A status update on the **neutrino mechanism of core-collapse supernovae**

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Introduction:

What questions do we aim to answer?

The core-collapse puzzle and its history.

Physical Processes:

Core collapse.

The stalled shock and its revival.

The Delayed-Neutrino Mechanism:

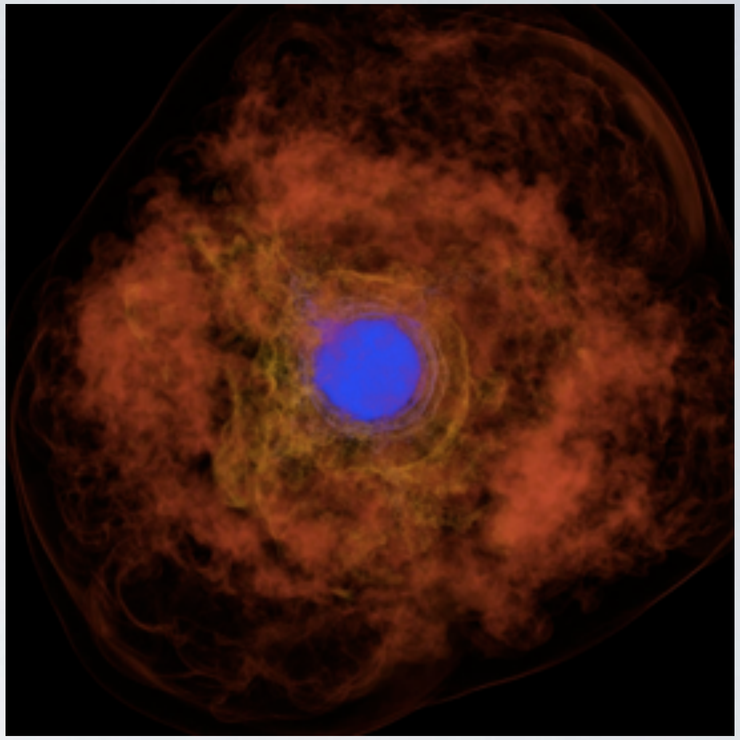
The status of current simulations.

Alternative Ideas:

Jets / nuclear burning / GR / MHD?

Pulsar Kicks:

Recoil from core-collapse explosions.



Collaborators: T. Brandt (IAS), M. Rantsiou (MPA), C. Ott (Caltech), E. Livne (Hebrew Univ.), A. Almgren (LBL), J. Bell (LBL), A. Burrows (Princeton), O. Papish (Technion), N. Soker (Technion)

“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

Core-collapse supernovae background

Progenitors: Massive stars $8 - 50 M_\odot$

Energies:

Neutron star binding energy: $\sim 3 \times 10^{53}$ erg
Kinetic energy of ejecta: $\sim 10^{51}$ erg
Light-curve energy: $\sim 10^{49}$ erg

Timescales:

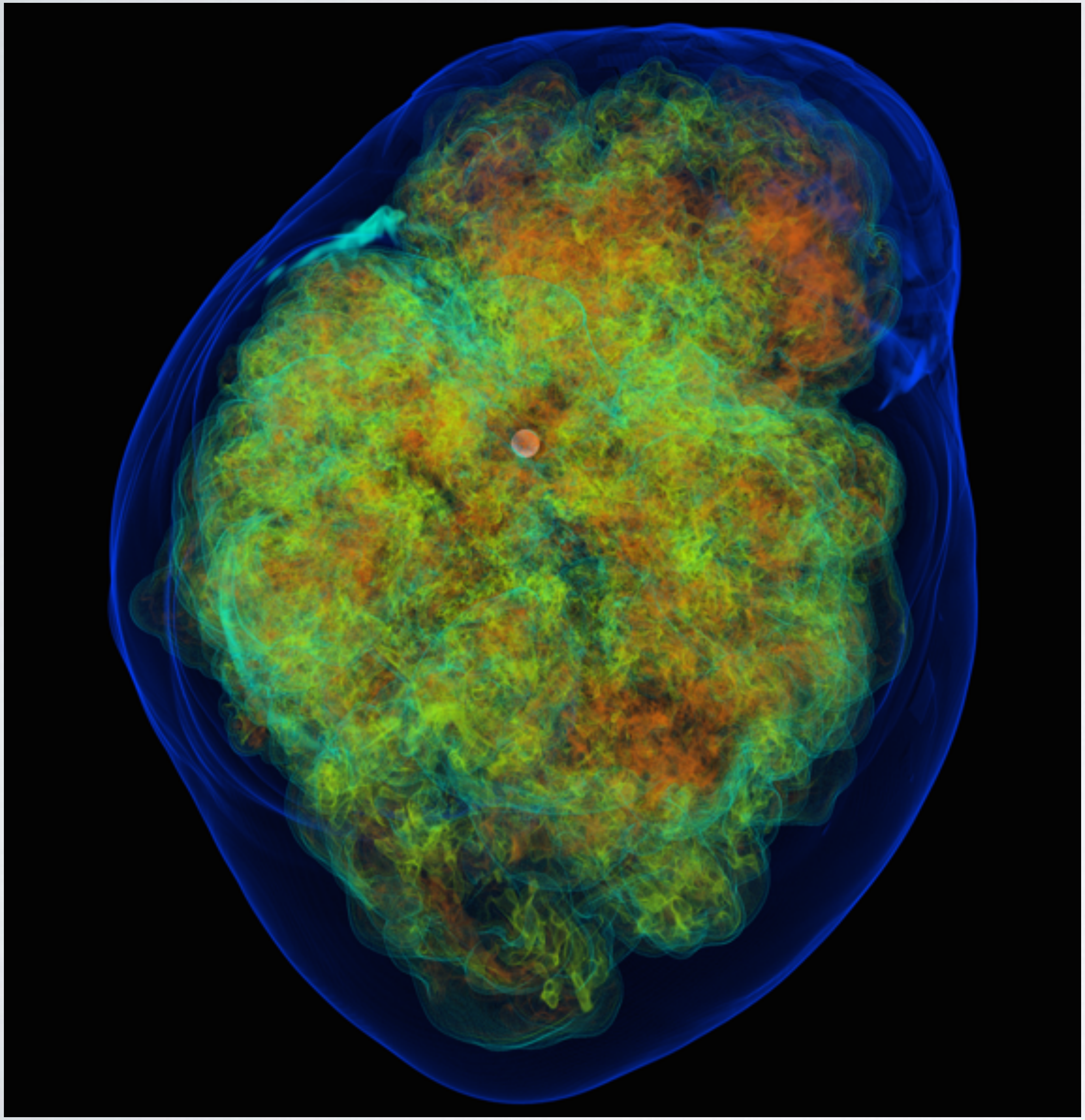
Core collapse: ~ 500 ms
Post-bounce time to explosion: ≤ 1 s
Core neutrino cooling time: ~ 10 s

Products: Blast wave, heavy-elements, compact object remnants.

What questions do we aim to answer?

1. Canonical explosion energy of 1 Bethe.
2. Neutron star mass distribution.
3. Nucleosynthetic yields and distributions.
4. Pulsar Kicks.

What physics is necessary?



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 canonical SN explosions

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Electron capture, nuclear dissociation initiate dynamical collapse.
Collapse halted at nuclear densities, shock wave forms as core matter is suddenly decelerated.
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Neutrinos proposed as an energy transport mechanism.

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Early simulations: Bounce shock stalls at ~100 - 200 km.
Sapped of pressure by electron capture, neutrino losses.

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Spherically symmetric: do not explode.
Axisymmetric: some explosions for weakly-bound atmospheres.

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3D simulations (2010 -):

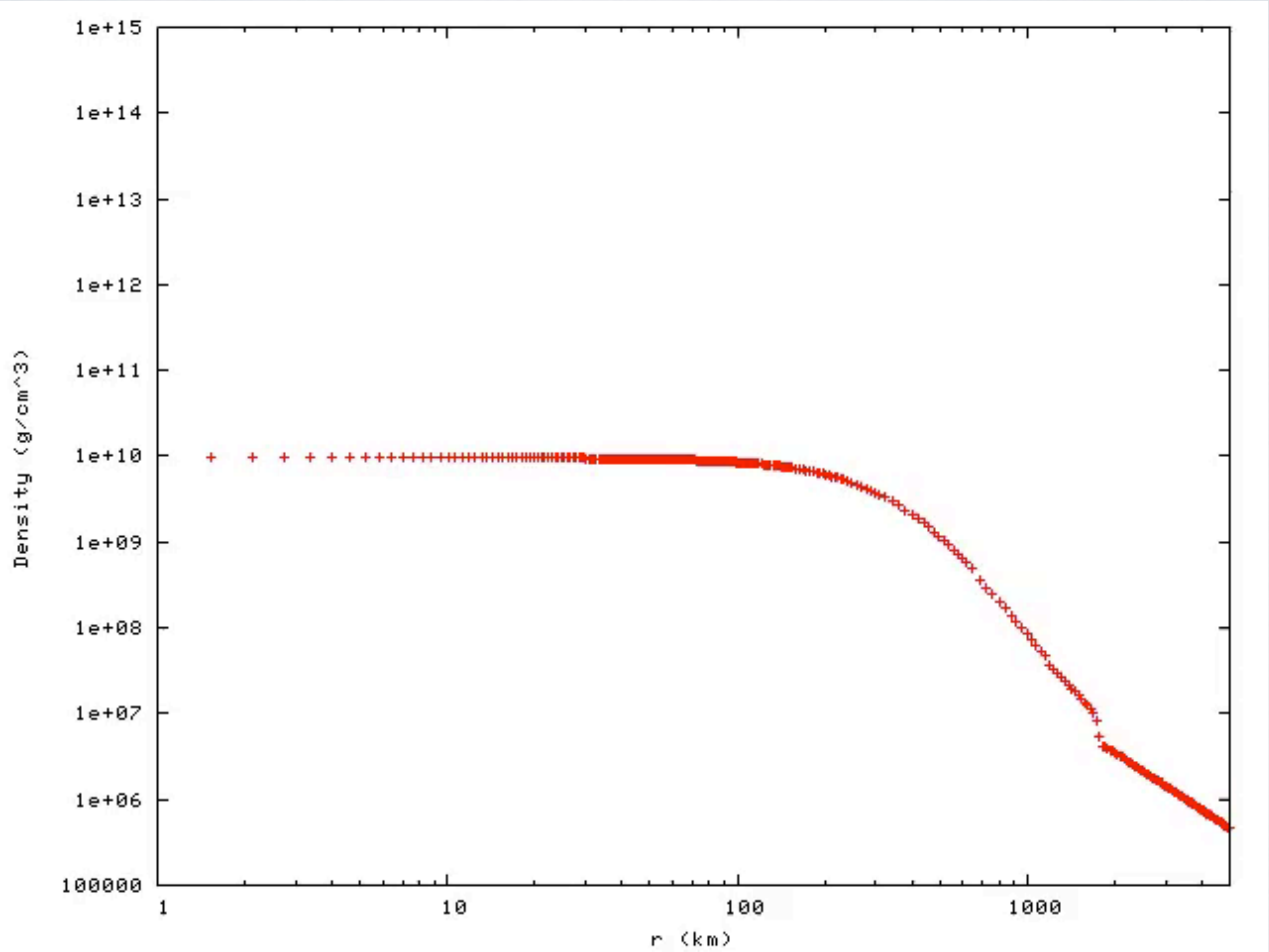
Detailed neutrino transport

Some weak explosions.

MHD, GR, other secondary physics.

No realistic simulation has produced a supernova with canonical energy.

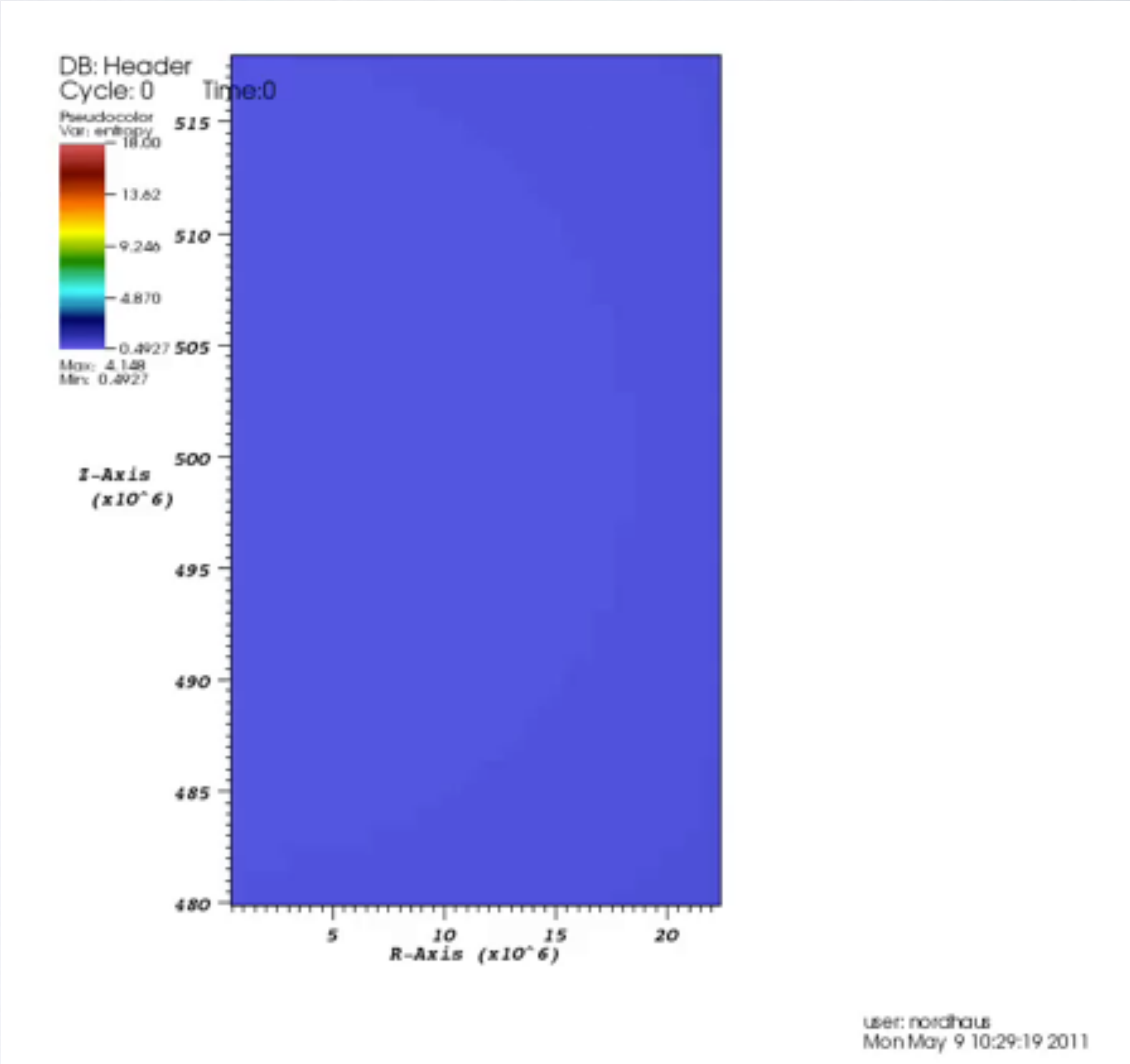
The core-collapse puzzle and its history



Physics of core collapse

Massive iron core electrons become relativistically degenerate.

Adiabatic exponent of $\gamma \leq \frac{4}{3}$ implies unstable to dynamical collapse.



Collapse halted when equation of state stiffens due to nucleons.

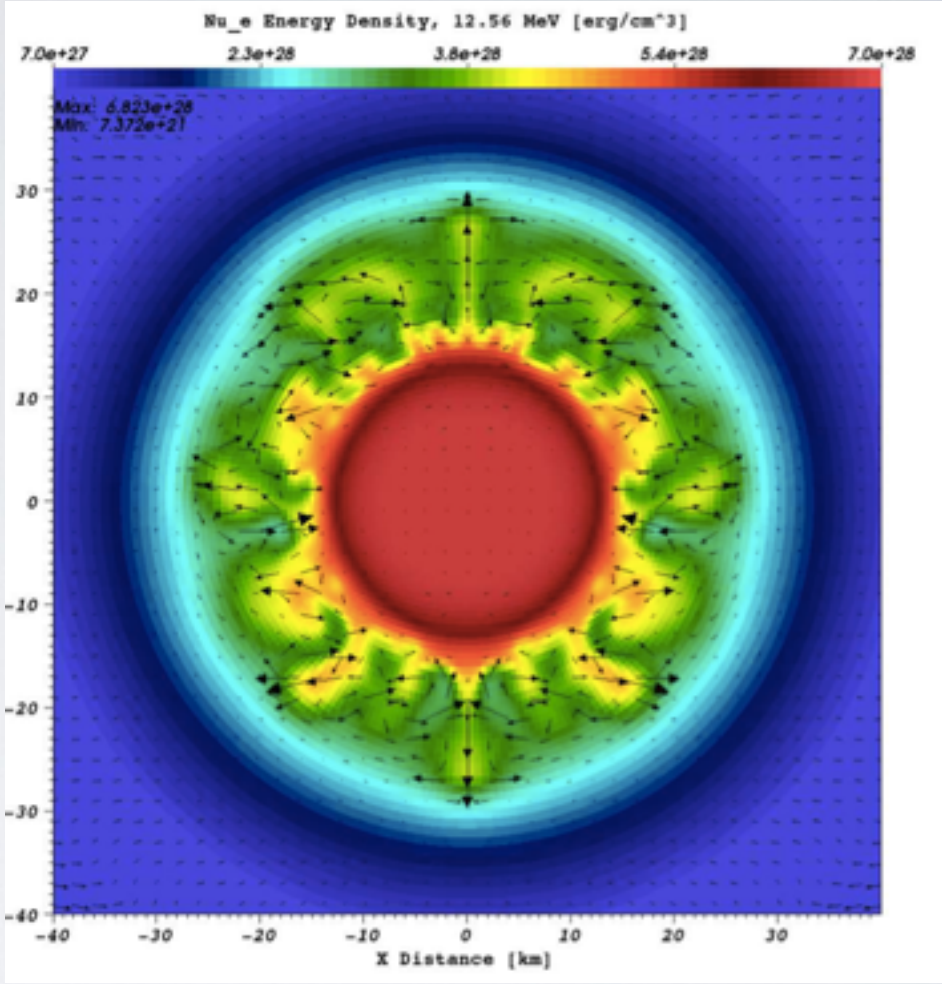
Inner core:

Remins in sonic contact, rebounds as a unit.
Bounce dissociates nuclei.
Outer material accretes supersonically, hits “wall” to produce a bounce shock.

Neutrino-matter interactions

Trapped electron neutrinos create a degenerate Fermi sea.

Stimulated absorption in reactions due to Pauli blocking (stimulated *emission* for photons).

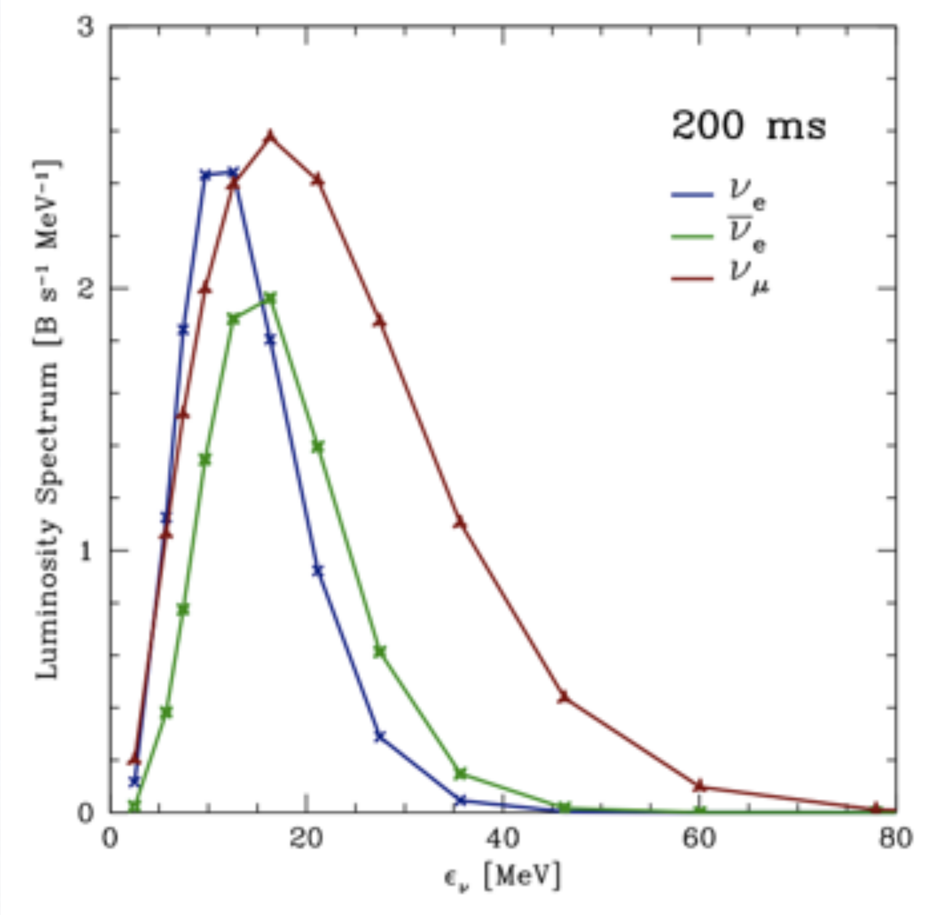


Neutrino Types:

Electron	ν_e	Anti-Electron	$\bar{\nu}_\mathrm{e}$
Muon	ν_μ	Anti-Muon	$\bar{\nu}_\mu$
Tau	ν_τ	Anti-Tau	$\bar{\nu}_\tau$

Typical Energies:

Beta Decay Neutrinos	≤ 0.5 MeV
Solar Neutrinos	$\sim 0.1 - 17$ MeV
Supernova Neutrinos	$\sim 5 - 40$ MeV



Neutrino-matter interactions

Neutrino-matter cross sections are *very* low.

Thomson electron scattering cross section: $\sim 10^{-24}\ \mathrm{cm}^2$

Weak interaction cross sections for supernova energies: $\sim 10^{-42}\ \mathrm{cm}^2$

Mean free path $\sim 100 \left(\frac{10^{15}\ \mathrm{g\ cm}^{-3}}{\rho}\right)\left(\frac{10\ \mathrm{MeV}}{\epsilon_\nu}\right)^2\ \mathrm{cm}$

Significant interactions:

Reaction	Neutrino Type	Cross Section $\sigma\ [\times 10^{-42}\mathrm{cm}^2]$
$\nu_e + n \longleftrightarrow e^- + p$	Electron	$\sim 8\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)^2$
$\bar{\nu_e} + p \longleftrightarrow n + e^+$	Anti-electron	$\sim 7\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)^2$
$\nu_i + p \longrightarrow \nu_i + p$	All species	$\sim 1.7\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)^2$
$\nu_i + n \longrightarrow \nu_i + n$	All species	$\sim 2.0\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)^2$
$\nu_i + A \longrightarrow \nu_i + A$	All species	$\sim 1.2\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)^2$
$\nu_i + e^- \longrightarrow \nu_i + e^-$	All species	$\nu_e : \sim 5\left(\frac{\epsilon_\nu}{10\ \mathrm{MeV}}\right)\left(\frac{T + \mu_e/4}{10\ \mathrm{MeV}}\right)$

Stalling of the shock

Shock wave propagates into heavy nuclei with high specific heat.

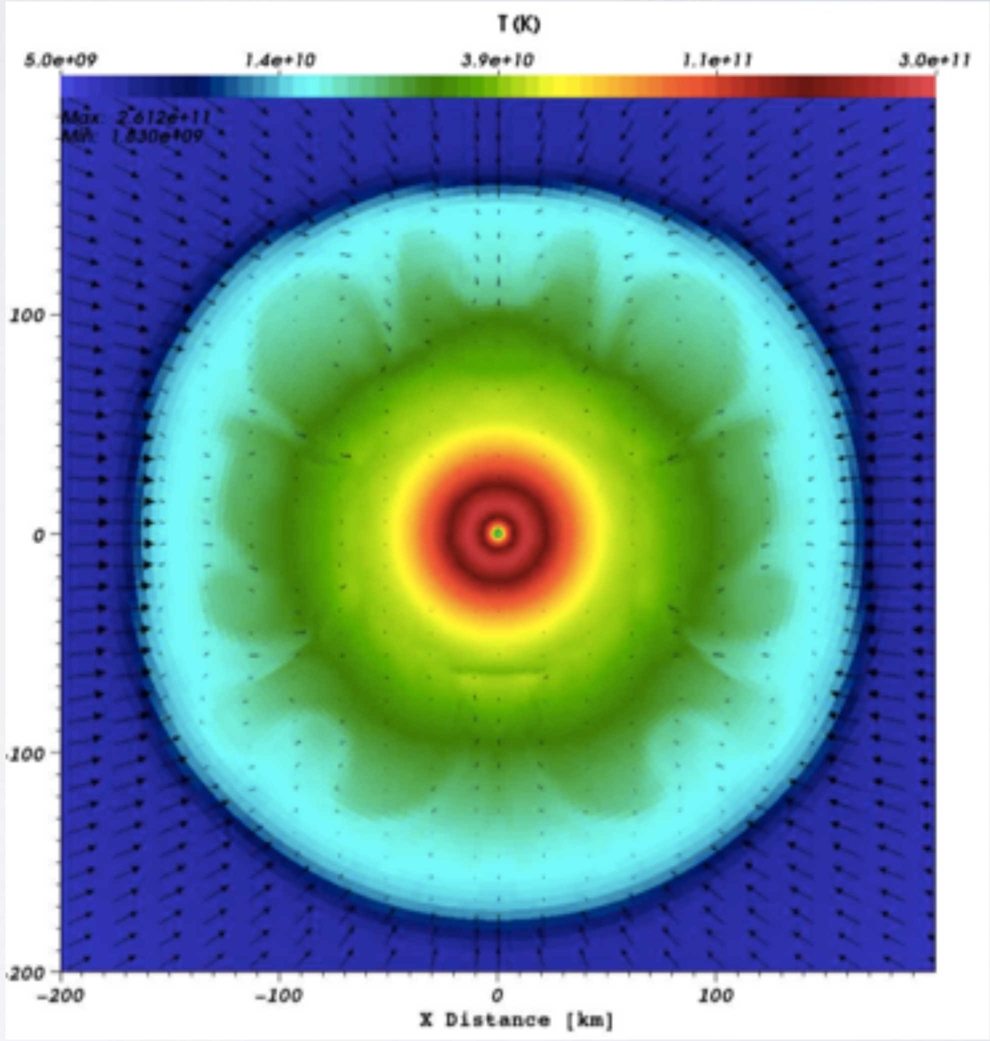
Shock energy goes into:

electron capture $A + e^- \rightarrow A' + \nu_e$

nuclear dissociation ${}^{56}_{26}\mathrm{Fe} \rightarrow 26p + 30n$

Post-shock pressure falls

Ram pressure $p_{\mathrm{ram}} = \rho v^2$ may be more than post shock pressure



Prompt explosion will only work if ram pressure drops.

Requires a steep density gradient. $8 - 10 M_\odot$

Otherwise $p_{\mathrm{ram}} > p_{\mathrm{post-shock}}$ implies that the shock stalls.

Reviving the shock

Need to either increase increase $p_{\mathrm{post-shock}}$, decrease p_{ram}, or both by:

Depositing additional energy behind the shock

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Using progenitor models with steeper density profiles (no).

Reviving the shock

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Possible energy sources:

Nuclear burning (O into Fe).
Releases $\sim 5 \times 10^{17}$ erg g$^{-1} \ll 10^{19}$ erg g$^{-1} \sim U_{\mathrm{grav,be}}(r = 200\ \mathrm{km})$
For 10^{51} erg need to burn $1 M_{\odot}$ of oxygen explosively, implies need to already have enormous blast wave at large radii. See Kushnir 2015.

Annihilation: $\nu_e + \bar{\nu}_e \rightarrow e^+ + e^- \rightarrow 2\gamma$
Most efficient where neutrino-cooling is severe

Delayed neutrino heating: the neutrino mechanism.

Neutrino Transport

Simplified neutrino radiation transport, neglecting scattering:

$$\frac{\partial I_\epsilon(r)}{\partial r} = \kappa_\epsilon \rho [B_\epsilon(T) - I_\epsilon(r)]$$

$B_\epsilon(T)$ is the neutrino blackbody function.

Integrated over $\epsilon_\nu : \dfrac{\partial F(r)}{\partial r} = \bar{\kappa}\rho[acT^4 - F(r)]$

$\bar{\kappa}\rho acT^4$ is emission from matter (cooling).

$\bar{\kappa}\rho F(r)$ is absorption by matter (heating).

Neutrino cooling dominated by URCA processes:

Electron capture: $p + e^- \rightarrow \nu_e + n$

Positron capture: $n + e^+ \rightarrow \bar{\nu}_e + p$

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Neutrino energy loss rate per gram: $\bar{\kappa} a c T^4$

$\bar{\kappa} \propto \epsilon_\nu^2 \Rightarrow \bar{\kappa} \propto T^2$

Cooling rate per gram: $\mathcal{C} \approx 1.4 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}}\right)^6 \ \mathrm{erg\ g^{-1}\ s^{-1}}$

Cooling dominates at R < 80 km where matter is hot.

Neutrino Heating

Neutrino heating rate per gram: $\bar{\kappa} F_\nu$

Neutrino capture, inverses of URCA processes:

$$\bar{\nu_e} + p \rightarrow n + e^+$$
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Heating rate per gram: $\mathcal{H} \propto T_{\nu_e}^2 \frac{L_\nu}{4\pi r^2}$

$$\mathcal{H} \approx 1.5 \times 10^{20} L_{\nu_e} \left(\frac{100 \text{ km}}{r}\right)^2 \left(\frac{T_{\nu_e}}{4 \text{ MeV}}\right)^2 \text{ erg g}^{-1} \text{ s}^{-1}$$

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Gain region: Net neutrino heating

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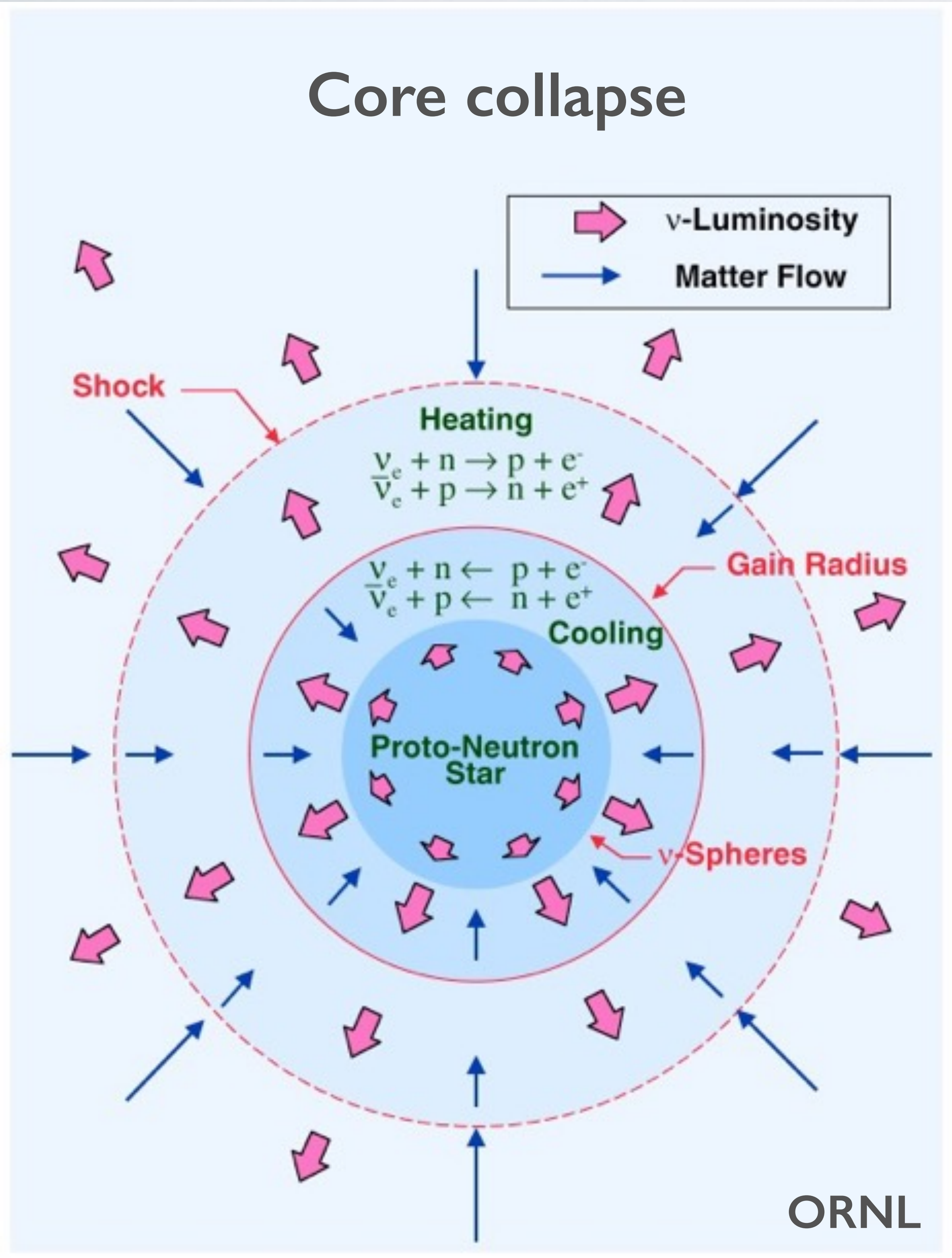
Gain Region



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Does it work?

Net neutrino heating adds $\sim 10^{20}$ erg g^{-1} s^{-1} to the gain region.

Matter gains sufficient energy to become unbound in ~100 ms.

Timescales and Quantities

Quantity	Definition	Description
Residence Time	τ_{res}	Mean dwell time in the gain region.
Heating Time	$\tau_{\mathrm{q}} \equiv \frac{\int_{\mathrm{gain}} U_{\mathrm{int}}}{\int_{\mathrm{gain}} (\mathcal{H} - \mathcal{C})}$	Characteristic timescale to heat gain region.
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$L_\nu - \dot{\mathcal{M}}$ relation $\frac{\tau_{\rm res}}{\tau_q} \sim \frac{\mathcal{M}_{\rm gain}}{\dot{\mathcal{M}}} \frac{L_\nu}{\int_{\rm gain} U_{\rm int}} \sim \frac{L_\nu}{\dot{\mathcal{M}}} \frac{m_p}{k_B T_{\rm gain}}$

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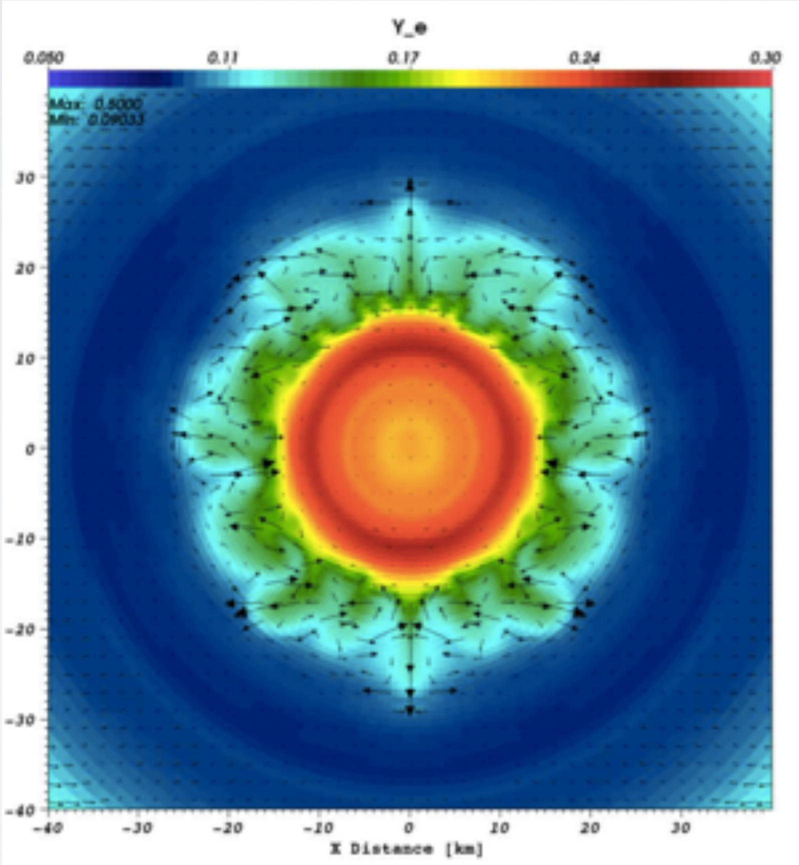
To make neutrino mechanism work, need to increase $\tau_{\rm res}$ and/or L_ν .

Convection and GR: Increasing $\mathcal{P} \equiv \tau L_\nu$

Core convection can dredge up trapped neutrinos, potentially increasing the neutrino luminosities.

Not seen in high-res multi-D simulations.

Outer core convection only.



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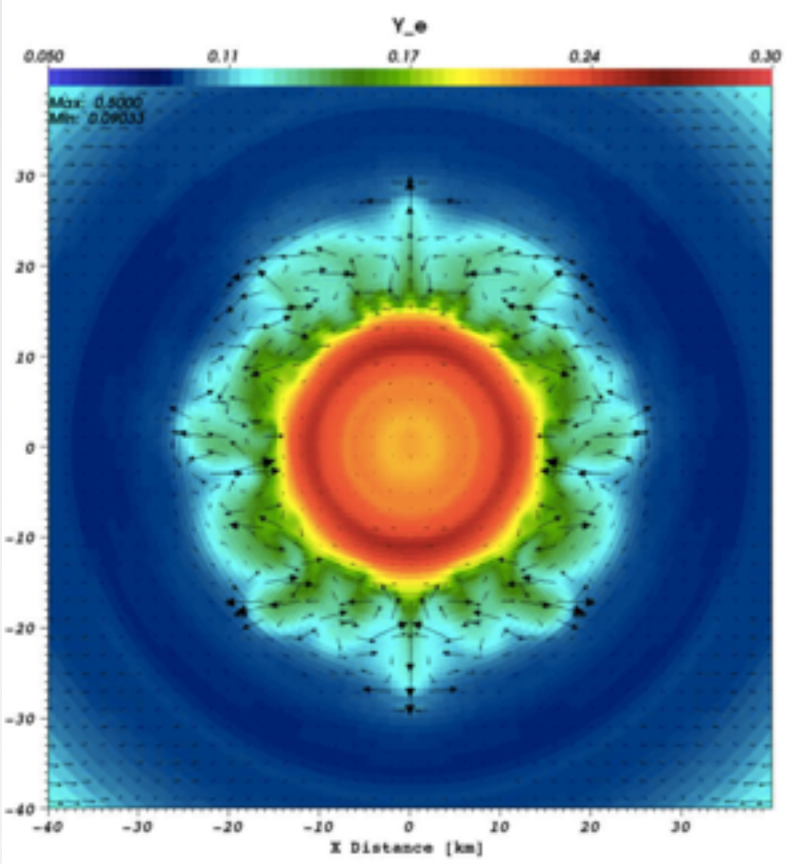

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General Relativity

Relativity tends to make the core more compact.

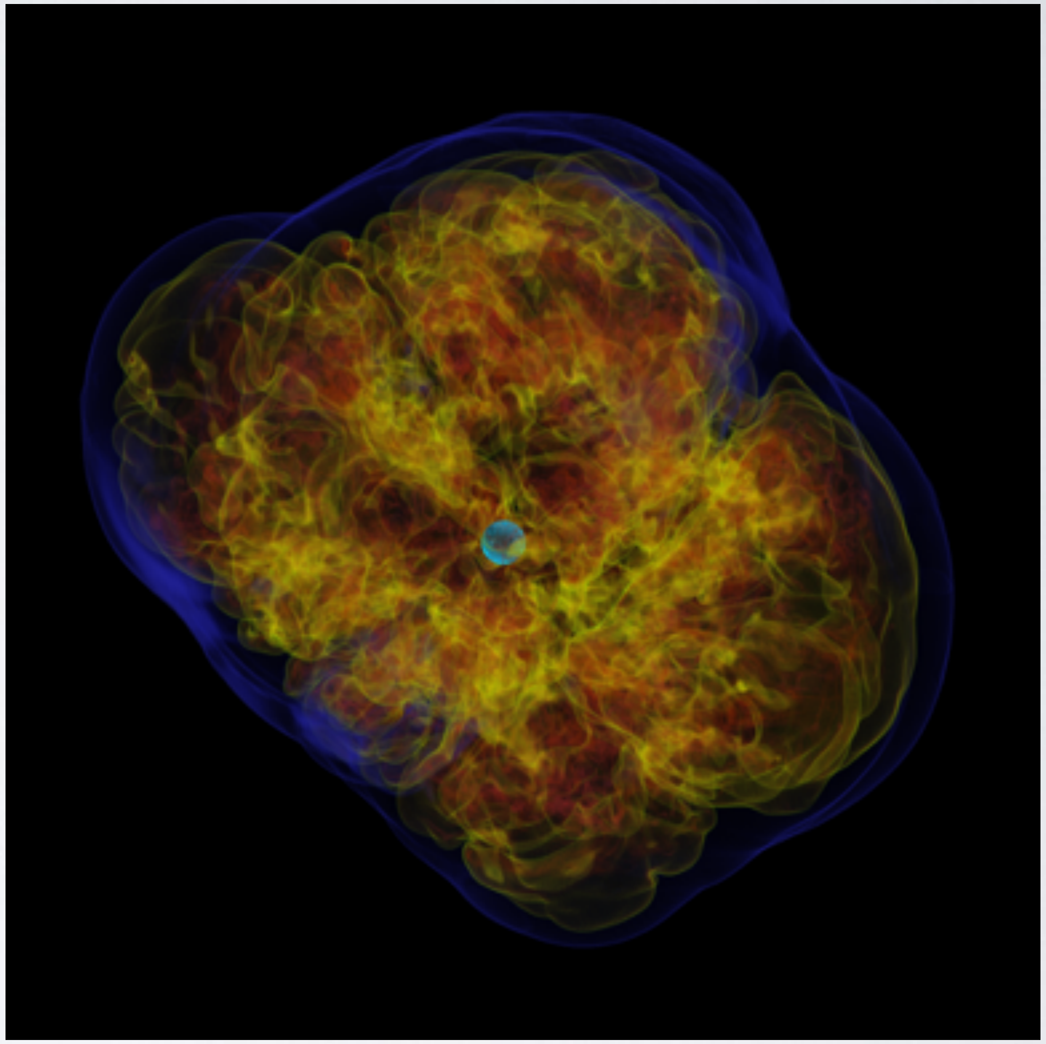
Hotter neutrino-spheres imply higher cross-sections which imply more heating.
But neutrinos are redshifted from the deeper well…

GR effects seem to give minor corrections to P.

Multidimensional Effects: Increasing τ_{res}

Enormous computing power: Fully 3D simulations.

Fundamentally different results in spherically symmetric, axisymmetric, 3D simulations.



Dynamics different.

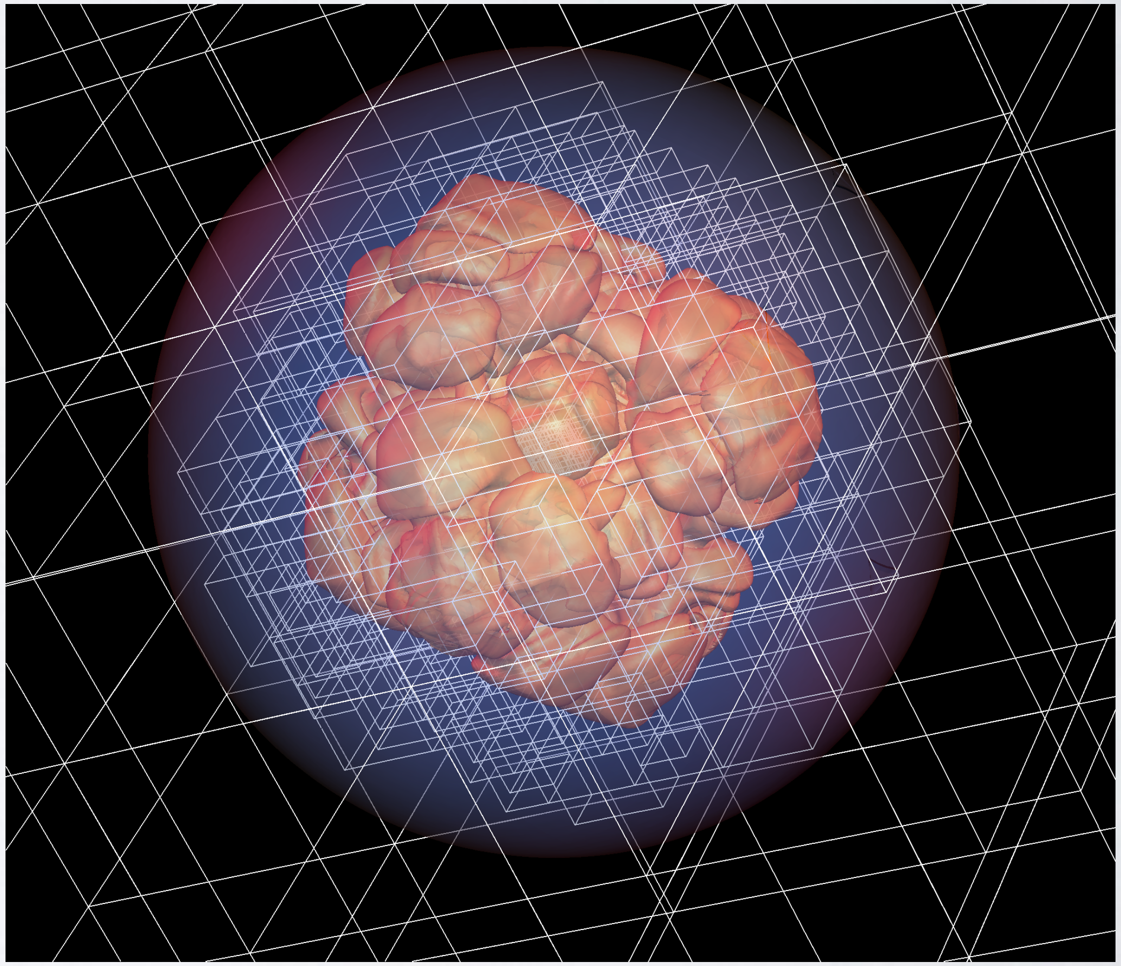
Dwell times different.

Turbulence different.

CASTRO: Compressible Astrophysics

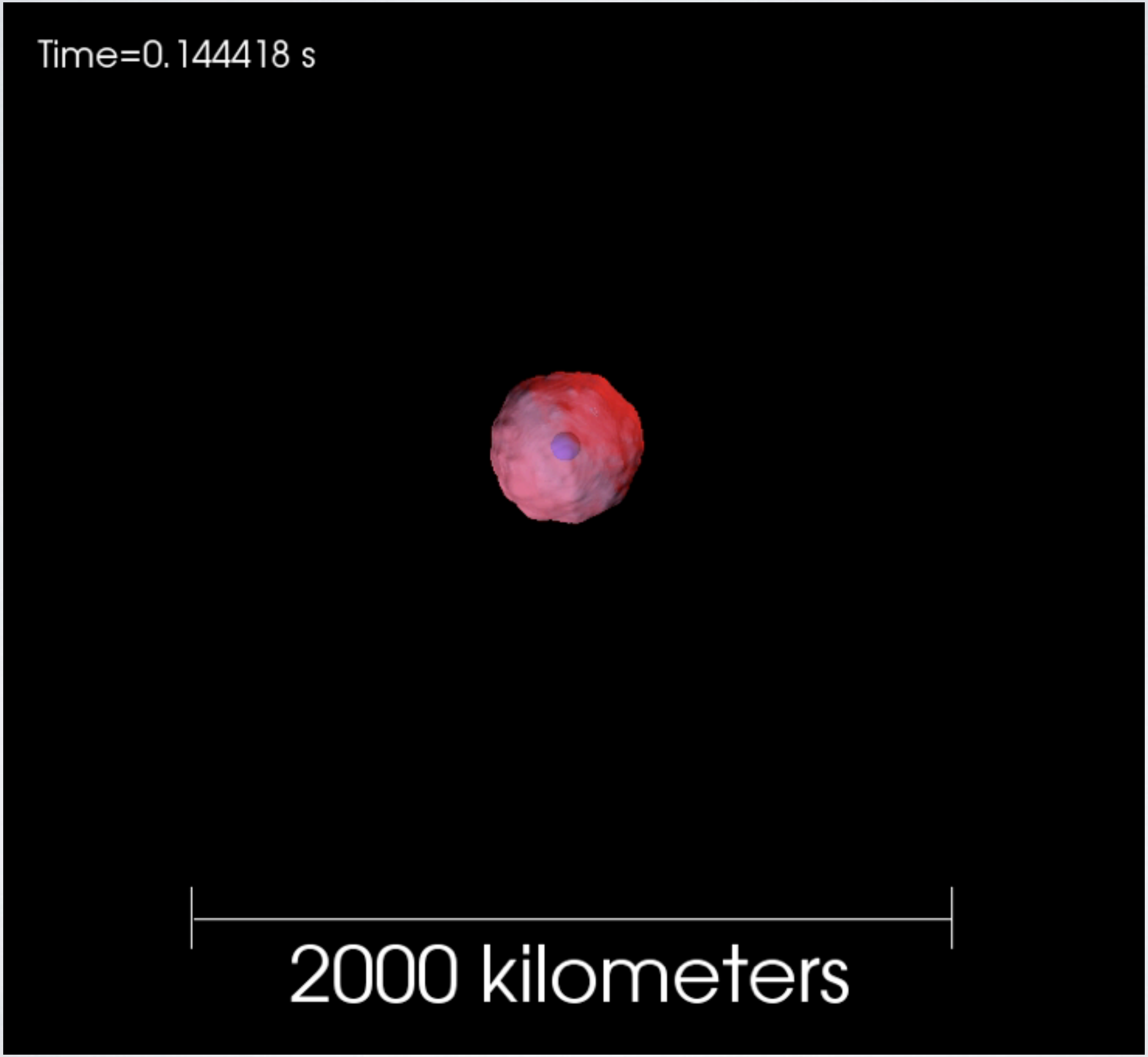
- Multi-D radiation-hydrodynamics code
- Adaptive mesh refinement (AMR) with sub-cycling in time
- Advection: 2nd order, unsplit piecewise-linear or PPM
- Radiation: multi-group flux limited diffusion
- Gravity: Monopole or multi-grid Poisson solve
- Scales to over 200,000 cores!

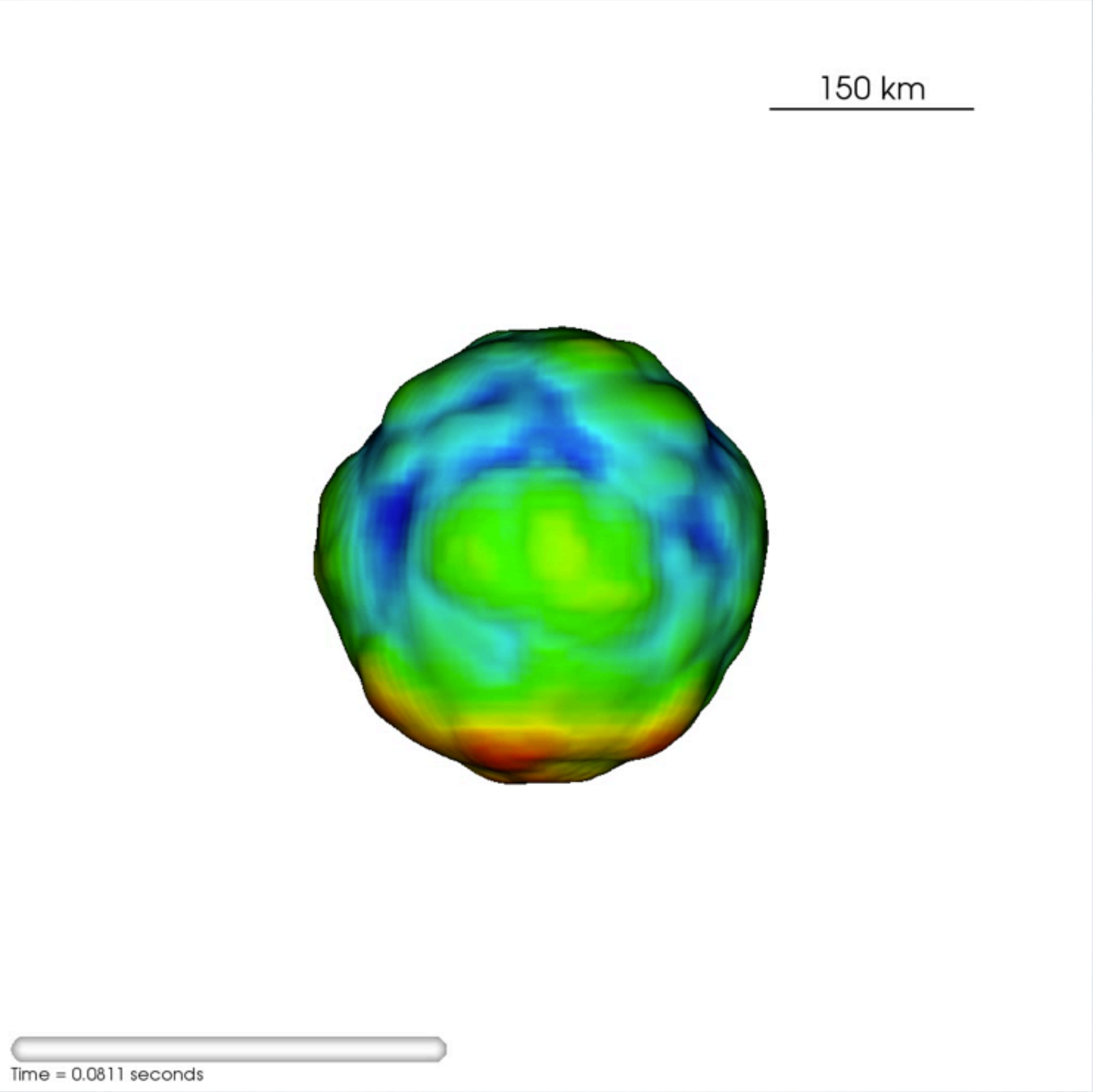
Ann Almgren (LBL)
John Bell (LBL)
Louis Howell (LLNL)



3D AMR block structure

Non-Rotating Initial Model




150 km
Time = 0.0811 seconds

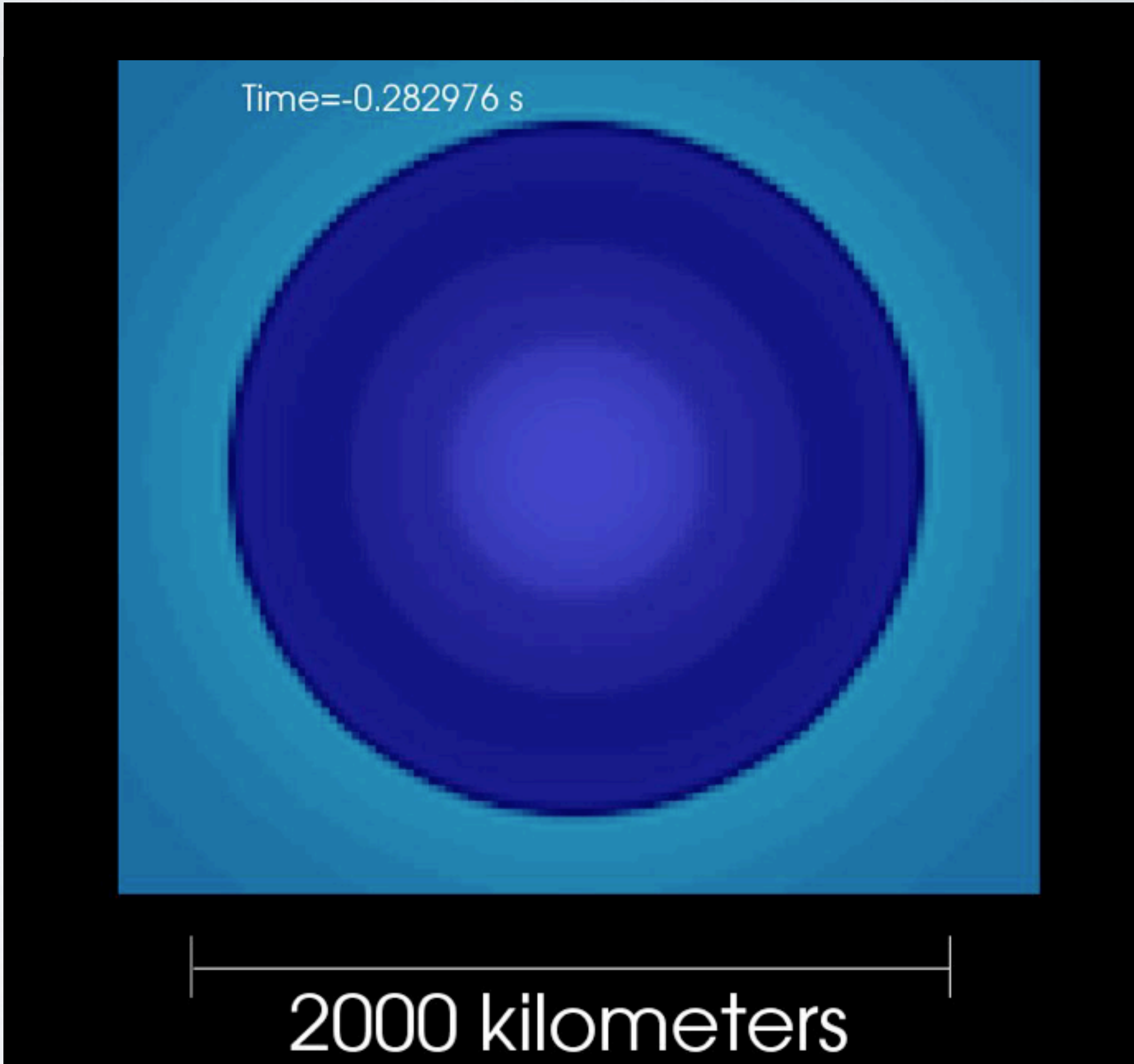
Standing Accretion Shock Instability (SASI)

Axisymmetric

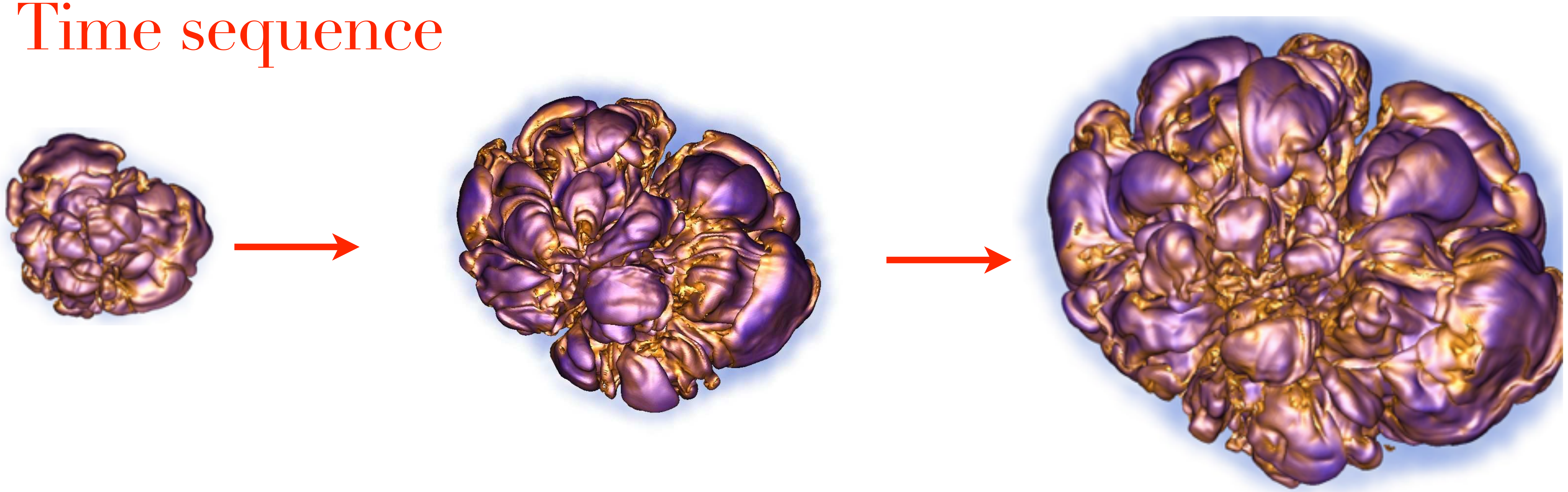
$\ell = 1$ mode is dominant

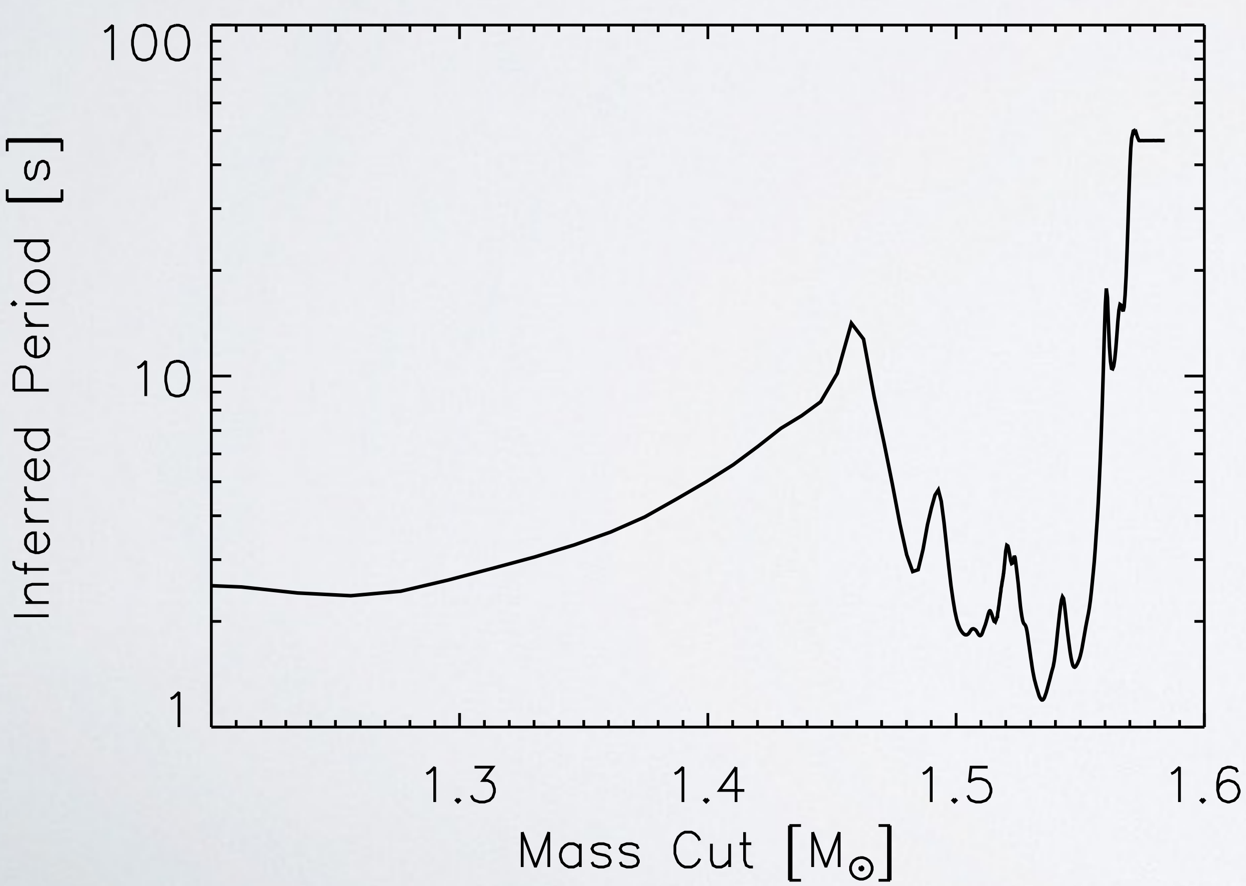
Suggested as a fundamental characteristic of SN dynamics and way to spin-up pulsars;

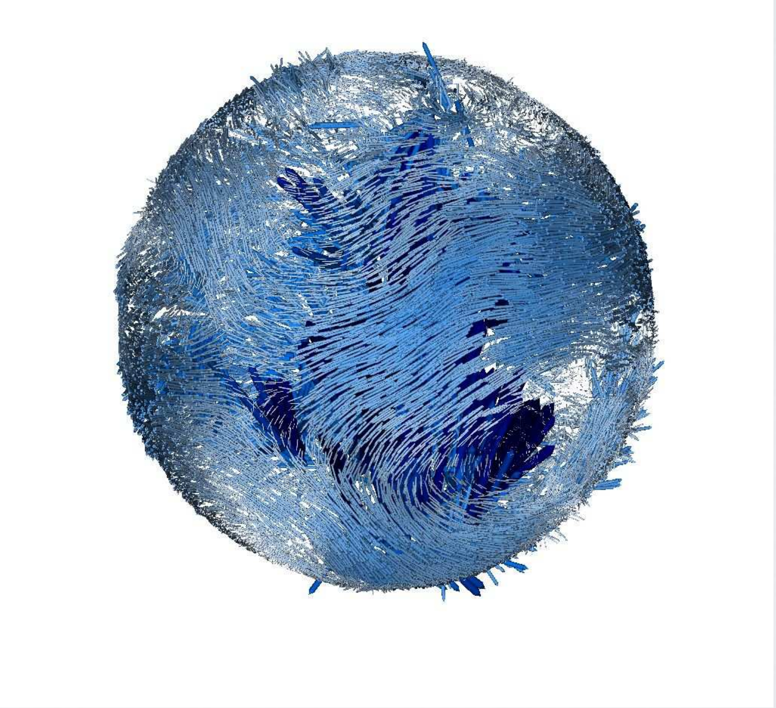
Blondin & Mezzacappa 2007



Time sequence

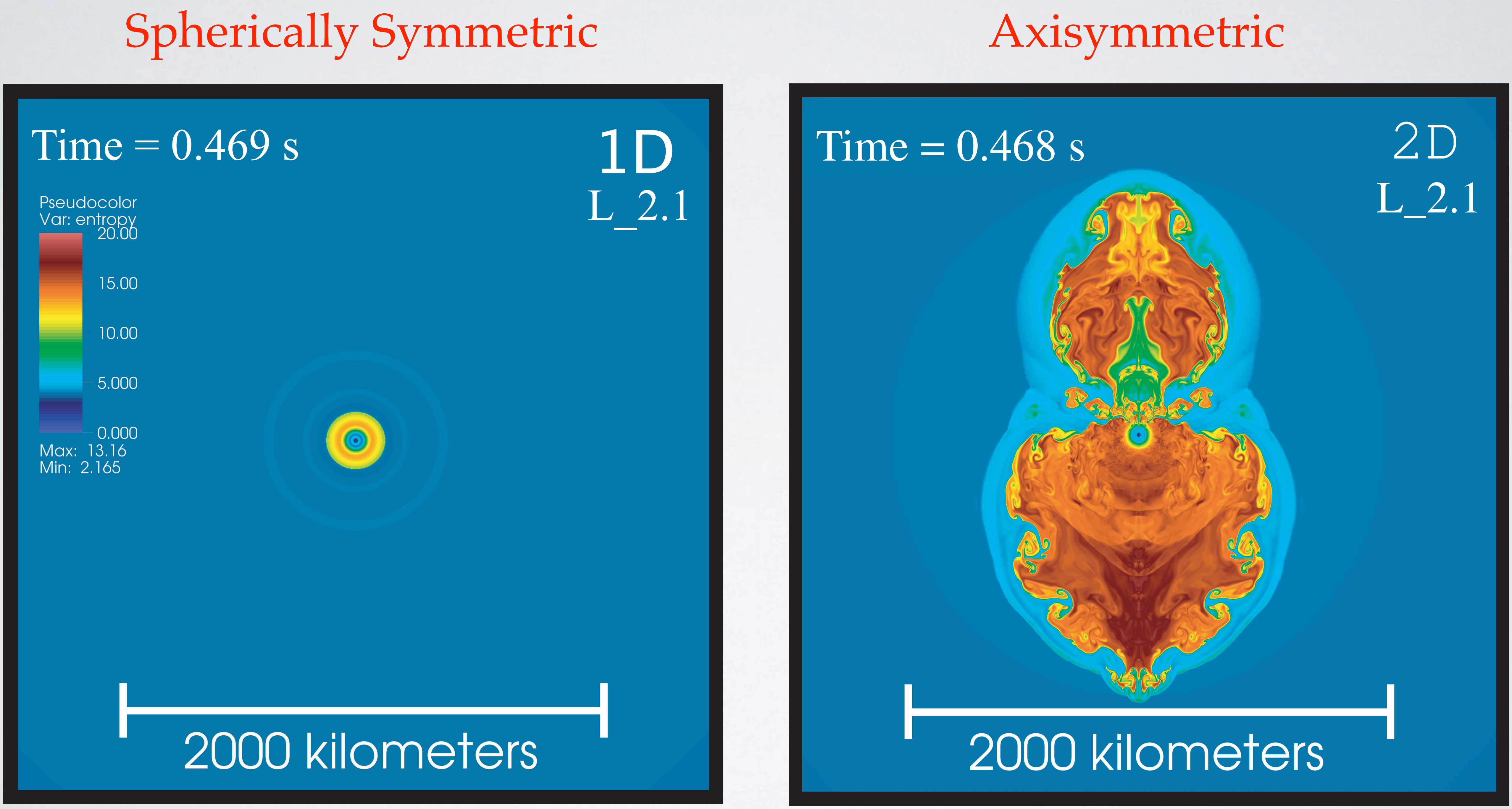






Rantsiou et al. 2012

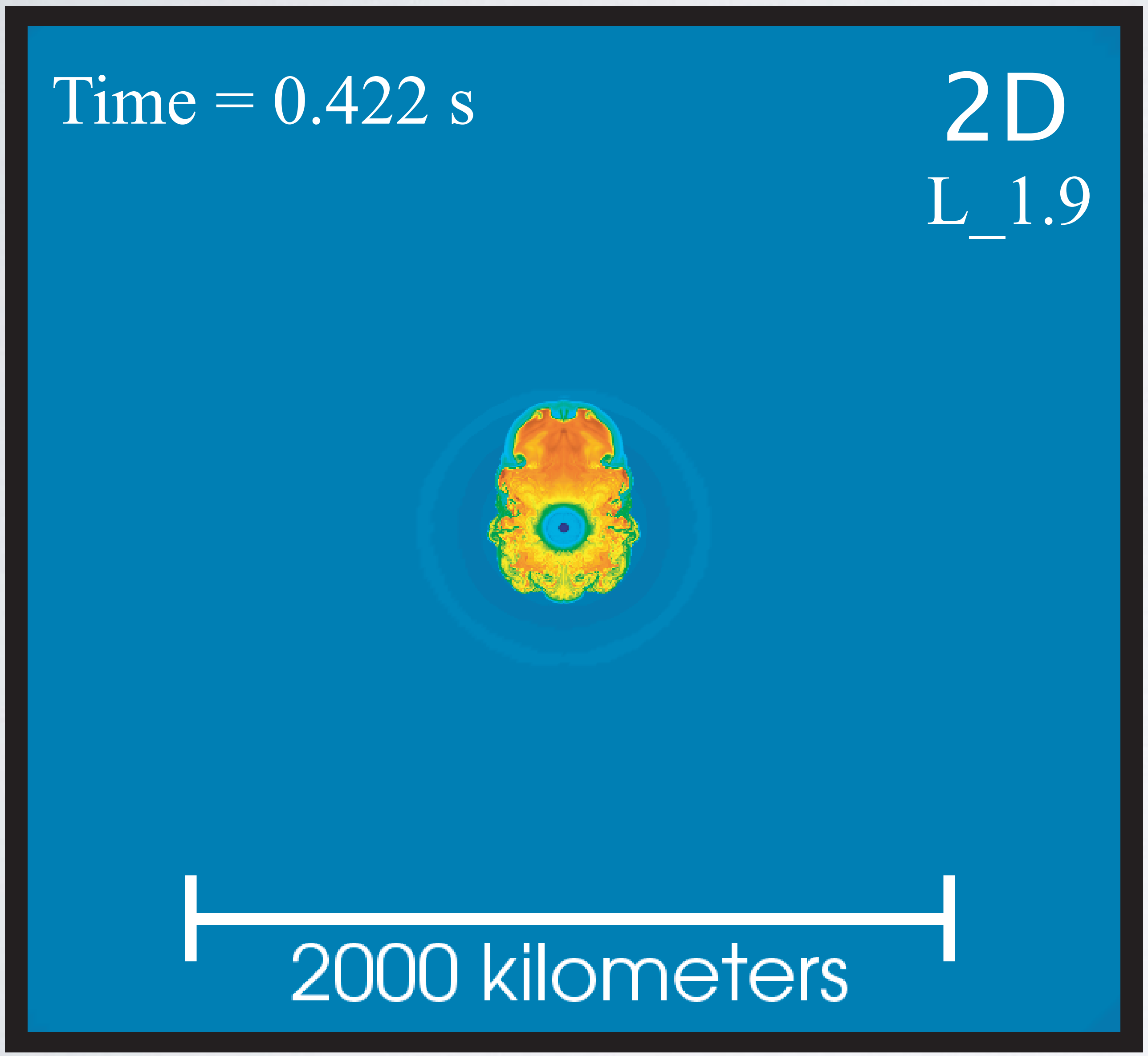
Dimensional Dependence



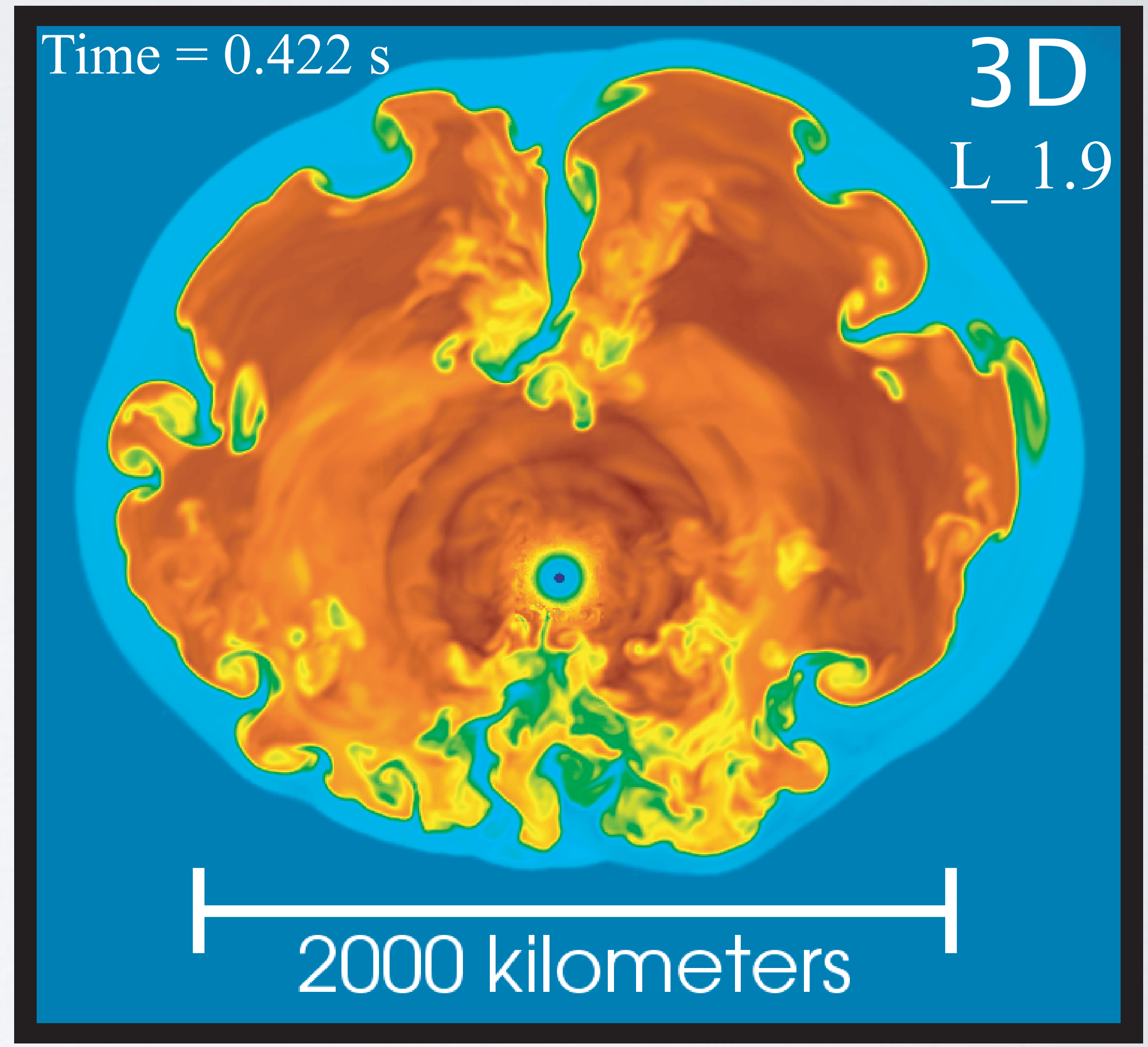
Nordhaus et al. 2010

Dimensional Dependence

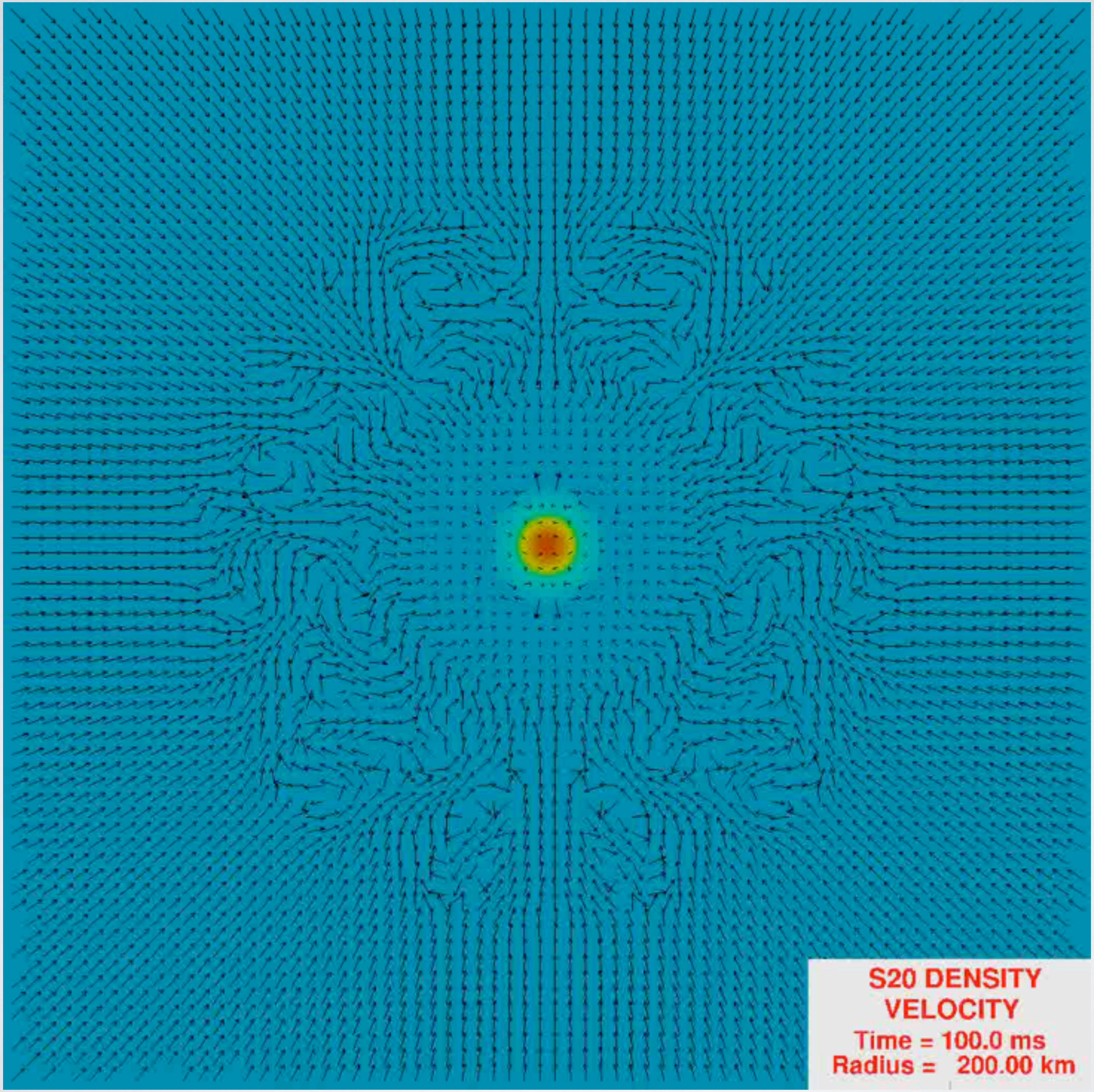
Axisymmetric

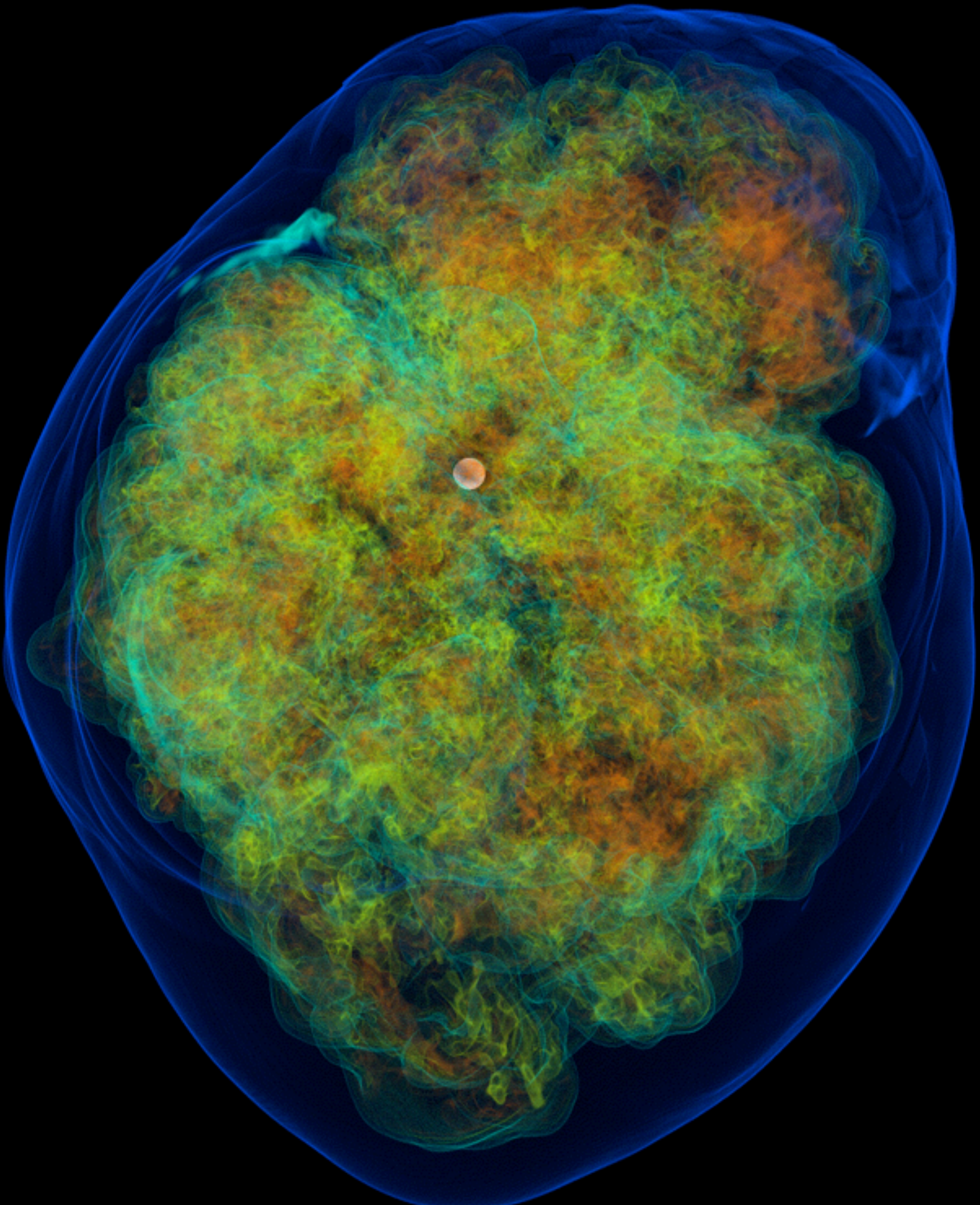


Three Dimensional

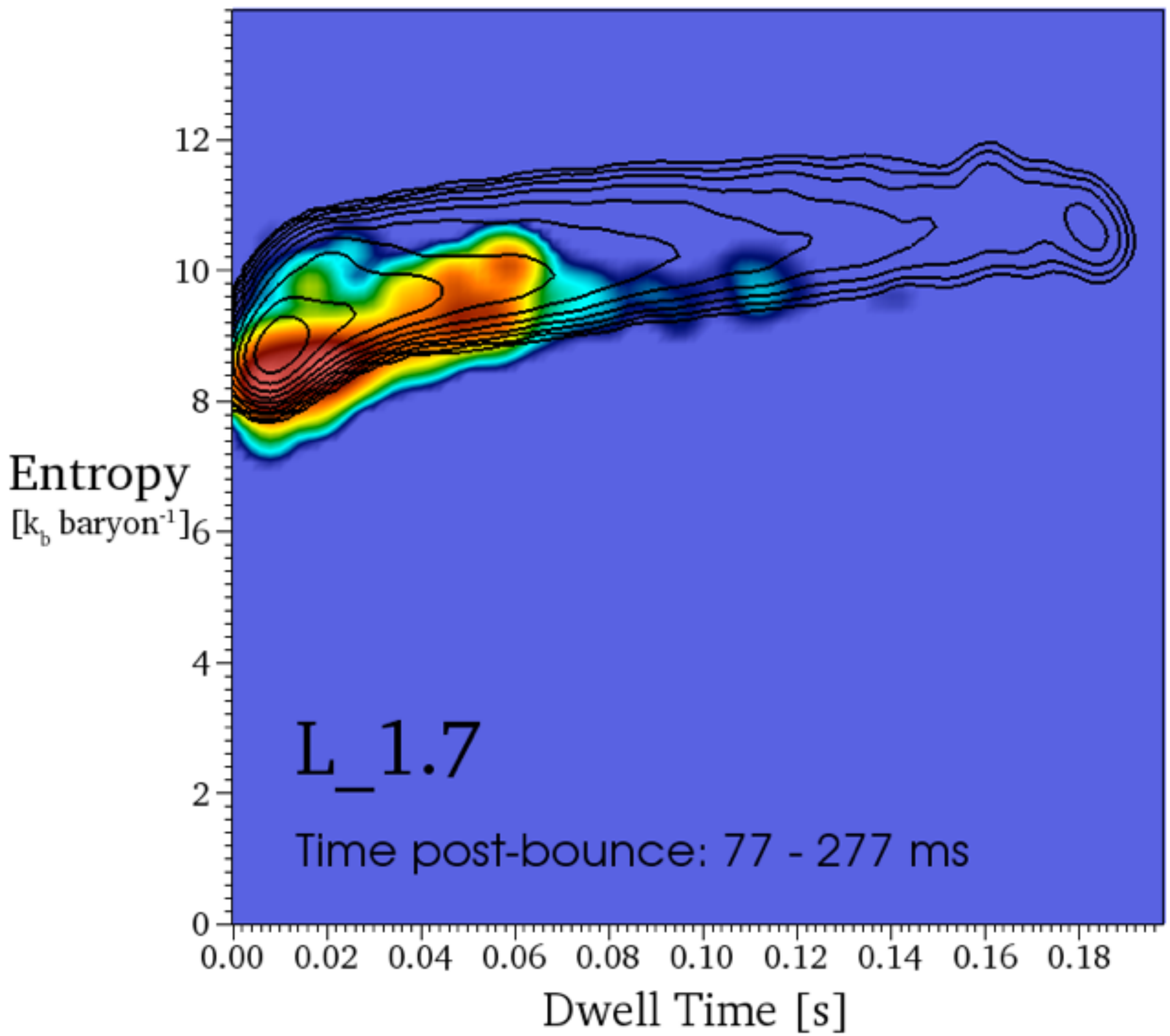


Nordhaus et al. 2010


S20 DENSITY
VELOCITY
Time = 100.0 ms
Radius = 200.00 km

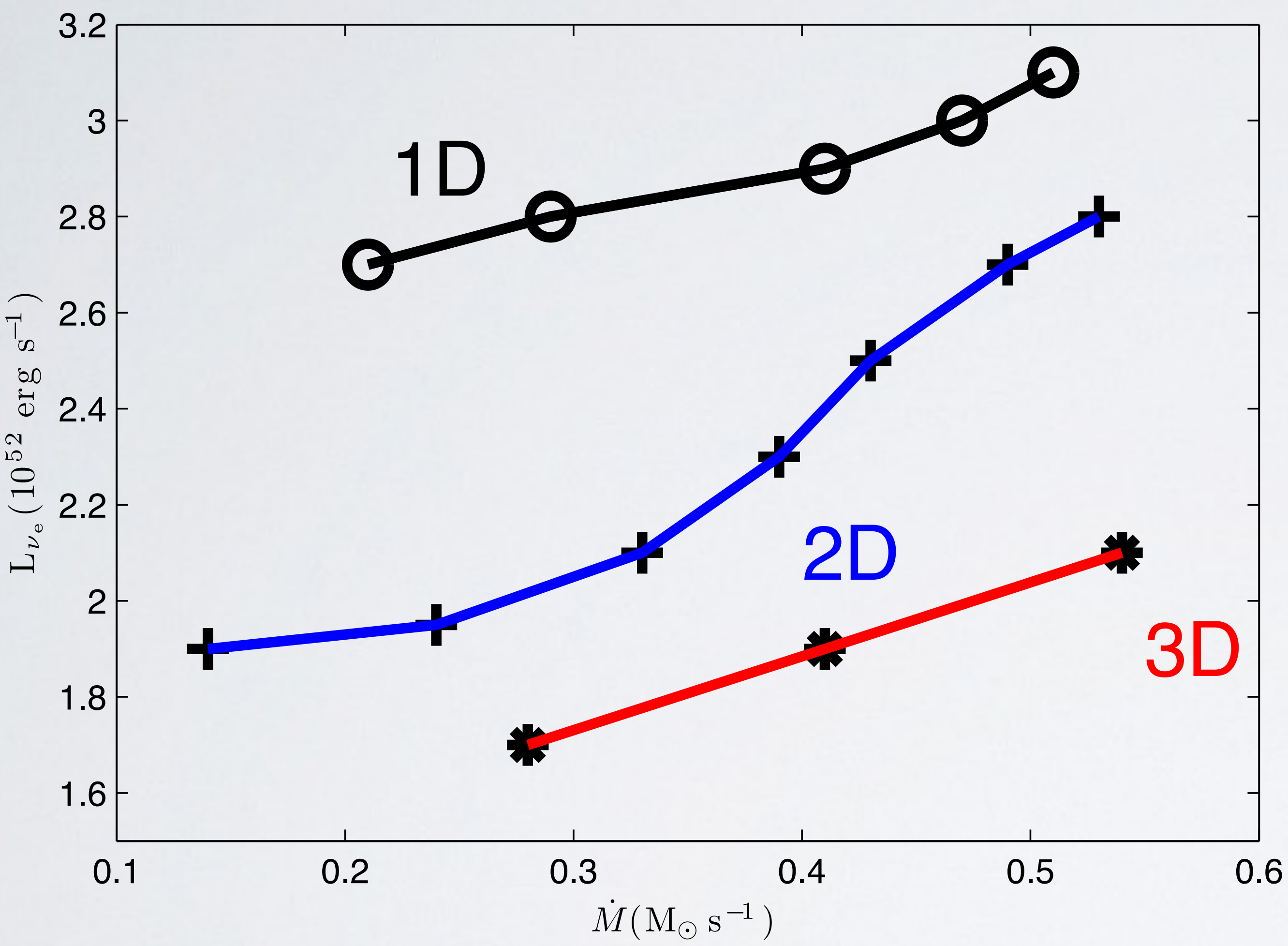


Multidimensional Effects: Increasing $\tau_{\rm res}$



Nordhaus et al. 2010

Critical curve for explosions



<u>3D explodes earlier</u>

Nordhaus et al. 2010
Dolence et al. 2014
Burrows et al. 2013
Hanke et al. 2012

<u>2D and 3D explode same time</u>

Hanke et al. 2012
Melson et al. 2014

<u>2D explodes earlier</u>

Couch 2014
Couch & O'Connor 2013
Takiwaki al. 2014

Controversial - different groups, different codes, different results.

Despite all this hope…

All 3D simulations to date:
if explosion, **under-energetic by factors of 10-100.**

Inherent limitation of the neutrino-mechanism?

Under the most extremely favorable conditions, neutrinos may accelerate the gas to energy of 5e50 erg.

Papish, Nordhaus, Soker 2015 MNRAS

Alternate ideas.

General relativistic effects: to date mostly 2D and conformally flat.

MHD: linear winding and compression only.

Nucleosynthesis: if neutrinos fail, perhaps nuclear burning.

Kushnir 2015

Jets, winds: angular momentum present, jets ubiquitous in astrophysics.

see Jittering-Jet model/papers of Oded Papish

What questions do we aim to answer?

1. Canonical explosion energy of 1 Bethe.
2. Neutron star masses and distribution.
3. Nucleosynthetic yields and distributions.
4. Pulsar Kicks.

What questions do we aim to answer?

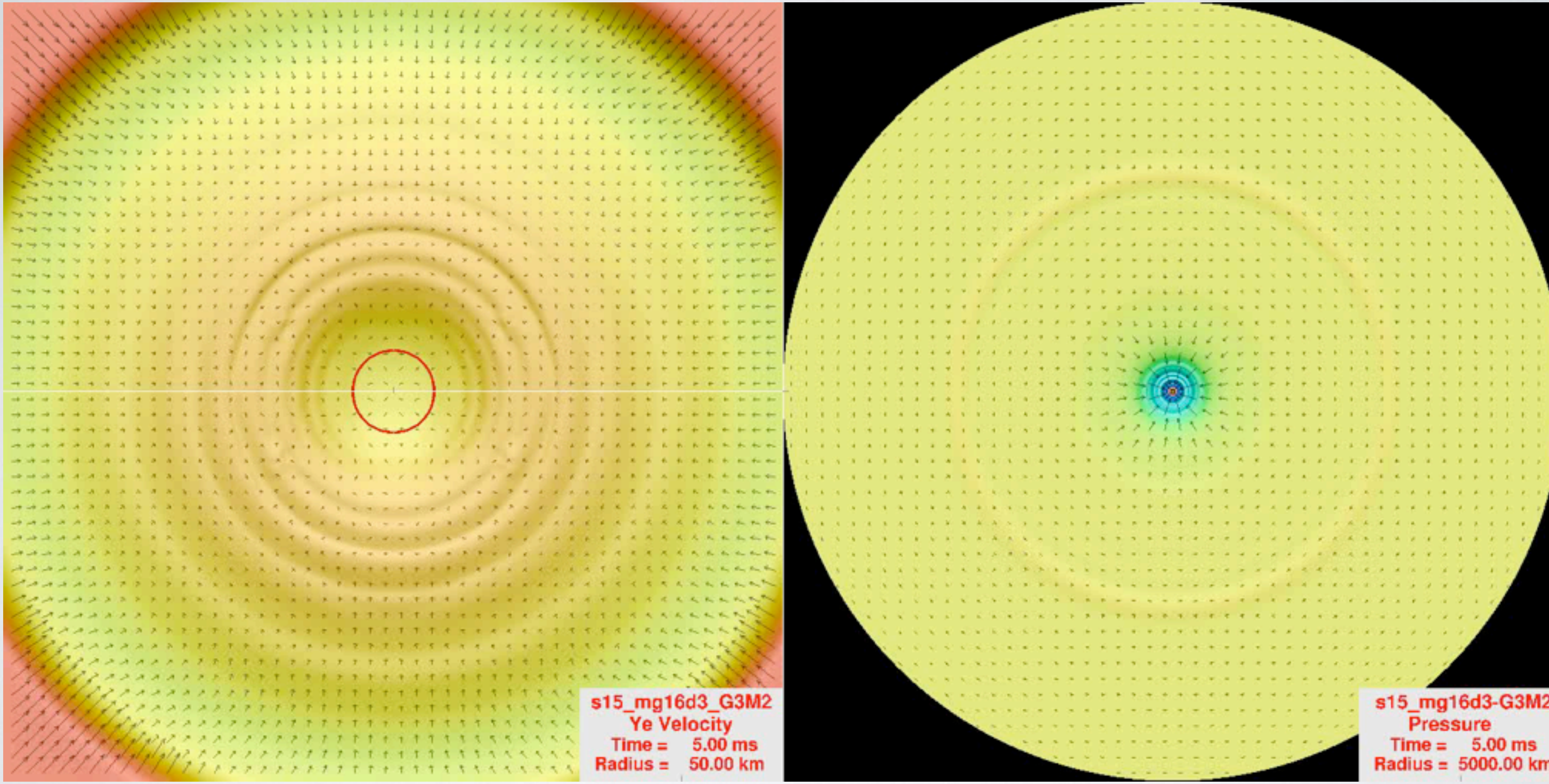
1. ~~Canonical explosion energy of 1 Bethe.~~

2. ~~Neutron star masses and distribution.~~

3. ~~Nucleosynthetic yields and distributions.~~

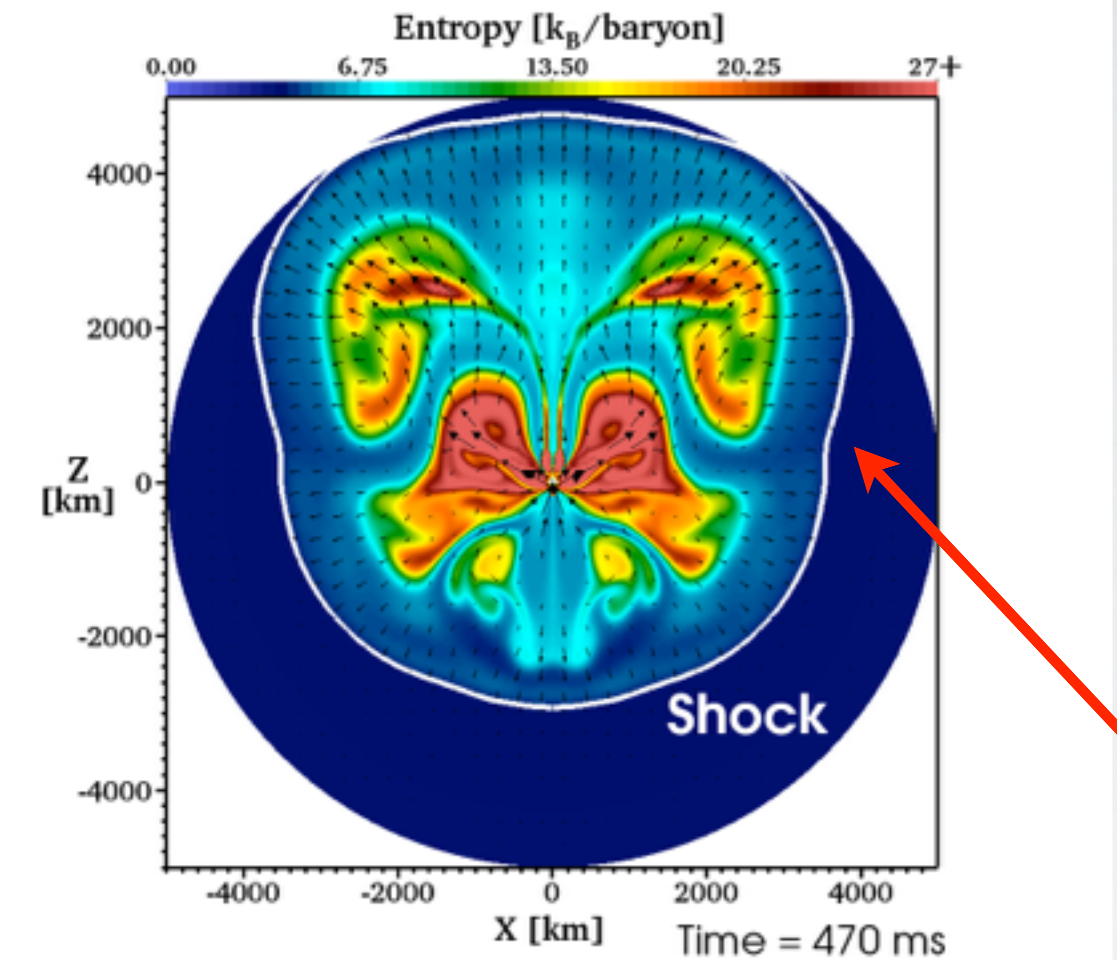
4. Pulsar Kicks.

Neutron Star Kicks



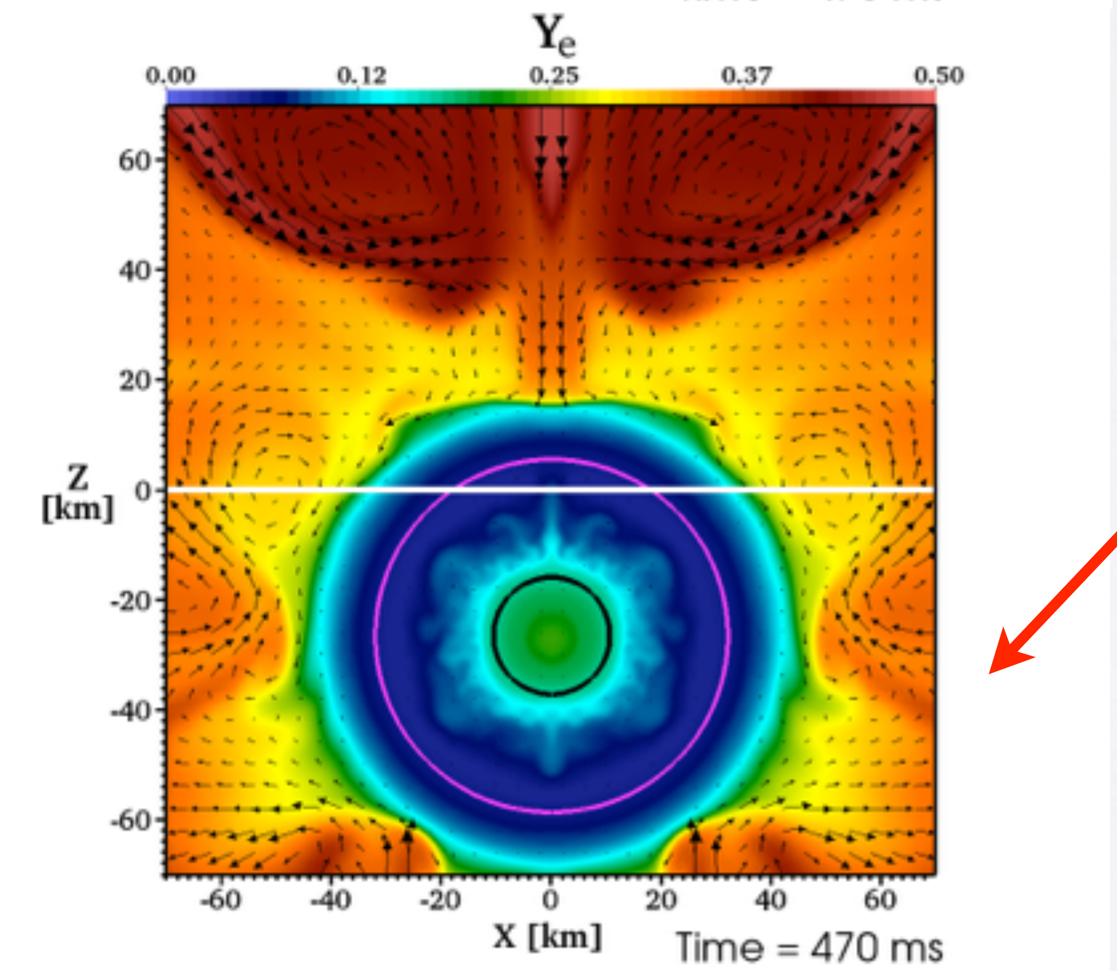
Nordhaus et al. 2010b

Neutron Star Kicks



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

Explosion primarily in +Z direction...



...leads to NS recoil in -Z direction

Hydrodynamic Origin of Pulsar Kicks

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

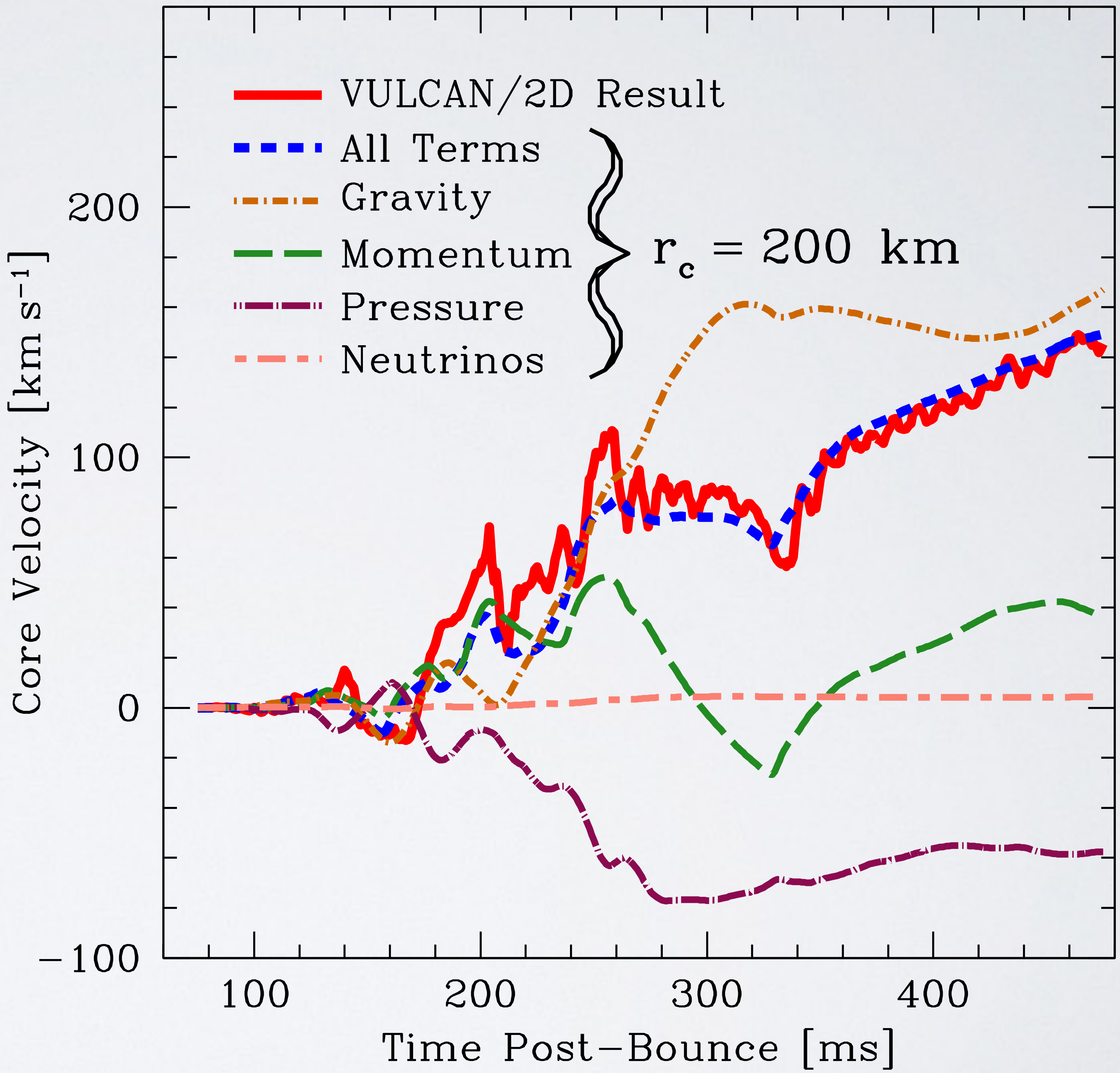
Gravitational tugboat effect is important.

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!

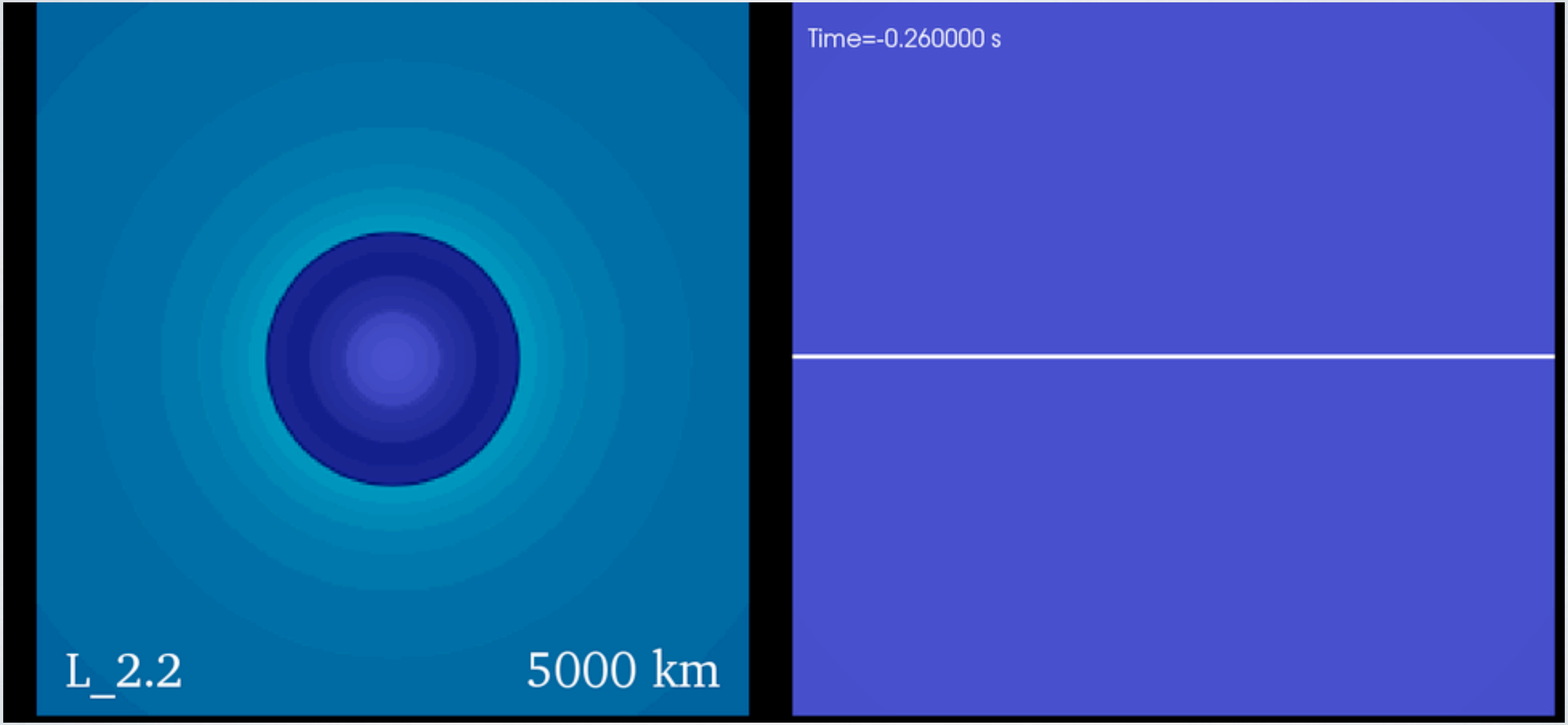


Nordhaus et al. 2010b

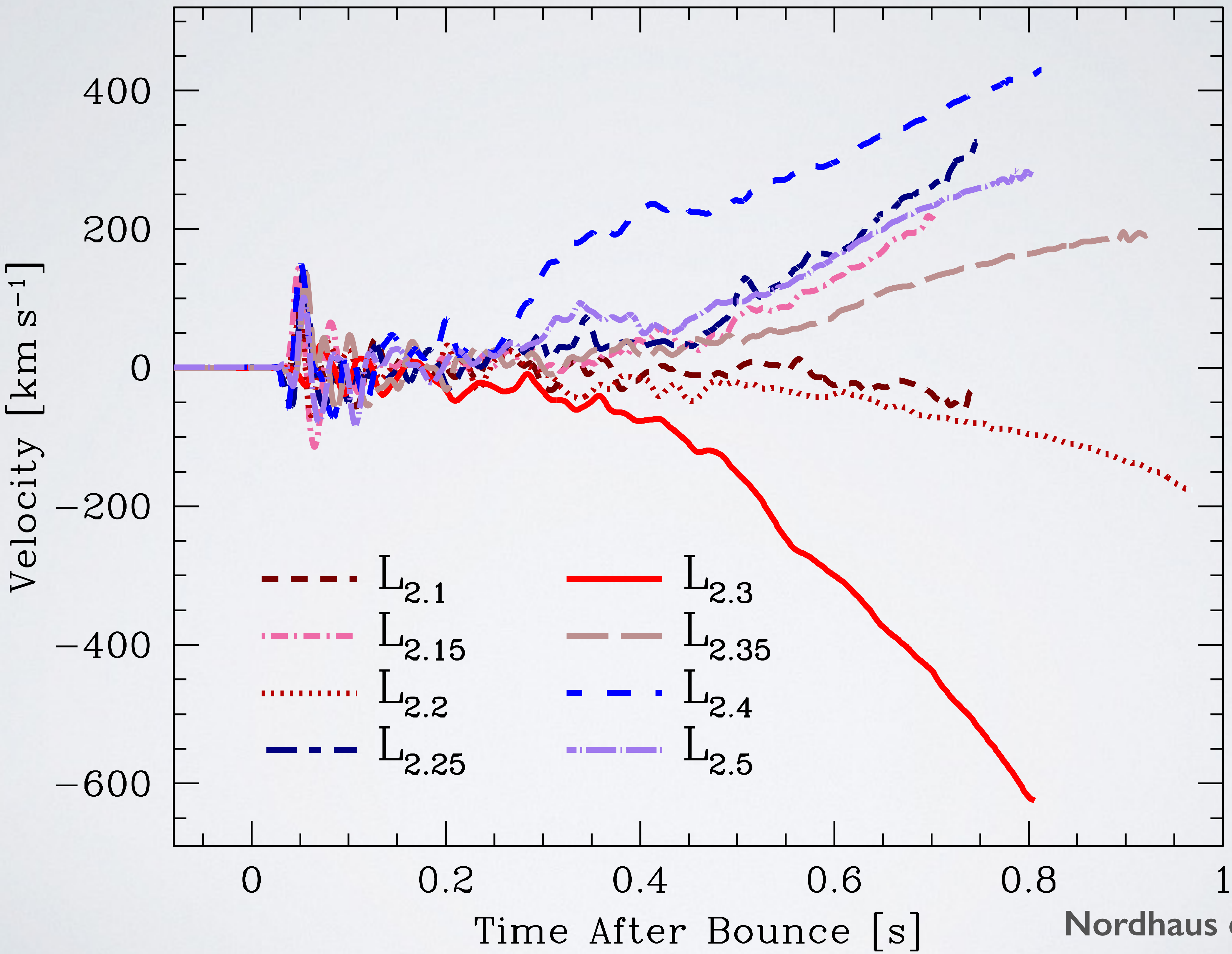
Radiation field is smooth...
... matter field is not.

Hydrodynamic Origin of Pulsar Kicks

CASTRO - with neutrino heating/cooling scheme

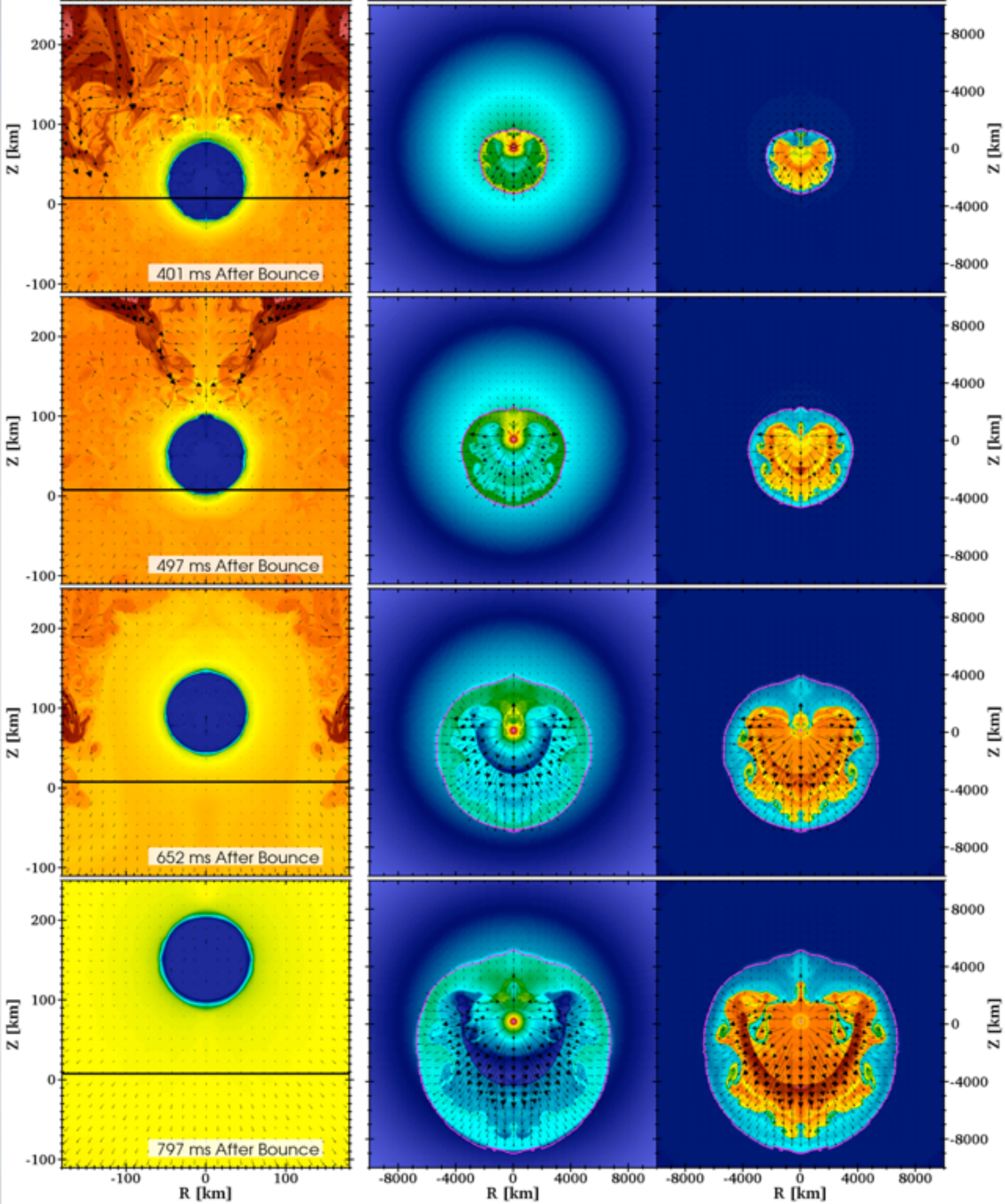


Hydrodynamic Origin of Pulsar Kicks



Nordhaus et al. 2012

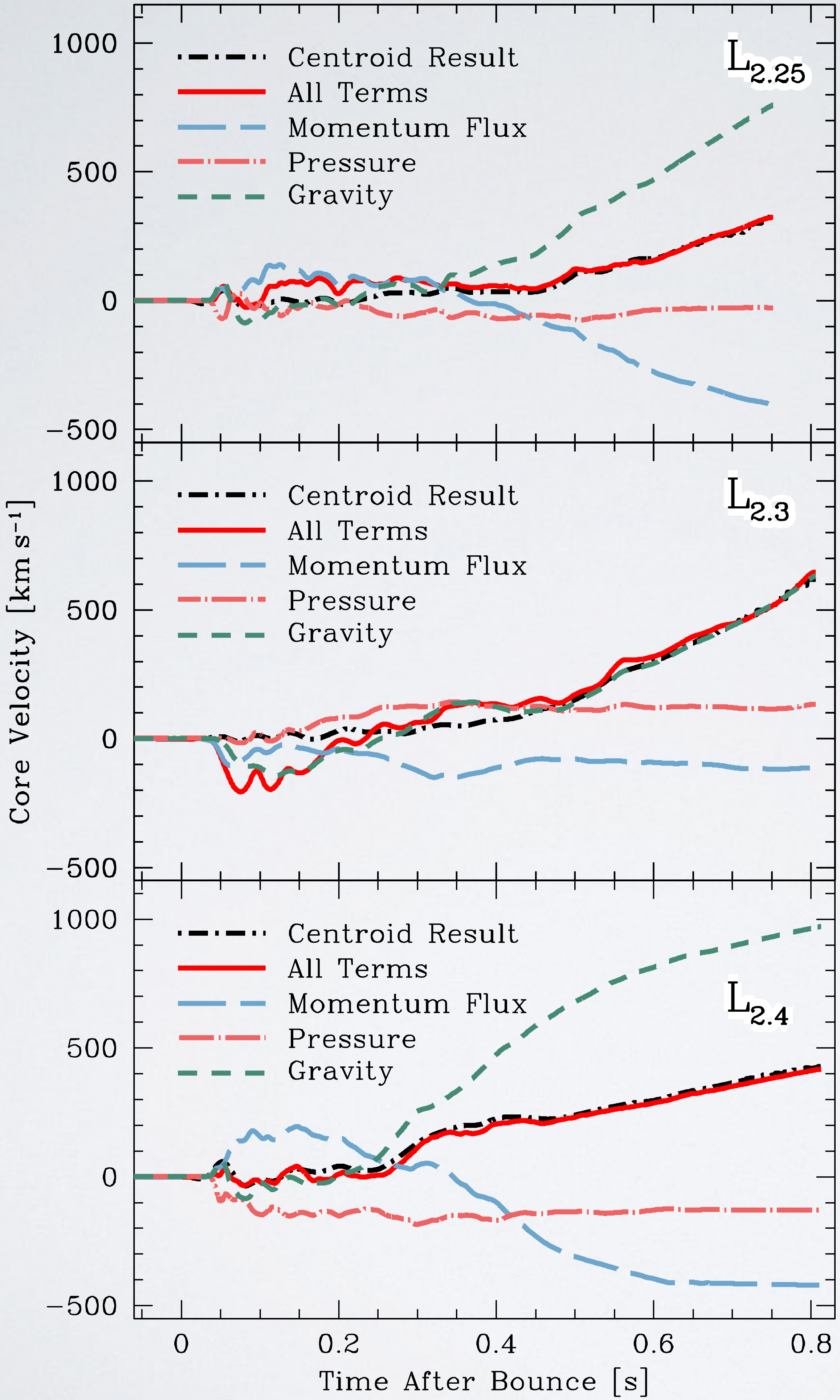
Pulsar Kicks



Gravitational effects are important.

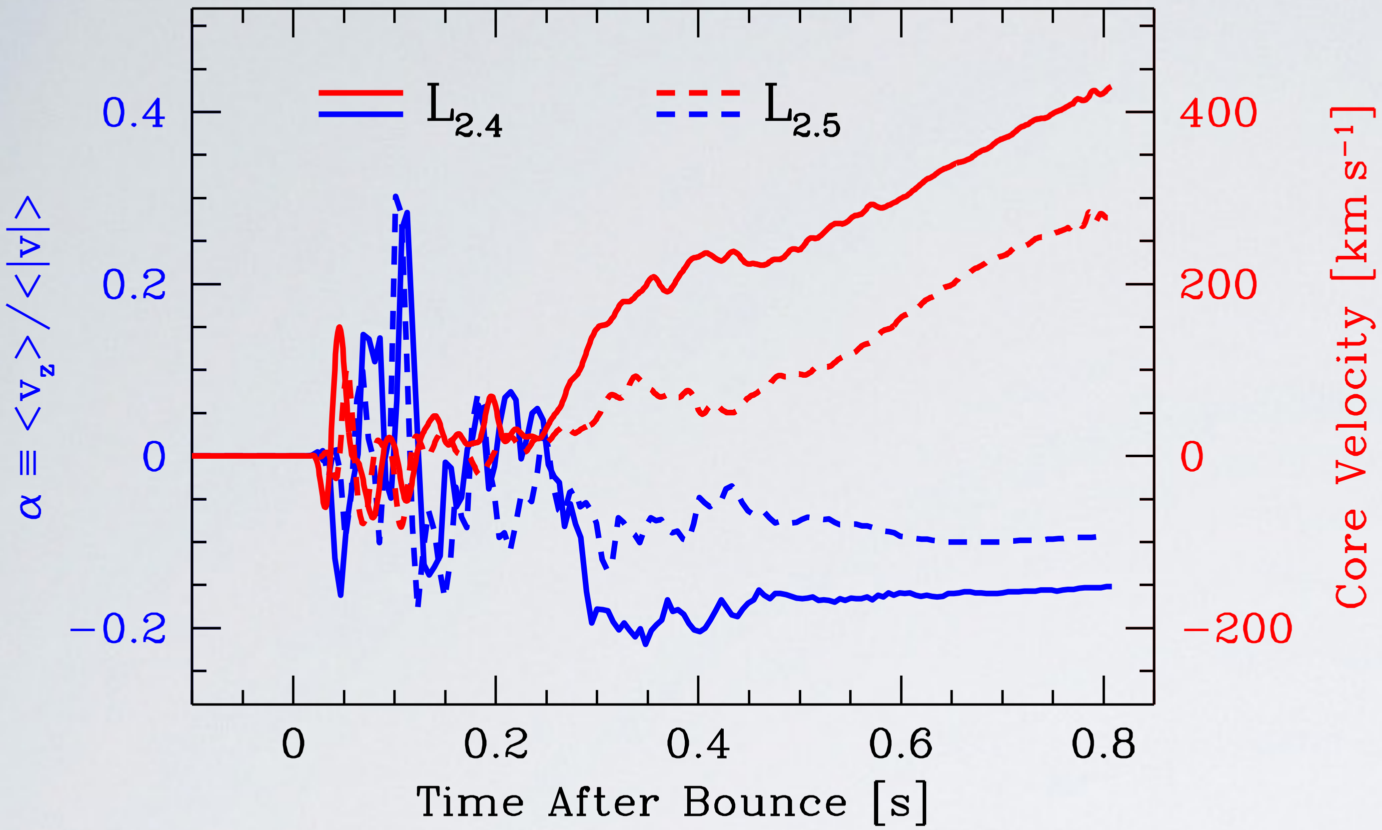
With AMR can follow evolution farther in time.

NS decoupled from surroundings



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

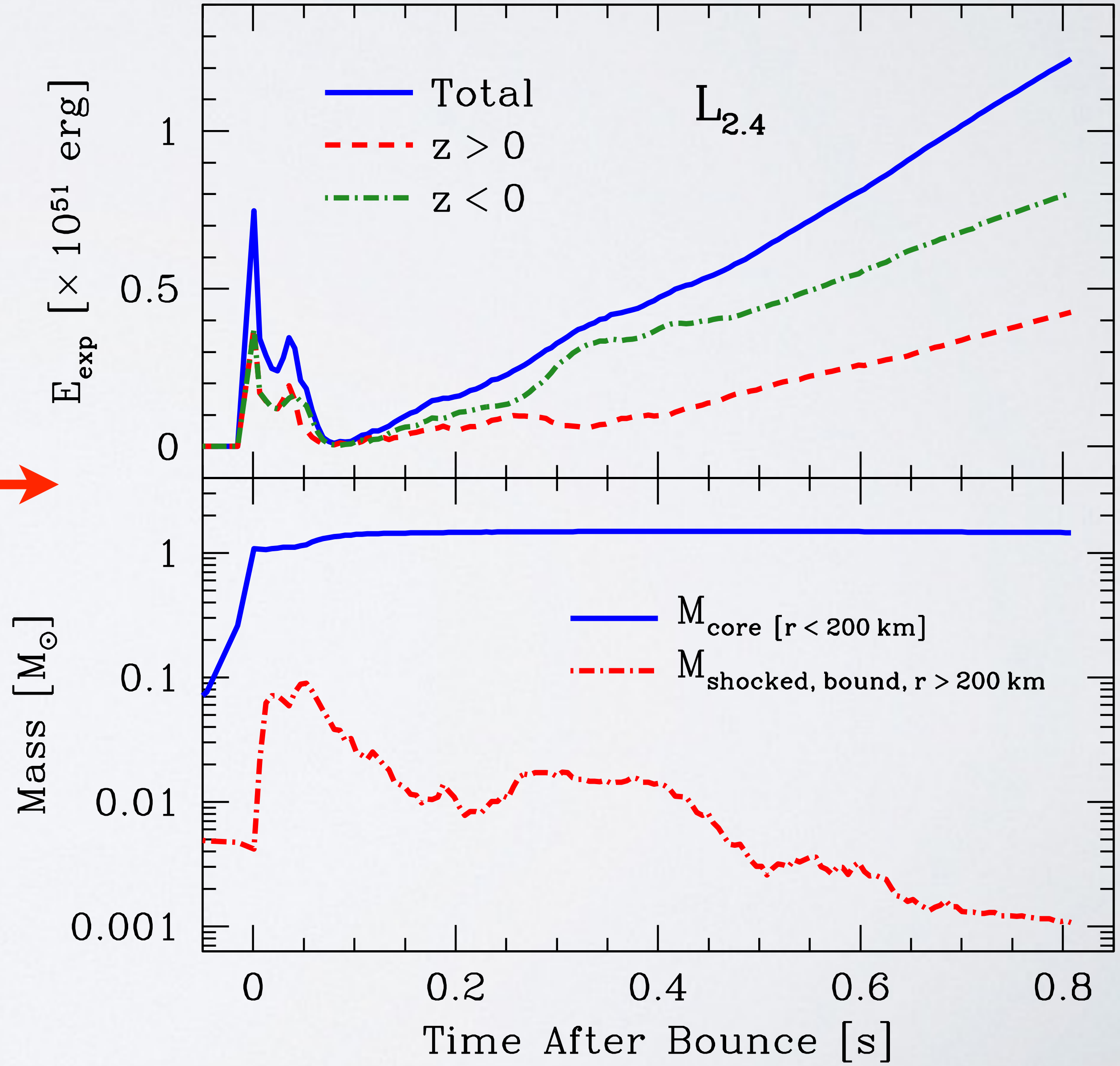
Nordhaus et al. 2012



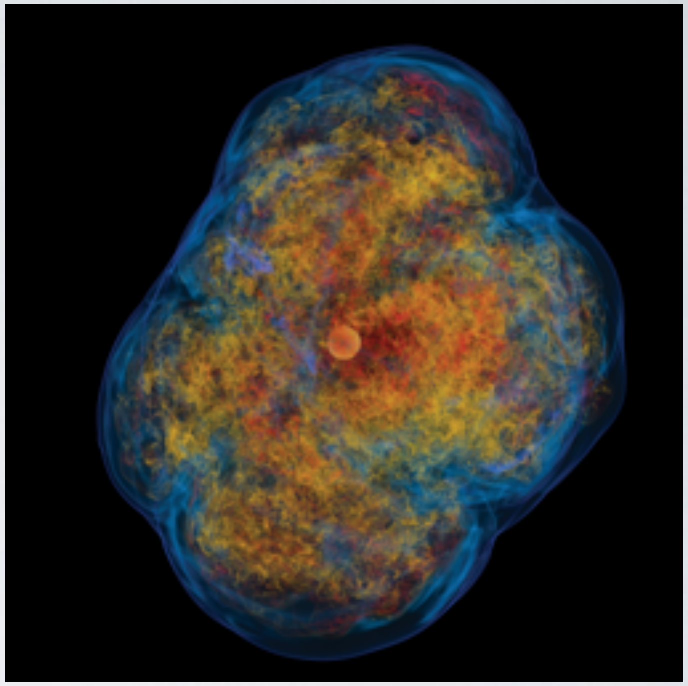
The larger the degree of asymmetry, the larger the kick

Simulations achieve canonical supernova explosion energies.

Very little bound mass at end of the simulation.



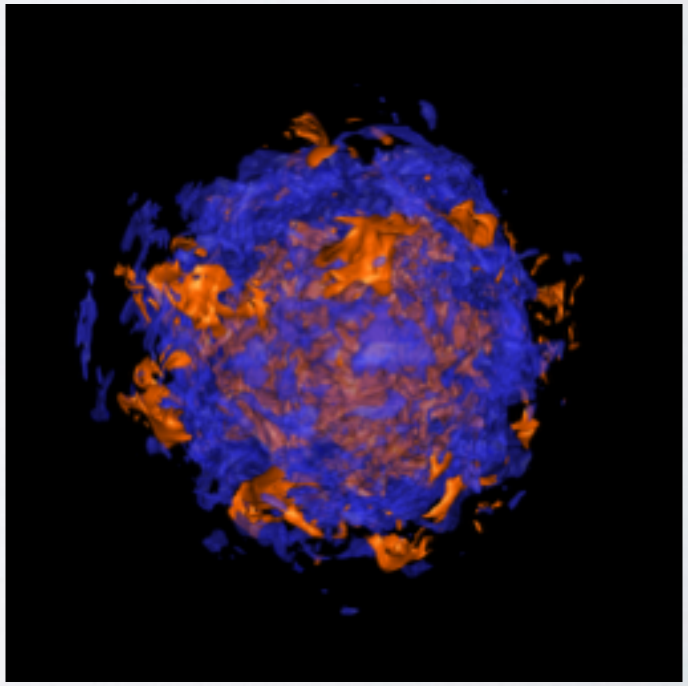
Takeaways



State-of-the-art neutrino-driven core-collapse simulations do not reach supernova energies when they explode.

Inherent limitation of the neutrino-mechanism: Papish, Nordhaus, Soker 2015.

Alternate theories/processes needed: GR, MHD, nuclear burning.



Pulsar kicks are a hydrodynamic outcome of explosions.