Core-collapse Supernovae:

Explorations in multi-dimensional numerical astrophysics

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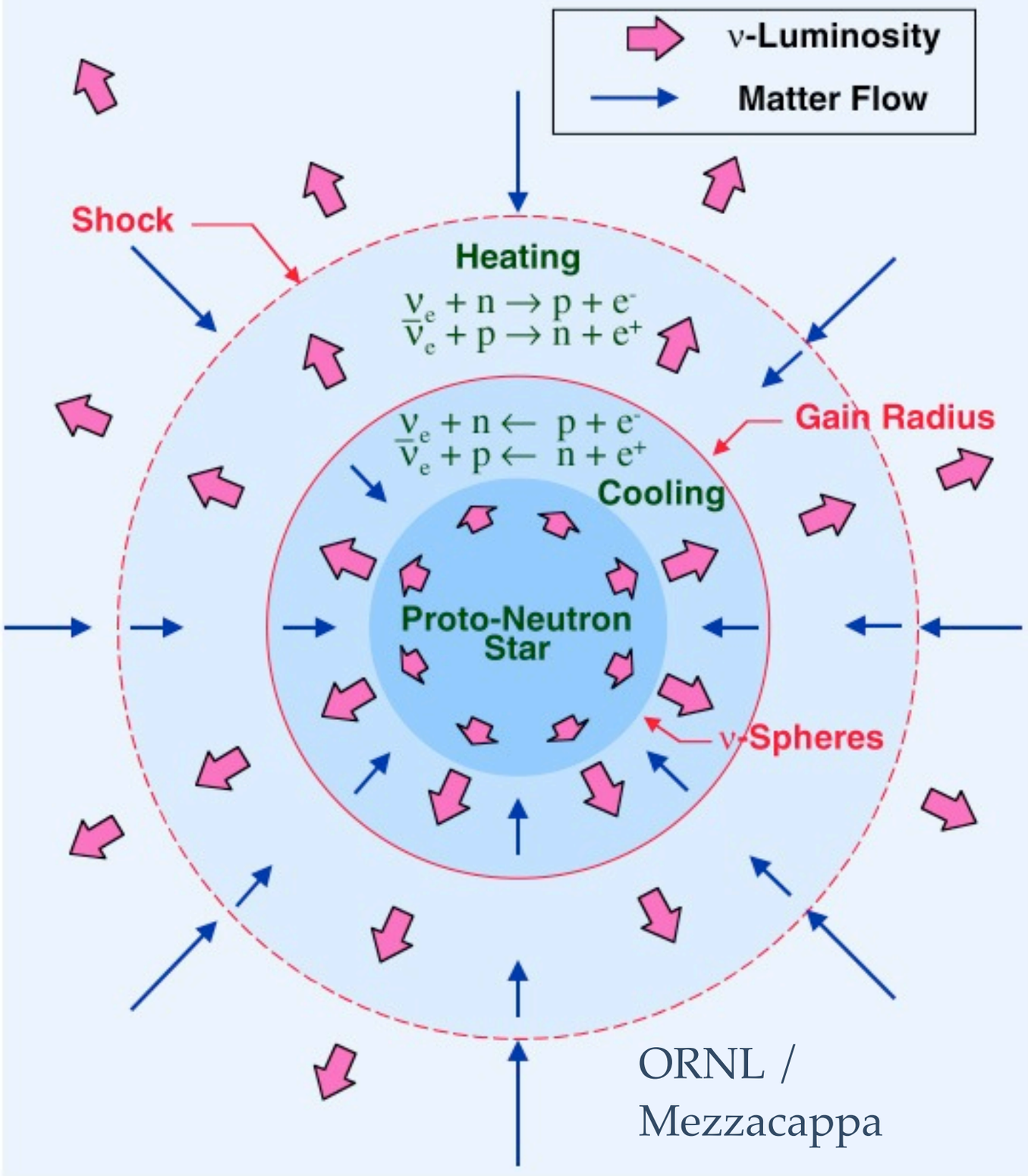
Core collapse



Brief History

Direct Hydrodynamic Collapse
Colgate et al. 1961

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

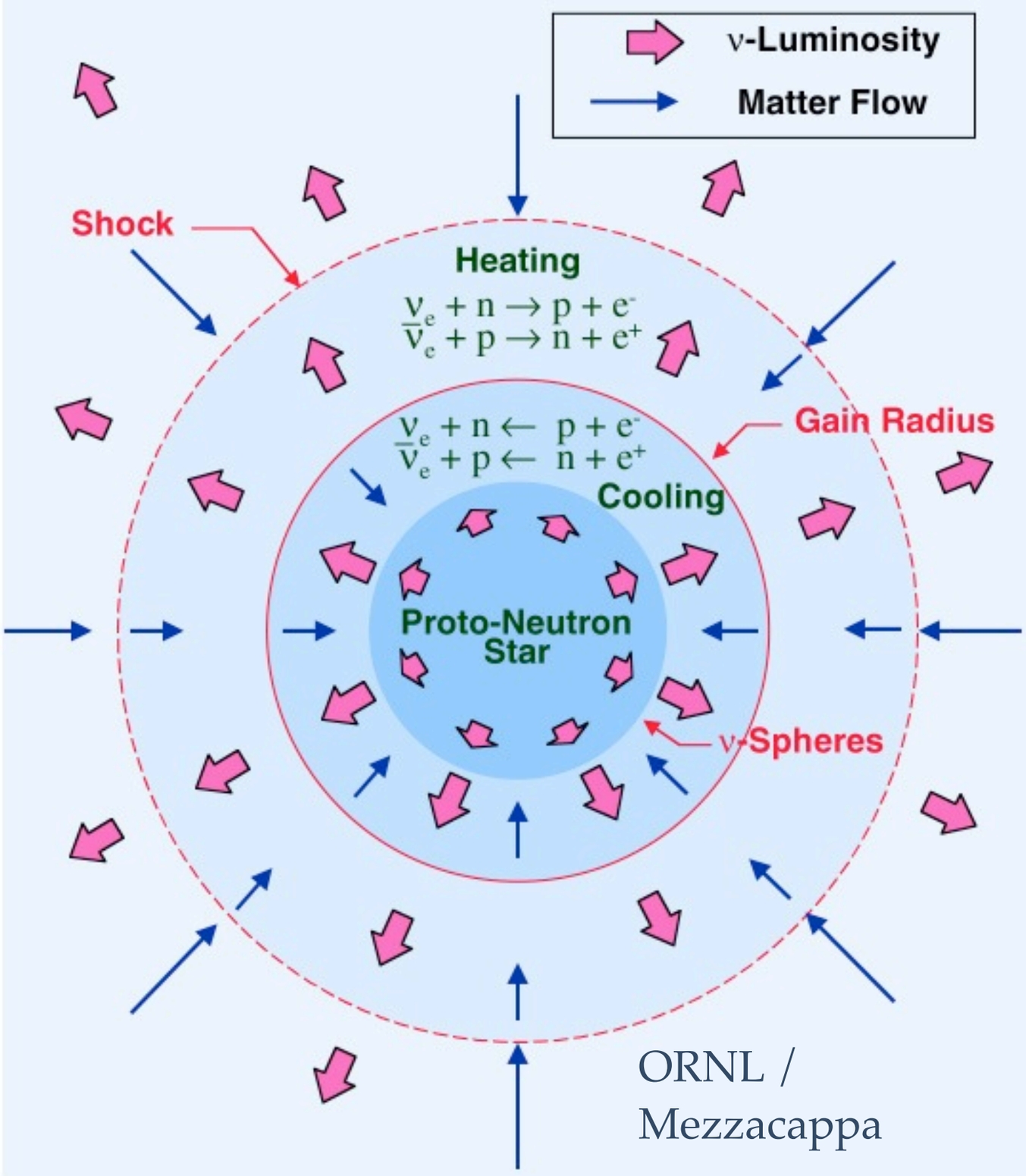
Current Status of Modern Simulations (from ~1995 - 2010):

Spherically Symmetric: Do not explode

Axisymmetric: Marginal explosions for a few cases

Three Dimensional: ???

Core collapse



ORNL / Mezzacappa

Potentially Important Ingredients

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

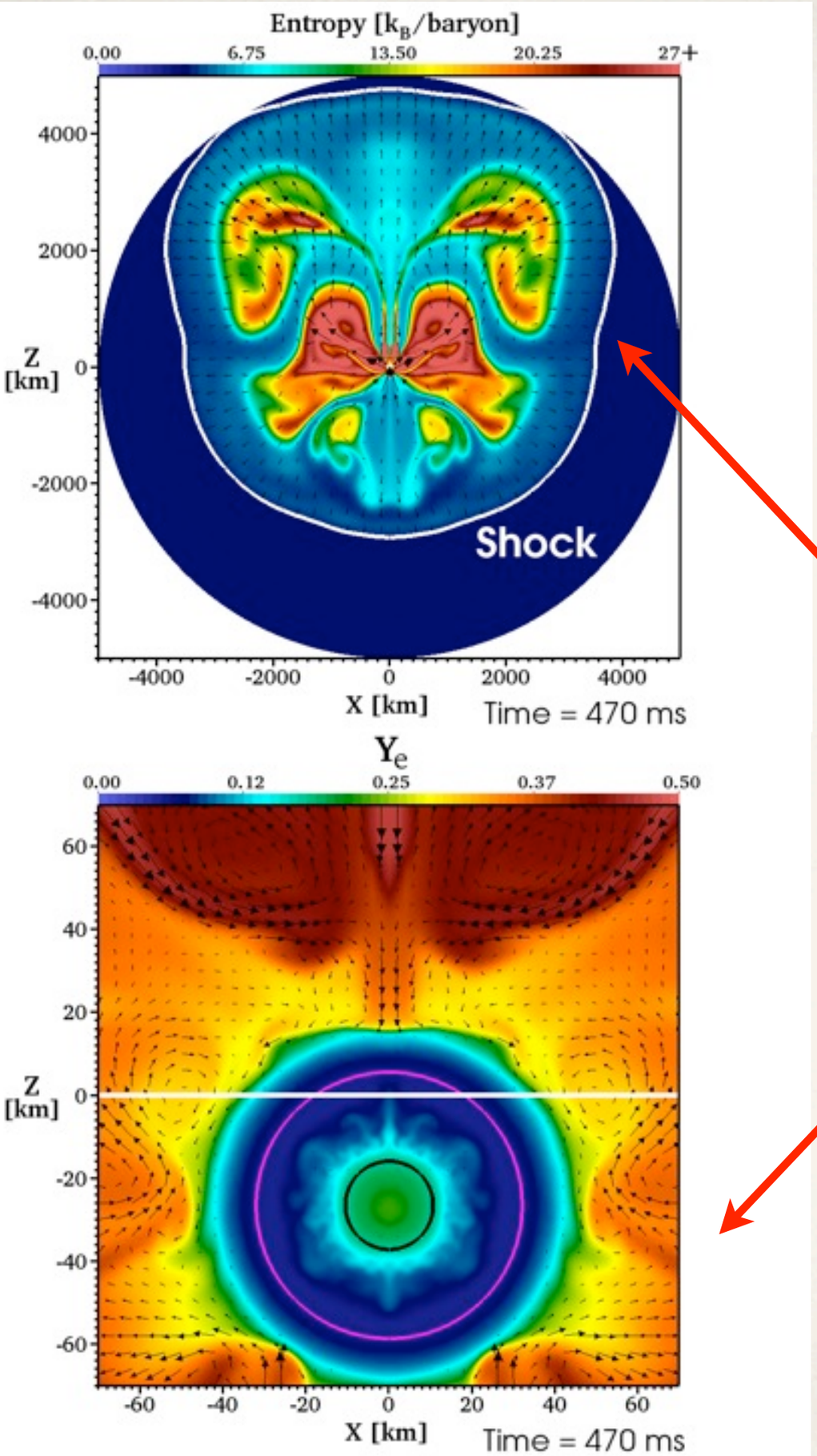
Multi-dimensional effects important!

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

Recoil from Core Collapse

The Hydrodynamic Mechanism of Pulsar Kicks

Neutron Star Kicks I



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

VULCAN/2D - Rad-hydro simulation

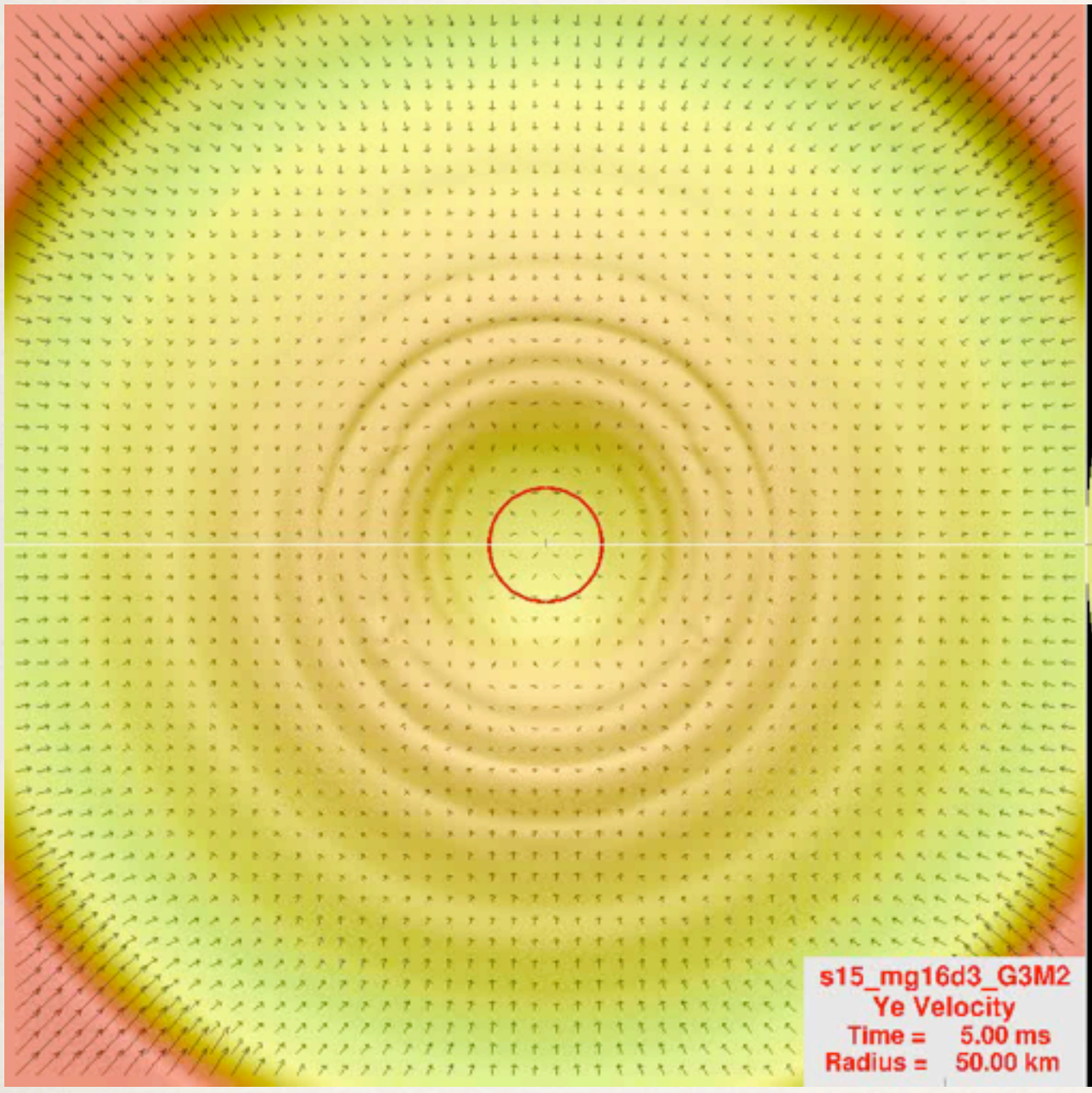
Nordhaus et al. 2010a

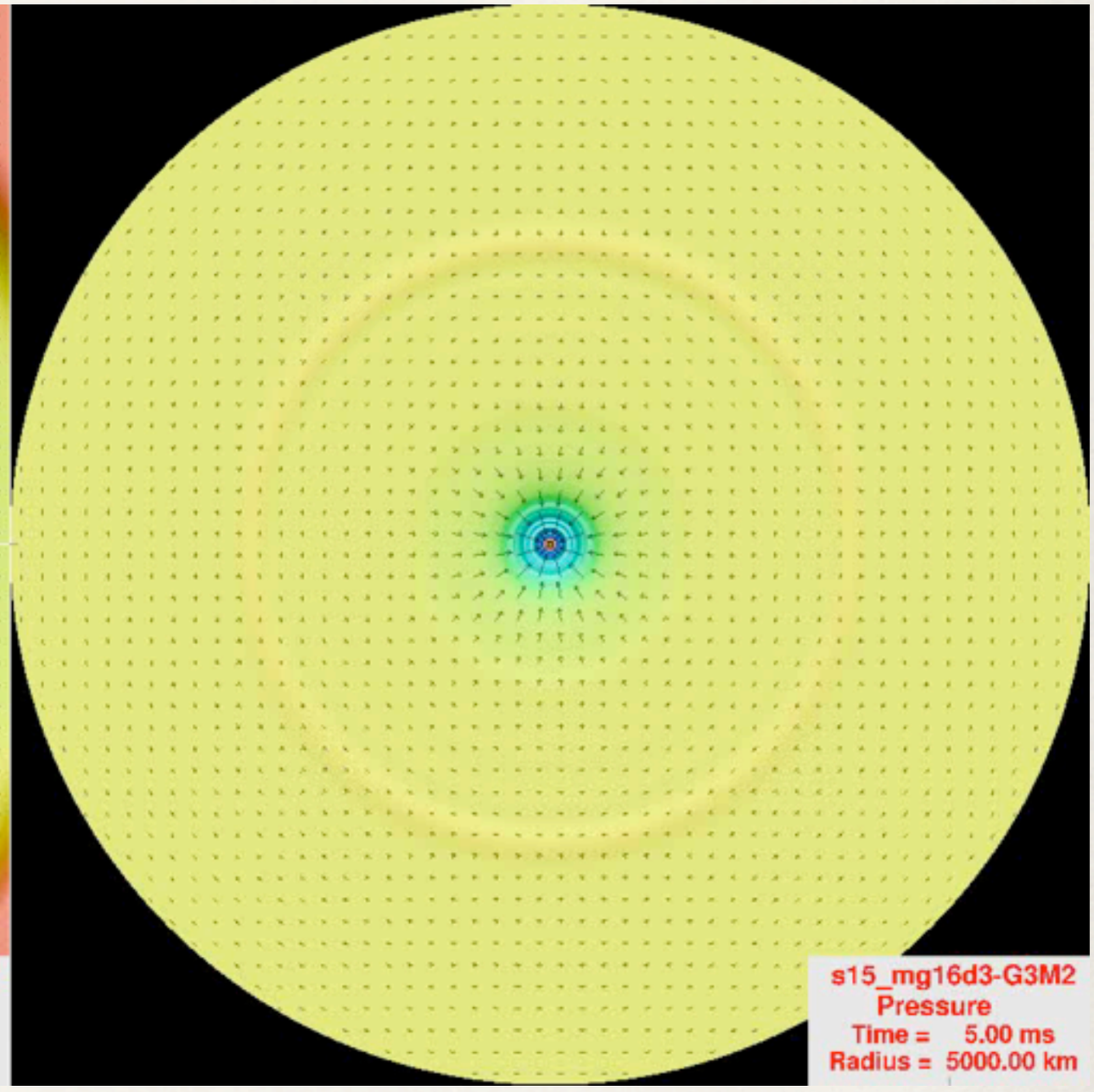
Explosion primarily in +Z direction...

...leads to NS recoil in -Z direction

see also Scheck et al. 2006;
Wongwathanarat et al. 2010

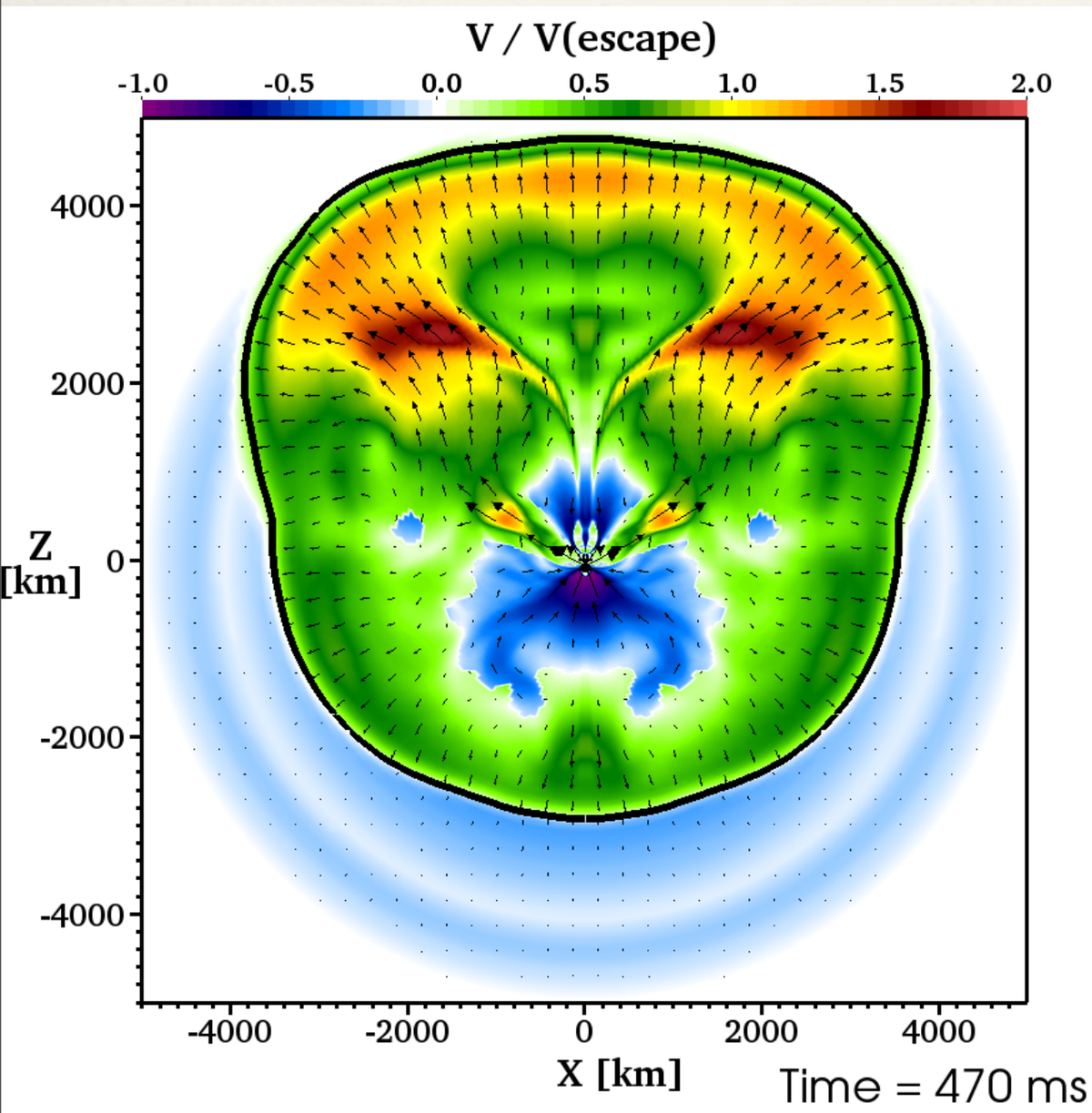
Neutron Star Kicks II

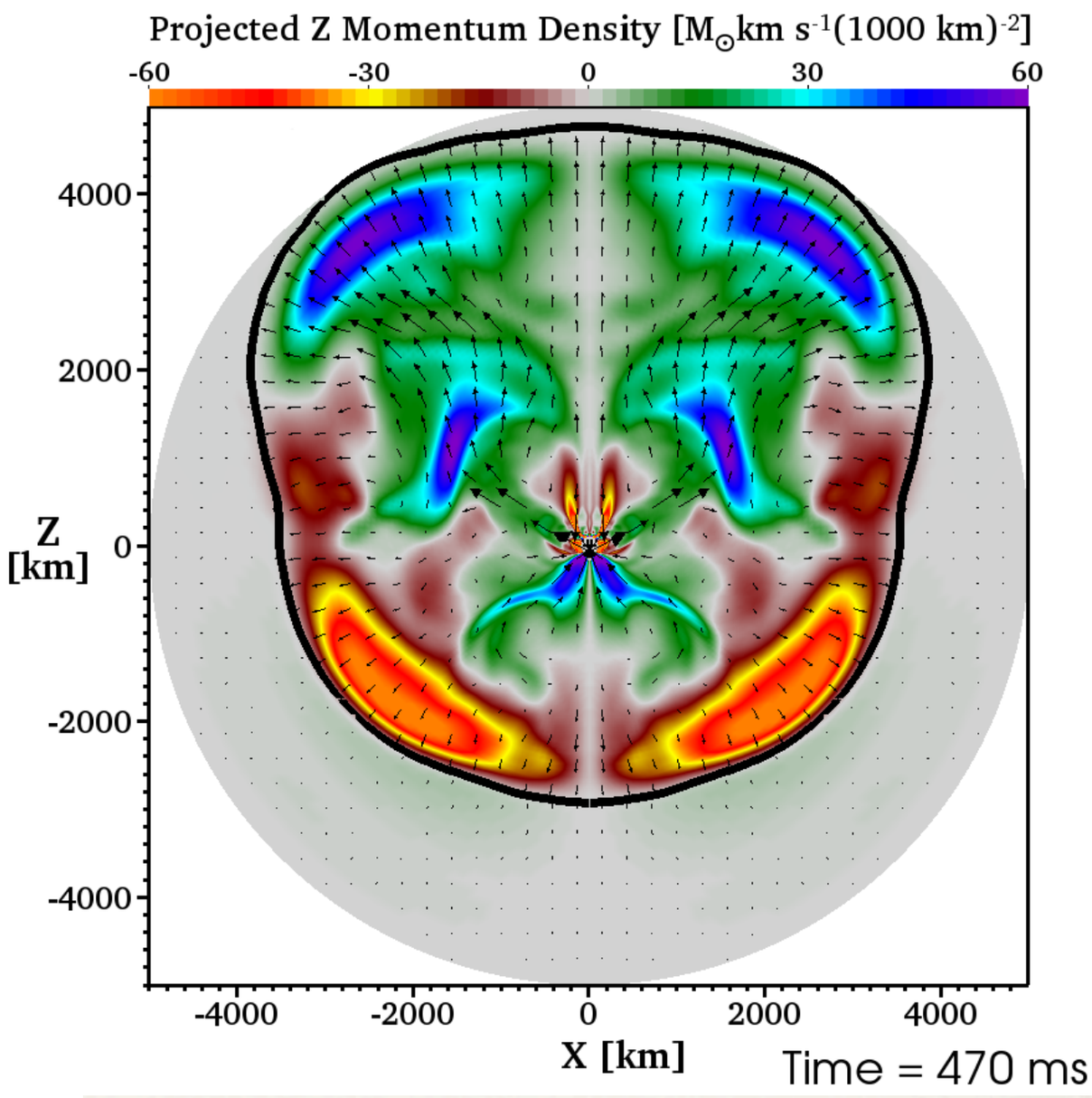




Nordhaus et al. 2010a

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!

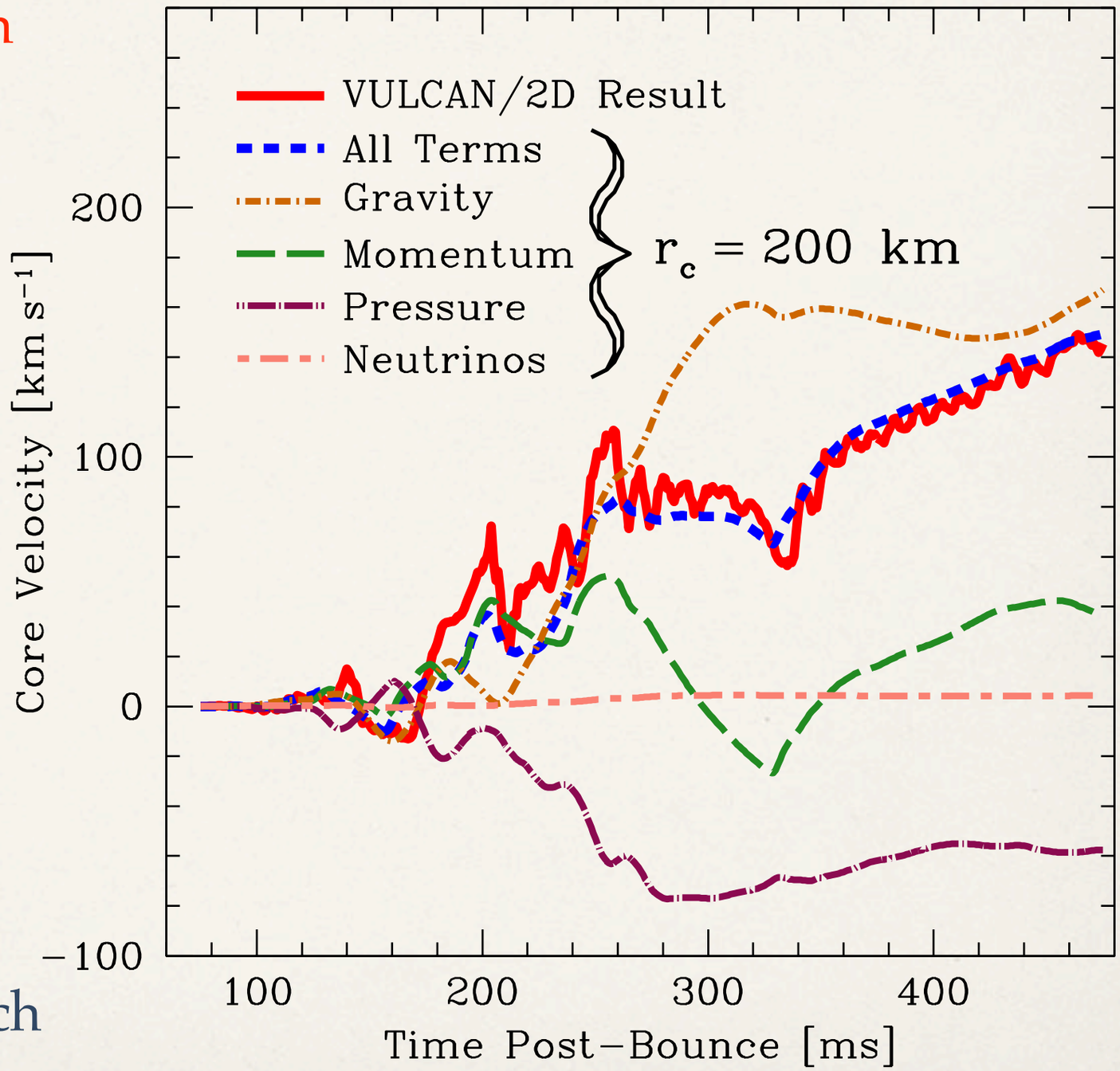
Gravitational tugboat effect
is important.

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

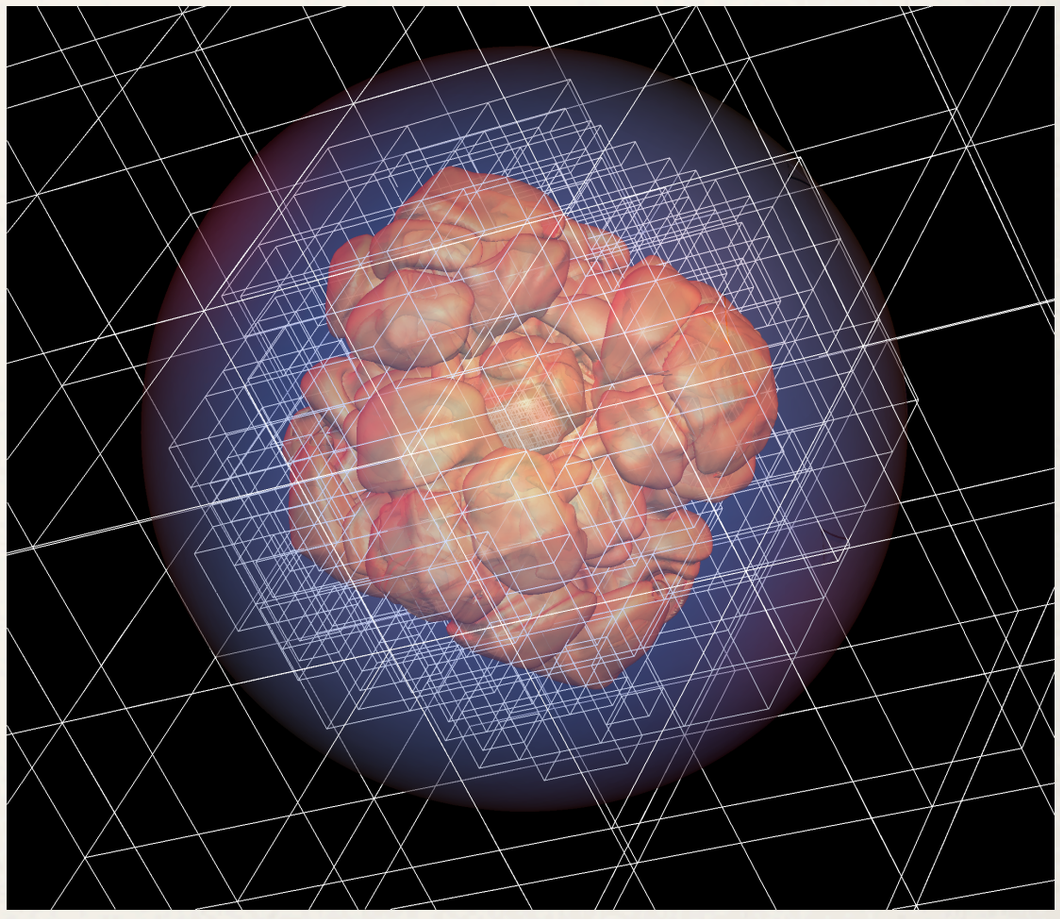
3D Core Collapse

Very different from 1D and 2D core collapse!

CASTRO: Compressible Astrophysics

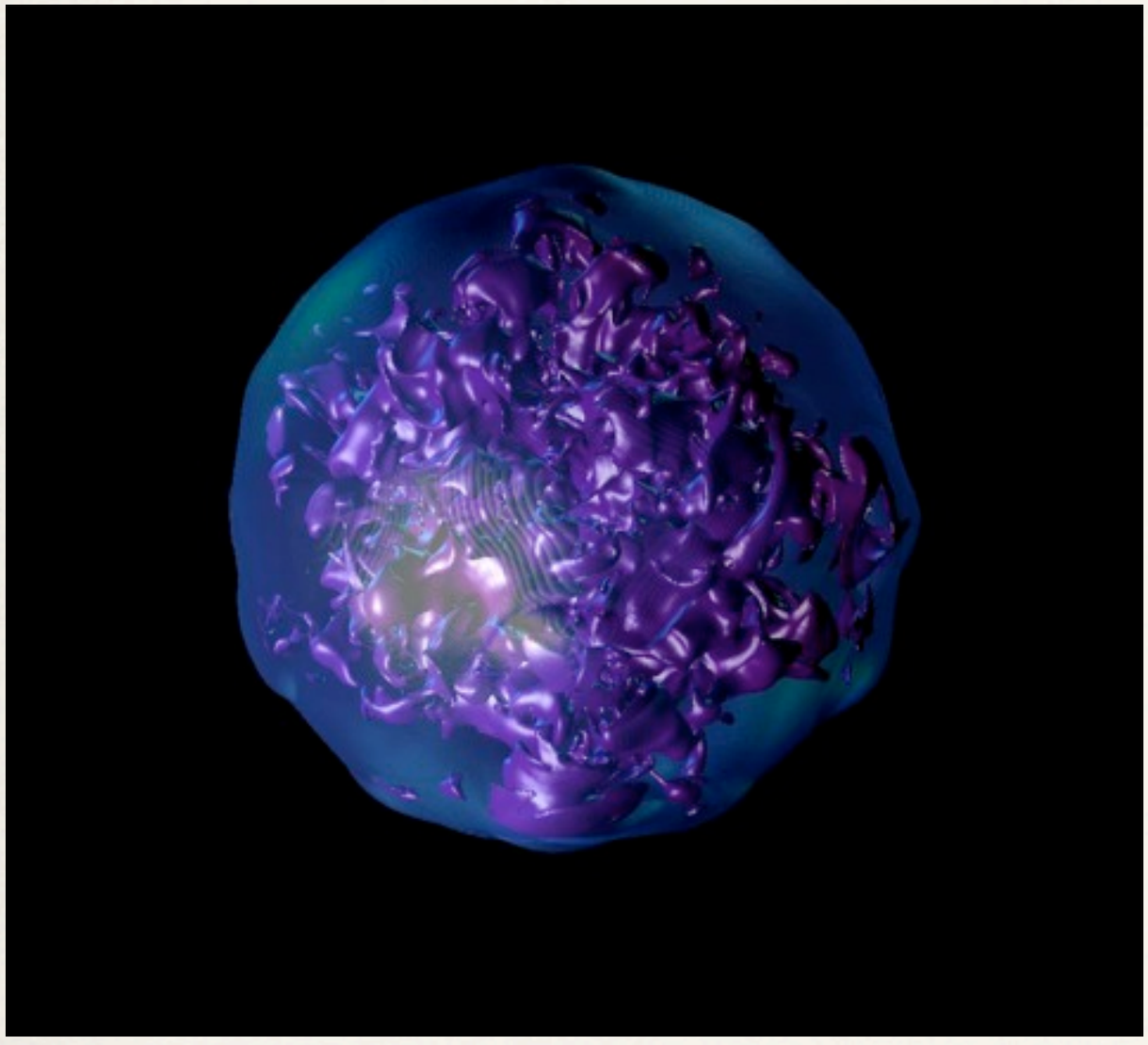
- New multi-D radiation-hydrodynamics code
- Adaptive mesh refinement (AMR) with sub-cycling in time
- Advection: 2nd order, unsplit piecewise-linear or PPM
- Radiation: multi-group flux limited diffusion
- Gravity: Monopole or multi-grid Poisson solve
- Scales to over 200,000 cores!

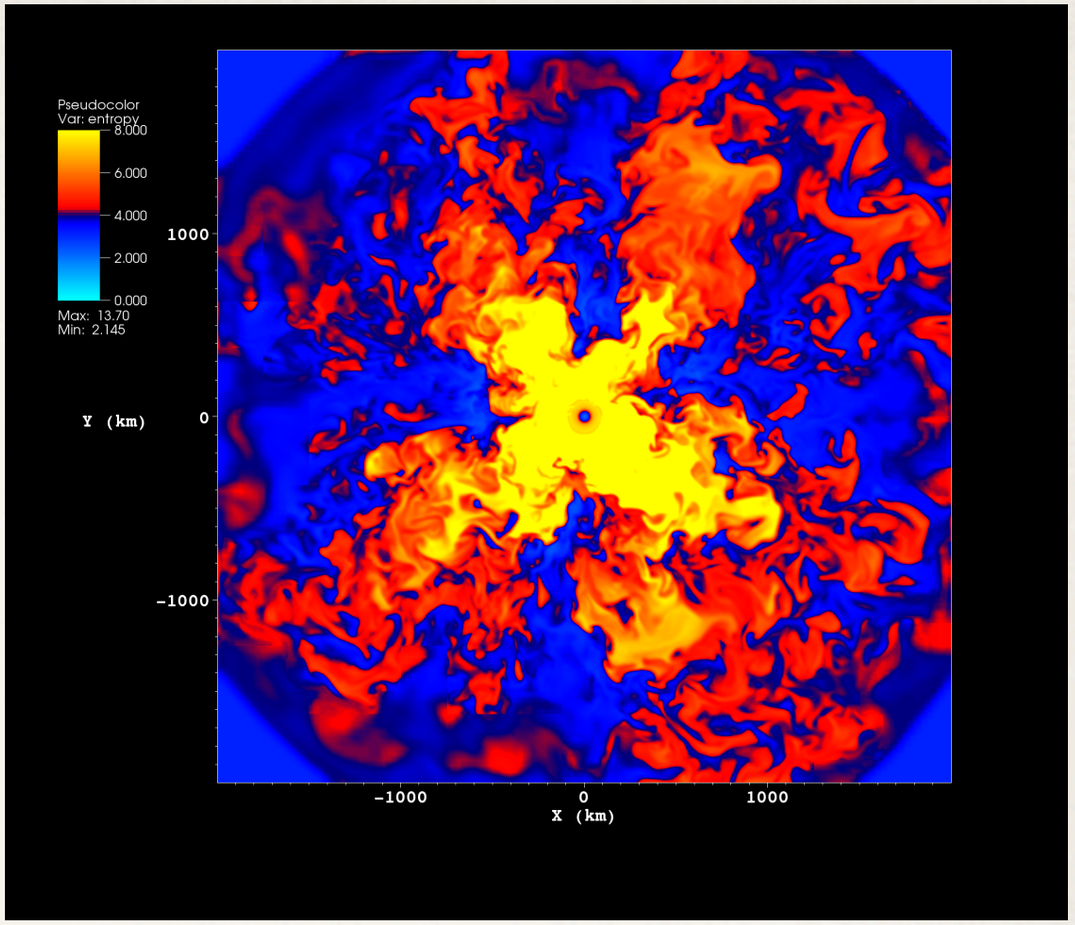
Team: Ann Almgren (LBL)
John Bell (LBL)
Louis Howell (LLNL)
Adam Burrows (Princeton)
Jason Nordhaus (Princeton)

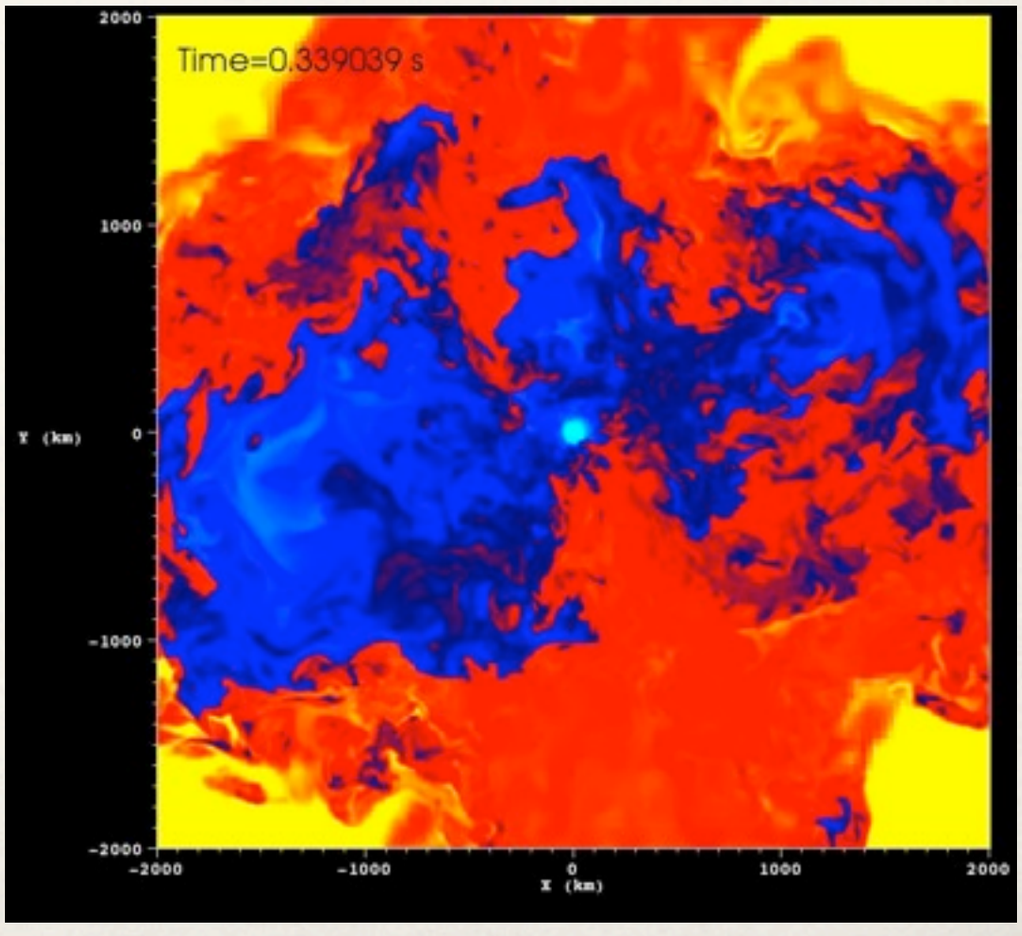


3D AMR block structure

CASTRO
Simulations

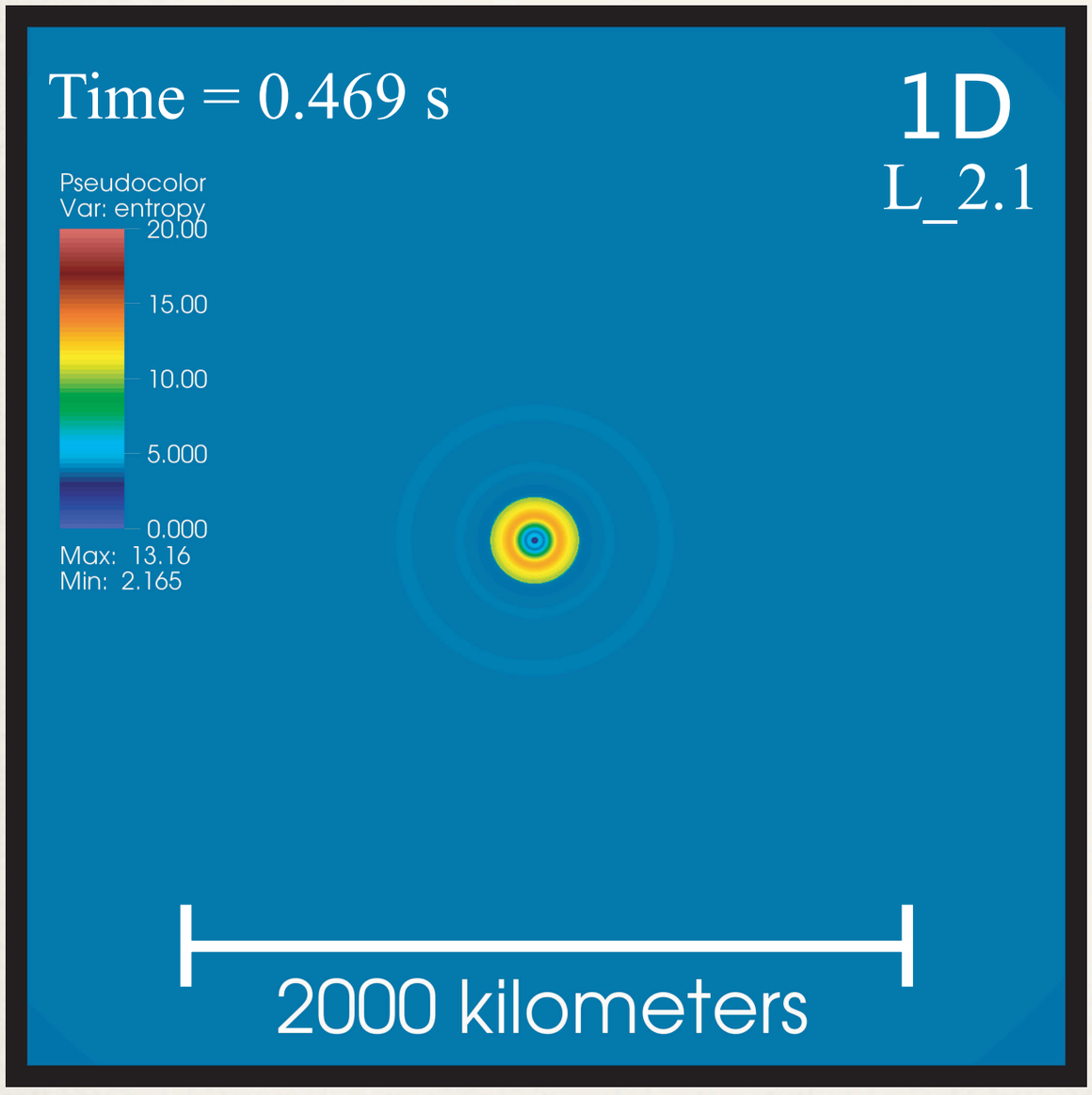




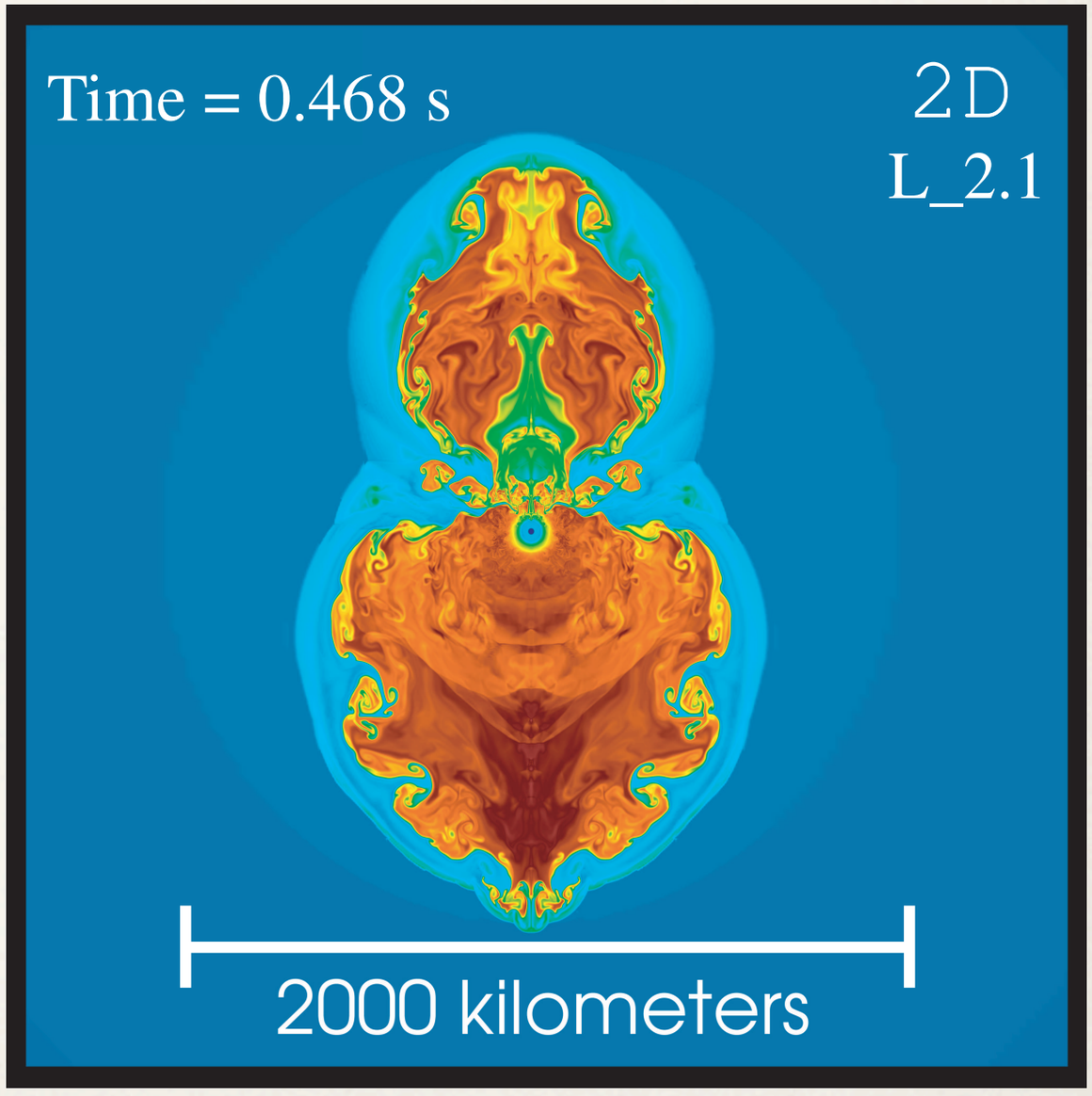


Dimensional Dependence

Spherically Symmetric



Axisymmetric

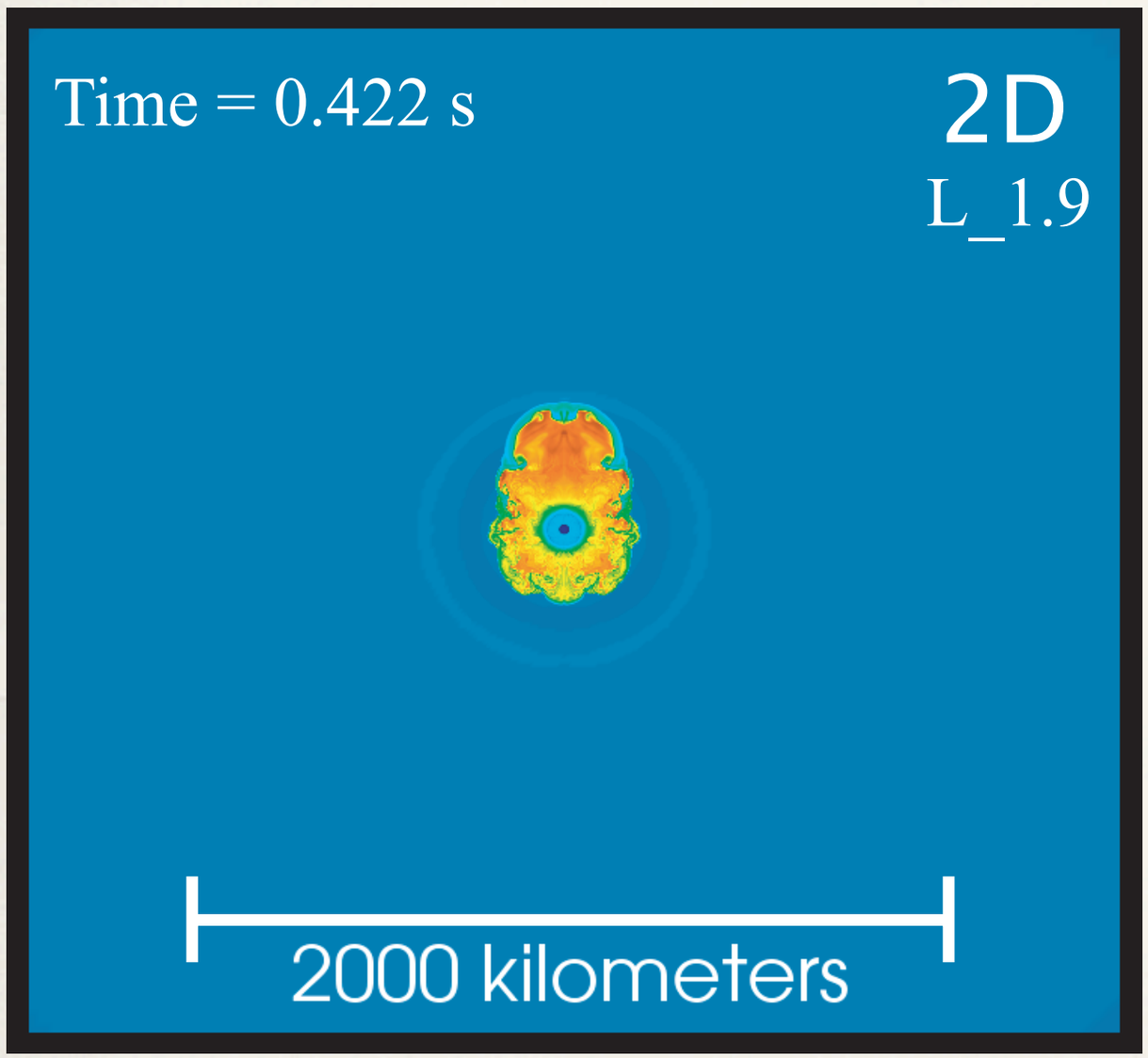


Nordhaus et al. 2010b

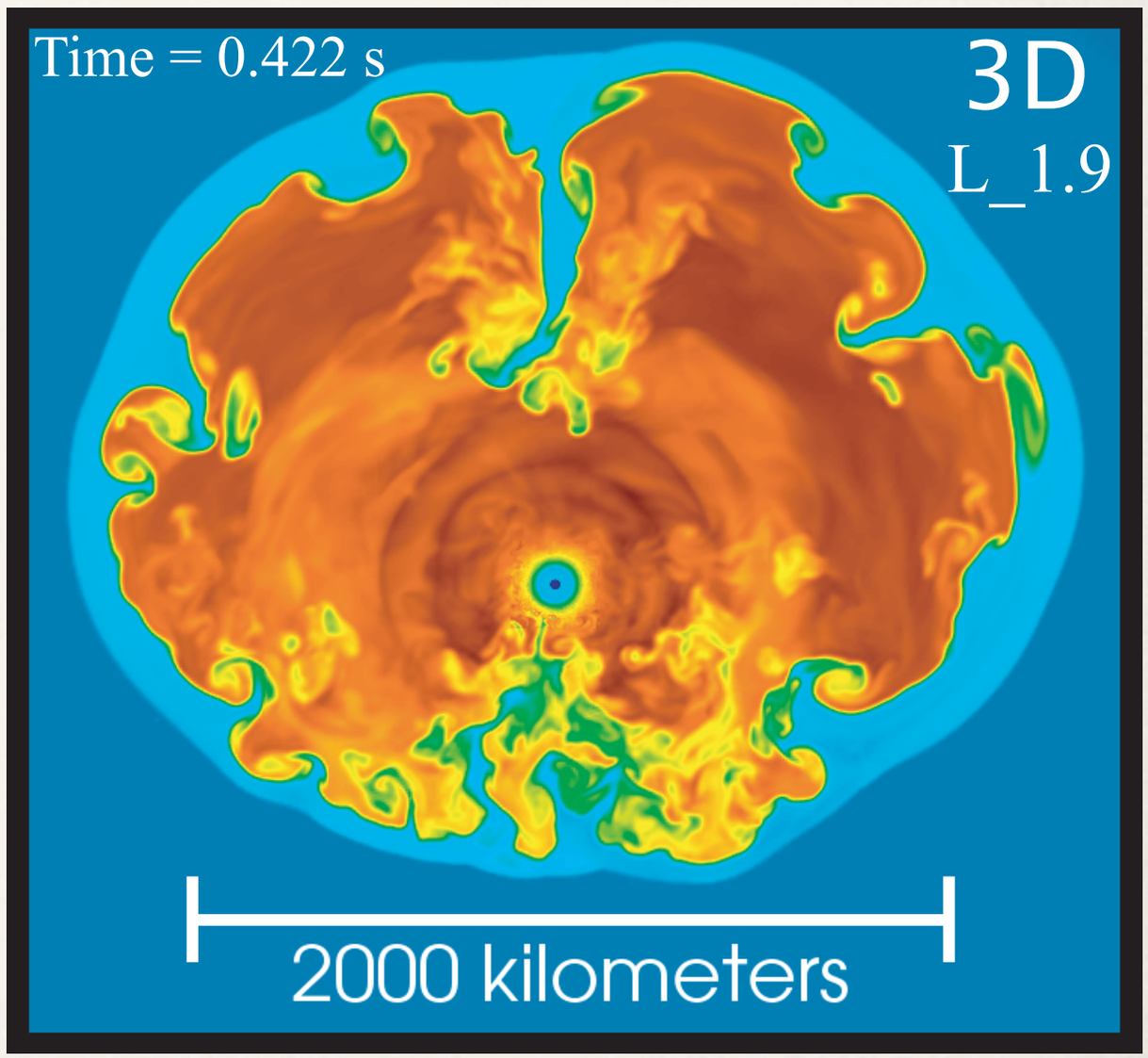
see also Burrows & Goshy 1993; Murphy & Burrows 2008

Dimensional Dependence

Axisymmetric



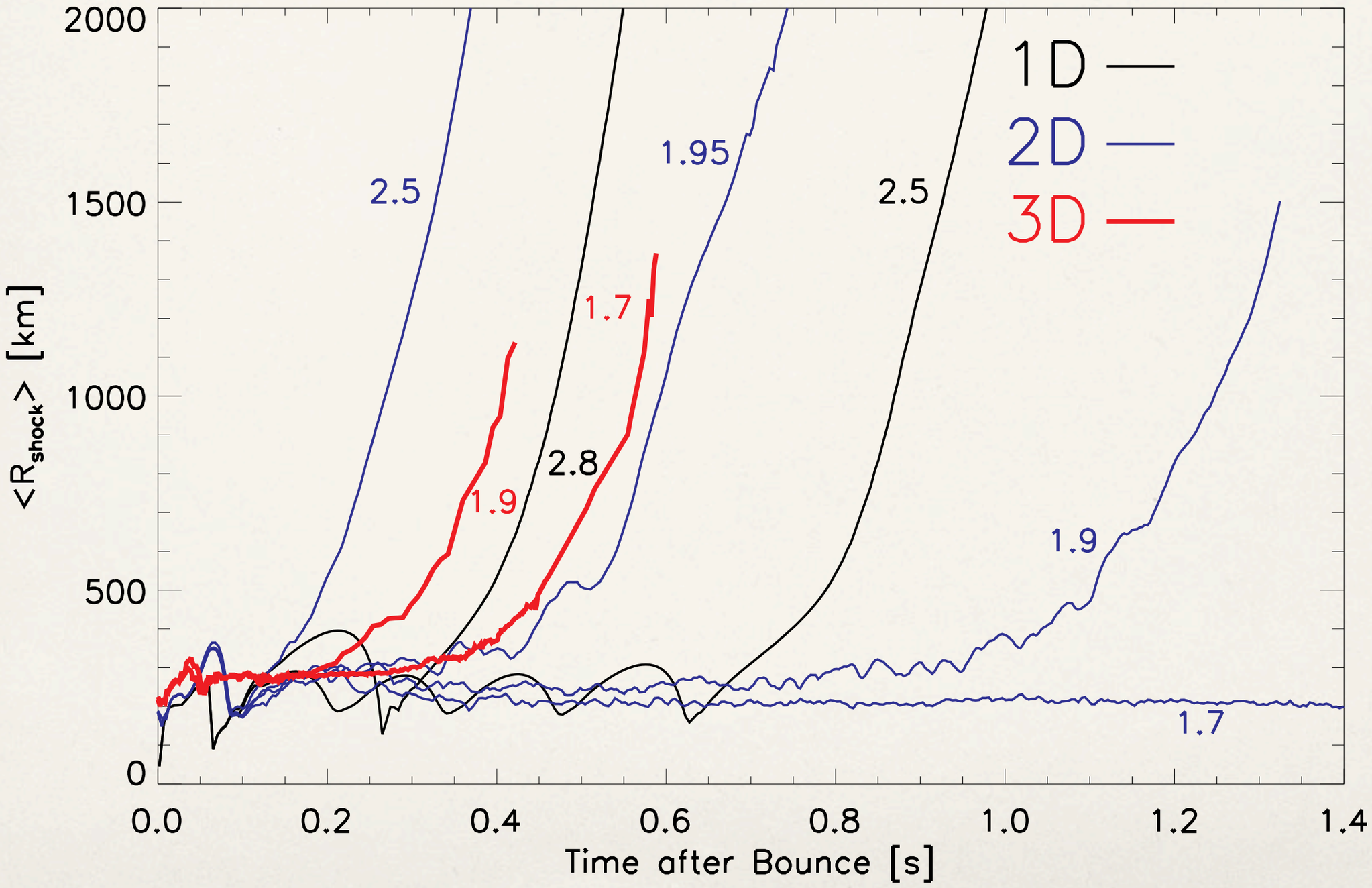
Three Dimensional



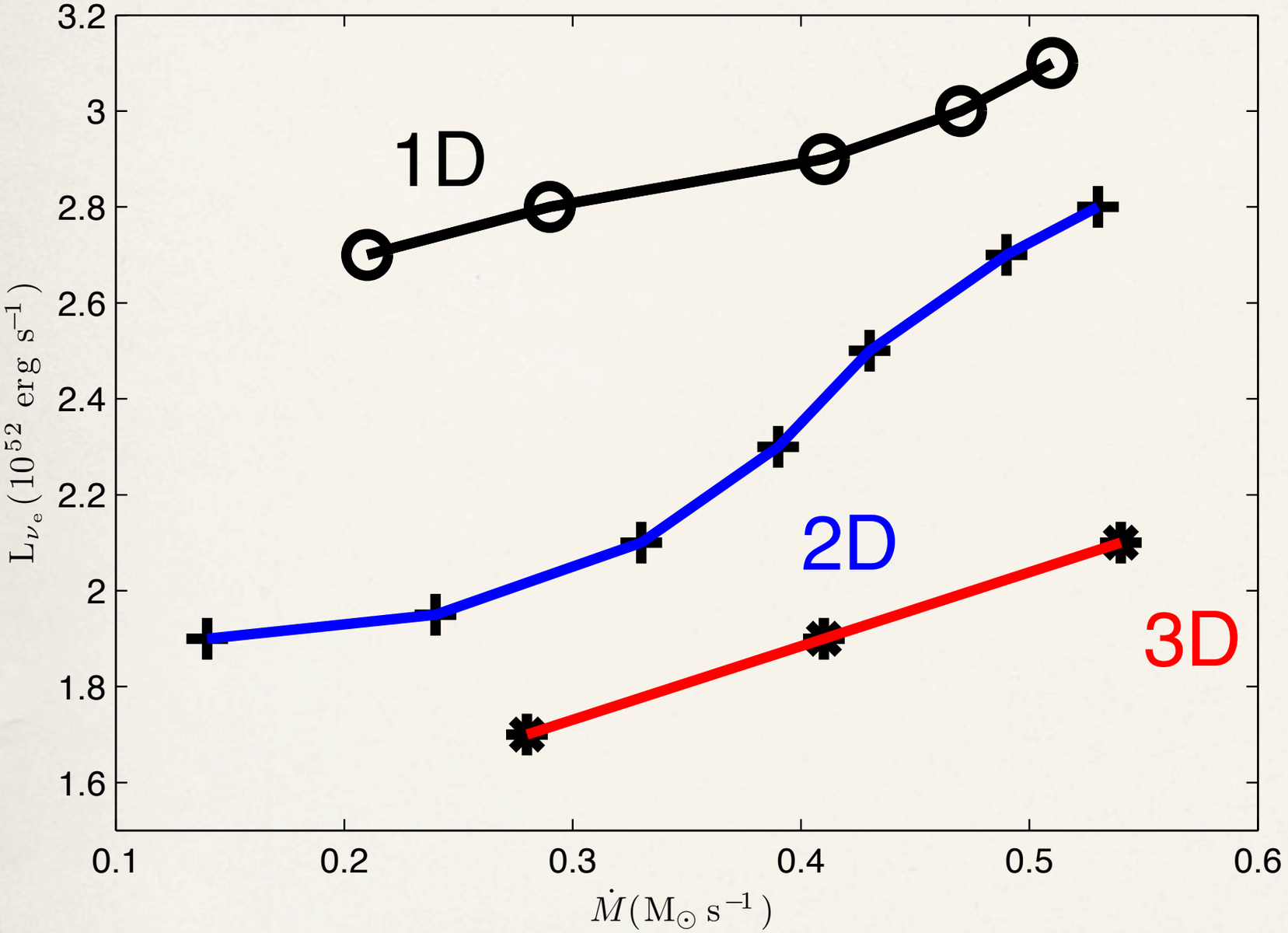
Nordhaus et al. 2010b

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!

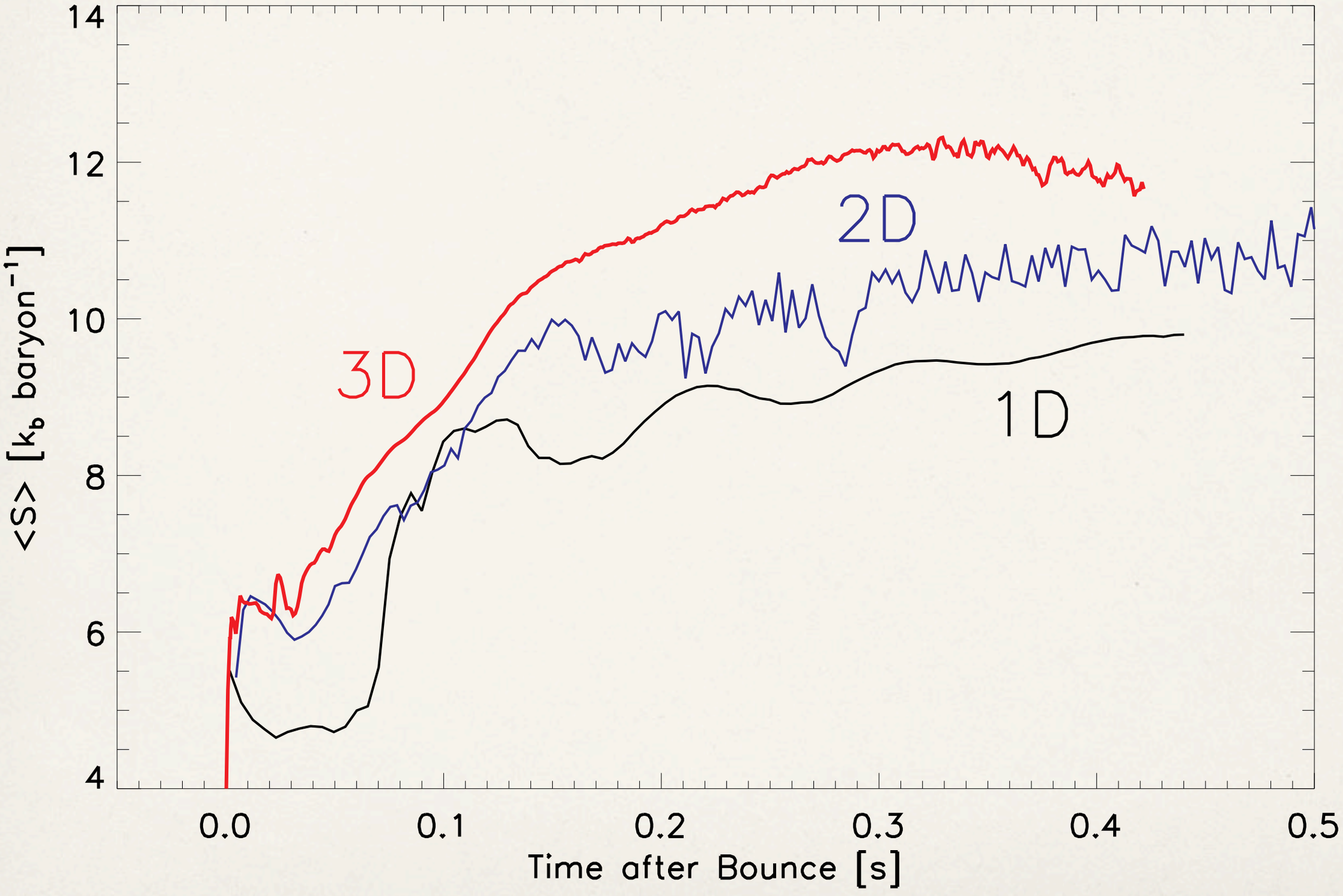
Bigger effect in magnitude than:

- inelastic scattering
- general relativity
- nuclear burning

Nordhaus et al. 2010b

see also Burrows & Goshy 1993; Murphy & Burrows 2008

Higher Entropy and Longer Dwell Times



Standing Accretion Shock Instability (SASI)

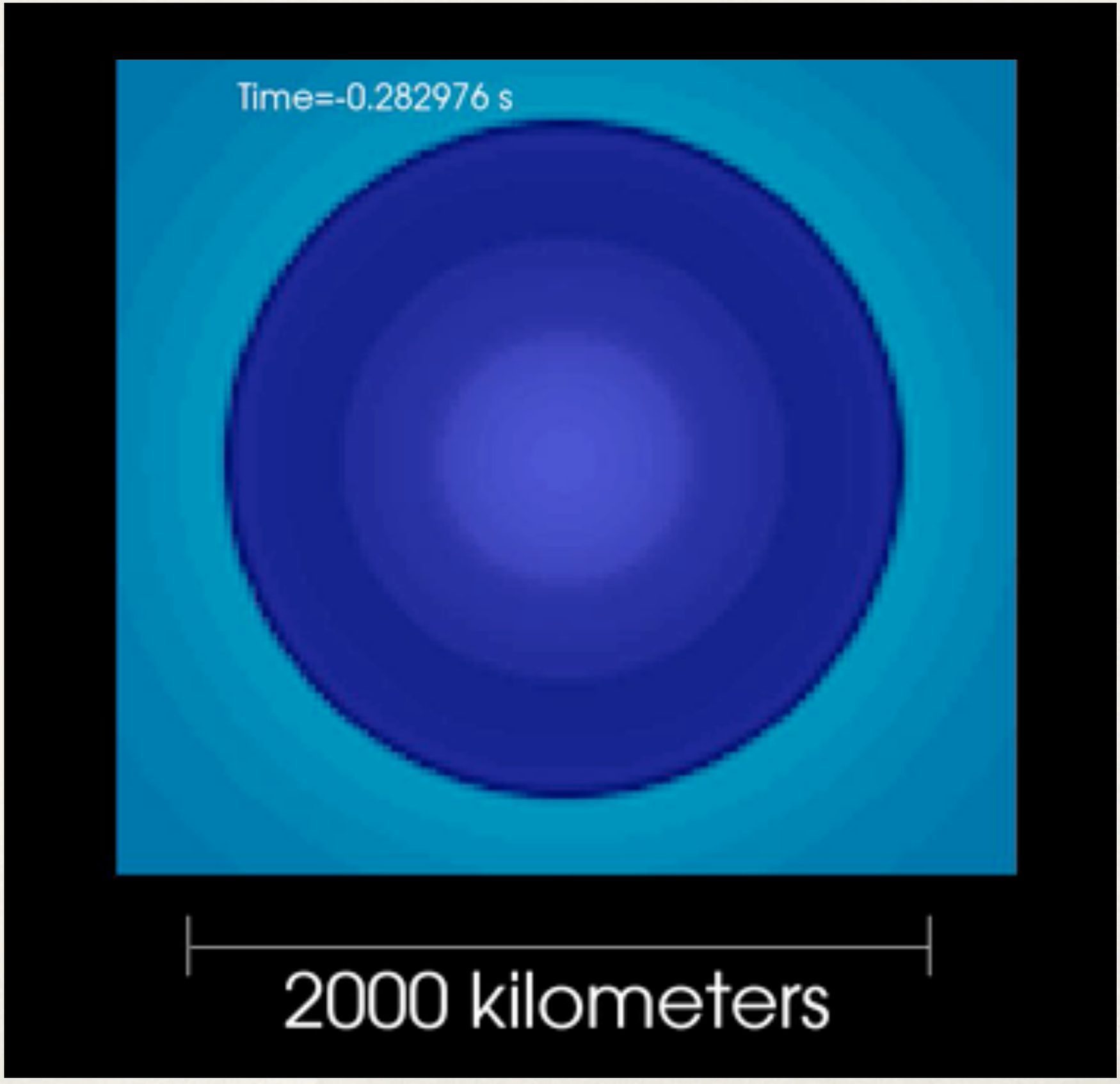
Axisymmetric

$\ell = 1$ mode is dominant

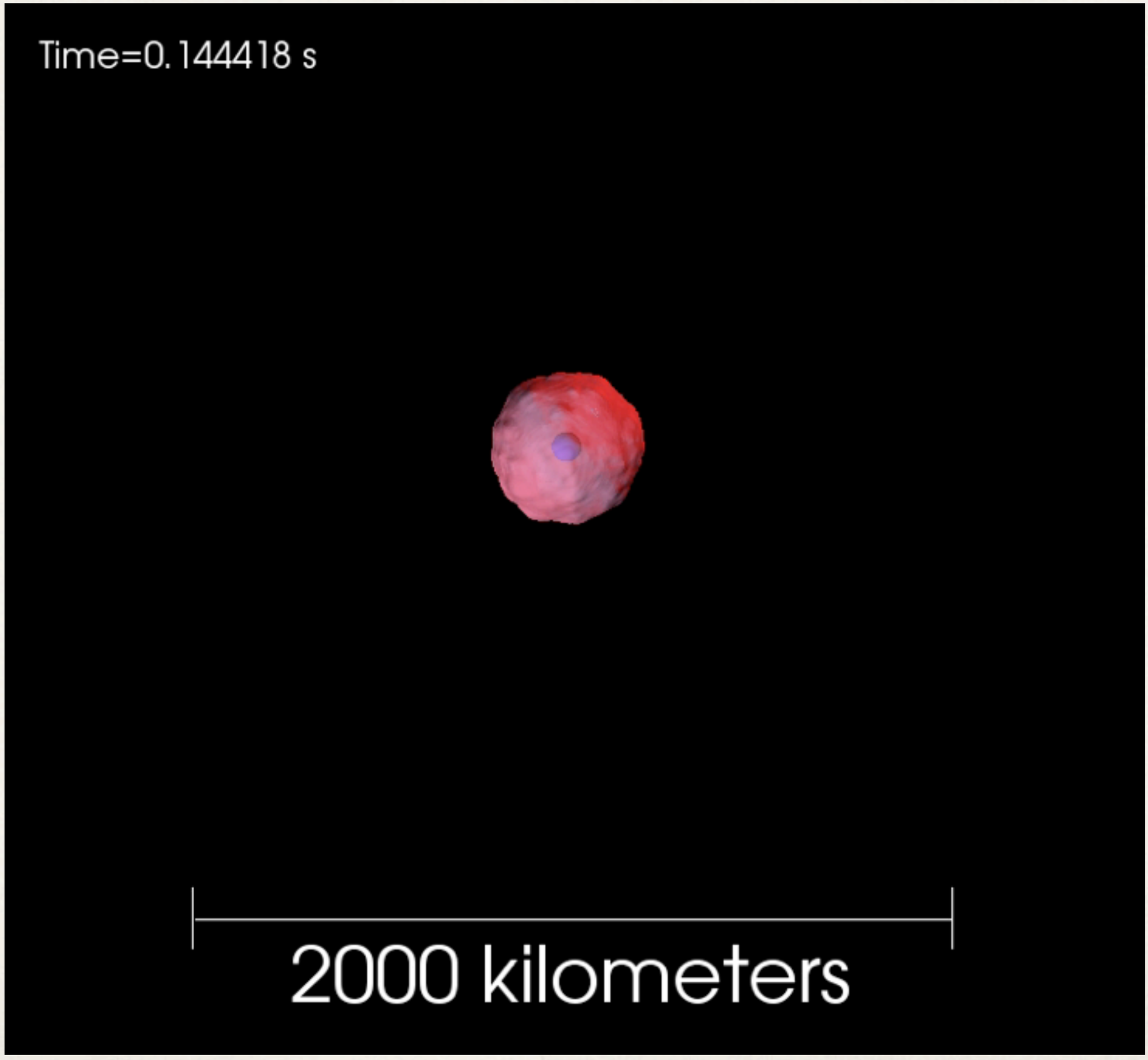
Suggested as a fundamental characteristic of SN dynamics and way to spin-up pulsars;

Blondin & Mezzacappa 2007

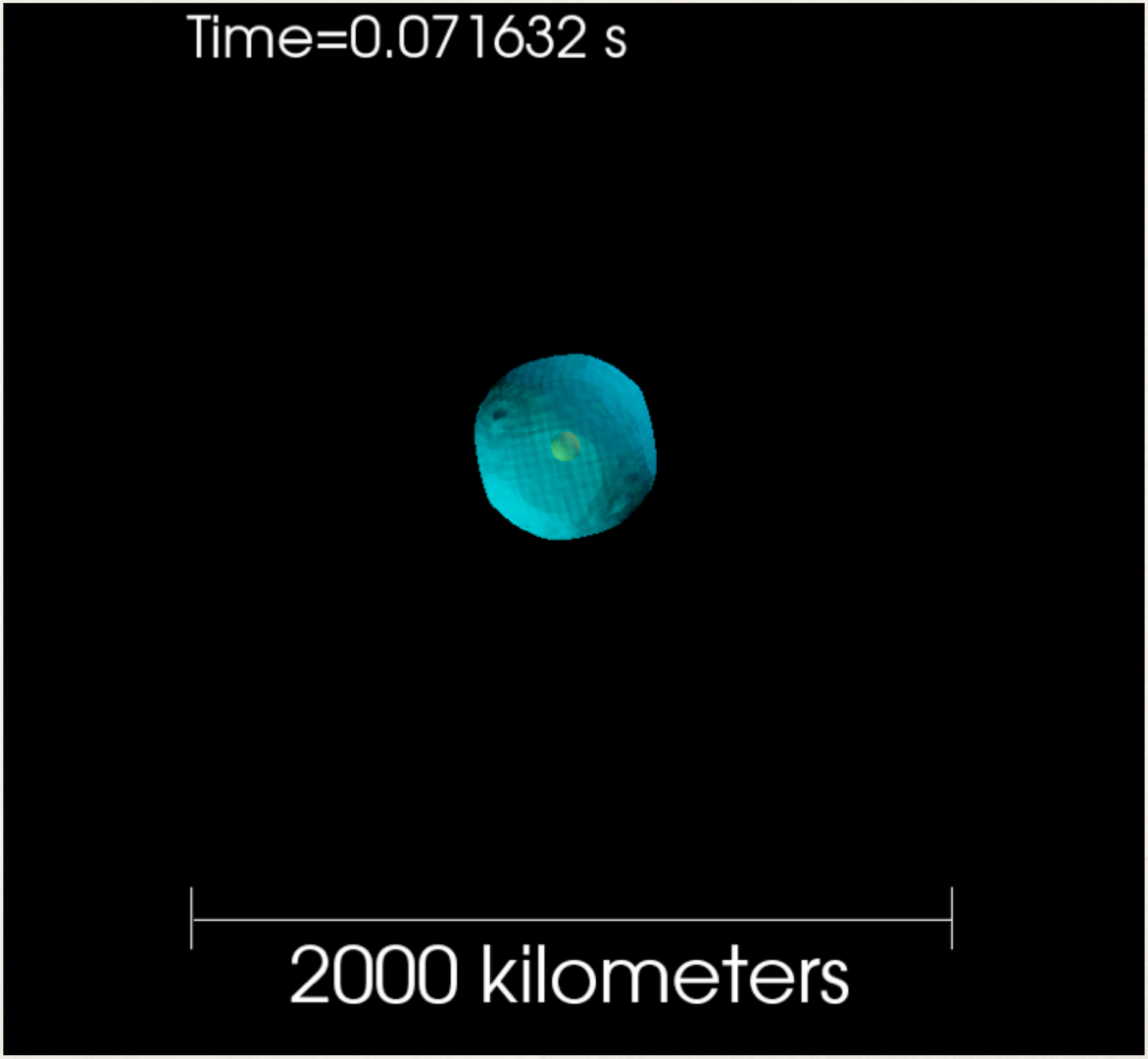
See talk by Emmanouela Rantsiou



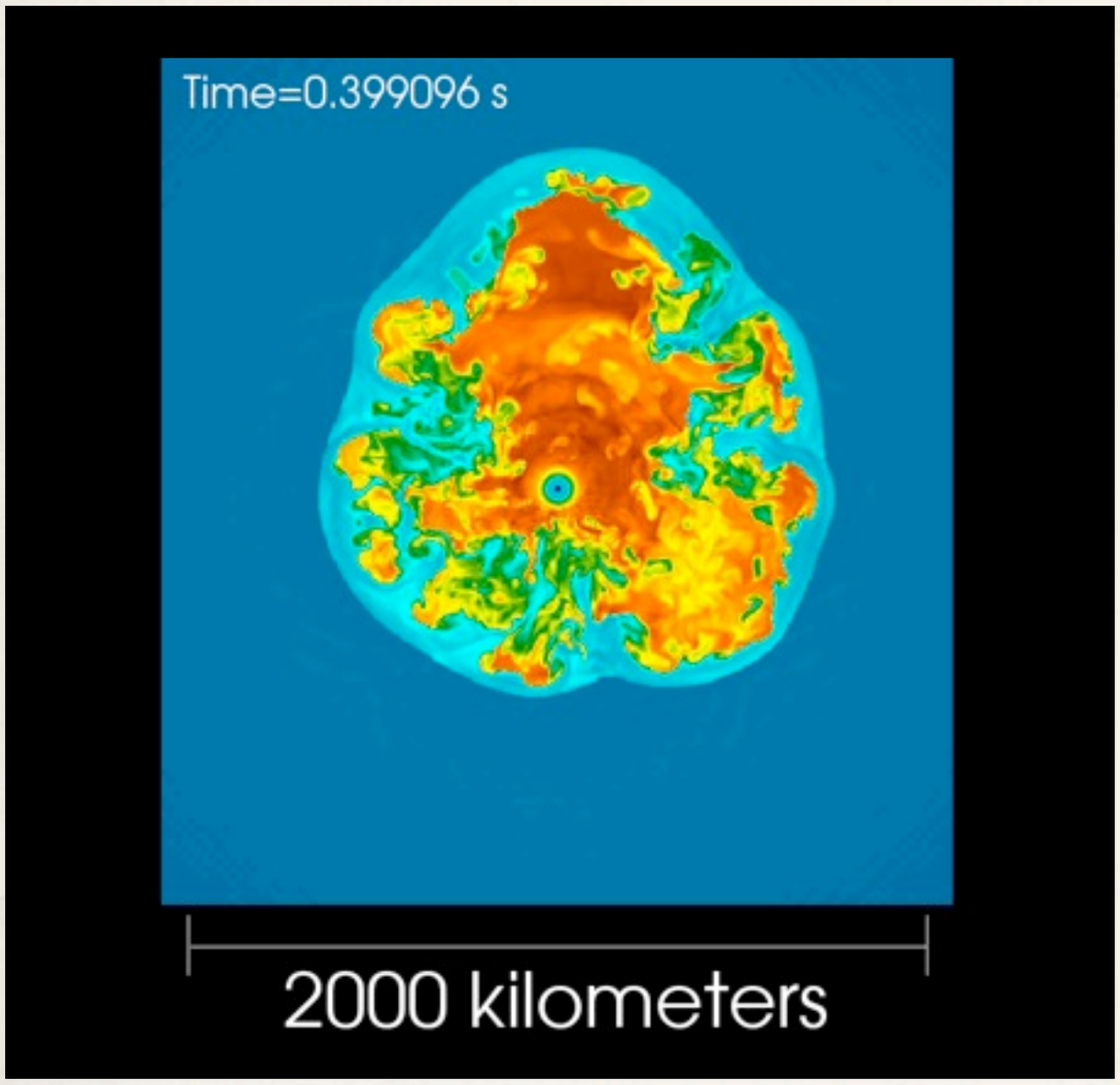
Non-Rotating Initial Model



Rotating Initial Model



Rotating Initial Model



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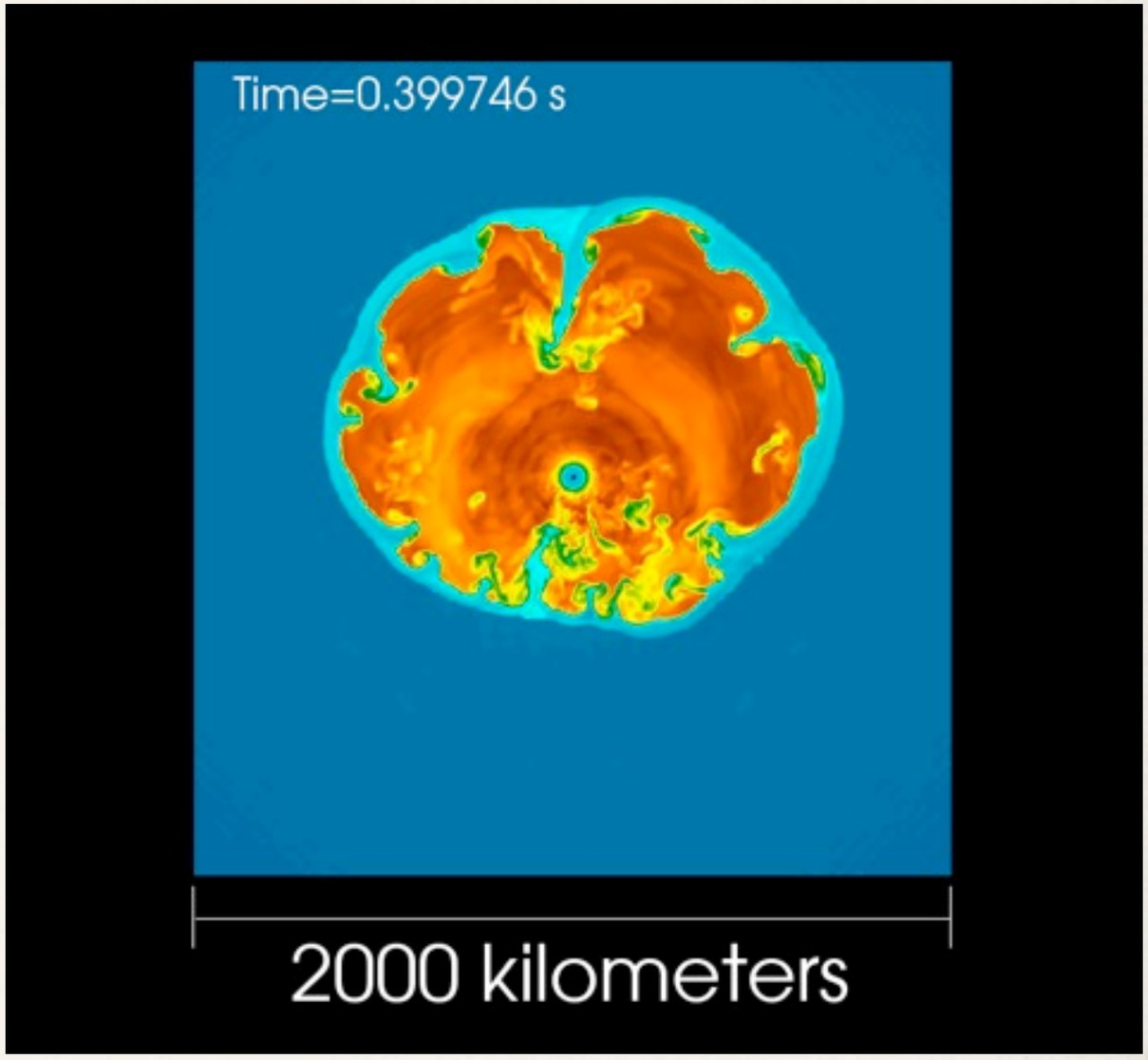


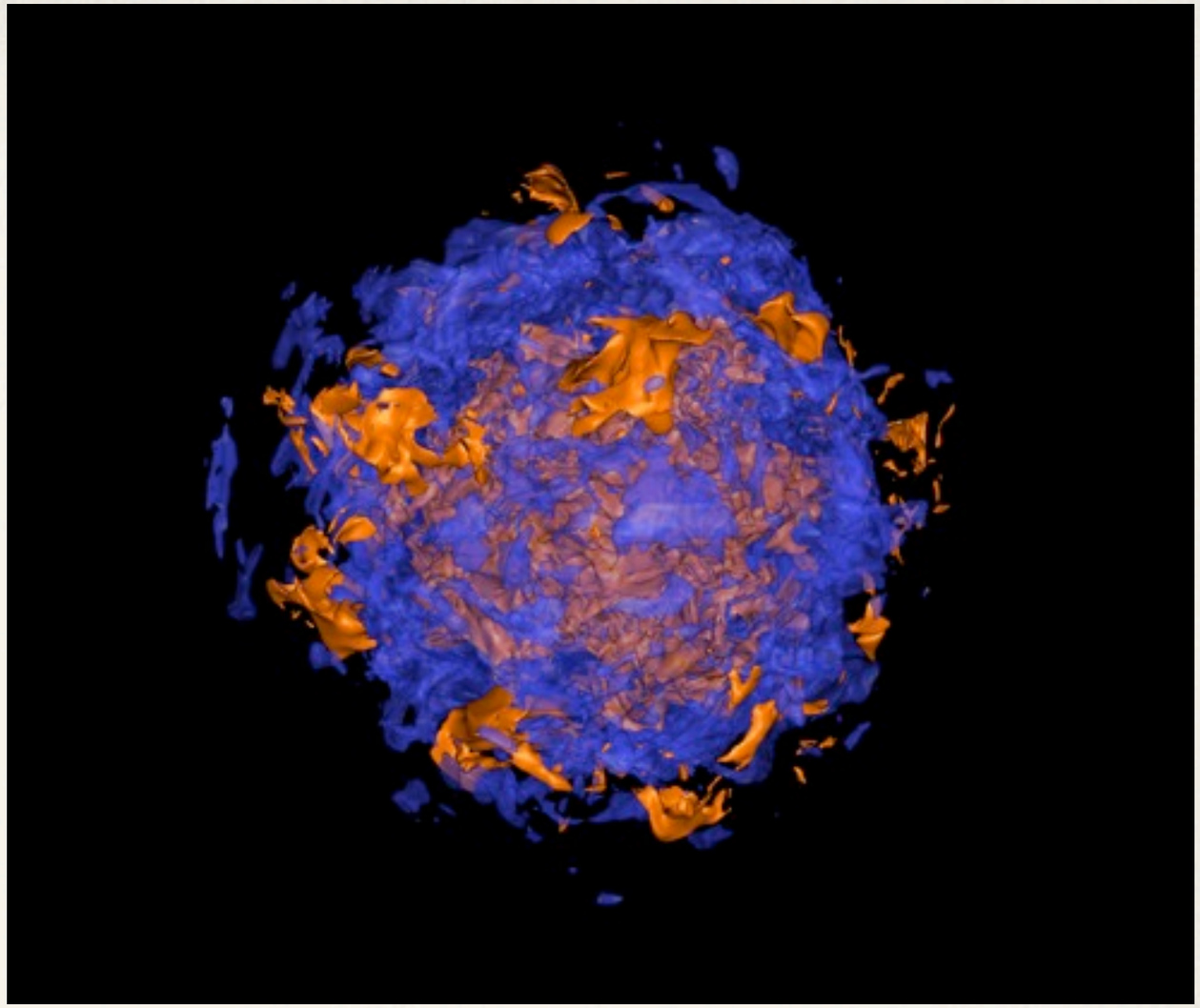
Explodes earlier and more mixing of ejecta

Initial rotation produces a preferred axis

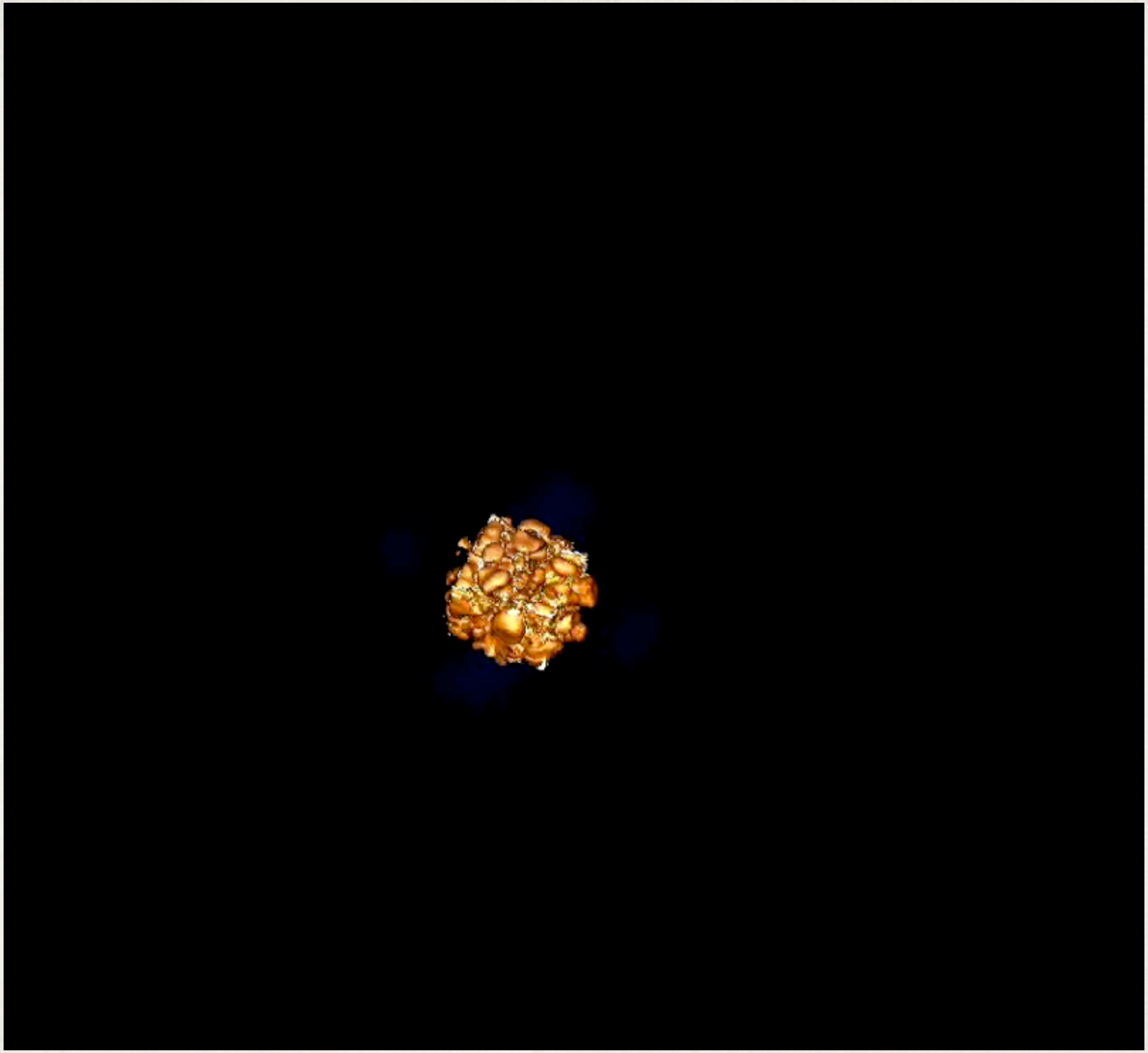
Visualization: Hank Childs [LBNL]

Conclusions

- Recoil may be natural outcome of hydrodynamics during core collapse.
- Need 3D calculations to produce kick velocity distribution.
- Dimensional dependence for core-collapse supernova explosions!
- 50% easier to explode in 3D vs. 1D - all else being equal.



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



Friday, October 22, 2010