Core Collapse Supernovae: Trying to Explode Stars at NERSC

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Terascale Supernova Initiative

&

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Progenitor Evolution

Stellar Core Collapse

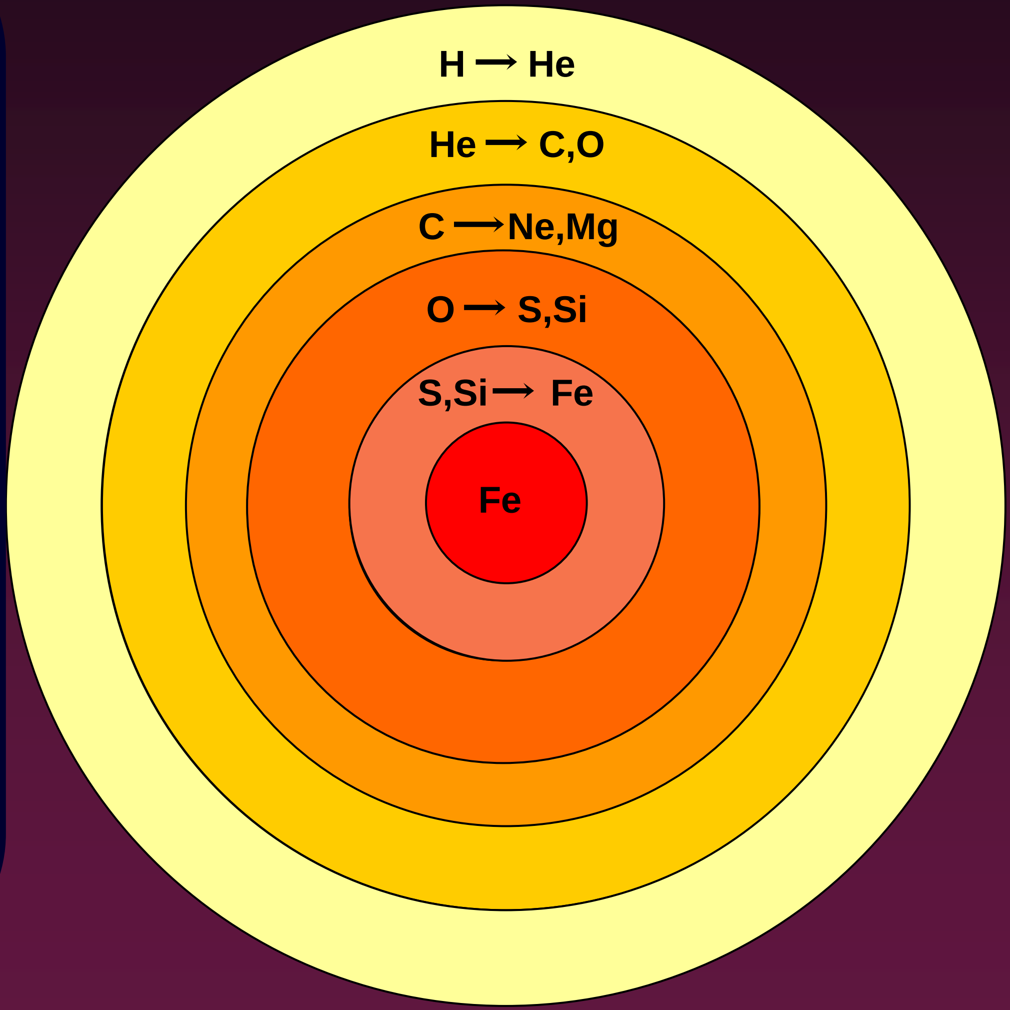
-Massive stars evolve by burning lighter elements, by thermonuclear fusion, into heavier elements

-High mass stars will produce elements up to Silicon & Sulfur , which then burn into Iron

-Star has an Onionskin-like structure with layers of successively heavier elements

-Each burning stage progresses more rapidly

-When the iron core mass becomes about 1.2-1.4 solar masses the core can no longer sustain itself against the pull of gravity & it collapses



"Prompt" Epoch

Core Collapse & Bounce

-Iron core collapses in 1/100th of a second

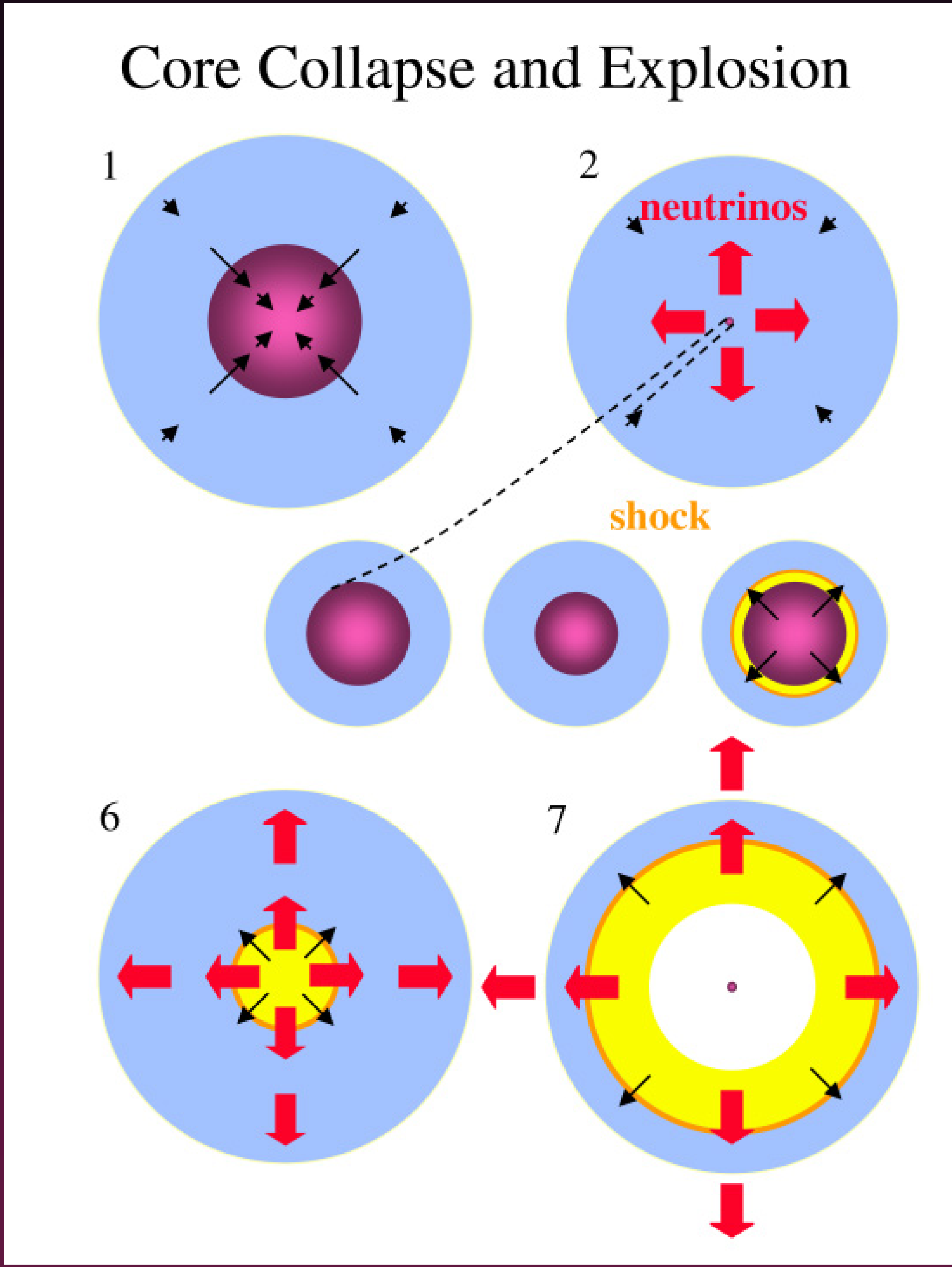
-Neutrinos are produced: $e^- + p$! $n + \bar{\nu}_e$

-Neutrinos escape from the collapsing core until the material becomes too dense

-The core collapses until densities of about 2.5×10^{14} g/cm^3 is reached

-Stiff nuclear forces cause the collapse to halt and the core rebounds outward

-Outward moving core forms a shock wave when it hits the exterior regions where matter is still falling inward



Convective Shock Revitalization Epoch

Supernova Explosion

-Shock wave heats matter as it moves outward

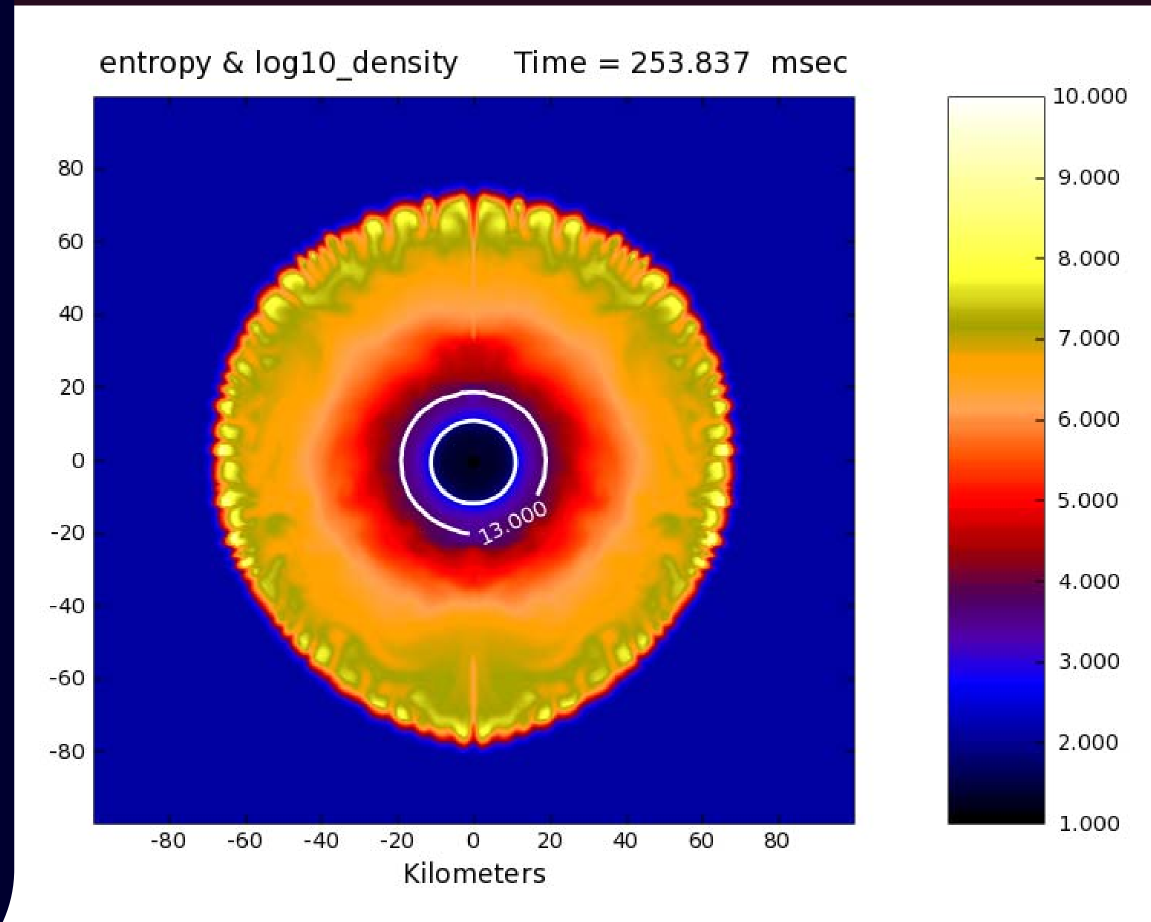
-Hot matter produces neutrino/ anti-neutrino pairs of three types
$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$

-Shock wave stalls before it reaches outer edge of iron core

-Hot (high entropy) matter starts rising upward (convection)

-A combination of convection and neutrino heating of the matter somehow revitalizes the stalled shock wave and causes the observed explosion

-Explosion leaves either a neutron star or a black hole behind



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Neutrino Radiation-Hydrodynamic Model

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad \frac{\partial (\rho Y_e)}{\partial t} + \nabla \cdot (\rho Y_e \mathbf{v}) = -m_b \sum_f \int d\epsilon \left(\frac{\mathcal{S}_\epsilon}{\epsilon} - \frac{\bar{\mathcal{S}}_\epsilon}{\epsilon} \right)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot (E\mathbf{v}) + P \nabla \cdot \mathbf{v} = -\sum_f \int d\epsilon \left(\mathcal{S}_\epsilon + \bar{\mathcal{S}}_\epsilon \right)$$

$$E = f(T, \rho, Y_e)$$

$$P = g(T, \rho, Y_e)$$

$$\frac{\partial (\rho v_i)}{\partial t} + \nabla \cdot (\rho v_i \mathbf{v}) + (\nabla P)_i + \rho (\nabla \Phi)_i + \nabla \cdot \left\{ \sum_f \int d\epsilon \left(\chi_\epsilon E_\epsilon + \bar{\chi}_\epsilon \bar{E}_\epsilon \right) \right\} = 0$$

$$\nabla^2 \Phi = 4\pi \rho G_N$$

$$\frac{\partial E_\epsilon}{\partial t} + \nabla \cdot (E_\epsilon \mathbf{v}) - \nabla \cdot (D_\epsilon \nabla E_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\chi_\epsilon E_\epsilon) : \nabla \mathbf{v} = \mathcal{S}_\epsilon \qquad 0 \le E_\epsilon \le \frac{\epsilon^3}{\alpha}$$

$$\frac{\partial \bar{E}_\epsilon}{\partial t} + \nabla \cdot (E_\epsilon \mathbf{v}) - \nabla \cdot (\bar{D}_\epsilon \nabla \bar{E}_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\bar{\chi}_\epsilon \bar{E}_\epsilon) : \nabla \mathbf{v} = \bar{\mathcal{S}}_\epsilon \qquad 0 \le \bar{E}_\epsilon \le \frac{\epsilon^3}{\alpha}$$

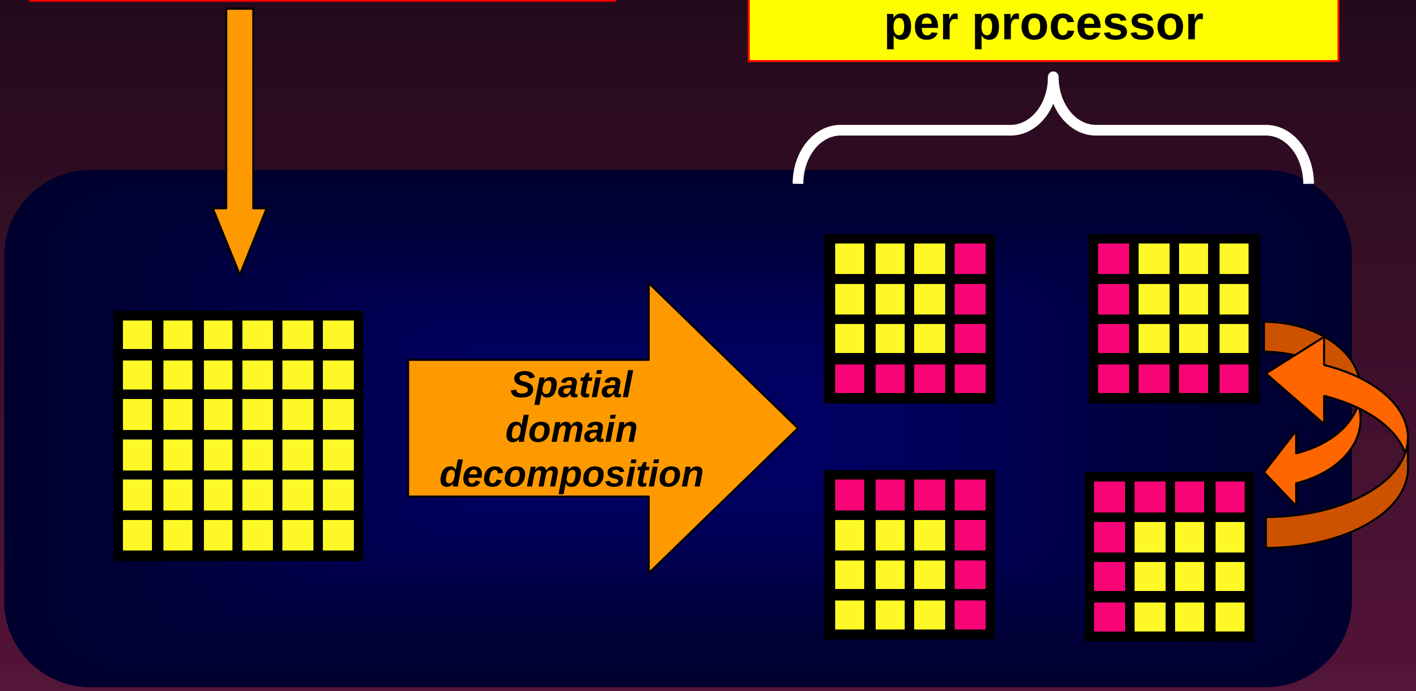
$$\mathcal{S}_\epsilon = S_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) - c\kappa^a_\epsilon E_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) c \int d\epsilon' \kappa^s(\epsilon', \epsilon) E_{\epsilon'}$$
$$- E_\epsilon c \int d\epsilon' \kappa^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'}\right) + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) \epsilon \int d\epsilon' G(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'}\right)$$

$$\bar{\mathcal{S}}_\epsilon = \bar{S}_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) - c\bar{\kappa}^a_\epsilon \bar{E}_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) c \int d\epsilon' \bar{\kappa}^s(\epsilon', \epsilon) \bar{E}_{\epsilon'}$$
$$- \bar{E}_\epsilon c \int d\epsilon' \bar{\kappa}^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'}\right) + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) \epsilon \int d\epsilon' G(\epsilon', \epsilon) \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'}\right)$$

Parallel Implementation

Global Problem Domain

Problem split up into one spatial sub-domain per processor



Adjacent processes in Cartesian topology must exchange ghost zones when needed by algorithms

- Code (V2D) written in F95
- Continuous process of Verification & Validation
- Componentized architecture
- Message passing done in MPI
- Parallel I/O done with parallel HDF5
- Scalable to at least 1024-2048 processors for “medium sized” problems

Implicit Neutrino Transport w/ Newton-Krylov Iteration

N-K solution accomplished via Newton-BiCGSTAB

Currently using sparse parallel approximate inverse preconditioning (physics based) -- highly parallel

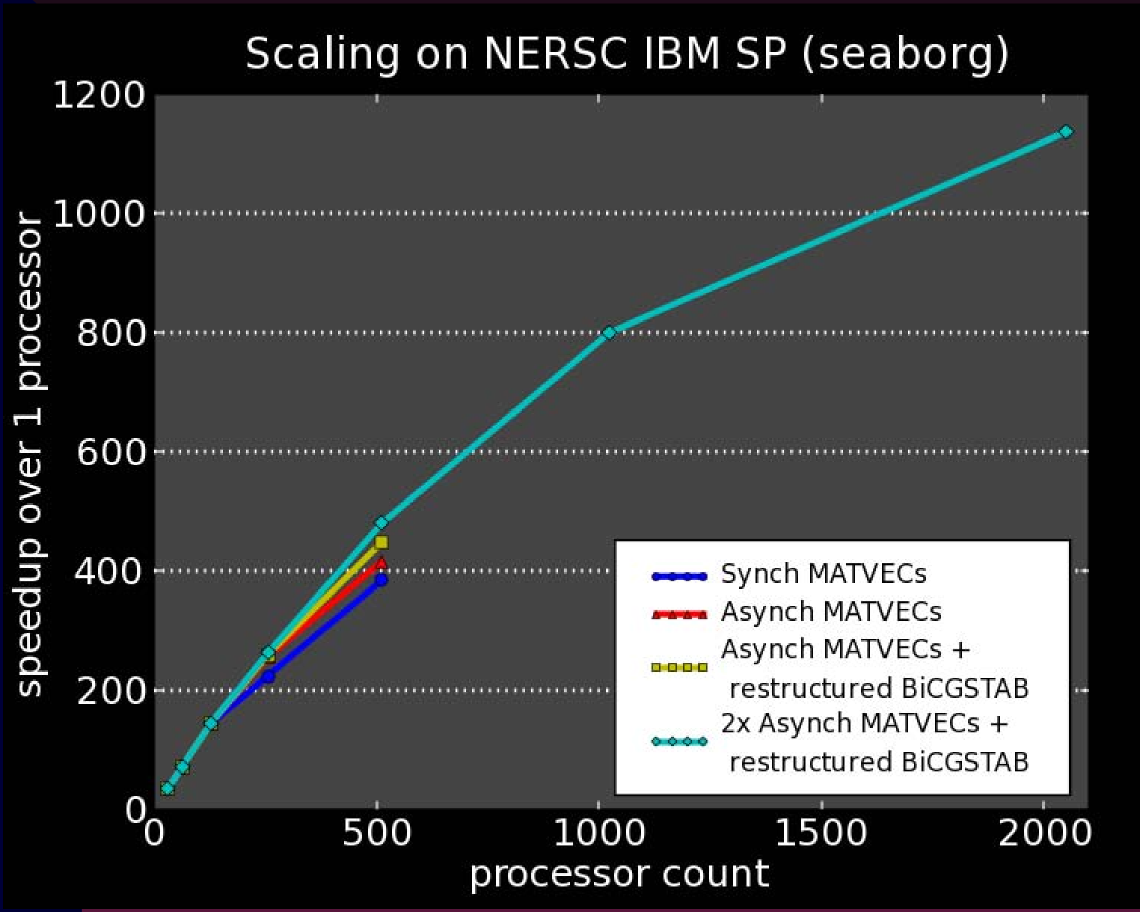
MATVECS can be carried out asynchronously to hide communication

BiCGSTAB can be restructured to reduce global reductions

Typically 10-20 Bicgstab iterations per Newton iteration; 2-3 Newton iterations

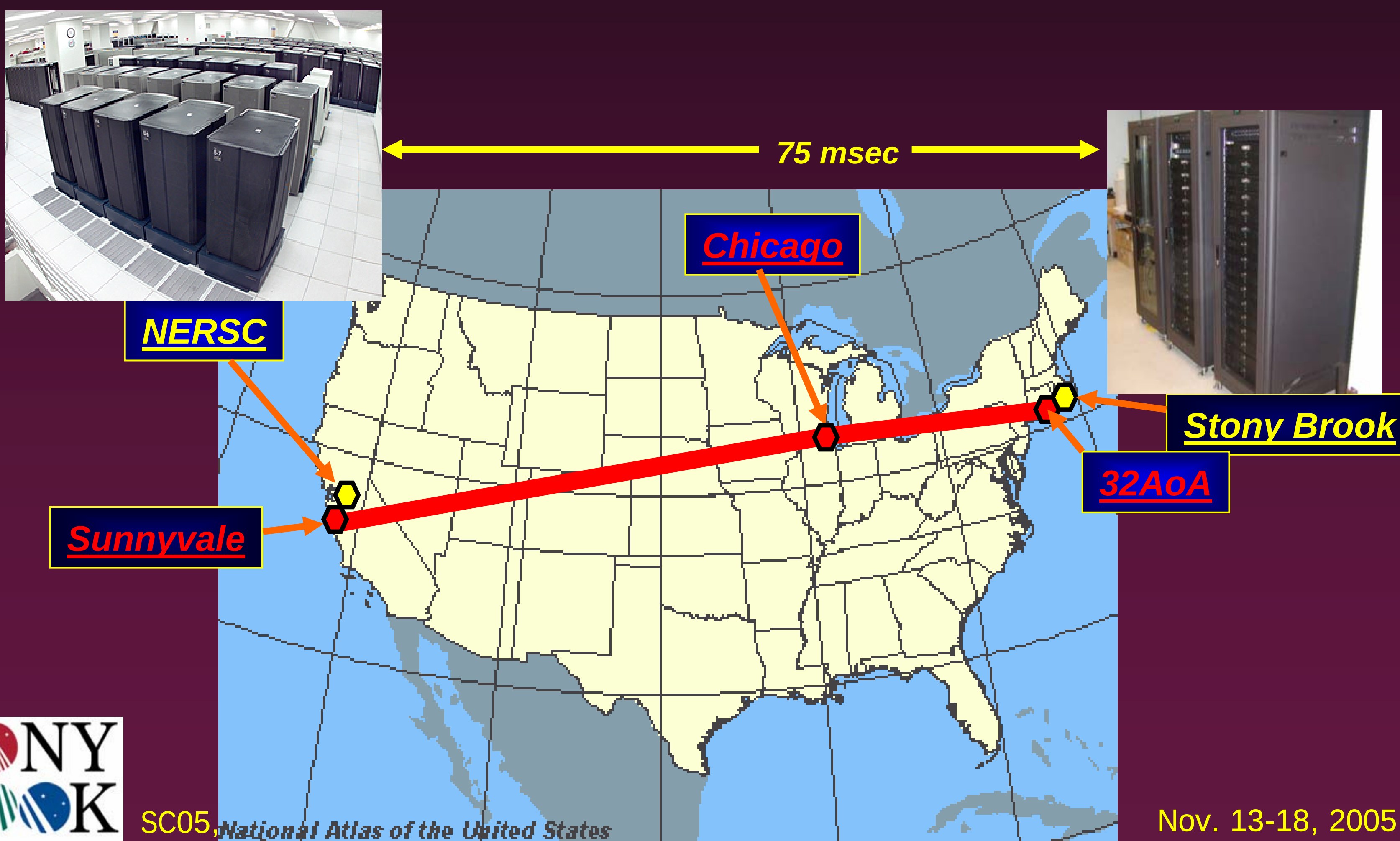
Implicit solvers have to be ultra-fast -- few x 10^5 timesteps to complete simulation!

Currently Incorporating TOPS SUNDIALS solvers into V2D for fully implicit radiation-hydro



Data Management & Networking Challenges

- Couldn’t handle the data without LBONE Depots & LORS Tools!
- Scientific Process Automation (SPA) systems is easing workflow management tremendously!



Models of the Convective Epoch

- Prior to a few years ago state of the art was:
  - 2-D models with gray transport approximation (produced explosions; assumed distribution function; approximated rates & opacities; no dynamic diffusion in Eulerian models)
  - Uncoupled radial-ray multi-group models (saw no explosions; lacked full coupling; no lateral movement of neutrinos; no dynamic diffusion)
- More Recently:
  - Fully coupled 2-D radiation-hydrodynamic MGFLD models
  - Partially coupled 2-D Multigroup Variable Eddington Factor models
  - Fully coupled 2-D Boltzmann transport models (coming soon!)

Baseline Model

-S15S7B progenitor model of Woosley & Weaver

-Neutrino Physics at the level of Bruenn (1985) w/ NES turned off

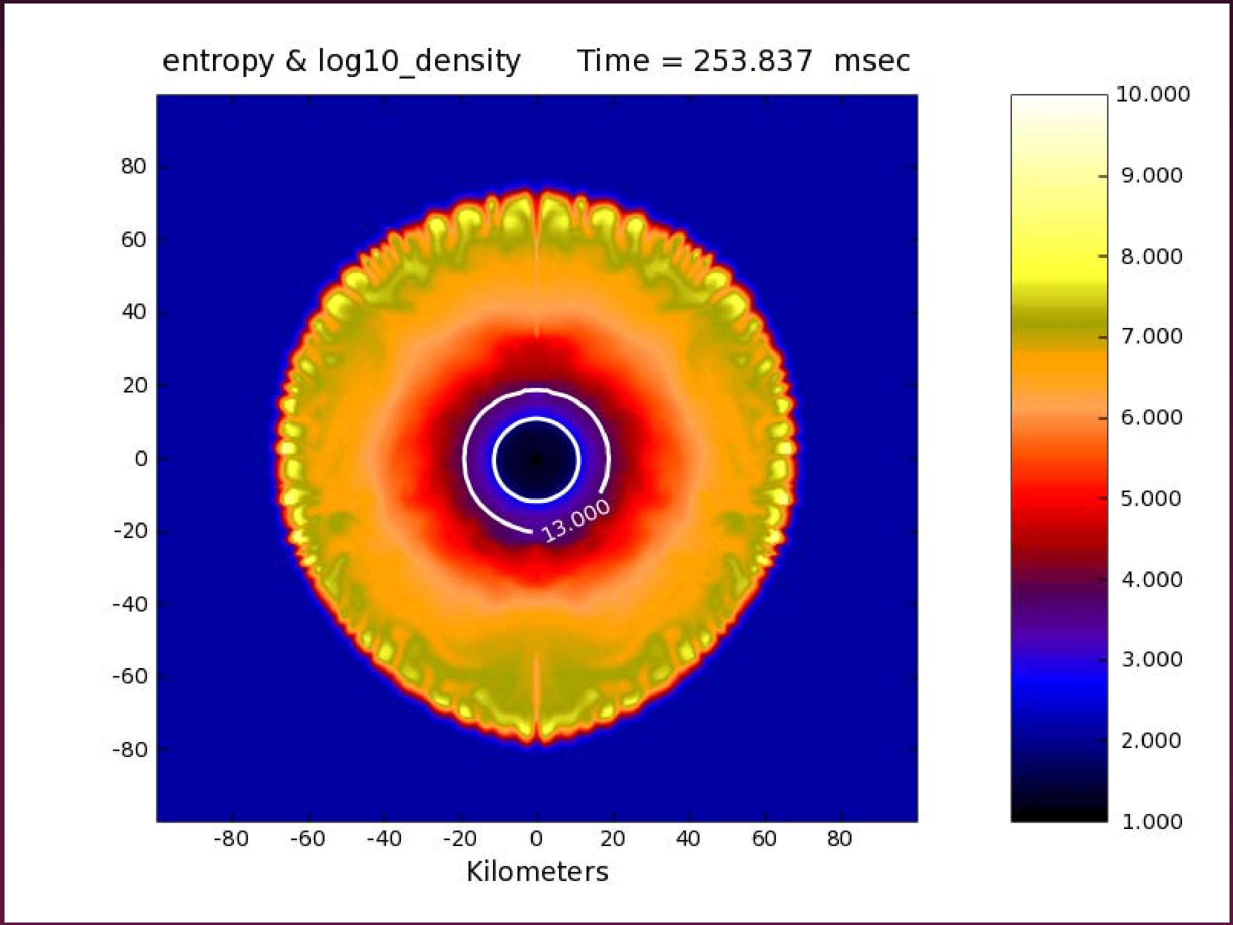
-EOS is LS K=180 MeV model

-Collapse run to $\rho=10^{14}$ g/cm^3 w/ 1-D Lagrangean code

-Baseline model does not explode on timescales of 35 msec

Early Onset of Convection

- Convection begins to occur early when 2-D models are initiated from bounce
  - Richtmyer-Meshkov (impulsive limit of Raleigh-Taylor) instability
  - Before shock gets out to > 100 Km
- At 256x256 spatial resolution we see much smaller scale convective flow features than other groups have reported
  - Fully resolved? Probably not…



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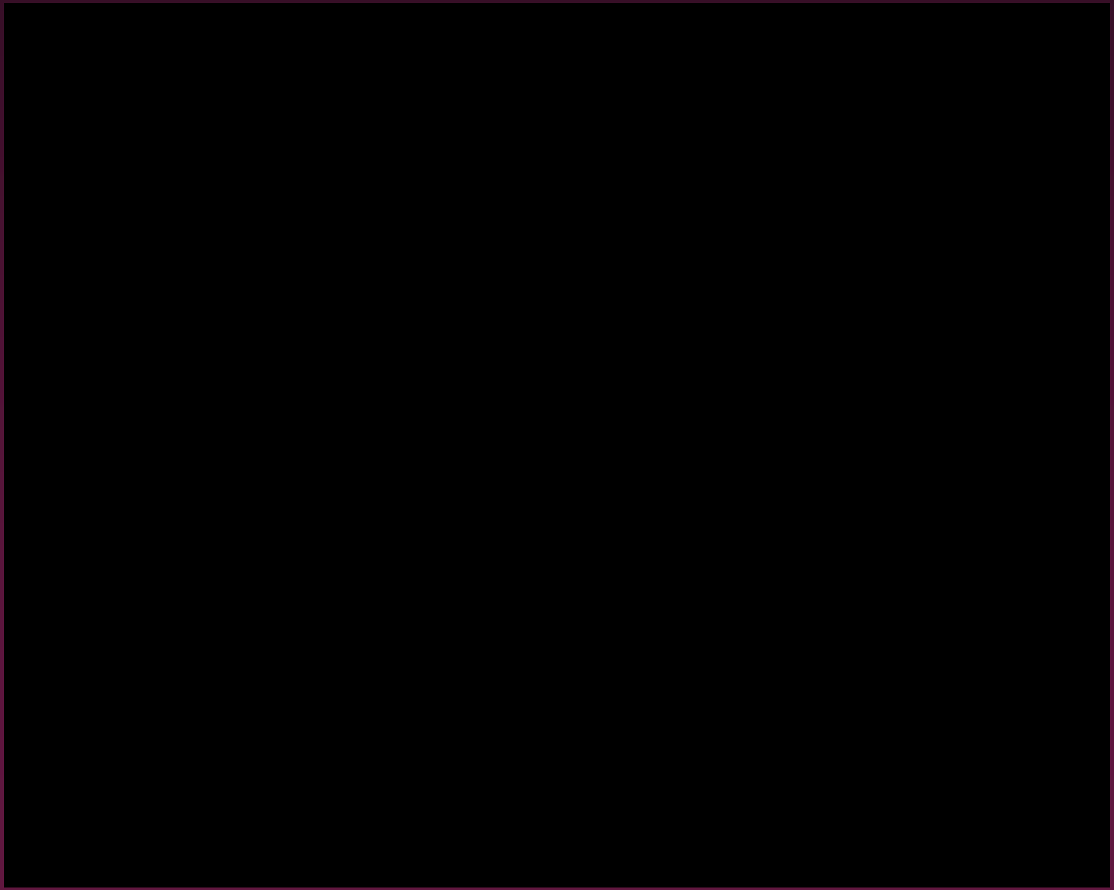

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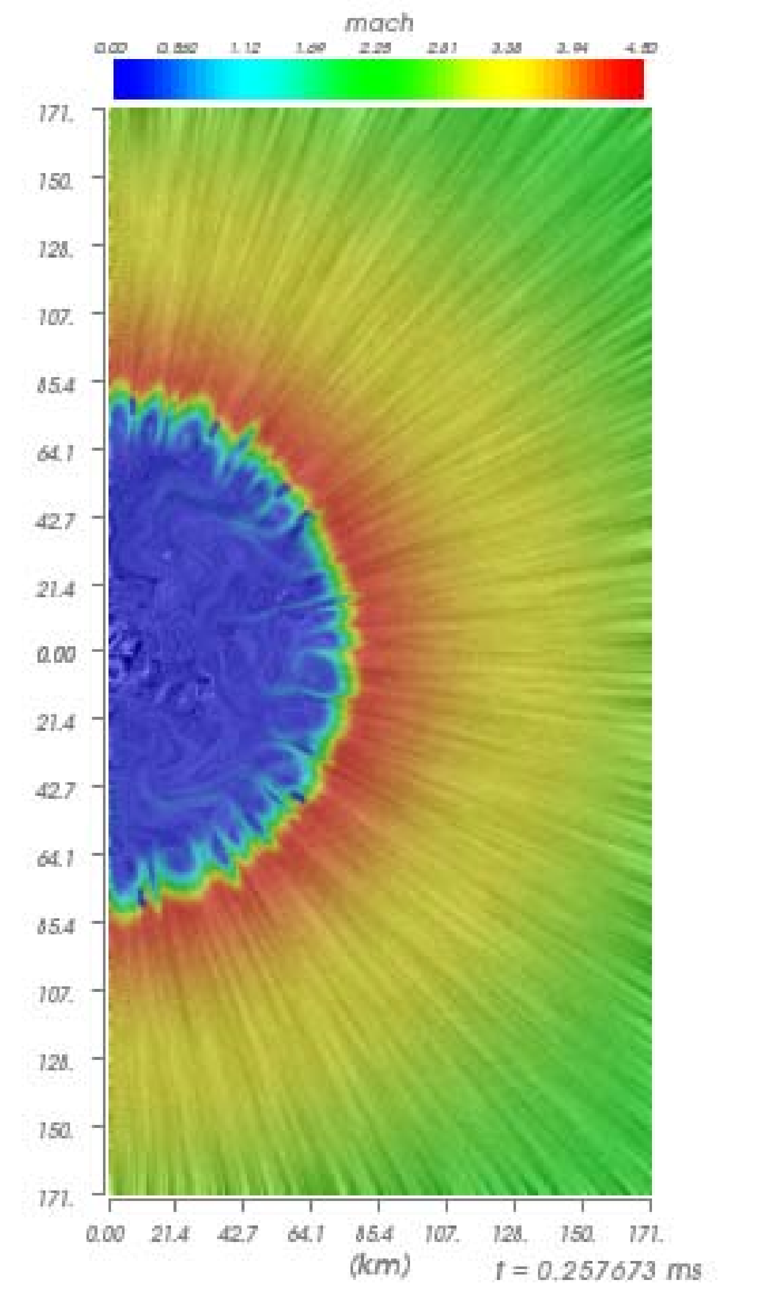
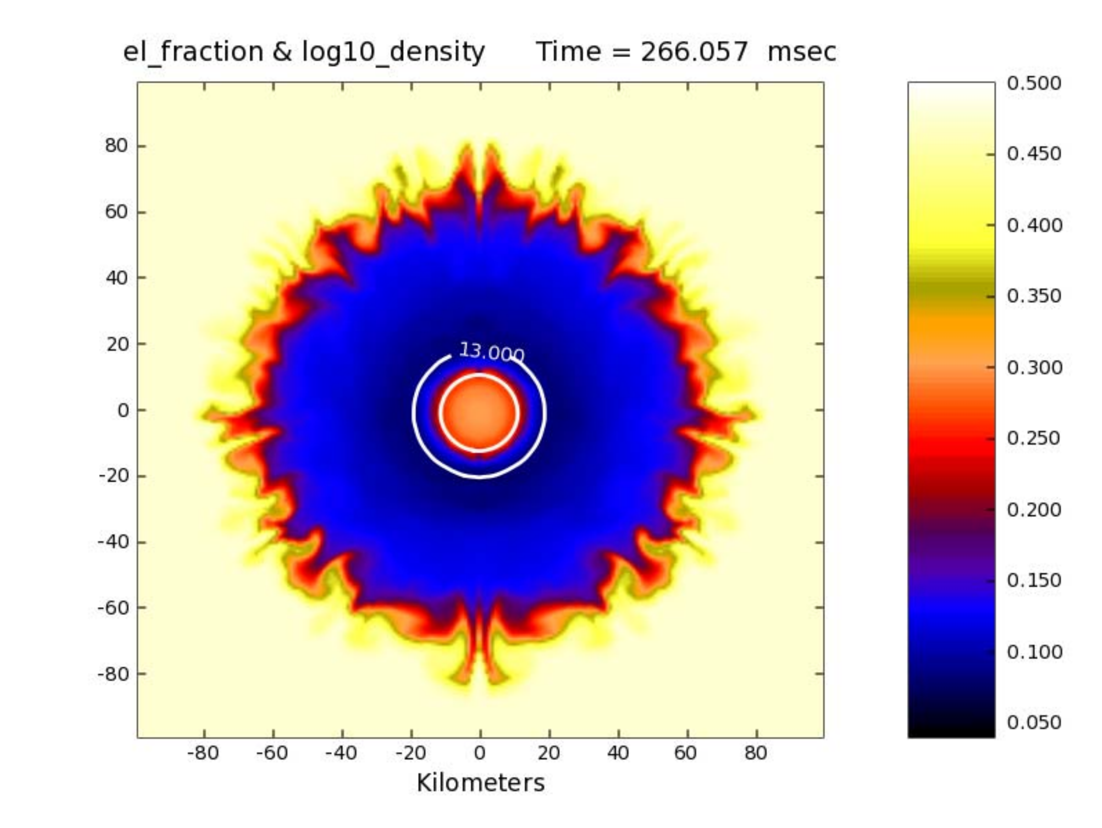
Behavior of Baseline Model

- ❑ Shock stagnates on timescales of 30 msec
- ❑ Shock is strong; flow into it @ Mach 4
- ❑ Shock initially shows large scale SASI mode which dies out & shock circularizes
- ❑ Could this reinitialize at later times?
- ❑ We see convection in both:
  - ❑ The proto-neutron star (in optically thick regions below the neutrinosphere)
  - ❑ Between stalled shock & neutrinosphere
- ❑ Vigorous Proto-Neutron Star convection is entropy driven and is short-lived
- ❑ Convection above the neutrinosphere maintains and is fueled by neutrino heating of base of the layer



Behavior of Ye in Optically Translucent Regions

- Convections maintains Ye (electron fraction) at a much higher level in regions around neutrinosphere
  - Convection cycles in high Ye (electron fraction) fuel into rapid deleptonization region
  - 1-D calcs show Ye down at 0.05 within 5-10 msec.
- Very few heavy nuclei below the shock
  - Little effect on opacity



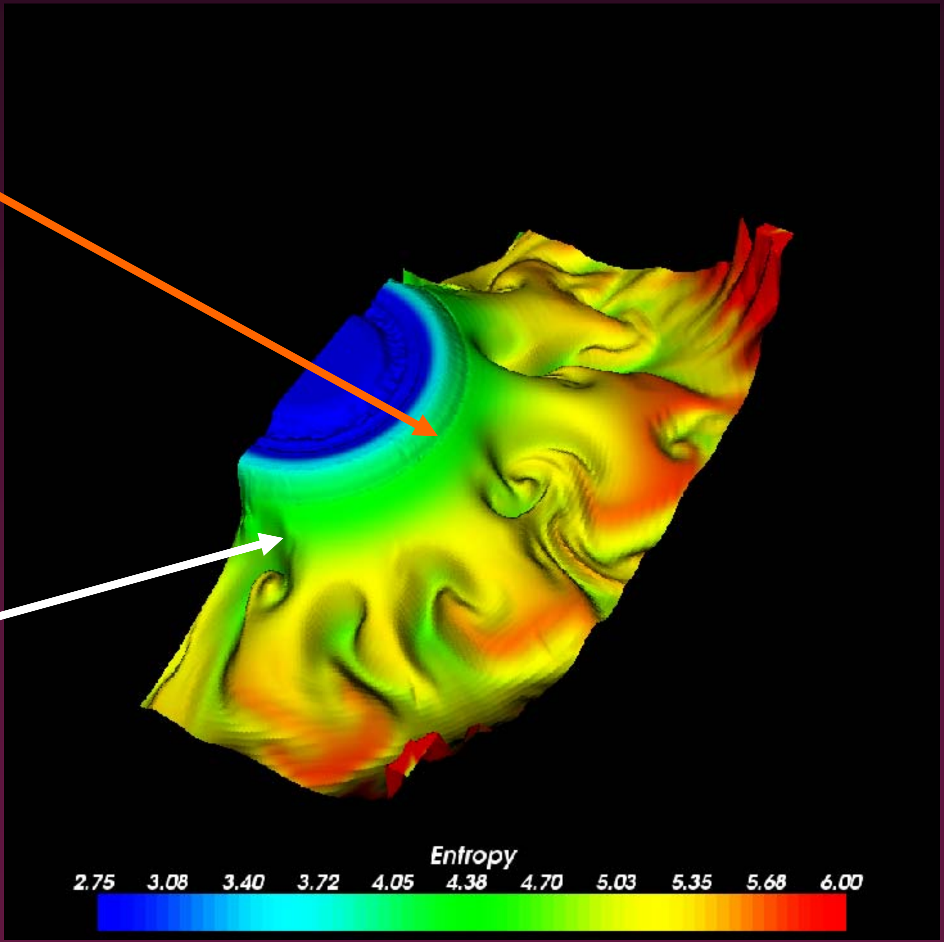
Proto-neutron star (PNS) convection

Vigorous convection takes place in regions where both the electron fraction and entropy have steep gradients

Colormap depicts entropy while height Illustrates electron fraction

The convection we see at the surface of the neutron star seems to be entropy driven. Further analysis is underway

The vigorous convective zone seems to end end at the neutron star surface. But…



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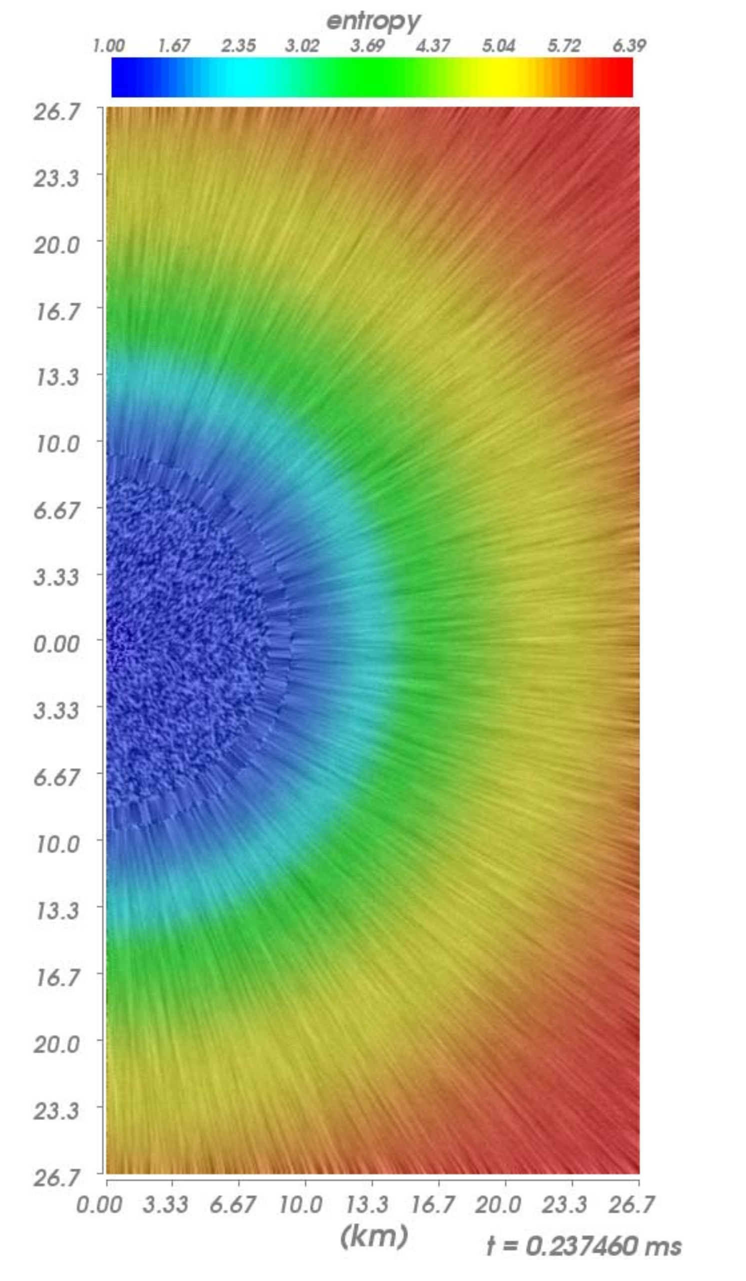

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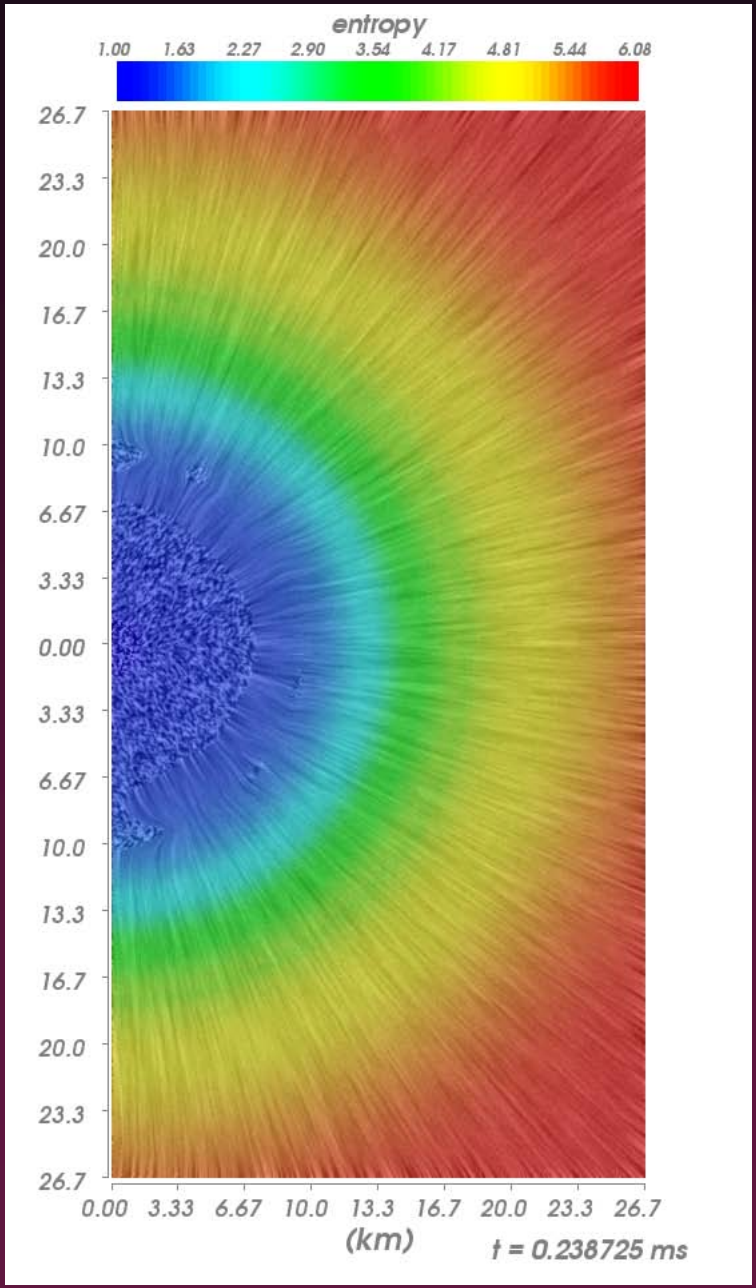

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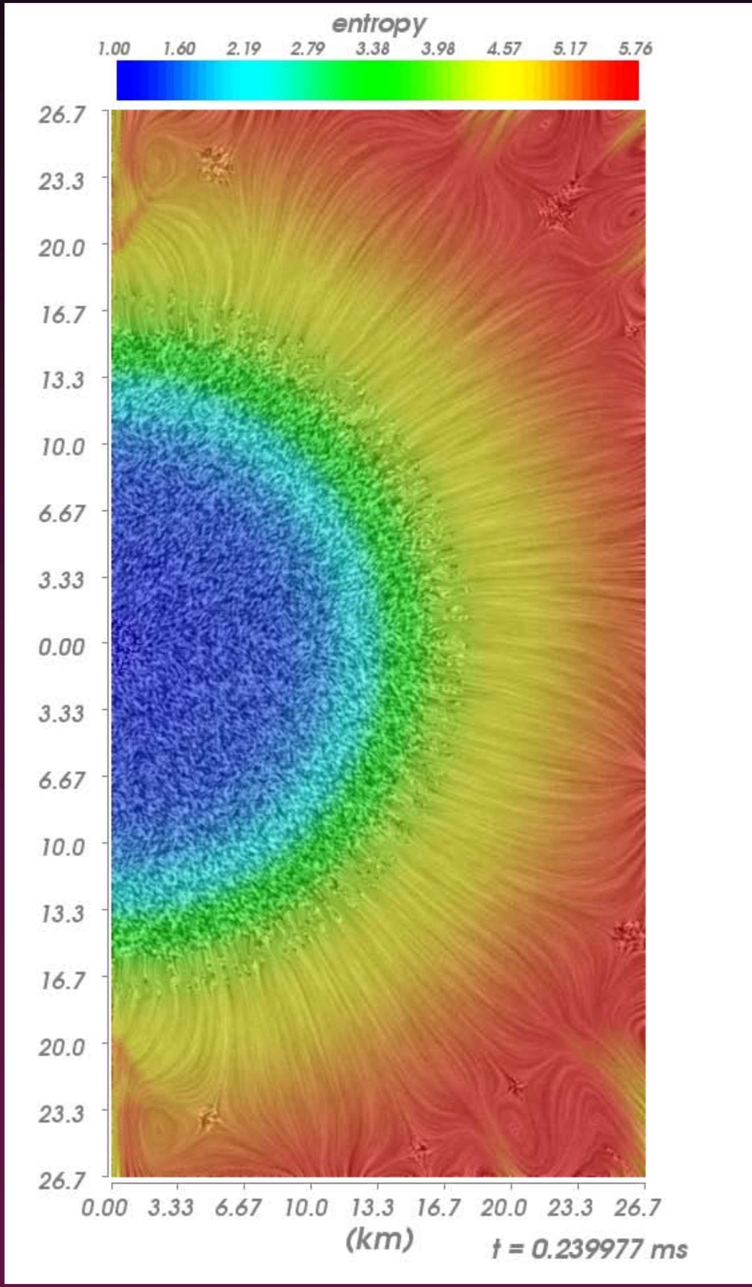

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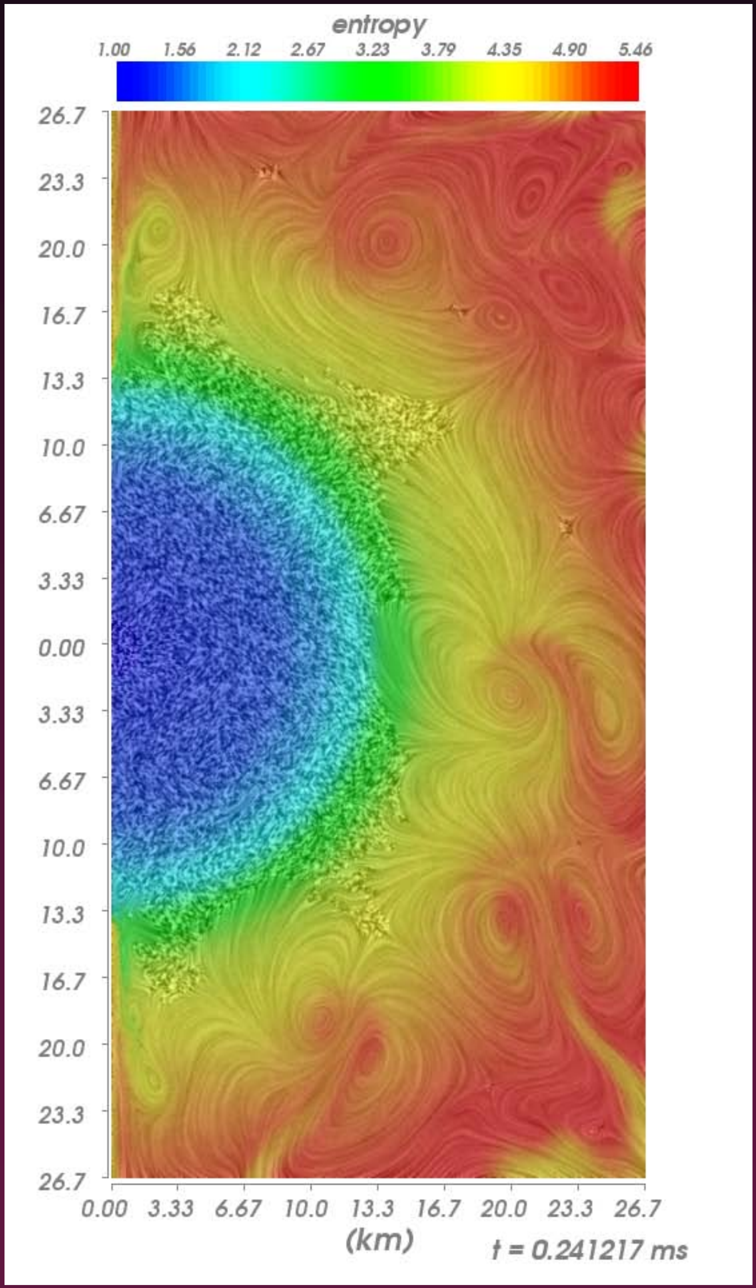

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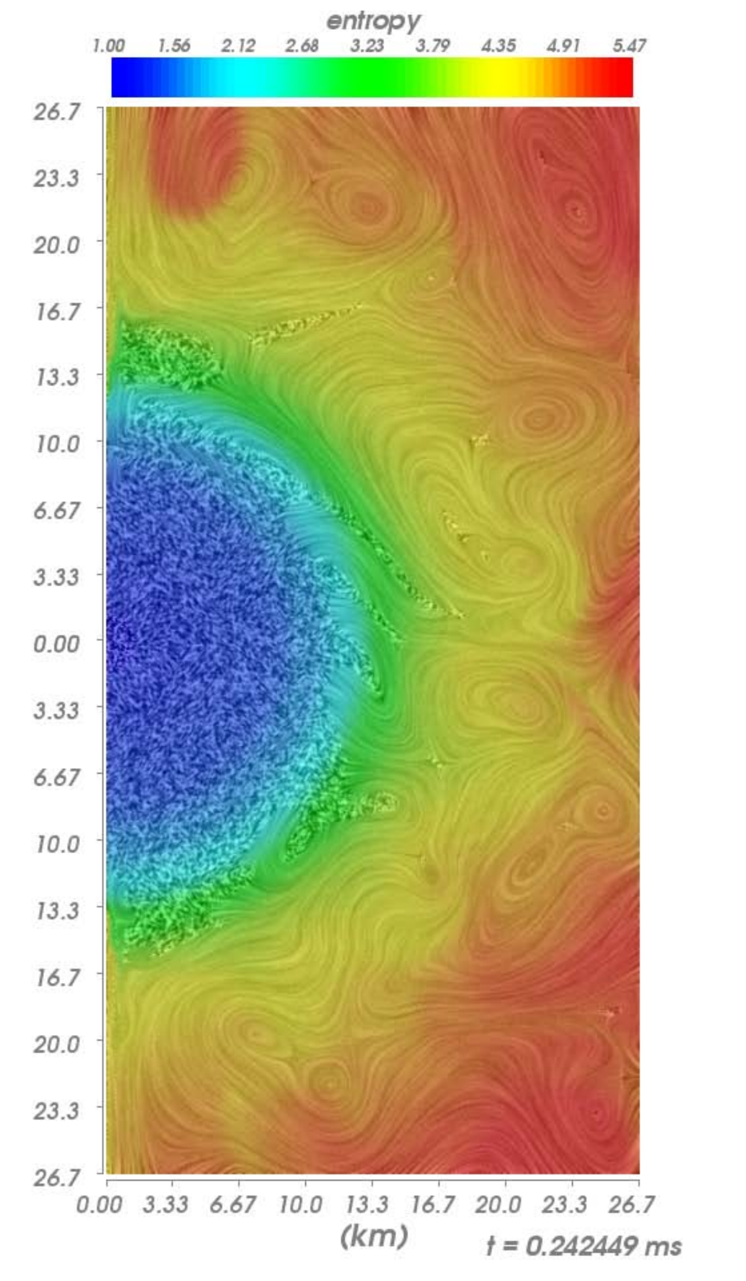

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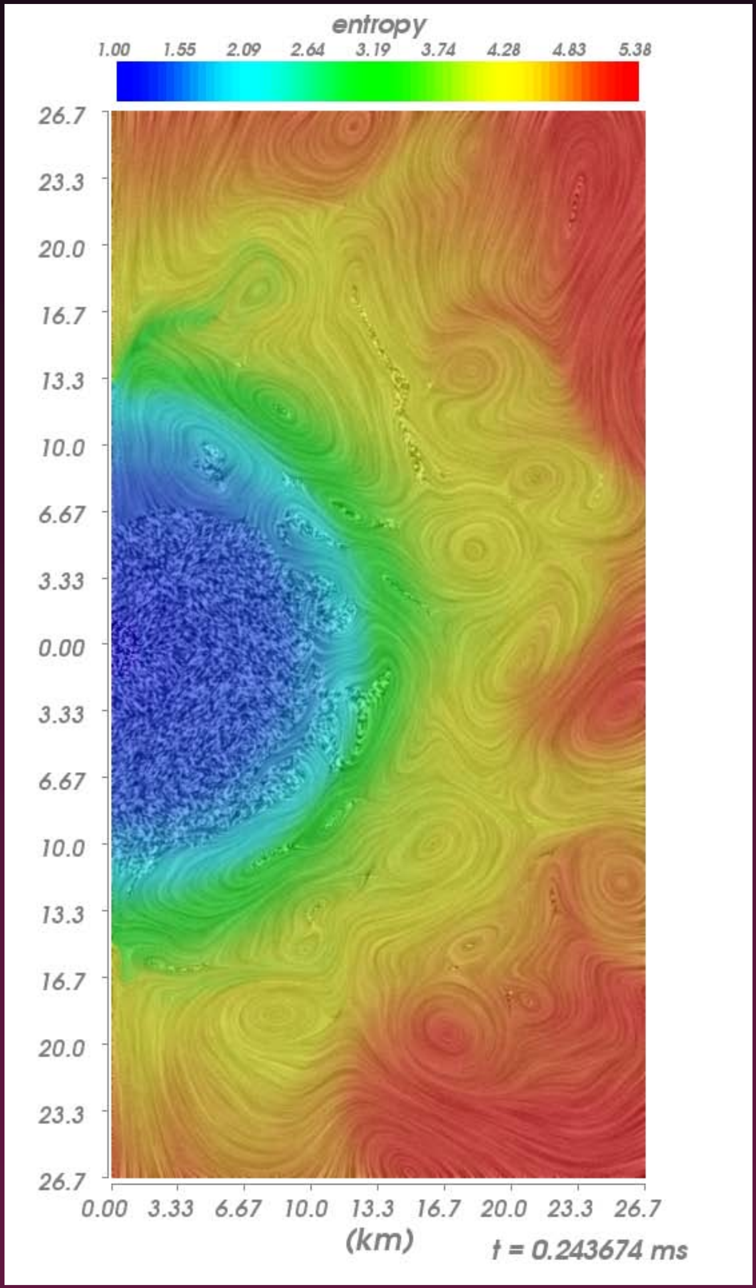

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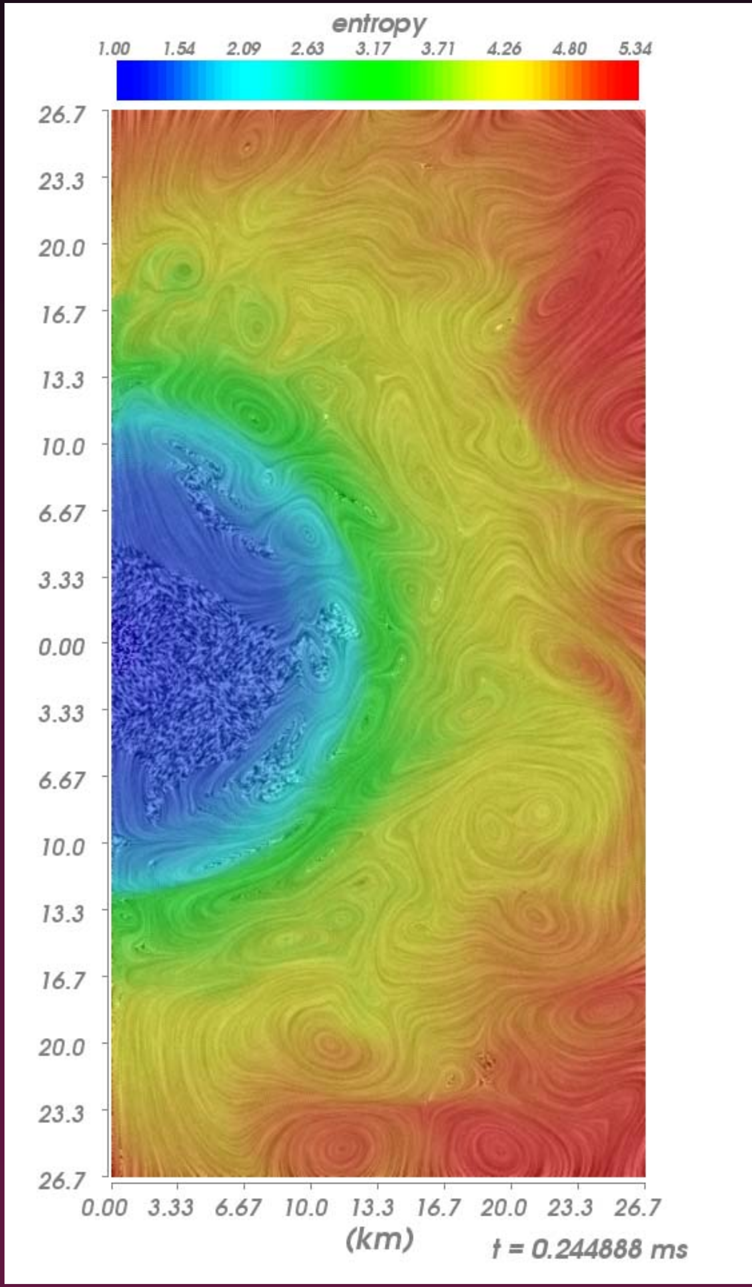

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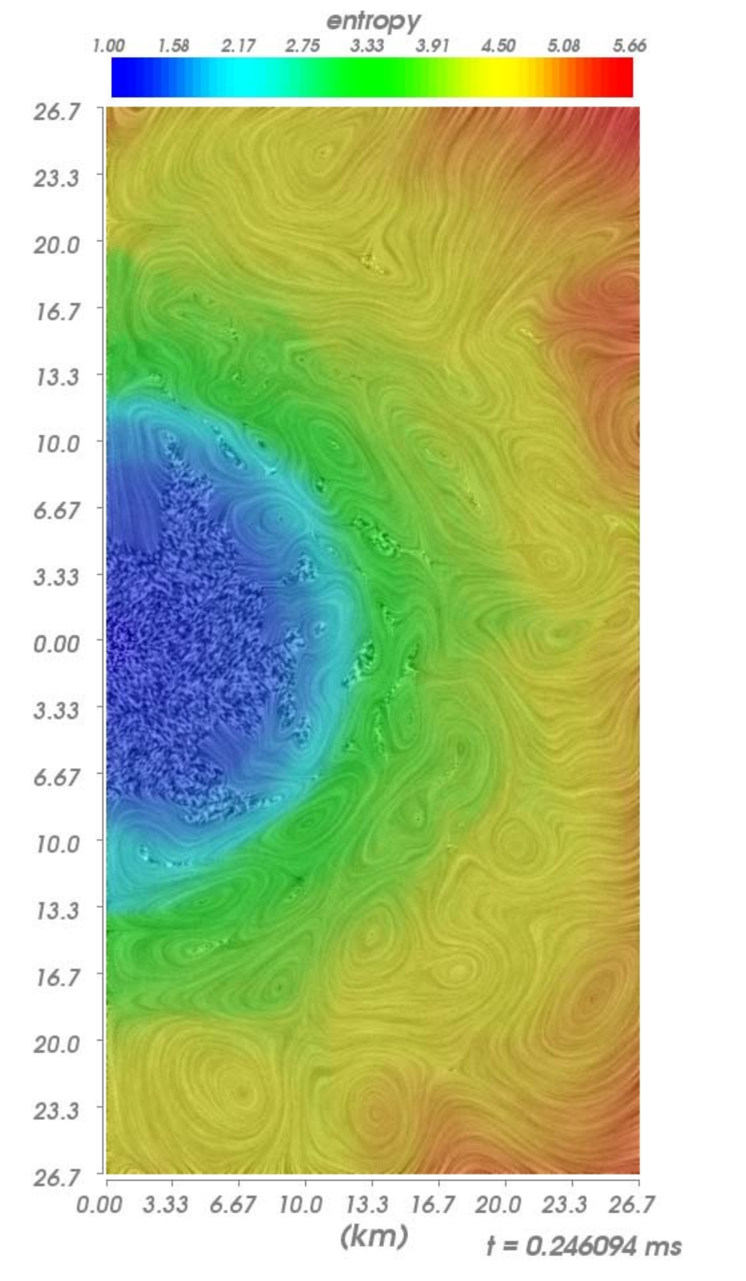

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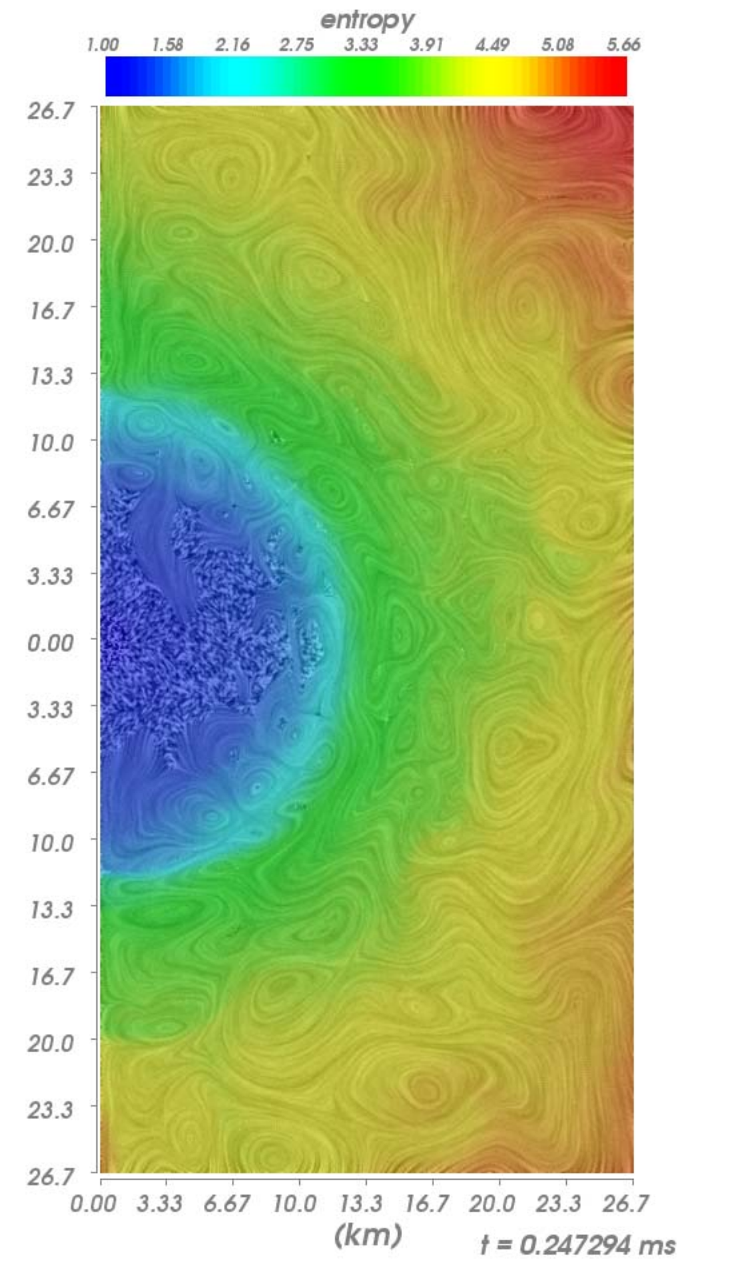

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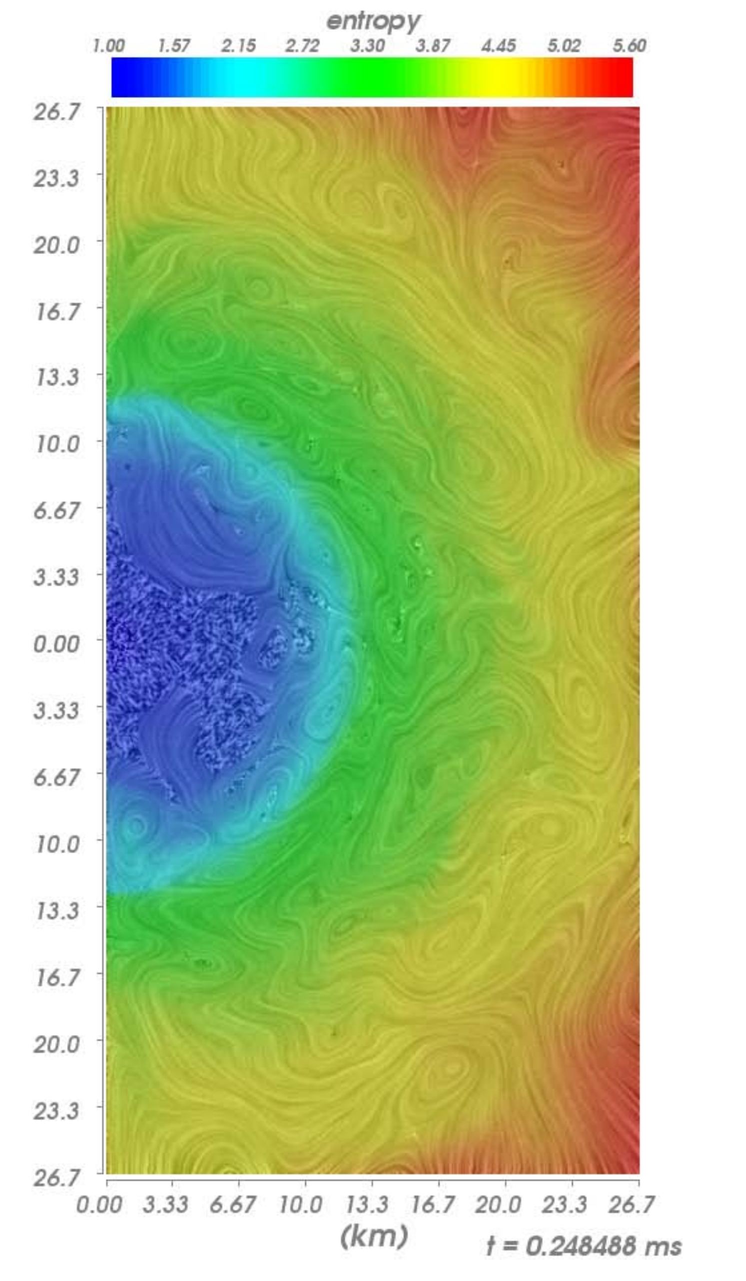

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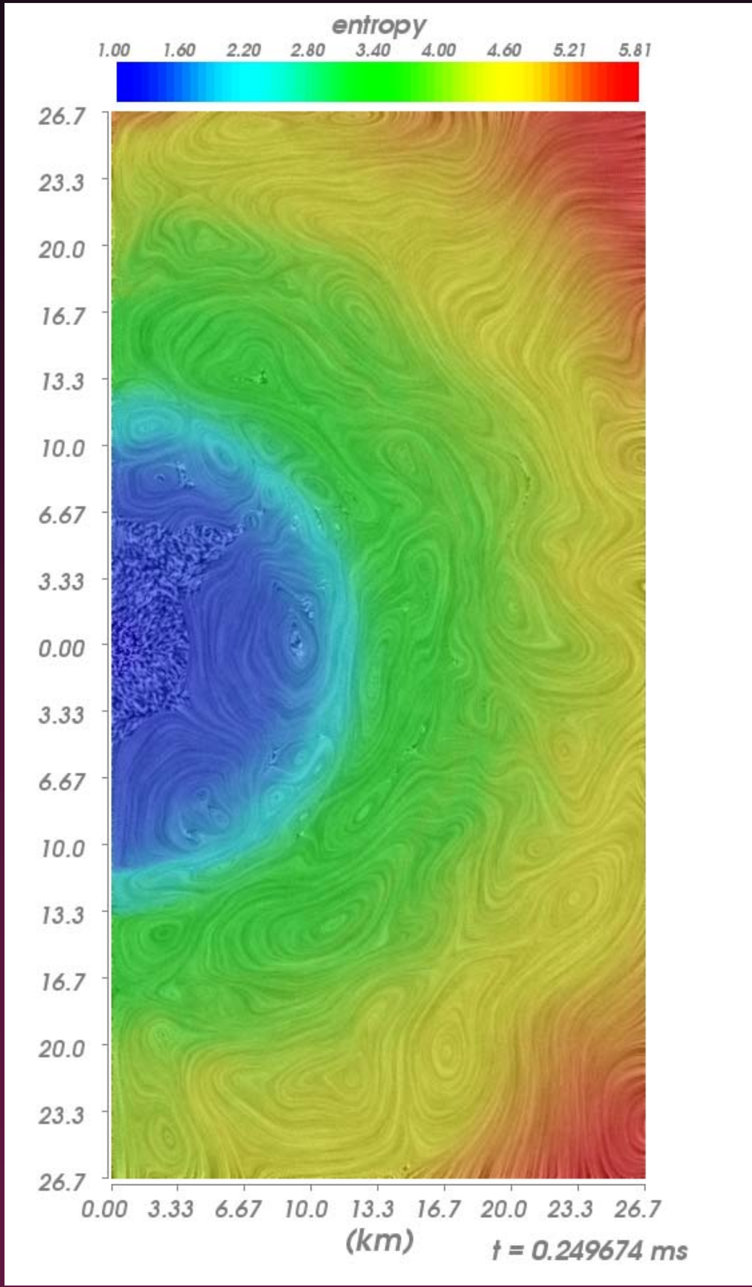

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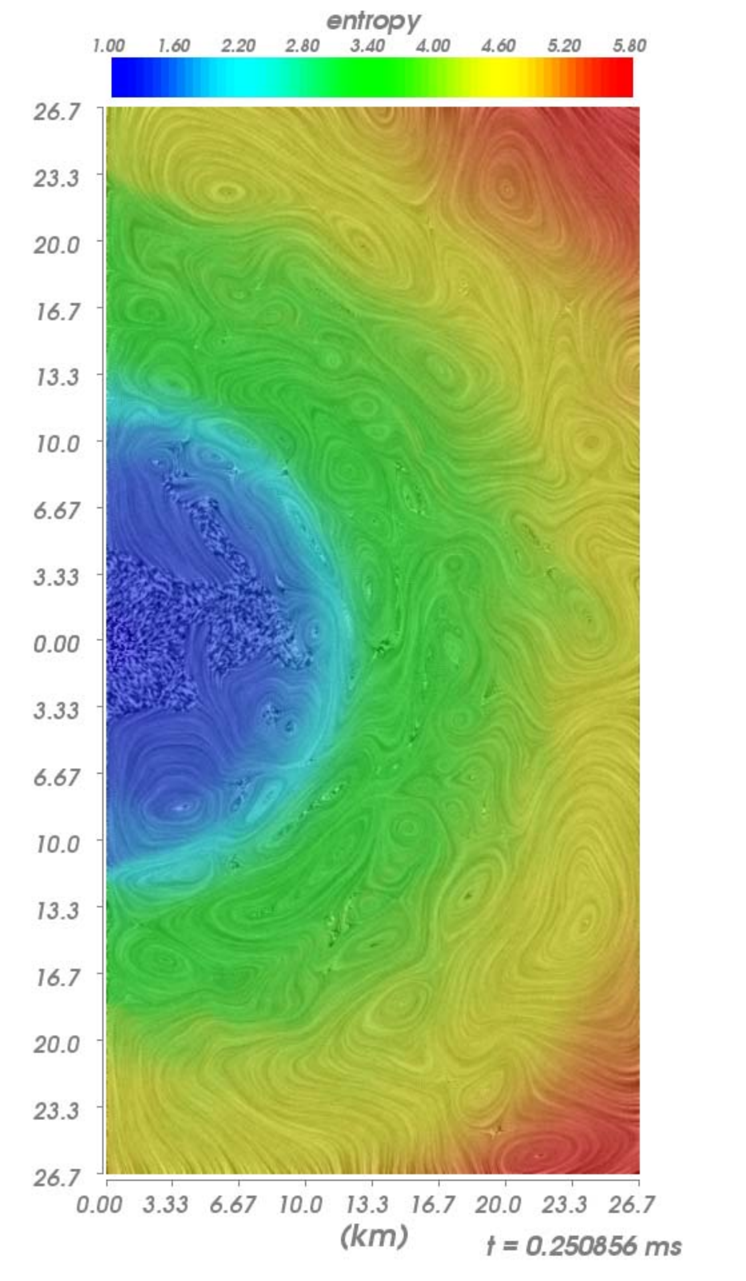

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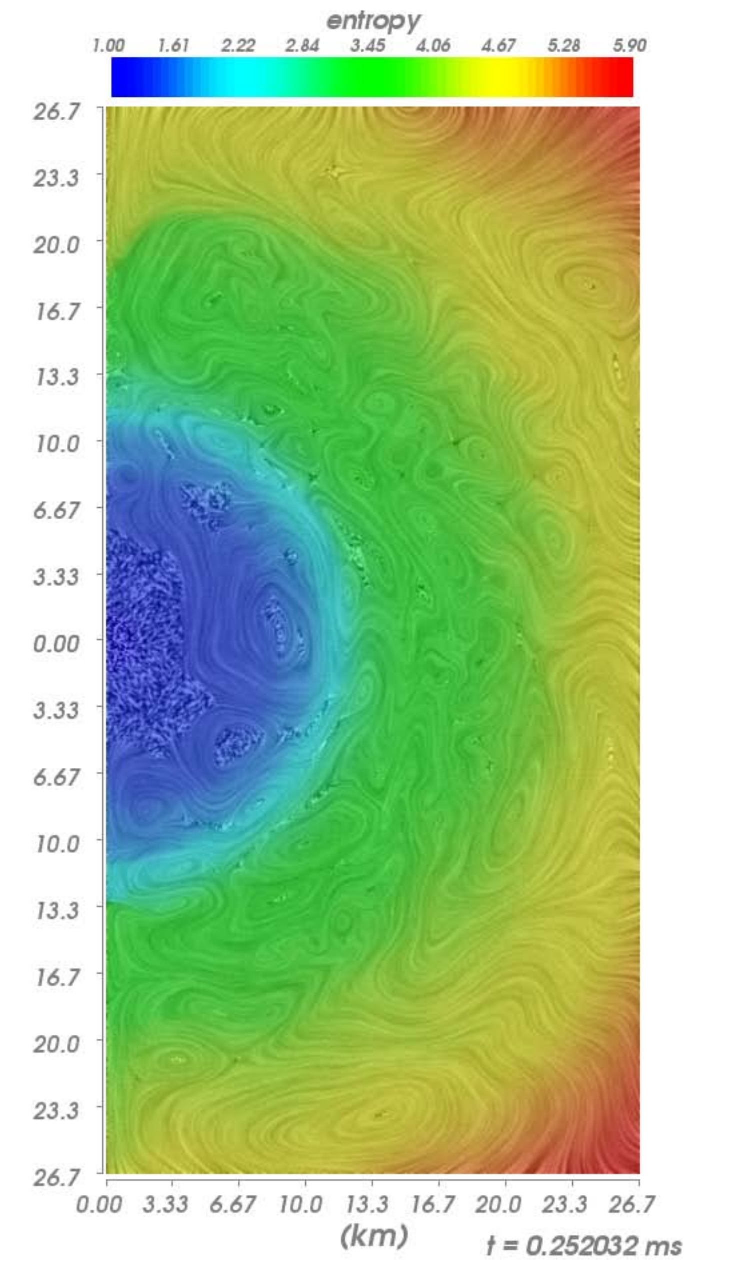

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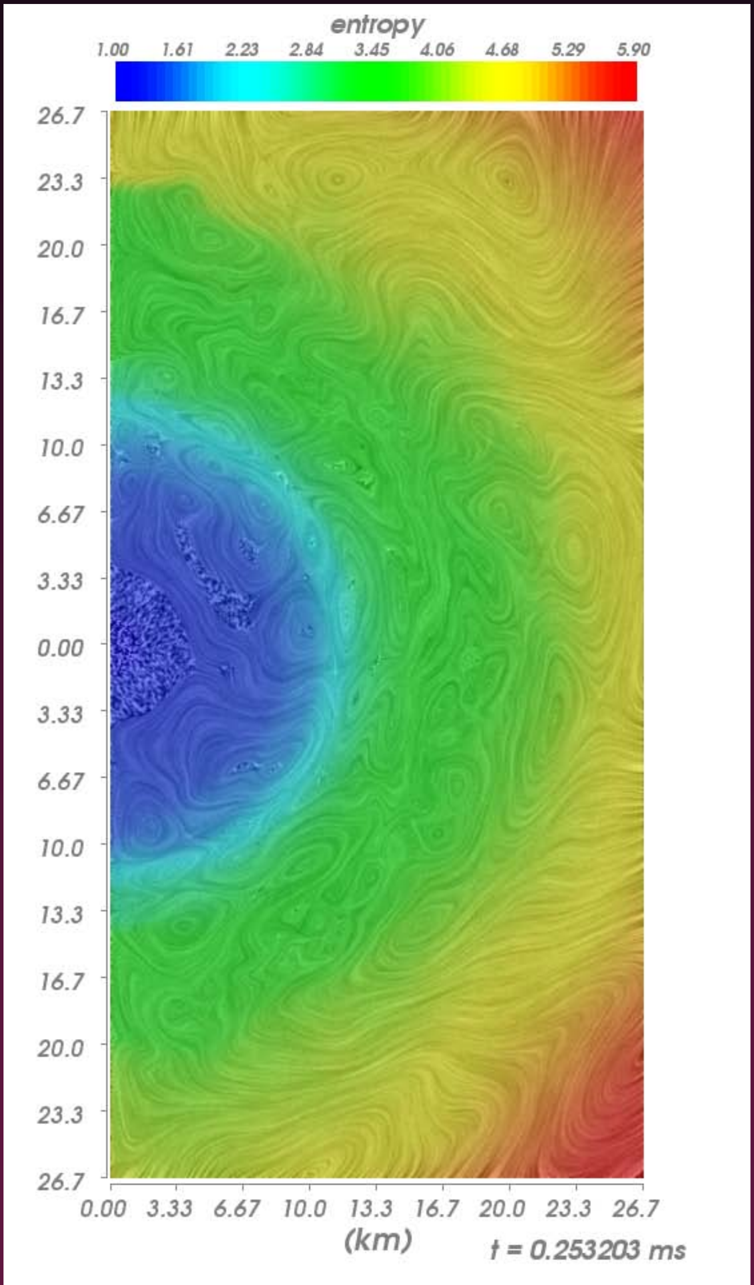

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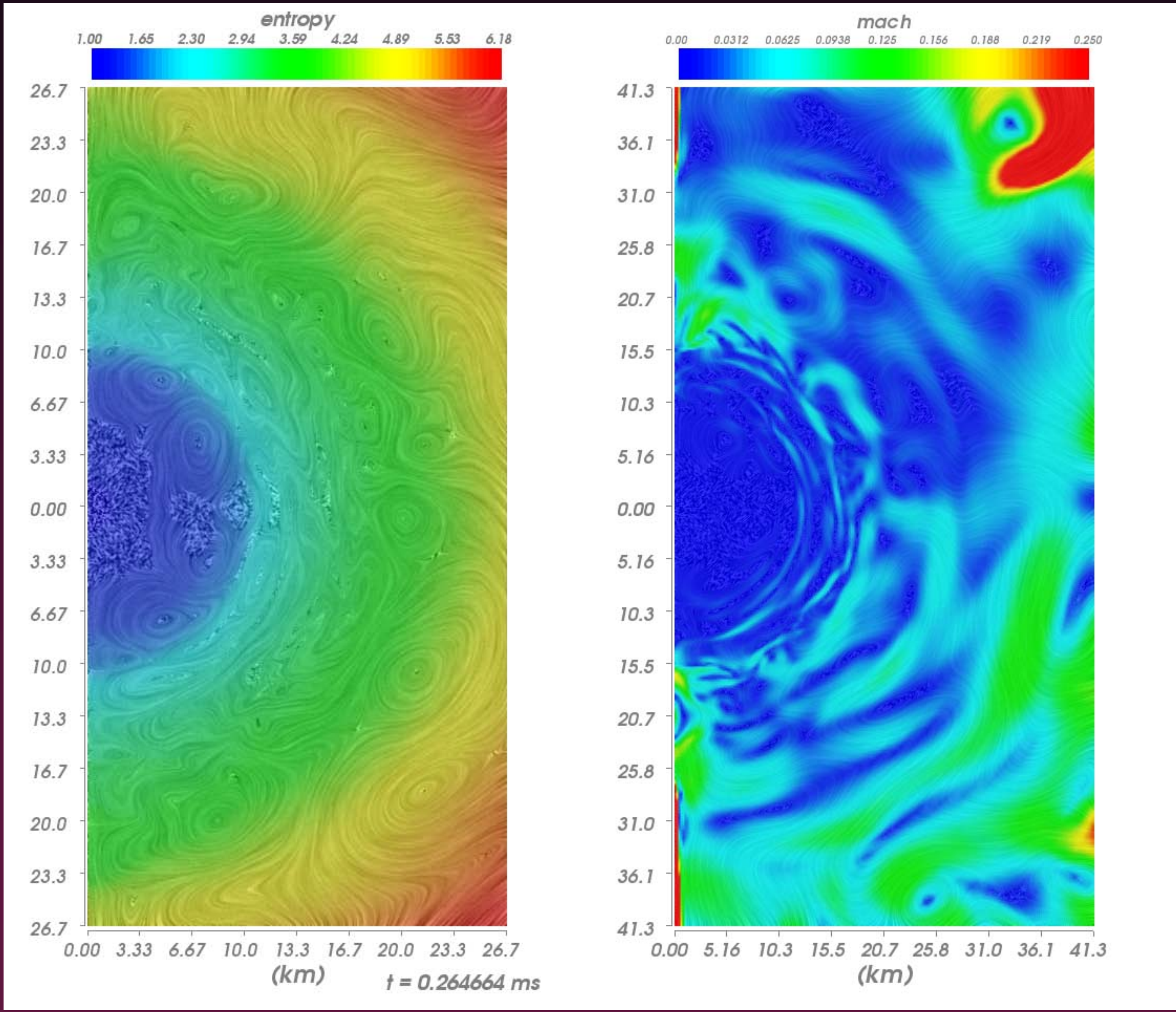


O(v/c) Multigroup Neutrino Energy Transport

One pair of neutrino/anti-neutrino energy eqns. for each of three neutrino flavors: e, μ,

$$\left\{ \begin{aligned} &\frac{\partial E_\epsilon}{\partial t} + \nabla \cdot (E_\epsilon \mathbf{v}) + \nabla \cdot \mathbf{F}_\epsilon - \epsilon \frac{\partial}{\partial \epsilon}(\mathsf{P}_\epsilon) : \nabla \mathbf{v} = \mathcal{S}_\epsilon \\ &\frac{\partial \bar{E}_\epsilon}{\partial t} + \nabla \cdot (\bar{E}_\epsilon \mathbf{v}) + \nabla \cdot \bar{\mathbf{F}}_\epsilon - \epsilon \frac{\partial}{\partial \epsilon}\left(\bar{\mathsf{P}}_\epsilon\right) : \nabla \mathbf{v} = \bar{\mathcal{S}}_\epsilon \end{aligned} \right.$$

$$\text{Energy density} = E_\epsilon \equiv \frac{1}{c}\int I_\epsilon d\Omega \qquad \text{Pressure tensor} = \mathsf{P}_\epsilon \equiv \frac{1}{c}\int I_\epsilon \Omega^2 d\Omega$$

$$\text{Flux} = \mathbf{F}_\epsilon \equiv \int I_\epsilon \Omega d\Omega$$

Flux-Limited Diffusion (FLD) Approximation

Diffusion coefficient

$$\mathbf{F}_\epsilon = -D_\epsilon \nabla E_\epsilon \qquad \bar{\mathbf{F}}_\epsilon = -\bar{D}_\epsilon \nabla \bar{E}_\epsilon$$

$$\mathsf{P}_\epsilon = \chi_\epsilon E_\epsilon \qquad \bar{\mathsf{P}}_\epsilon = \bar{\chi}_\epsilon \bar{E}_\epsilon$$

Tensor Eddington factor

Optically thin limit

$$D_\epsilon \rightarrow \frac{-cE_\epsilon}{|\nabla E_\epsilon|}$$

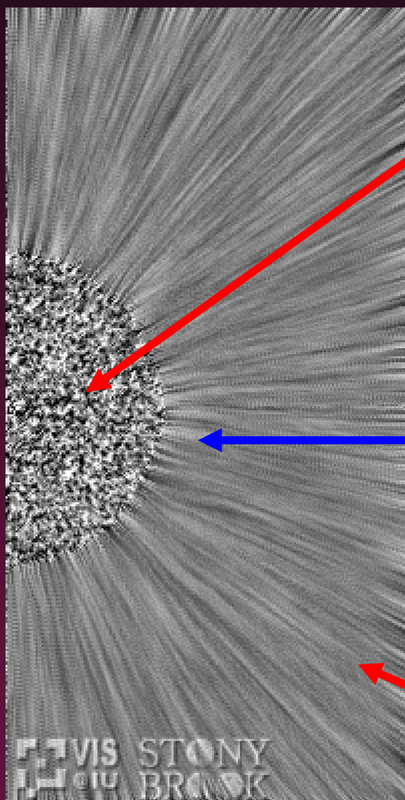
$$\chi_\epsilon \rightarrow 1$$

Optically thick limit

$$D_\epsilon \rightarrow \frac{c}{3\kappa_\epsilon}$$

$$\chi_\epsilon \rightarrow \frac{1}{3}$$

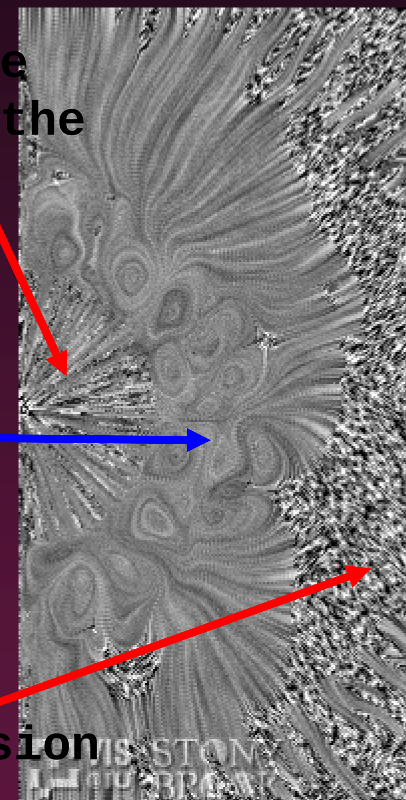
Dynamic diffusion (via advective flux) plays an important role in getting neutrinos out of the proto-neutron star core. Dynamic diffusion has thus far been neglected in other 2-D & 3-D supernova simulations.



Diffusive region where dynamic diffusion is the dominant effect

Optically translucent region where radiative & dynamic diffusion compete

Free-streaming region where radiative diffusion dominates



ε_ν = 1.5 MeV

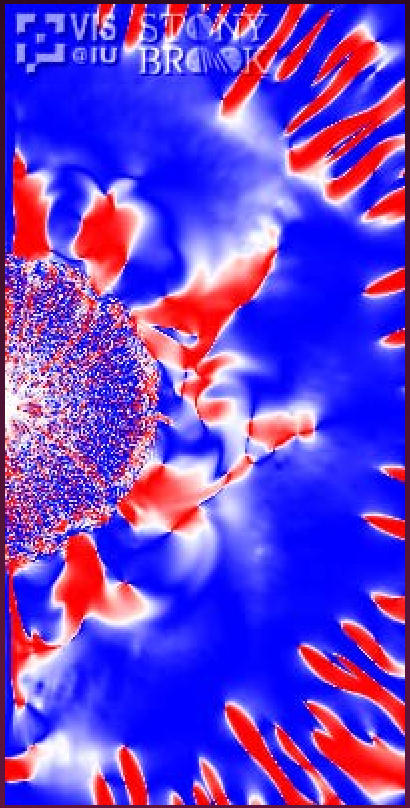
Radiative flux

$$\mathbf{F}_\epsilon = -D_\epsilon \nabla E_\epsilon$$

Advective flux

$$\mathbf{F}_\epsilon = \mathbf{v} E_\epsilon$$

Radiative & Advective Fluxes behave differently at different neutrino energies. Advective flux does not depend on opacity (which is a function of energy) while radiative flux is strongly opacity dependent.



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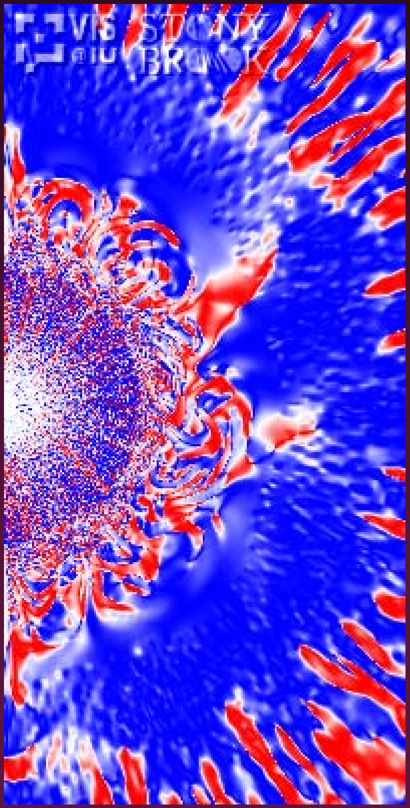
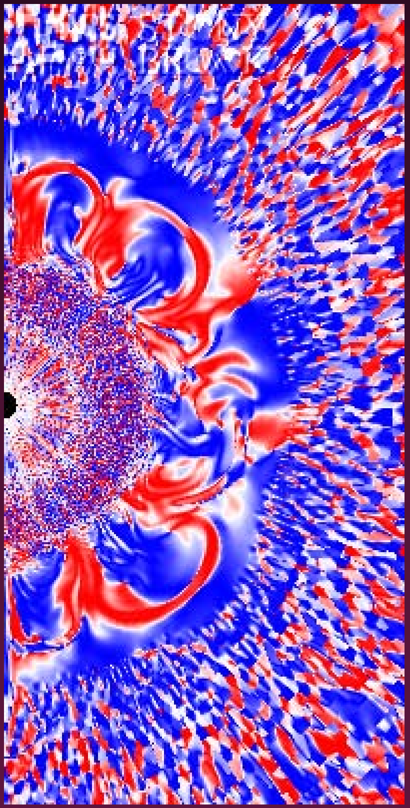


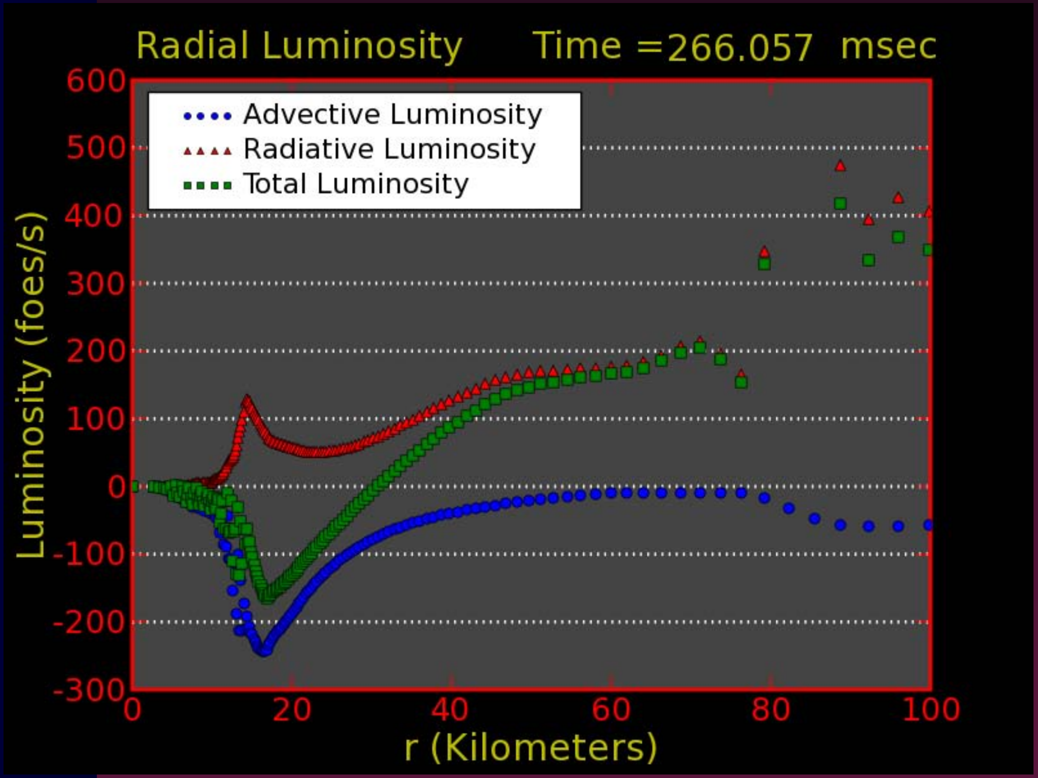
ϵ_ν = 18 MeV



ϵ_ν = 380 MeV

Radial luminosity & convection

- ❑ Convection at the PNS surface gives rise to a fast burst of deleptonization
- ❑ This instability is initiated and driven by an unstable entropy gradient around neutrinosphere
- ❑ Higher Ye (~0.3) material gets advected upward allowing it to deleptonize around neutrinosphere
- ❑ PNS surface convection enhances neutrino luminosity in a burst but does not maintain this enhancement
- ❑ Dynamic diffusion term r¢(E_ε v) (which has always been neglected) is the leading order term of neutrino transport equation inside of 30 Km!



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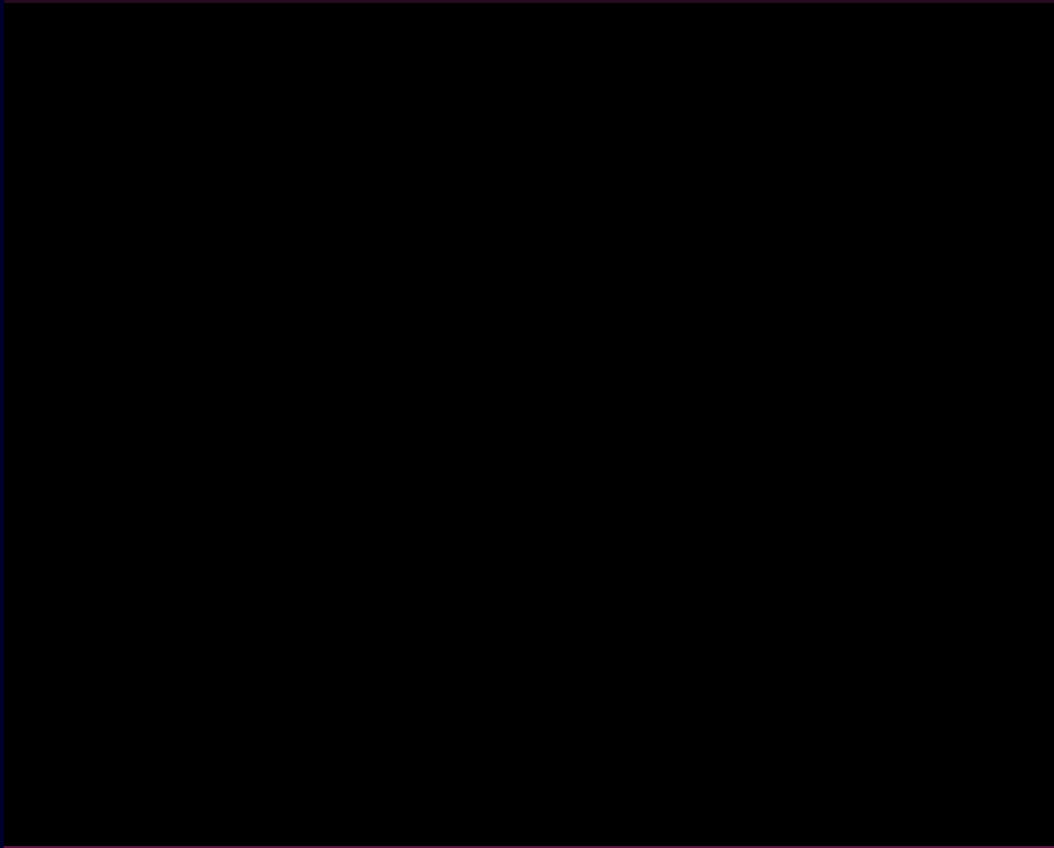

The Future

- We now have a computational laboratory to explore effects on nuclear and particle physics in convective epoch of supernovae
  - Currently starting to look at effects of nuclear force parameters such as the nuclea symmetry energy, nuclear specific heat & effective masses
  - Effects of neutrino electron scattering and other neutrino physics
    - NES models are coming very soon!
  - Will be looking at neutrino flavor mixing
  - Other progenitor models
- Will be extending simulations to later times
  - Can the SASI occur in baseline model at later times?
- Fully implicit hydro is in development and testing
  - Will allow us to solve technical limitations in looking at PNS convection
  - Will enable us to calculate neutrino signal
- Fully implicit radiation-hydro
  - Eliminate operator splitting and allow higher-order time integration
- 3-D Models with AMR
  - Accurately characterize convection
  - Will be able to deal with rotation
  - Additional goal: estimate gravitational wave signal

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  - Jim Lattimer (Stony Brook)
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  - Dan Reynolds, Carol Woodward (LLNL)
- SDM ISIC Team members:
  - Terrence Critchlow, Xiaowen Xin (LLNL)
- LBONE/LORS SAPP Team members:
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- CCA ISIC Team Members:
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- NERSC Staff:
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The Stony Brook TSI web site:
http://nuclear.astro.sunysb.edu