Title: Recent advances in core-collapse supernova theory

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Abstract: For approximately half a century, core-collapse supernovae have posed a vexing puzzle for theorists despite being a major ingredient (and uncertainty) in fields ranging from stellar and galaxy evolution to the interstellar medium. Historically, advances in core-collapse theory have been linked to advances in computing power and software. Supernovae are inherently multi-dimensional objects in which neutrino transport, gravity, hydrodynamic instabilities and convection play important roles. Three-dimensional simulations incorporating sufficient physical fidelity require extensive high-performance computing resources and codes efficient enough to use the associated architecture. In this talk, I will highlight recent advances in the field. In particular, I will discuss the dependence of spatial dimension on the viability of the neutrino mechanism and the origin of pulsar kicks.

Recent advances in core-collapse supernova theory

J. Nordhaus
Princeton University

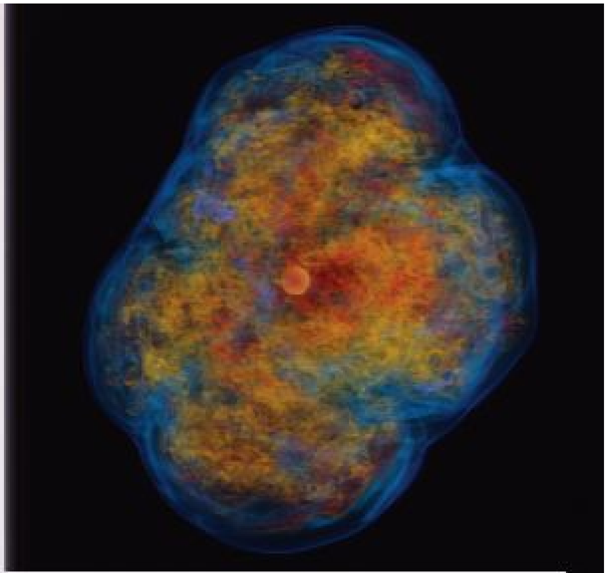
MICRA Workshop 6.21.11

SciDAC

Office of Science

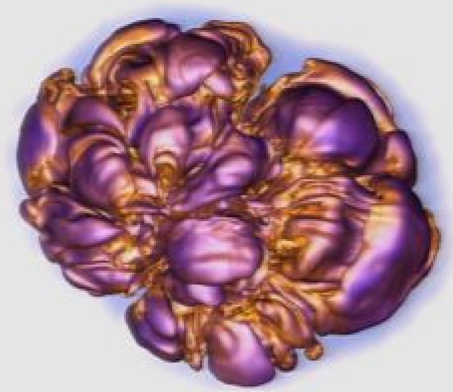
Multi-dimensional core collapse.

- spatial dependence of the neutrino mechanism: 1d vs. 2d vs. 3d



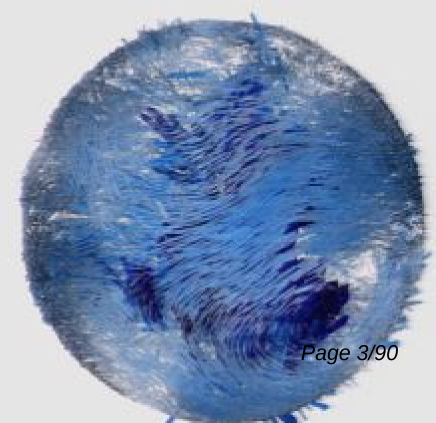
The origin of neutron star kicks.

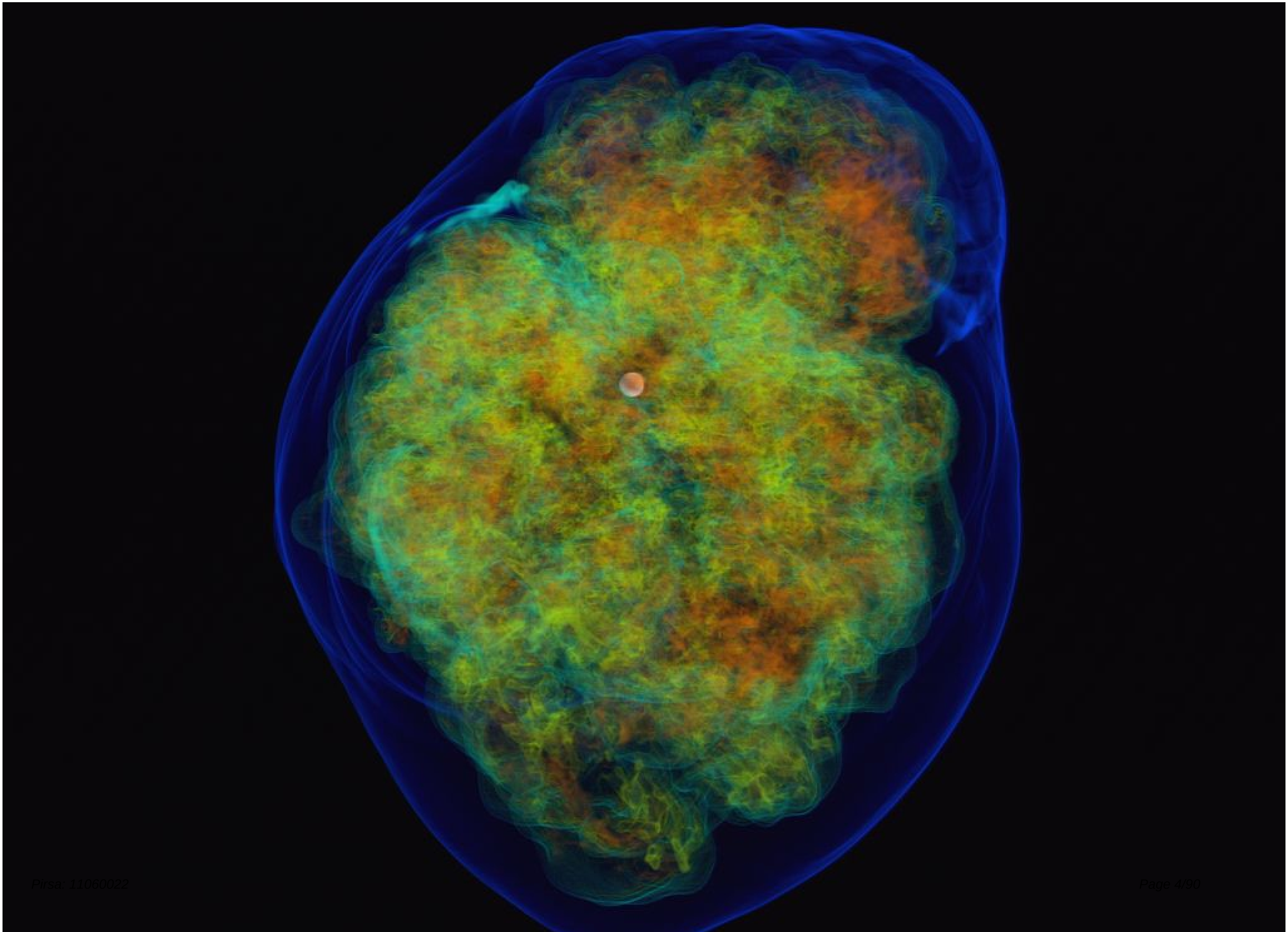
- hydrodynamic recoil naturally leads to observed pulsar kicks



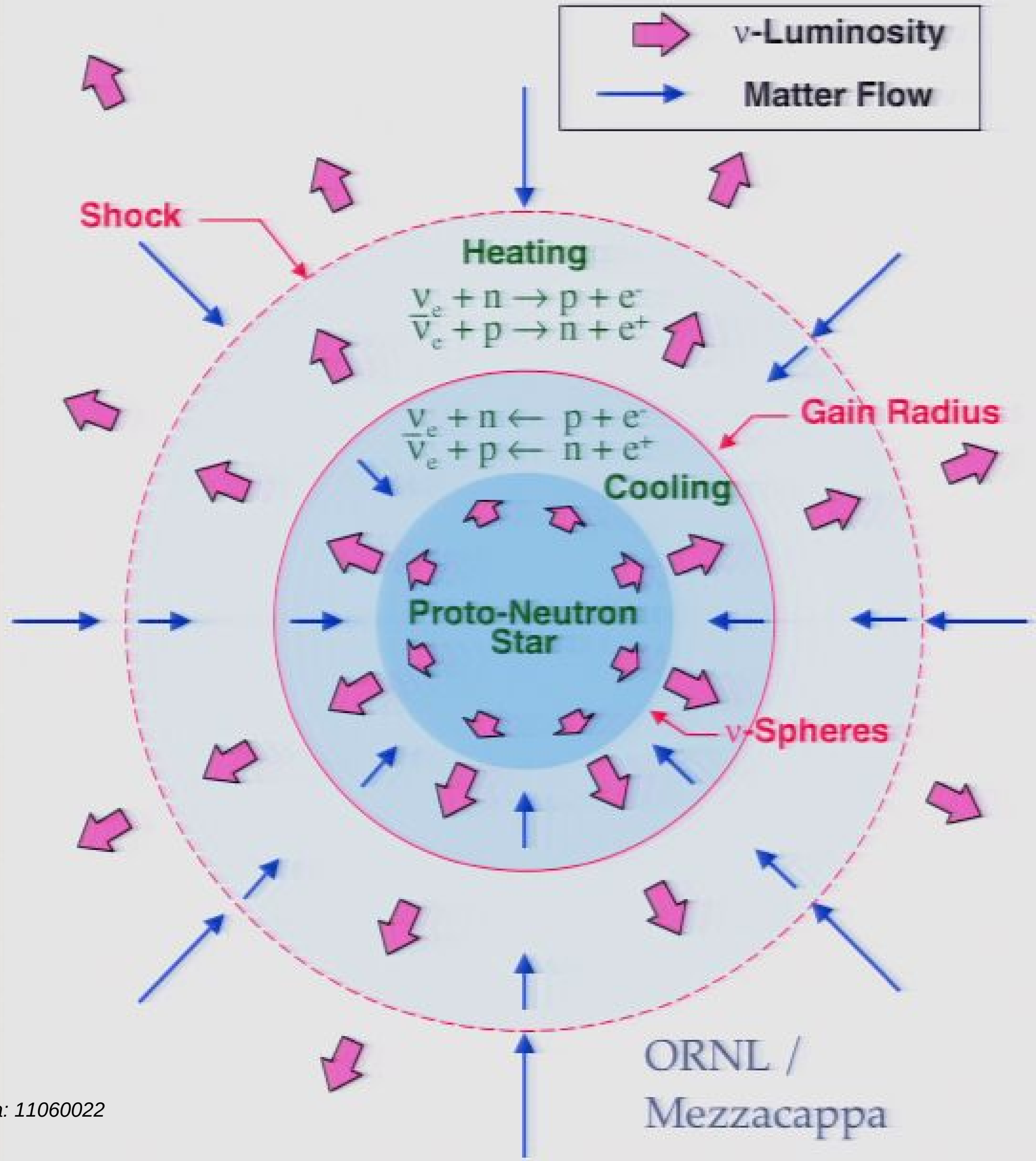
Collaborators:

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





Core collapse



ORNL / Mezzacappa

Potentially Important Ingredients

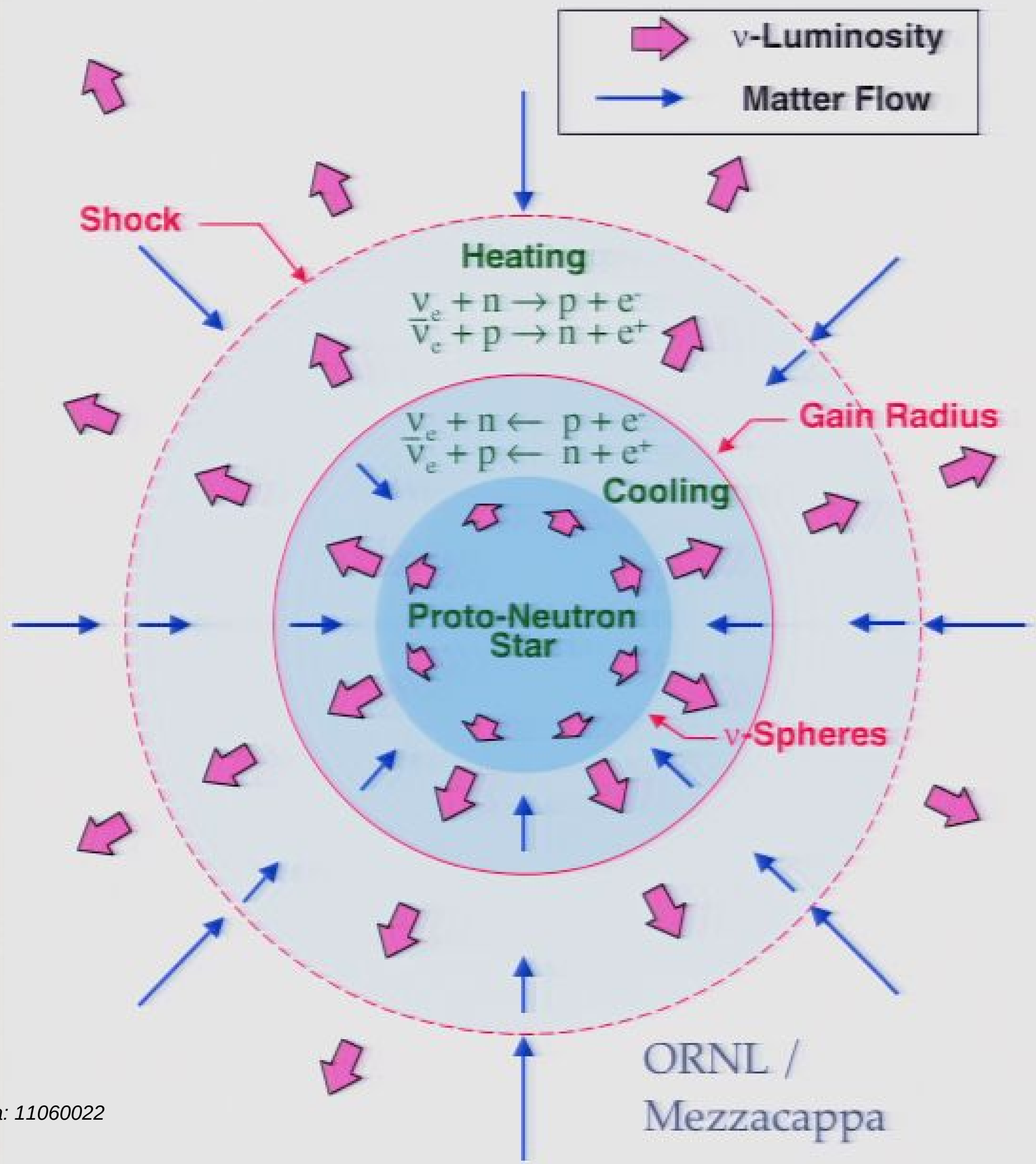
- Gravity
- Neutrino Heating
- Turbulence / Convectio
  and Shock Instabilitie
- Rotation
- Magnetic fields
- Nucleosynthesis
- General Relativity

Multi-dimensional effects important!

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

Core collapse

Brief History



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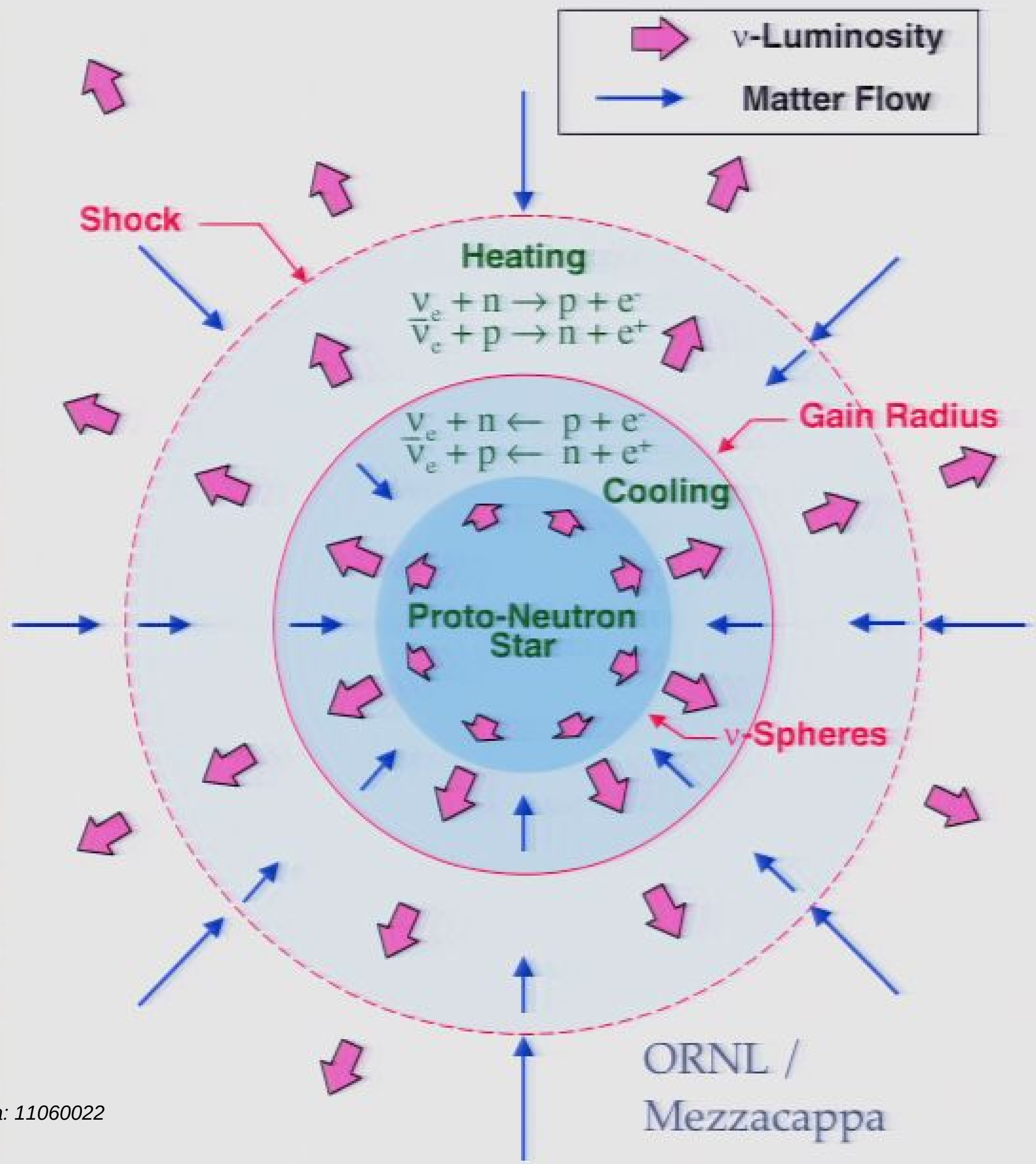
Core collapse



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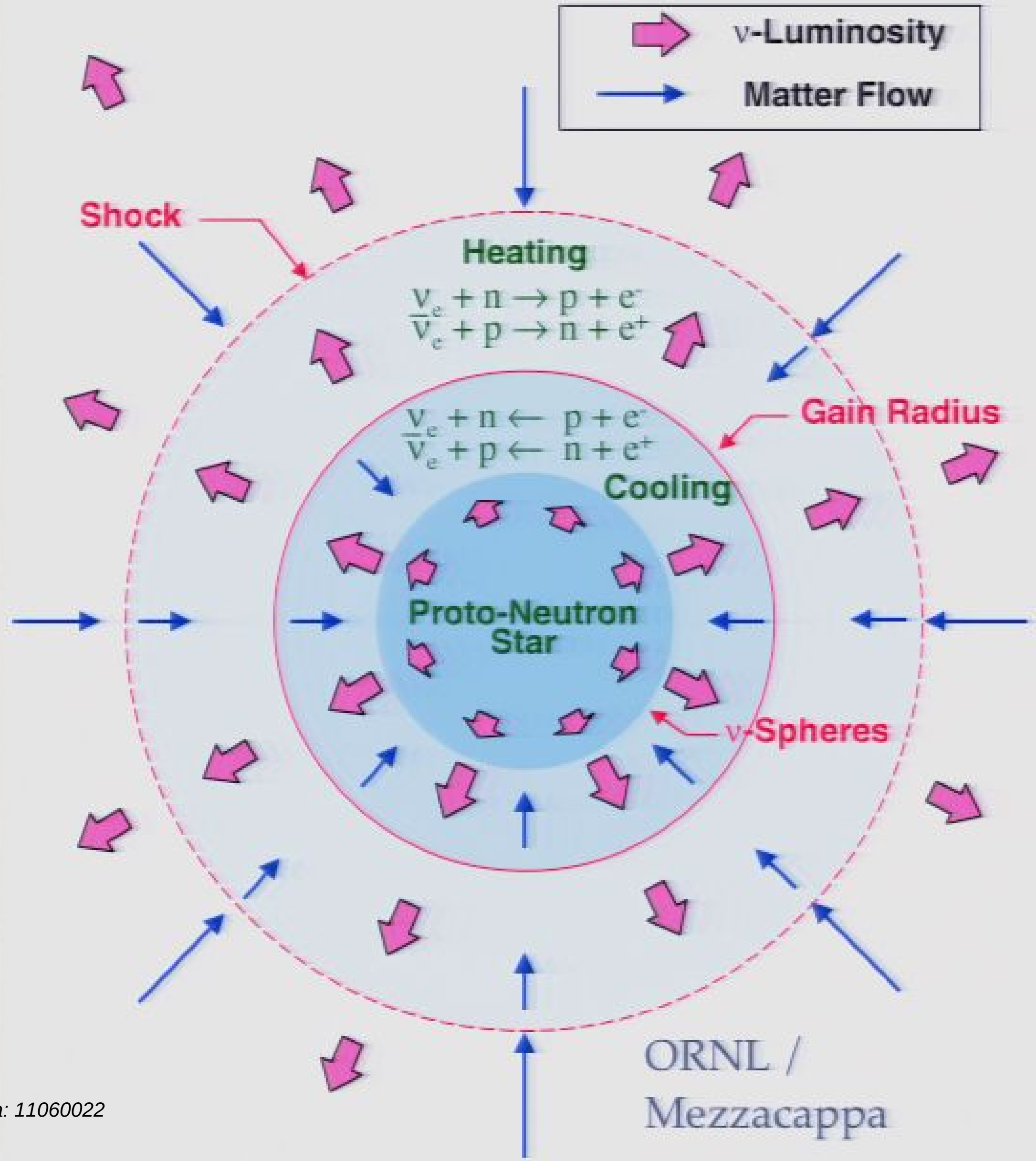
Brief History

Direct Hydrodynamic Collapse

Colgate et al. 1961

Core collapse



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Brief History

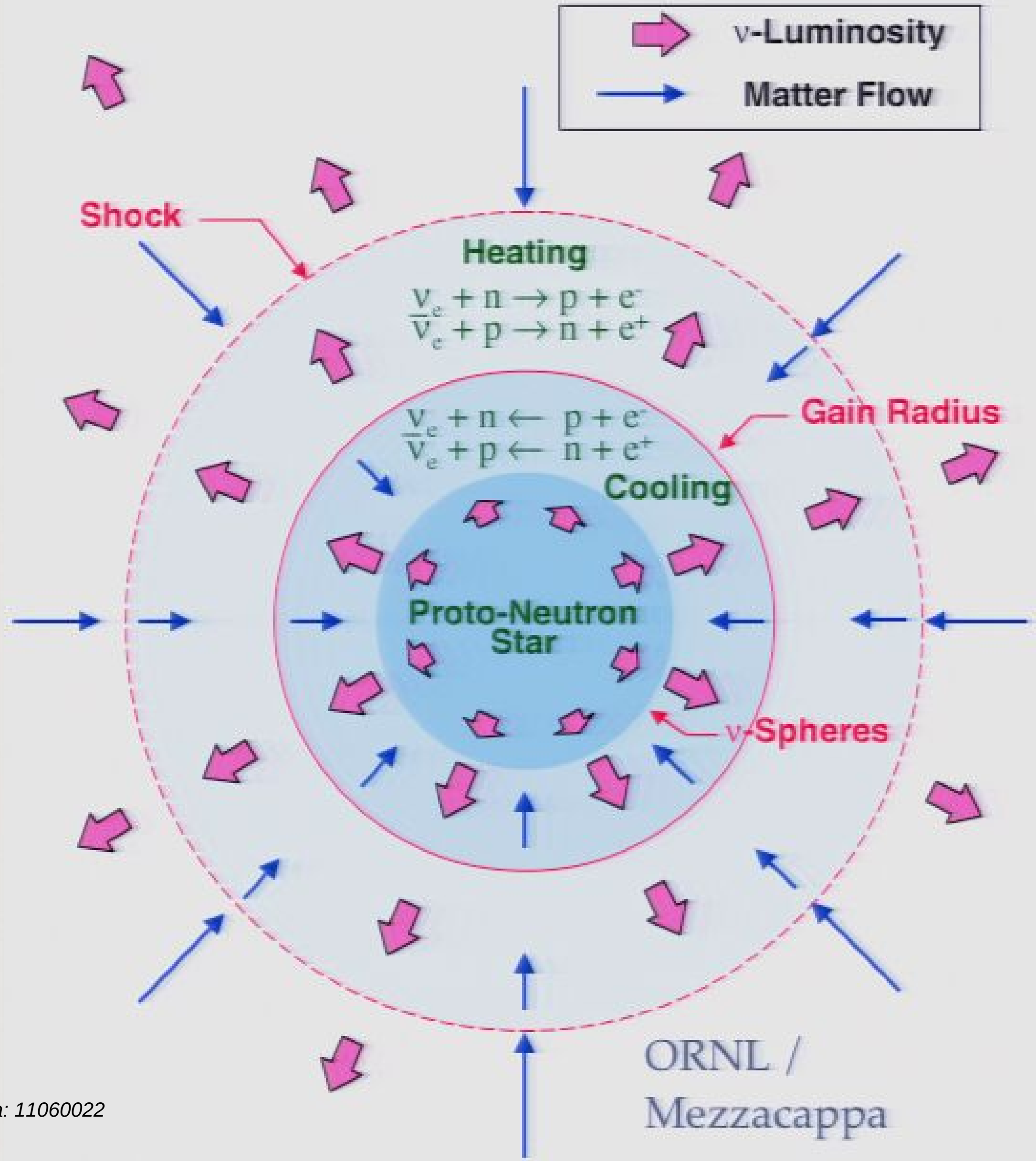
Direct Hydrodynamic Collapse

Colgate et al. 1961

Delayed Neutrino Mechanism

Colgate & White 1966; Arnett 1966; Wilson 1971

Core collapse



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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 explo

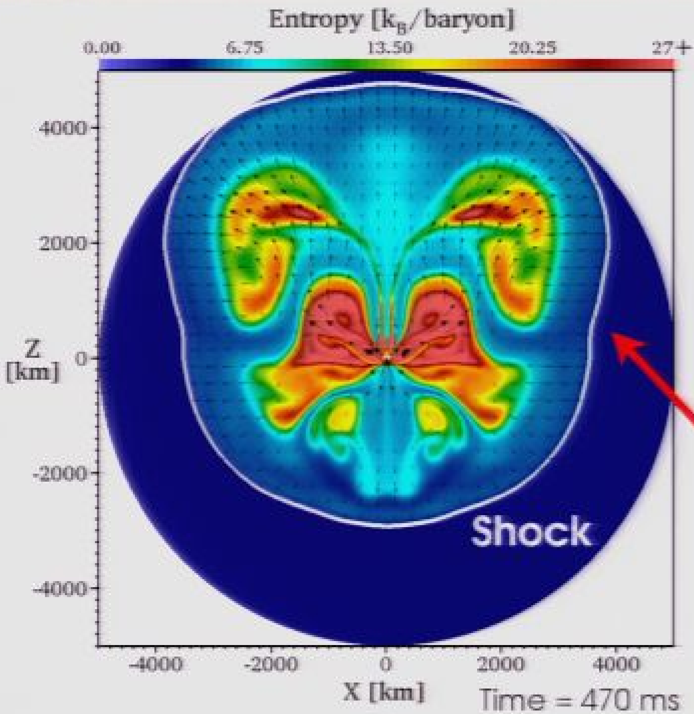
Axisymmetric: Marginal explosions fo few cases

Three Dimensional: !!!

Recoil from Core Collapse

The Hydrodynamic Mechanism of Pulsar Kicks

Neutron Star Kicks I

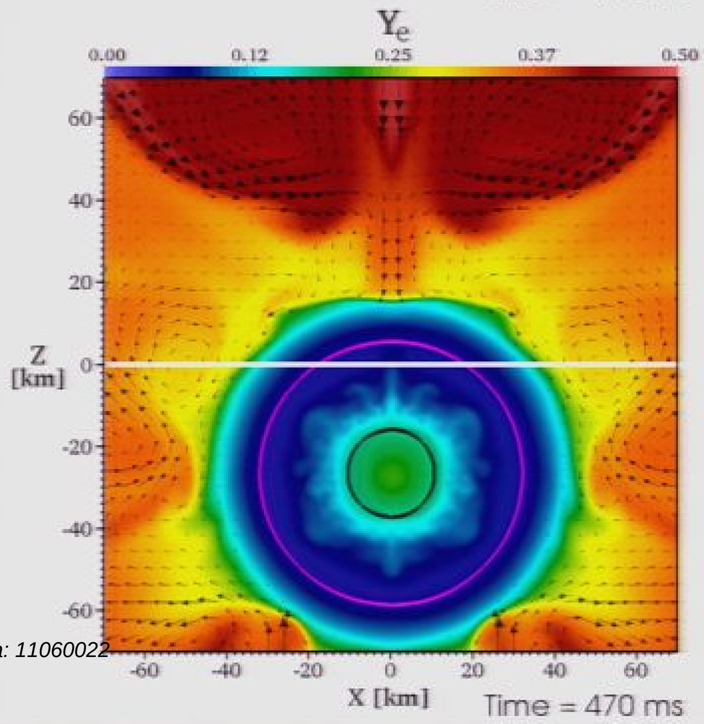


Pulsar birth velocities typically 300 - 400 km s

VULCAN/2D - Rad-hydro simulation

Nordhaus, Brandt, Burrows, Ott, Livne 2010

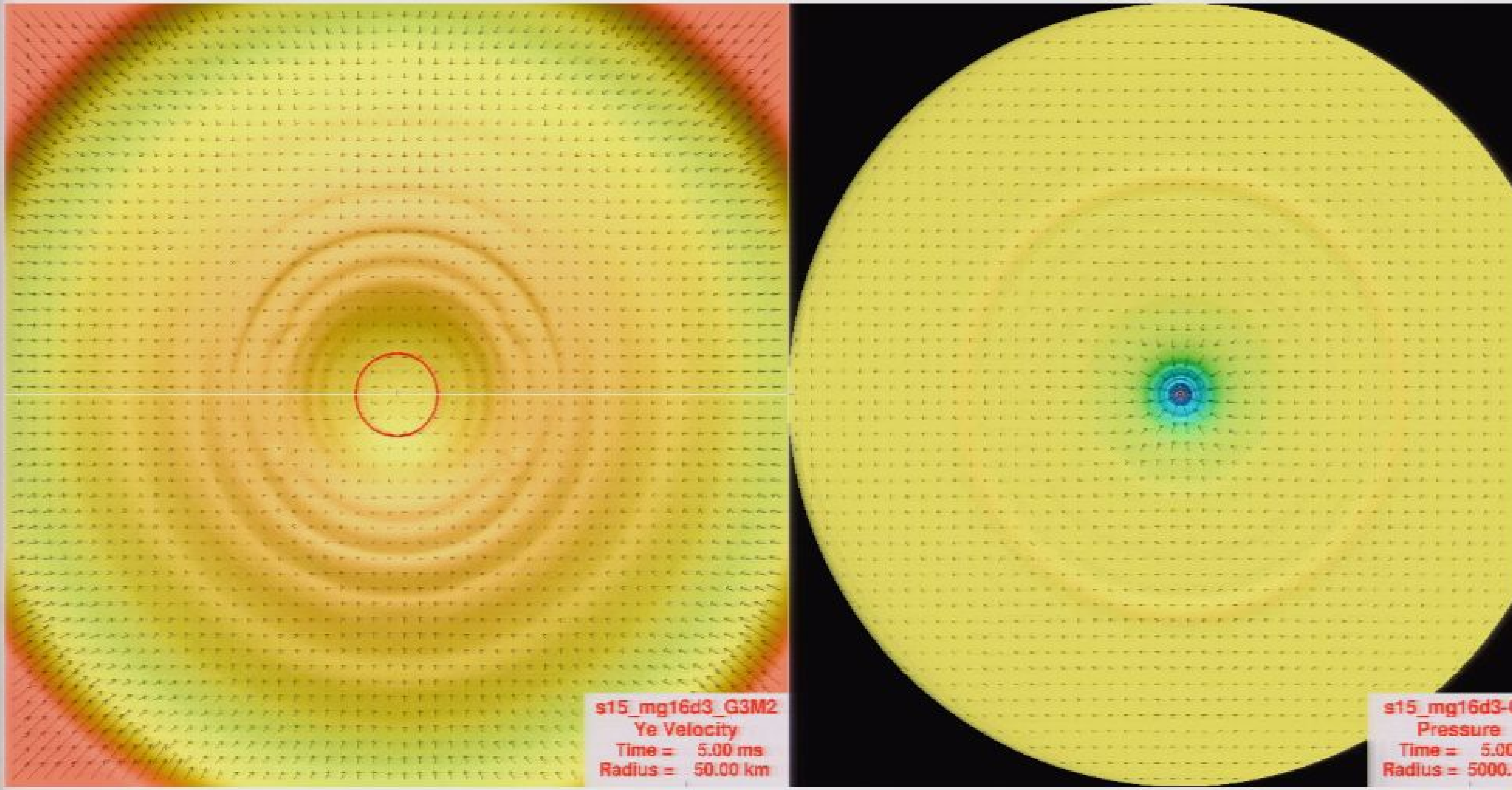
Explosion primarily in +Z direction...



...leads to NS recoil in -Z direction

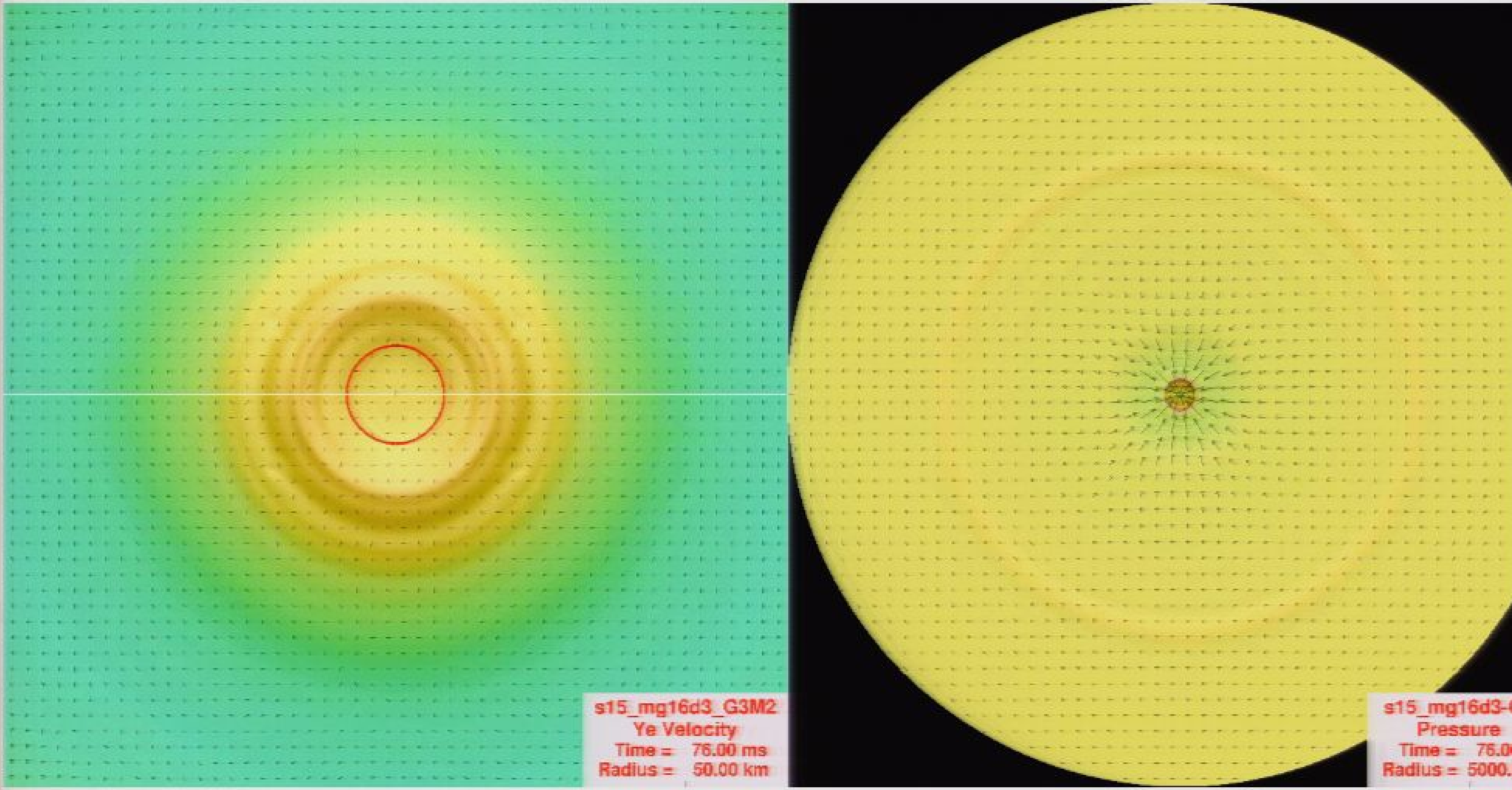
see also Scheck et al. 2006;
Wongwathanarat et al. 2010

Neutron Star Kicks II



Nordhaus et al. 2010a

Neutron Star Kicks II



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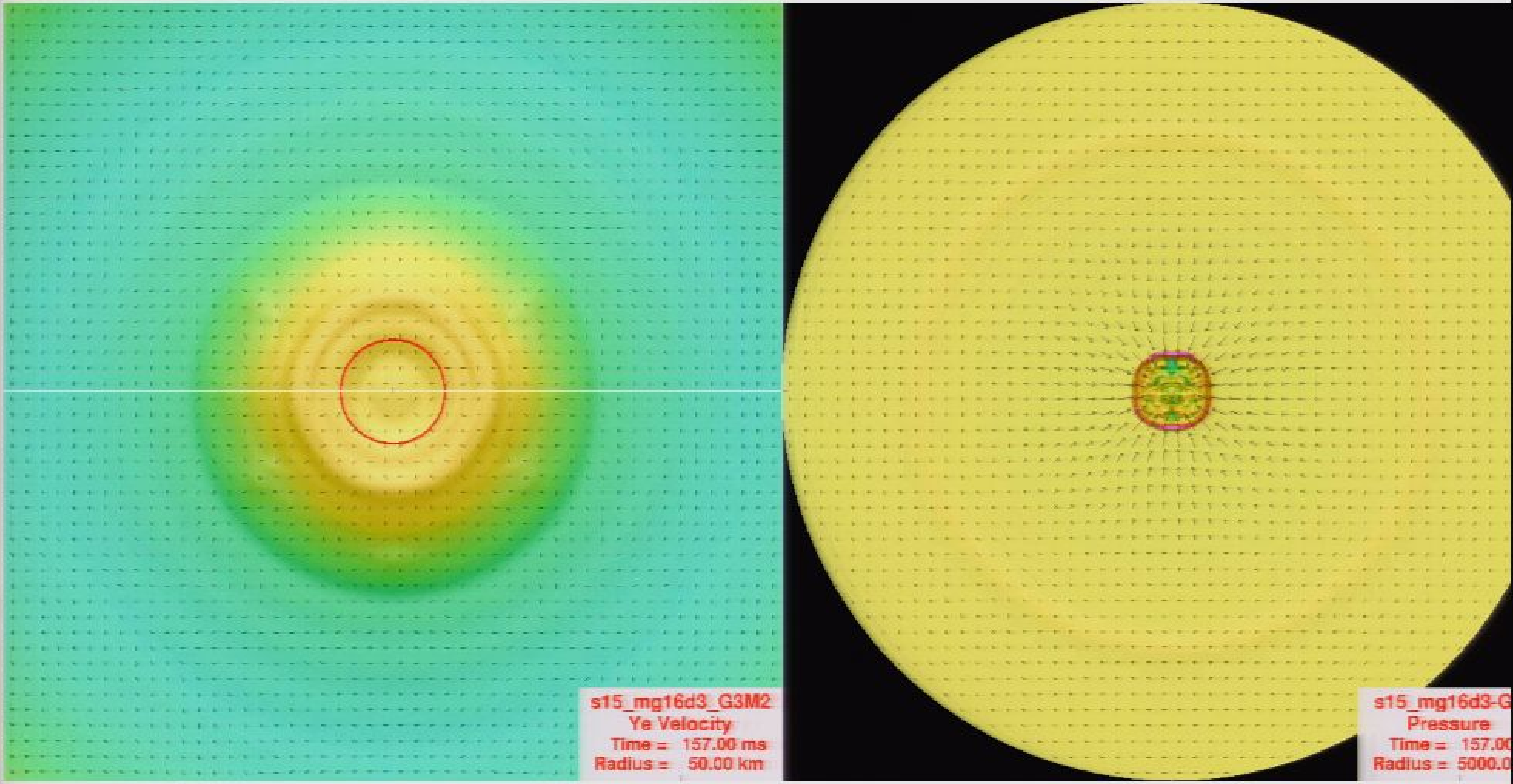

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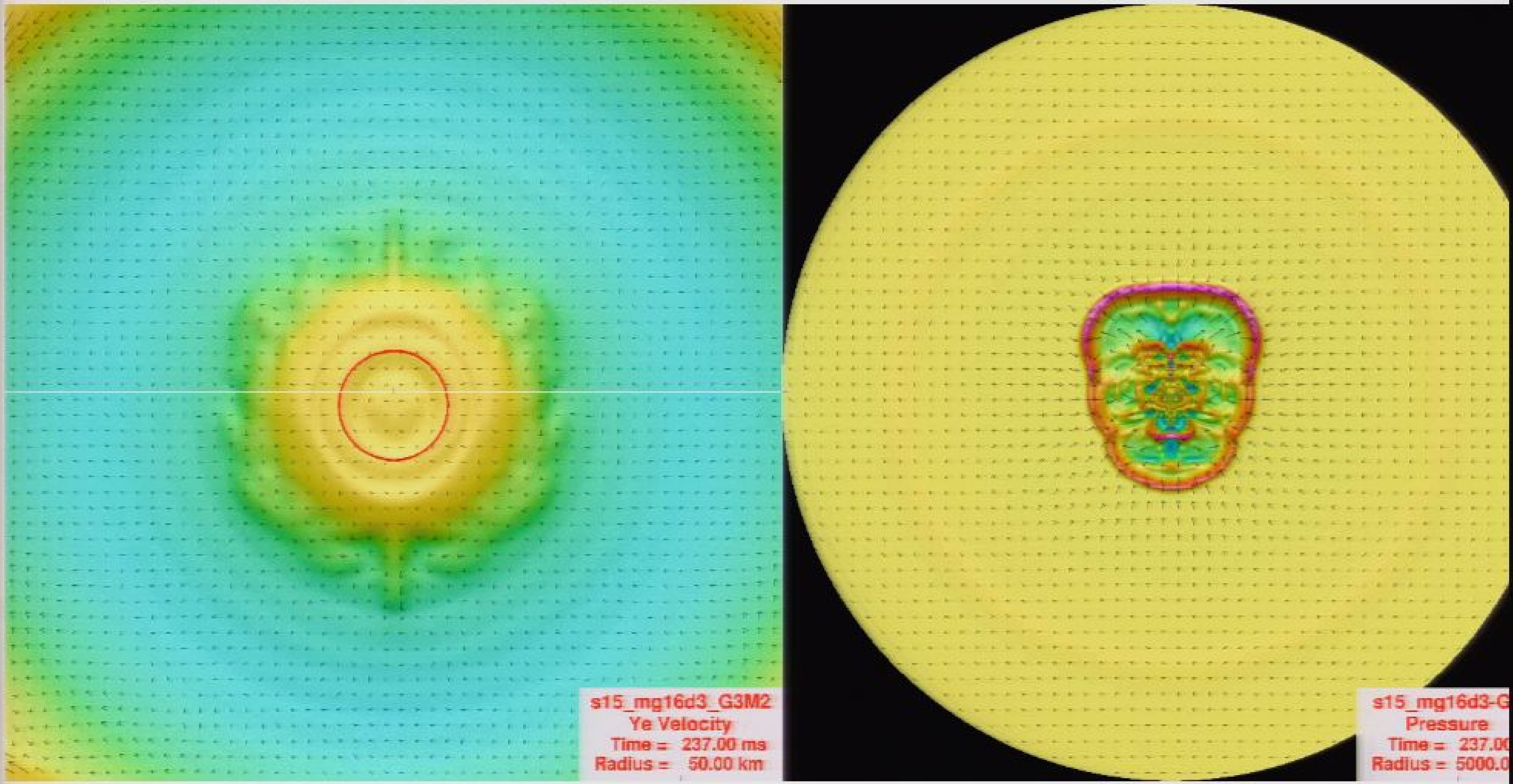

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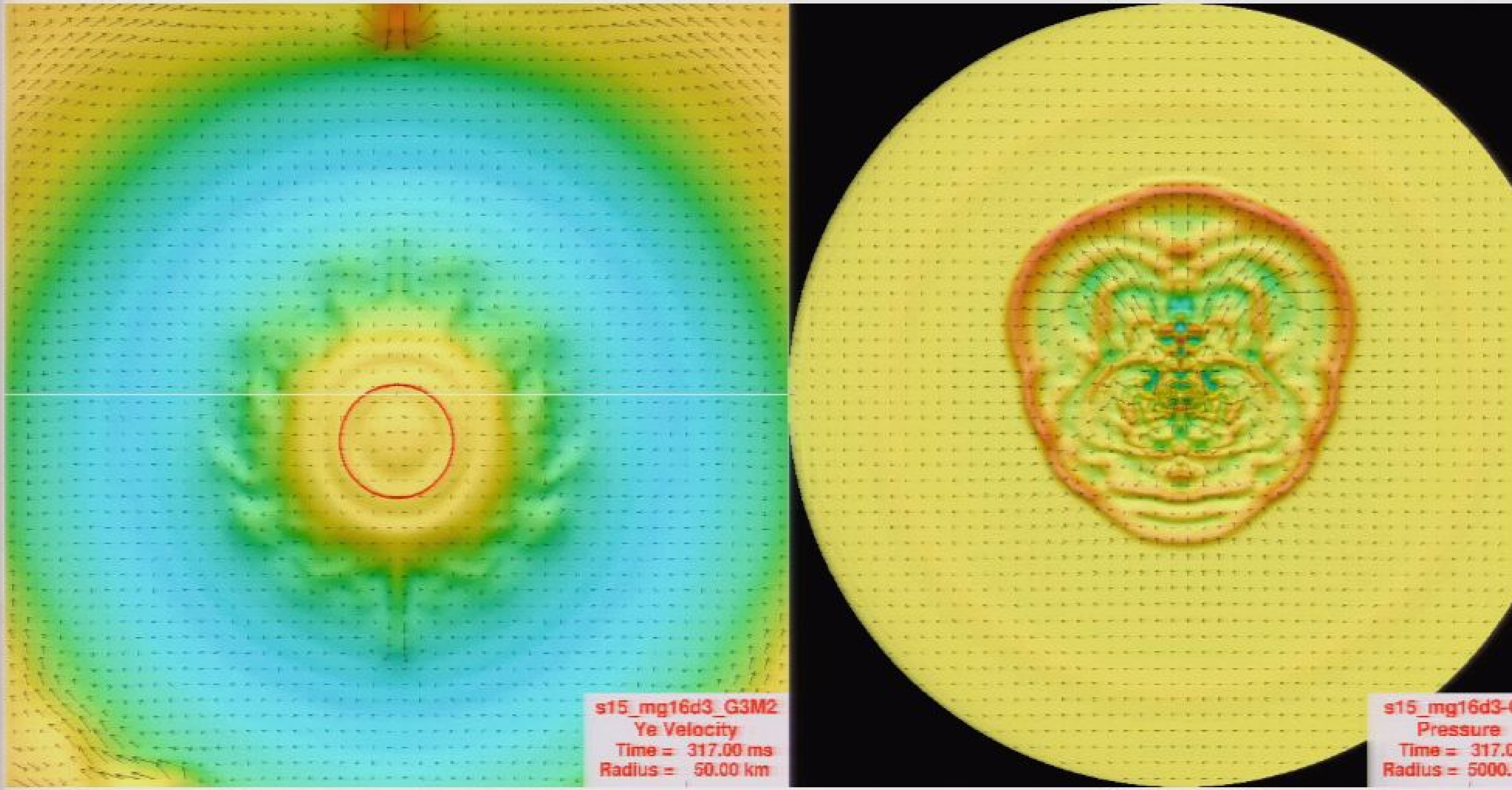

Nordhaus et al. 2010a

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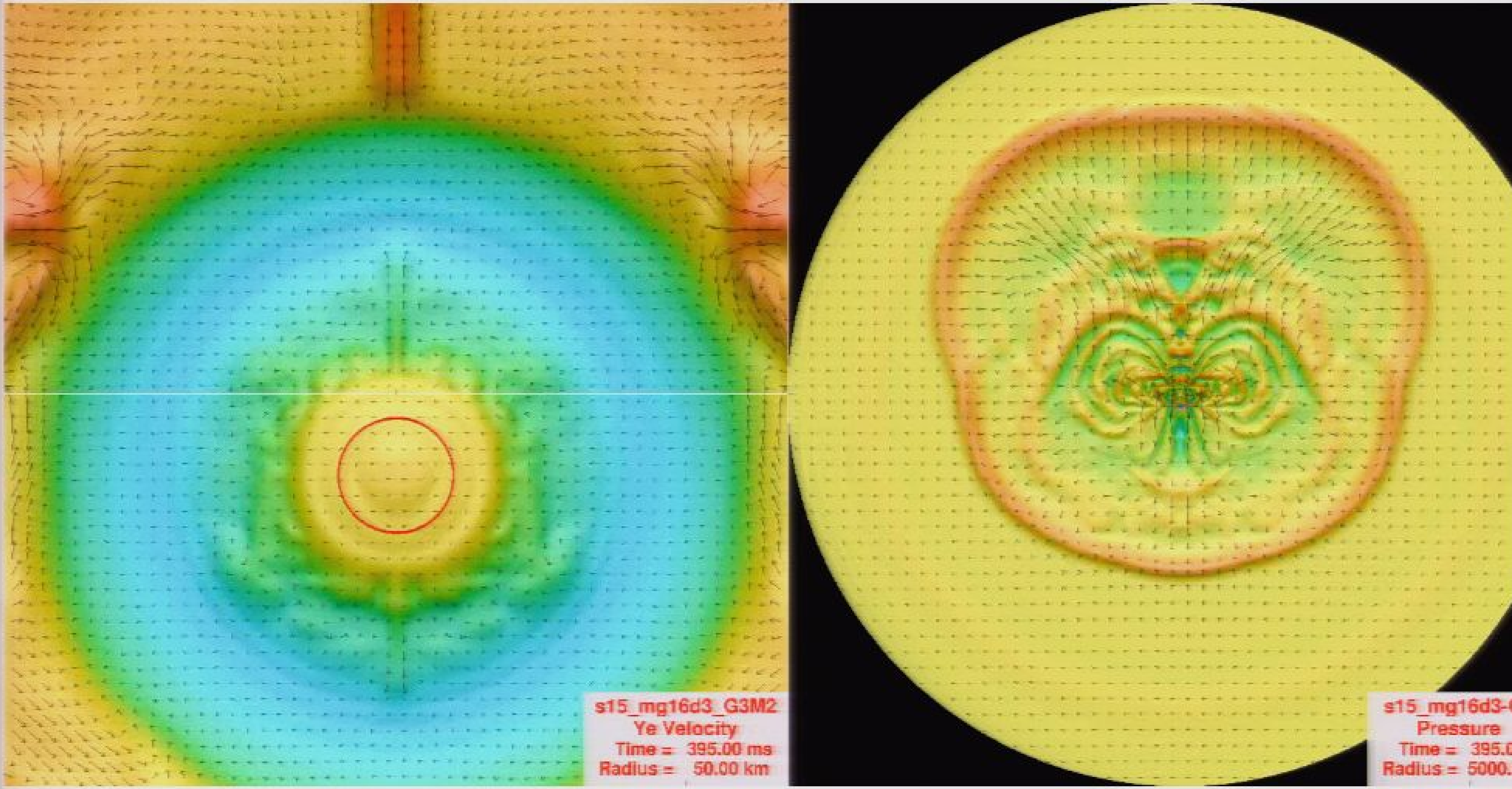
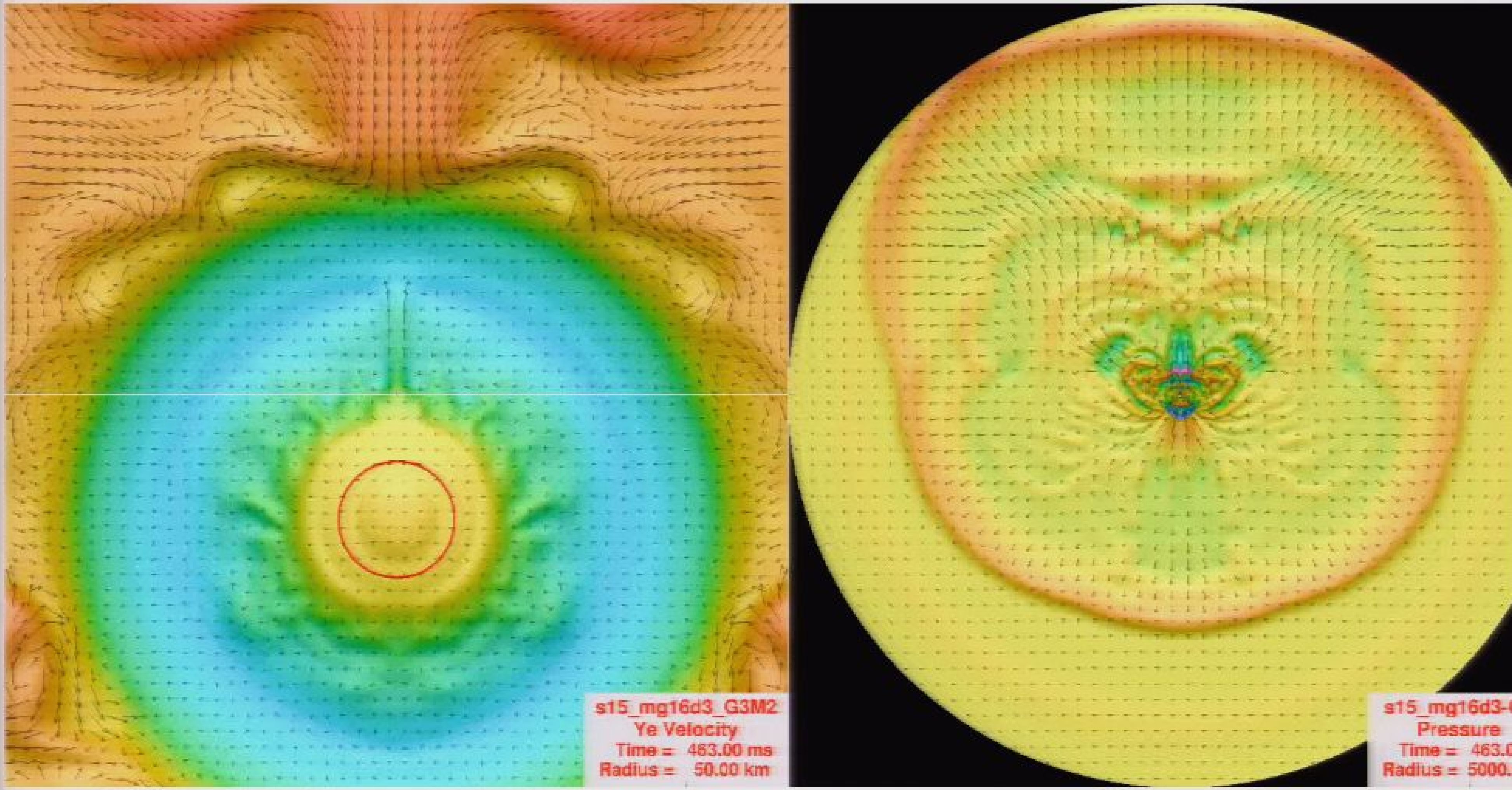


Nordhaus et al. 2010a

Neutron Star Kicks II



Nordhaus et al. 2010a

Hydrodynamic Mechanism of Pulsar Kicks

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

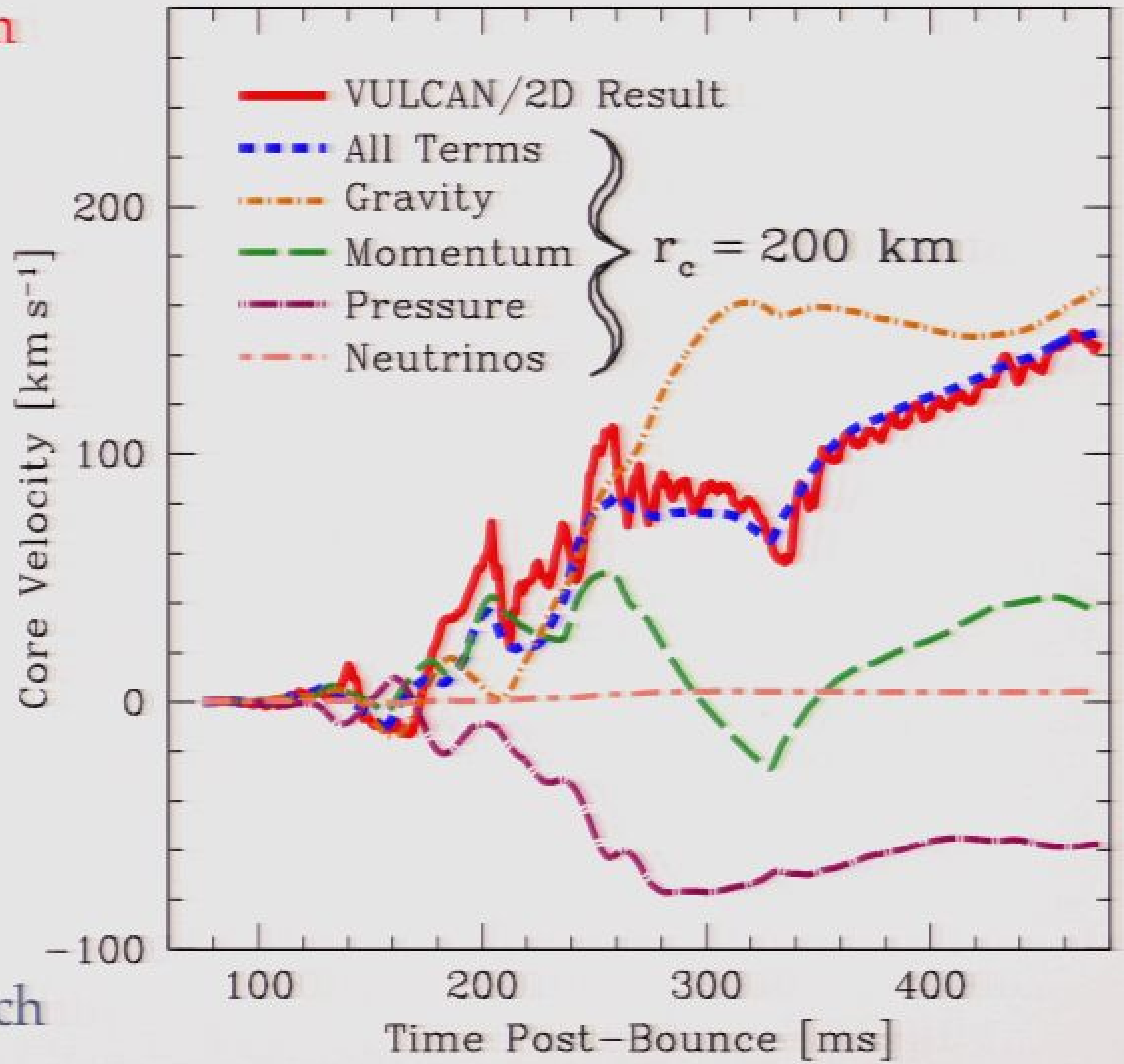
Gravitational tugboat effect is important.

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!



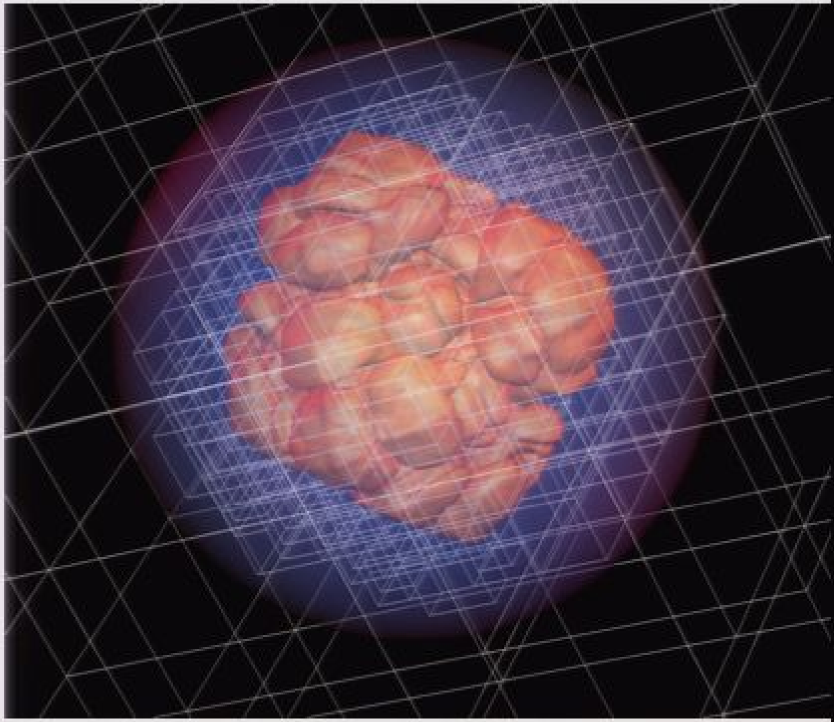
Nordhaus et al. 2010a

3D Core Collapse

Very different from 1D and 2D core collapse!

CASTRO: Compressible Astrophysics

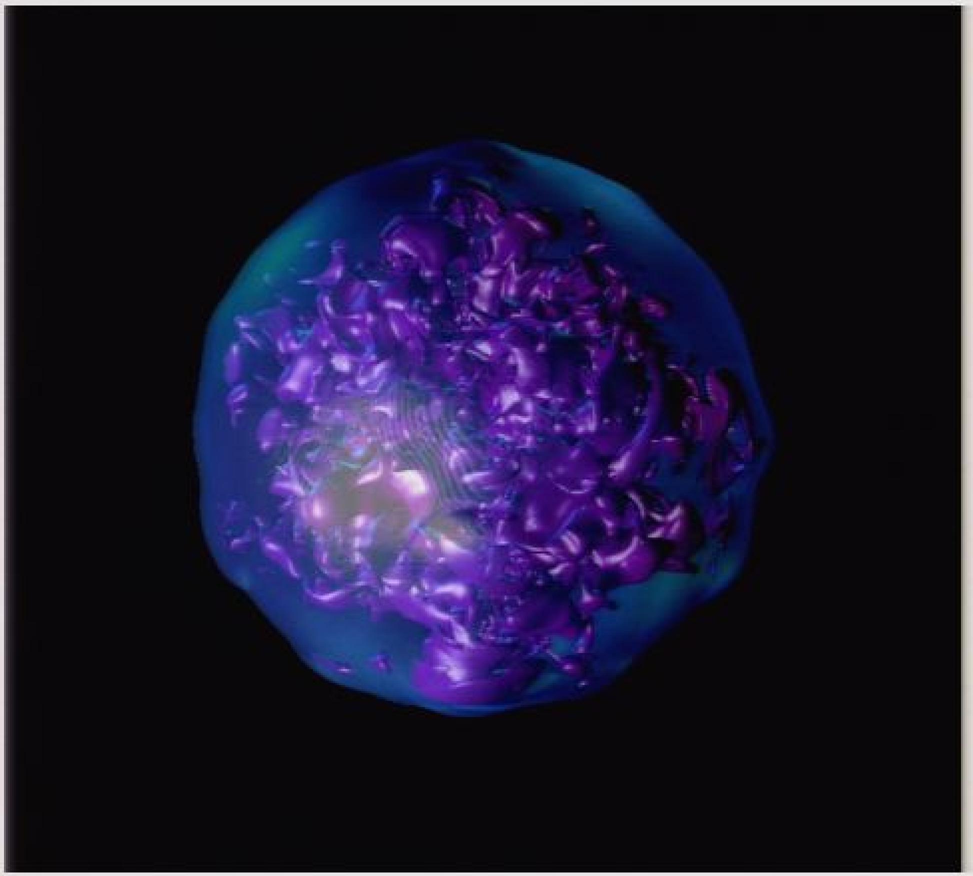
- New multi-D radiation-hydrodynamics code
- Adaptive mesh refinement (AMR) with sub-cycling in time
- Advection: 2nd order, unsplit piecewise-linear or PPM
- Radiation: multi-group flux limited diffusion
- Gravity: Monopole or multi-grid Poisson solve
- Scales to over 200,000 cores!

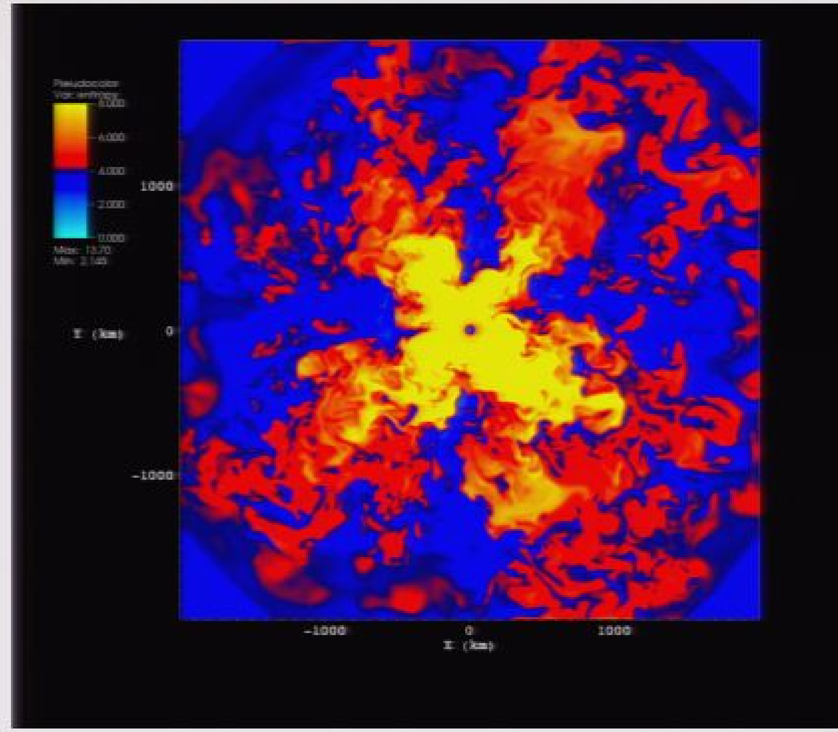


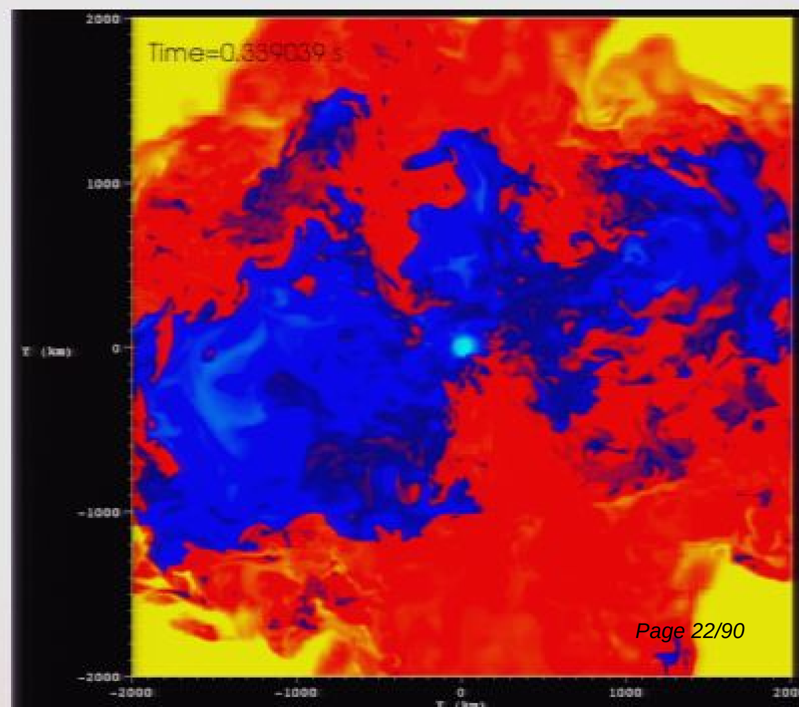
3D AMR block structure

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

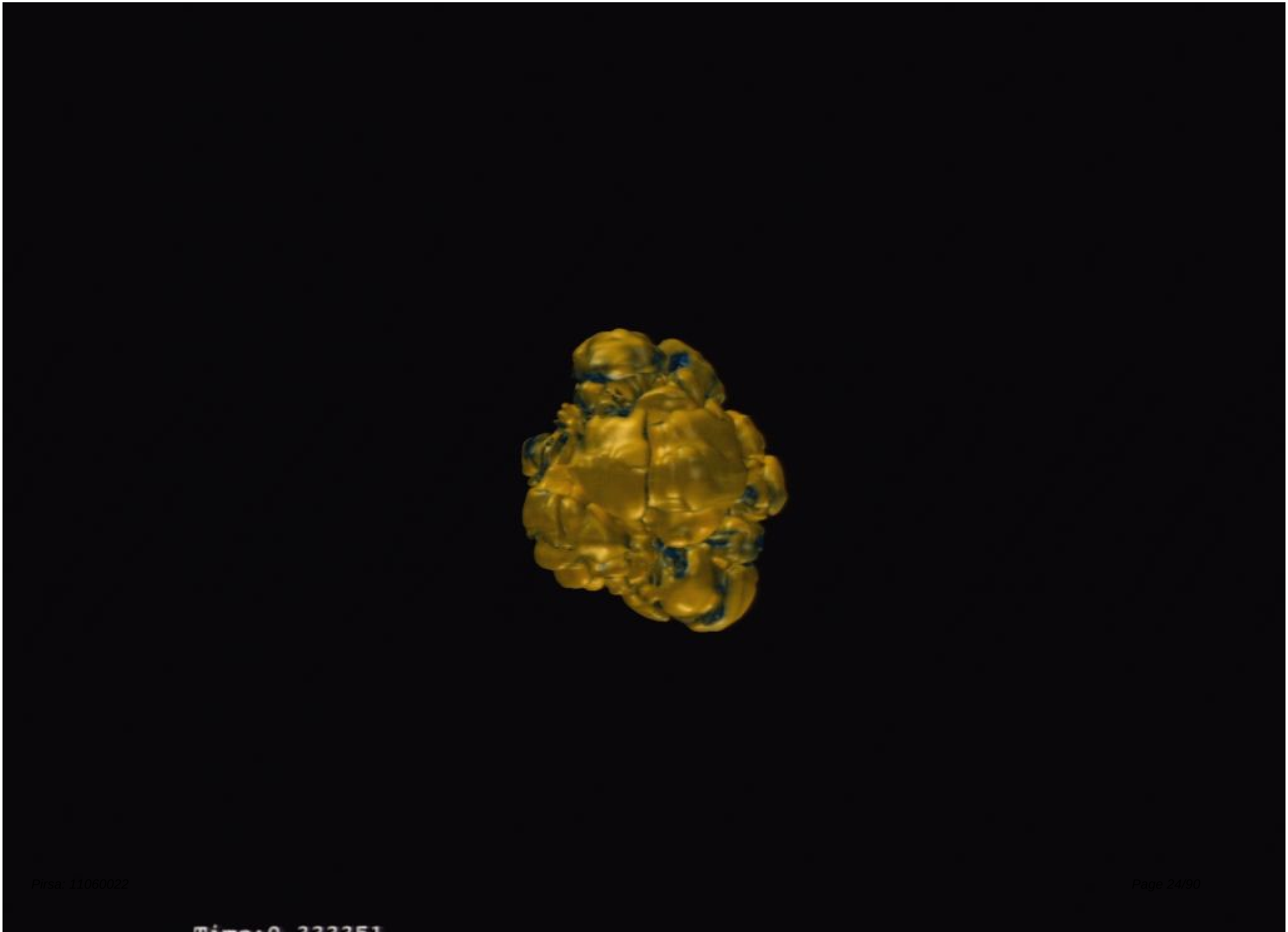
CASTRO
Simulations

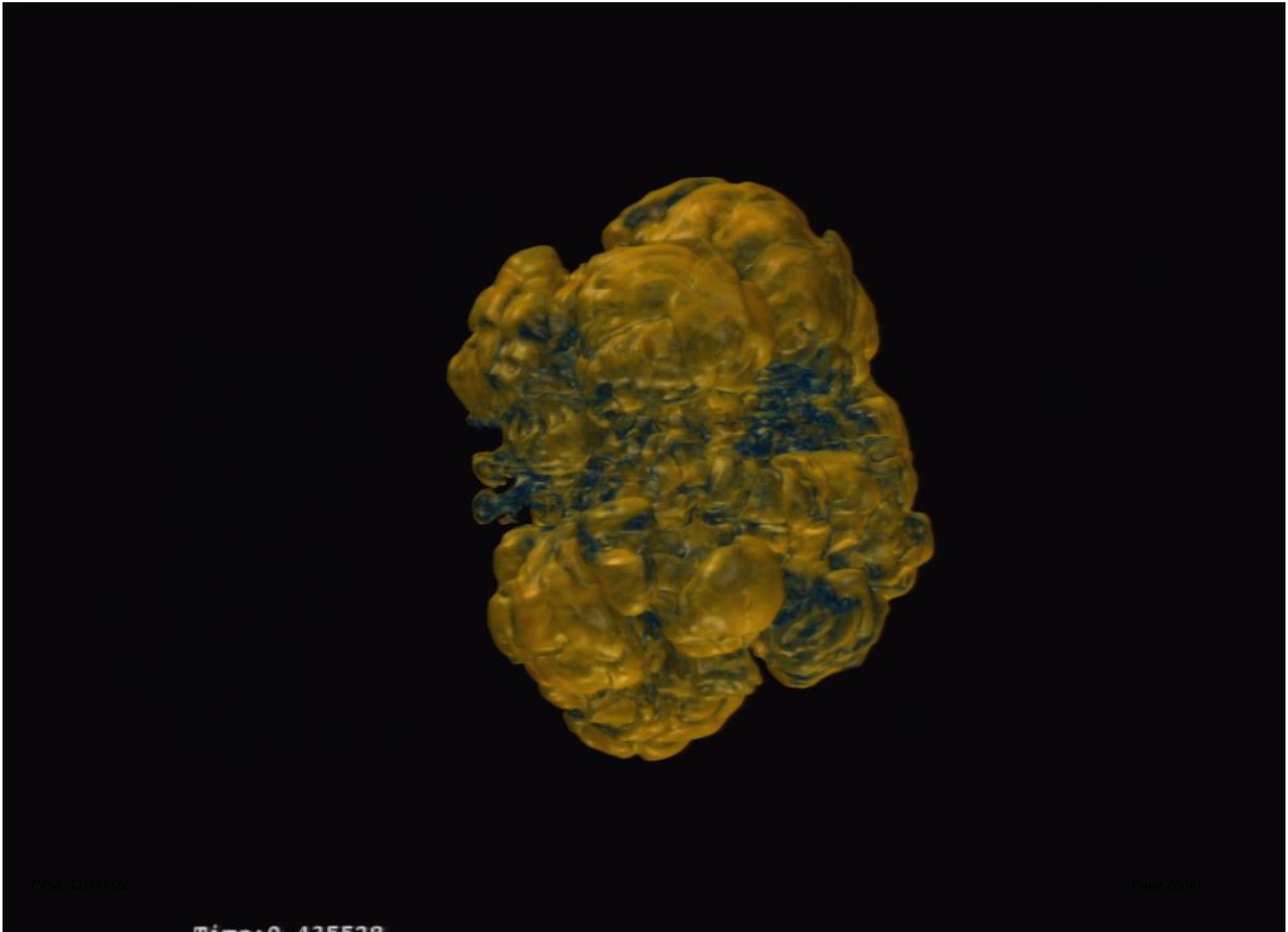


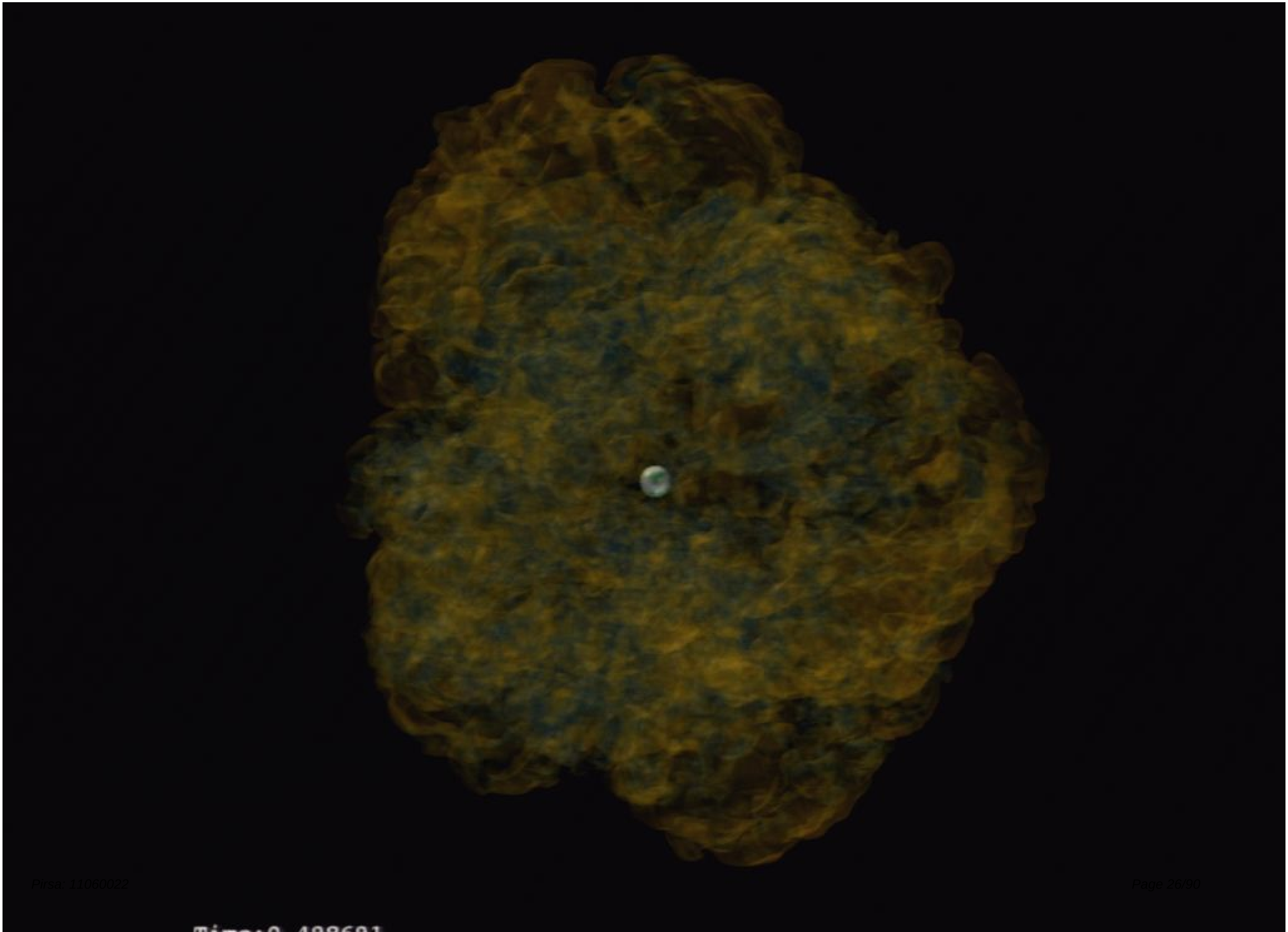





Time: 0.382


Time:0.333351





Spatial Dimension

A key to the neutrino mechanism

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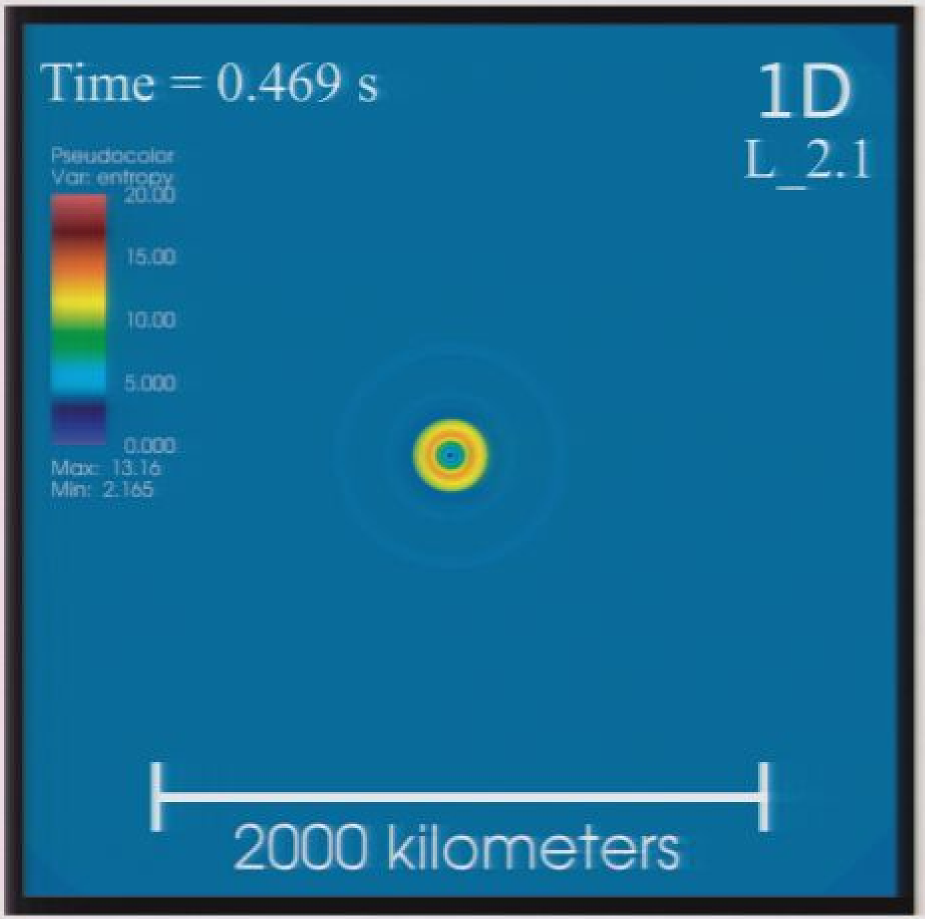
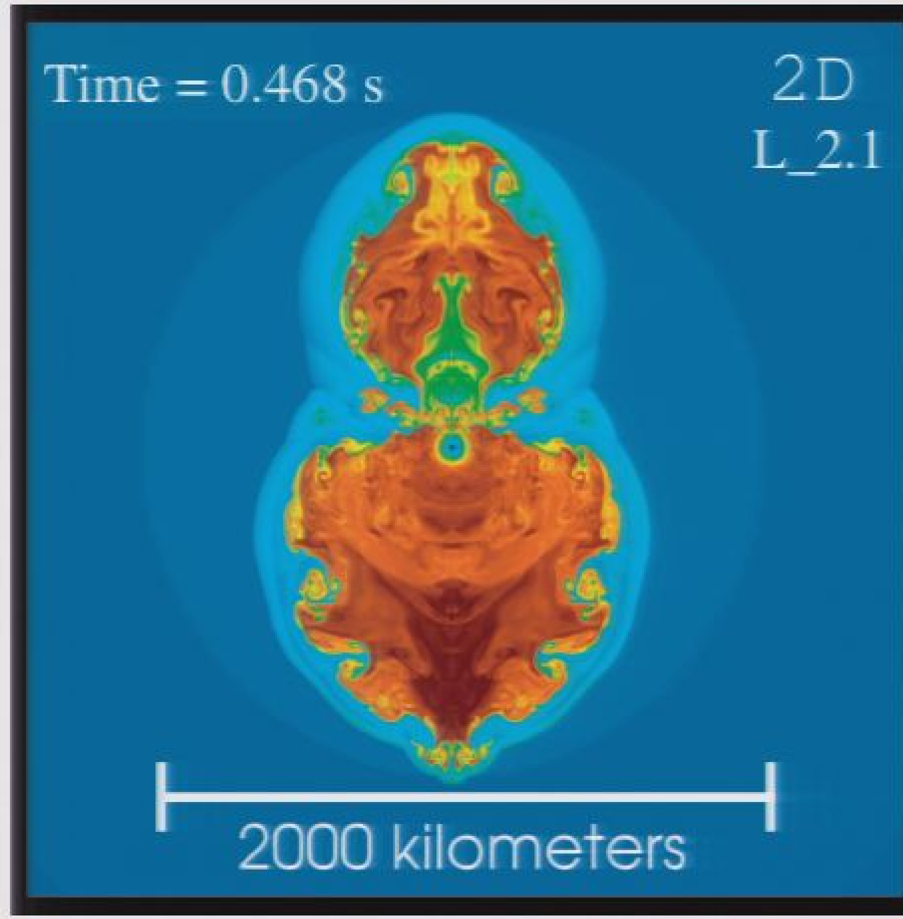
Dimensional Dependence

Spherically Symmetric



Axisymmetric

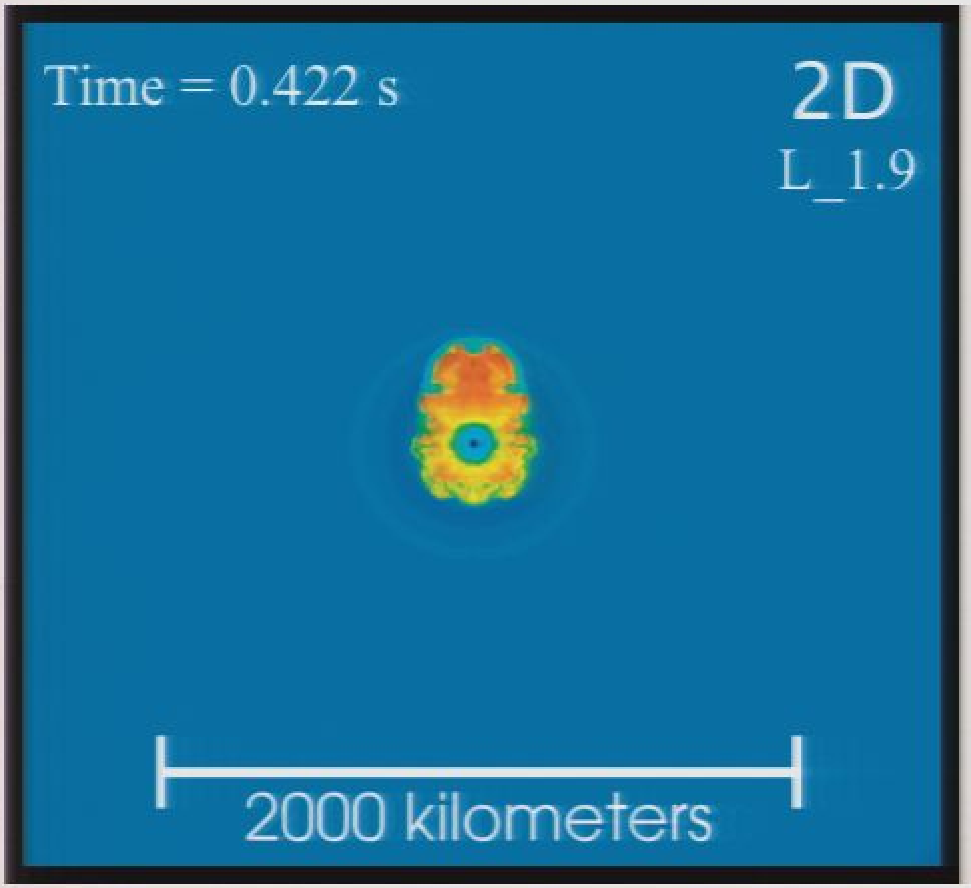


Nordhaus, Burrows, Almgren, Bell 2010b

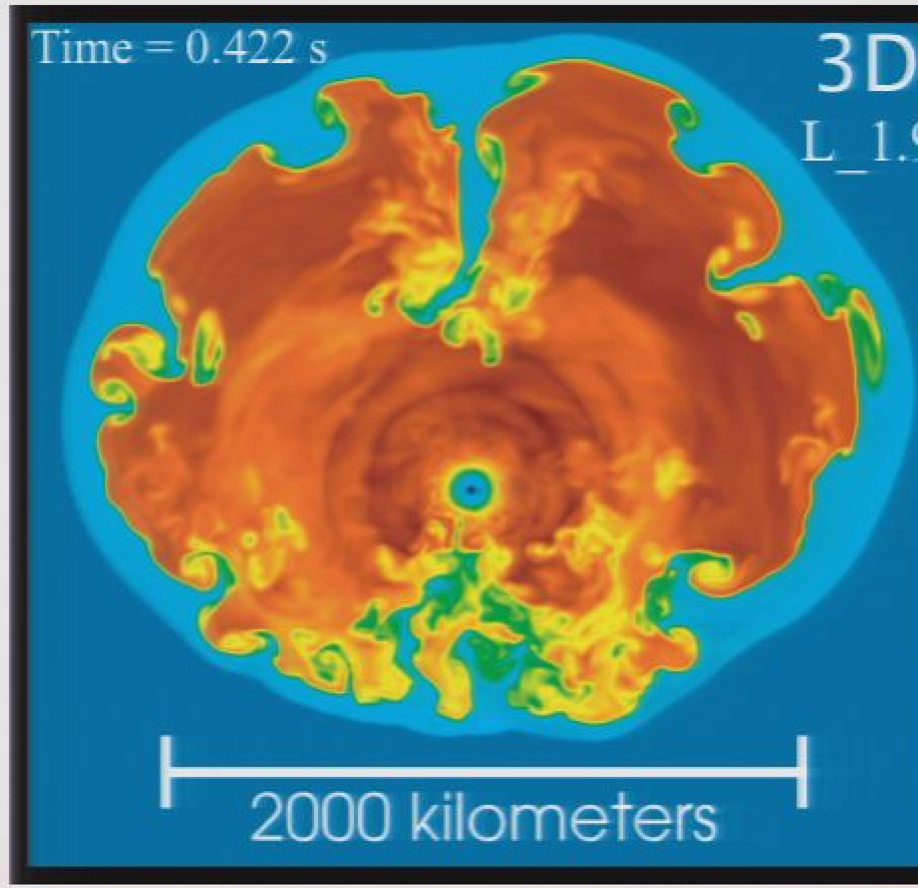
see also Pejcha & Thompson 2011; Murphy & Burrows 200
Burrows & Goshy 1993

Dimensional Dependence

Axisymmetric



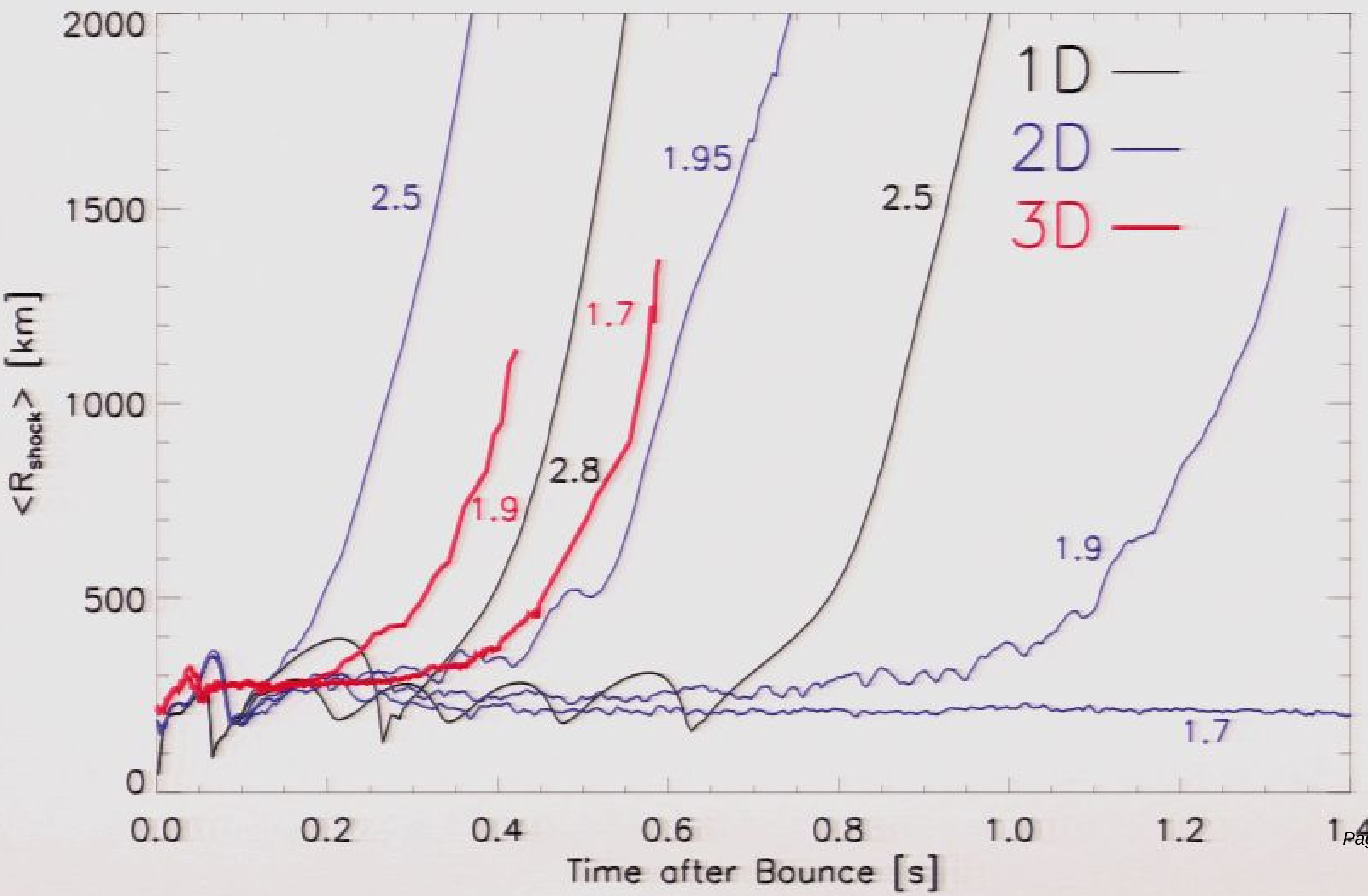
Three Dimensional



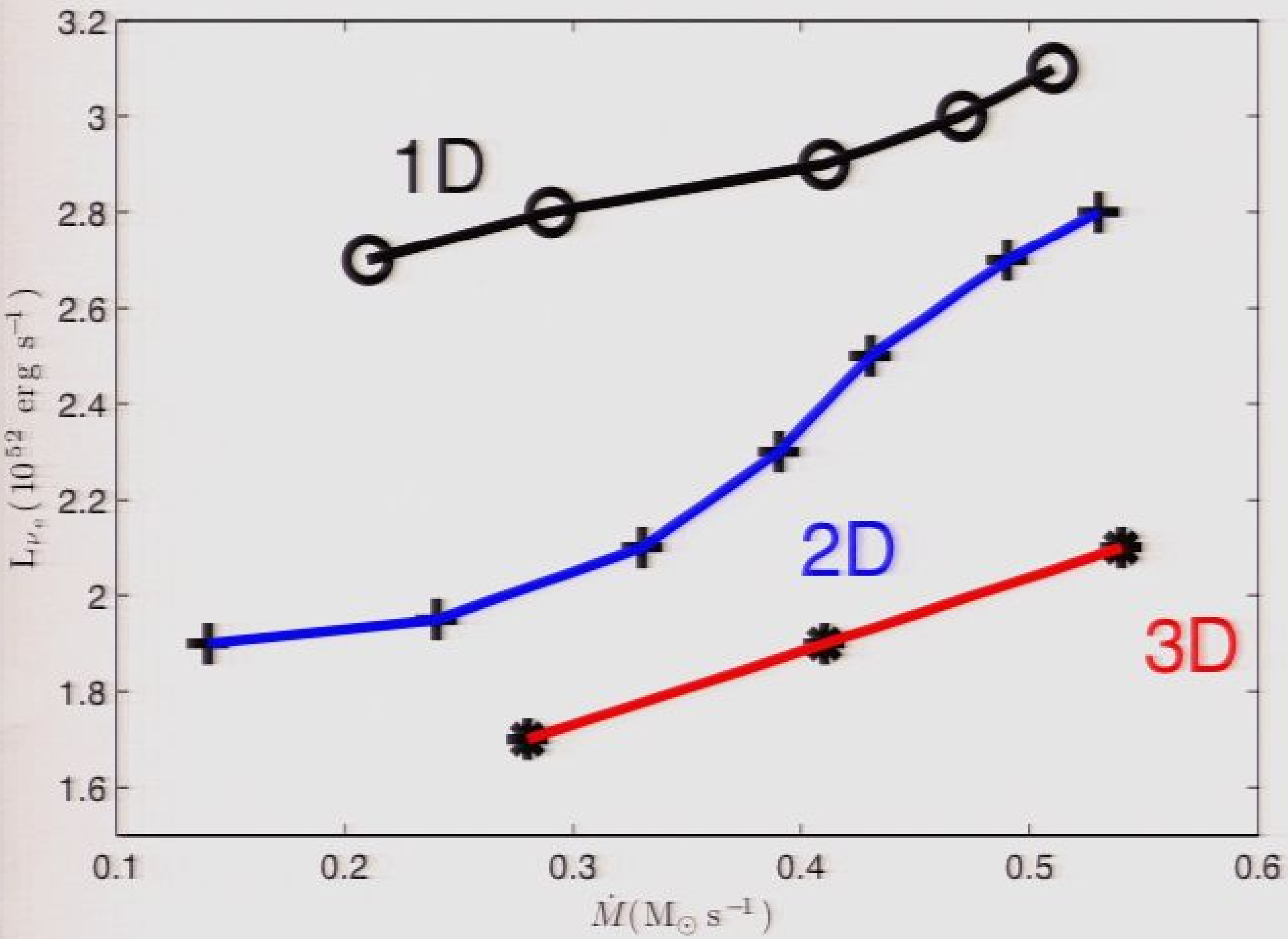
Nordhaus et al. 2010b

Average Shock Radii

Time of explosion is a strong function of dimension!



Critical Curve for Explosions



Nordhaus et al. 2010b

3D vs. 1D/2D

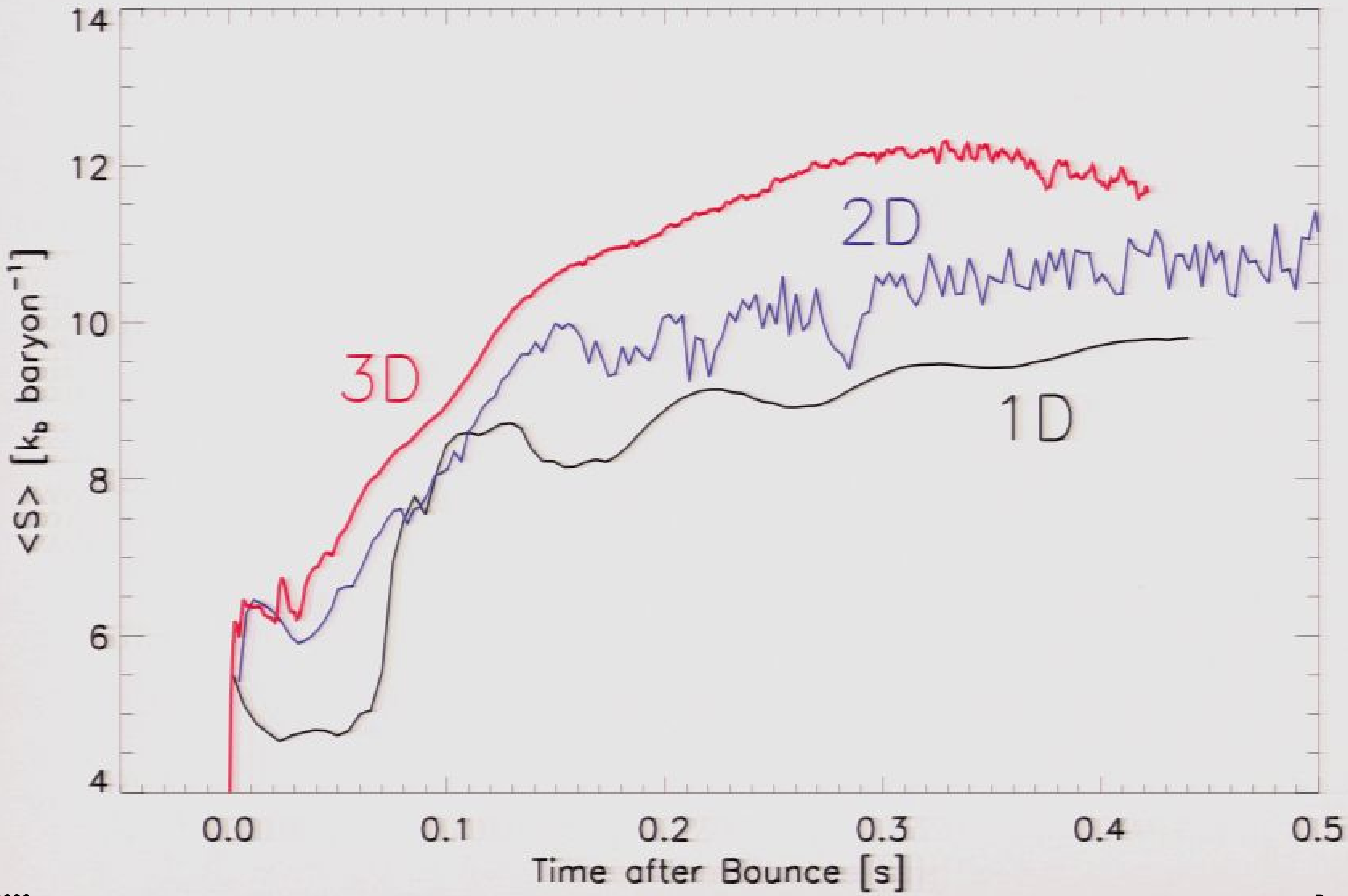
~50% easier to explode than 1D!

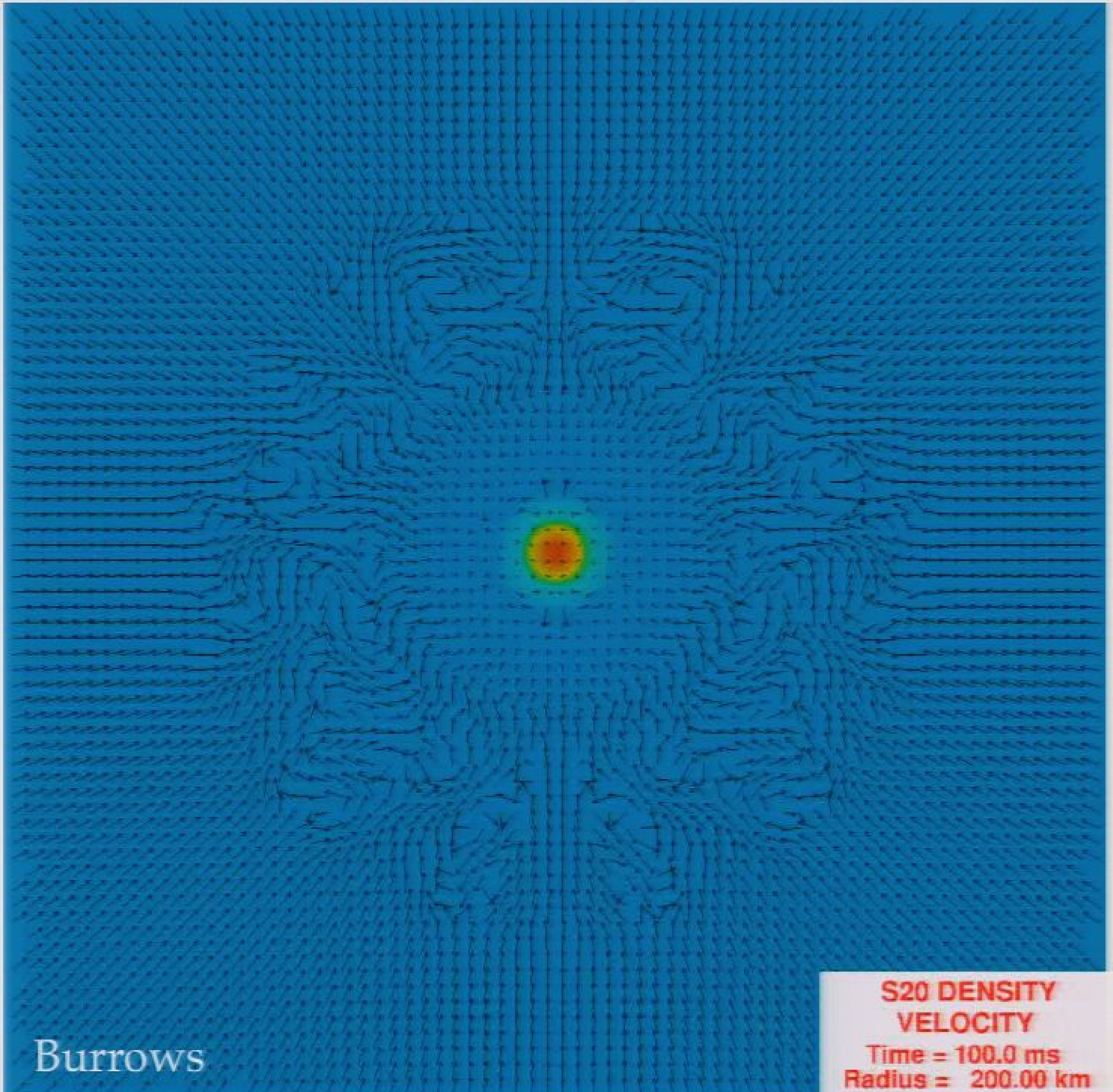
~25% easier to explode than 2D!

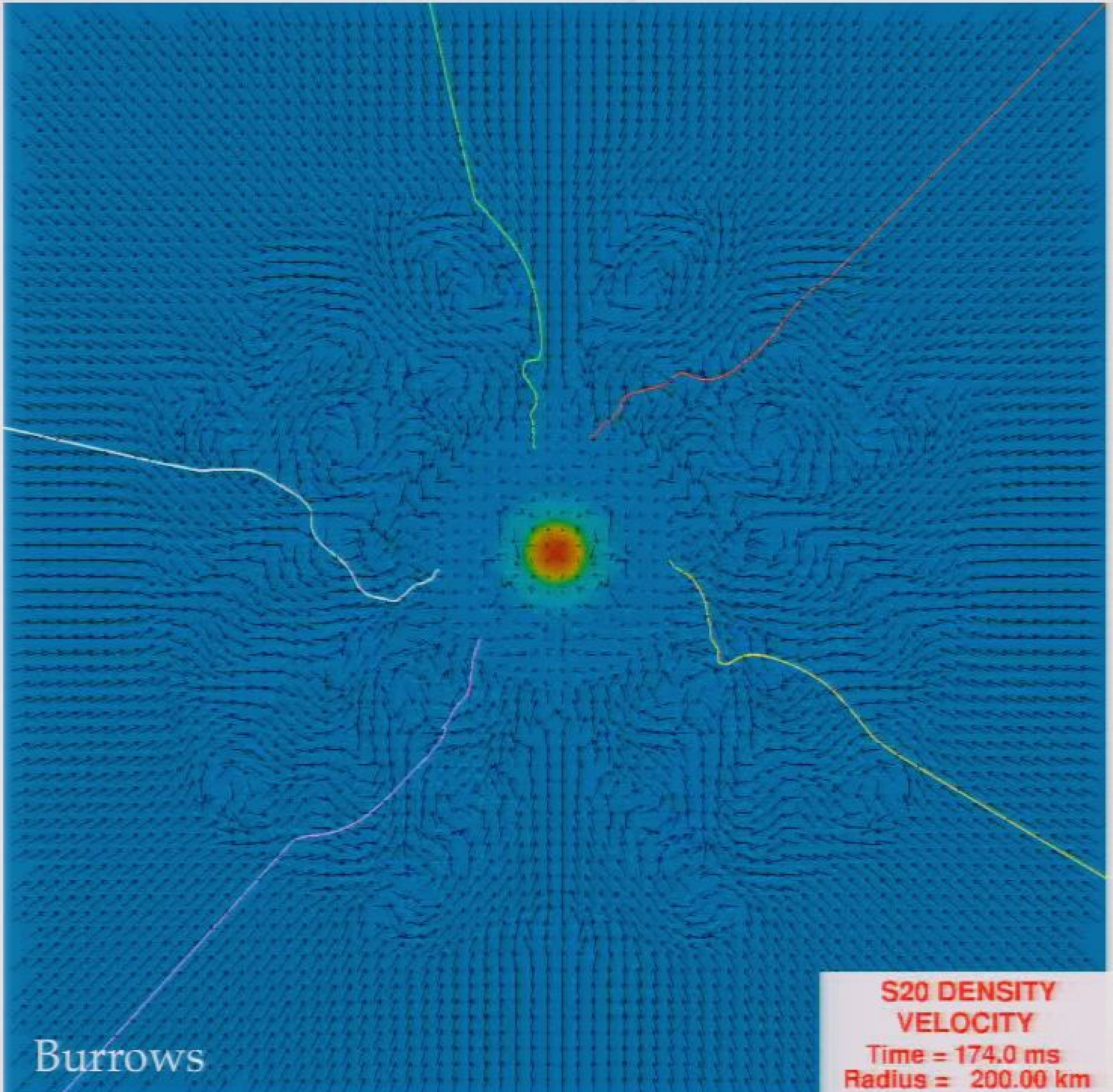
Bigger effect in magnitude than:

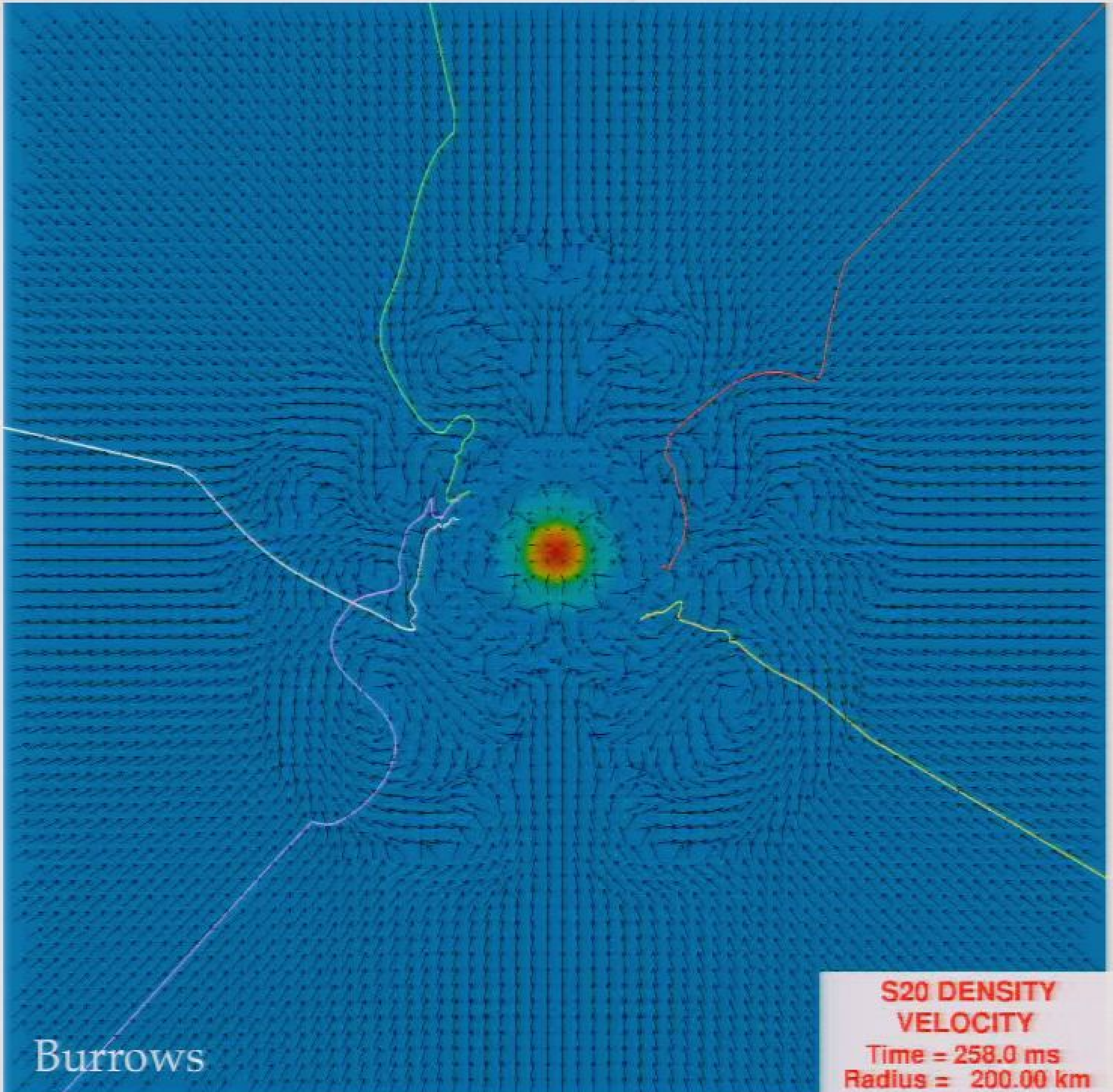
- inelastic scattering
- general relativity
- nuclear burning

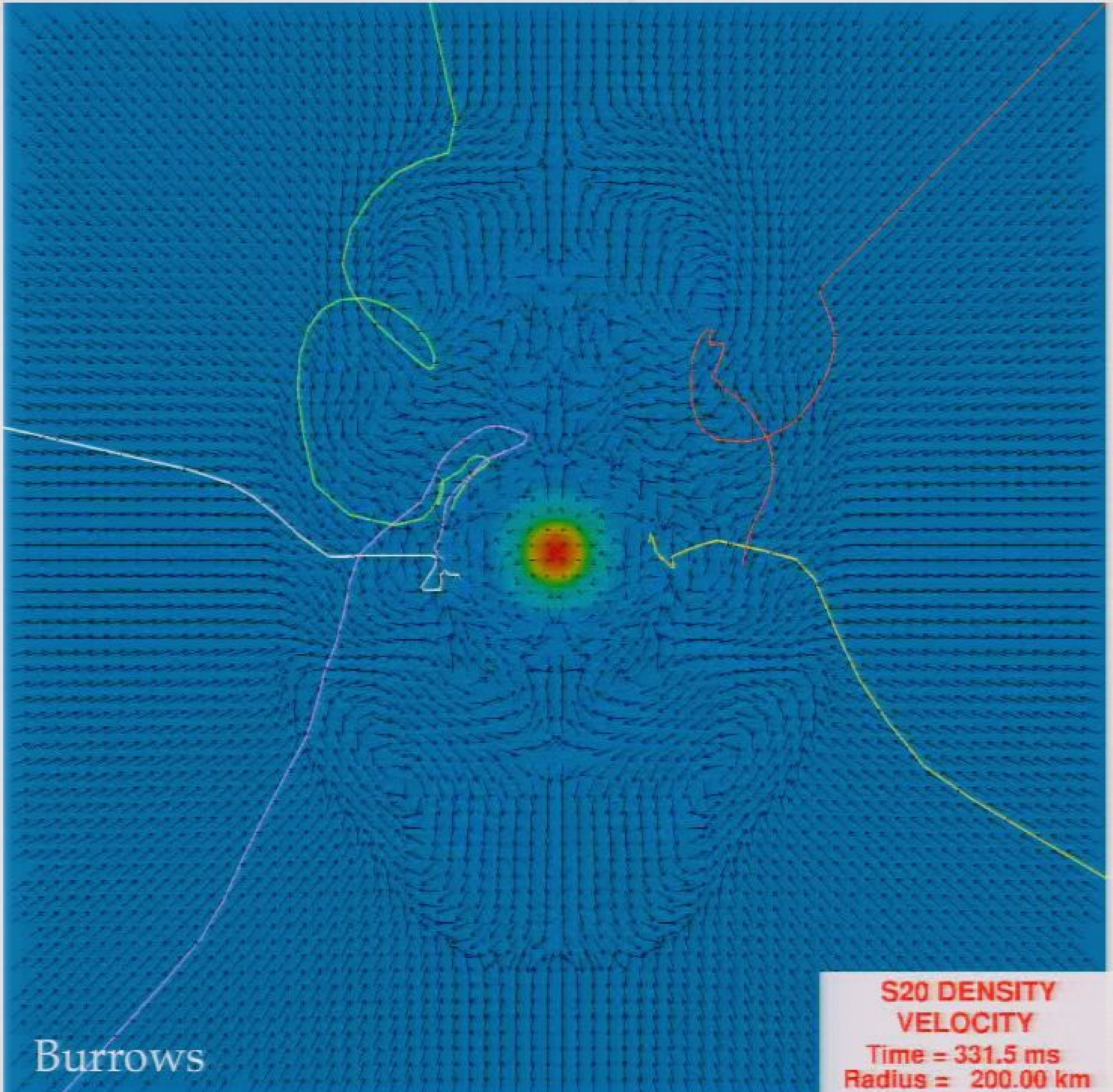
Higher Entropy and Longer Dwell Times



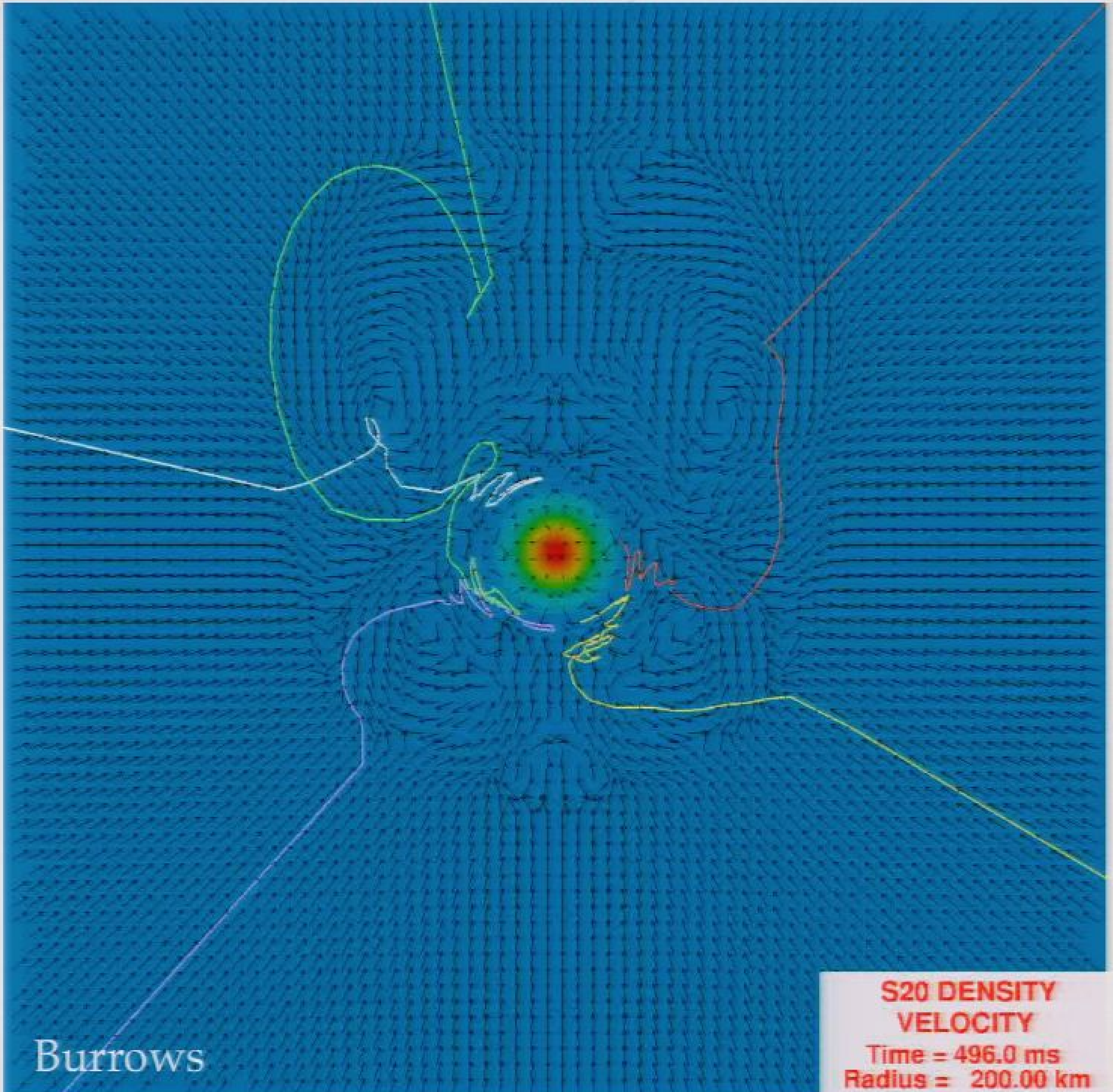

S20 DENSITY
VELOCITY
Time = 100.0 ms
Radius = 200.00 km
Burrows

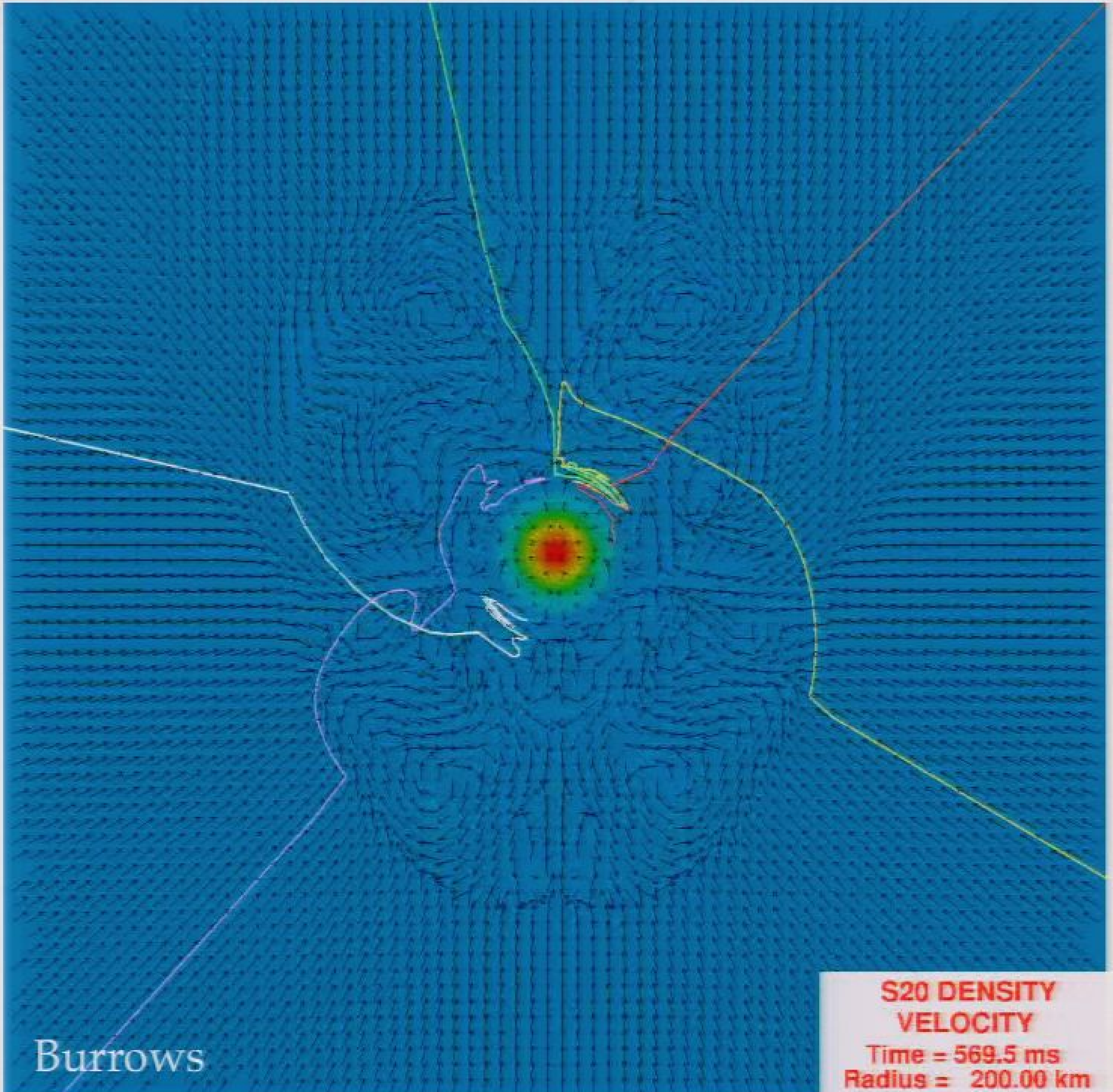

Burrows
S20 DENSITY
VELOCITY
Time = 174.0 ms
Radius = 200.00 km

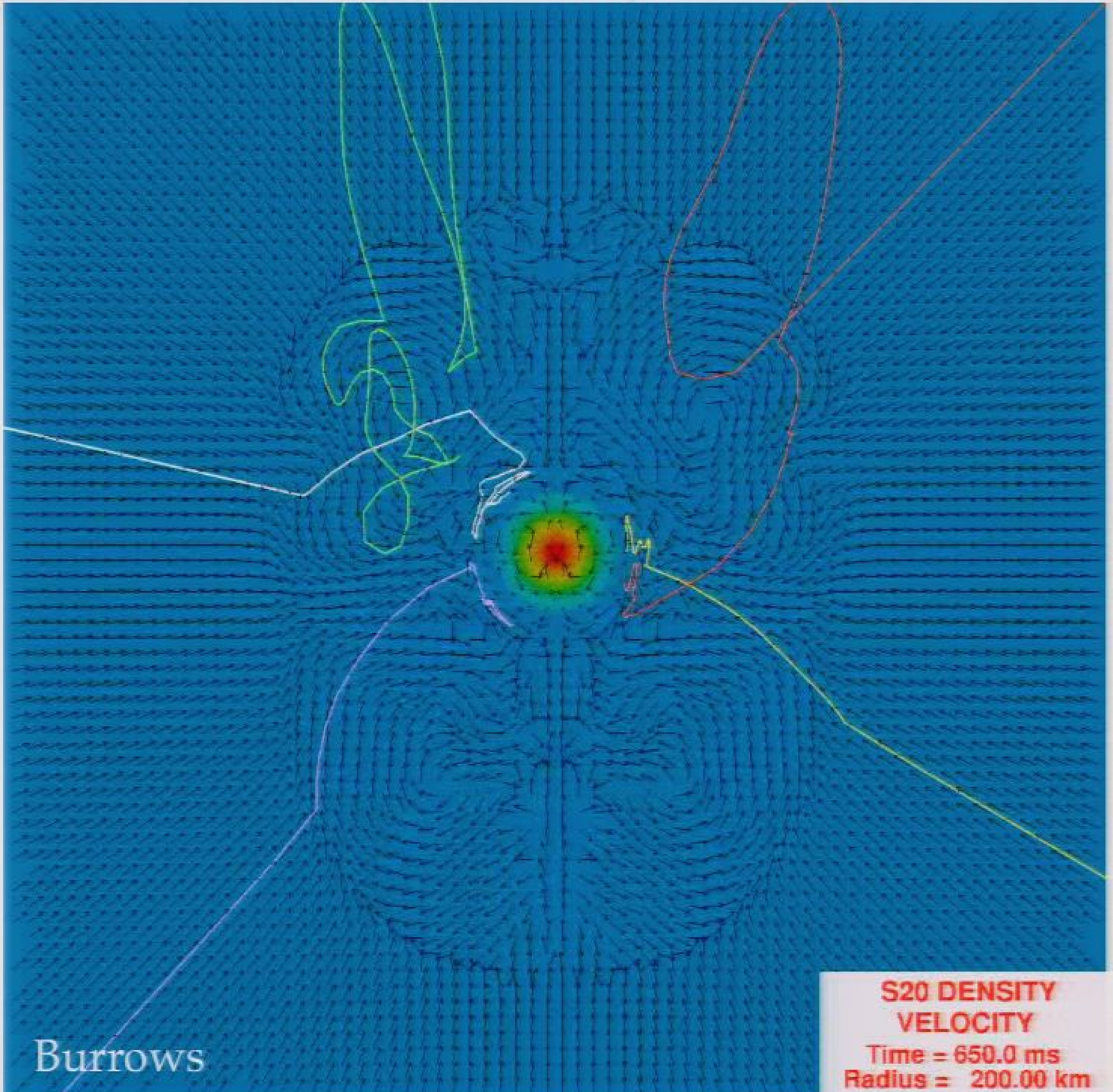

Burrows
S20 DENSITY
VELOCITY
Time = 258.0 ms
Radius = 200.00 km


S20 DENSITY
VELOCITY
Time = 331.5 ms
Radius = 200.00 km
Burrows

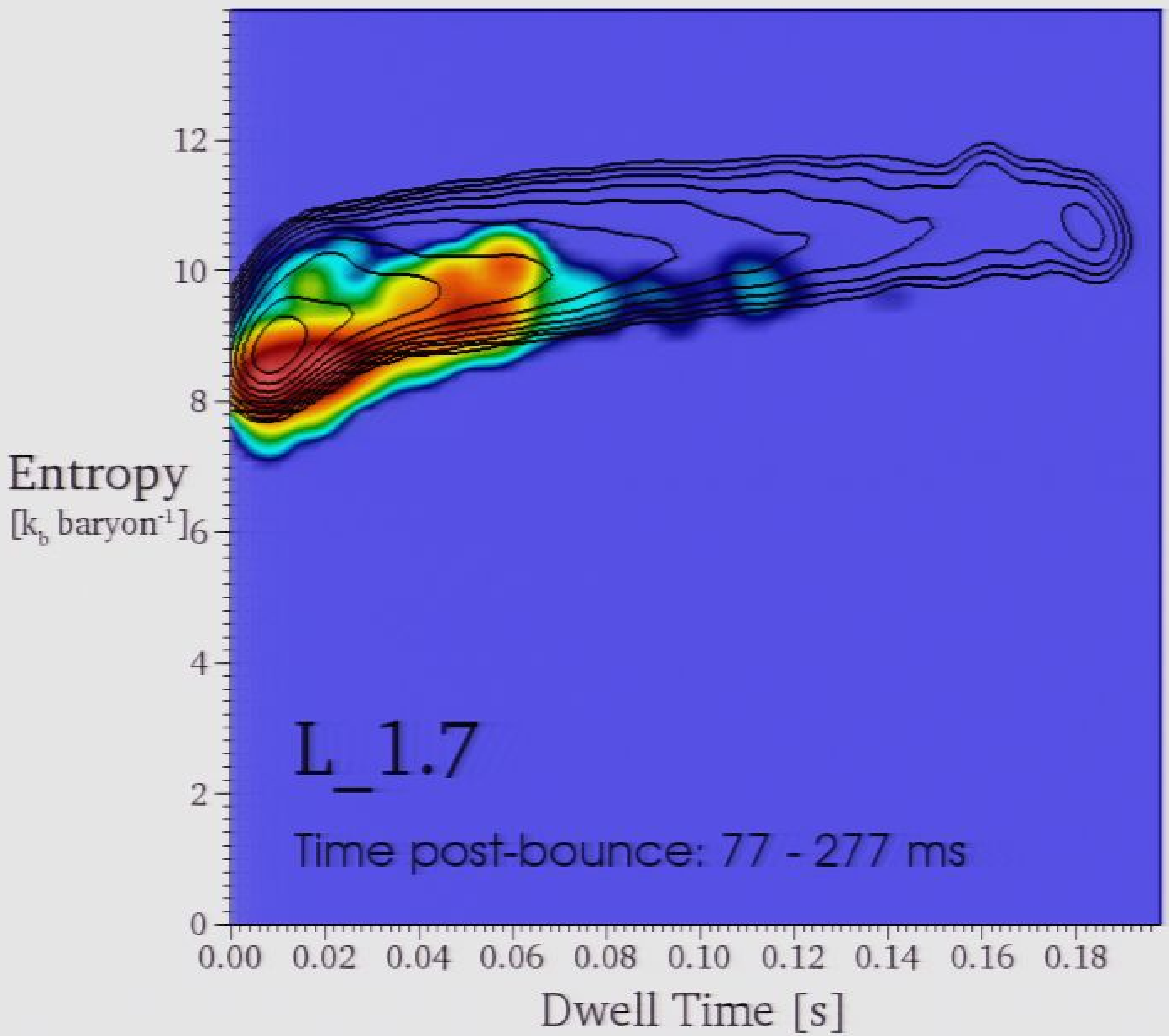

S20 DENSITY
VELOCITY
Time = 412.0 ms
Radius = 200.00 km
Burrows

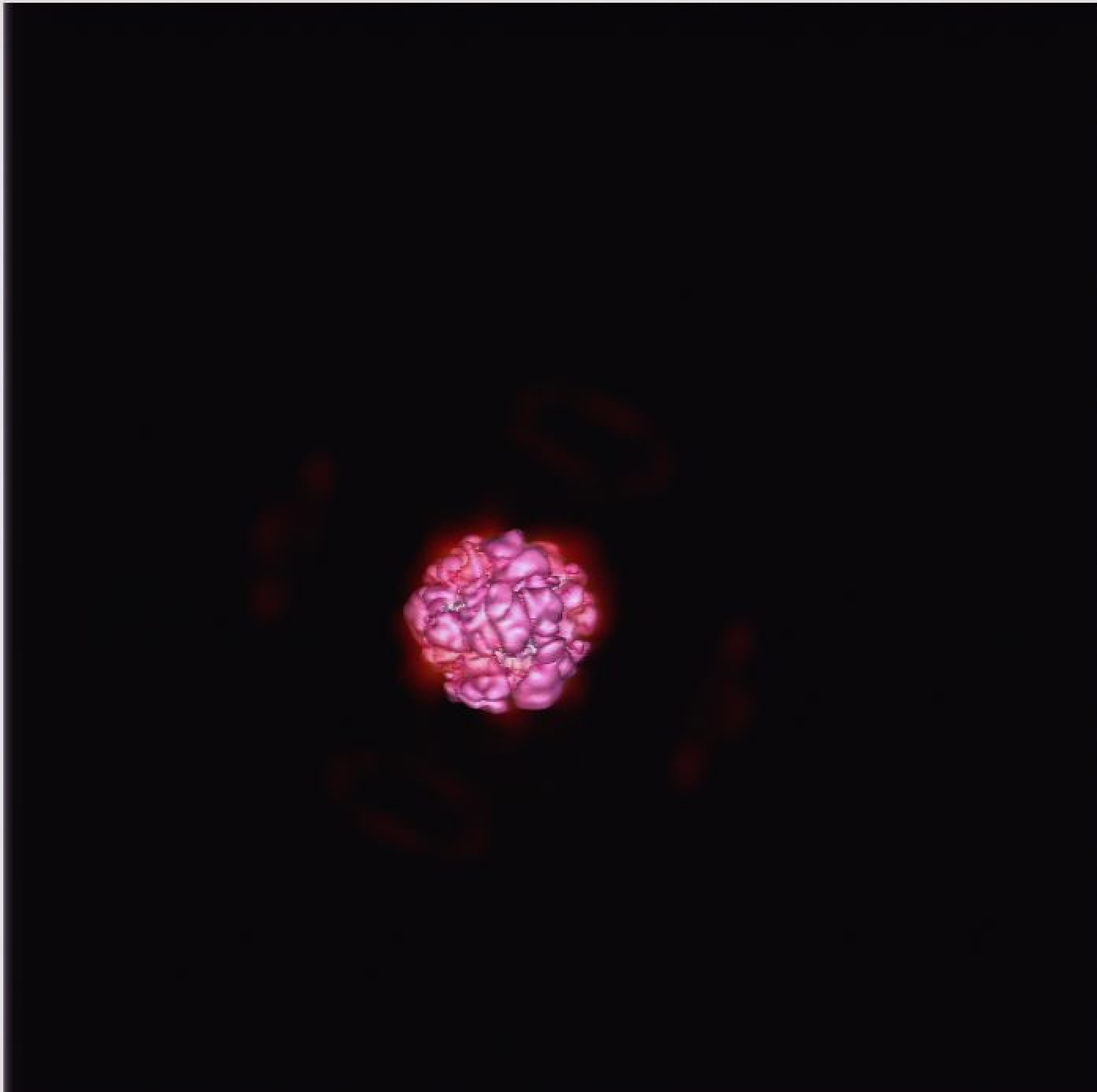

S20 DENSITY
VELOCITY
Time = 496.0 ms
Radius = 200.00 km
Burrows

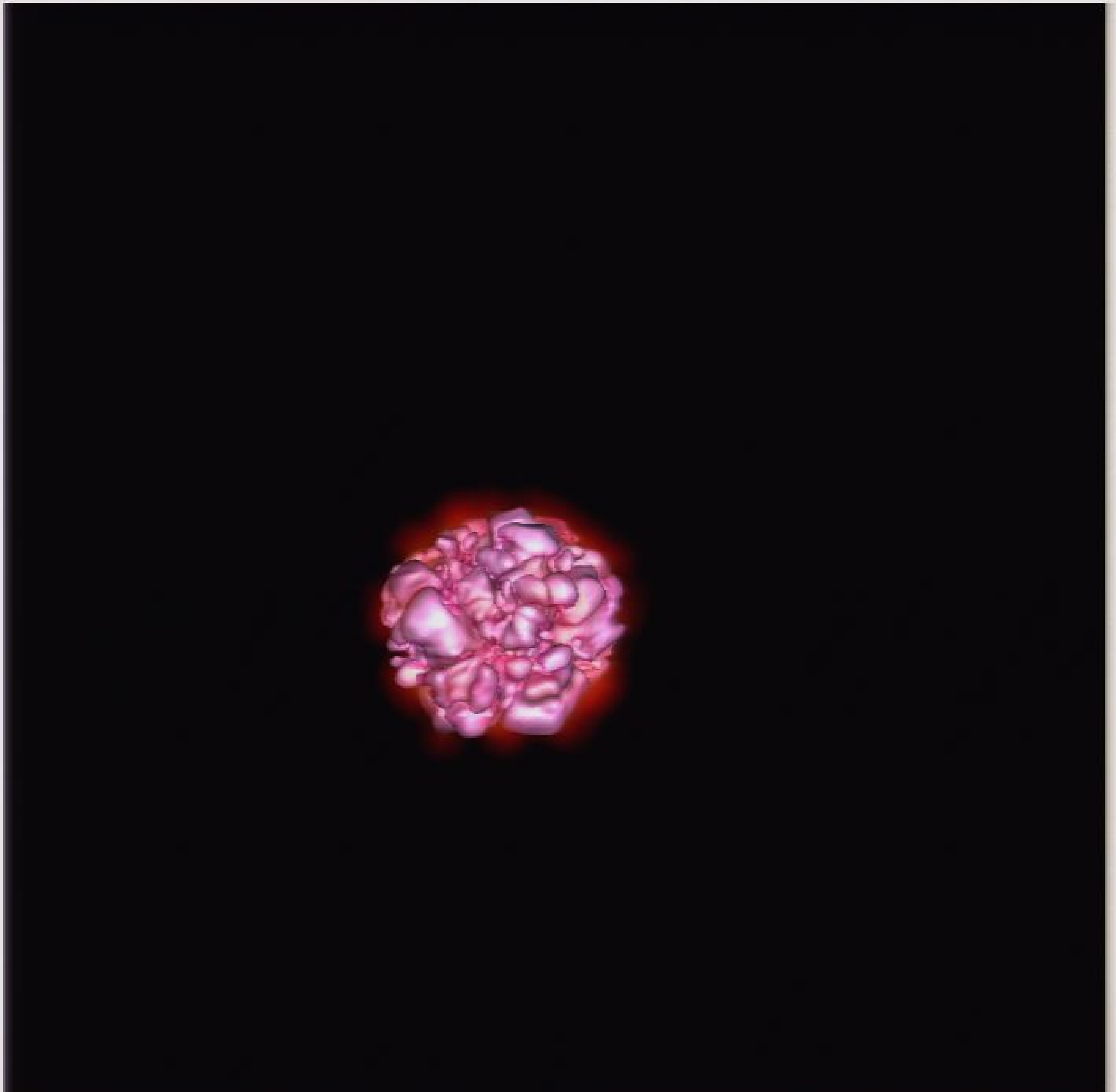

S20 DENSITY
VELOCITY
Time = 569.5 ms
Radius = 200.00 km
Burrows

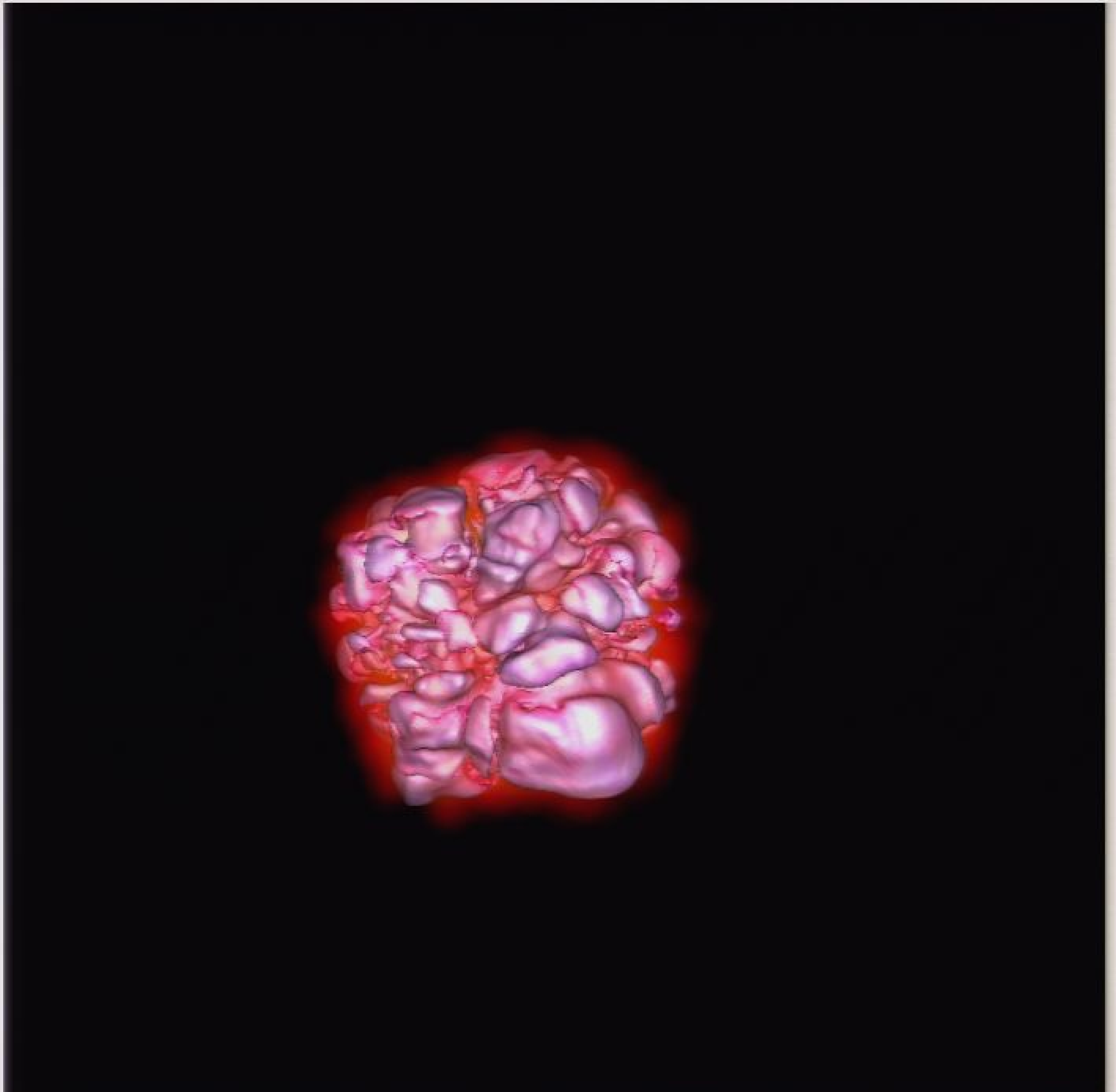

S20 DENSITY
VELOCITY
Time = 650.0 ms
Radius = 200.00 km
Burrows

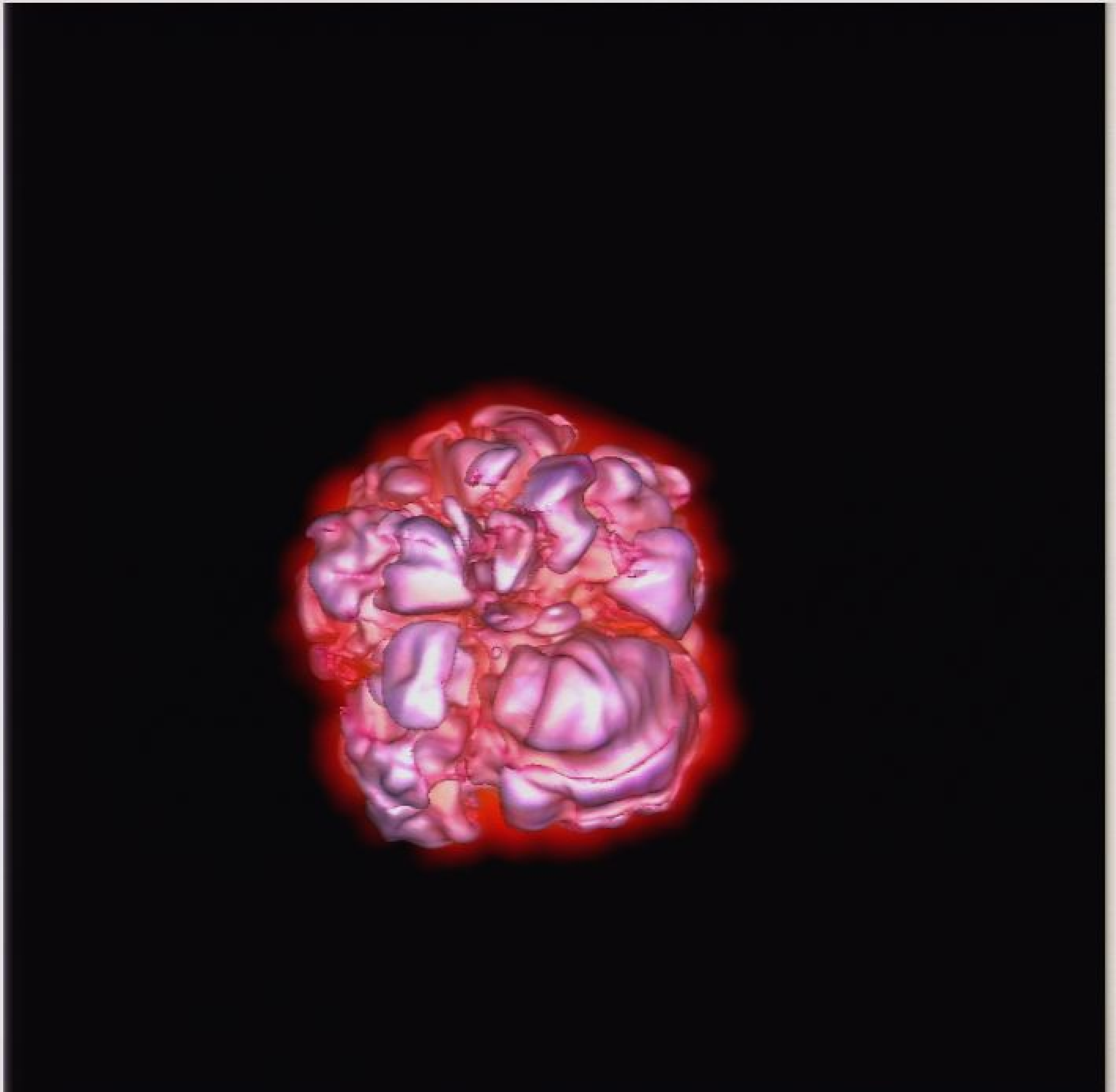
Dwell Time Distribution

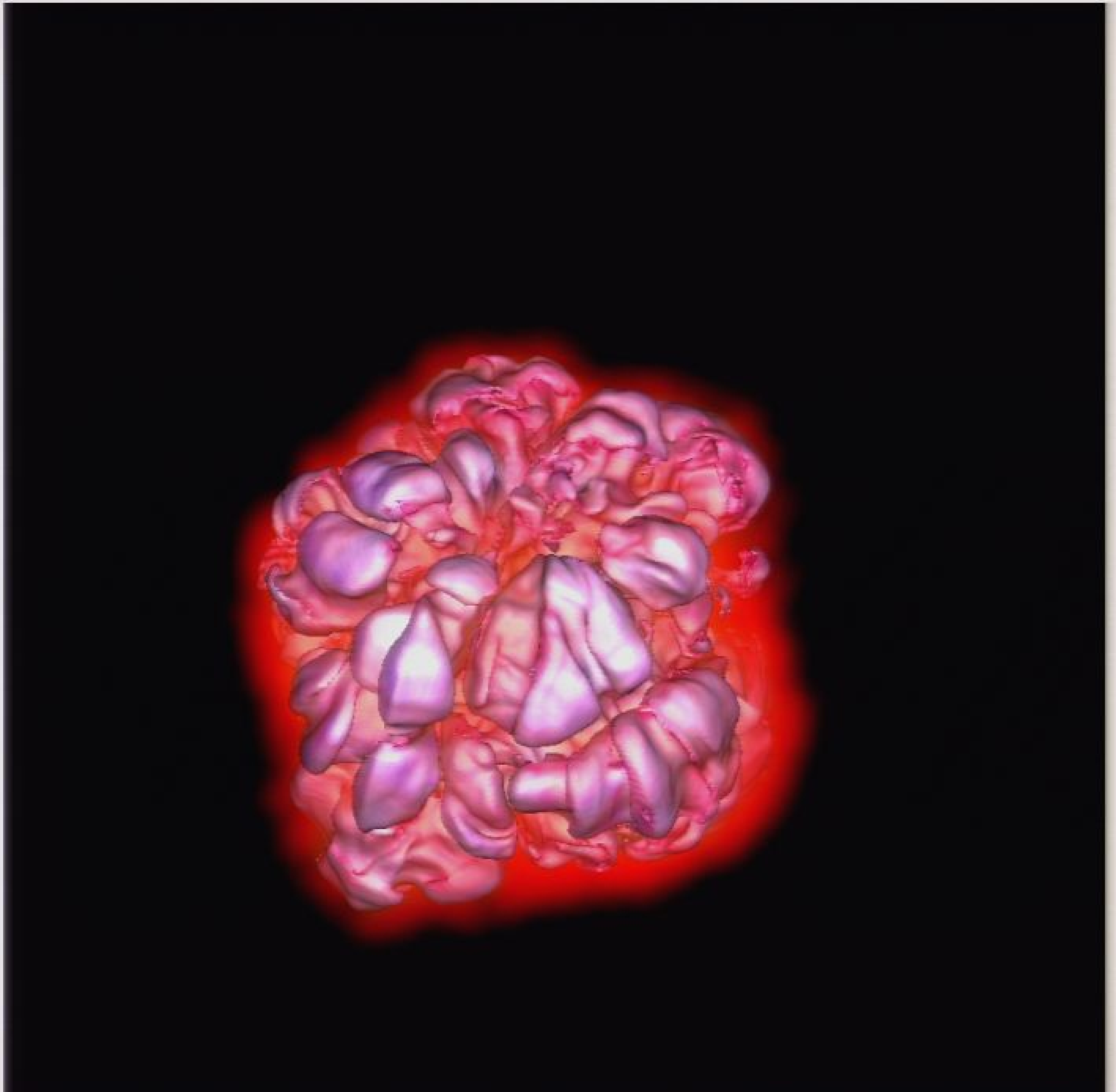


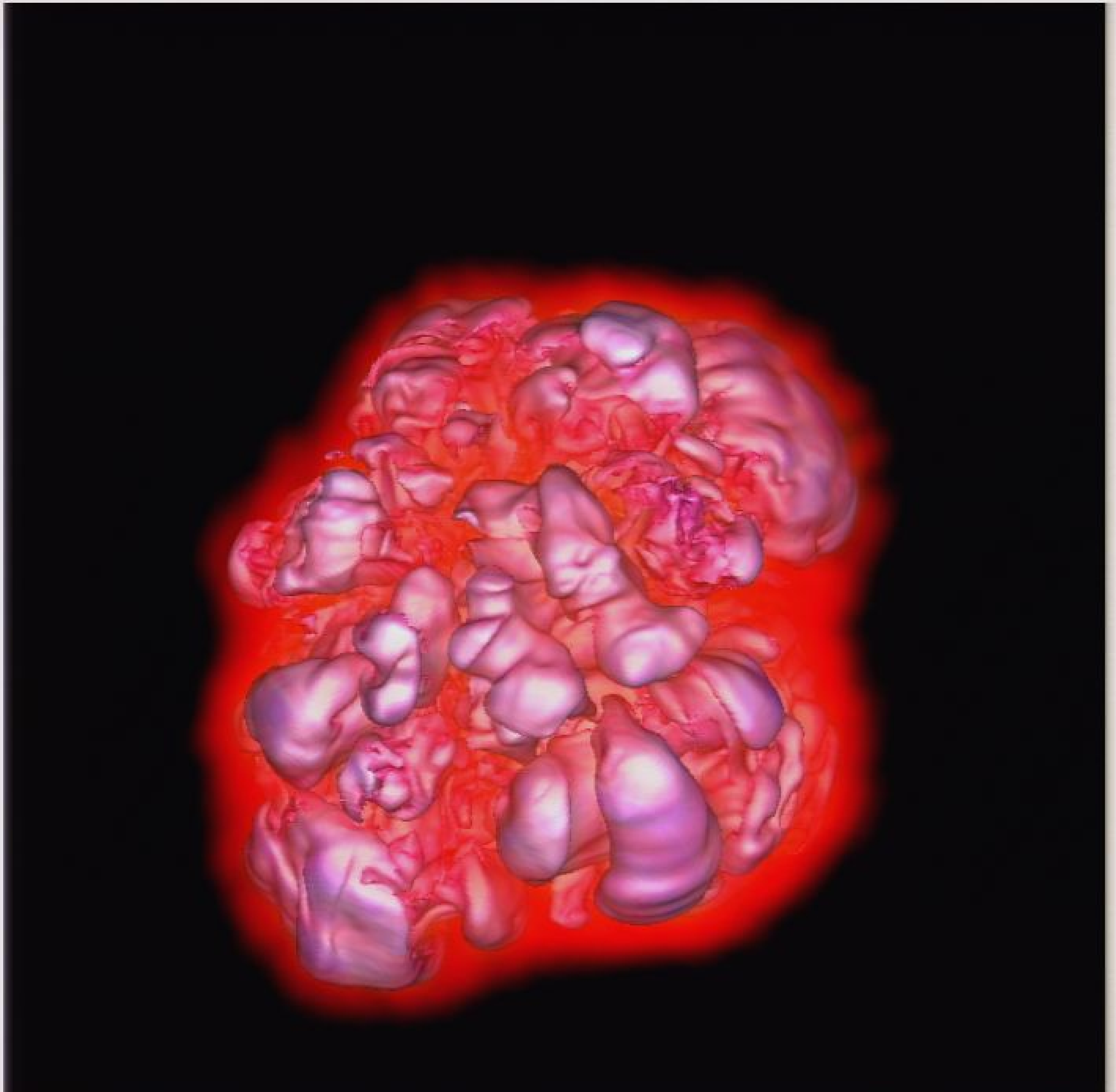


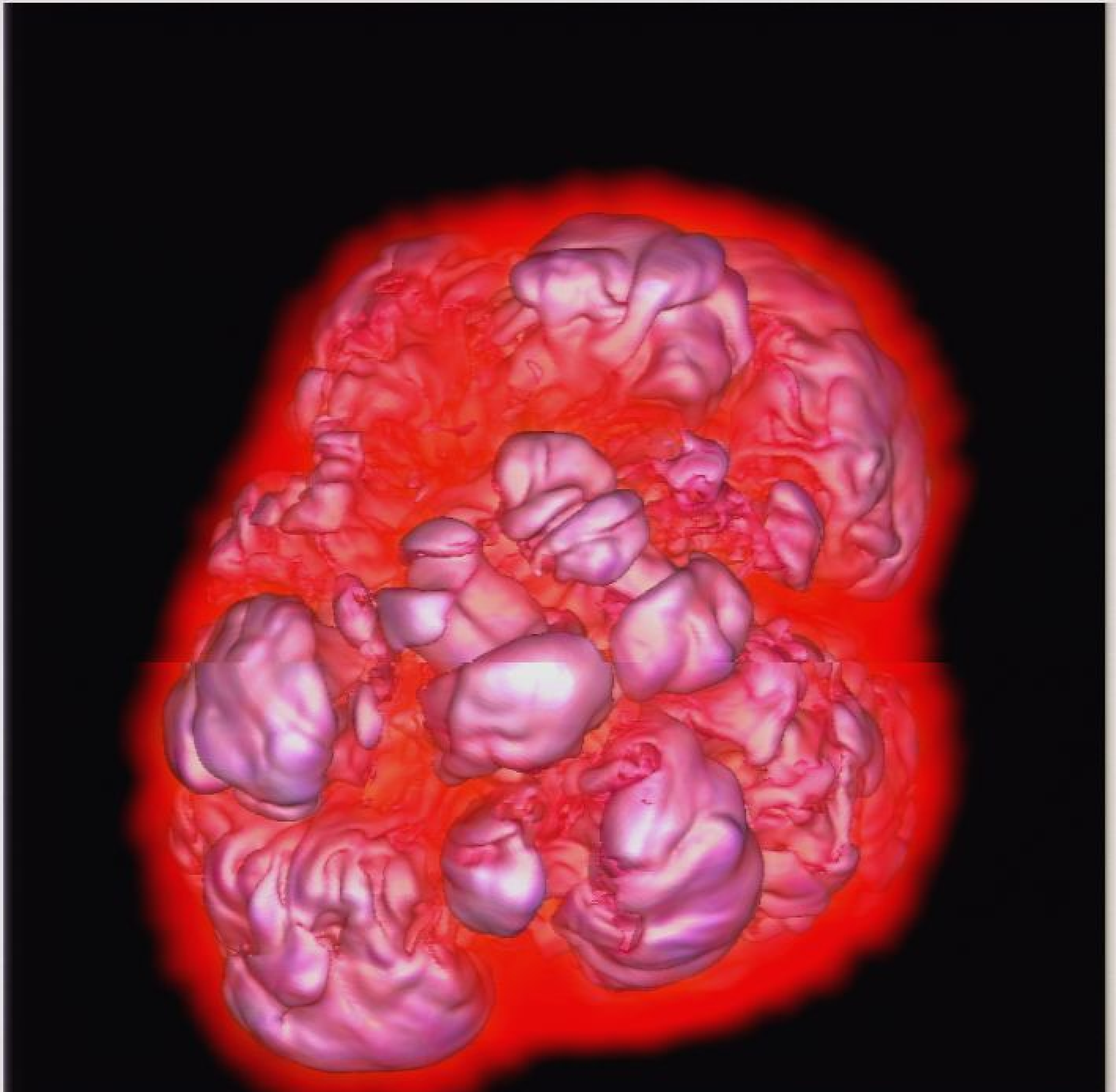


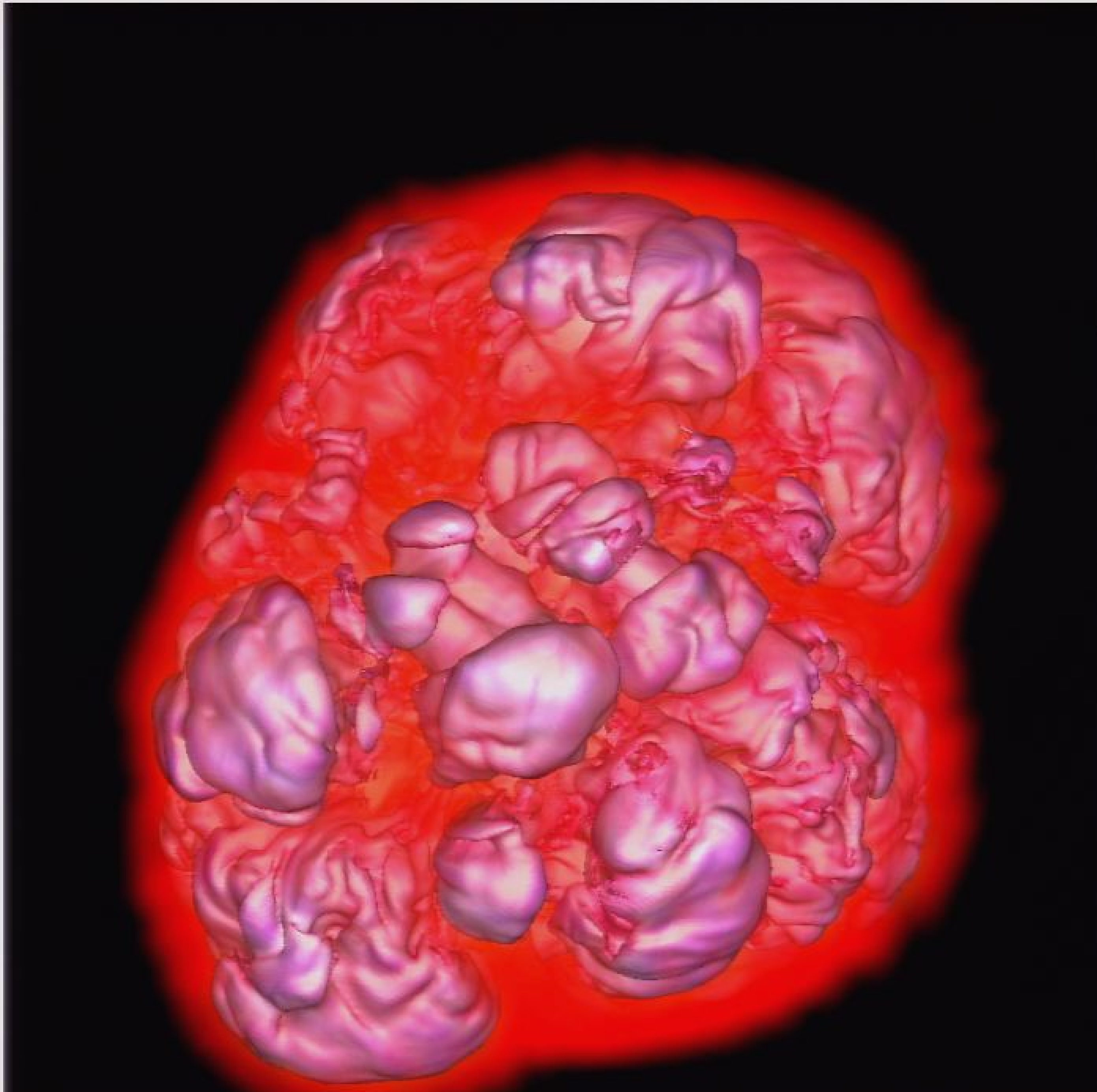












Standing Accretion Shock Instability (SASI)

Axisymmetric

$\ell = 1$ mode
is dominant

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

Blondin & Mezzacappa 2007

3D no significant spin-up!

Rantsiou et al. 2011

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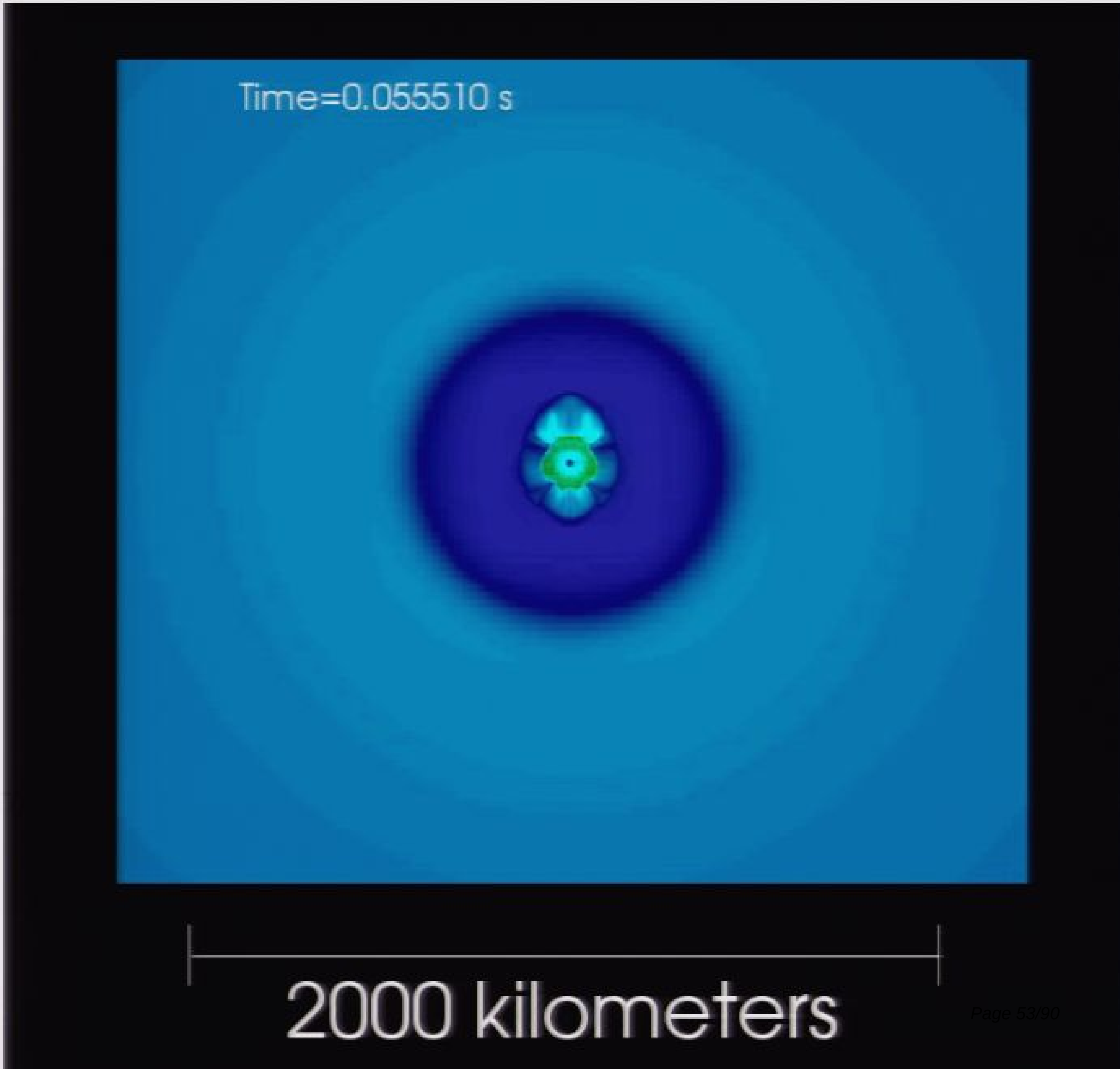

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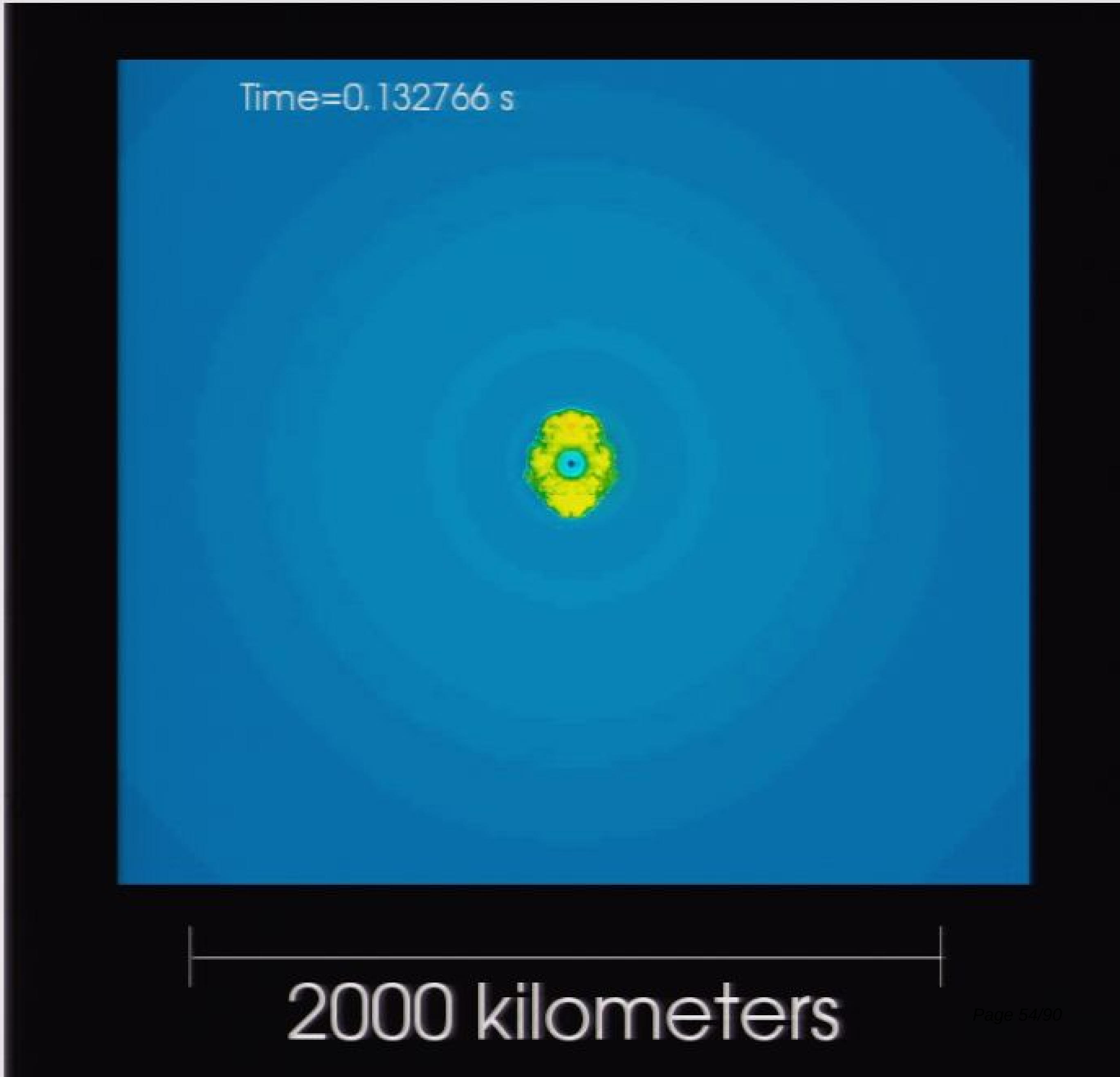

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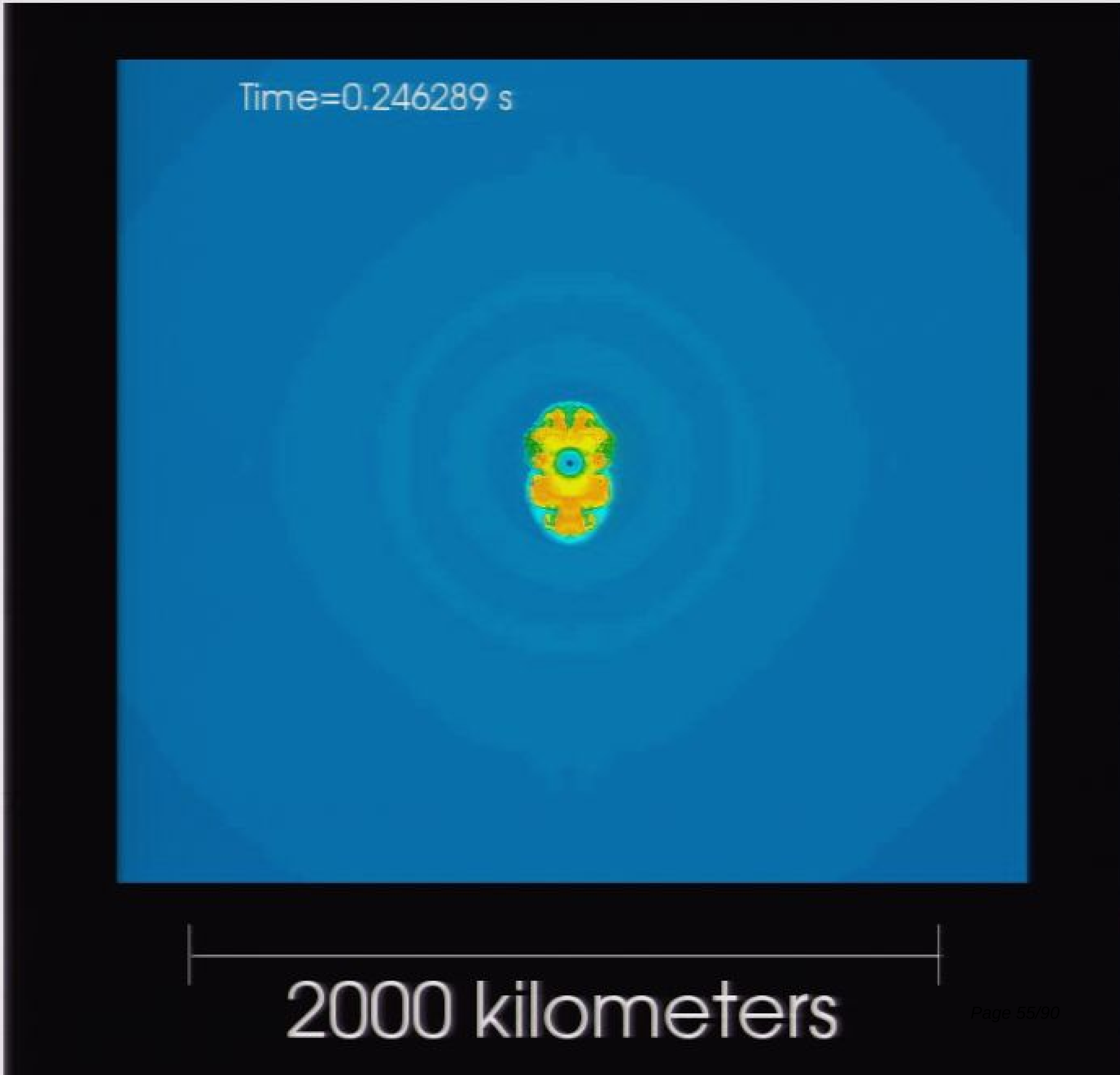

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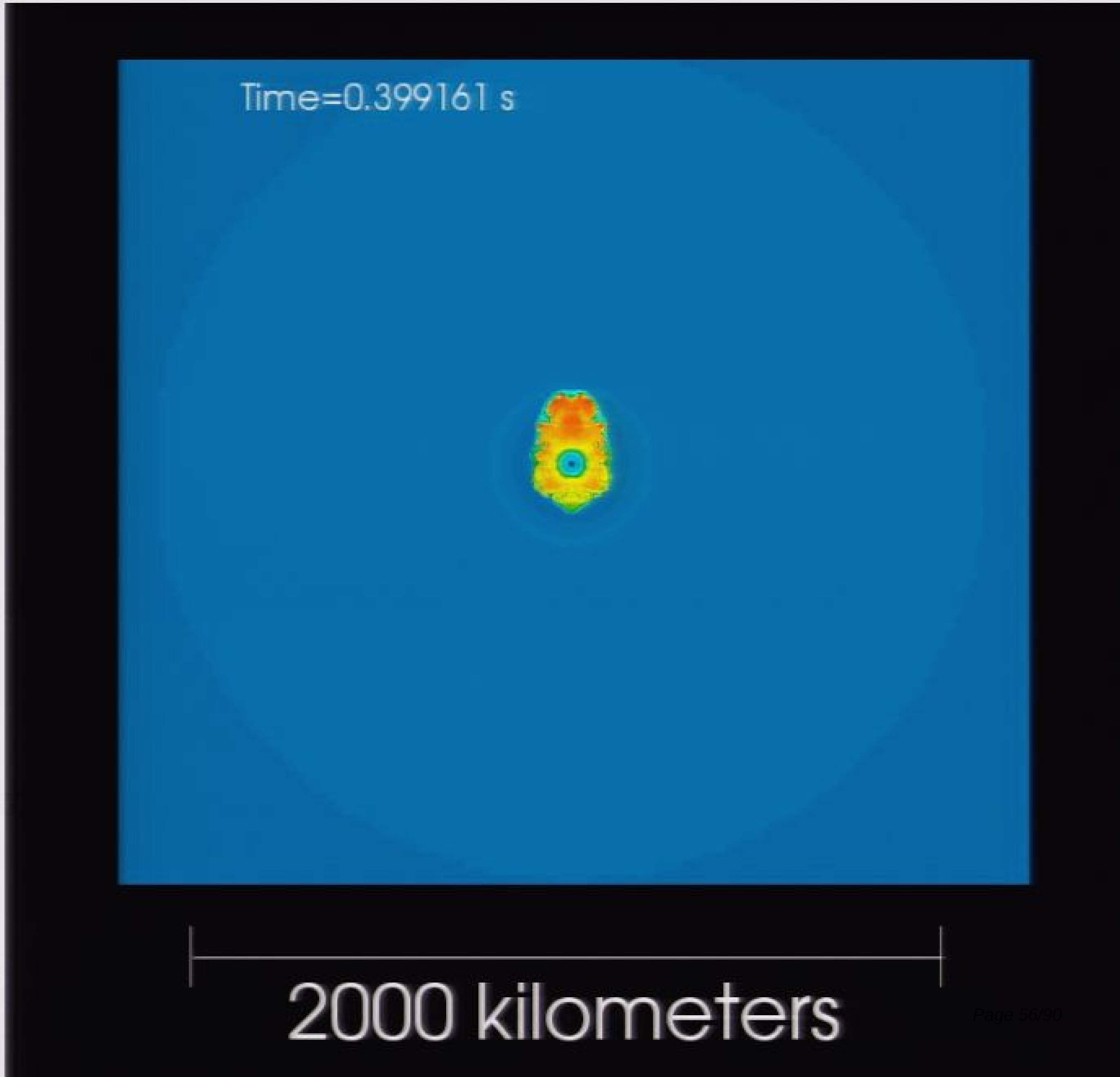

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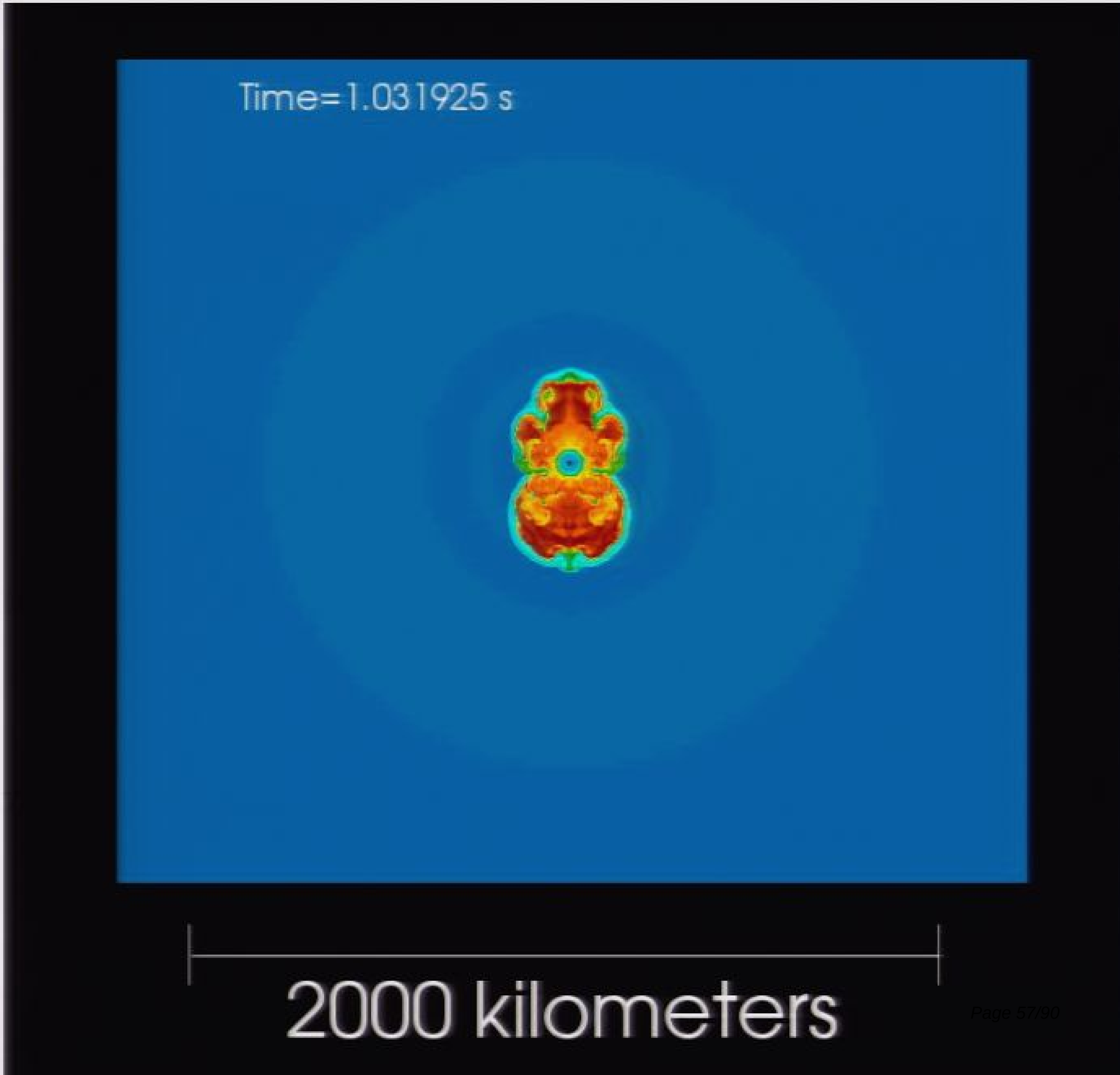

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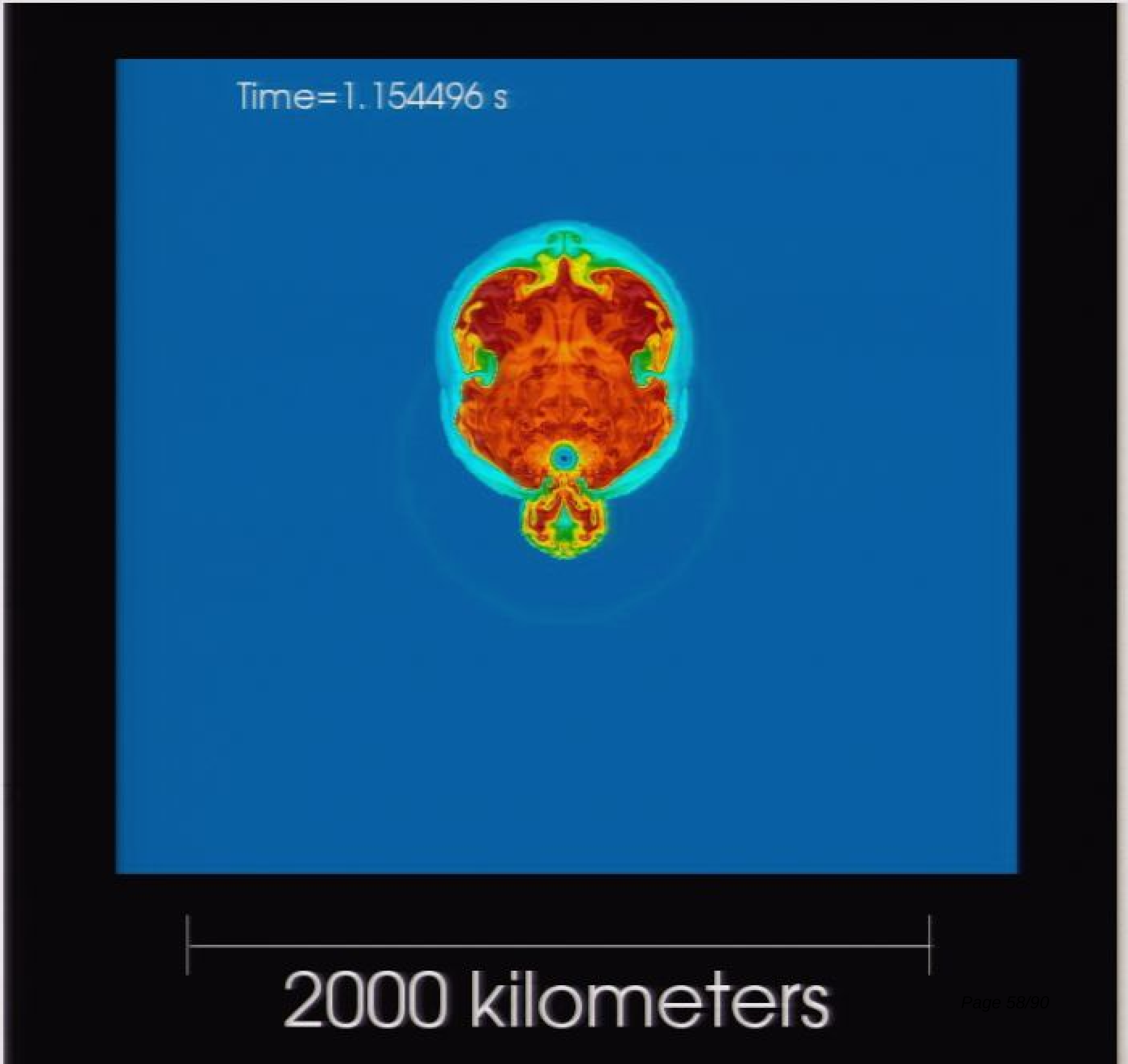

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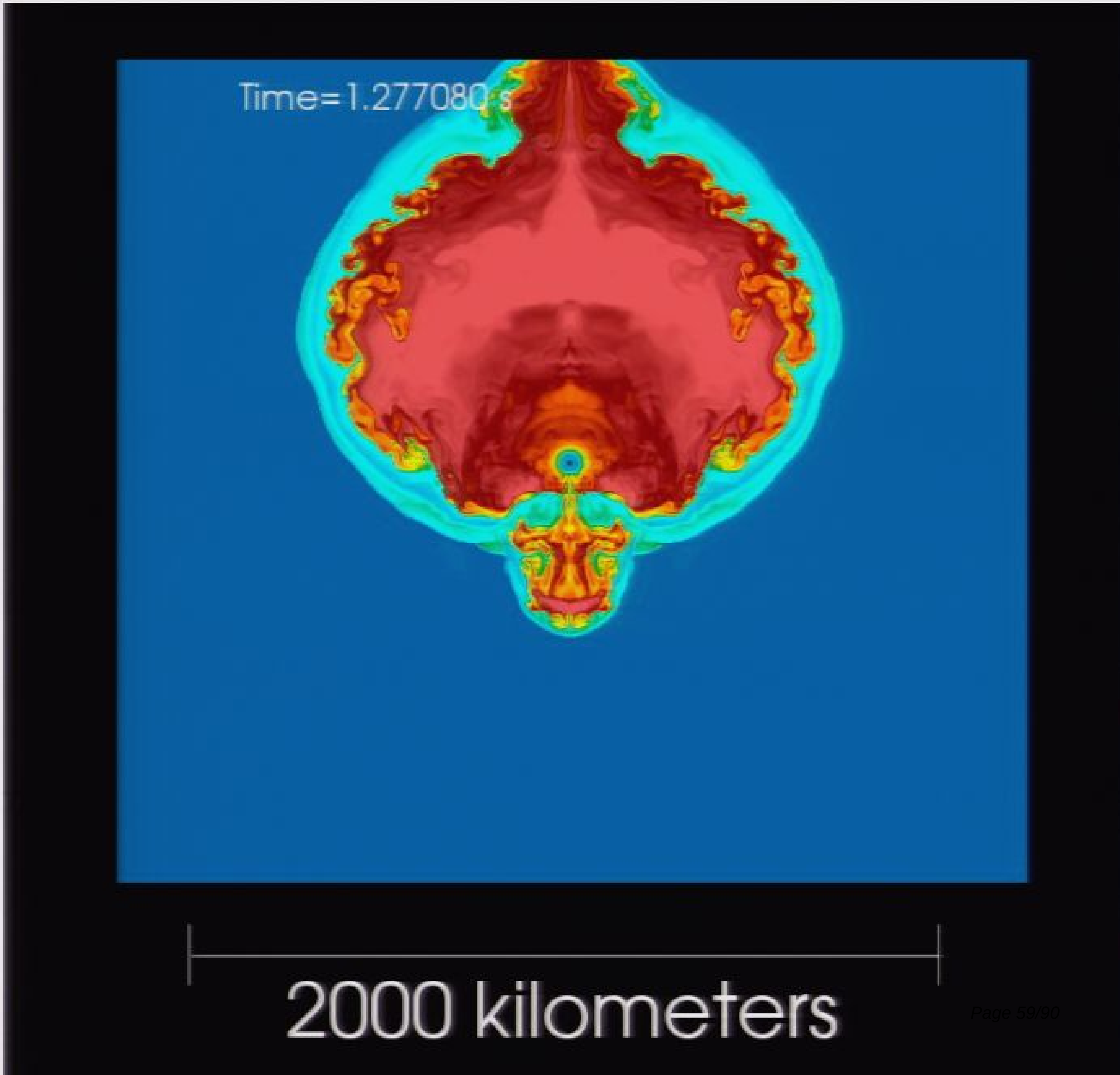

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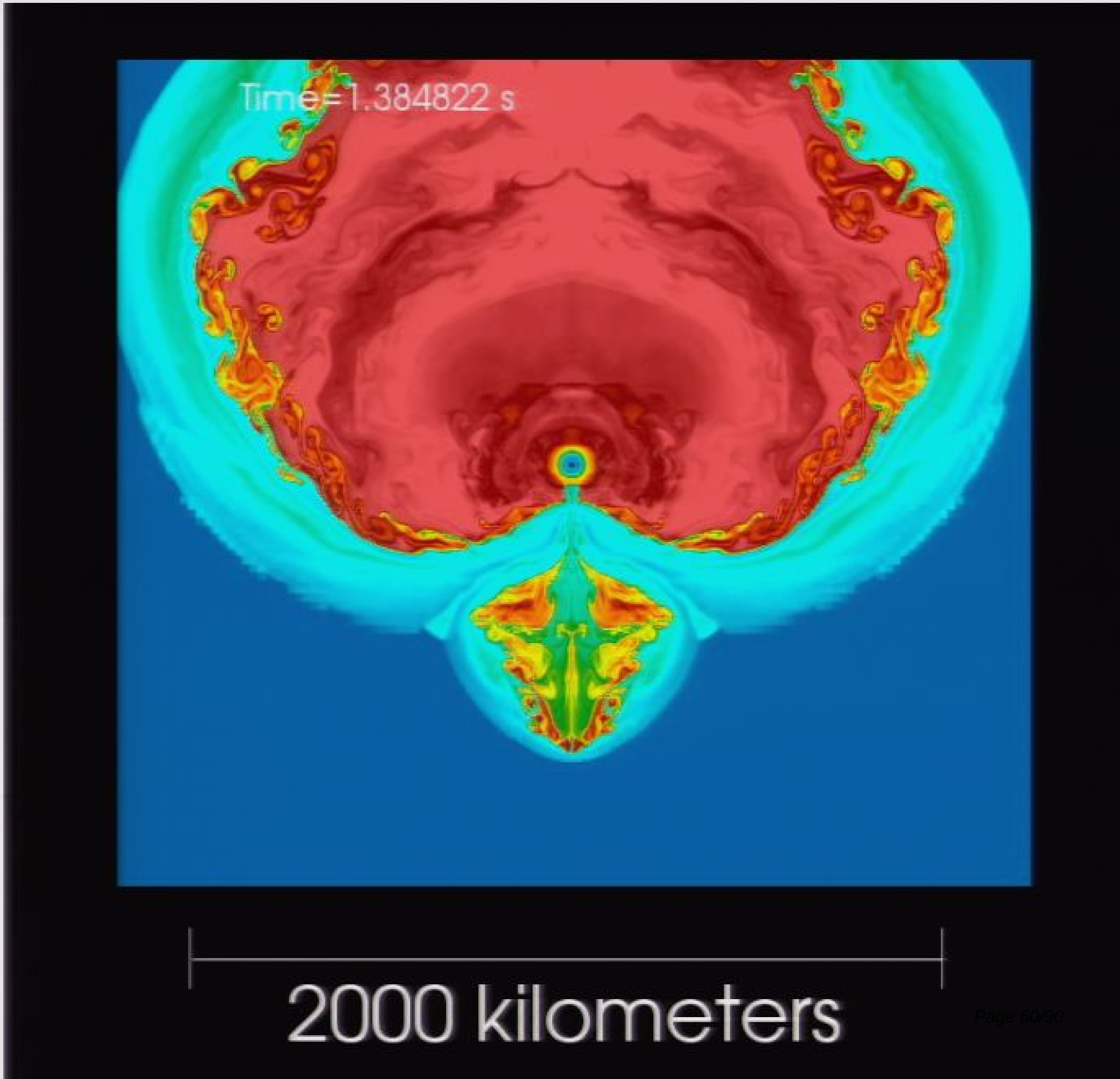
Suggested as a fundamental characteristic of SN dynamics and way to spin-up pulsars;

Blondin & Mezzacappa 2007

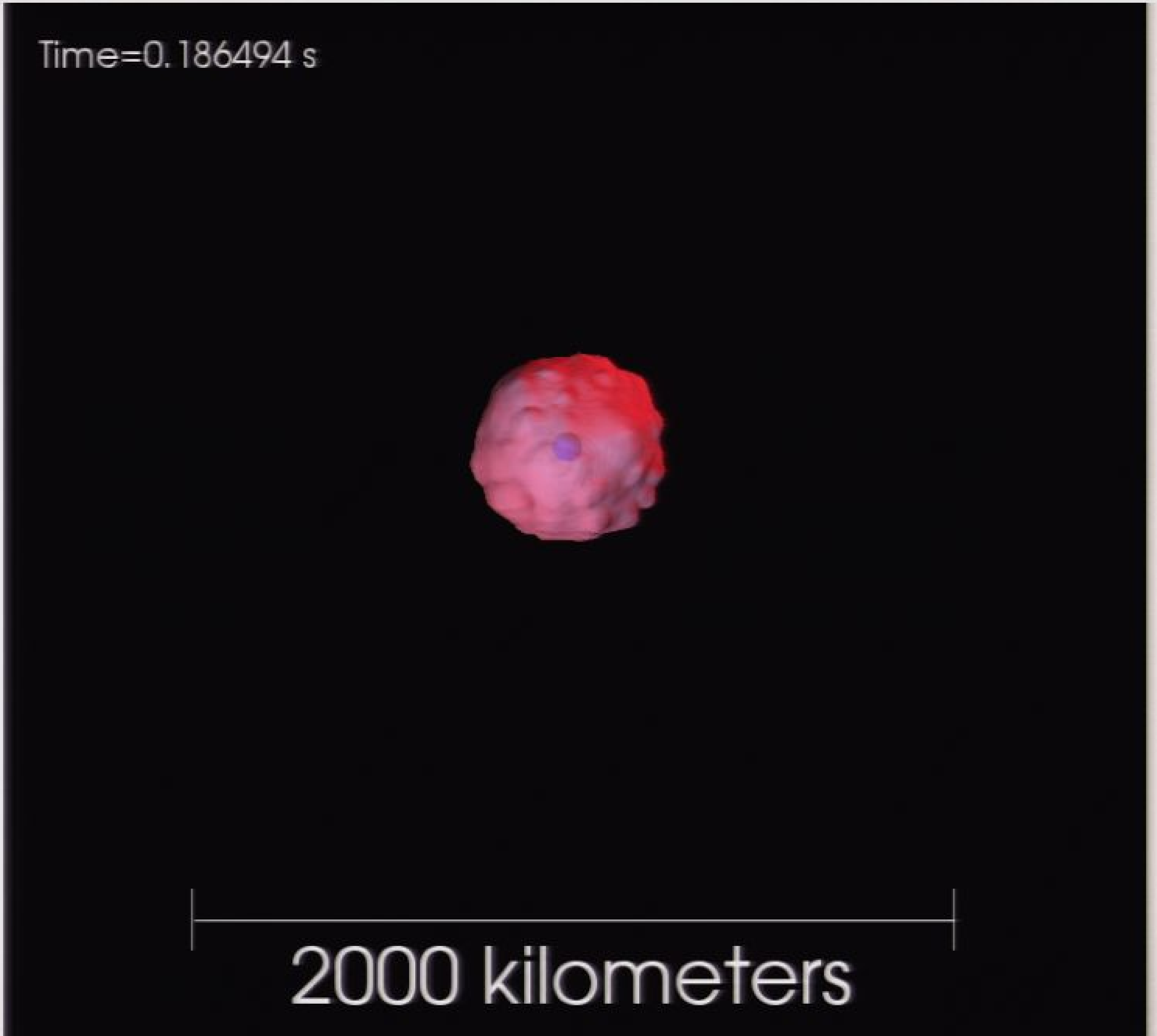
3D no significant spin-up!

Rantsiou et al. 2011



Non-Rotating Initial Model

Non-Rotating Initial Model



Non-Rotating Initial Model

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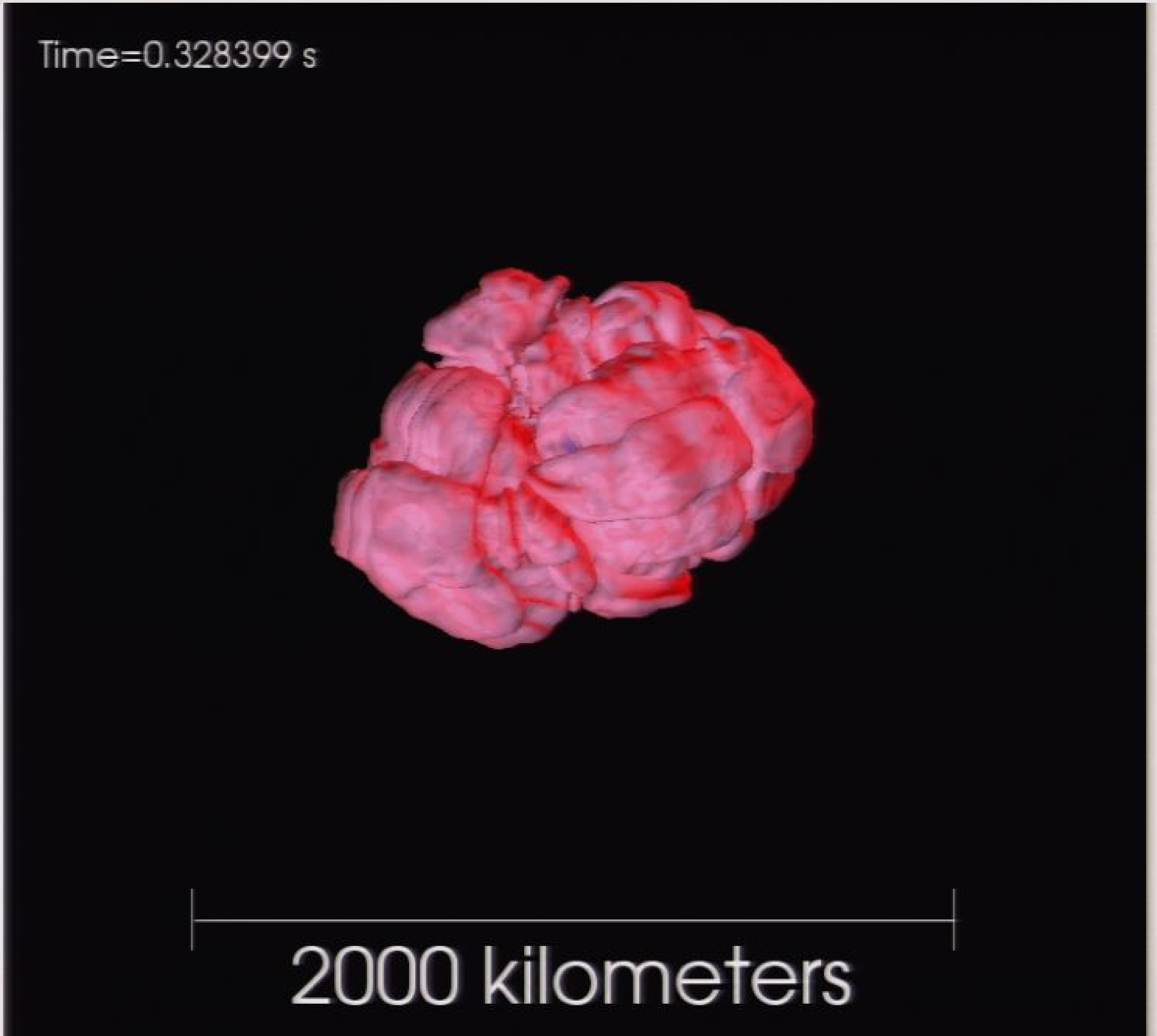

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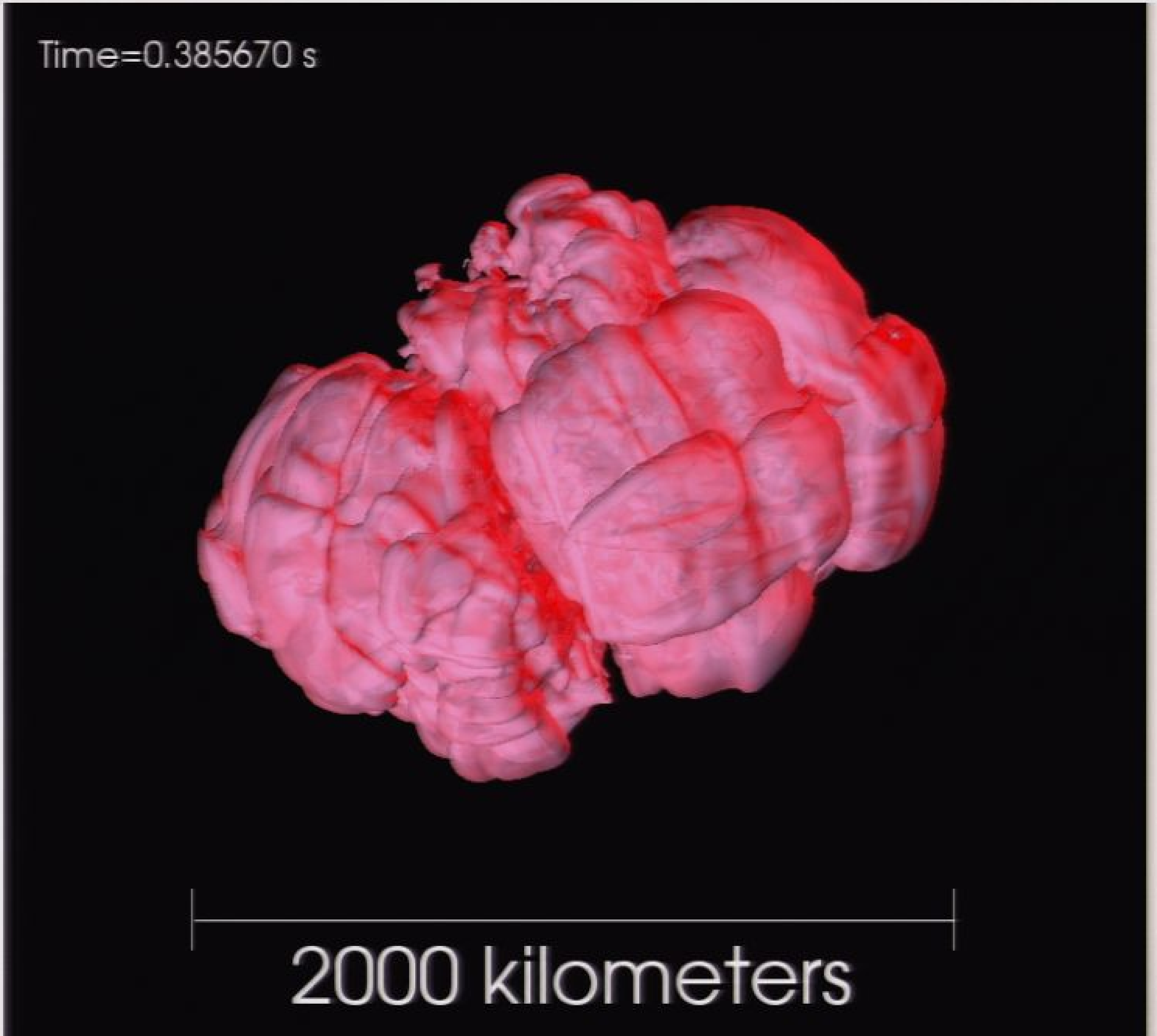

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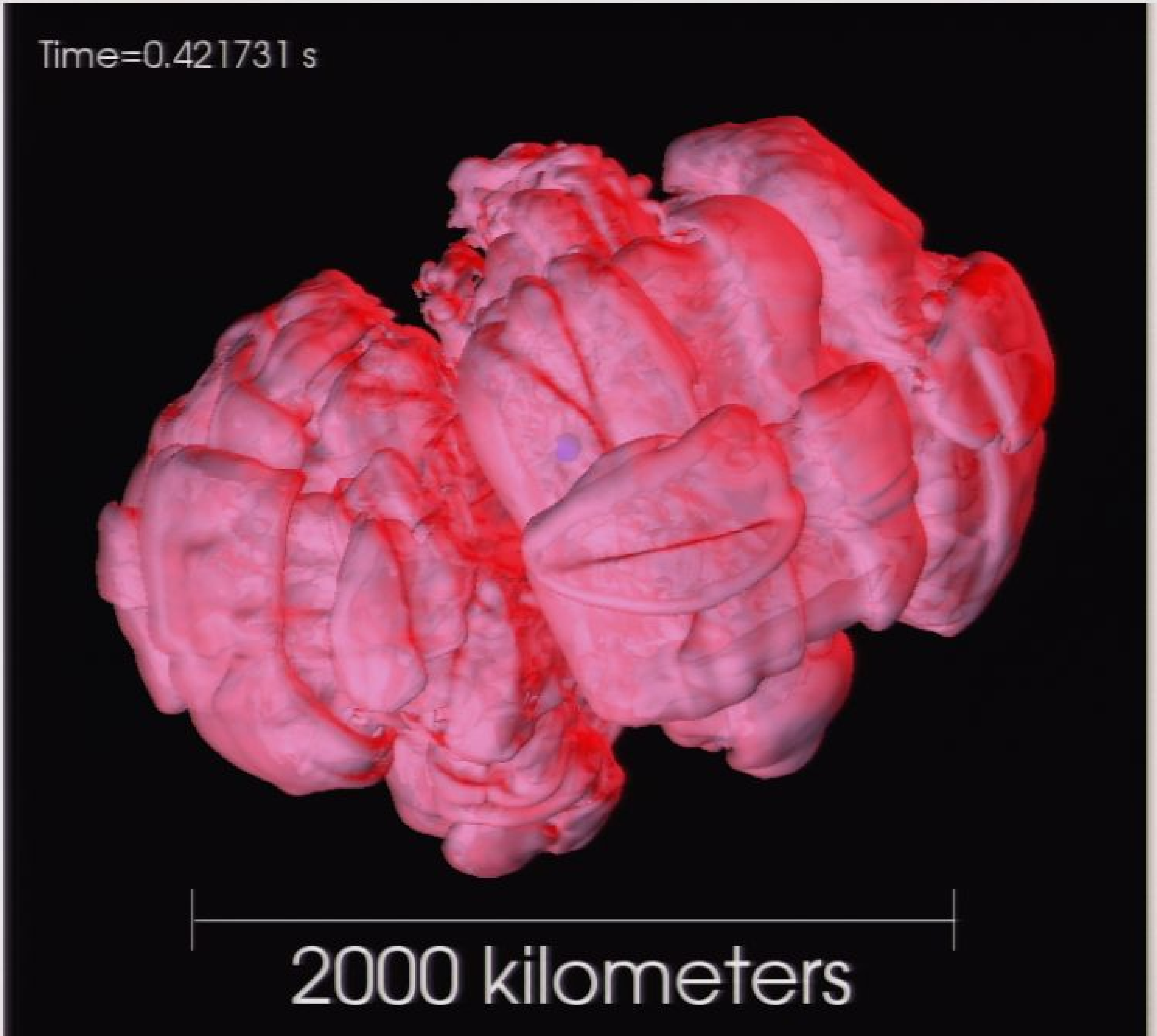
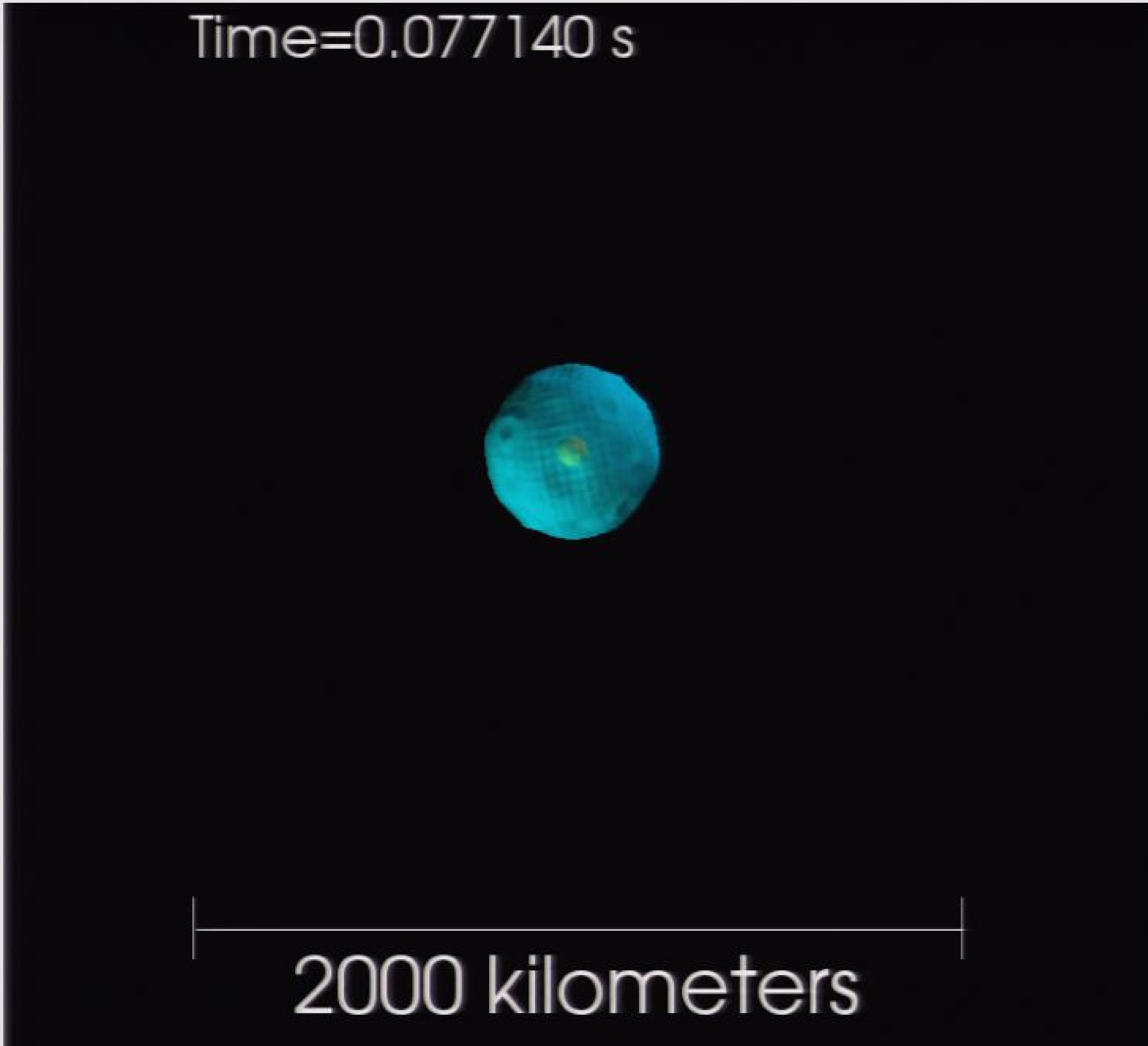


Rotating Initial Model



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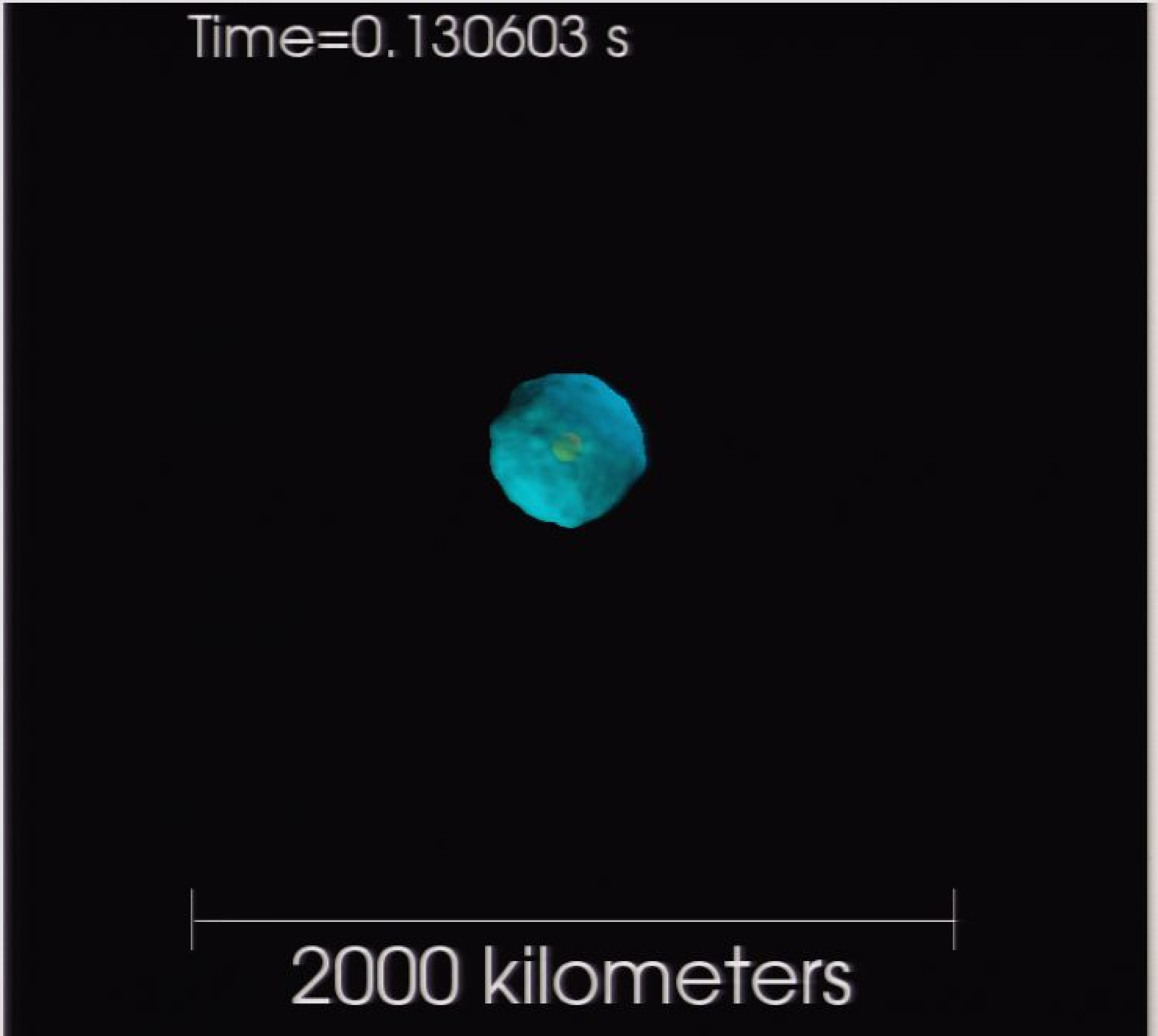

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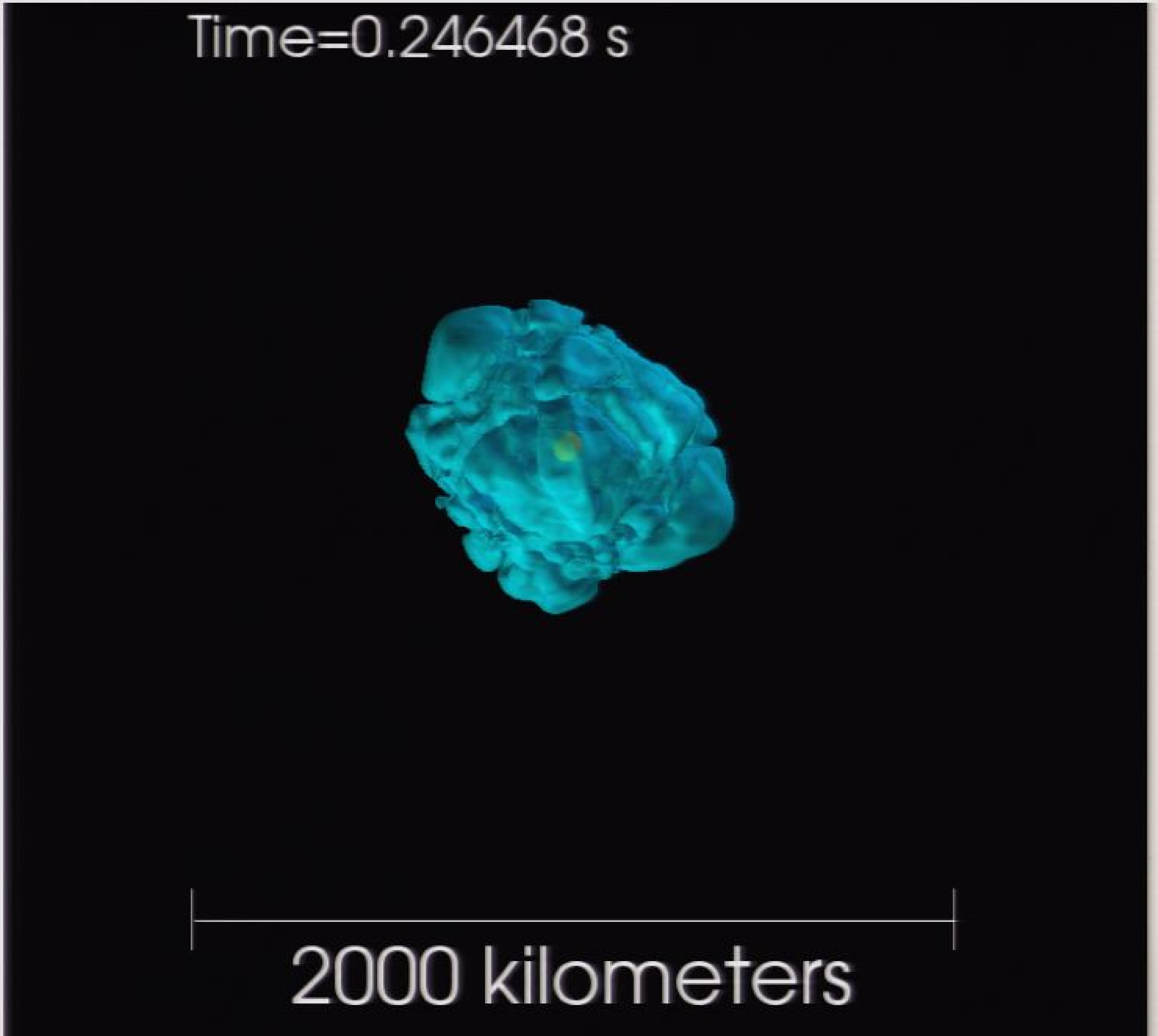

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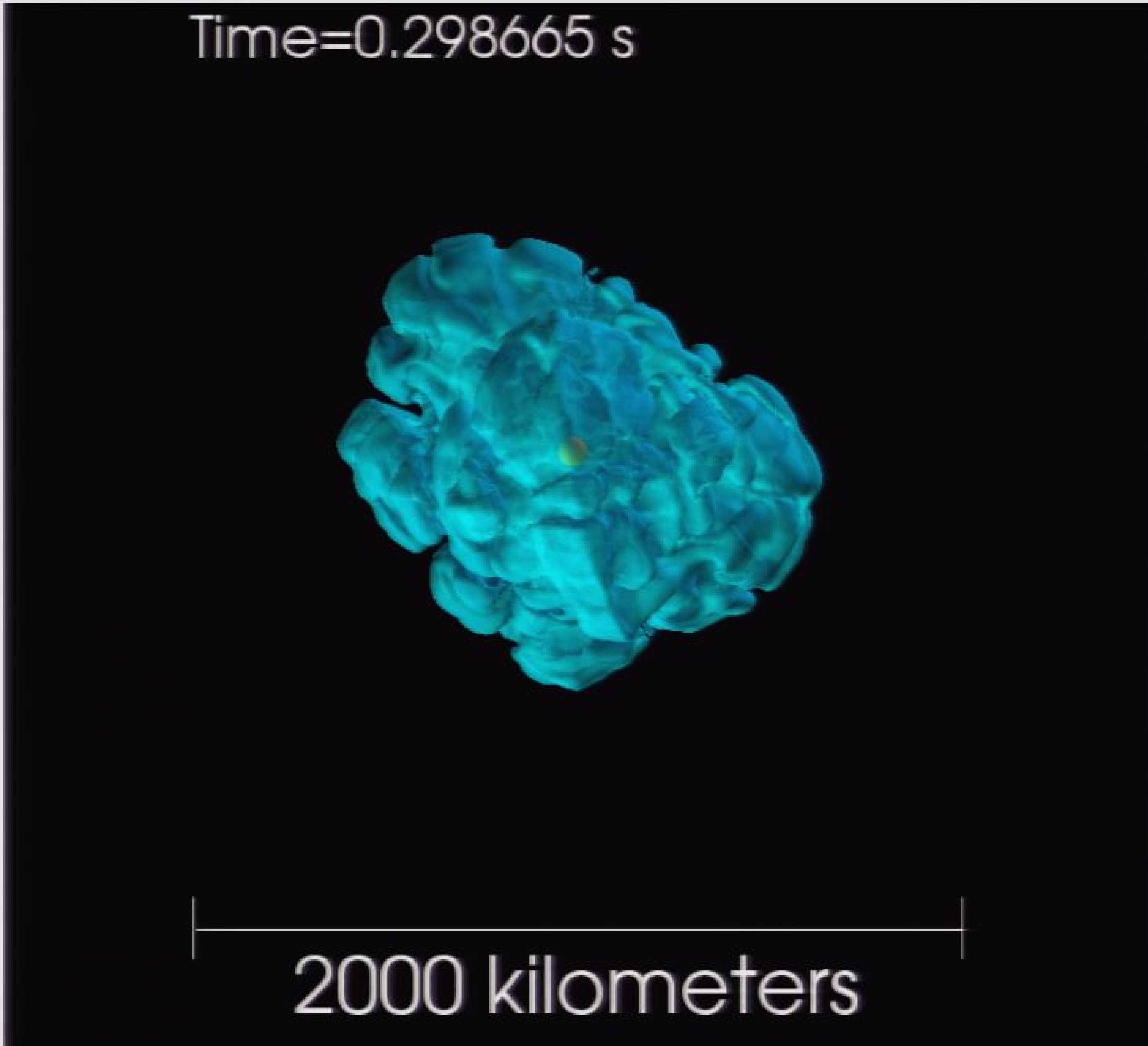

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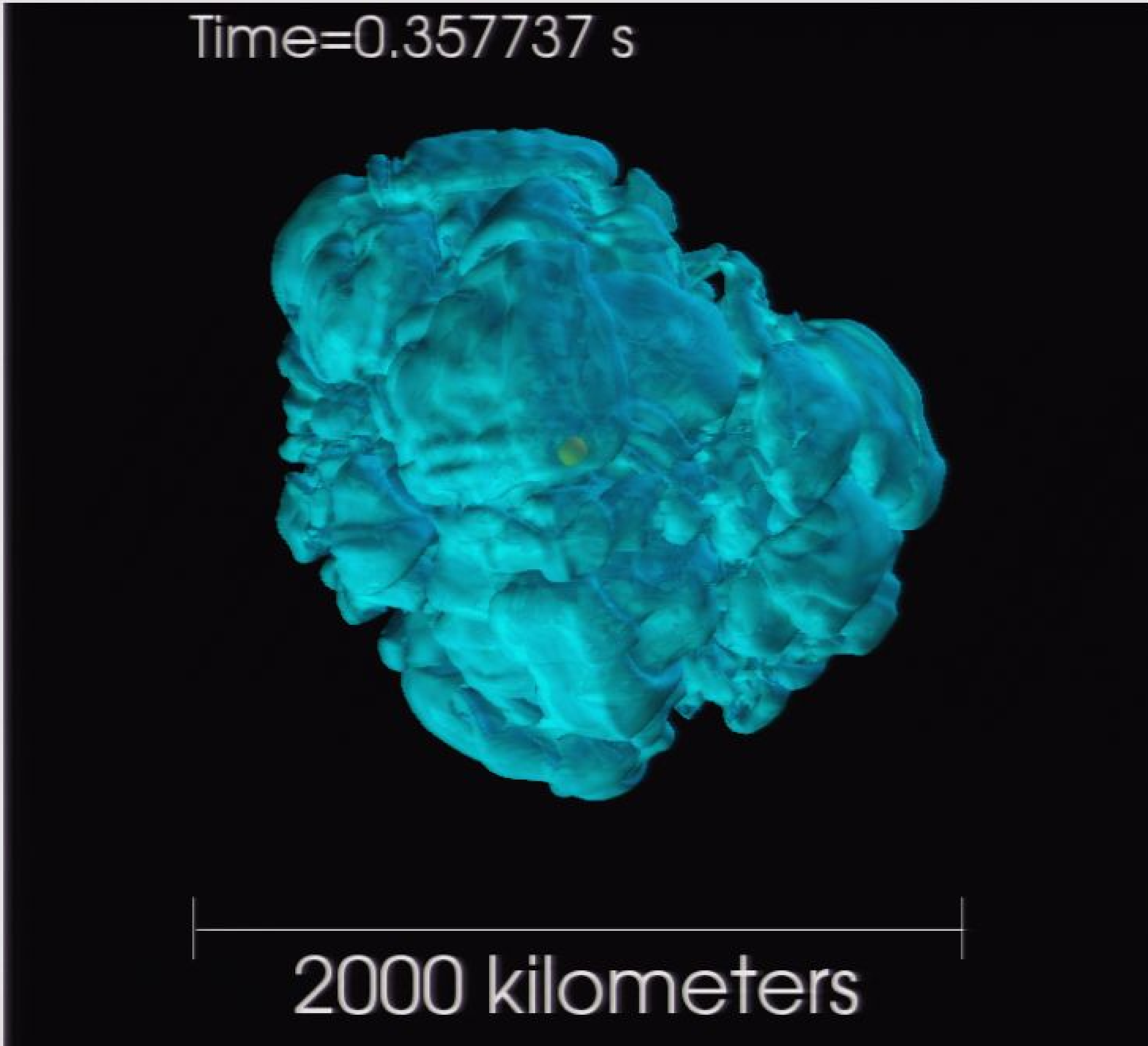

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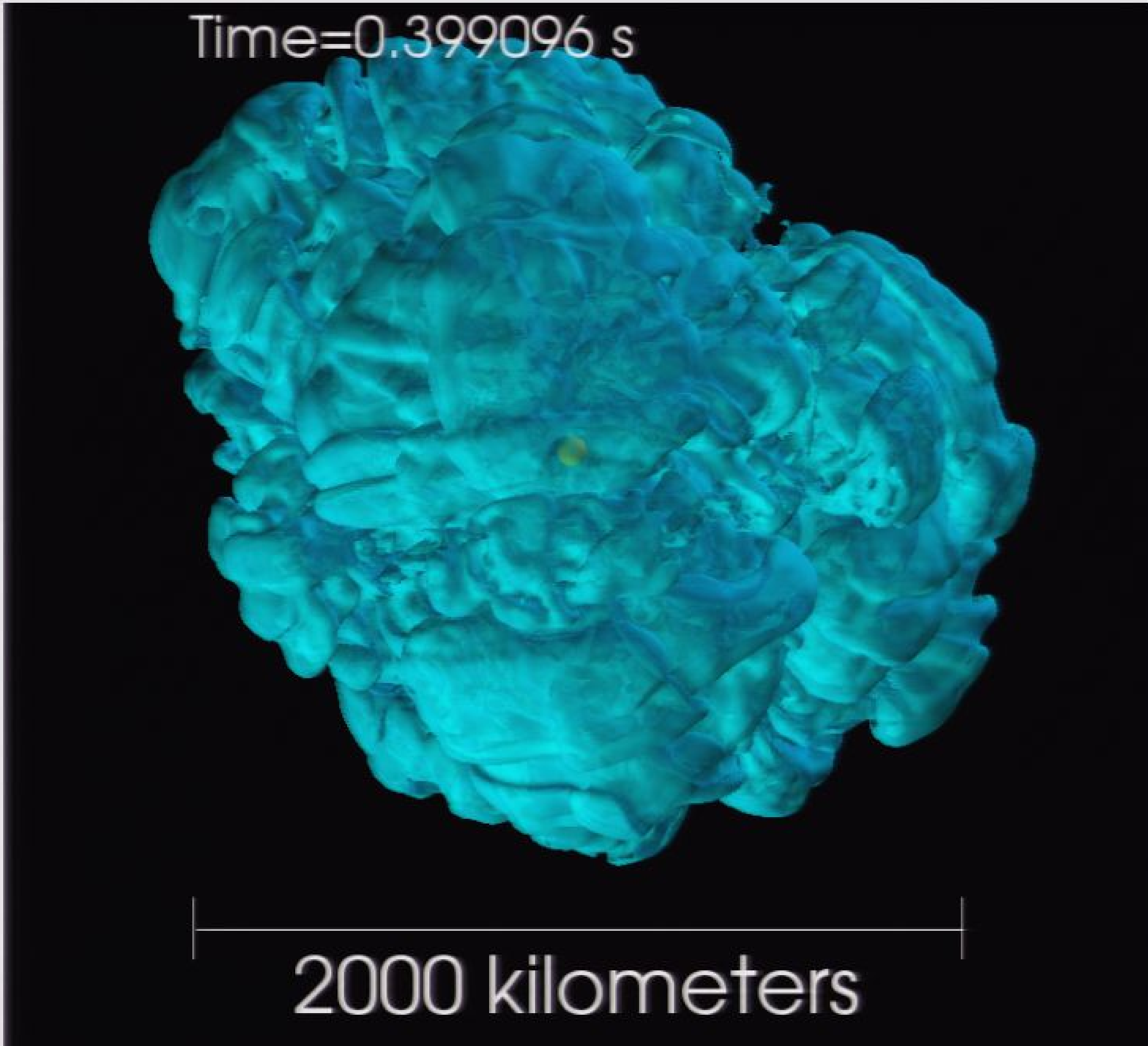
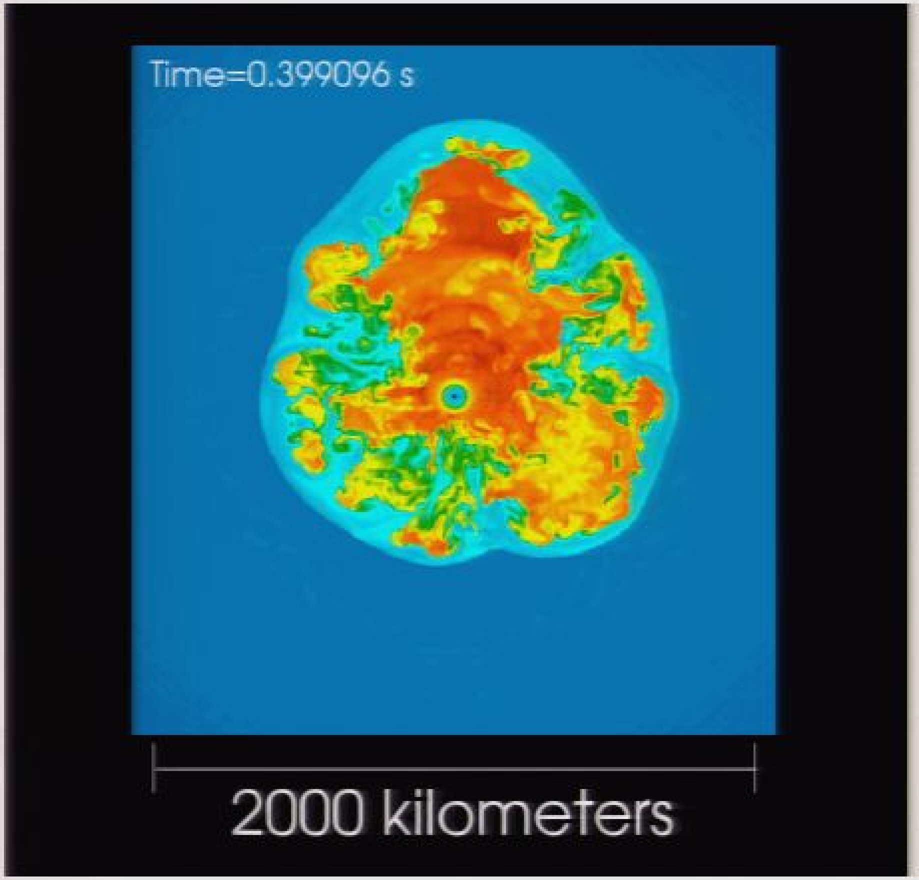
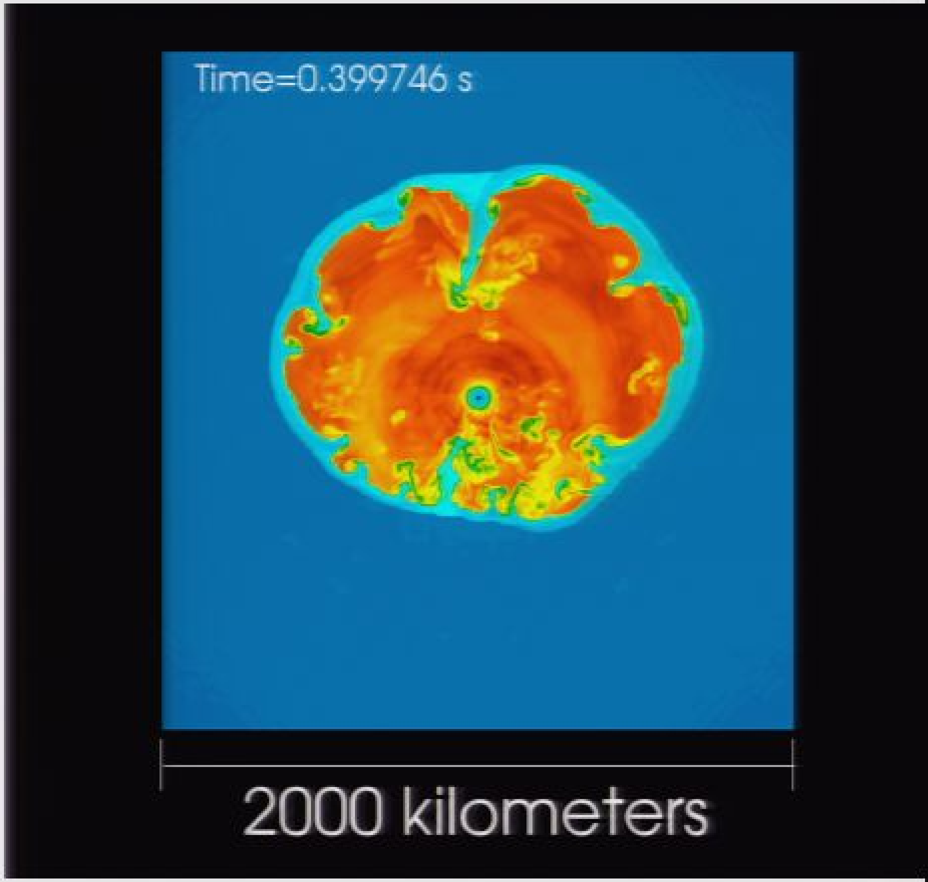


Rotating Initial Model   Non-Rotating Initial Model





Explodes earlier and more mixing of ejecta

Initial rotation produces a preferred axis

Visualization: Hank Childs [LBNL]

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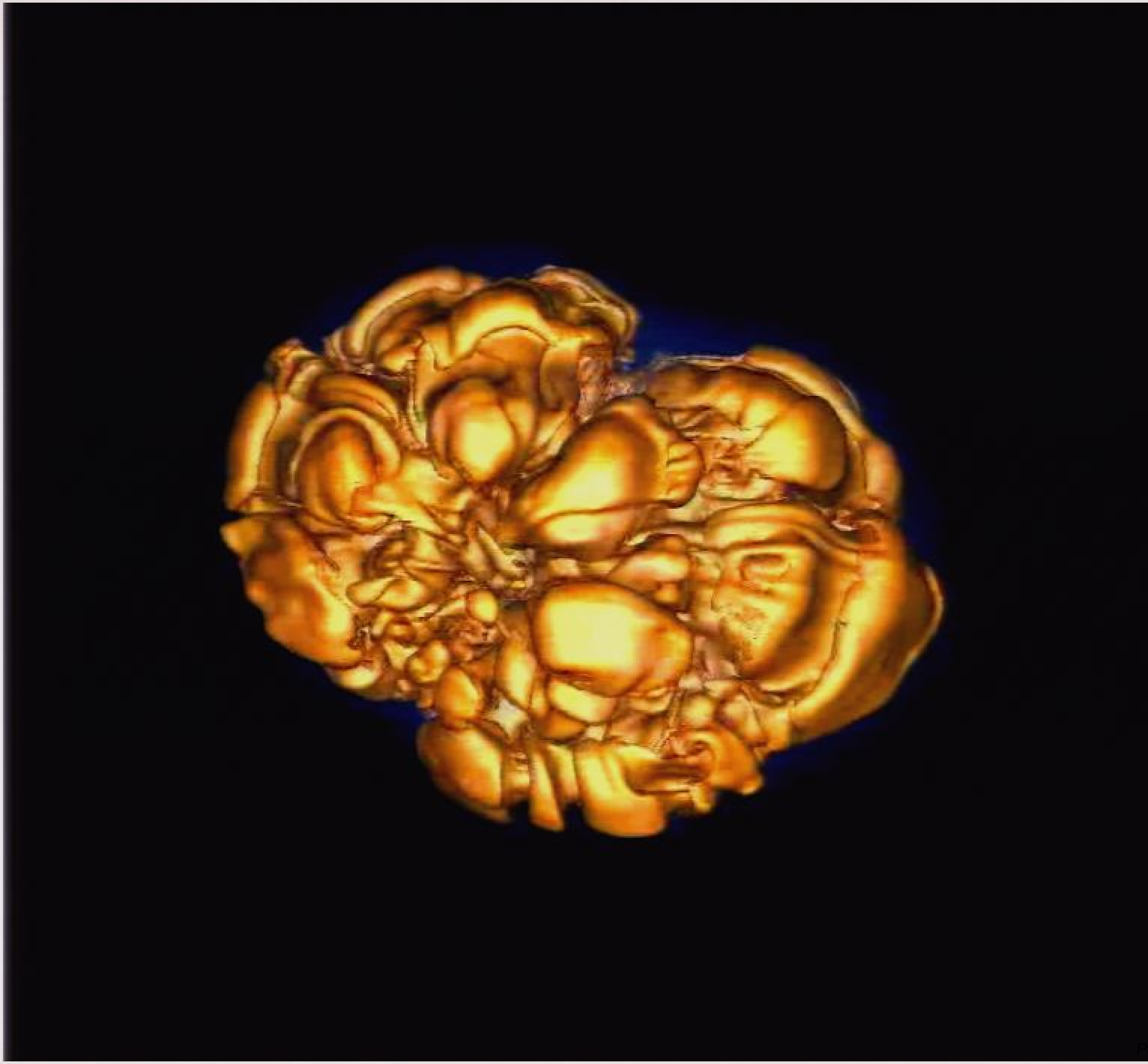

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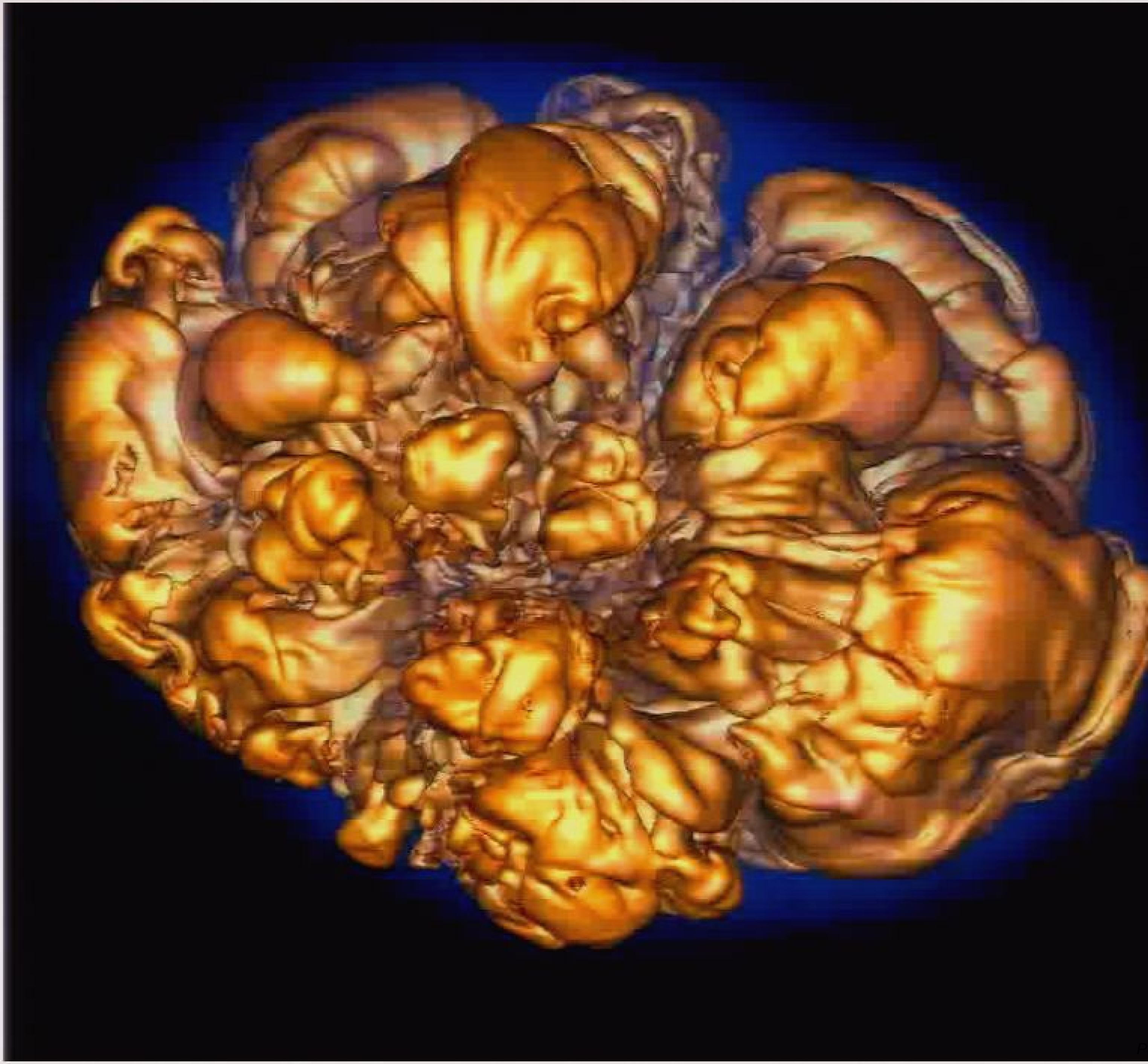


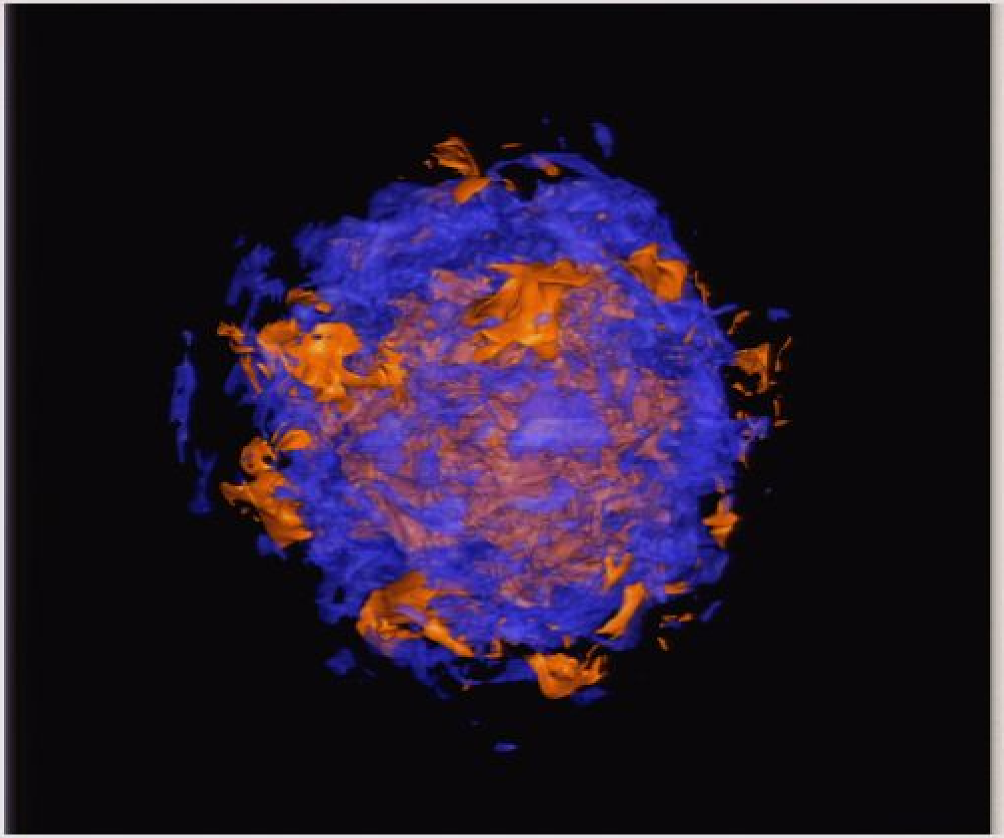
Visualization: Hank Childs [LBNL]

Conclusions

- Dimensional dependence for core-collapse supernova explosions!

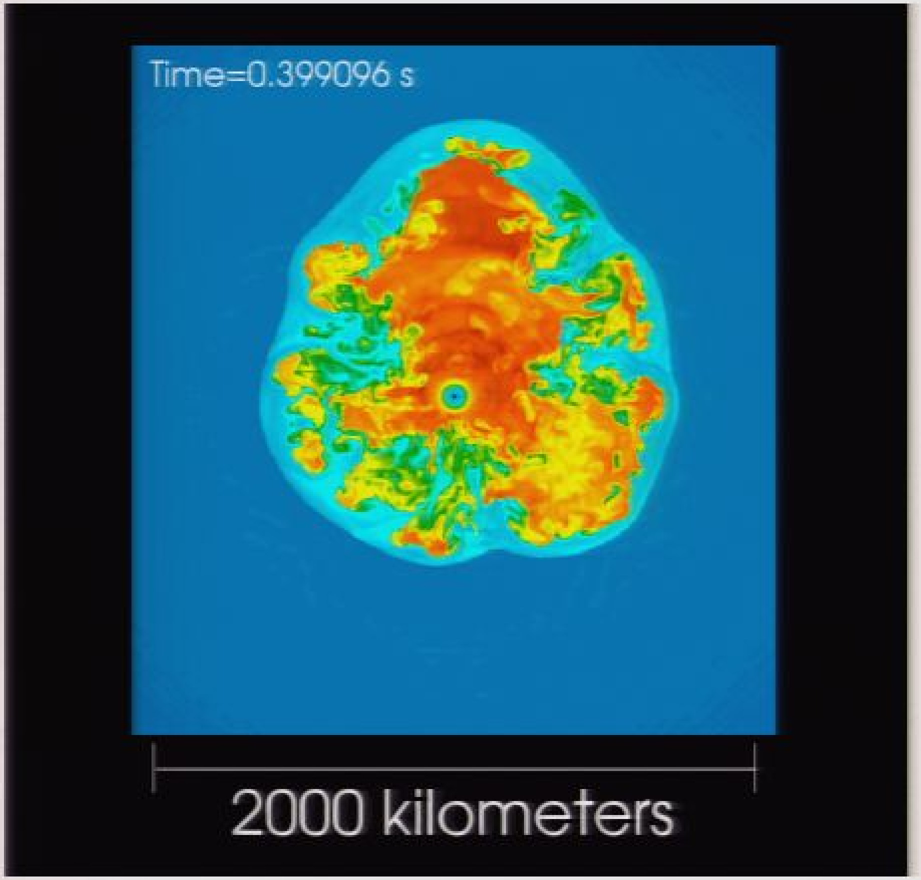
- 50% easier to explode in 3D vs. 1D - all else being equal.

- Recoil is a natural outcome of hydrodynamics and asymmetric explosion.

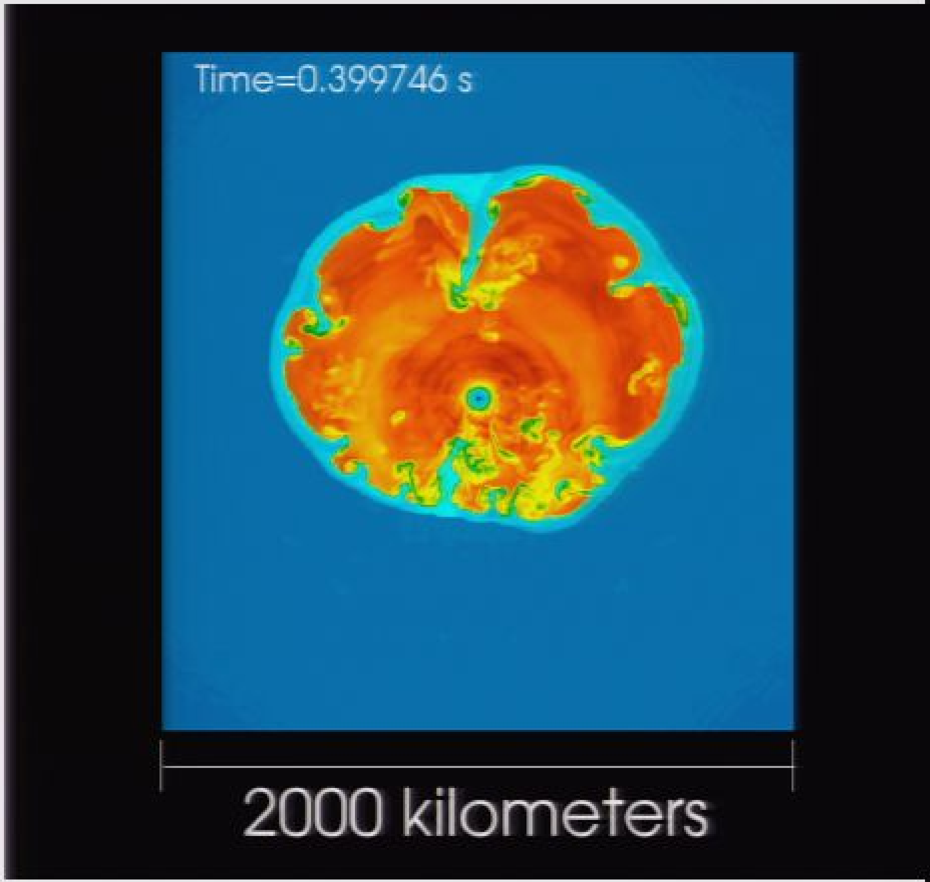


Started fully 3D rad-hydro simulations of core collapse

Rotating Initial Model



Non-Rotating Initial Model



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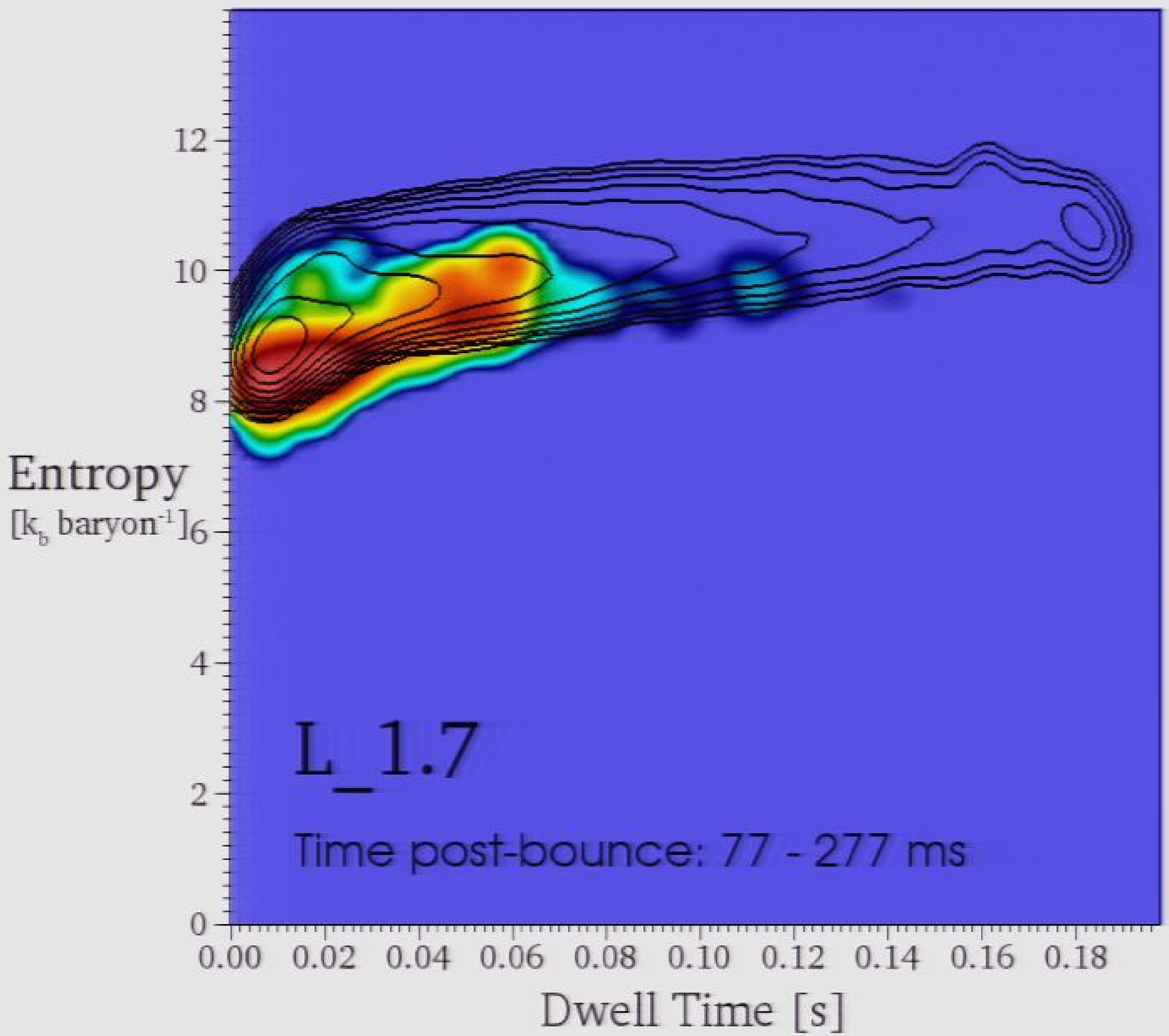
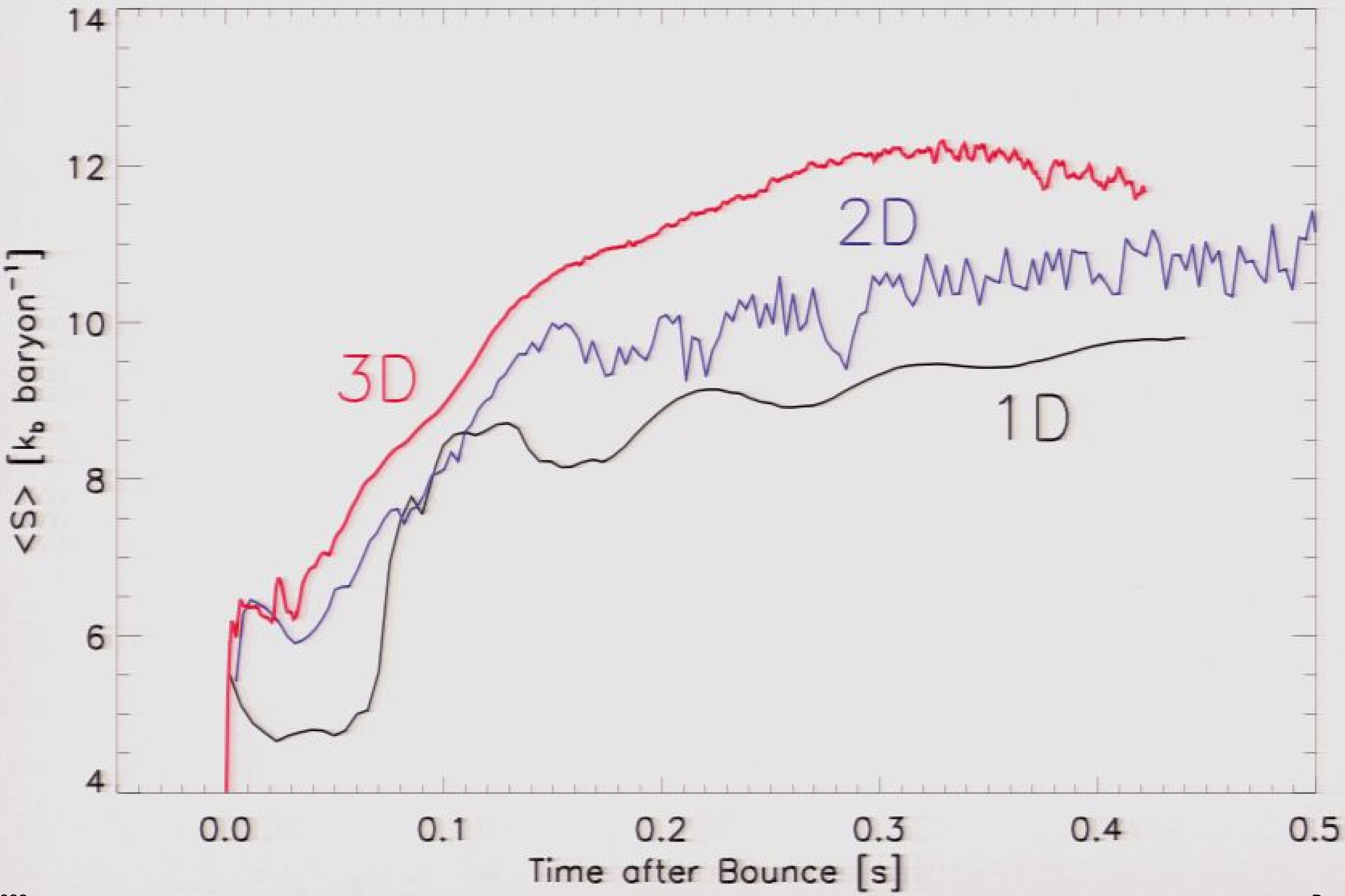
Non-Rotating Initial Model

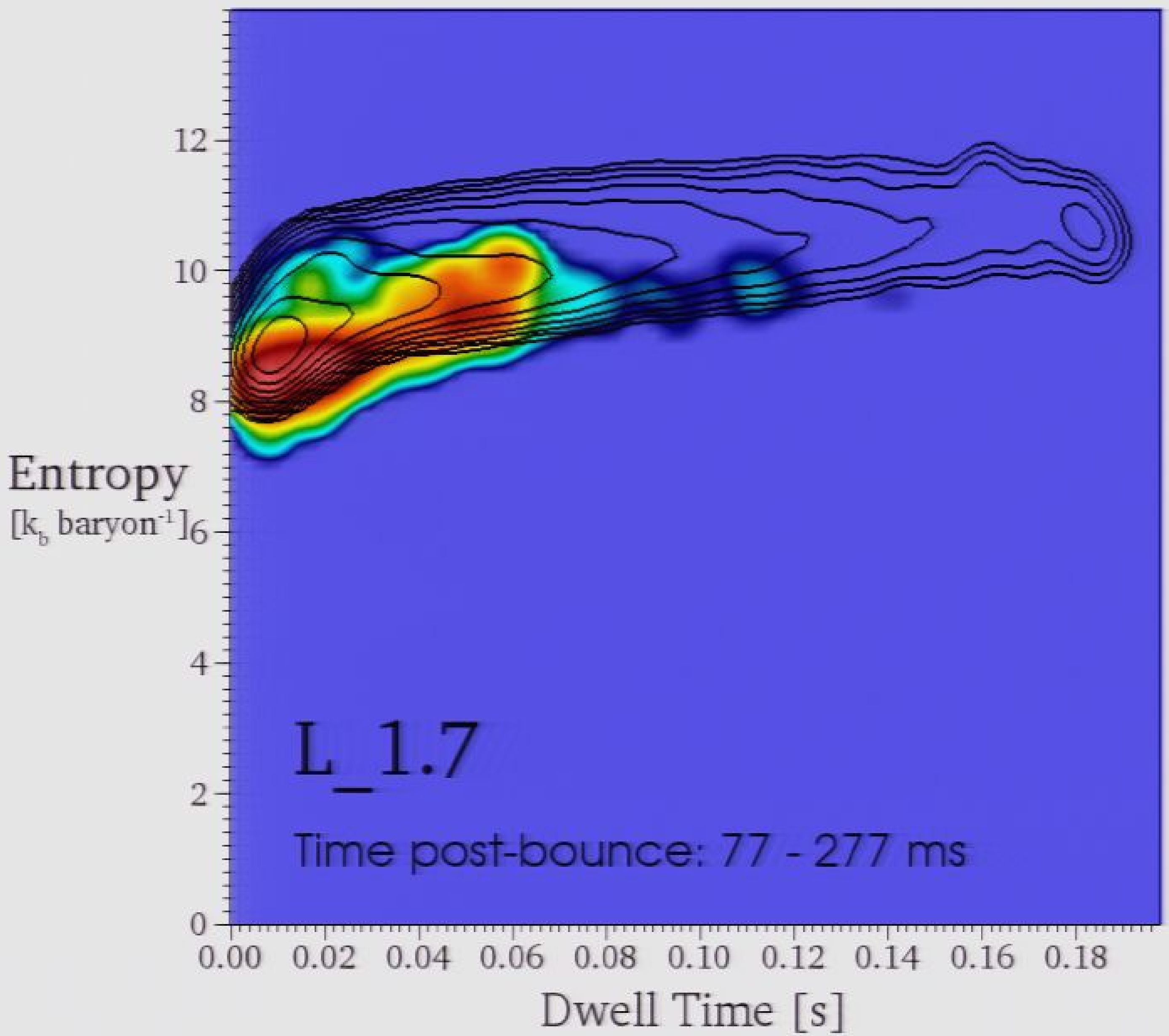
Dwell Time Distribution



Higher Entropy and Longer Dwell Times



Dwell Time Distribution



Non-Rotating Initial Model

Non-Rotating Initial Model

Rotating Initial Model

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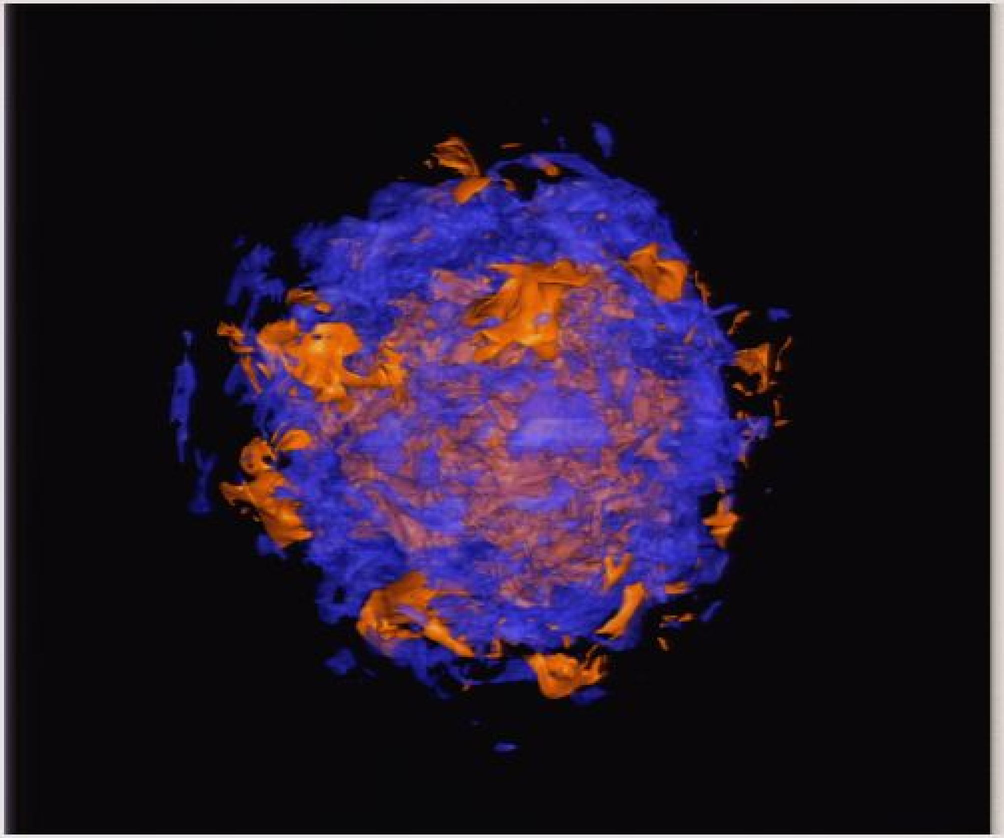

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