Oak Ridge National Laboratory

The Indispensable Role of Visualization In Obtaining Insight from Astrophysical Simulation

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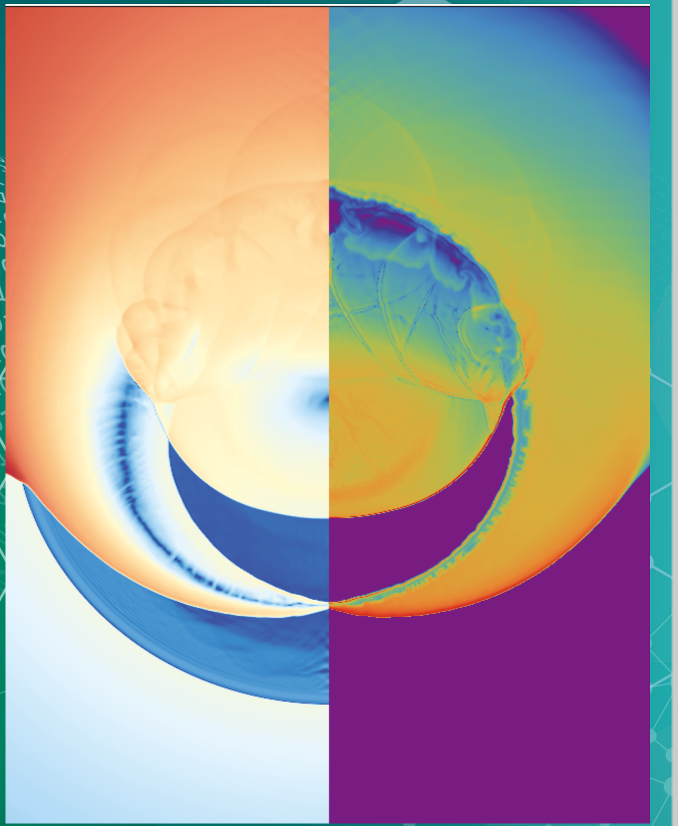


U.S. DEPARTMENT OF ENERGY

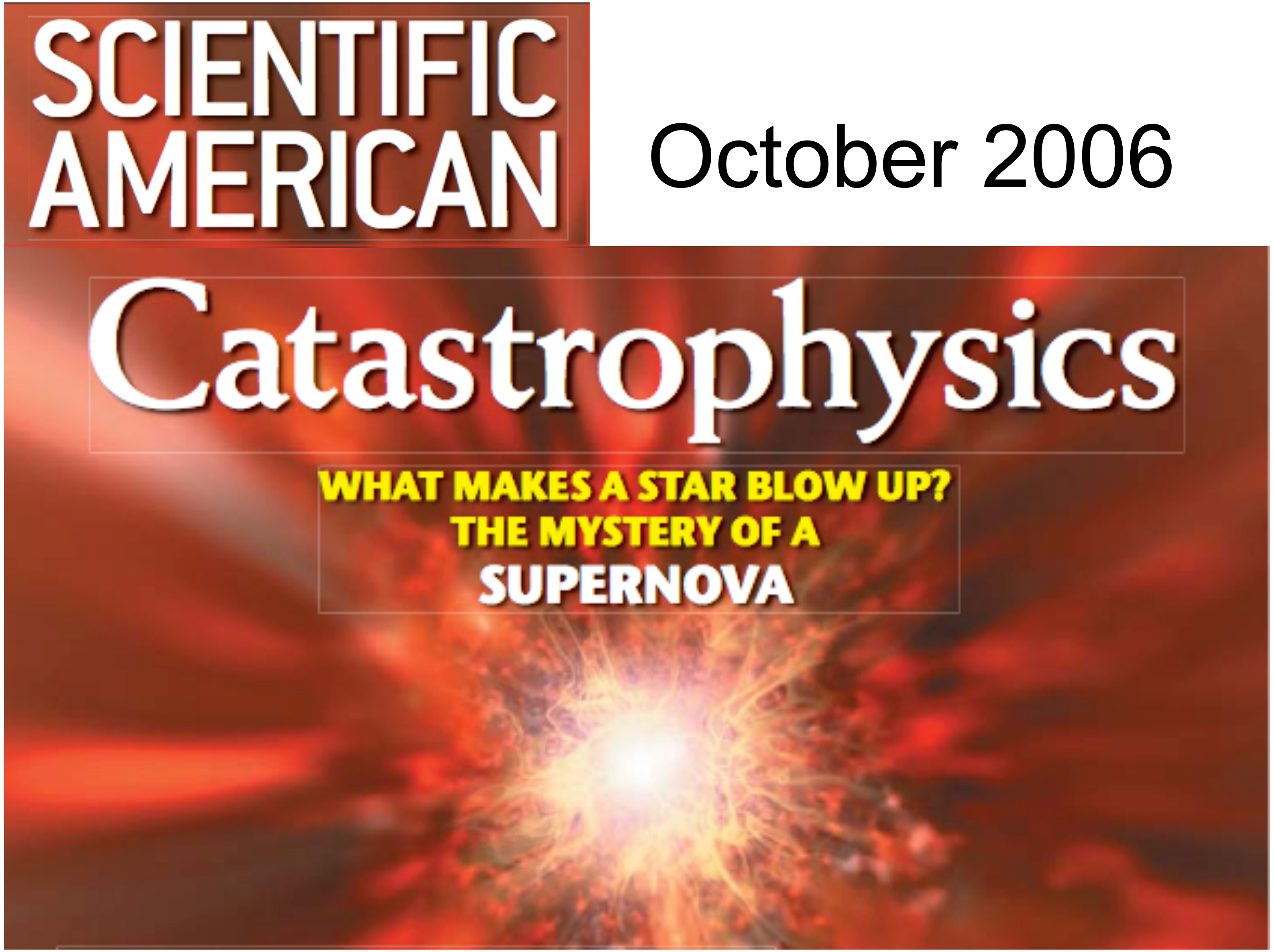
CENTER for NUCLEAR FEMTOGRAPHY SURA

Topics

- Introduction and context – supernovae
- Visualization for understanding
- Visualization for debugging/correctness
- Visualization as an essential part of a workflow
- Conclusions

Enabling understanding

- The evolution of many degrees of freedom—each used to evolve essential pieces of physics—is the central “problem” for viz in computational stellar astrophysics
  - Hydrodynamic turbulence, multi-species flows, radiation transport
- ”Eye candy” viz is not disconnected from quantitative understanding: It provides essential context.
- Sometimes, it leads directly to a deeper understanding (e.g. SASI, as we will see later)



October 2006

How to Blow Up a Star

By Wolfgang Hillebrandt, Hans-Thomas Janka and Ewald Müller

TEN SECONDS AFTER IGNITION, a thermonuclear flame has almost completed its incineration of a white dwarf star in this recent simulation. Sweeping outward from the deep interior (*cutaway*), the nuclear chain reaction has transformed carbon and oxygen (*lilac, red*) to silicon (*orange*) and iron (*yellow*). Earlier simulations, which were unable to track the turbulent motions, could not explain why stars exploded rather than dying quietly.

On November 11, 1572, Danish astronomer and nobleman Tycho Brahe saw a new star in the constellation Cassiopeia, blazing as bright as Jupiter. In many ways, it was the birth of modern astronomy—a shining disproof of the belief that the heavens were fixed and unchanging. Such "new stars" have not ceased to surprise. Some 400 years later astronomers realized that they briefly outshine billions of ordinary stars and must therefore be spectacular explosions. In 1934 Fritz Zwicky of the California Institute of Technology coined the name "supernovae" for them. Quite apart from being among the most dramatic events known to science, supernovae play a special role in the universe and in the work of astronomers: seeding space with heavy elements, regulating galaxy formation and evolution, even serving as markers of cosmic expansion.

Zwicky and his colleague Walter Baade speculated that the explosive energy comes from gravity. Their idea was that

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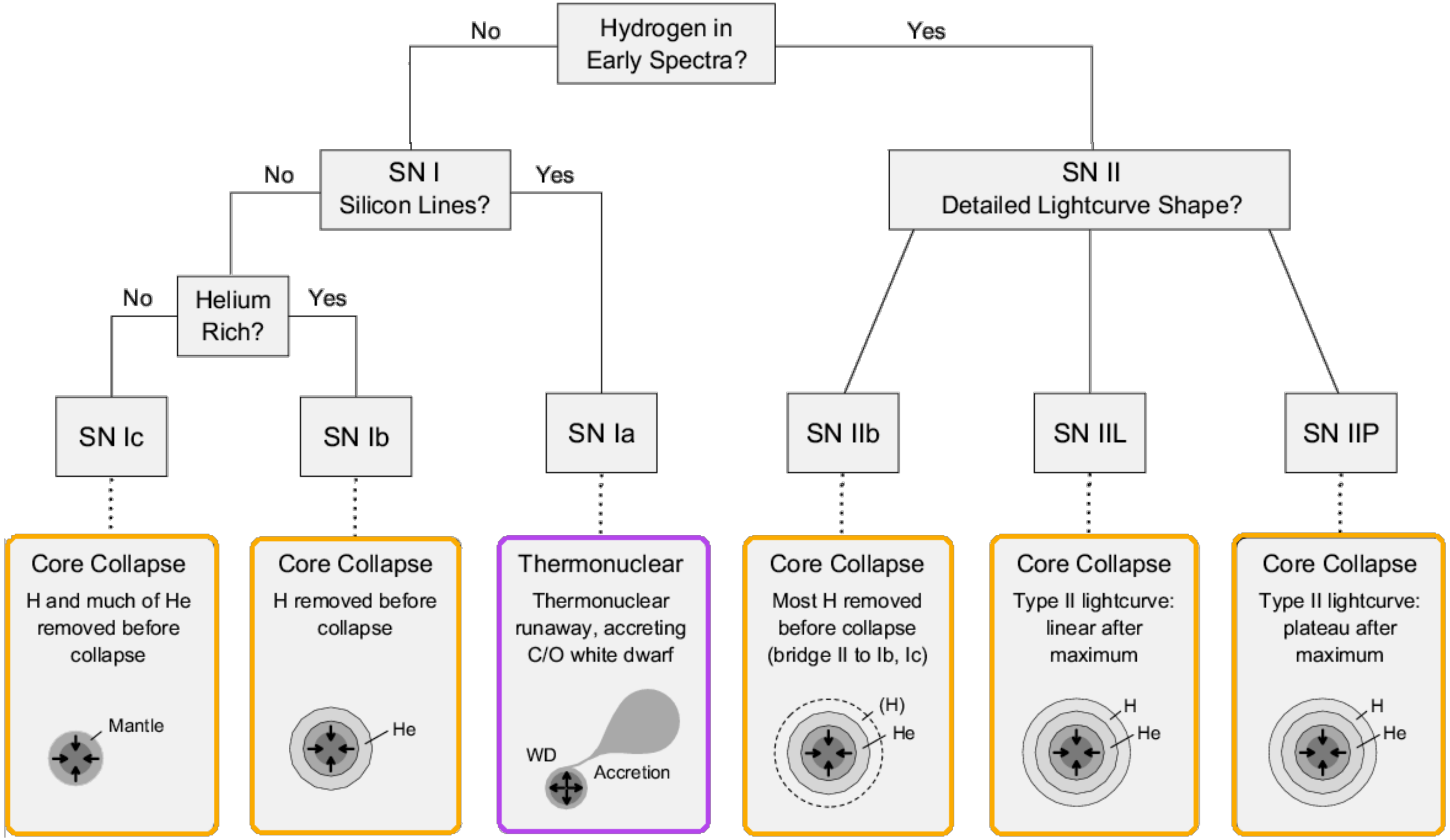
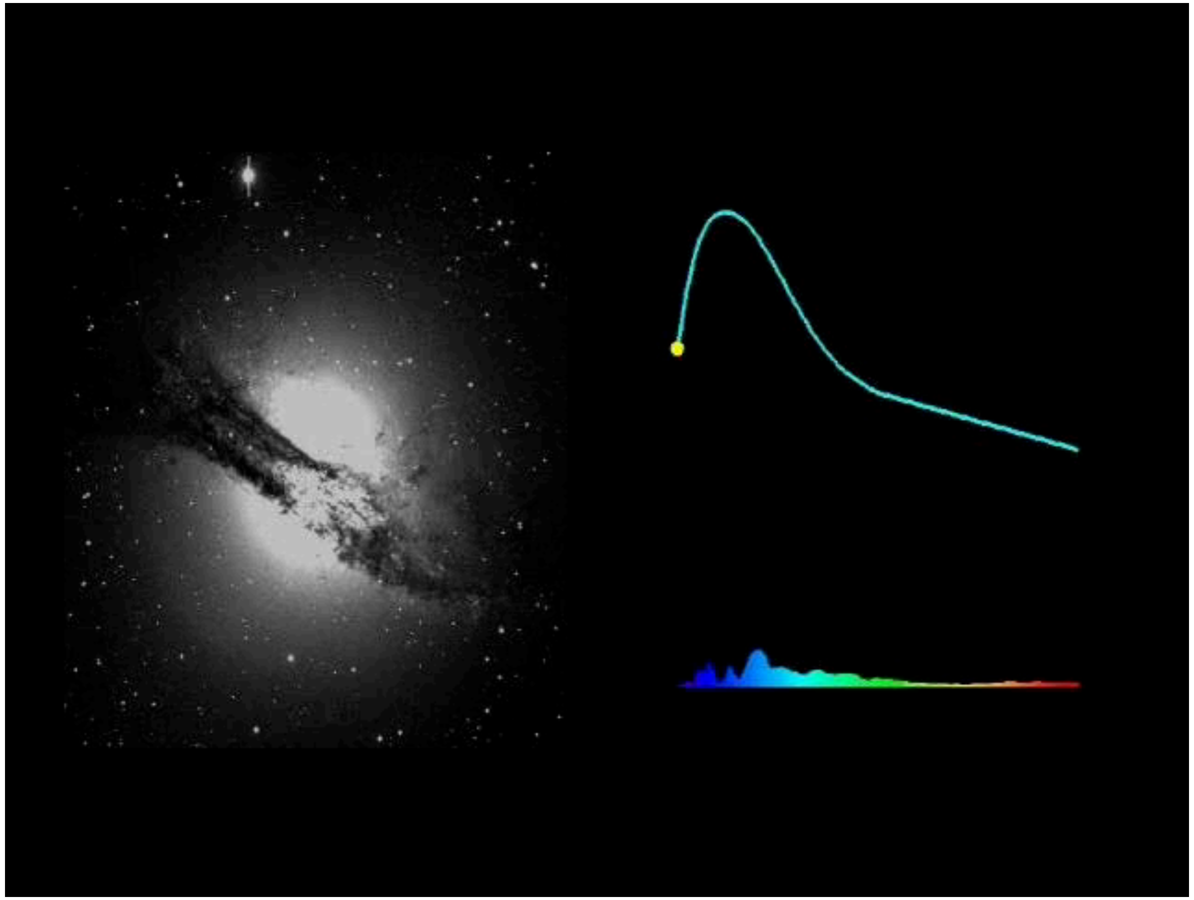
It is not as easy as you would think.

Supernova types



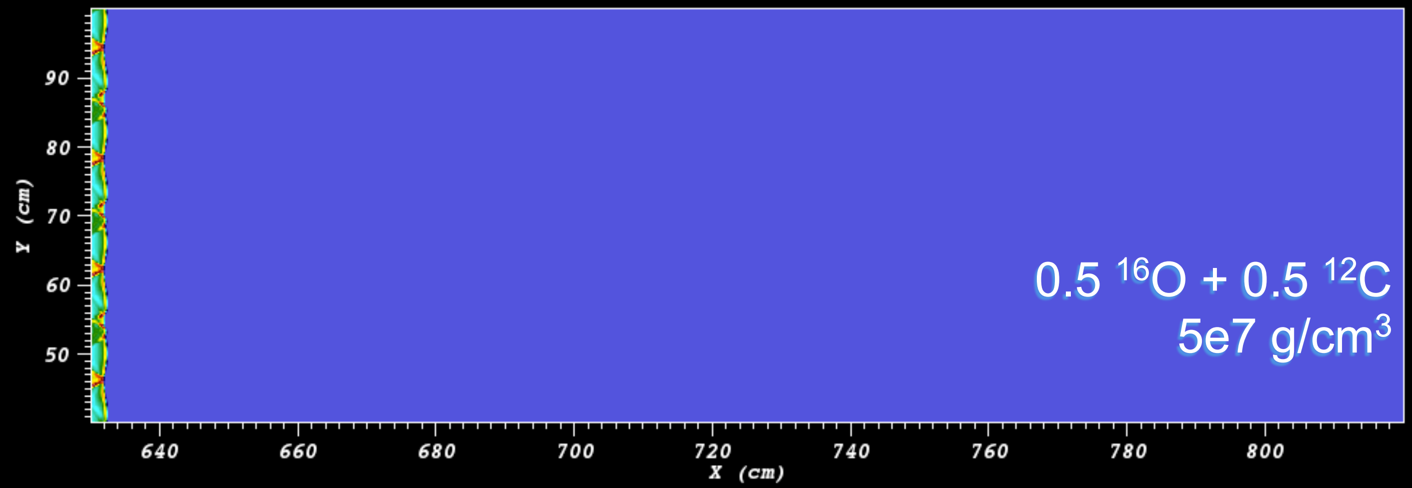
Type Ia supernovae

- Brightness rivals that of the host galaxy (L ~ 10^{43} erg/s)
- Larger amounts of radioactive ^{56}Ni produced than in CCSNe
- Radioactivity powers the light curve ("Arnett's Law")
- Not associated with star-forming regions (unlike CCSNe)
- No compact remnant - star is completely disrupted
- Likely event – the accretion-induced **thermonuclear explosion** of a white dwarf



Small scales: Detonations in WD matter

- Deflagrations make their own turbulence (RT), but detonations are also subject to instabilities.
- These instabilities can increase the burning length(time) for a given species.
  - becomes important at lower densities where these burning lengths are already $O(R_{WD})$
- Network size, resolution, and dimensionality all impact the formation of cellular structures

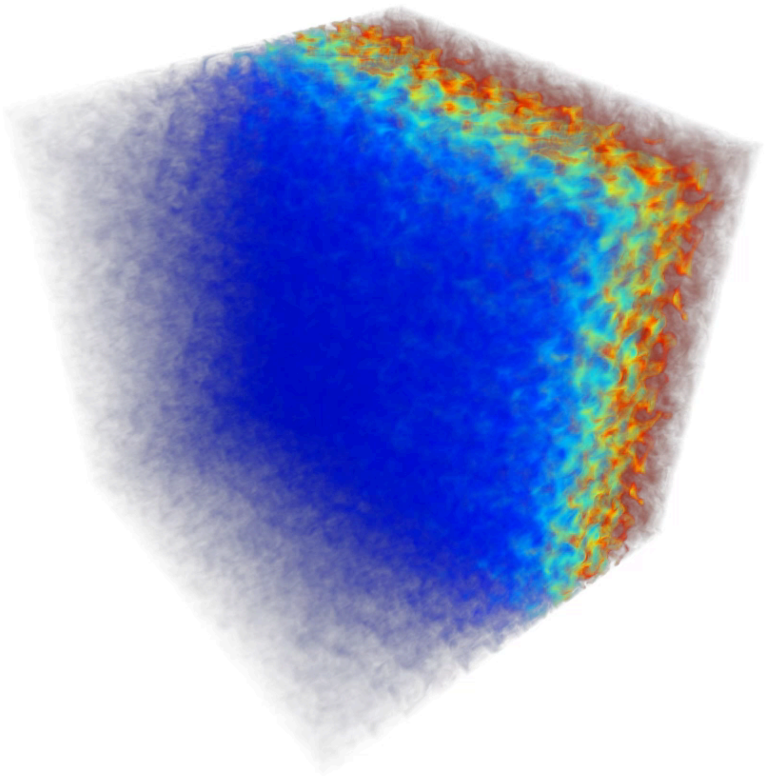


Papatheodore & Messer (2014)

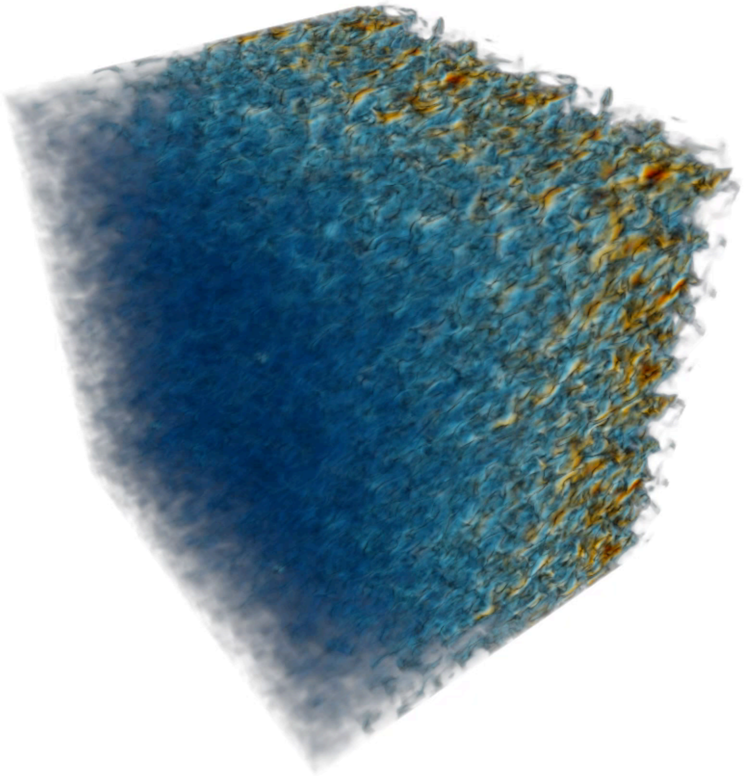
3D detonations

Papatheodore & Messer (2014)

^{16}O

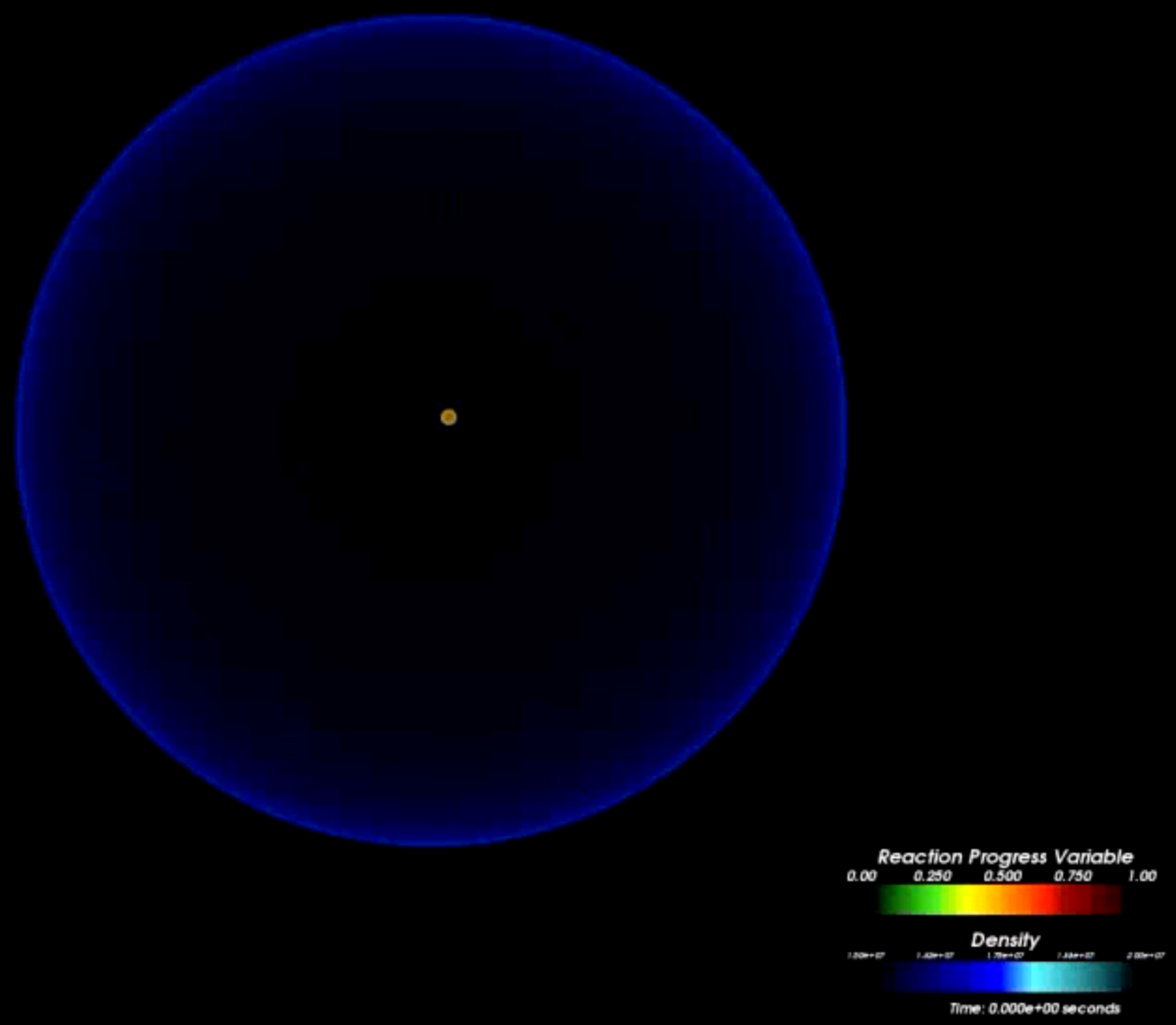


^{28}Si



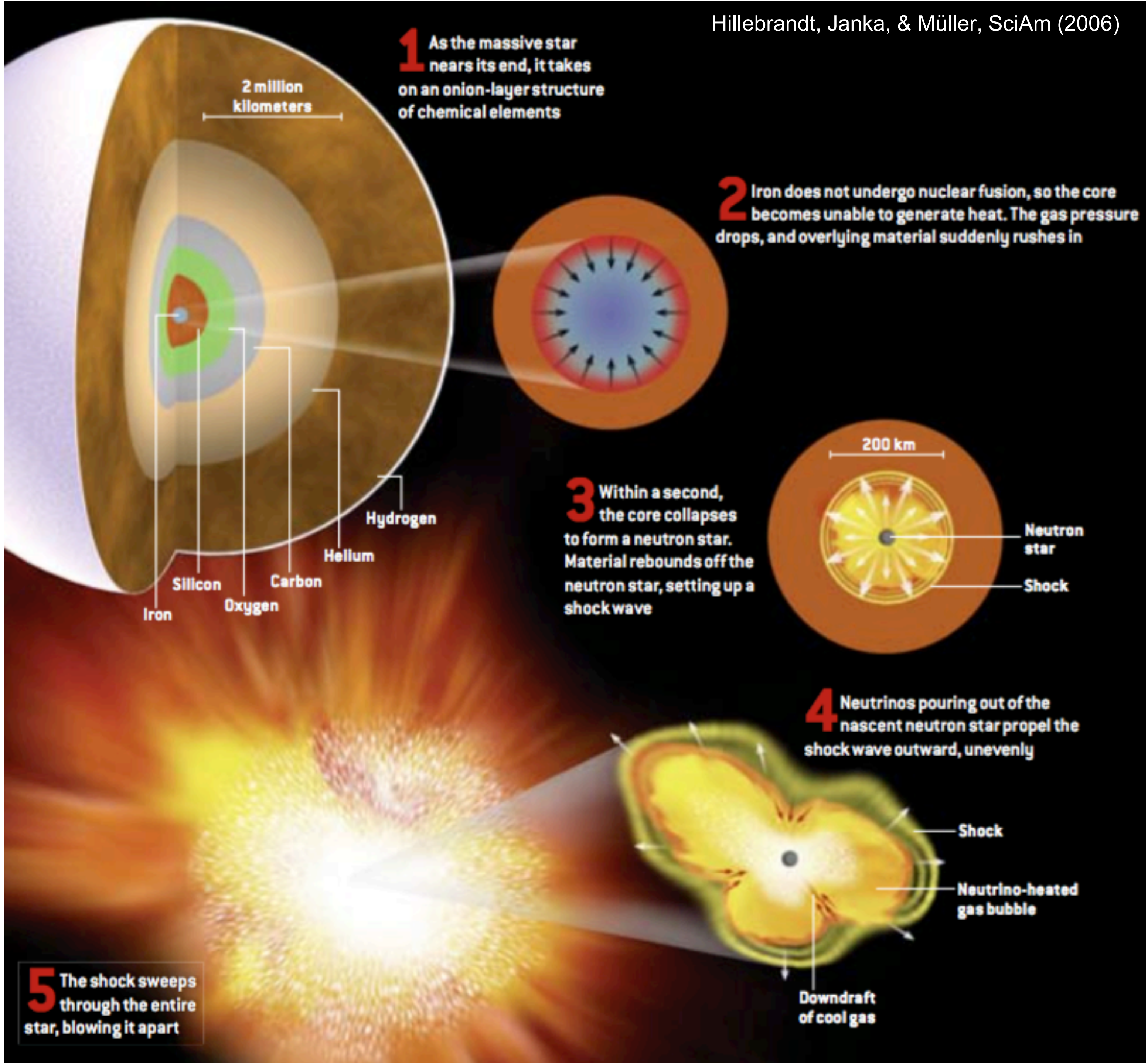
roughly 30 cm on a side

Gravitationally confined detonation

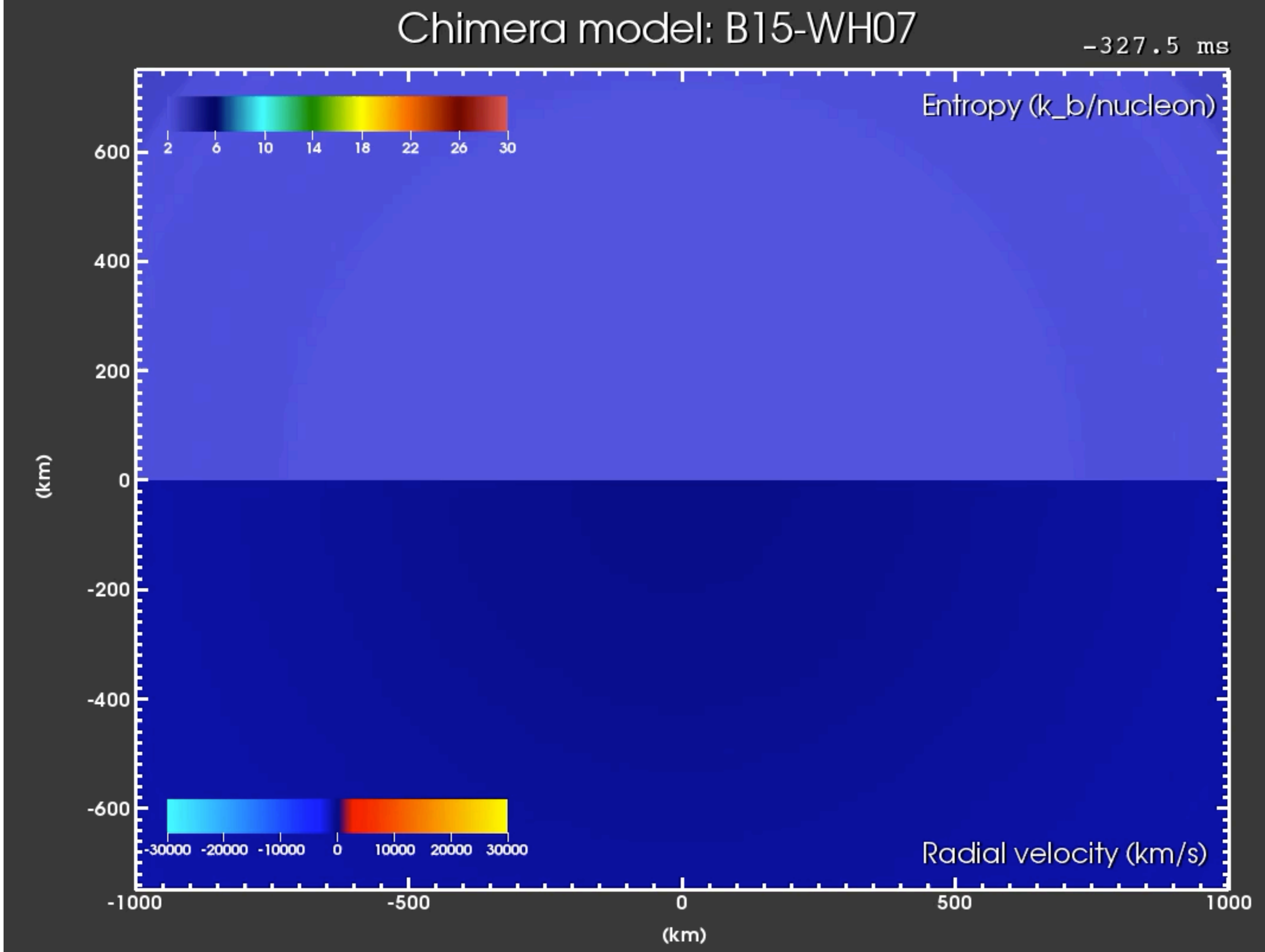


Core-collapse SNe

- Similar amount of energy release compared to SNe Ia
- Smaller amounts of radioactive ^{56}Ni produced than in SNe Ia
- Compact remnant remains: either neutron star or black hole



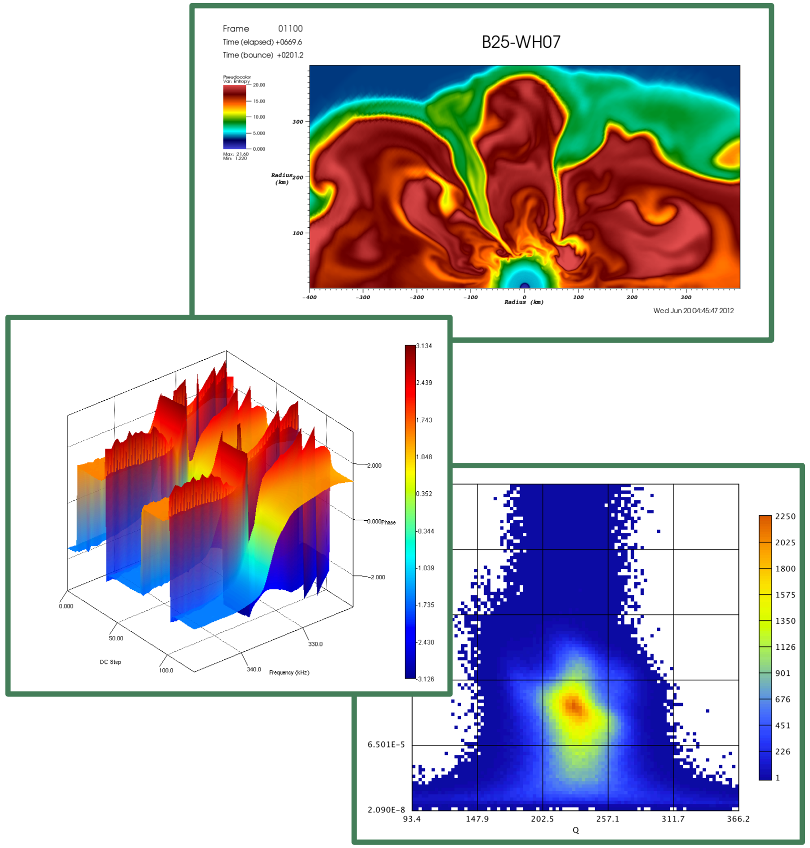
2D


Chimera model: B15-WH07
-327.5 ms
Entropy (k_b/nucleon)
2 6 10 14 18 22 26 30
600
400
200
0
-200
-400
-600
(km)
-30000 -20000 -10000 0 10000 20000 30000
Radial velocity (km/s)
-1000 -500 0 500 1000
(km)

Bellerophon | Design Approach

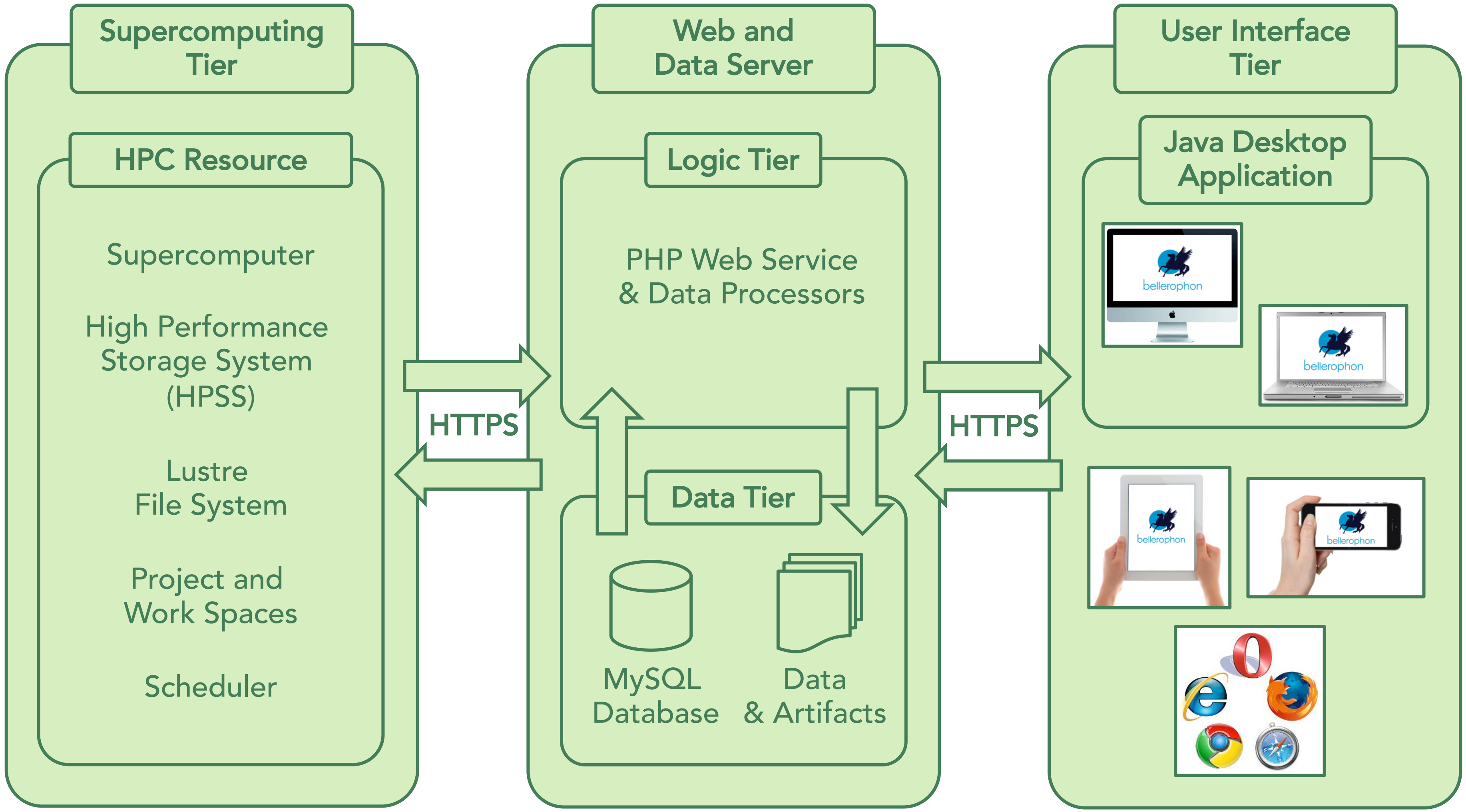
- Provide a "one-stop shop"
  - Encapsulated end-to-end solution
  - Central, easy-to-use SaaS portal
  - Fully automate cumbersome, repetitive tasks
  - Integrate (not replace) current workflow tools
    - VisIt, Trac, Subversion
- Utilize DOE HPC compute and data resources seamlessly
- **Allow authenticated access to data analysis and modeling workflows and remotely stewarded data from anywhere in the world at any time**
- Provide customizable data views using state-of-the-art, multi-dimensional visualization tools

bellerophon

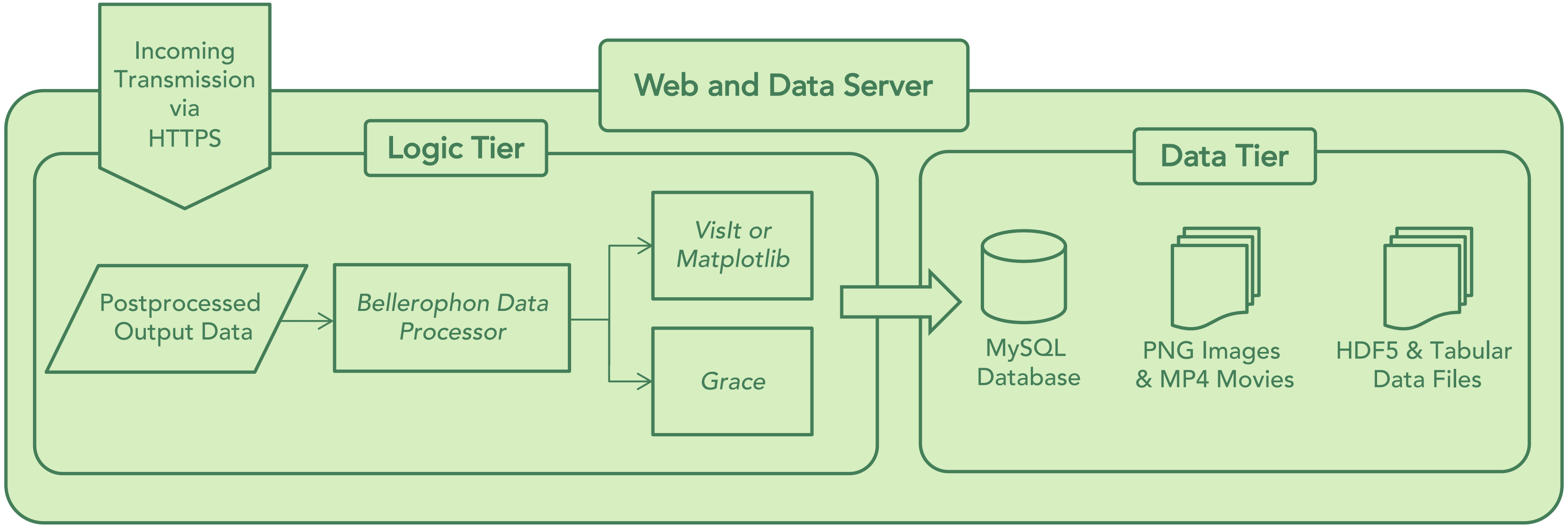


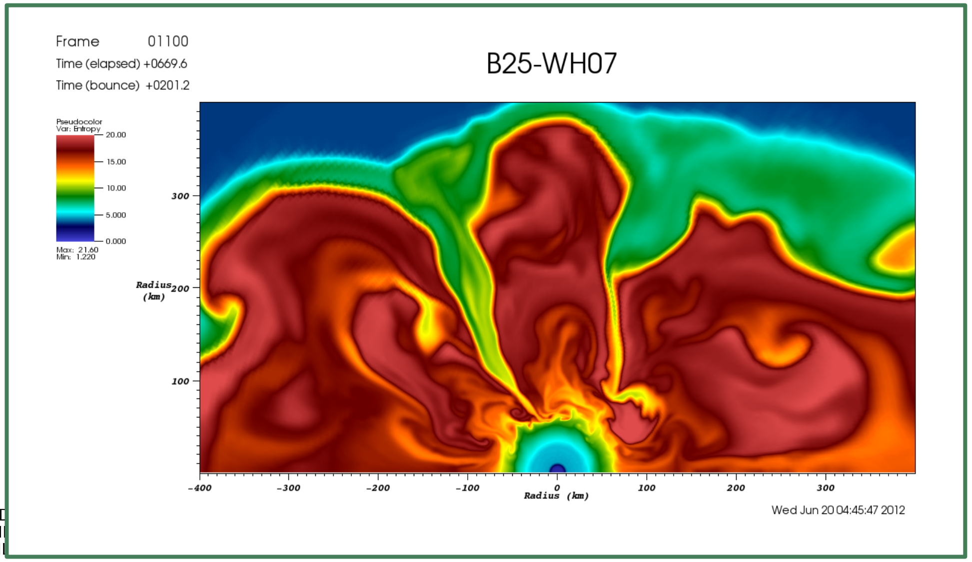
Bellerophon | Multi-tier Architecture

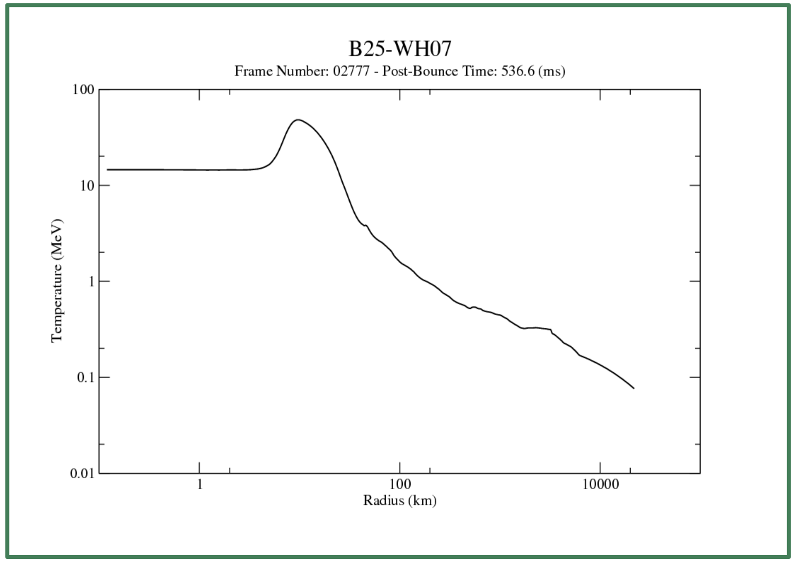
Reliable mechanism for authenticated, secure two-way communication and file transfer between all tiers.



Bellerophon | Real-time Data Analysis for Chimera

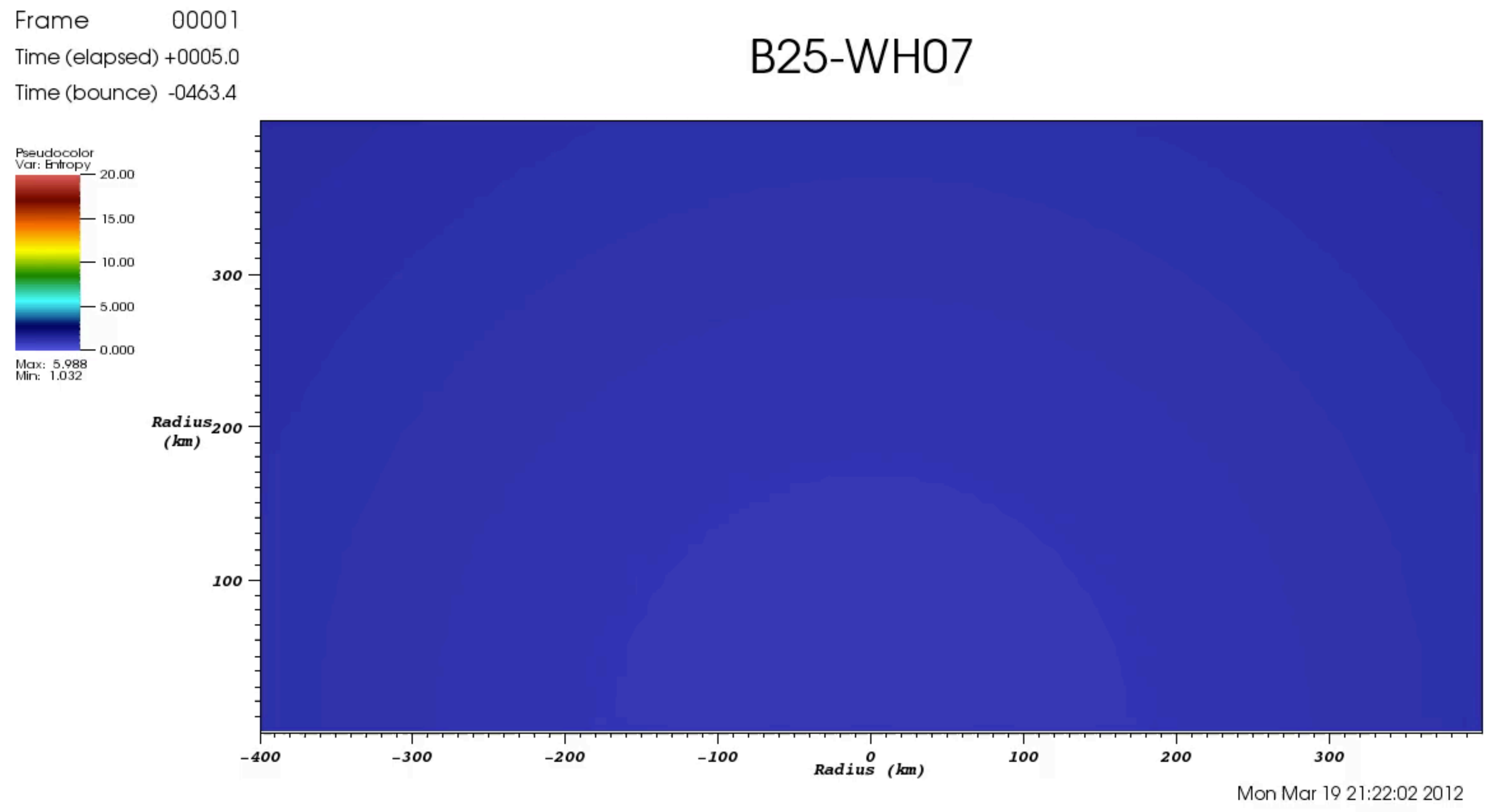




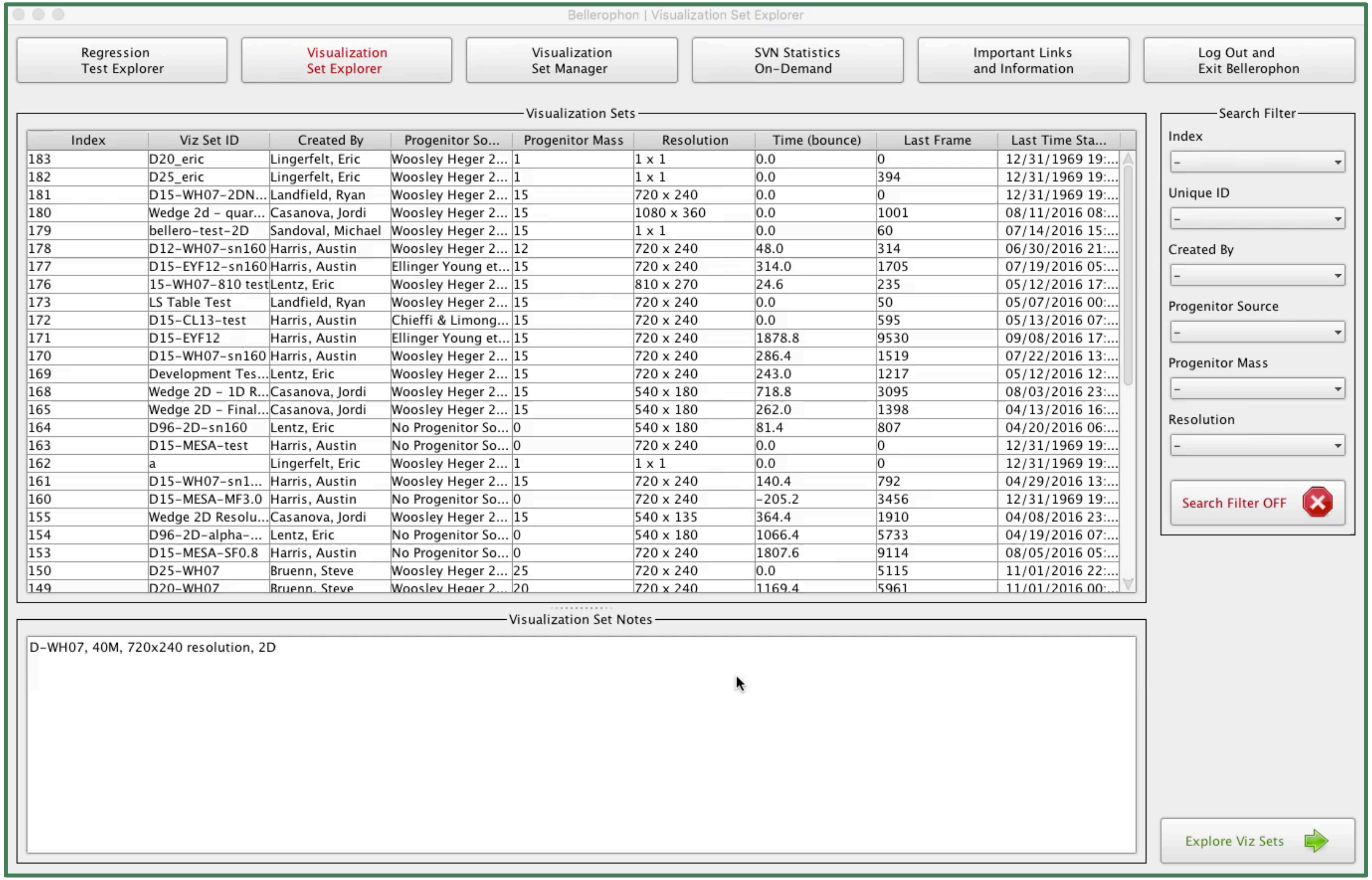


Belleraphon | Visualization Artifacts for Chimera

40 CCSn models, >150K data files, ~1150 animations comprised of 1.5 MILLION real-time rendered images – all under database management with provenance



Bellerophon | *Visualization Set Explorer* Tool



Index	Viz Set ID	Created By	Progenitor So...	Progenitor Mass	Resolution	Time (bounce)	Last Frame	Last Time Sta...
183	D20_eric	Lingerfelt, Eric	Woosley Heger 2...	1	1 x 1	0.0	0	12/31/1969 19:...
182	D25_eric	Lingerfelt, Eric	Woosley Heger 2...	1	1 x 1	0.0	394	12/31/1969 19:...
181	D15-WH07-2DN...	Landfield, Ryan	Woosley Heger 2...	15	720 x 240	0.0	0	12/31/1969 19:...
180	Wedge 2d - quar...	Casanova, Jordi	Woosley Heger 2...	15	1080 x 360	0.0	1001	08/11/2016 08:...
179	bellero-test-2D	Sandoval, Michael	Woosley Heger 2...	15	1 x 1	0.0	60	07/14/2016 15:...
178	D12-WH07-sn160	Harris, Austin	Woosley Heger 2...	12	720 x 240	48.0	314	06/30/2016 21:...
177	D15-EYF12-sn160	Harris, Austin	Ellinger Young et...	15	720 x 240	314.0	1705	07/19/2016 05:...
176	15-WH07-810 test	Lentz, Eric	Woosley Heger 2...	15	810 x 270	24.6	235	05/12/2016 17:...
173	LS Table Test	Landfield, Ryan	Woosley Heger 2...	15	720 x 240	0.0	50	05/07/2016 00:...
172	D15-CL13-test	Harris, Austin	Chieffi & Limong...	15	720 x 240	0.0	595	05/13/2016 07:...
171	D15-EYF12	Harris, Austin	Ellinger Young et...	15	720 x 240	1878.8	9530	09/08/2016 17:...
170	D15-WH07-sn160	Harris, Austin	Woosley Heger 2...	15	720 x 240	286.4	1519	07/22/2016 13:...
169	Development Tes...	Lentz, Eric	Woosley Heger 2...	15	720 x 240	243.0	1217	05/12/2016 12:...
168	Wedge 2D - 1D R...	Casanova, Jordi	Woosley Heger 2...	15	540 x 180	718.8	3095	08/03/2016 23:...
165	Wedge 2D - Final...	Casanova, Jordi	Woosley Heger 2...	15	540 x 180	262.0	1398	04/13/2016 16:...
164	D96-2D-sn160	Lentz, Eric	No Progenitor So...	0	540 x 180	81.4	807	04/20/2016 06:...
163	D15-MESA-test	Harris, Austin	No Progenitor So...	0	720 x 240	0.0	0	12/31/1969 19:...
162	a	Lingerfelt, Eric	Woosley Heger 2...	1	1 x 1	0.0	0	12/31/1969 19:...
161	D15-WH07-sn1...	Harris, Austin	Woosley Heger 2...	15	720 x 240	140.4	792	04/29/2016 13:...
160	D15-MESA-MF3.0	Harris, Austin	No Progenitor So...	0	720 x 240	-205.2	3456	12/31/1969 19:...
155	Wedge 2D Resolu...	Casanova, Jordi	Woosley Heger 2...	15	540 x 135	364.4	1910	04/08/2016 23:...
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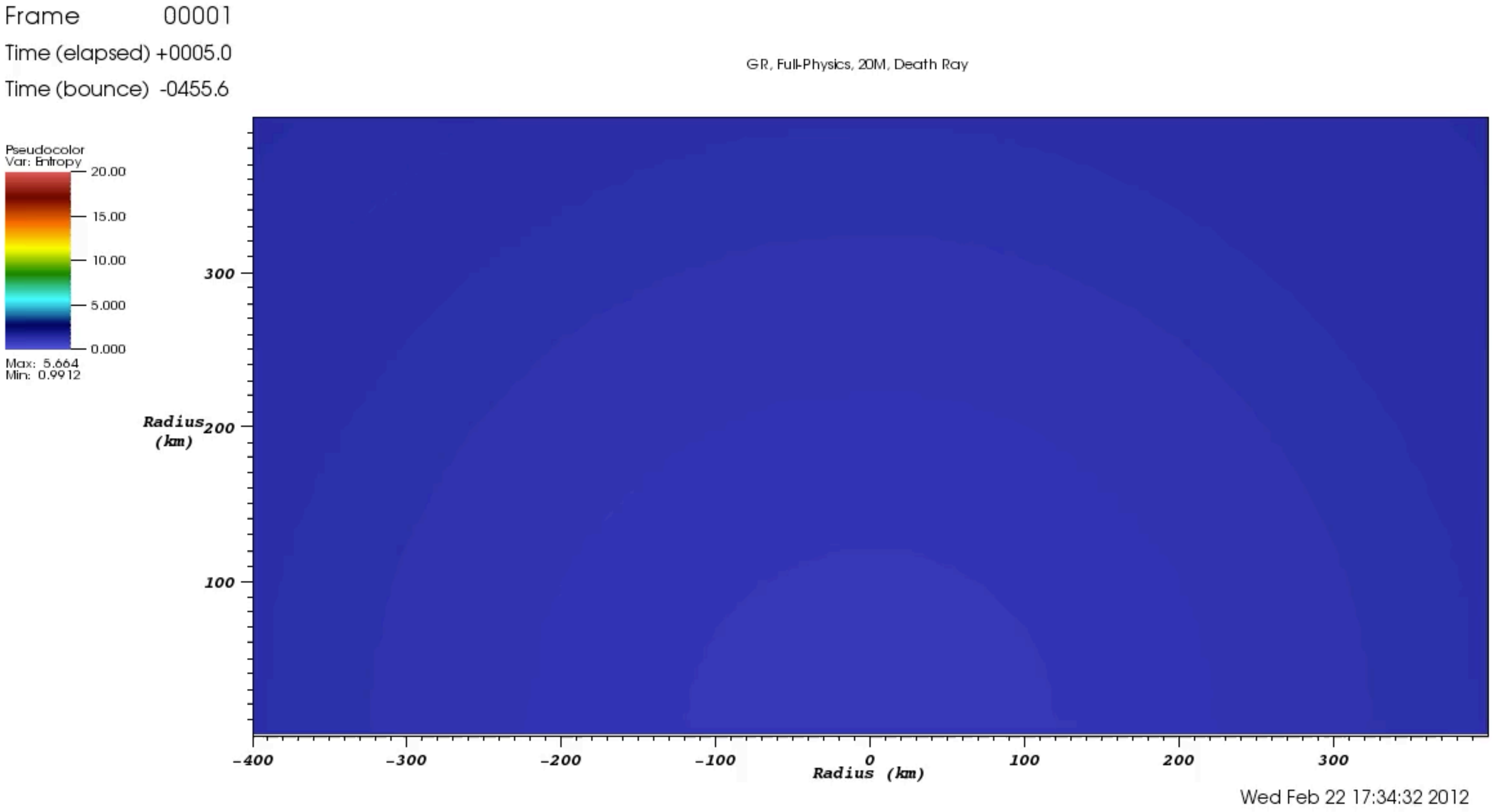
153	D15-MESA-SF0.8	Harris, Austin	No Progenitor So...	0	720 x 240	1807.6	9114	08/05/2016 05:...
150	D25-WH07	Bruenn, Steve	Woosley Heger 2...	25	720 x 240	0.0	5115	11/01/2016 22:...
149	D20-WH07	Bruenn, Steve	Woosley Heger 2...	20	720 x 240	1169.4	5961	11/01/2016 00:...

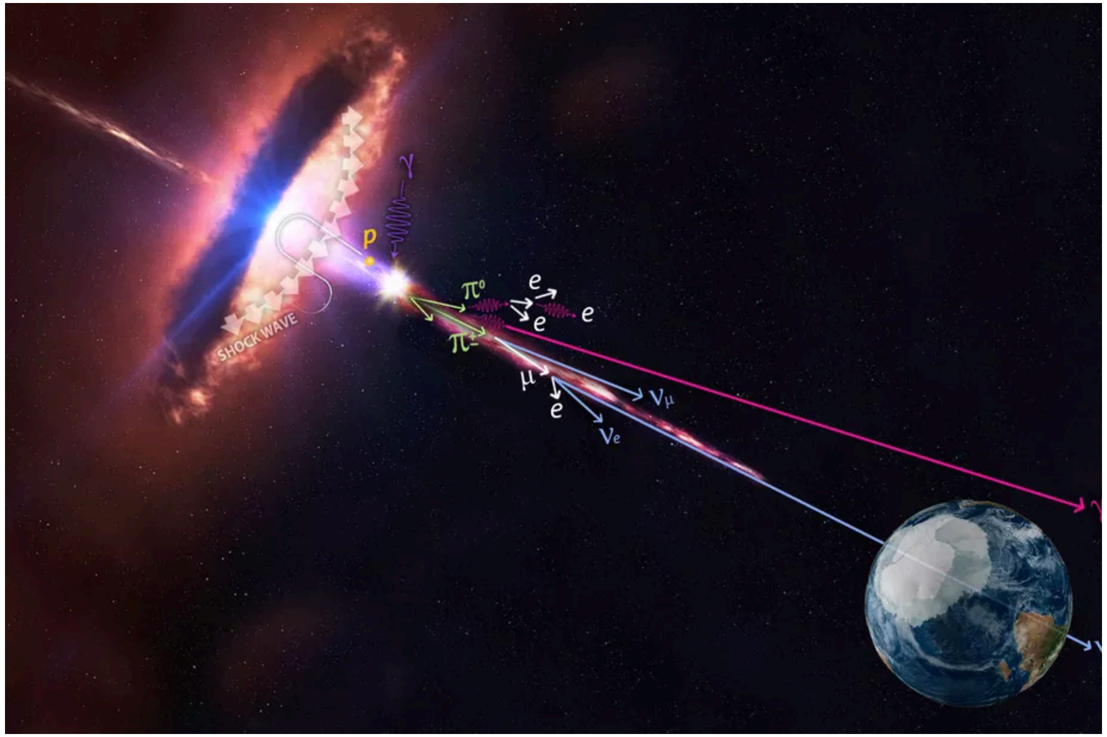
Bellerophon | *Important links and Information* Tool

The known unknowns, the unknown unknowns…



There are more things in Heaven and Earth…

"Extensive background radiation studies by IBM in the 1990s suggest that computers typically experience about one cosmic-ray-induced error per 256 megabytes of RAM per month. If so, a superstorm, with its unprecedented radiation fluxes, could cause widespread computer failures. Fortunately, in such instances most users could simply reboot" (*Supplement to the feature "Bracing the Satellite Infrastructure for a Solar Superstorm," August 2008 issue,* Scientific American.)

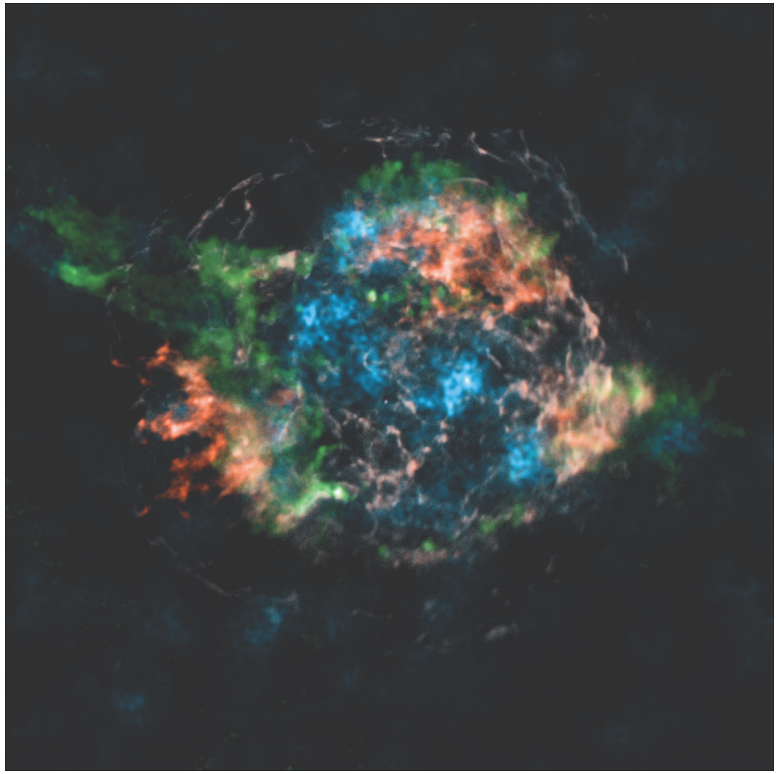


"While double bit flips were deemed unlikely, the density of DIMMs at Oak Ridge National Lab's Cray XT5 causes them ***to occur on a daily basis*** (at a rate of one per day for 75,000+ DIMMs)" (Fiala+, 2012)

CCSNe in nature are 3D

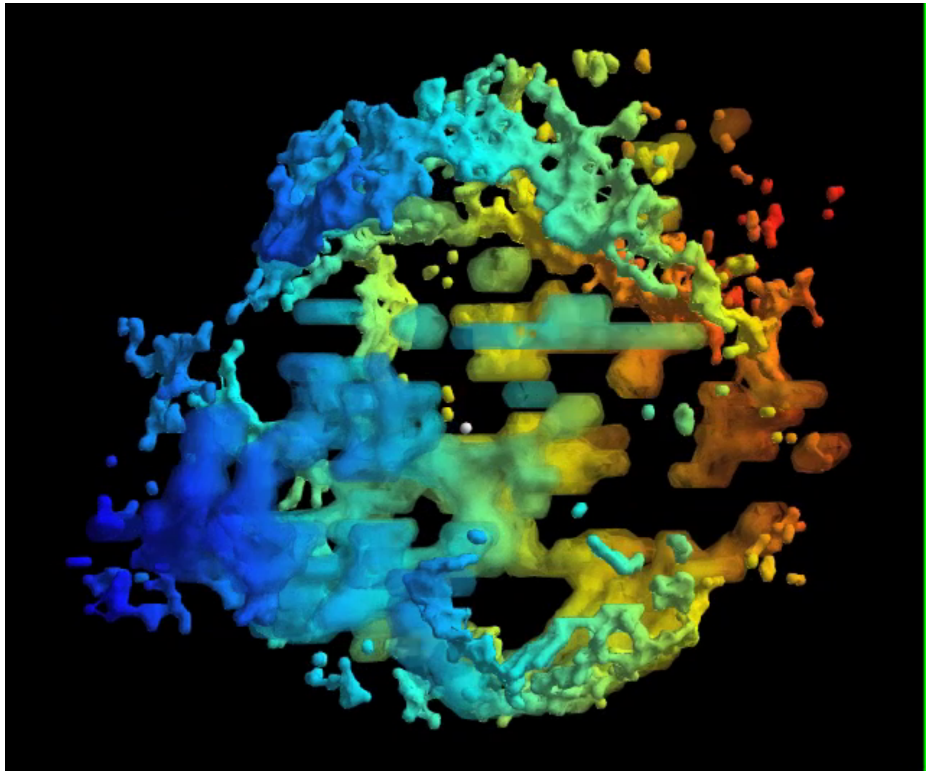
Beyond total yields, reconciling nucleosynthesis calculations and observations require following the explosion to the stellar surface (and beyond).

X-ray: Si/Mg, ^{44}Ti, Fe



Grefenstette+ (2014)

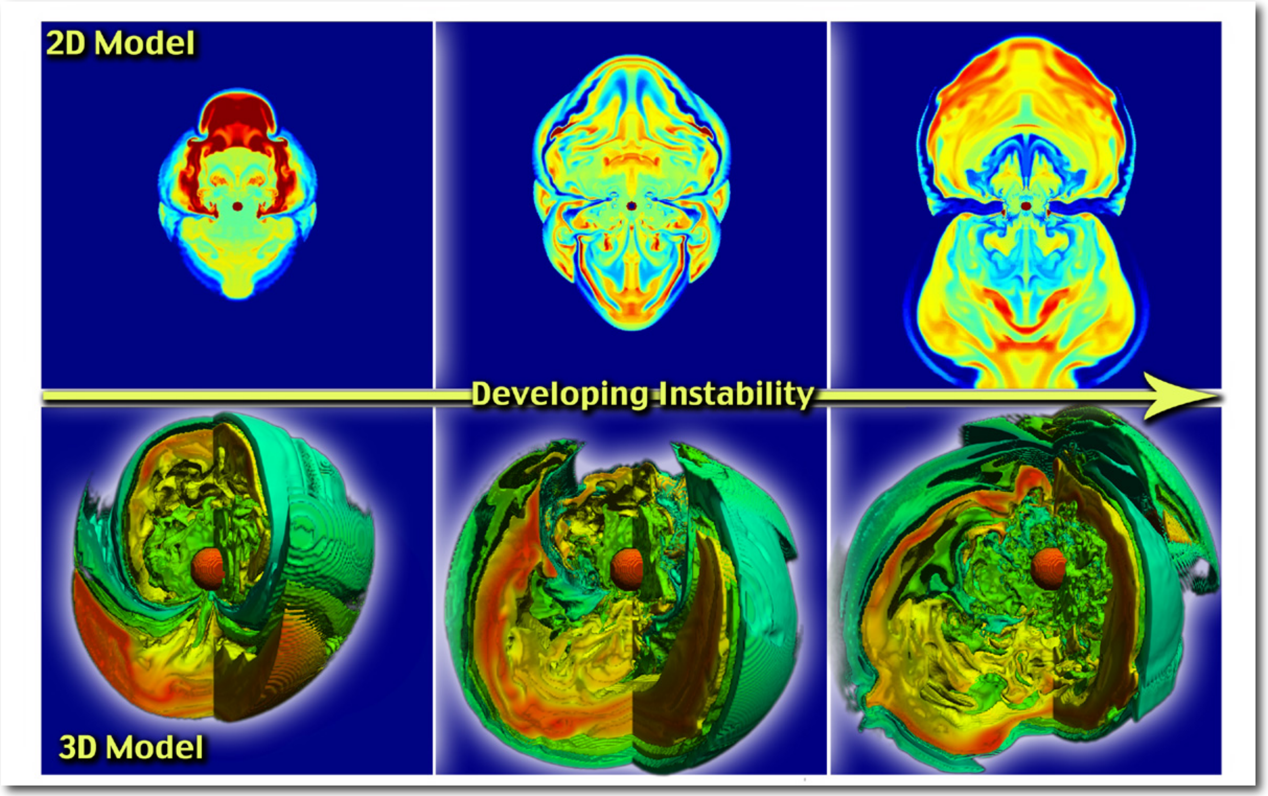
Infrared: Sulfur



Milisavljevic & Fesen (2015)

Interaction with the envelope, particularly the shell interfaces, continues to shape the ejecta.

Stationary Accretion Shock Instability (SASI)

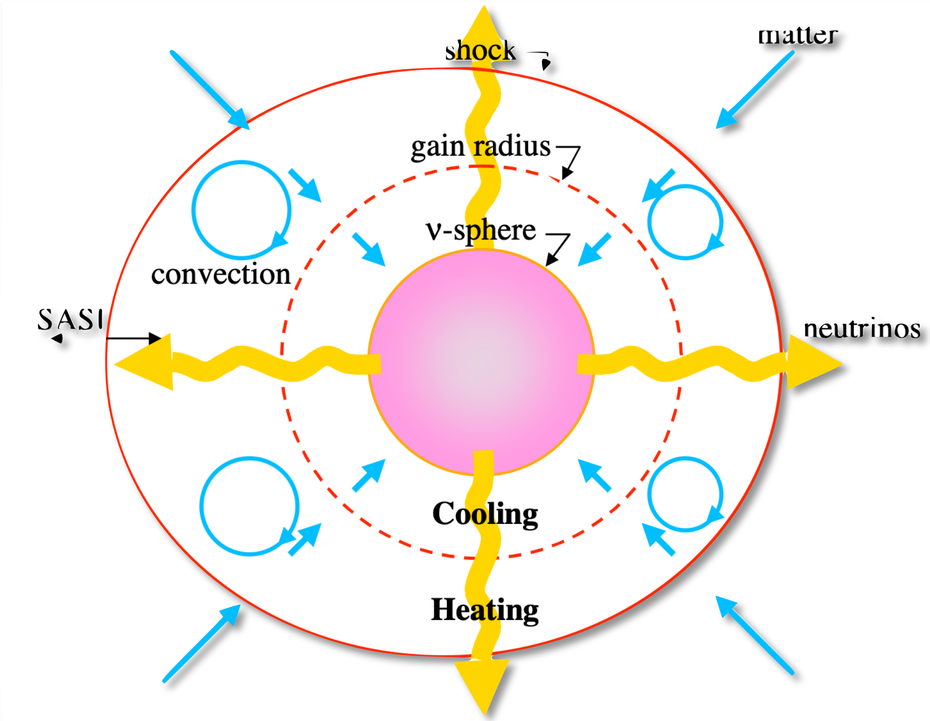


Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

Shock wave unstable to non-radial perturbations.

Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

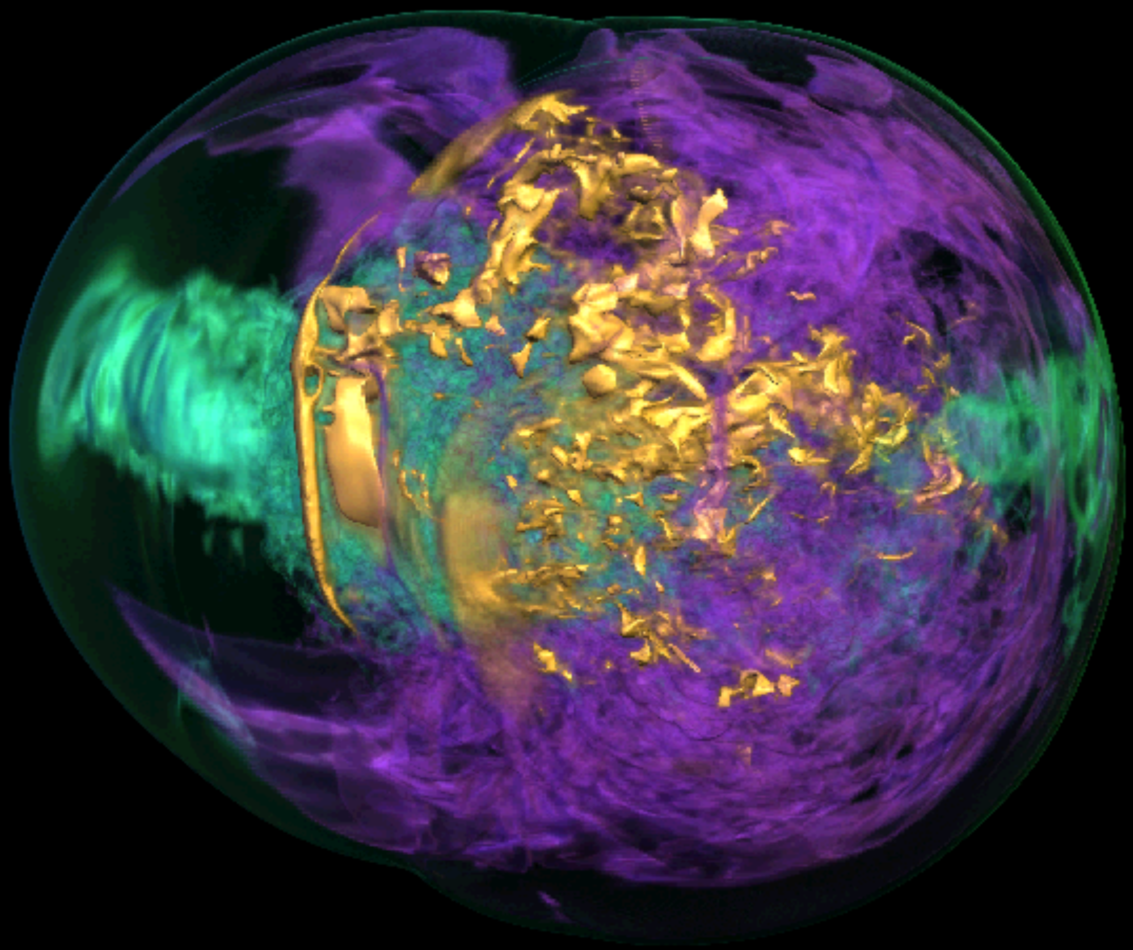
- Decreases advection velocity in gain region.
- Increases time in the gain region.
- Generates convection.



SASI has *axisymmetric and nonaxisymmetric* modes that are both linearly unstable!

– Blondin and Mezzacappa, *Ap.J.* **642**, 401 (2006)
– Blondin and Shaw, *Ap.J.* **656**, 366 (2007)

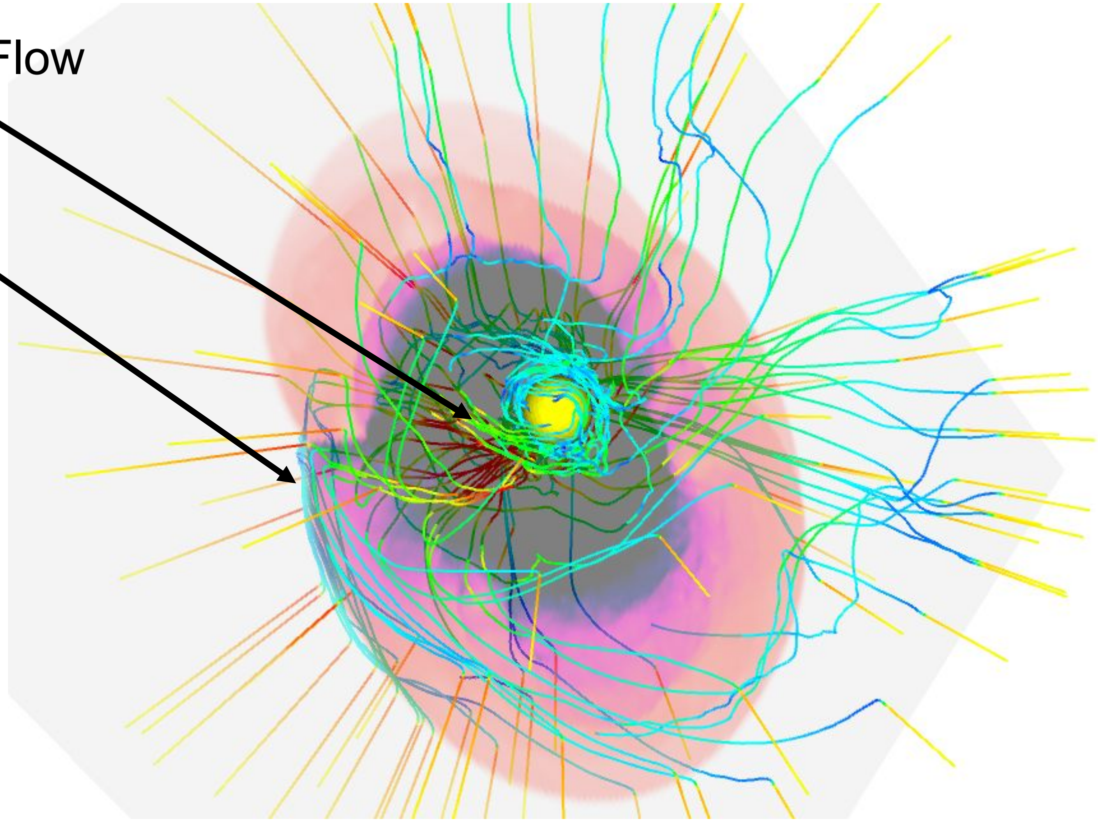
SASI in 3D



Blondin & Mezzacappa *Nature* **445**, 58 (2007)

Generating Pulsar Spin in Supernovae

SASI-Induced Rotational Flow



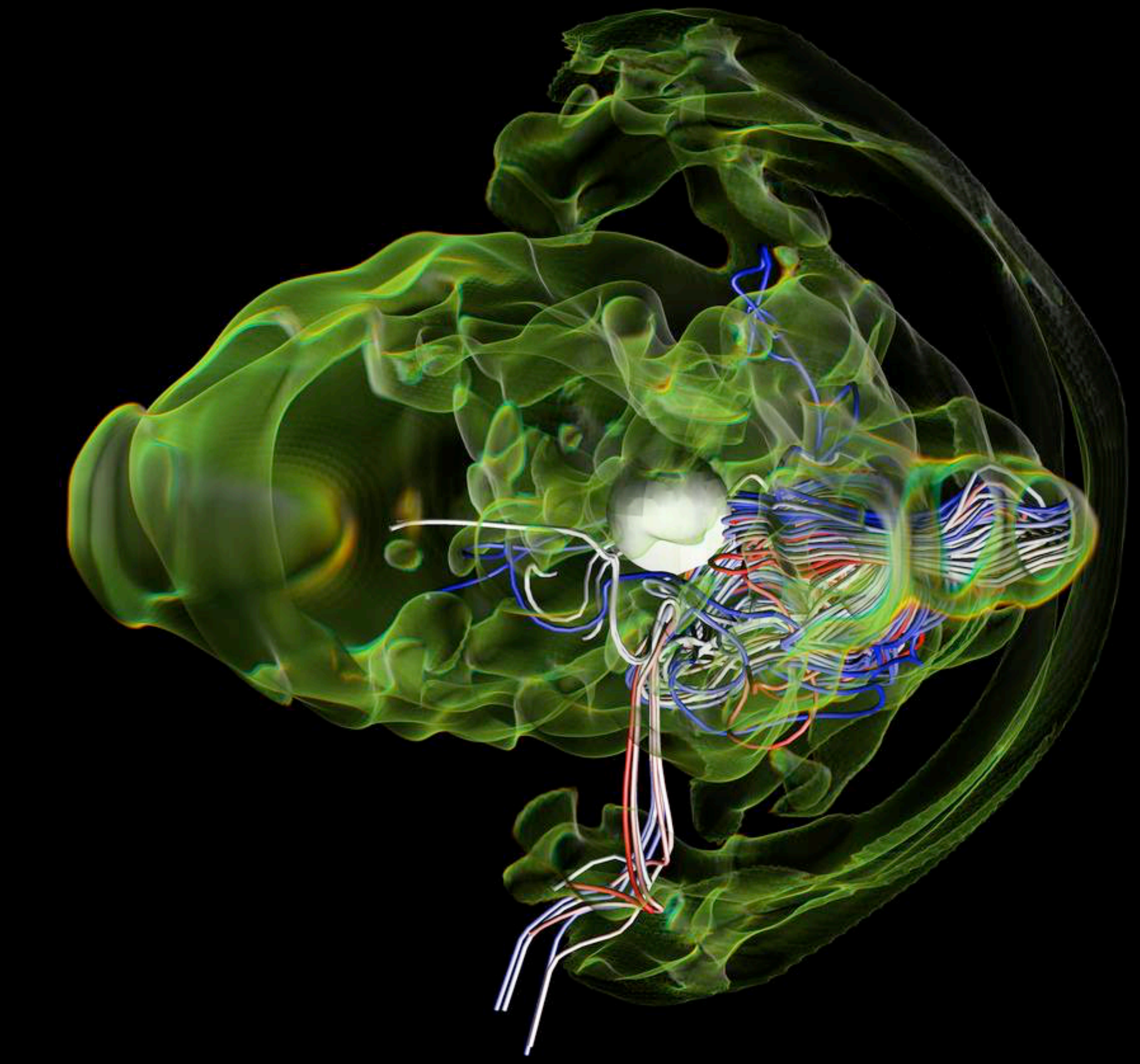
Visualization was the only reason this mechanism was posited!

Blondin and Mezzacappa (2006)

Deduced pulsar spin period from deposited angular momentum: 50 ms!
Consistent with pulsar observations.

OK, some eye candy…

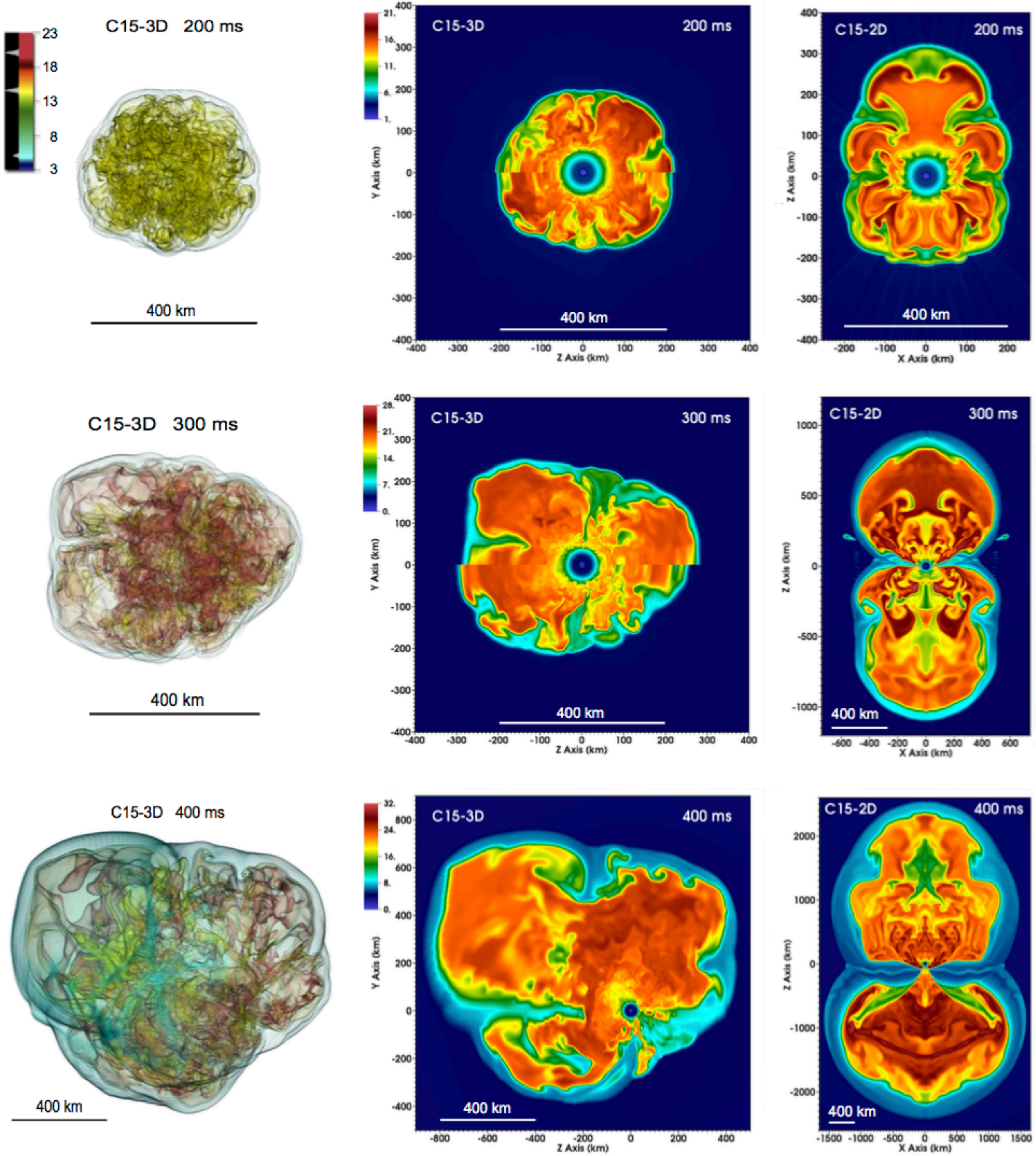
- This image from an MHD version of the SASI graced the front of Titan for >7 years.

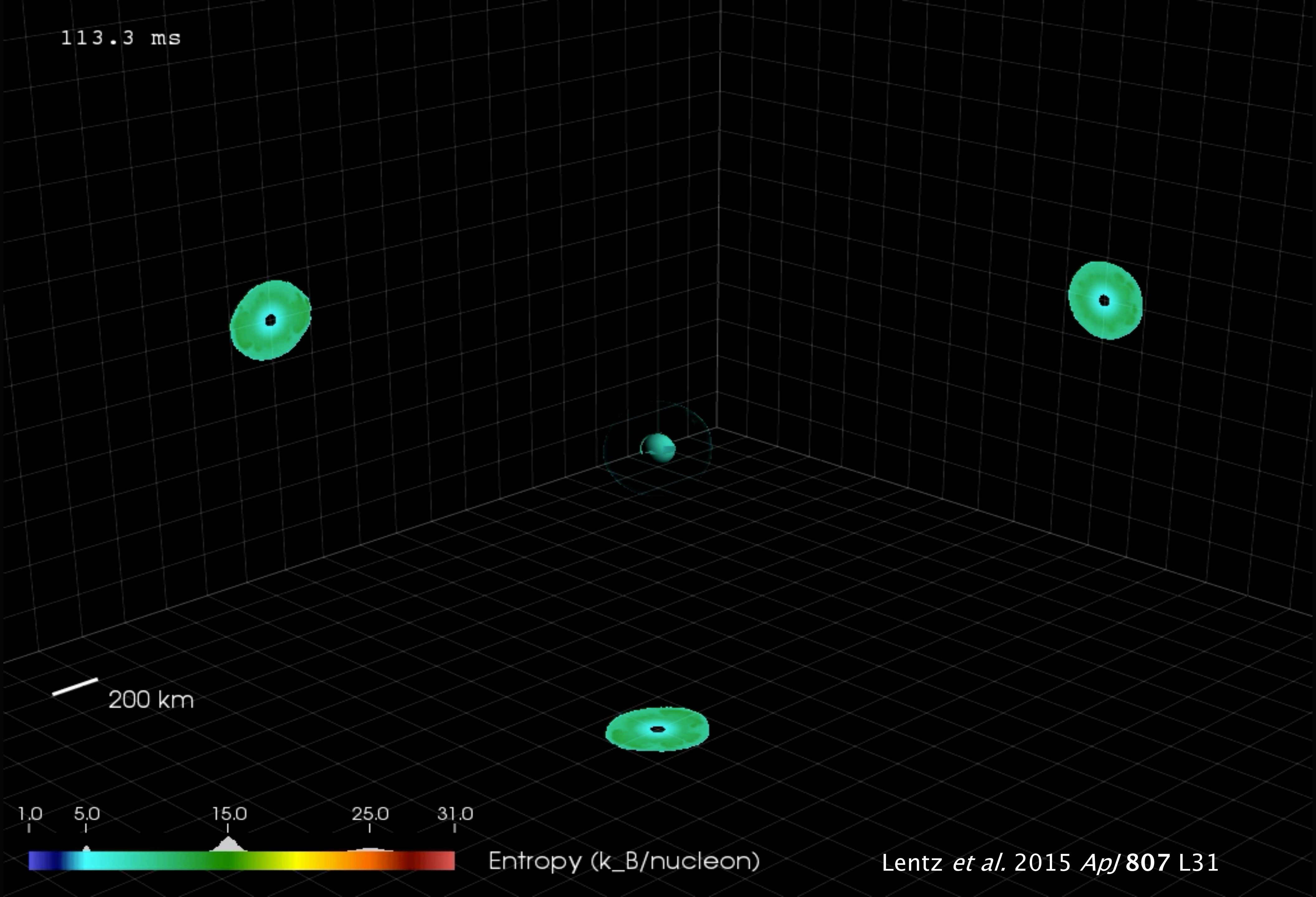


Cardall+ (2012)

3D

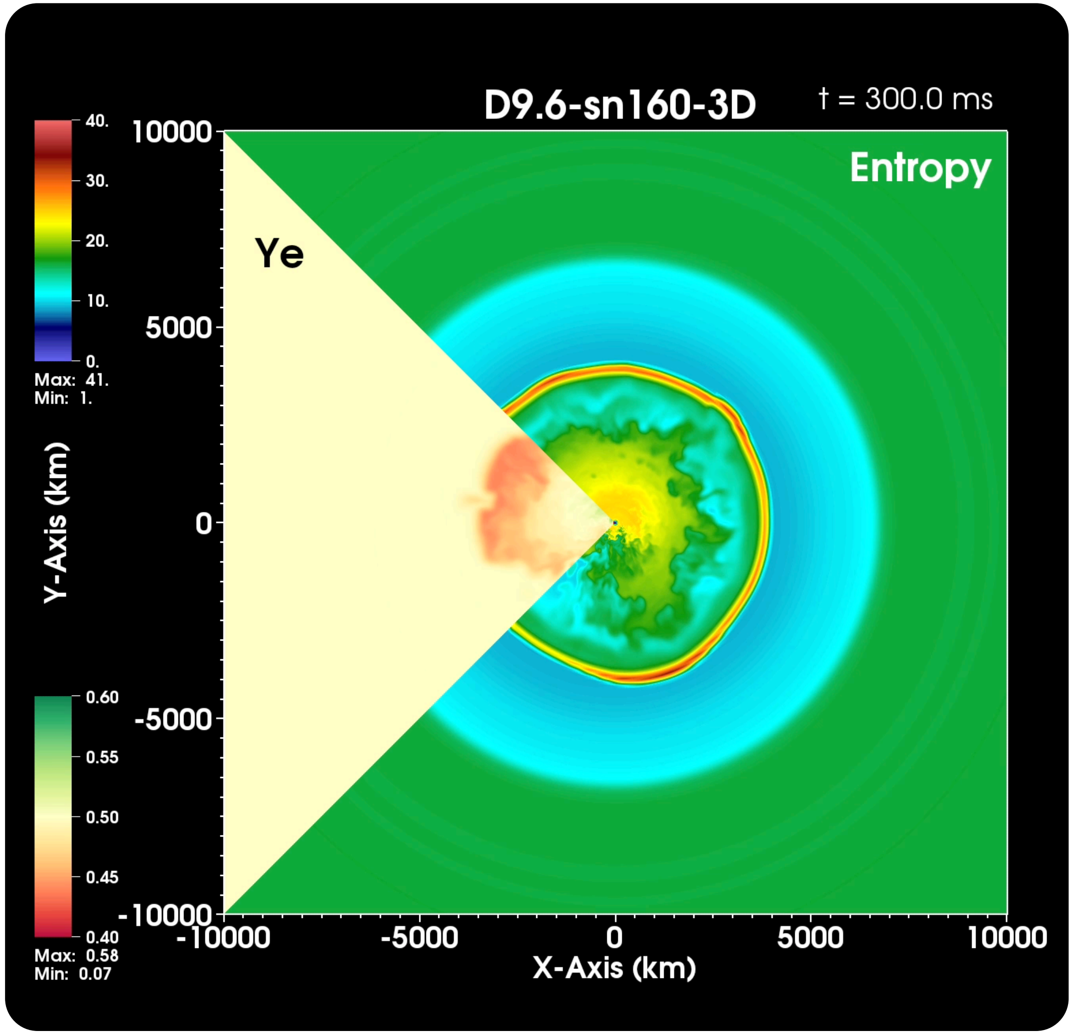
Lentz, et al. (2015)




113.3 ms
200 km
1.0
5.0
15.0
25.0
31.0
Entropy (k_B/nucleon)
Lentz *et al.* 2015 *ApJ* **807** L31

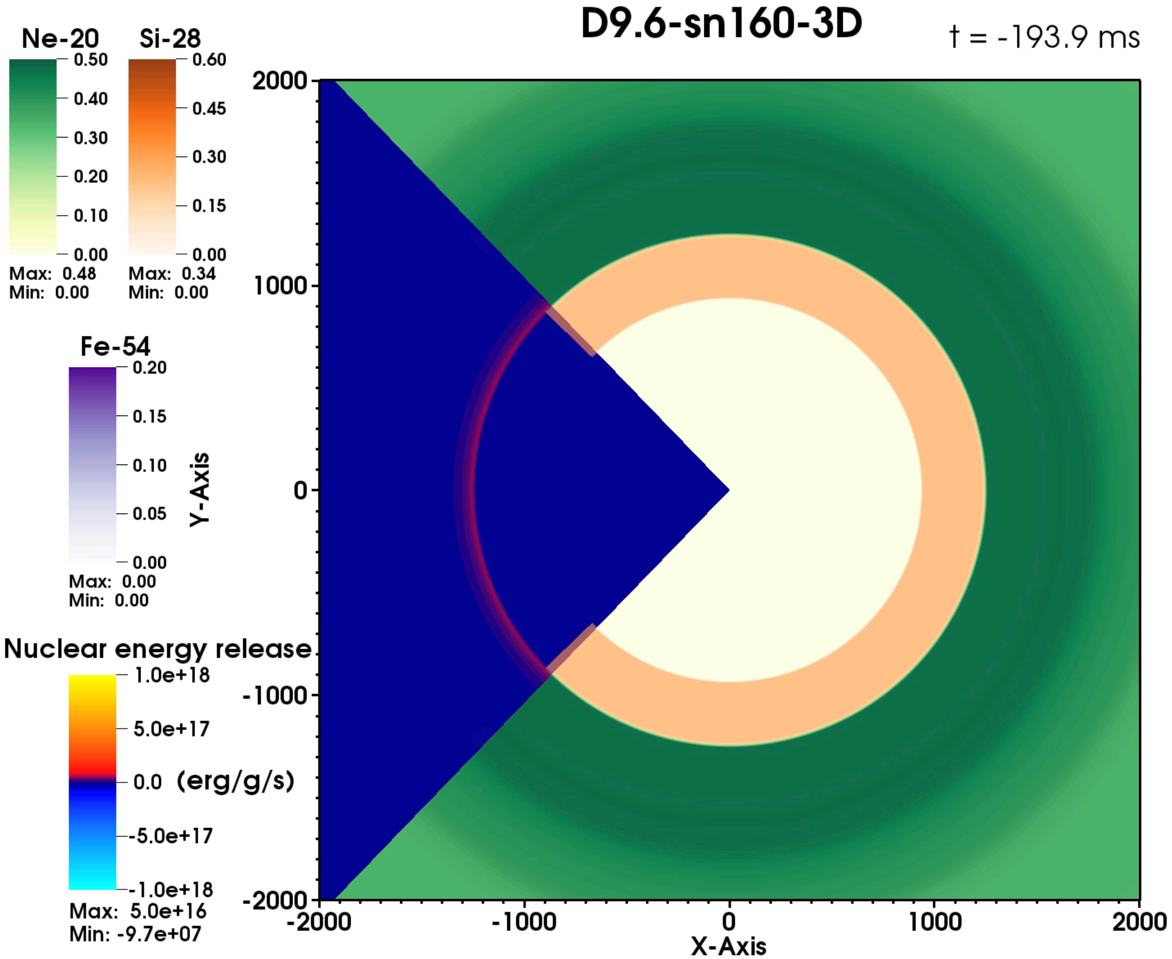
3D CCSNe with large networks

- We are also exploring 3D models with large networks, with one model completed, a 9.6 solar mass, zero metallicity star from Heger.
- As Melson et al (2015) showed, this progenitor behaves like a ONe core.
- Model exhibits a pre-bounce Silicon Flash.
- Convection near the edge of the newborn PNS dredges up neutron-rich matter, which is followed by neutrino-driven wind.
- Overall explosion is quite spherical.



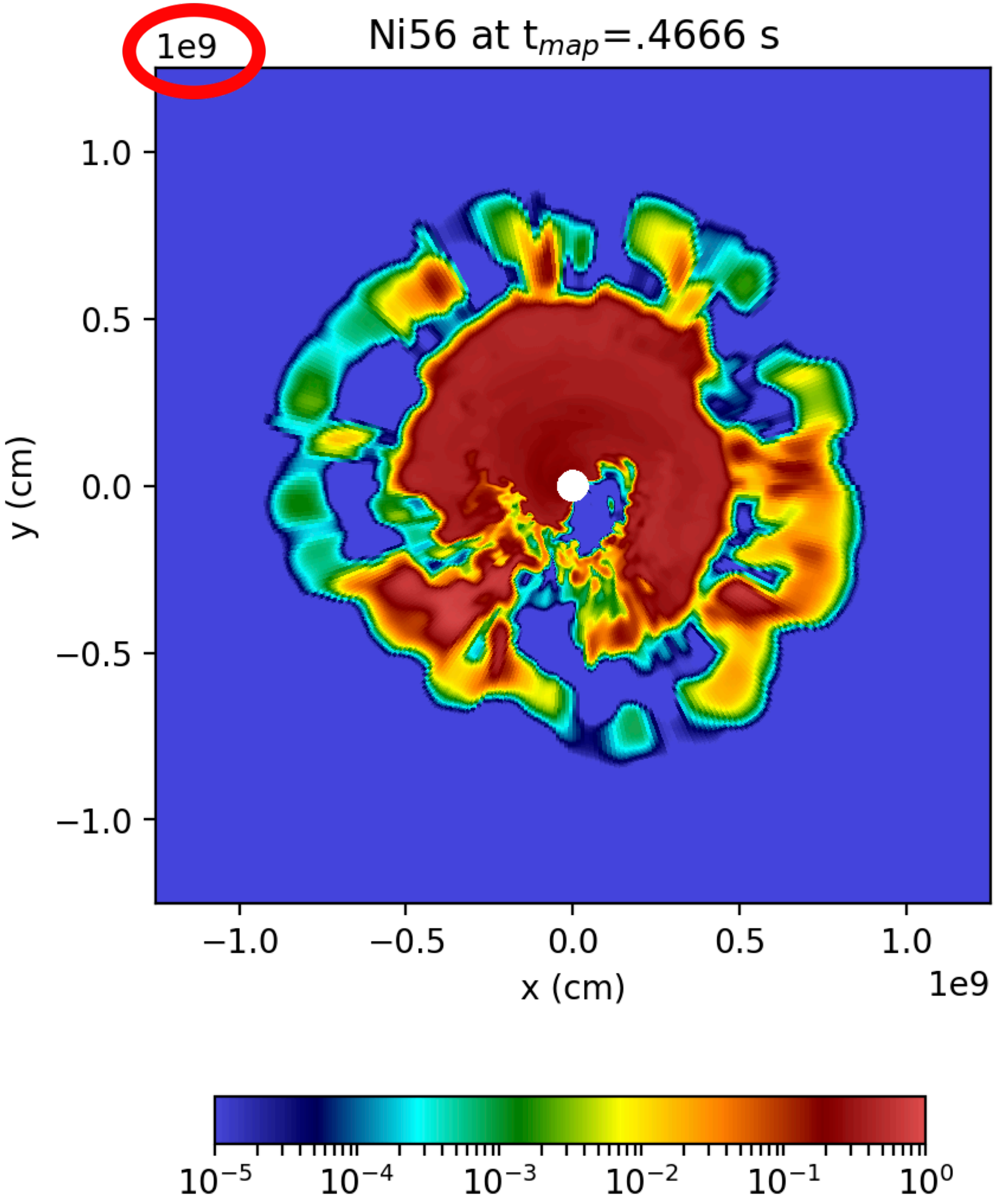
CCSNe w/ large networks: Silicon flash

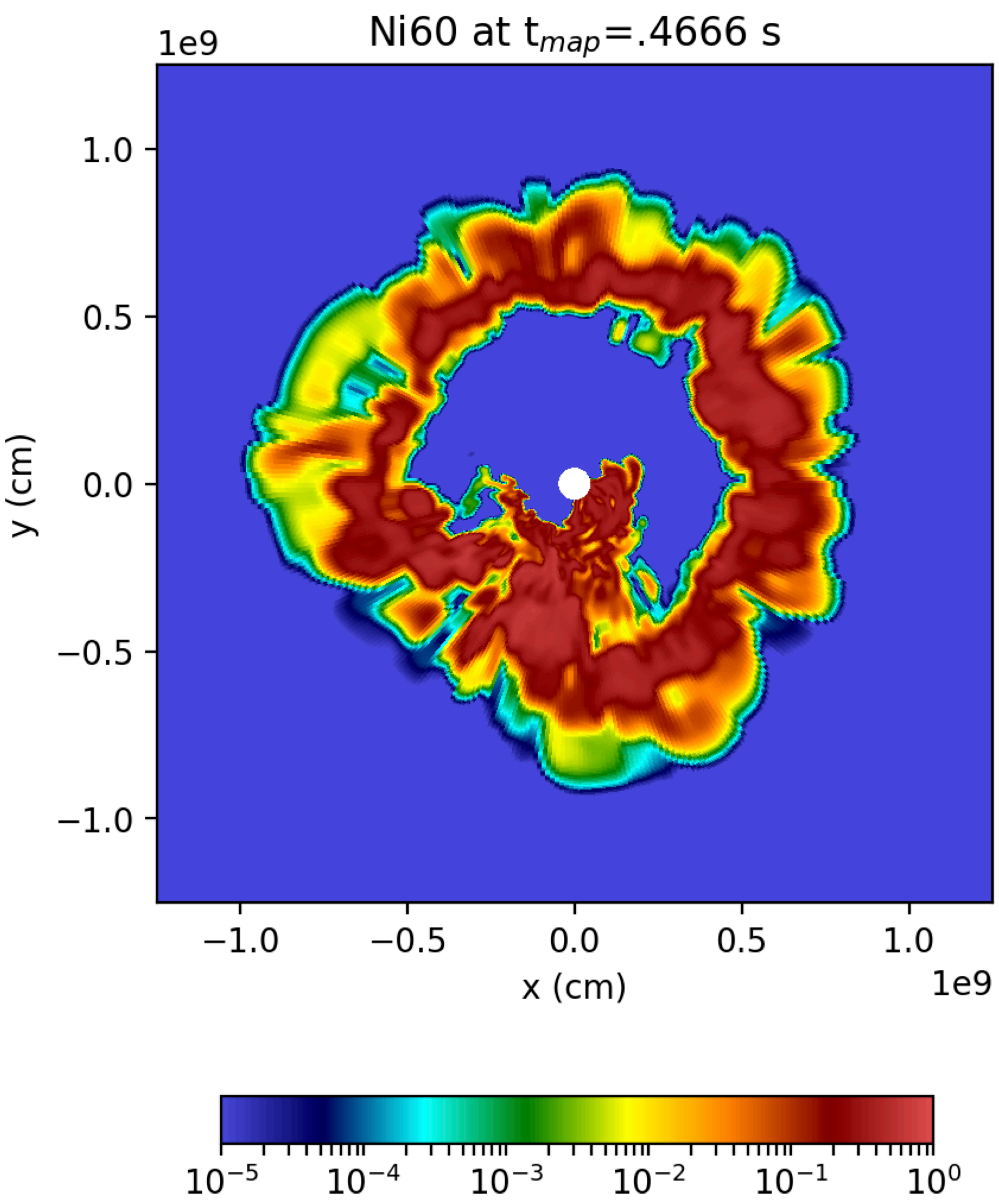
- Compressional heating during collapse leads to accelerated burning in the neon and silicon burning shells.
- Eventually the shells generate a combined flash.
- This flash propagates to several thousand km before it is caught by the supernova shock.



Hot off Summit…

Sandoval + (in prep)
Summit Early Science

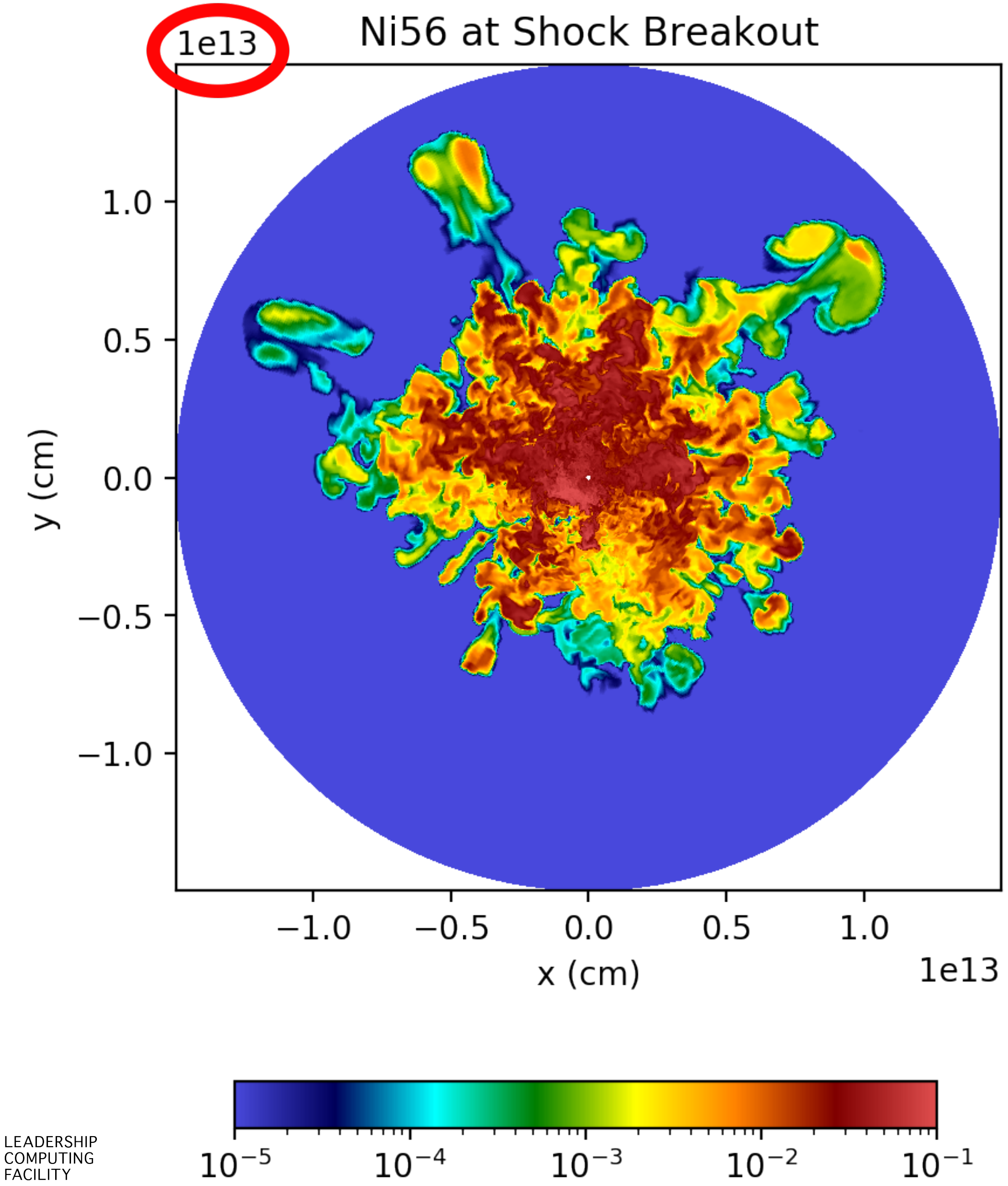


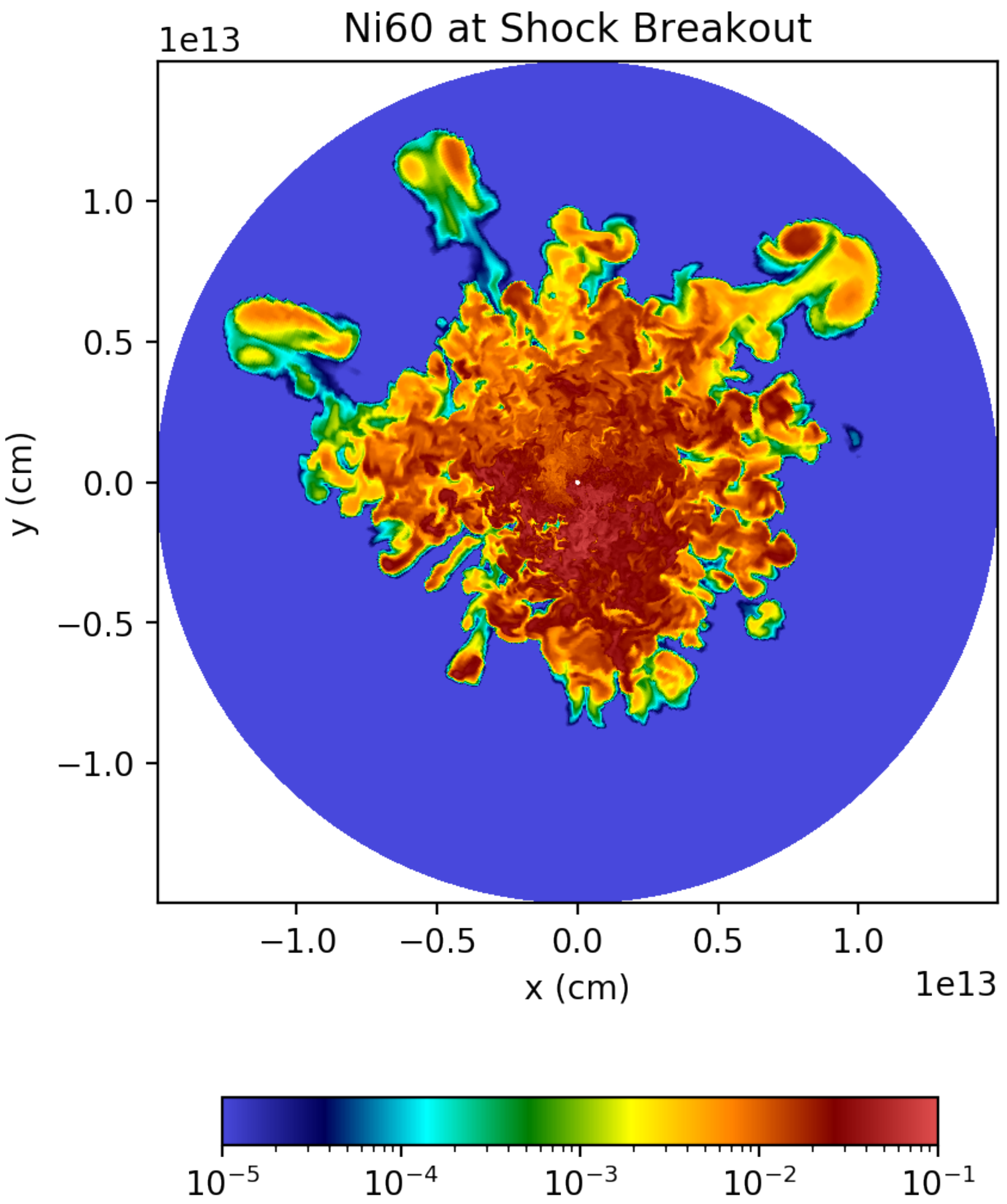


Hot off Summit…

17 hours later, 10,000 times bigger

Sandoval + (in prep)
Summit Early Science





https://cdn.soft8soft.com/AROAJSY2GOEHMOFUVPIOE:9365cb3419/applications/Spun_Up_Comparison/Spun_Up_Comparison.html

EXASCALE COMPUTING PROJECT

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Sean Couch, Michael Pajkos, Jennifer Ranta (Michigan State)

Anshu Dubey, Saurabh Chawdhary, Carlo Graziani, Jared O’Neal (ANL)

Klaus Weide (UChicago)

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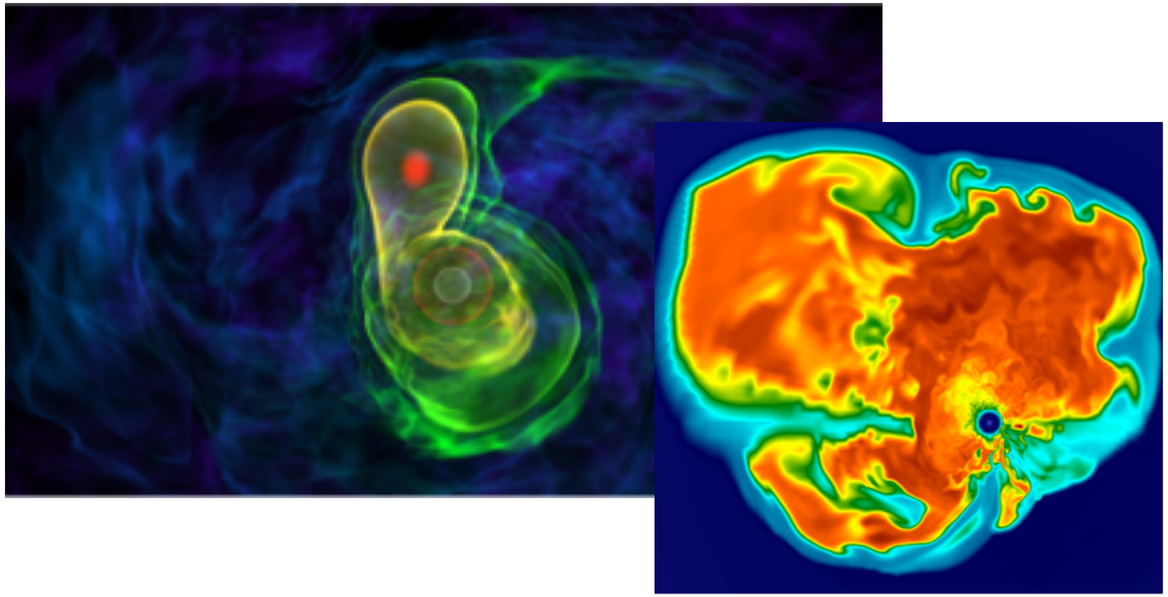
EXASCALE COMPUTING PROJECT

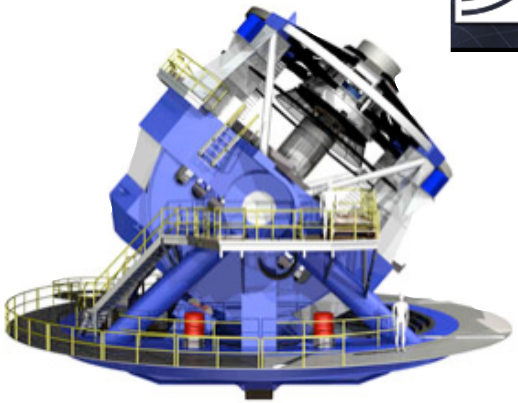


- ExaStar simulations are essential to:
  - Guide future nuclear physics experimental programs
    – siting the r-process directly impacts which rates are most important to measure
  - Provide reliable templates for gravitational wave and neutrino detectors
    – Low signal-to-noise requires templates for matching
  - Interpret X-ray and gamma-ray observations

- ExaStar simulations will have connections to:
  - experimental nuclear physics data
  - satellite observations of astrophysical phenomena
  - GW detections
  - neutrino experimental data, including solar and reactor experiments to improve predictive power

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

LIGO



FRIB

Summary

- Stellar astrophysics and other multi-physics simulations produce a series of challenges to understanding that can be ameliorated by good visualization.
- For astrophysics, the tie to observations that include imaging is a major motivator.
- “Playing” with visualization approaches is vitally important to glean maximum benefit. Interactivity is paramount.
- Including extensive visualization as a part of any HPC workflow can provide on-the-fly information that can prevent huge losses of time/power, and therefore, $$.

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