Supernovae: Elements of Theory, Computations, Experiments

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Lecture 3

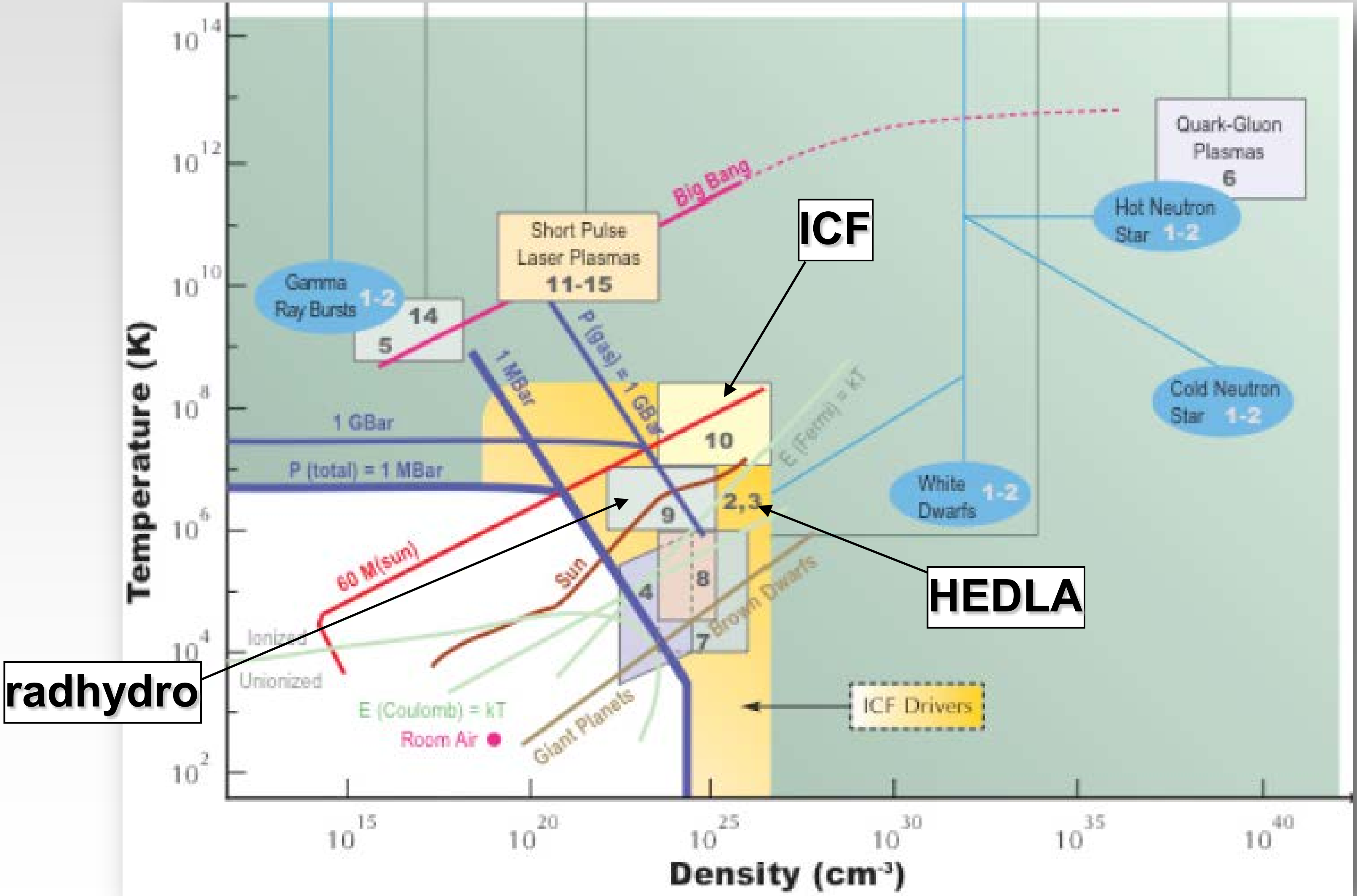
High-Energy Density Supernova Experiments

Recap

- Thanks to Lecture 1, we now are excited about coming back to our offices to verify and validate our codes
- Thanks to Lecture 2, we now appreciate the level of physical complexity of exploding stars that computer simulations are to capture
- Clearly, we would be much better off if supernova conditions and physics was reproduced in controlled laboratory settings
- Plus that offers opportunities for conducting code validation

HED Laboratory Astrophysics

- **High Energy Density**: pressure > 1 Mbar (100 Mbar in IFC), energies > 10^{11} J/m^3 or > 10^{12} erg/cm^3, temperatures > 5x10^6 K or > 400 eV



Davidson et al. (2004)

High-Energy Density Laboratory Astrophysics

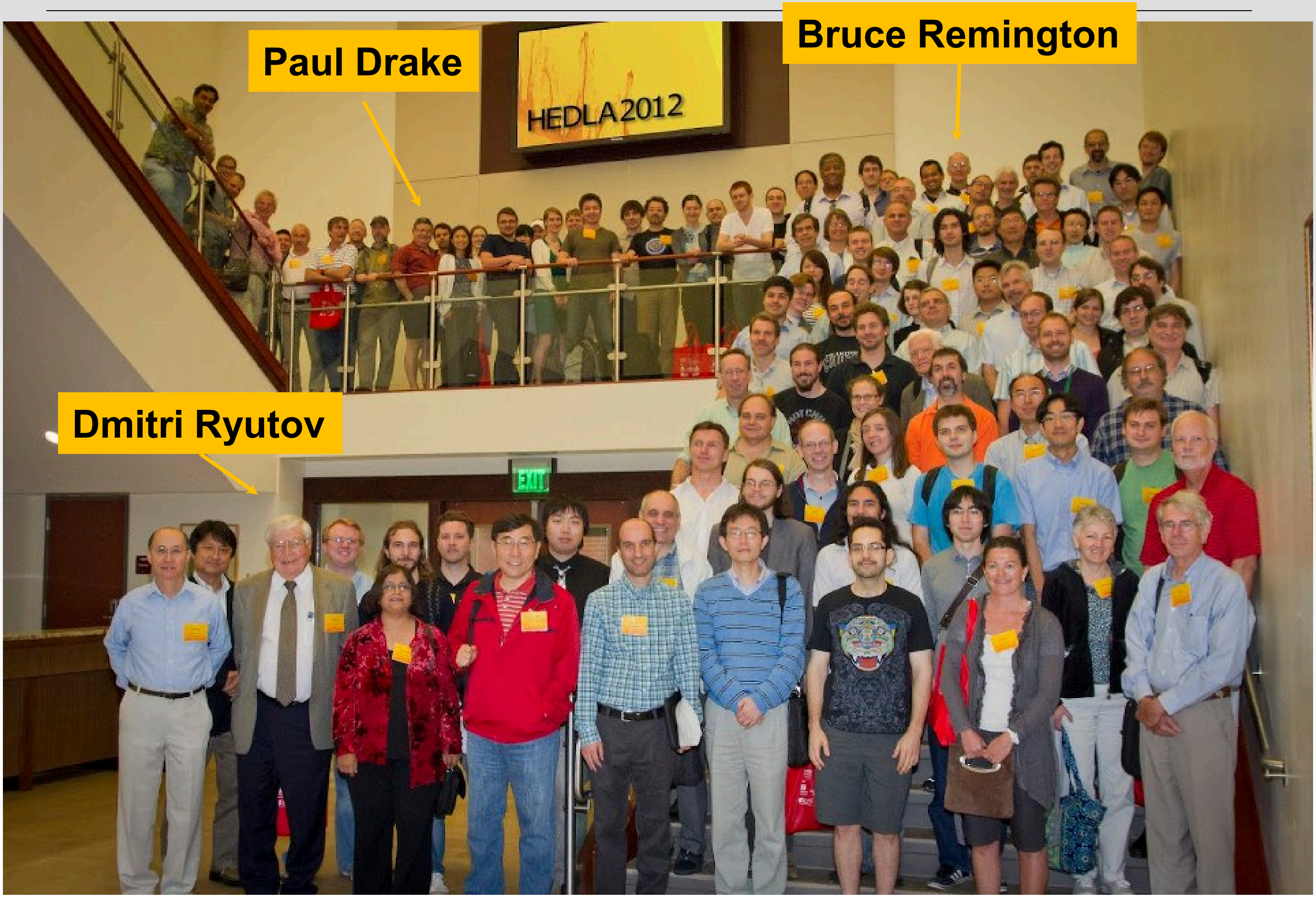
Ablation	nebulae, molecular clouds
Equation of state	planetary interiors
Jets	protostars, active galaxies
Magnetic dynamo	stellar physics, accretion disks
Magnetic reconnection	solar physics, ISM
Nuclear cross sections	stellar evolution, nova/SN/xrb/GRB/etc
Opacities	radiatively driven winds
Particle acceleration	solar physics, SN remnants
Plasma emission	interstellar medium, X-ray binaries
Radiative shocks	SN explosions/remnants, jets, ISM
RMI/RTI interface dynamics	supernovae, stellar interiors
Ultrastrong fields	pulsars, magnetars, GRBs…

HEDLA bi-annual conferences

Facebook, www.hedla.org

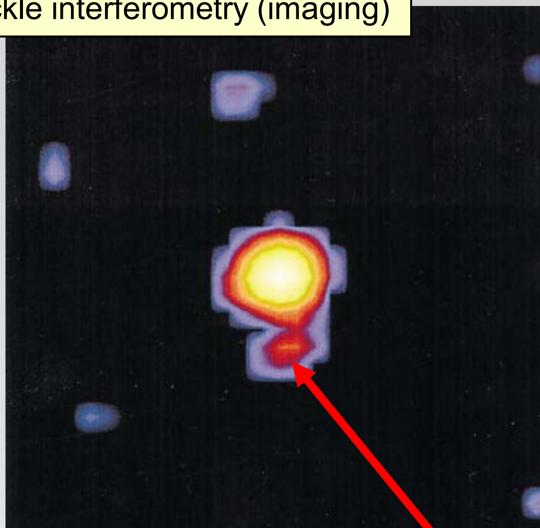
High-Energy Density Laboratory Astrophysics 2012

HEDLA Founding Fathers

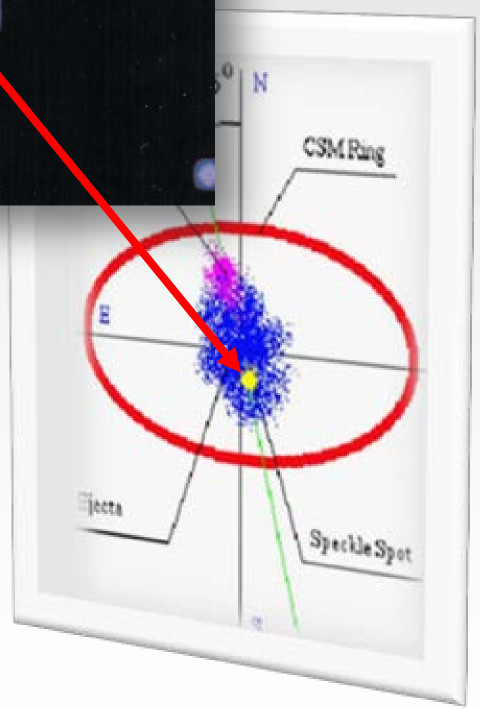


Back to Supernova Mixing

speckle interferometry (imaging)

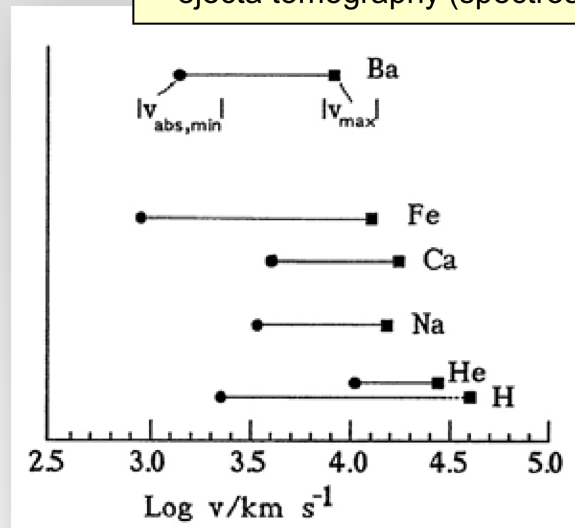


Niesenson & Papaliolios (1999)



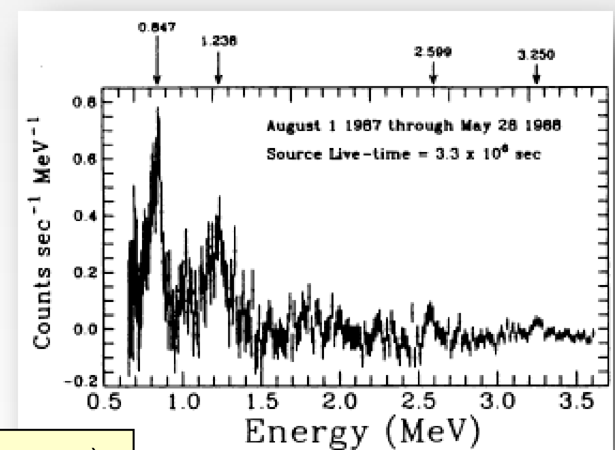
Wang et al. (2002)

ejecta tomography (spectroscopy)



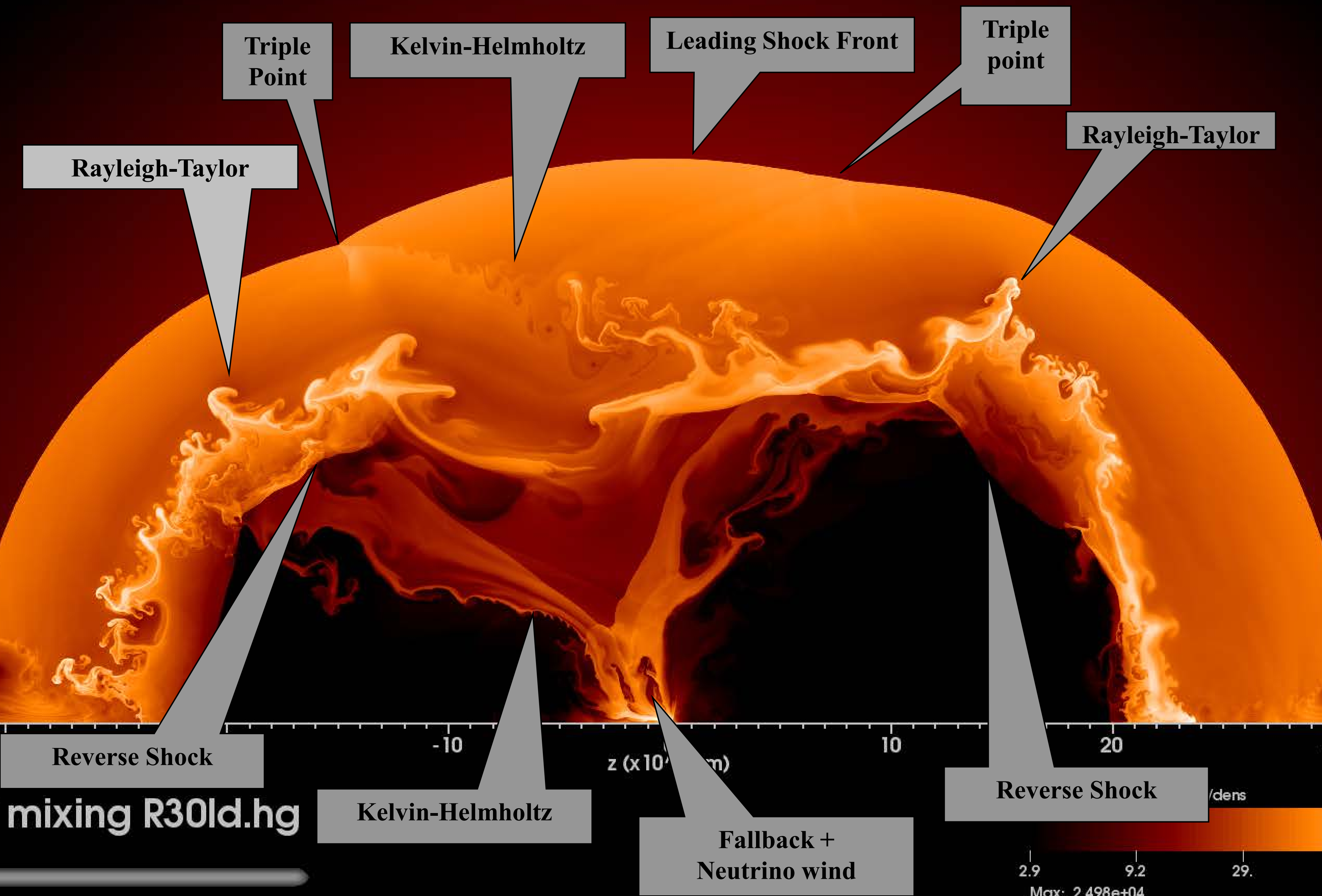
Hanuschik et al. (1991)

gamma rays (spectroscopy)



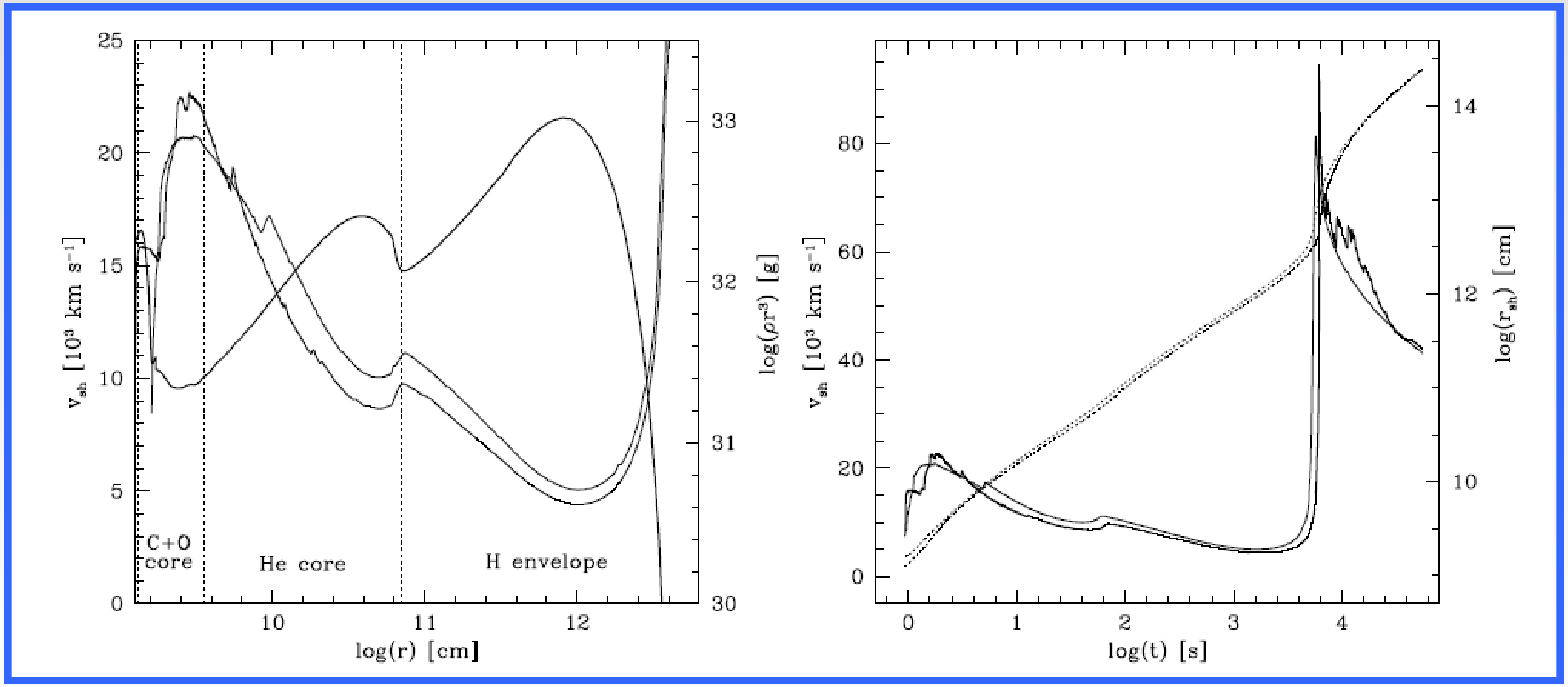
Leising & Share (1990)

(Infamous) richness of computational models



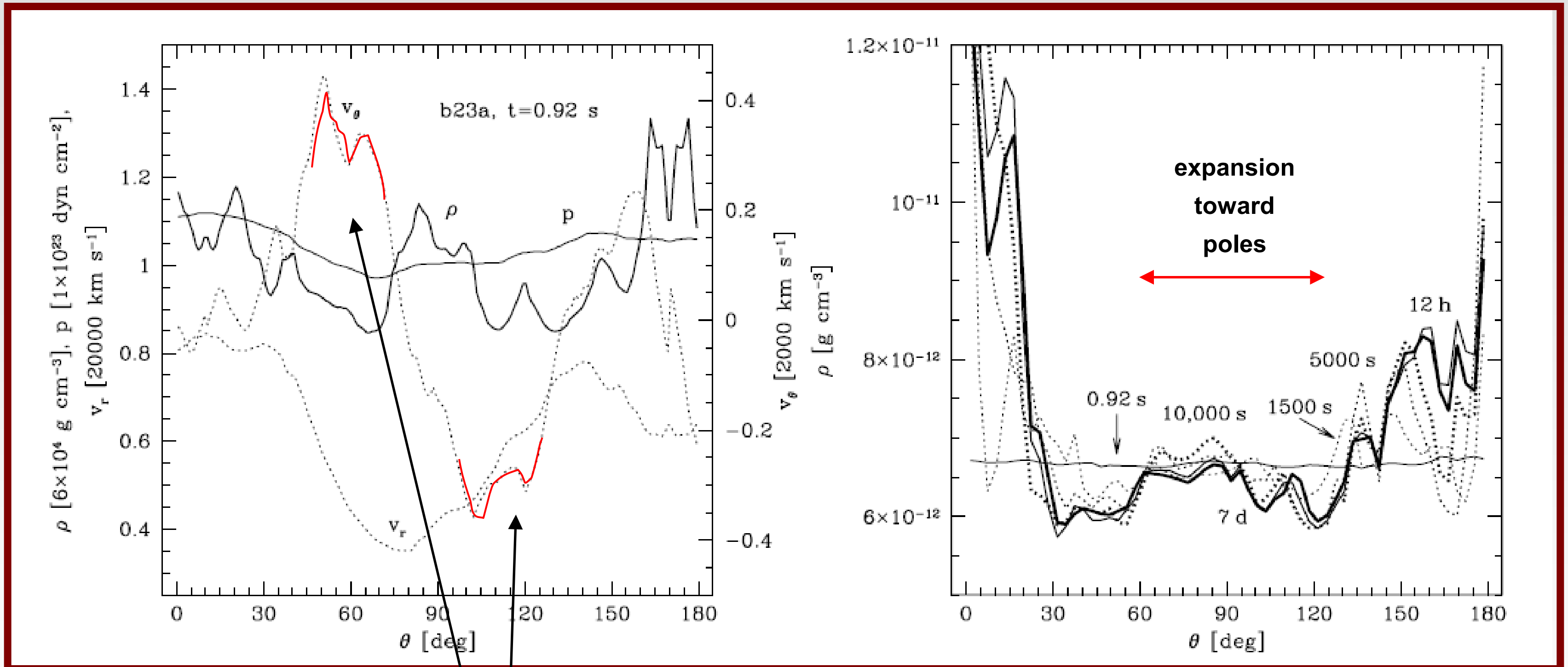
Mixing after the Shock Breakout (II)

- Time-dependent deceleration of dense layers due to unsteady supernova shock motion though the



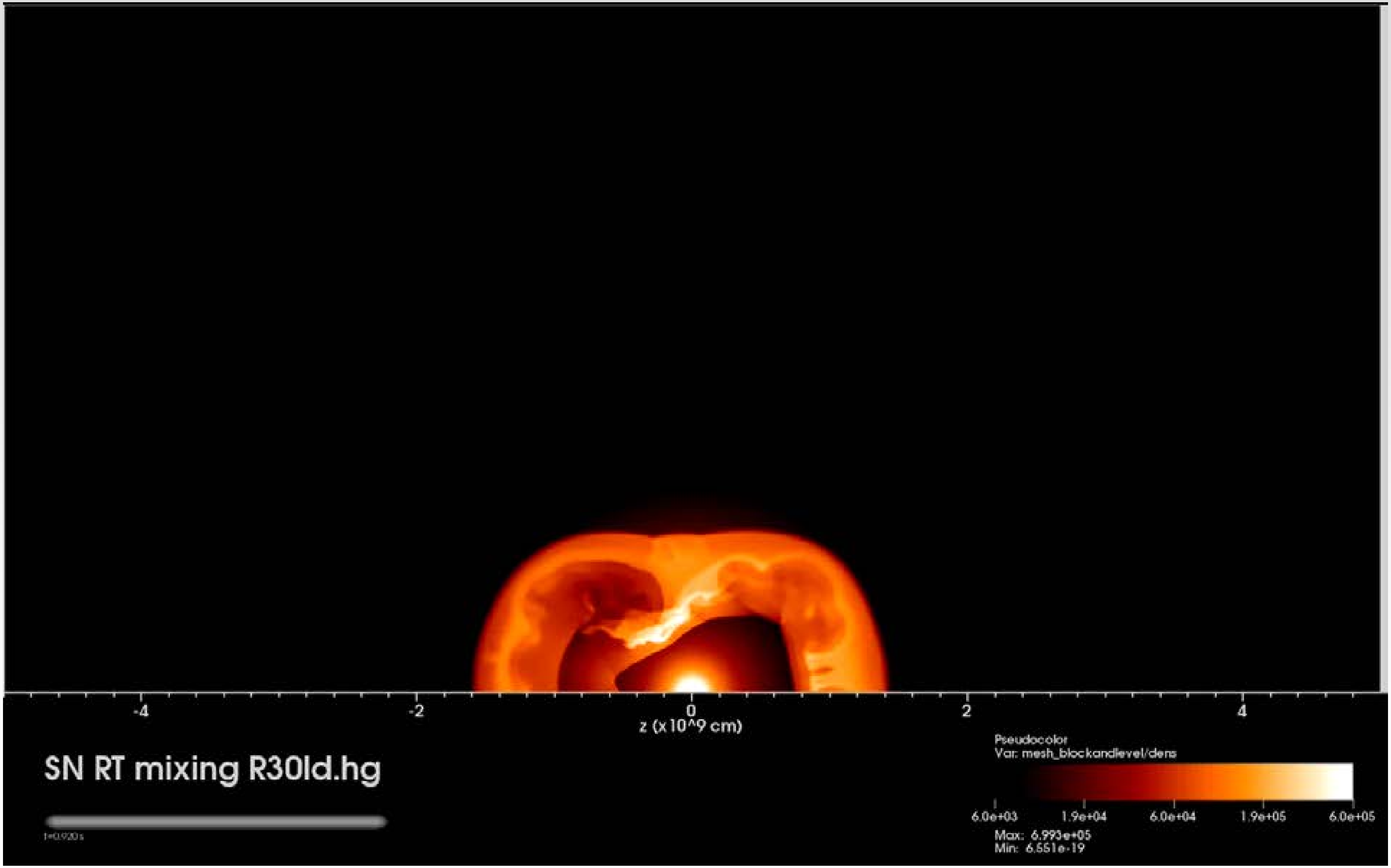
Memory of the Explosion

- Angular evolution of the ejecta mass distribution



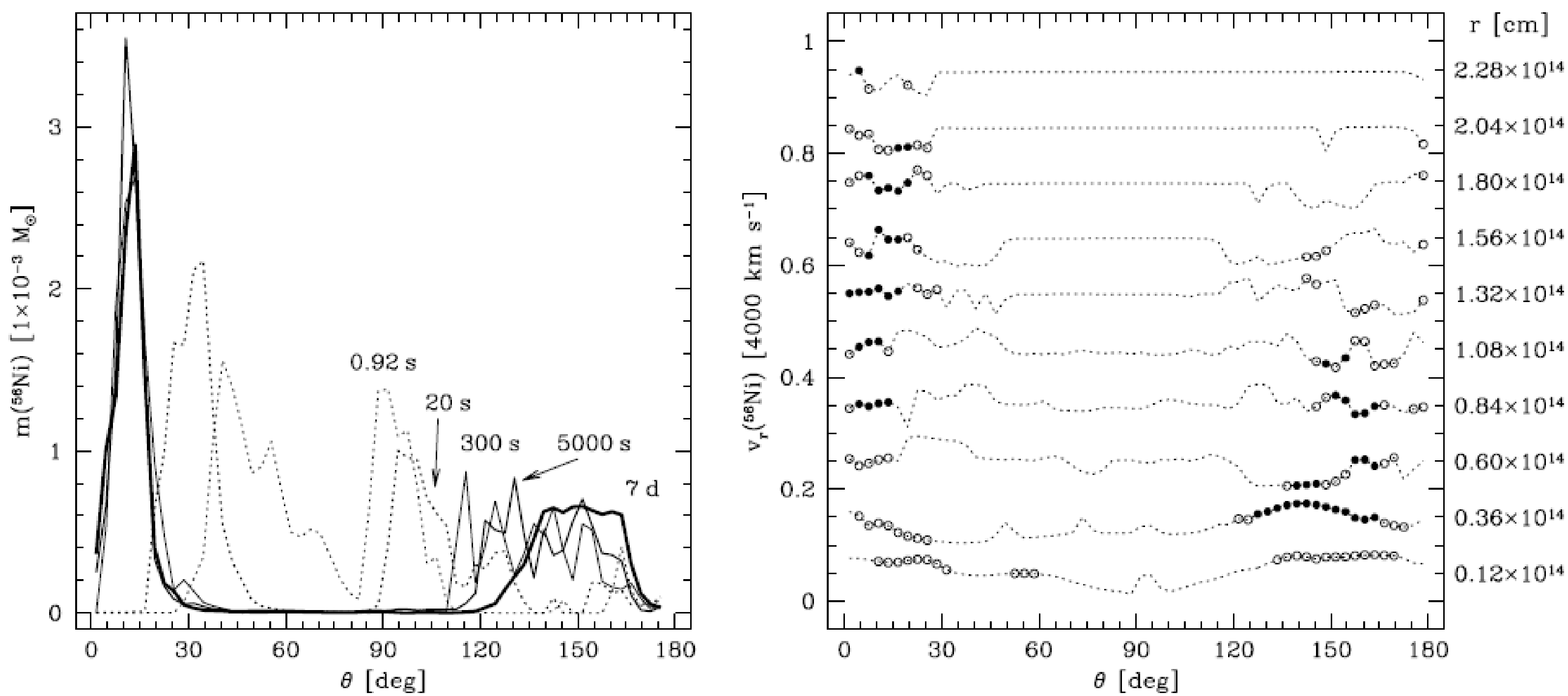
SASI imprint

Post-Explosion: Shocking the Envelope

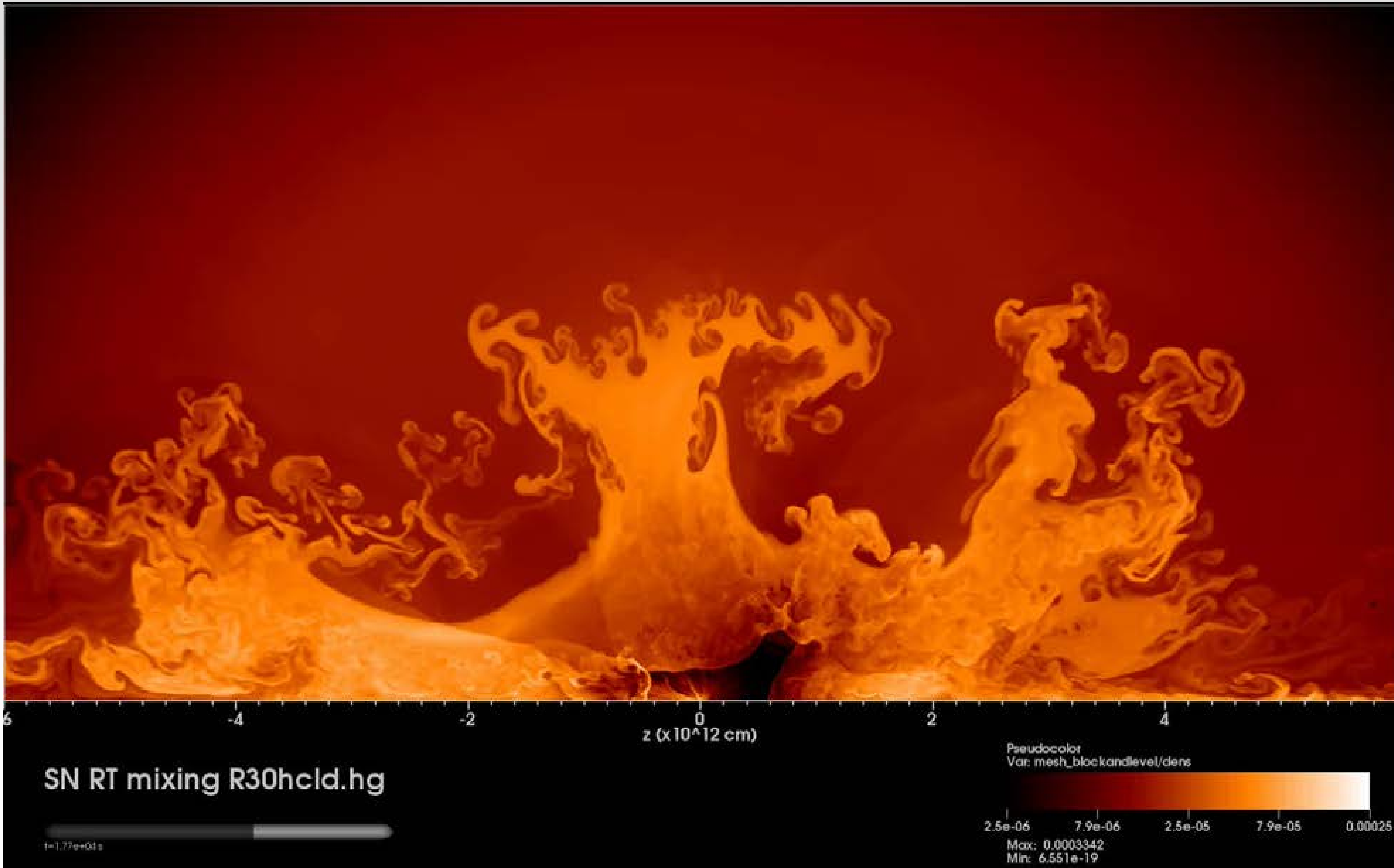


^{56}Ni. How Much? How Fast?

- Following SN 1987A observations, ^{56}Ni distribution evolution is one of the primary model evaluation criteria



Young ccSNR with radioactive decay



HEDLA Connection to Supernovae

- Initially motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

- **Research directions**

  SASI: ccSN explosion

  DivSNRT: ccSN post-explosion RT mixing

  RT: the Braginskii model

HED SNRT Experiment Scaling

Fundamental Hydro Properties

Parameter	Supernova
Length scale (cm)	9×10^{10}
Velocity (km s^{-1})	2000
Density (g cm^{-3})	0.0075
Pressure (dyne cm^{-2})	3.5×10^{13}
Temperature (eV)	900
Z_i	2.0
A	4.0
Density of nuclei (cm^{-3})	1.1×10^{21}

TABLE 2

DERIVED PARAMETERS

Derived Parameter	Supernova
→ $v/(p/\rho)^{1/2}$	2.2
Collisional mfp (cm)	3.6×10^{-3}
Kinematic viscosity (cm^2 s^{-1})	7.0×10^7
→ Reynolds number	1.9×10^{11}
Thermal diffusivity (cm^2 s^{-1})	1.2×10^6
Peclet number	1.1×10^{13}
Radiation mfp (cm)	6.8×10^2
Radiation Peclet number	1.6×10^{16}

Drake et al. (2002)

HED SNRT Experiment Scaling

Fundamental Hydro Properties

Parameter	Supernova	Omega Experiment
Length scale (cm)	9×10^{10}	0.0023
Velocity (km s^{-1})	2000	14
Density (g cm^{-3})	0.0075	0.4
Pressure (dyne cm^{-2})	3.5×10^{13}	1.5×10^{11}
Temperature (eV)	900	2
Z_i	2.0	0.5
A	4.0	8.7
Density of nuclei (cm^{-3})......	1.1×10^{21}	2.8×10^{22}

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→ $v/(p/\rho)^{1/2}$	2.2	2.3
Collisional mfp (cm).................	3.6×10^{-3}	4.0×10^{-9}
Kinematic viscosity (cm^2 s^{-1})......	7.0×10^{7}	0.02
→ Reynolds number....................	1.9×10^{11}	1.4×10^{5}
Thermal diffusivity (cm^2 s^{-1})	1.2×10^{6}	0.55
Peclet number	1.1×10^{13}	5.9×10^{3}
Radiation mfp (cm)..................	6.8×10^{2}	2.0×10^{-6}
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Drake et al. (2002)

This apparent difference in Re is not a real issue for supernova experiments

Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
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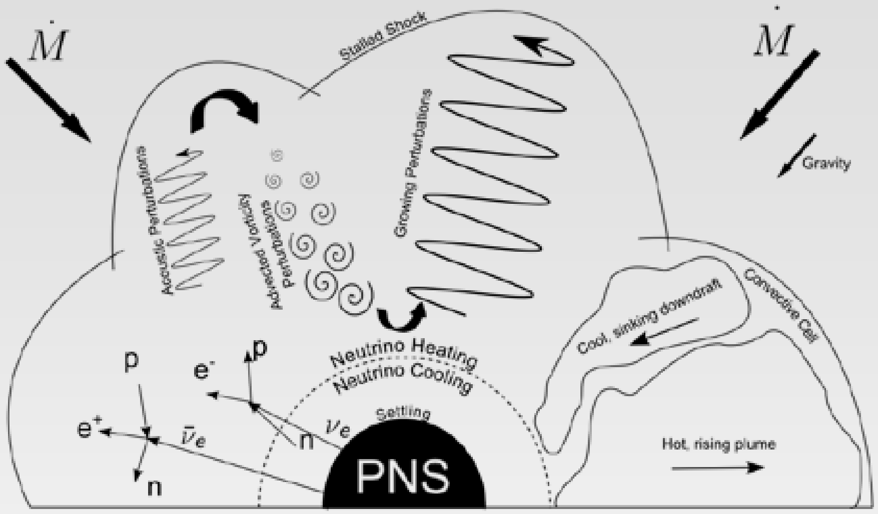
- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical… => spherical targets and diverging and/or converging flow configurations

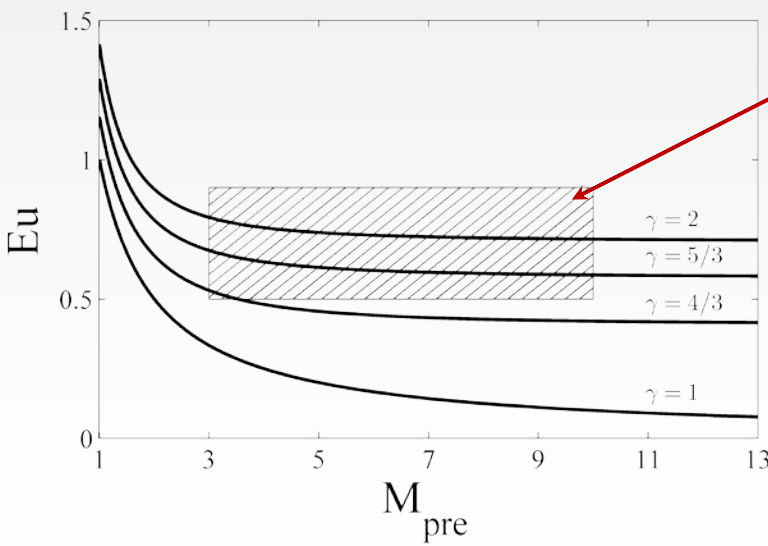
NIF SASI Study

Handy et al. (2012)



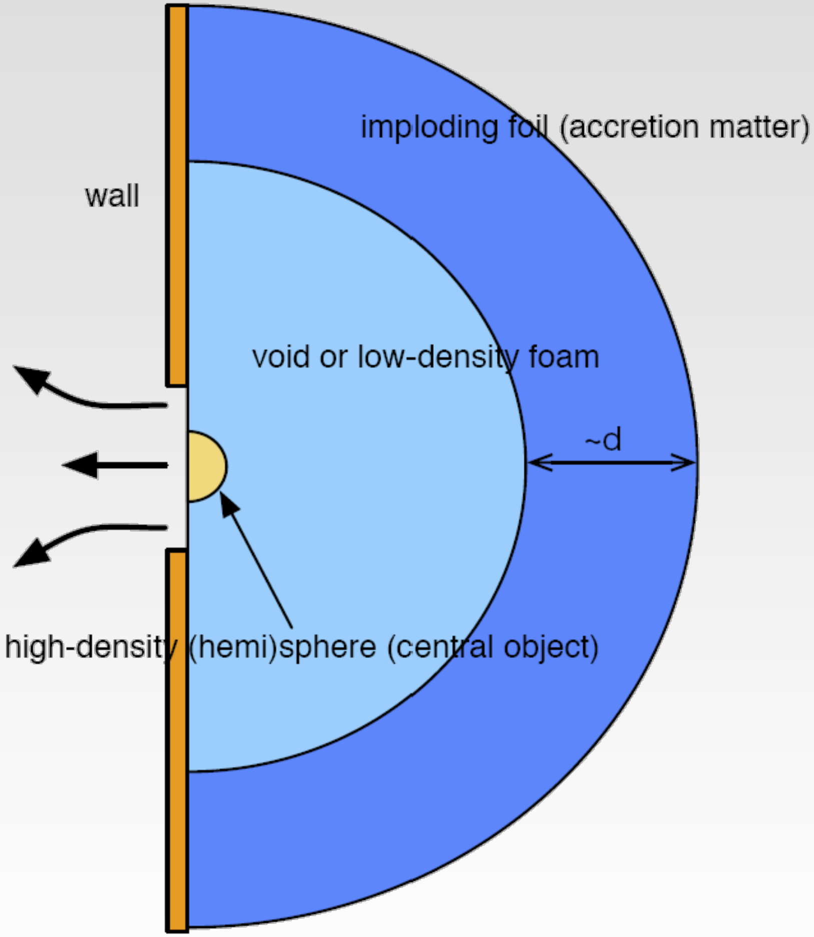
- HED/SN scaling

$$(Eu)^2 = \frac{1+\frac{\gamma-1}{2}M_{pre}^2}{M_{pre}^2-\frac{\gamma-1}{2}}$$



Gedanke Experiment

Gedanke Experiment



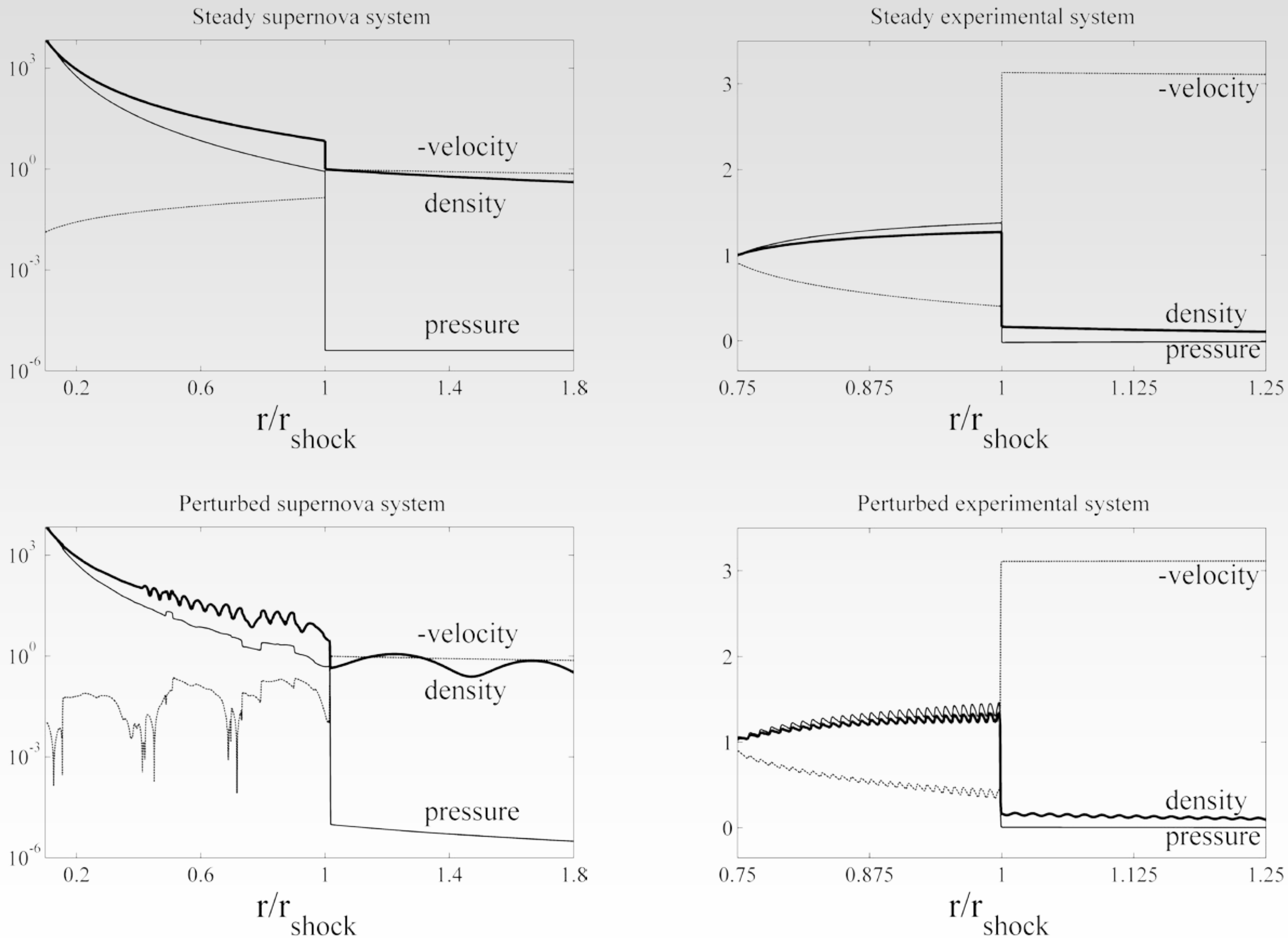
Ohnishi et al. (2008)

Can We Test It?

- NIF concept development: Handy et al. (2012)

NIF SASI Study

Handy et al. (2012)



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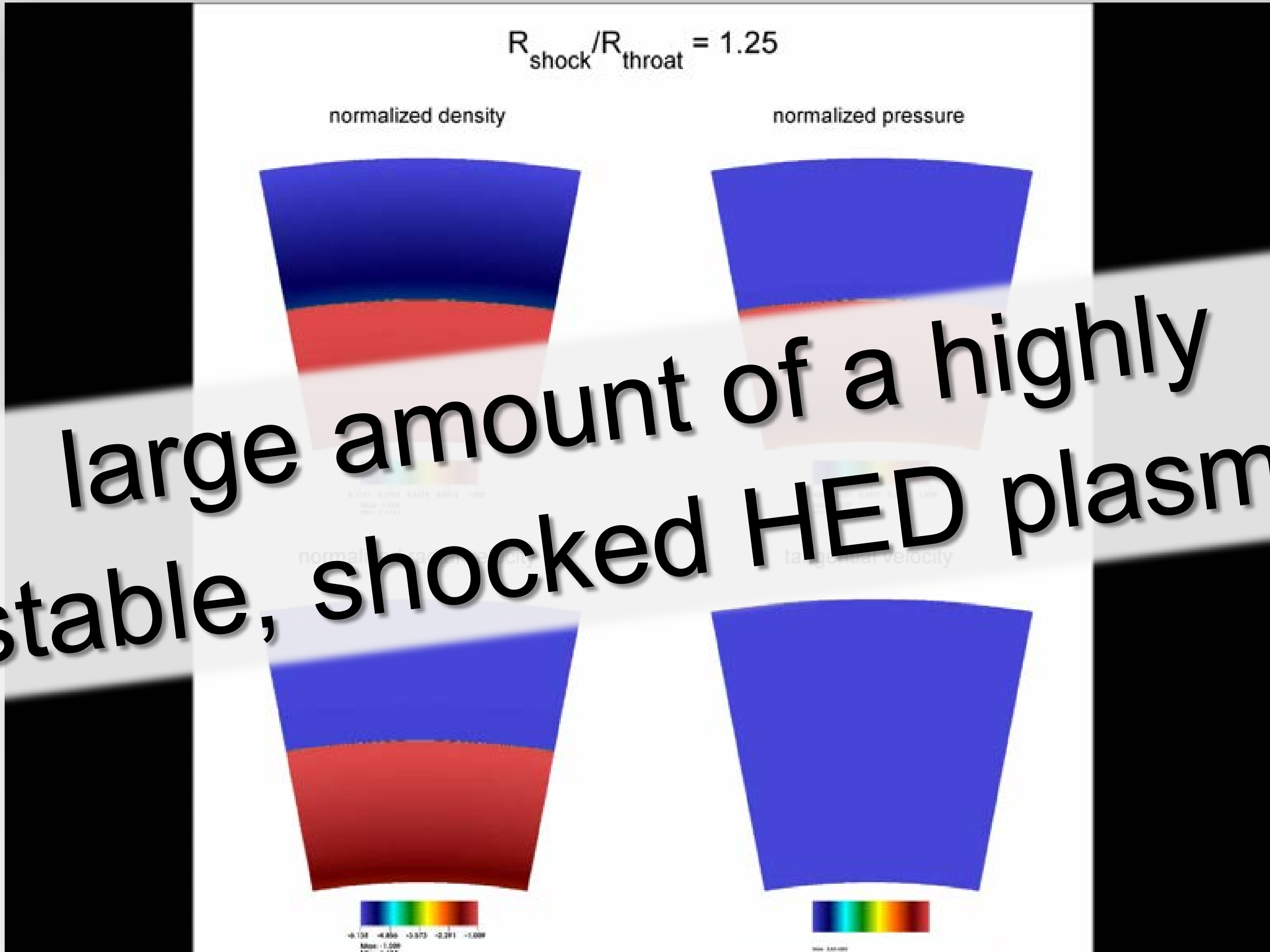

large amount of a highly stable, shocked HED plasma

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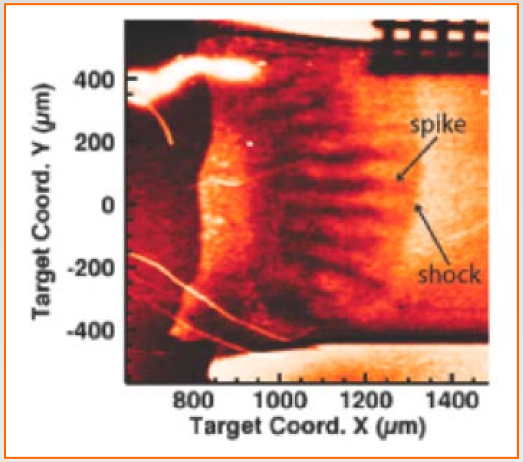
apparent difference in Re is not a real issue for DivSNRT

Drake et al. (2002)

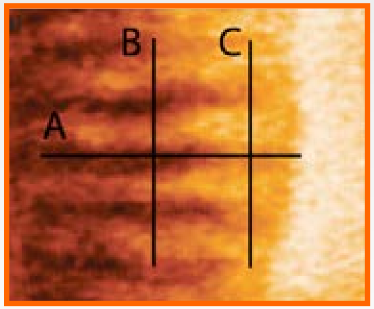
Surprises from HED RT Experiments

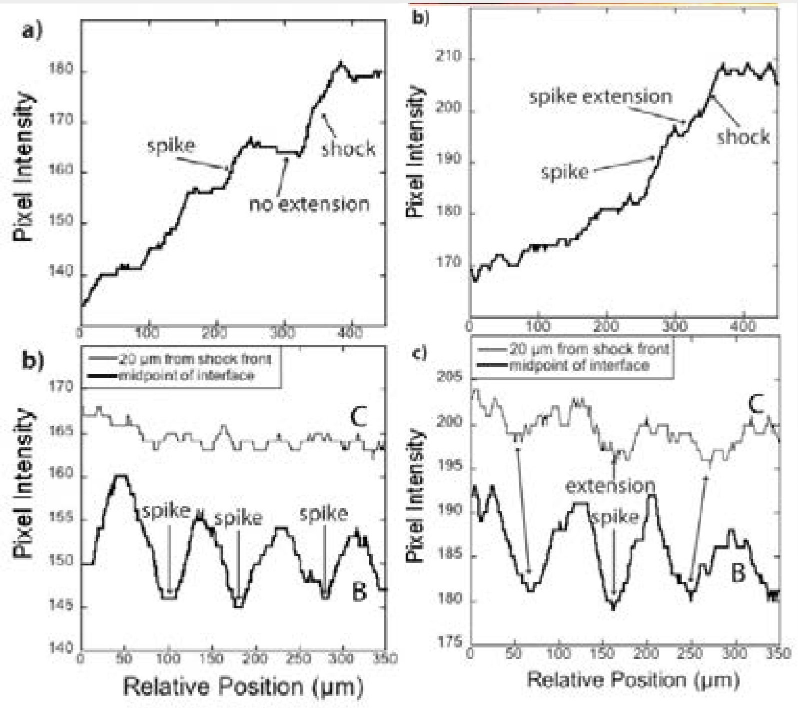
- Smooth spike morphology
- Spike mass extensions



Kuranz et al. (2009)

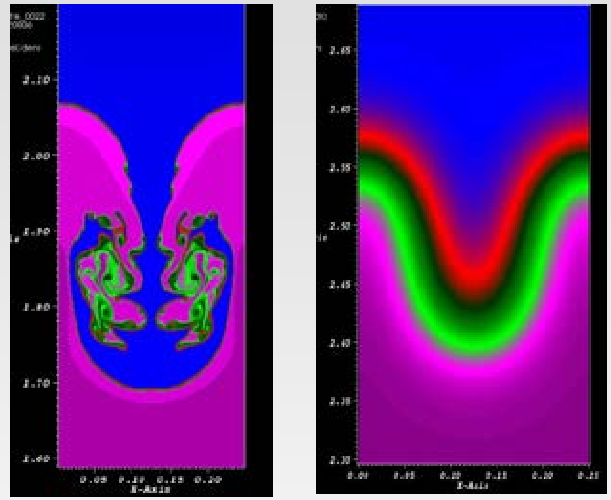
- Density profile analysis





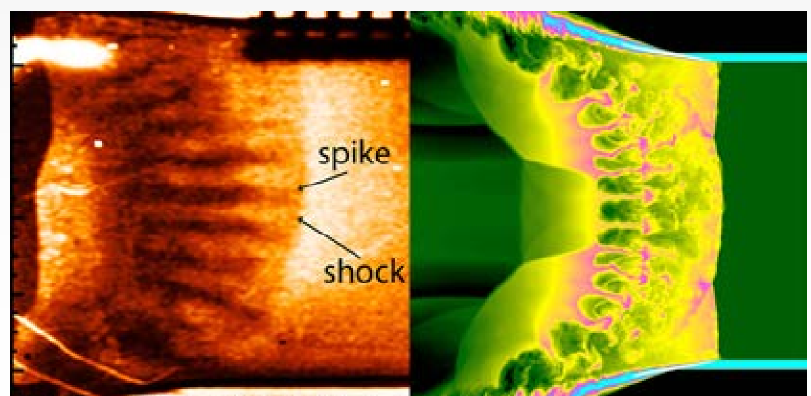
Successful Gedanke Experiments

- **Smooth spike morphology**
  - Thermal conduction?



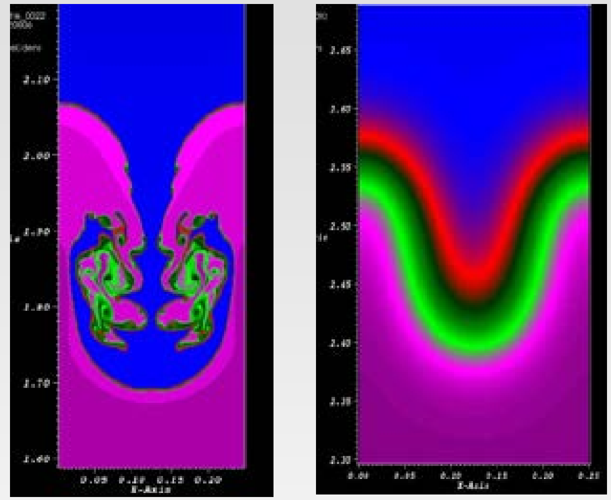
Harden & Plewa (2009)

- **Spike mass extensions**



Gedanke Experiments

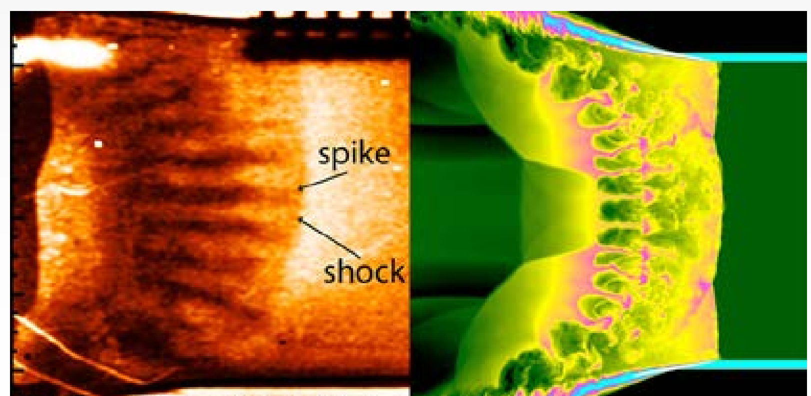
- **Smooth spike morphology**
  - Thermal conduction?



Harden & Plewa (2009)

Success!

- **Spike mass extensions**
  - Not seen in the above model with thermal conduction, nor in pure hydro models



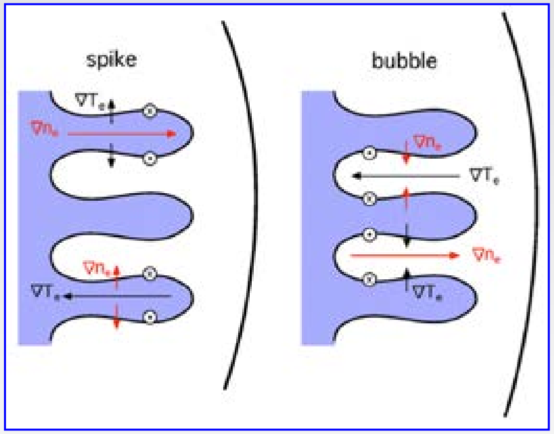
Failure!

Discovery Science, At Last?

- In-situ generation of magnetic fields via the **Biermann battery** mechanism (Kuranz et al. 2010)
  - cross of electron density and temperature gradients

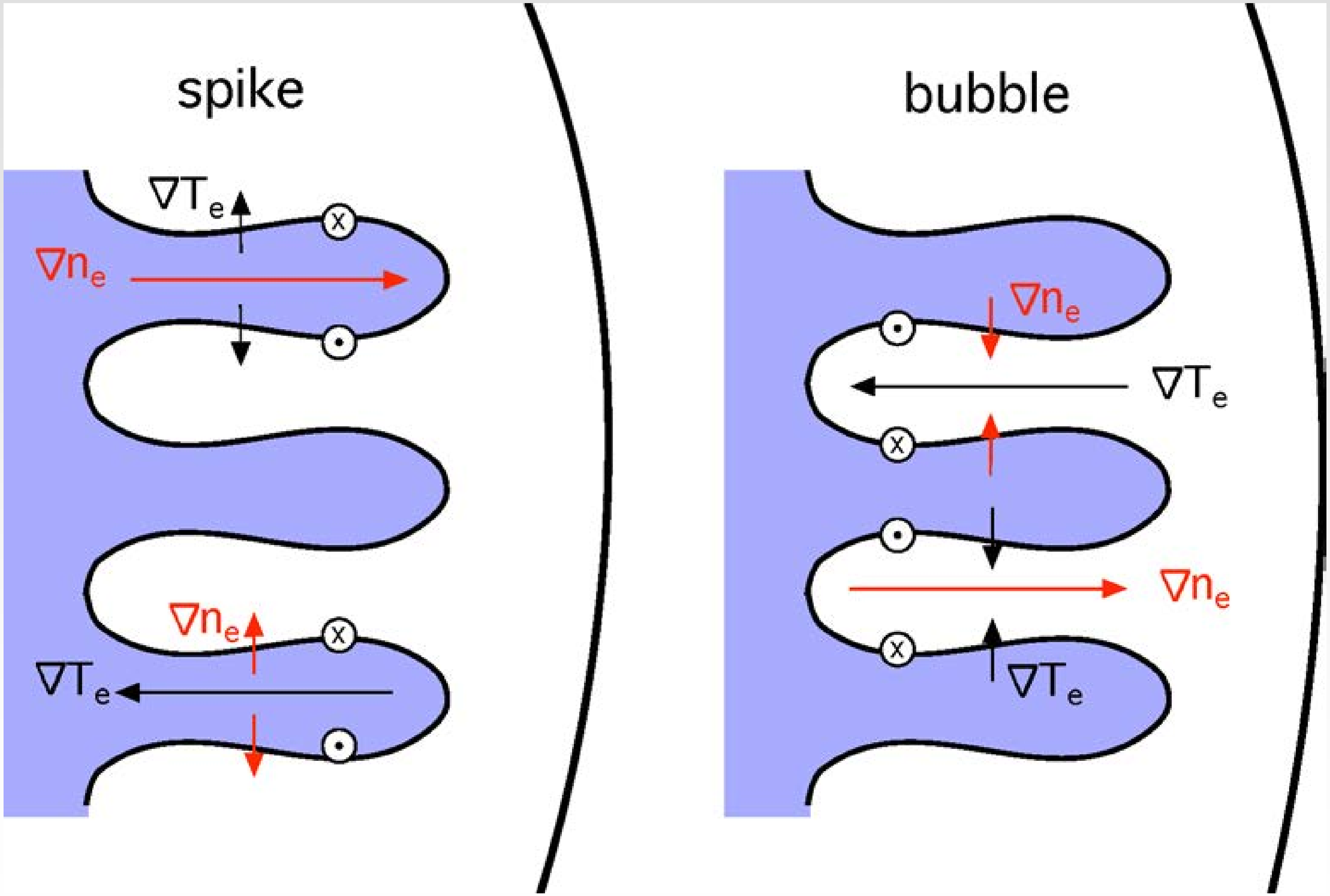
$$\frac{\partial \mathbf{B}}{\partial t} = \frac{c k_B}{e}\left[\nabla T_e \times \nabla \ln n_e\right]$$

  - usually neglected term in the induction equation
  - induced magnetic field => extra pressure



Fryxell et al. (2010)

Biermann battery only



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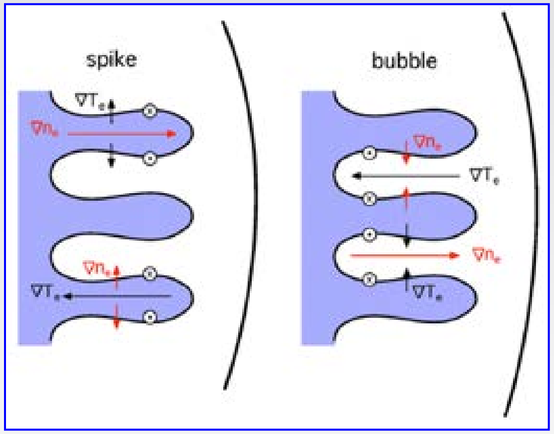


Fryxell et al. (2010)

- **Consequences for supernovae**
  - Magnetic pressure contribution to the thermal pressure at the deflagration front (impact unknown)
  - Rayleigh-Taylor spikes in core-collapse (estimated negligible)

Non-ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} - \frac{\mathbf{B}\cdot\mathbf{B}}{4\pi} \right) + \nabla P = \rho \mathbf{g}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot \left[(\rho E + P)\mathbf{u} - \frac{\mathbf{B}\cdot\mathbf{B}}{4\pi} \cdot \mathbf{u} \right] = \rho \mathbf{u} \cdot \mathbf{g} + \nabla \cdot (\mathbf{q}_e + \mathbf{q}_i) + Q$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = \frac{c}{e}\left[\nabla \times \frac{\nabla P_e}{n_e} - \nabla \times \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi n_e} - \nabla \times \frac{\mathbf{R}_T + \mathbf{R}_U}{n_e} \right]$$

Verification tests

A number of test simulations were done to verify that our magnetic field generation and anisotropic heat conduction modules were working properly. The first test is for the Biermann battery term with the following initial conditions (Toth et al., 2010):

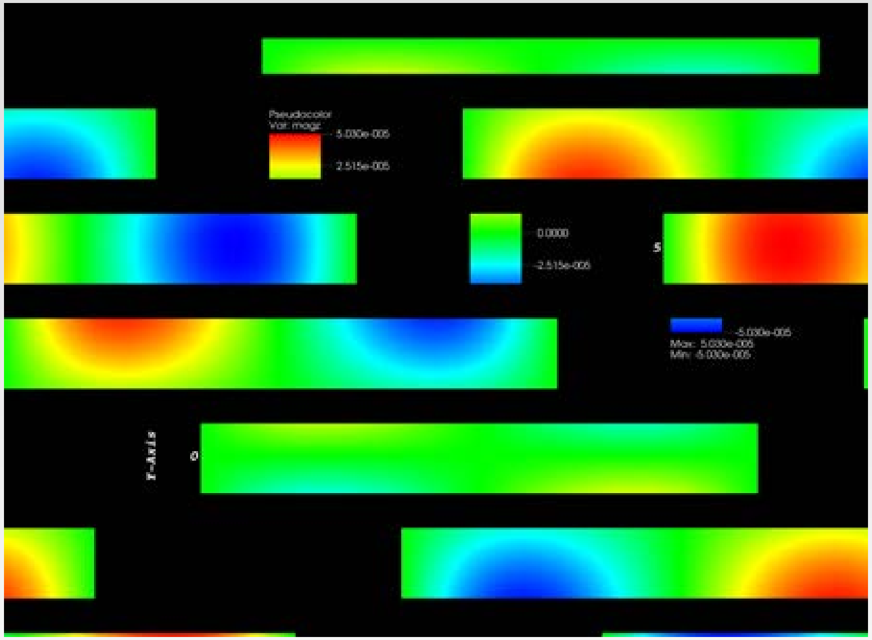
$$\mathbf{B} = 0, \mathbf{u} = 0, n_e = n_0 + n_1 \cos(k_x x), p_e = p_0 + p_1 \cos(k_y y),$$

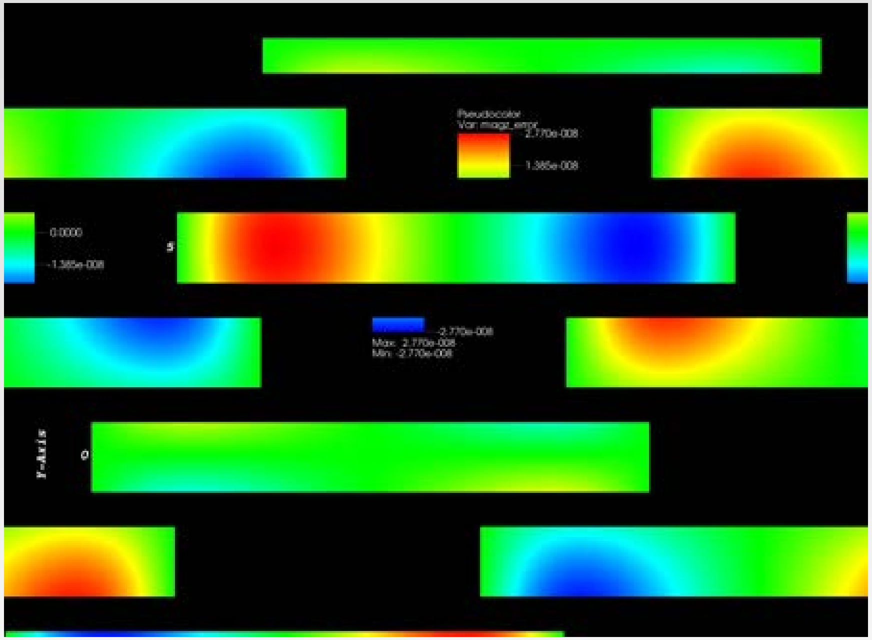
$$k_x = k_y = \frac{\pi}{10}, n_0 = p_0 = 1, n_1 = p_1 = 0.1$$

The exact solution for the rate of magnetic field generation is:

$$\frac{\partial B_z}{\partial t} = -\frac{k_x k_y n_1 p_1 \sin(k_x x)\sin(k_y y)}{\left[n_o + n_1 \cos(k_x x)\right]^2}$$

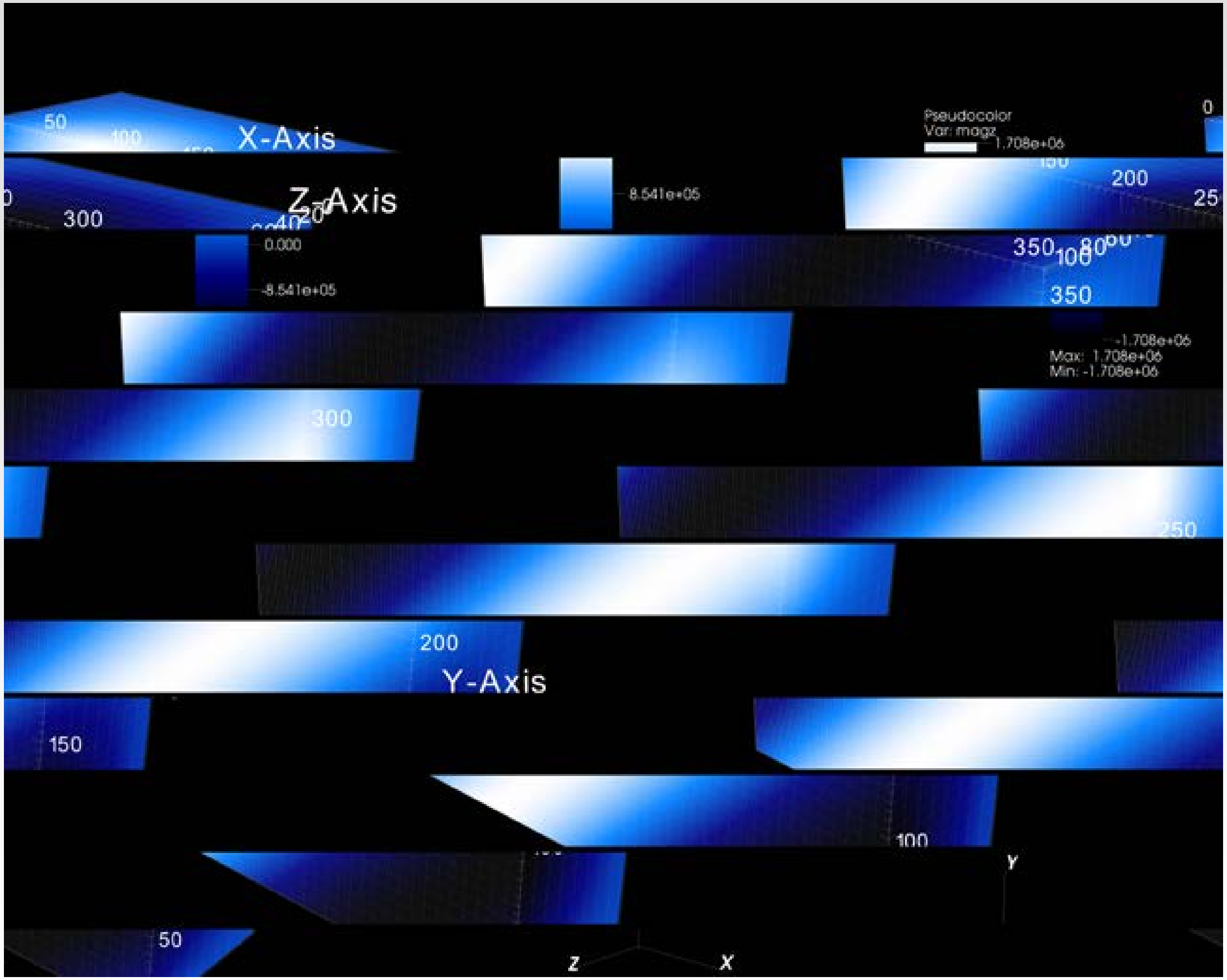
Biermann battery term verification





(left panel) Numerical solution of the generated magnetic field source term, $\frac{\partial B_z}{\partial t}$, on a 160 x 160 grid.
(right panel) Error relative to the analytical solution. Time t = 0.05 s.

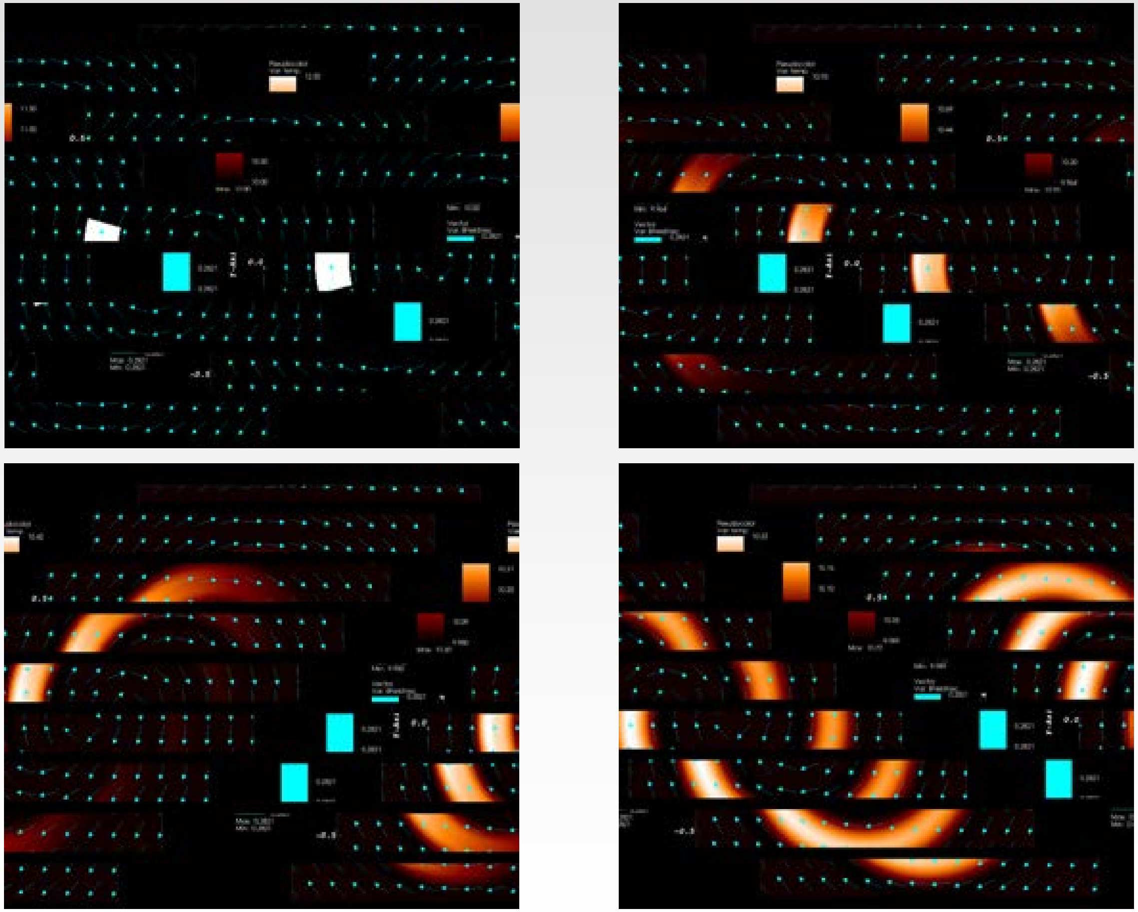
More comprehensive BB test



Magnetic field generation source term, $\dot{B}_z$, as a function of electron number density and temperature gradient orientation.

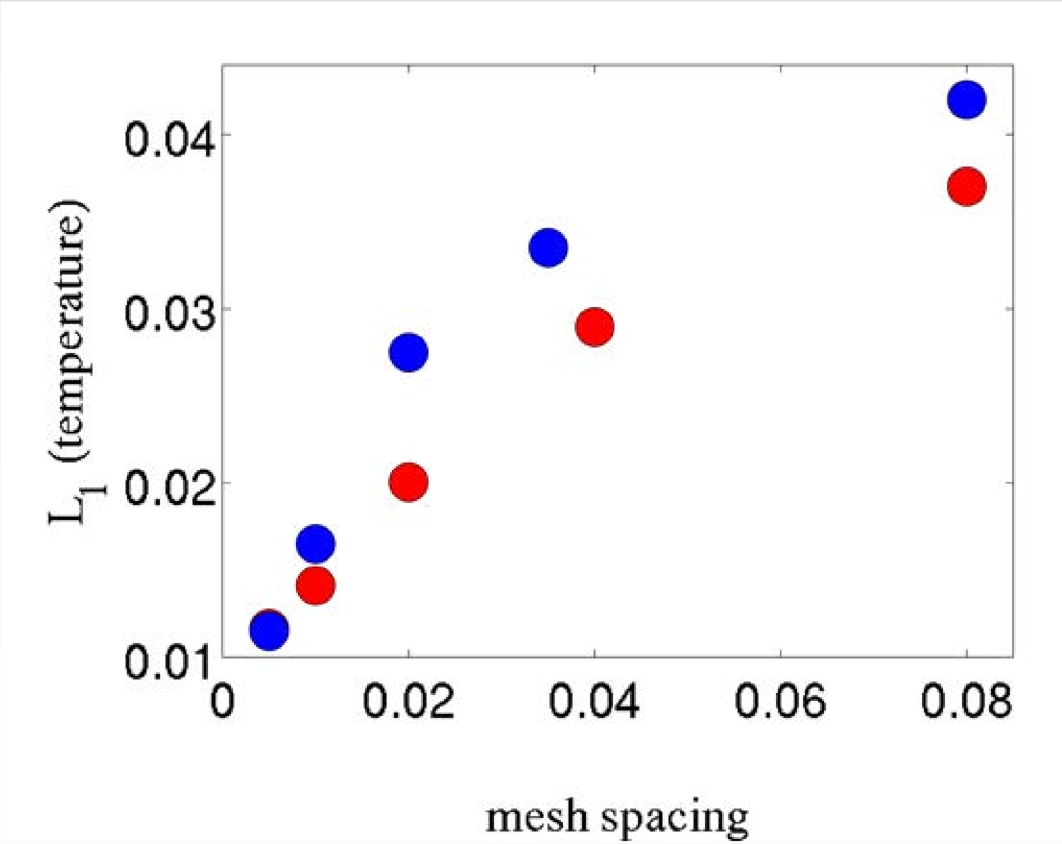
Thermal transport is anisotropic

$$T(r,\theta)=\begin{cases}12 \text{ if } (0.5\le r\le 0.7) \text{ and } \left(\frac{11}{12}\le\theta\le\frac{13}{12}\right), \\ 10 \text{ otherwise}\end{cases}$$



Results of the Parrish & Stone anisotropic thermal conduction verification test on a 400 x 400 grid. The temperature distribution is shown at times t = 0, 10, 50, and 200. Heat flows along magnetic field lines, as expected.

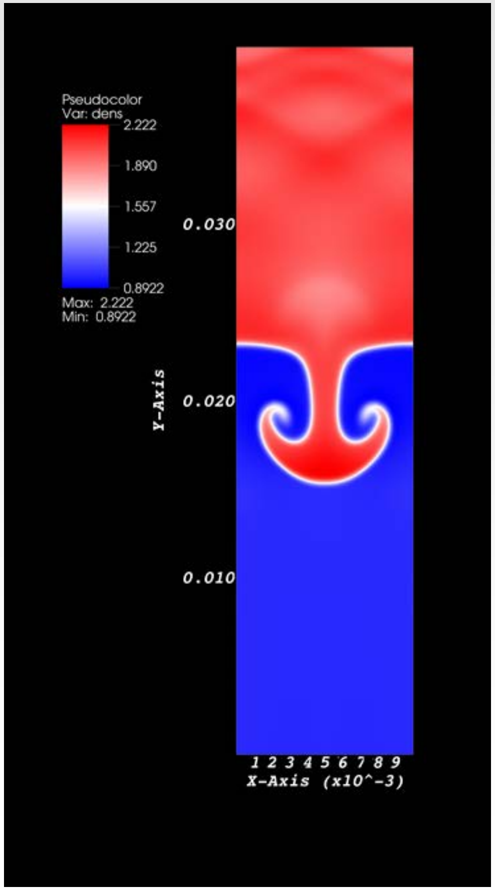
(Self-)Convergence study

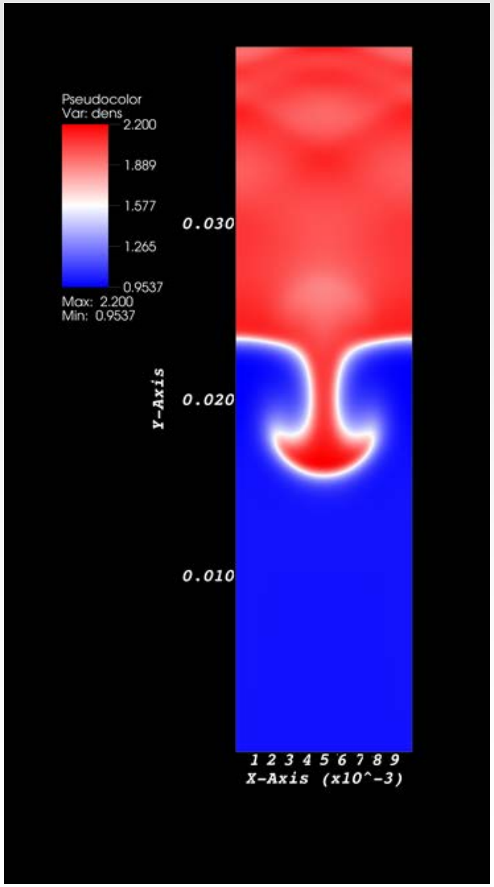


Convergence of the L1 error norm of temperature as a function of the mesh resolution for the Parrish & Stone test problem. Our results are shown in red, and those of Parrish & Stone are shown in blue.

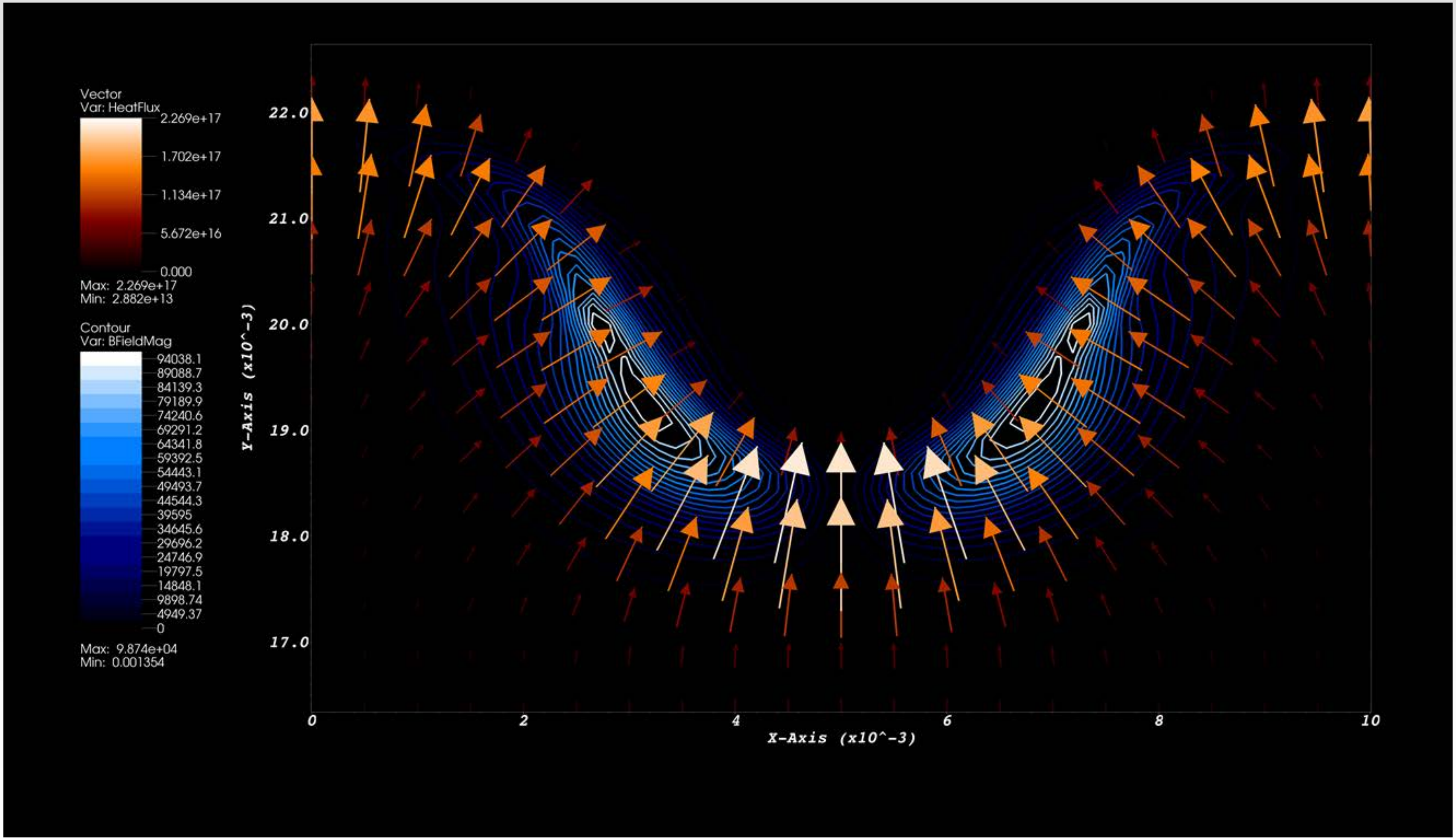
Extended Physics RT Model

- Single mode RT
- Generalized Ohm's law with the Braginskii coefficients

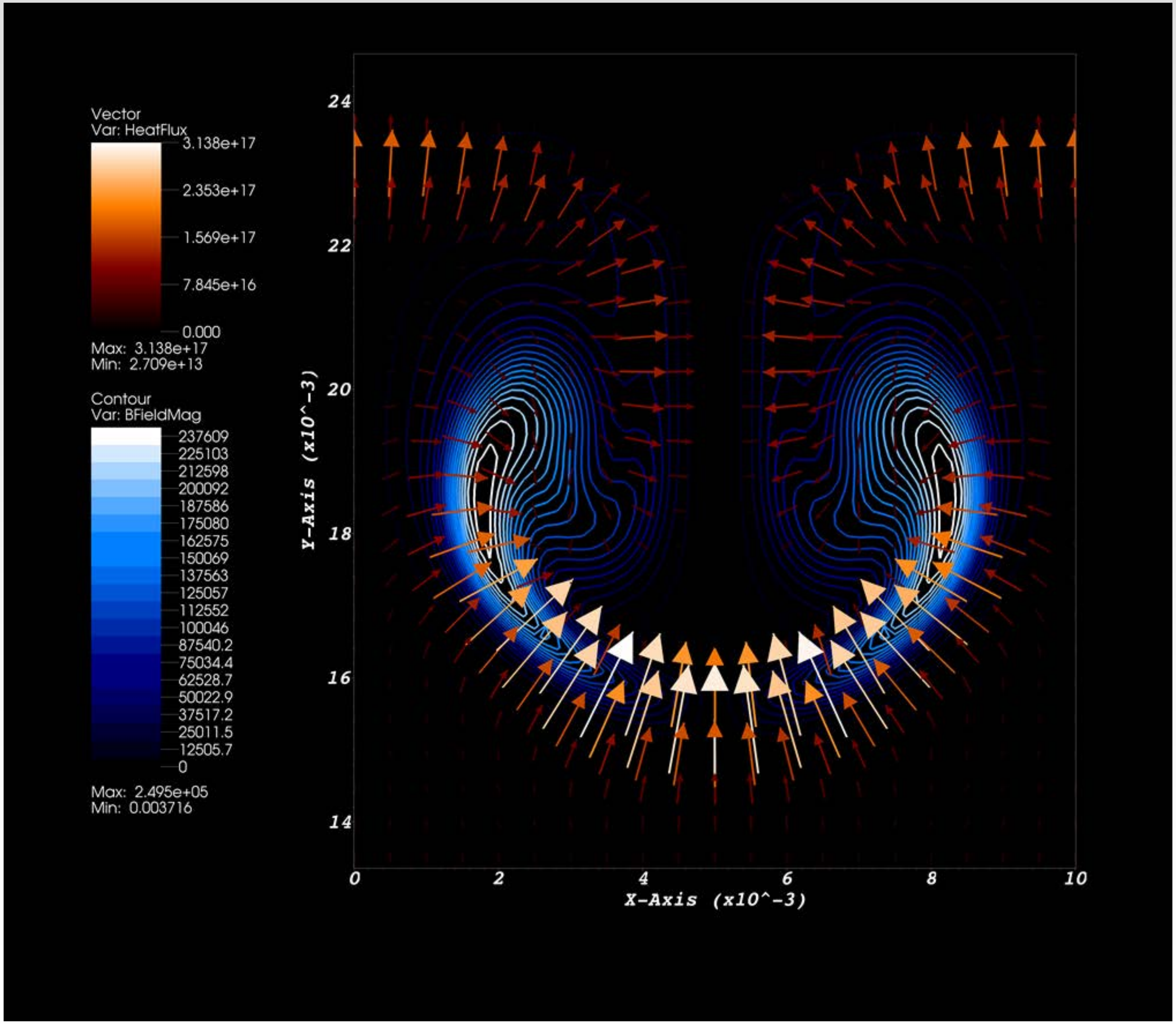




Braginskii's RT Model (early time)



Braginskii's RT Model (late time)



Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical… => spherical targets and diverging flow configurations, or DivSNRT

Diverging Supernova Explosion Experiments on NIF

Purpose

- This experiment attempts to observe extensive Rayleigh-Taylor driven mixing in the exploding massive stars.
- Data will give physics insights of inter-shell penetration outwards to surface via turbulent mixing, shell breakouts, growth of secondary instabilities, vorticity-enhanced mixing.

Comments

- NIF is the unique facility enabling studies with spherical targets (diverging flow geometry)
- Natural continuation of the previous work on Omega
- New diagnostics (IXTS, Dante, proton radiography…) in addition to standard diagnostics (x-ray radiography)
- 15 shots starting in FY 2013 ($70k per target cost)

Purpose

- DivSNRT experiment is designed to study and reproduce by means of a well-scaled experimental design the extensive mixing observed in the exploding massive stars.

- DivSNRT experiment will probe fundamental physics of
  - inter-shell penetration outwards to surface via turbulent mixing;
  - shell breakouts;
  - growth of secondary instabilities;
  - vorticity-enhanced mixing.

DivSNRT Team

- Paul Drake (experimenter, UM)
- Mike Grosskopf (designer, UM)
- Tim Handy (designer, SN hydro exp, FSU grad)
- Konstantinos Kifonidis (designer, SN hydro mixing)
- Carolyn Kuranz (experimenter, UM)
- Aaron Miles (designer, LLNL)
- Frank Modica (designer, multiphysics RT, FSU grad)
- Hye-Sook Park (experimenter, liaison scientist, LLNL)
- Tomasz Plewa (PI, FSU)
- Kumar Raman (designer, LLNL)
- Bruce Remington (experimenter, LLNL)

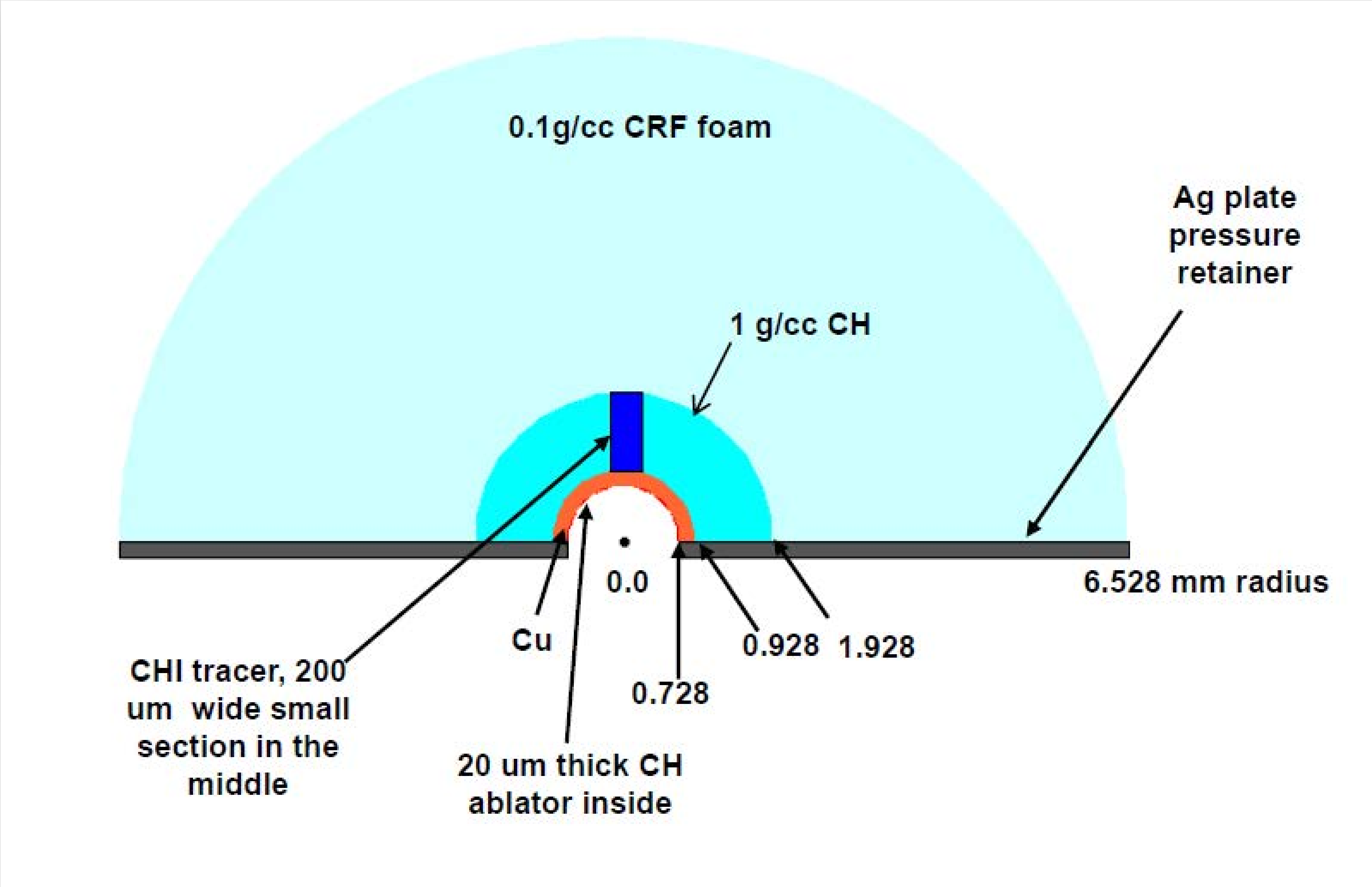
Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

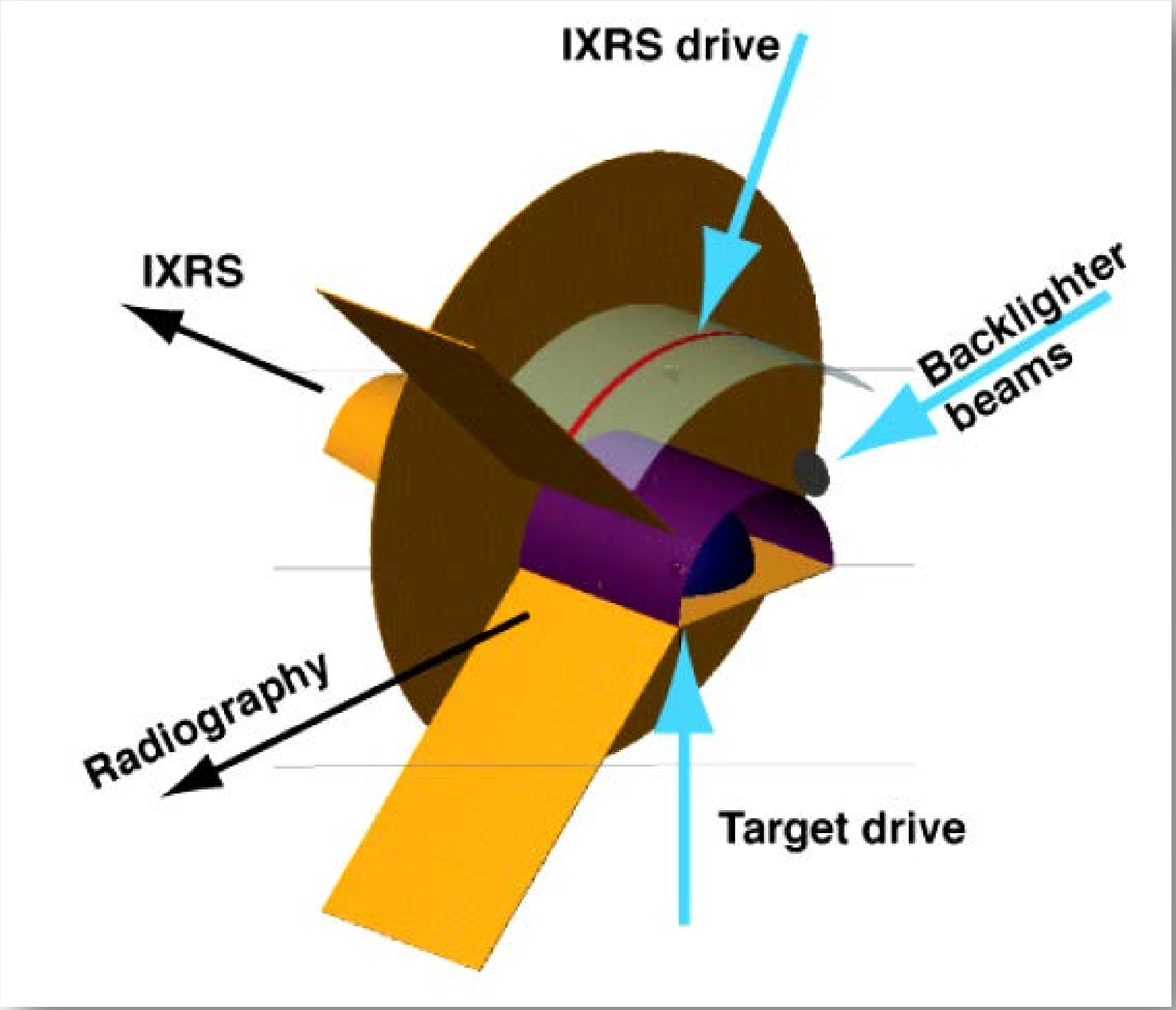
- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical… => spherical targets and diverging flow configurations, or DivSNRT

- Much more mass involved than in the planar case, thus requiring much more energy to drive
- Early attempts on Omega (Drake et al.) unsuccessful (shell breakup) => NIF!

DivSNRT 3 Layer Target

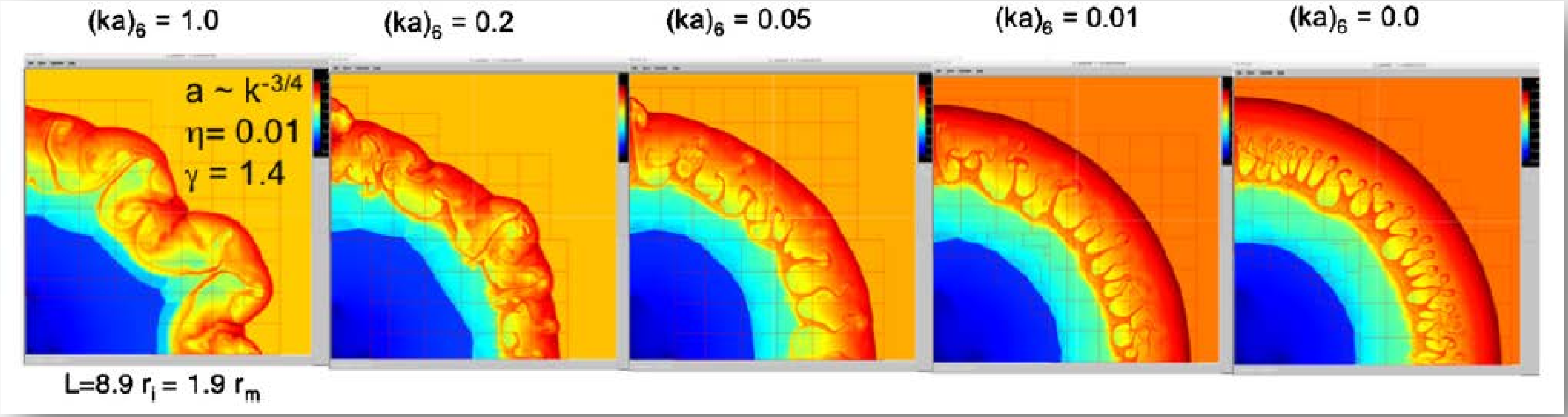


DivSNRT Diagnostics



DivSNRT Theory for Target Design

- **A. Miles (2009)** analysis of the blast wave instability problem provides analytic framework for target design
- The model combines drag-buoyancy, bubble merger, and assumes (quasi) self-similarity to account for the flow divergence and compressibility effects
- Demonstrates that **the memory of the explosion is generally preserved** by the system unless modes are very high (higher than considered typical in ccSN)
- **High-amplitude perturbations favor RM over RT**, at least at early times, resulting in the shock proximity to growing spikes (if ka_0 > 1/3 for adiabatic index 5/3; if ka_0 > 0.2 for index 4/3).



Relevant Computer Model

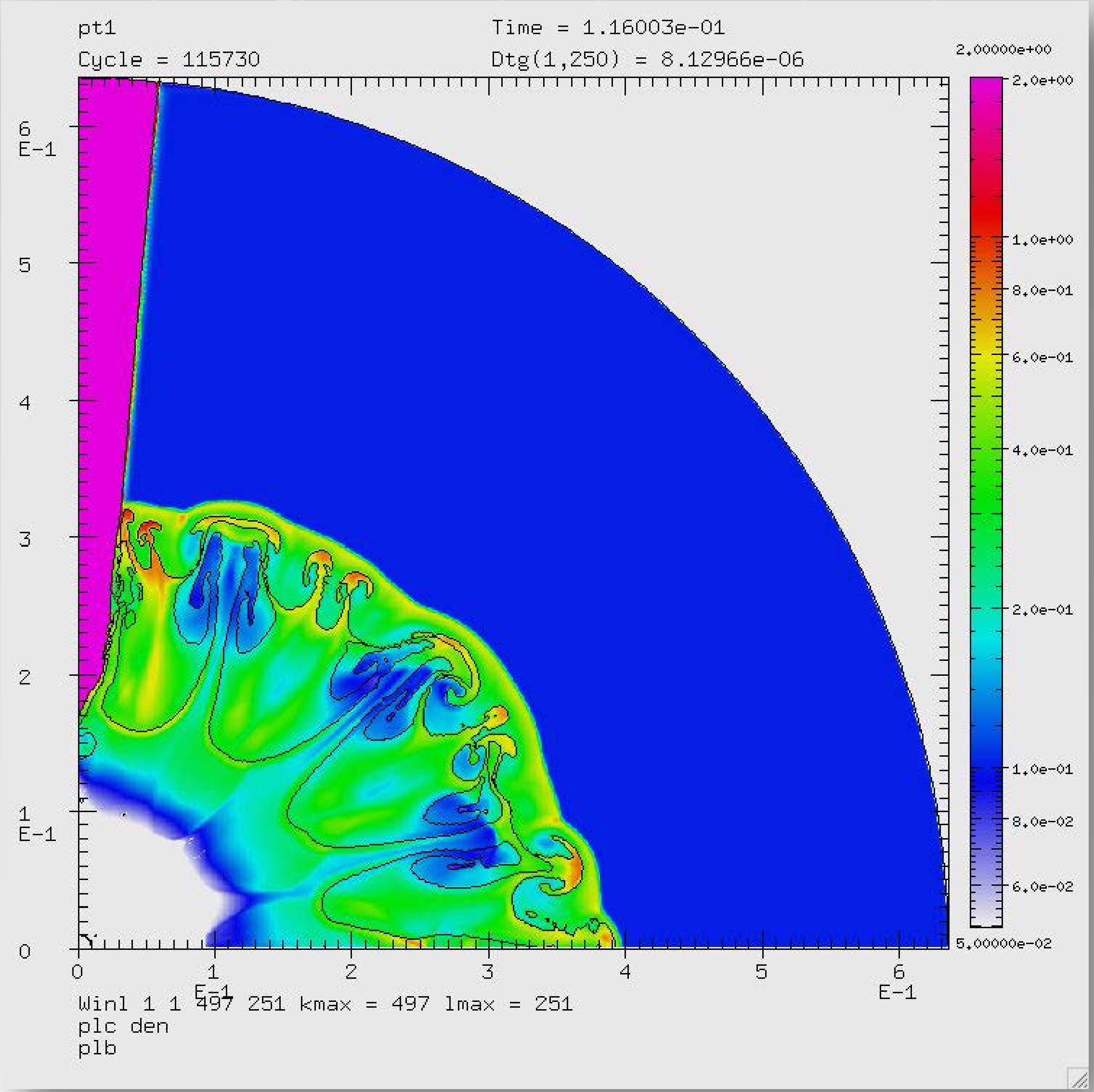
- Radiation hydrodynamics with the laser energy deposition.

$$\partial_t \mathbf{U} + \nabla \mathbf{F}(\mathbf{U}) = \mathbf{S}(\mathbf{U})$$

- A coupled set of parabolic and hyperbolic PDEs
- Radiation transport in multigroup flux limited diffusion
- Linearized Newton-Krylov solver
- Ray tracing for the laser energy depositions
- Level sets for tracing material interfaces
- Adaptive in space and time (AMR)

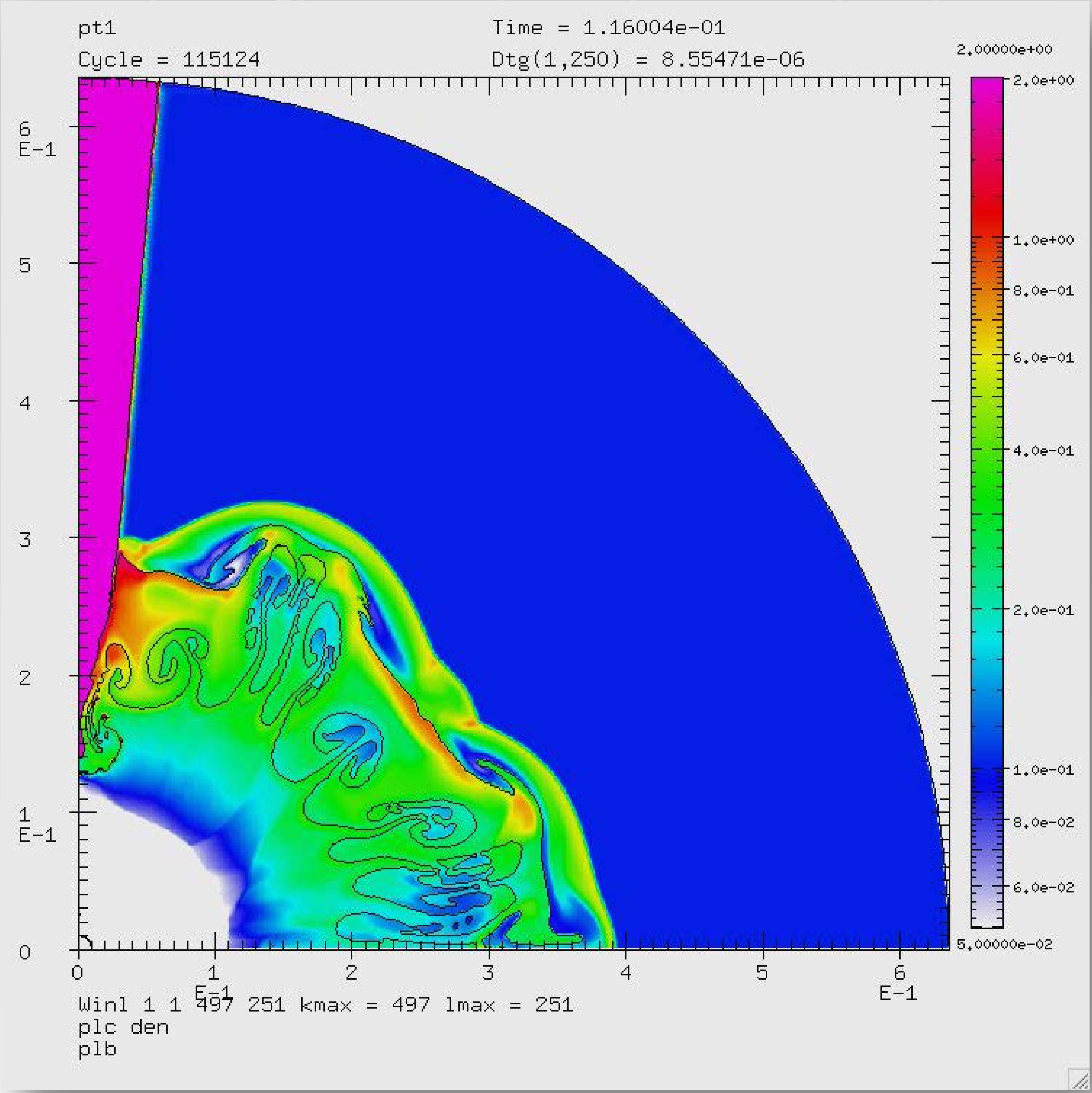
DivSNRT Target Evolution

(k, ka_0): inner(4,2), outer(10,2)

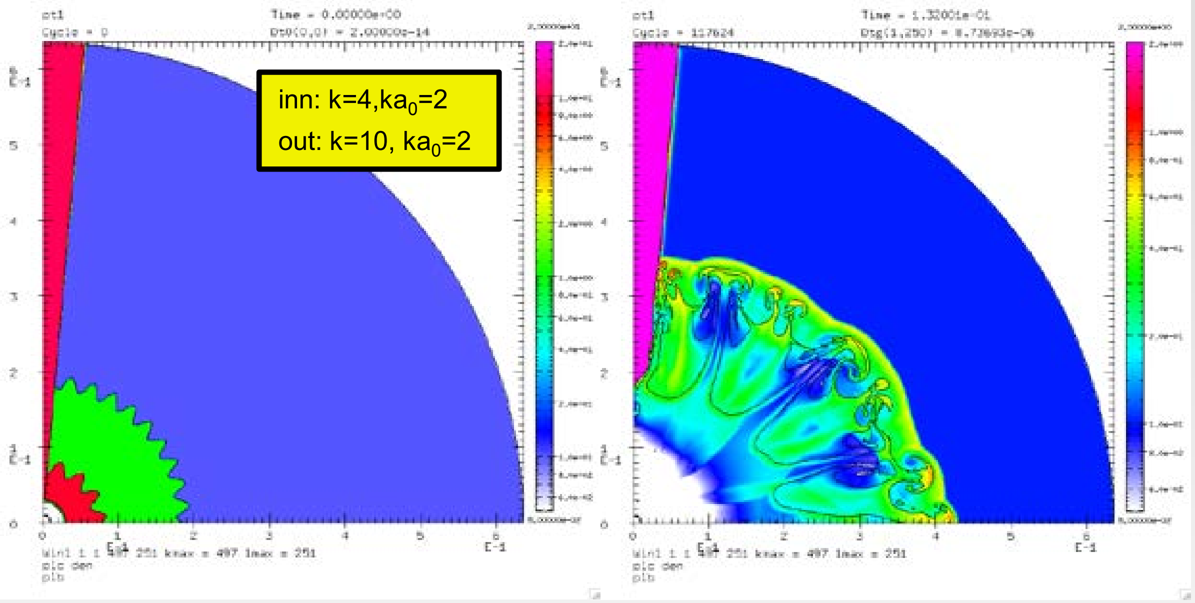


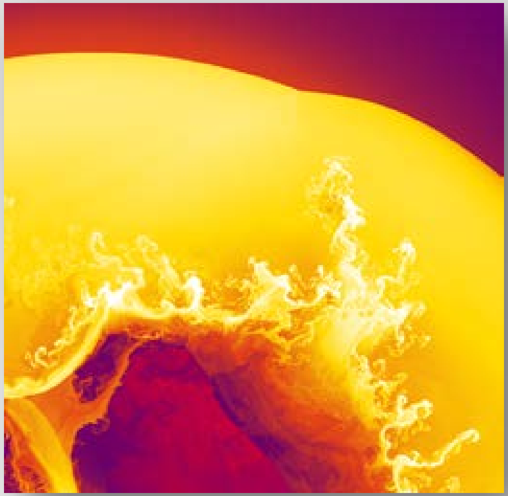
DivSNRT Target Evolution

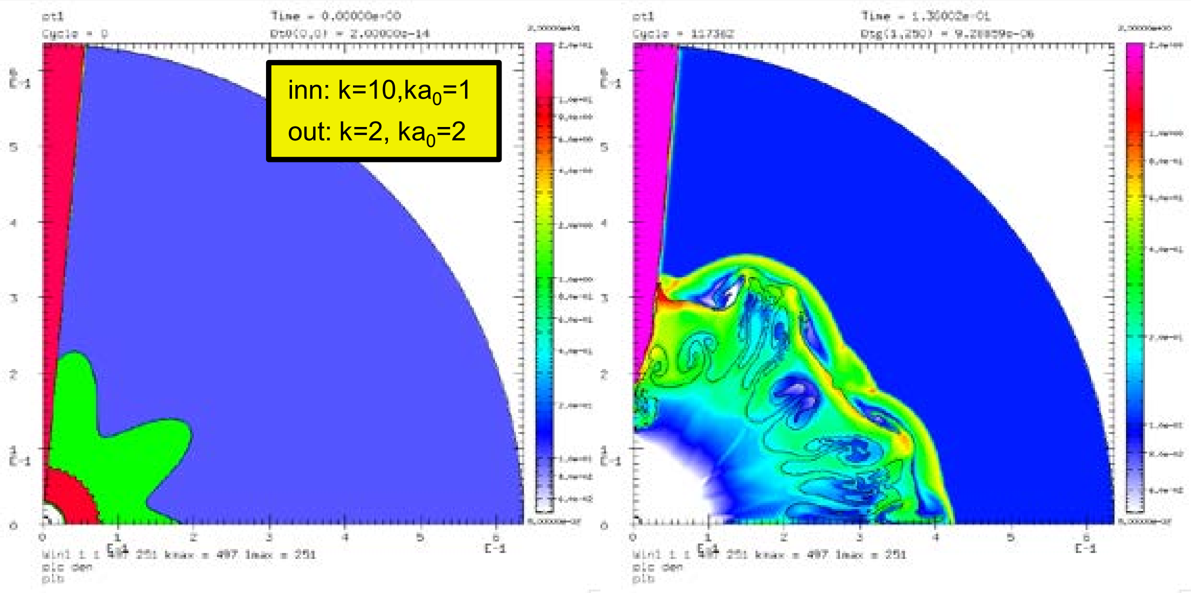
(k, ka_0): inner(10,1), outer(2,2)

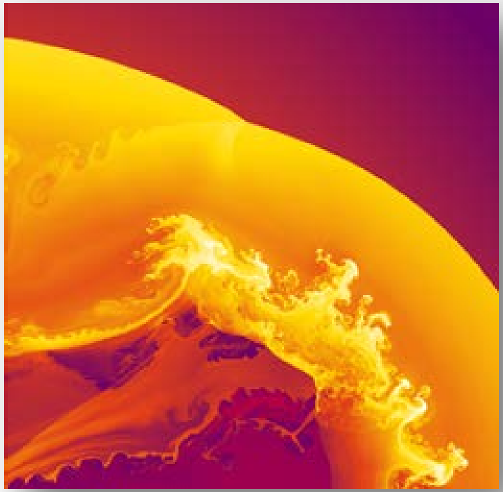


SN Model vs Sample Designs

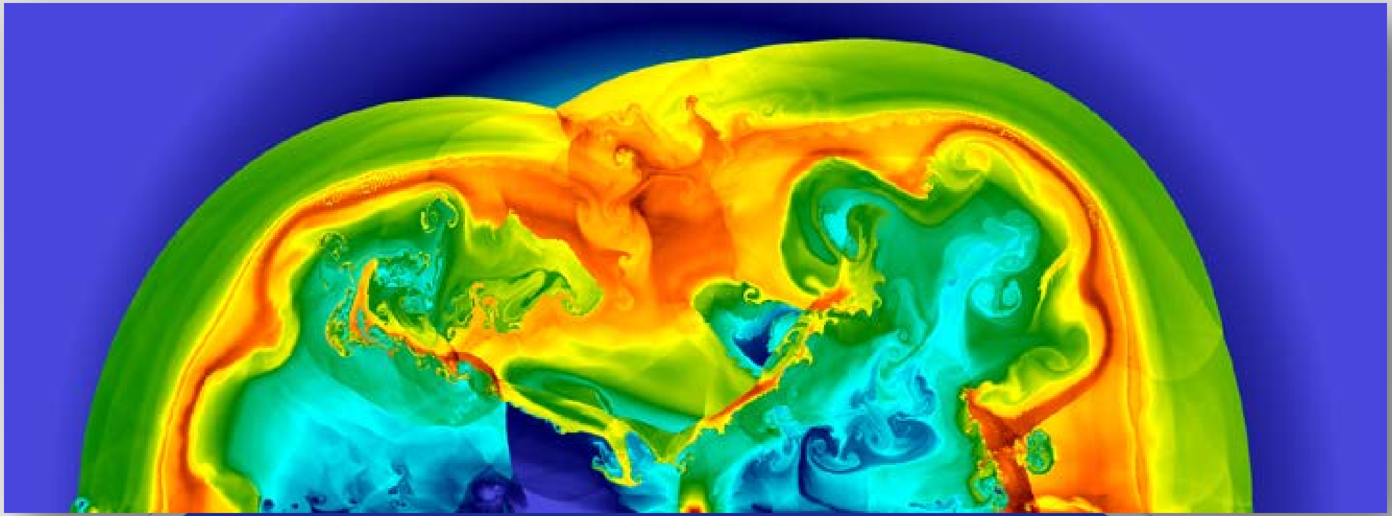


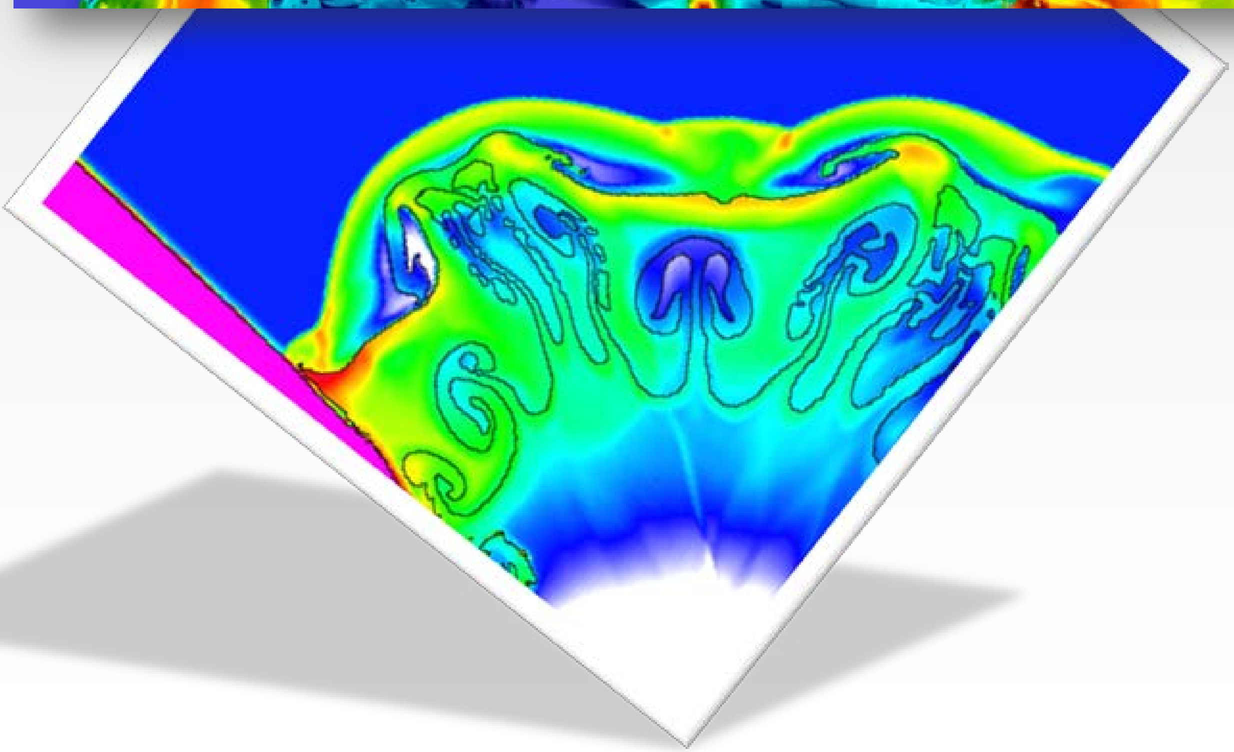






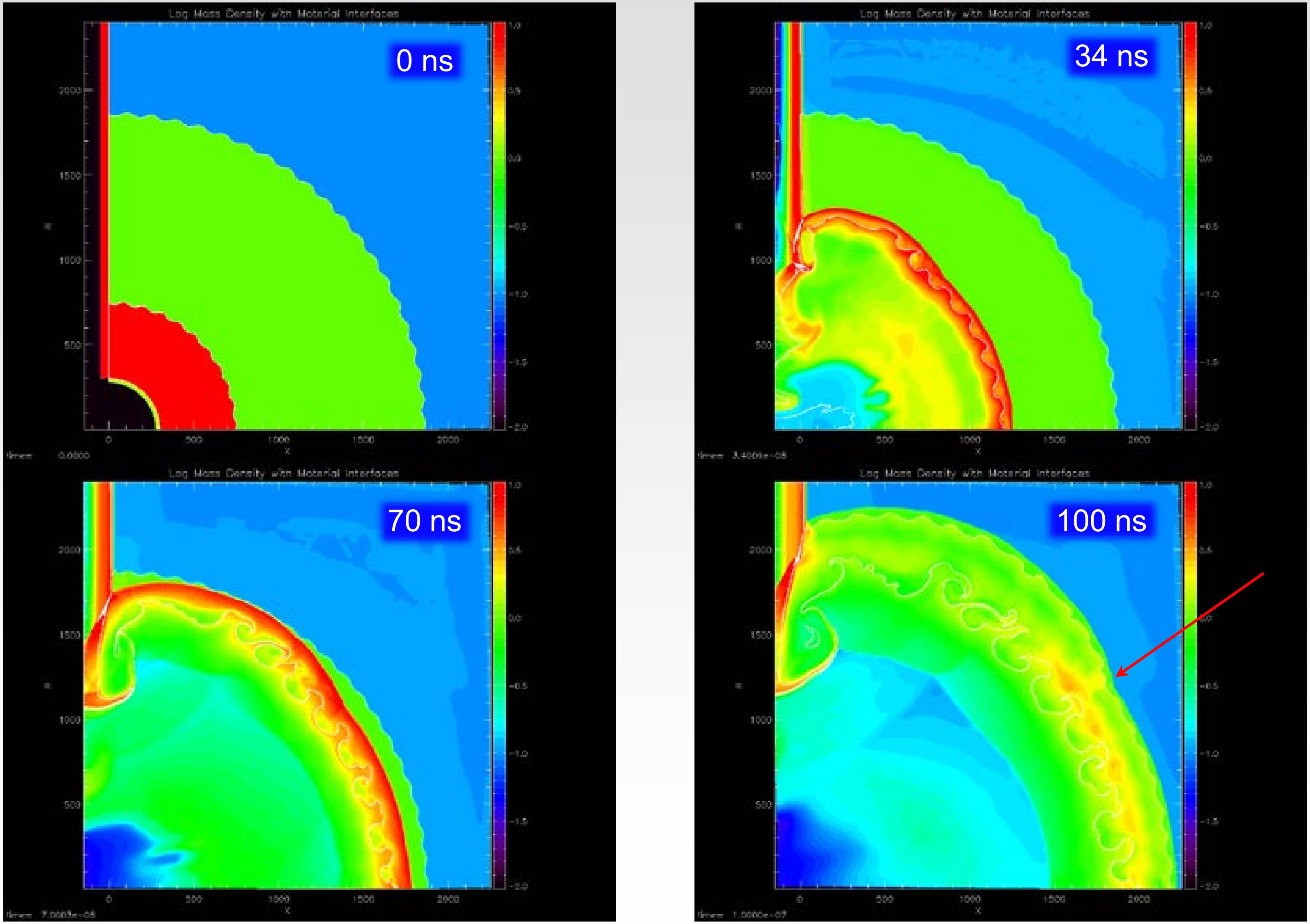
CALE Designs vs SN Model





News: CRASH DivSNRT

by Mike Grosskopf



Proposed Schedule of Shots

FY13

Shot Number	Target Type	Perturbation between interfaces	Drive	Diagnostic Technique	Note
1	hemispherical 2 layers	none	80-300kJ 3ns	radiography	drive test, RT/RM at a nominally smooth interface
2	as above	$(kA)_1$	as above	as above	RT/RM at high-Z/med-Z interfaces
3	as above	$(kA)_2$	as above	as above	as above
4	as above	$(kA)_{(1,2)}$	as above	as above	reproducibility test
5	hemispherical 3 layers	none	as above	as above	drive test, RT/RM at a nominally smooth interface

FY14

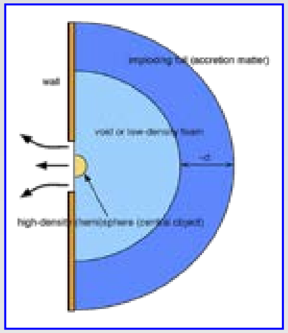
3 layer target studies, demonstrate Imaging X-ray Thomson Scattering technique

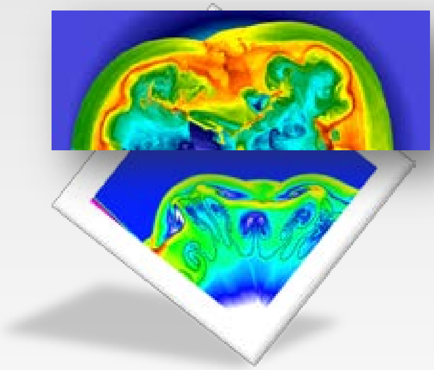
FY15

3 layer target studies with aspherical shocks with radiography and IXTS

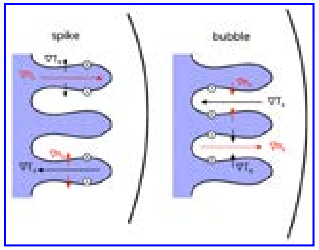
Summary

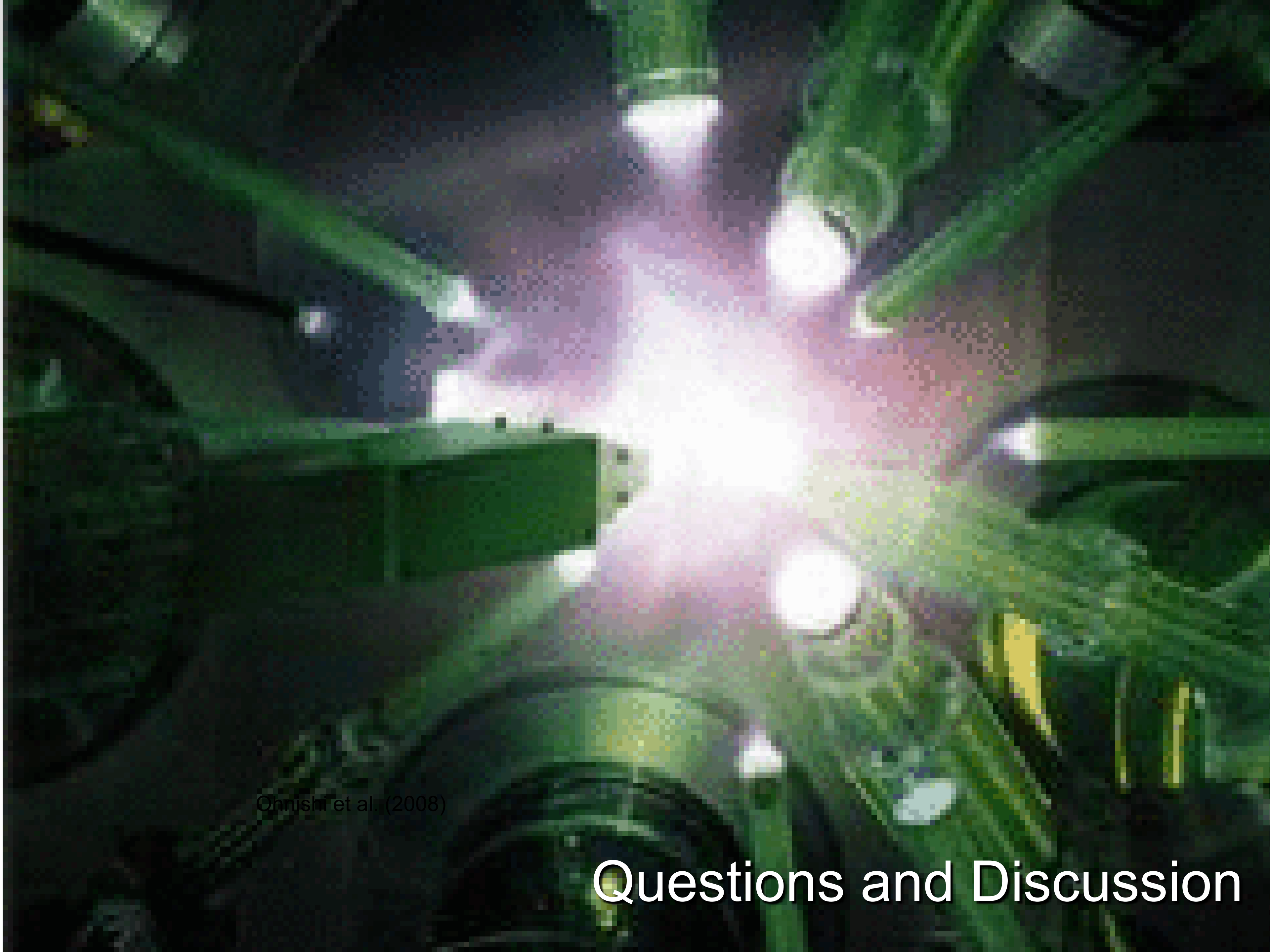
- Mixing of elements in core-collapse SNe
  - Exploring possible SASI experimental designs
  - SASI asymmetries may suffice to explain SN 1987A and alikes
  - Crab-like spongy morphologies at late times (months) due to radioactive decay





- In-situ generated magnetic fields
  - Constructed required computational machinery
  - Identified as a possible new physics in HED RTI experiments




Ohnishi et al. (2008)
Questions and Discussion