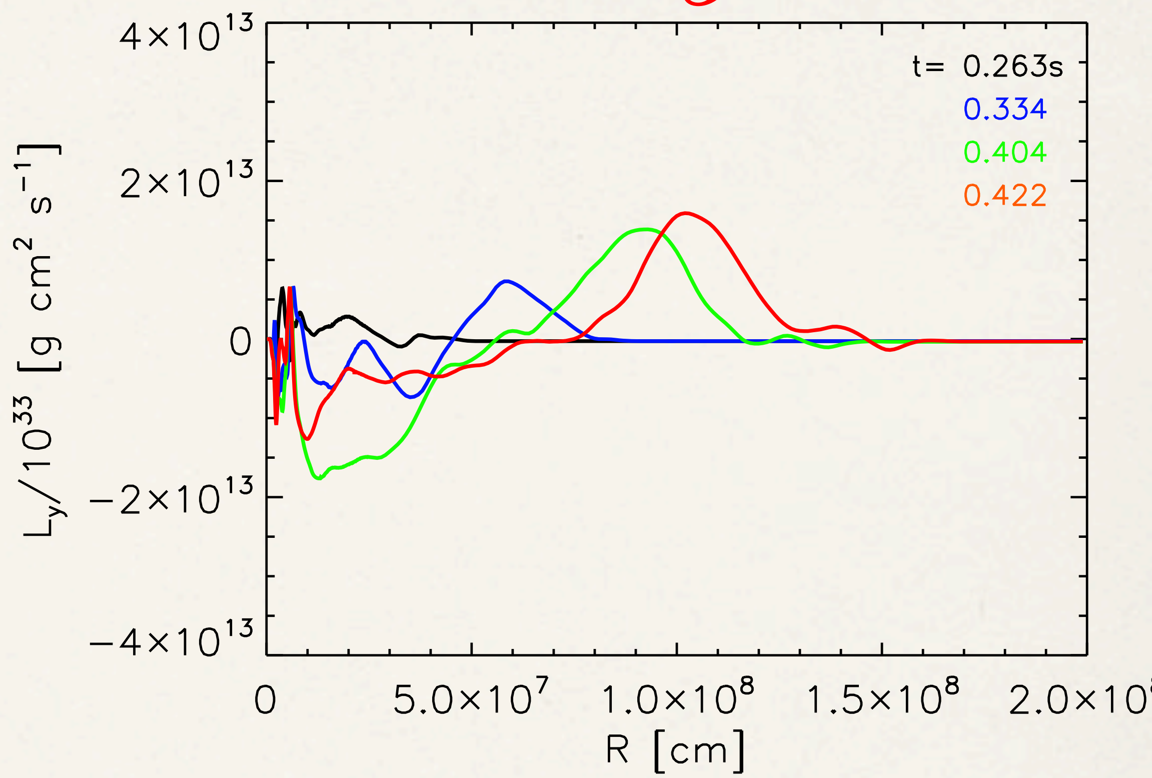

Time=0.085279 s

Angular Momentum

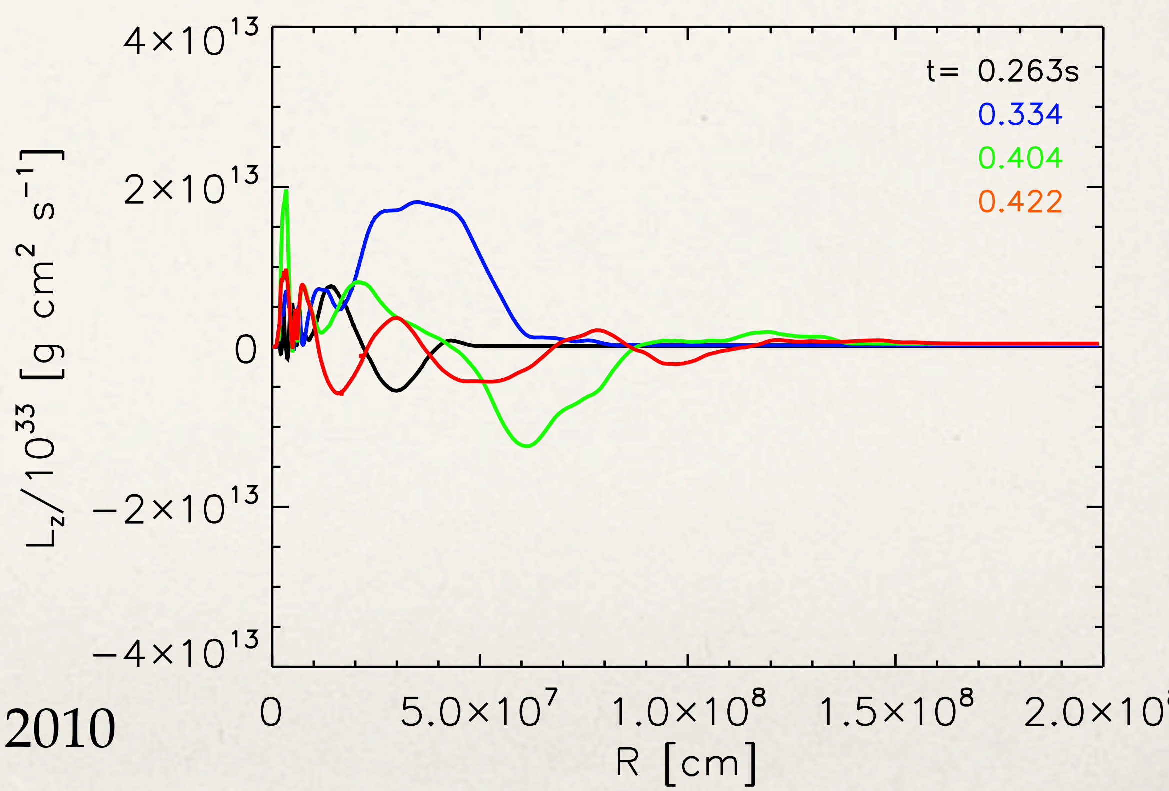
L_x



L_y



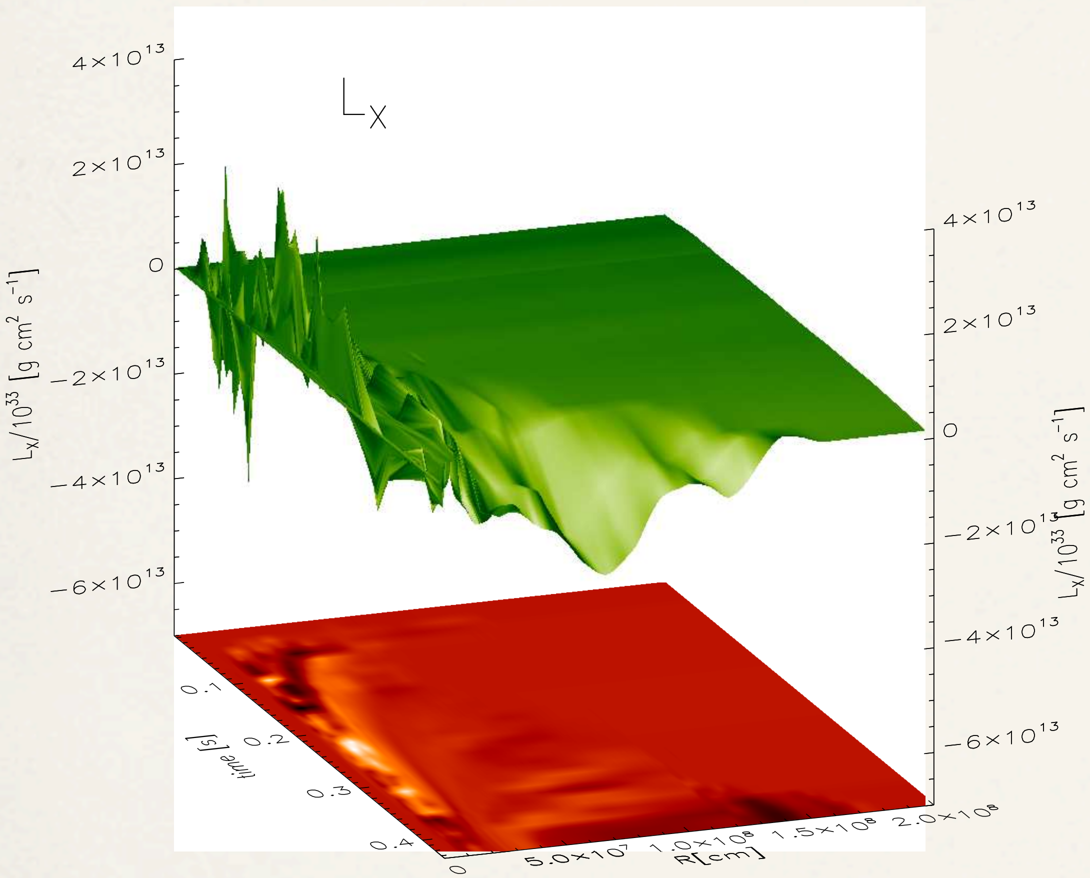
L_z

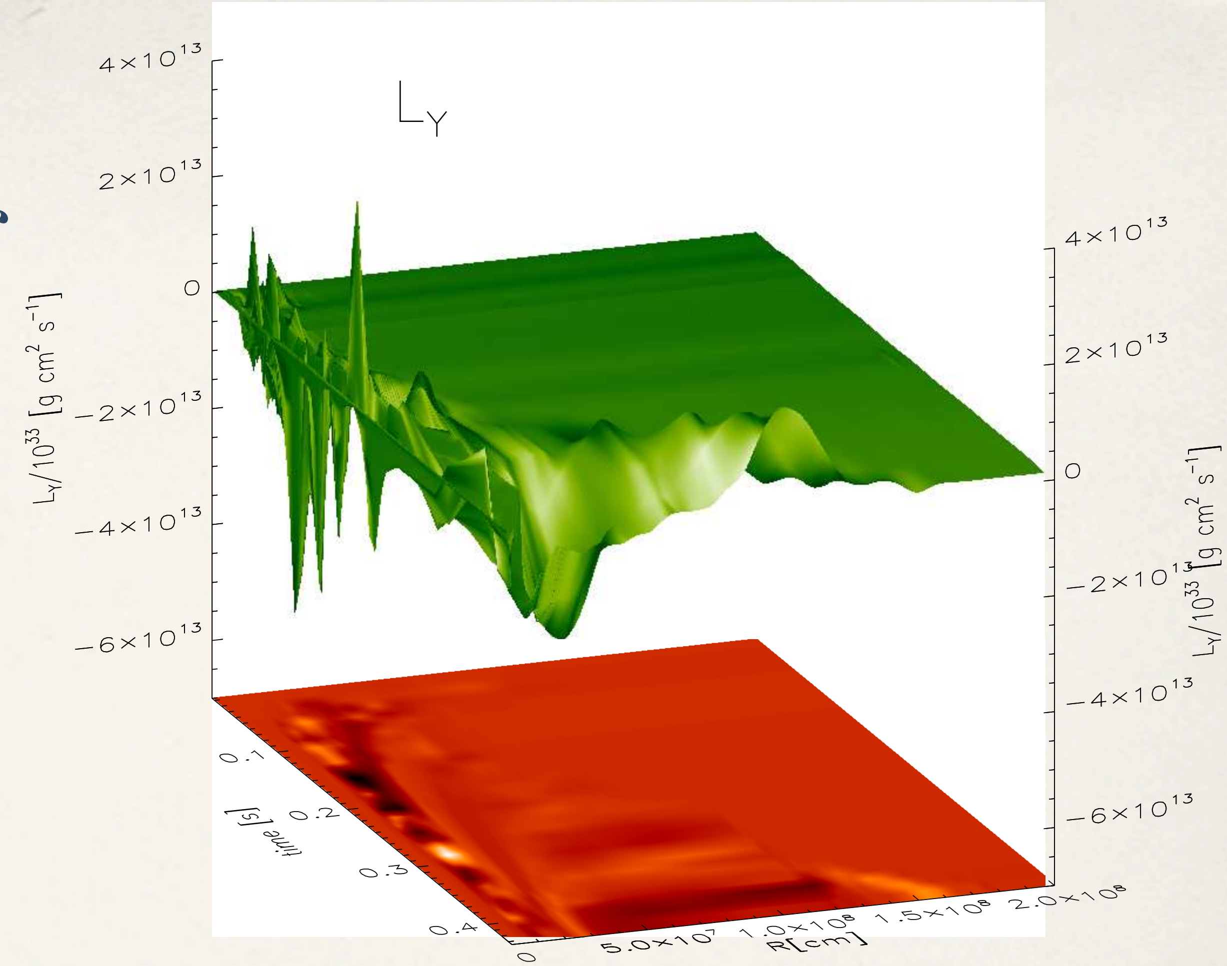


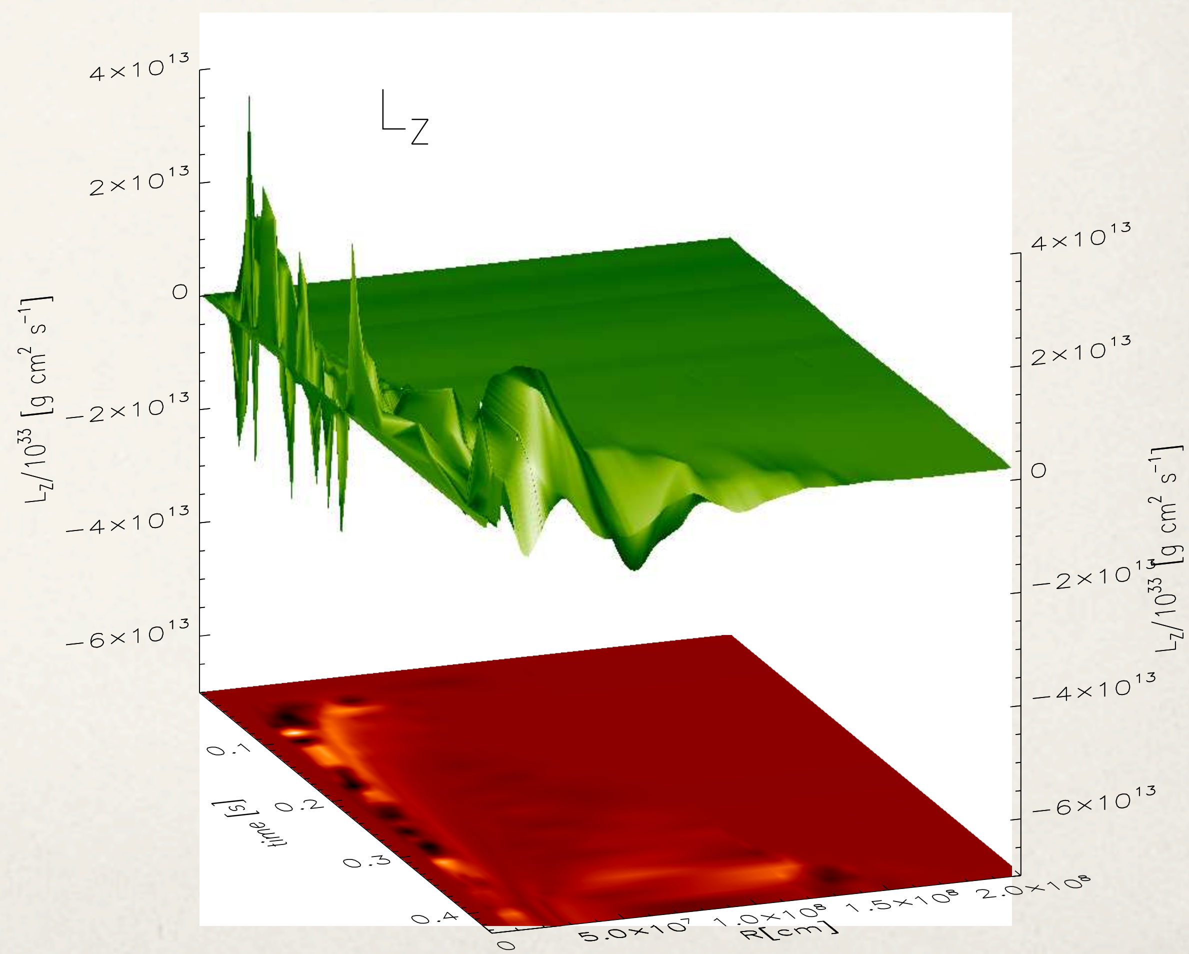
- ``Ejected" angular momentum bump
- Final NS period is ~3 seconds

Rantsiou et al. 2010

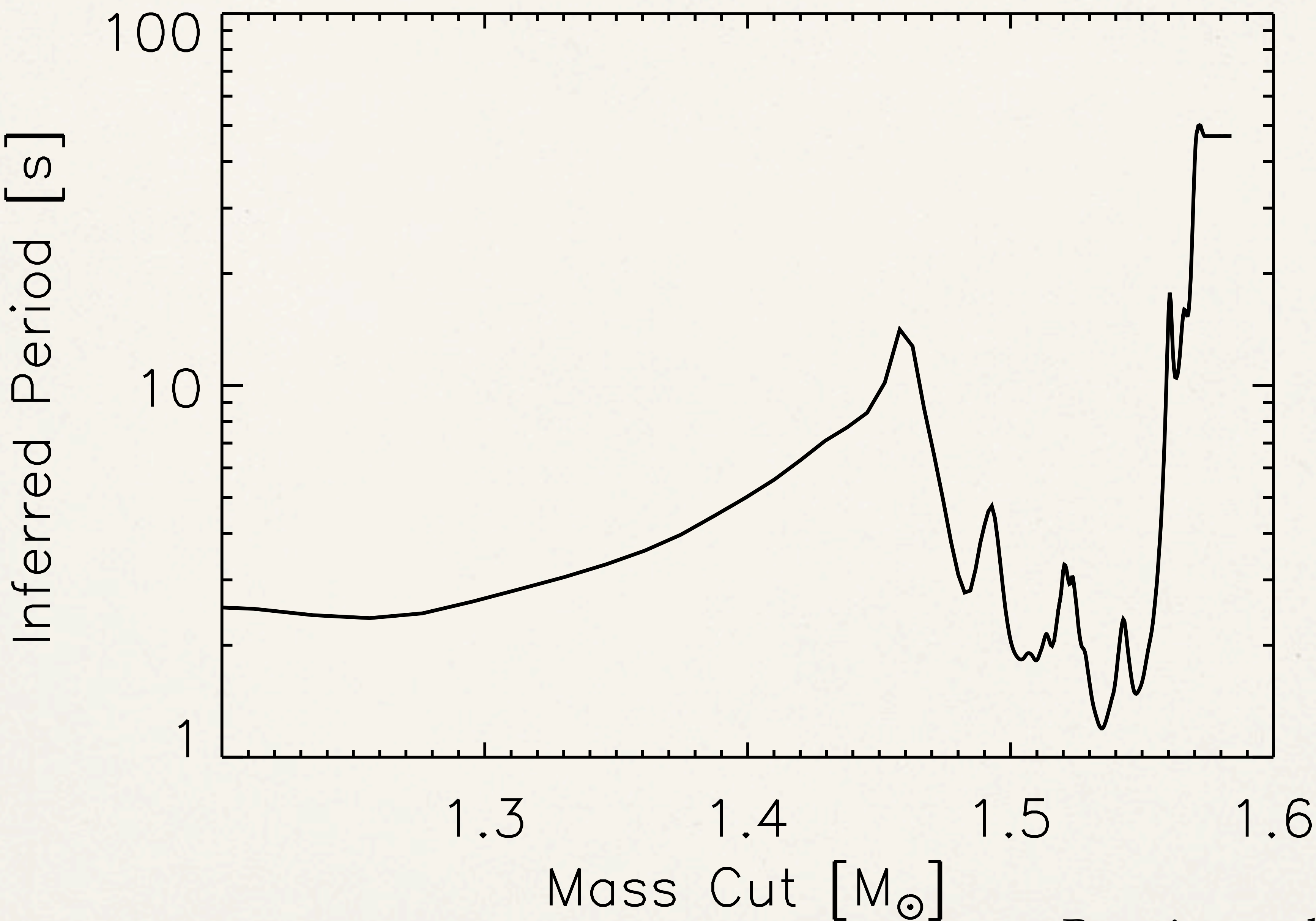
Spatial and temporal evolution of angular momentum







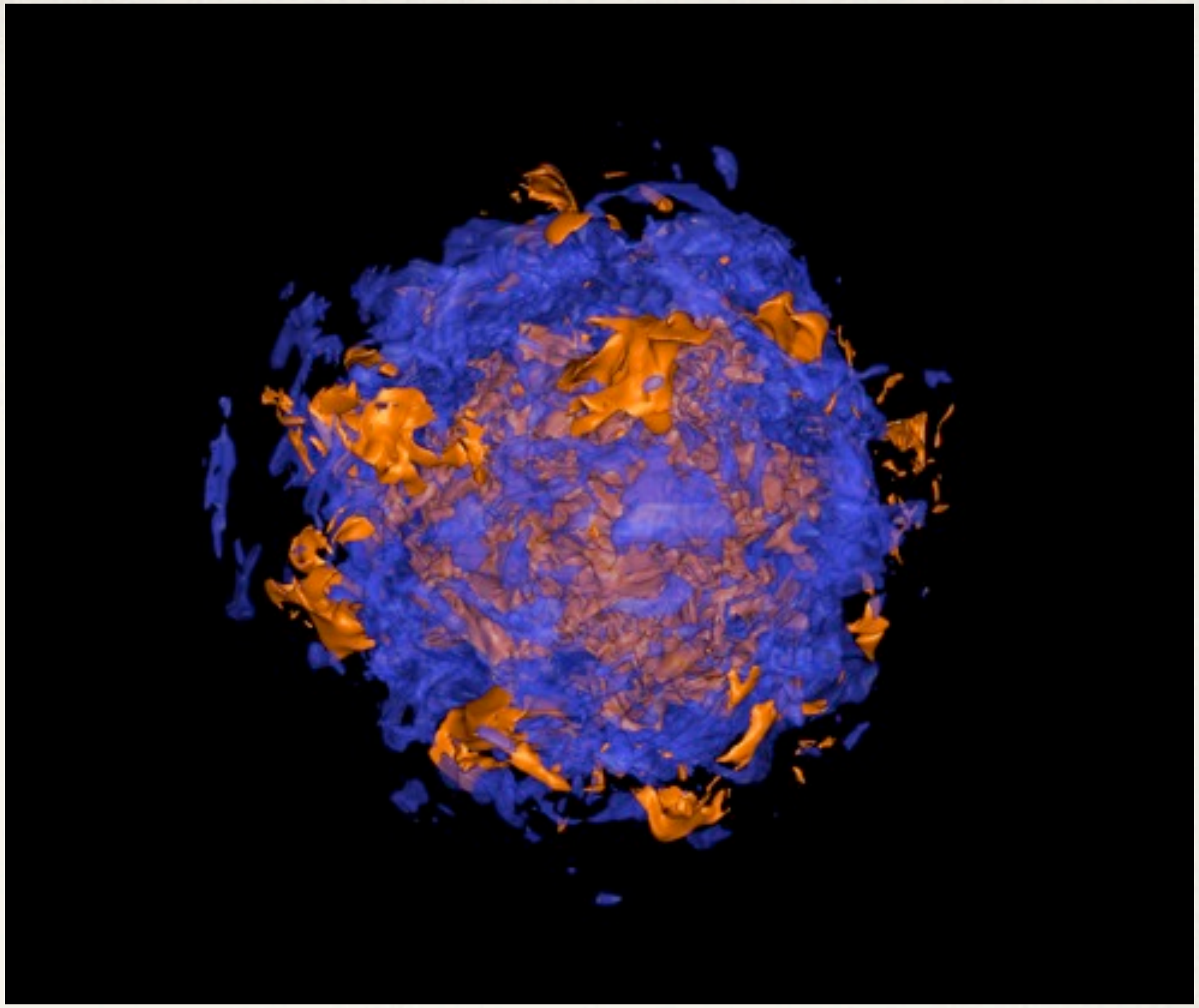
What about fallback?



Rantsiou et al. 2010

Conclusions

- Dimensional dependence for core-collapse supernova explosions!
- 50% easier to explode in 3D vs. 1D - all else being equal.
- Recoil is a natural outcome of hydrodynamics during core collapse.
- High pulsar spin periods are not a result of core collapse of non-rotating cores.



We're eagerly awaiting petascale computations on NSF's Blue Waters!