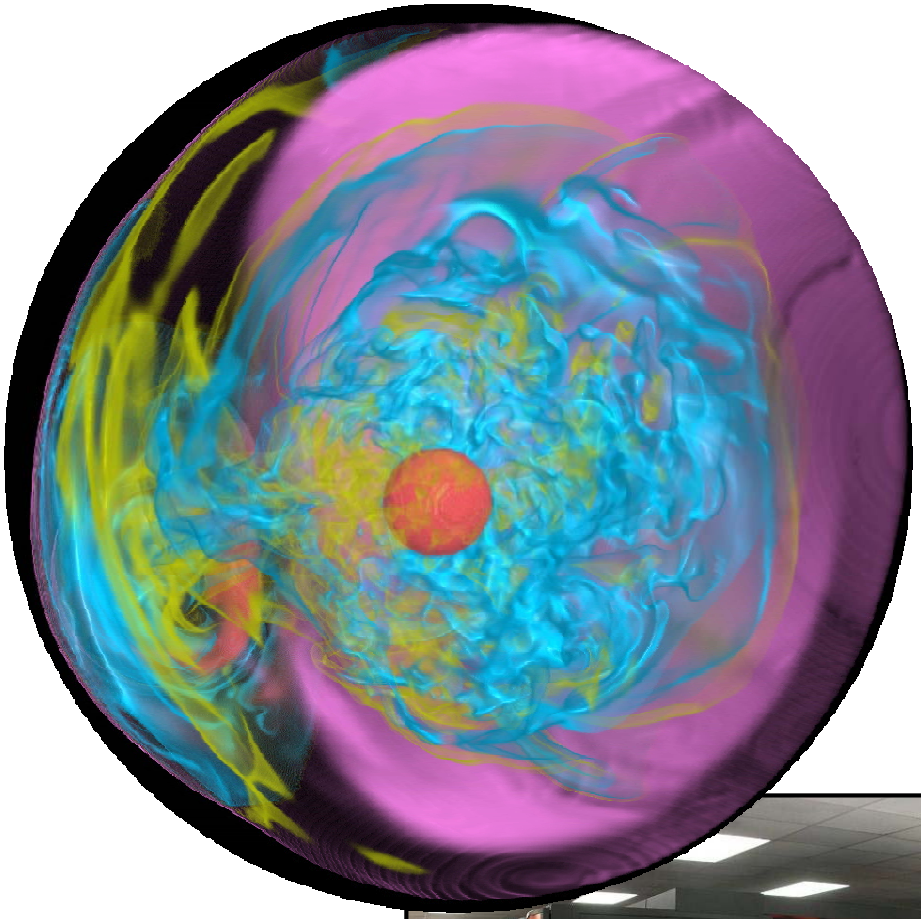
Multidimensional, Multiphysics Simulations of Core-Collapse Supernovae



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  - NP
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- NSF PetaApps Program
- NASA Astrophysics Theory and Fundamental Physics Program

Outline

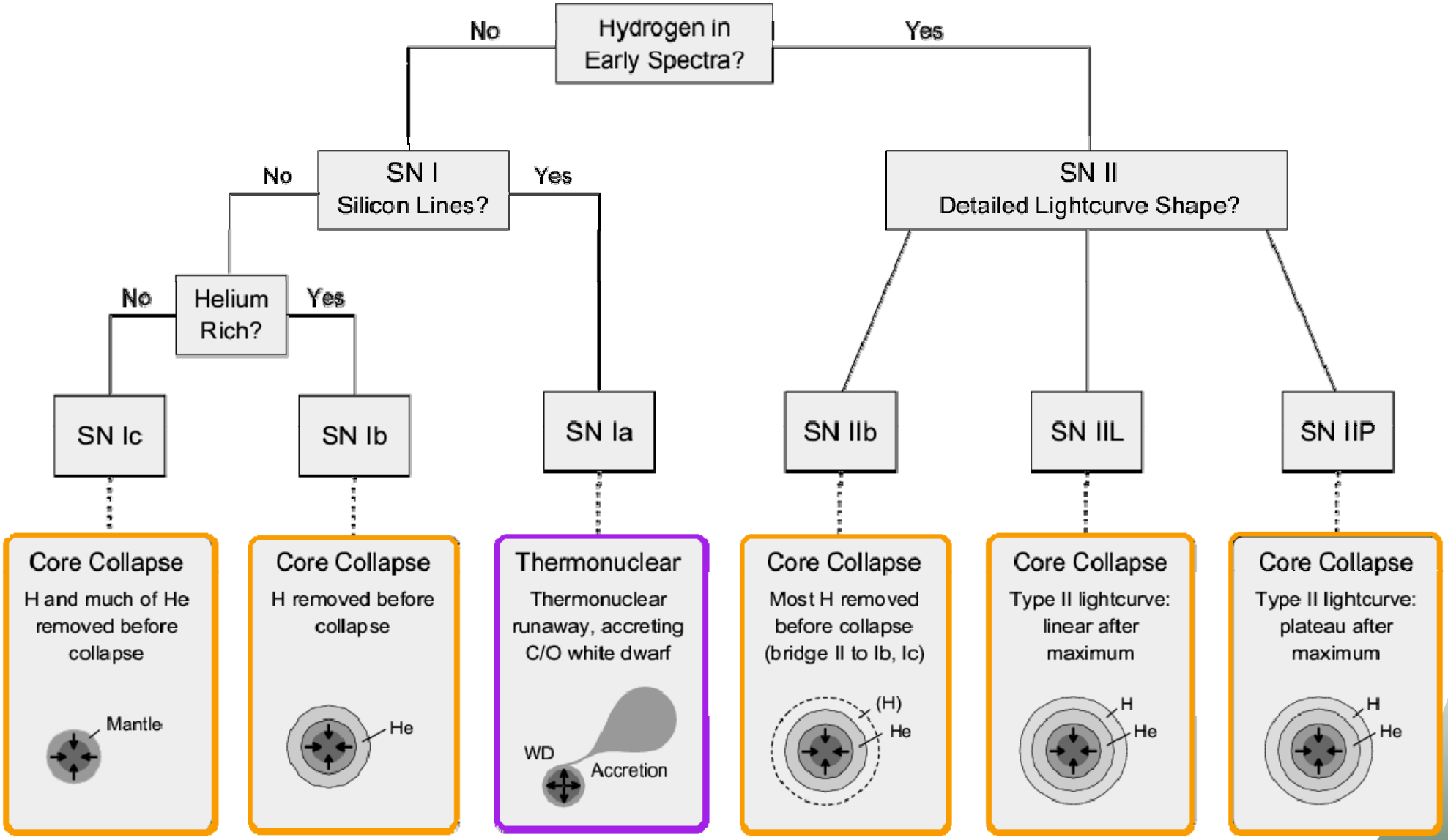
- Quick recap of supernova physics
- Introduction to CHIMERA
- Current computational issues/work
- Recent results
- The future

Supernovae

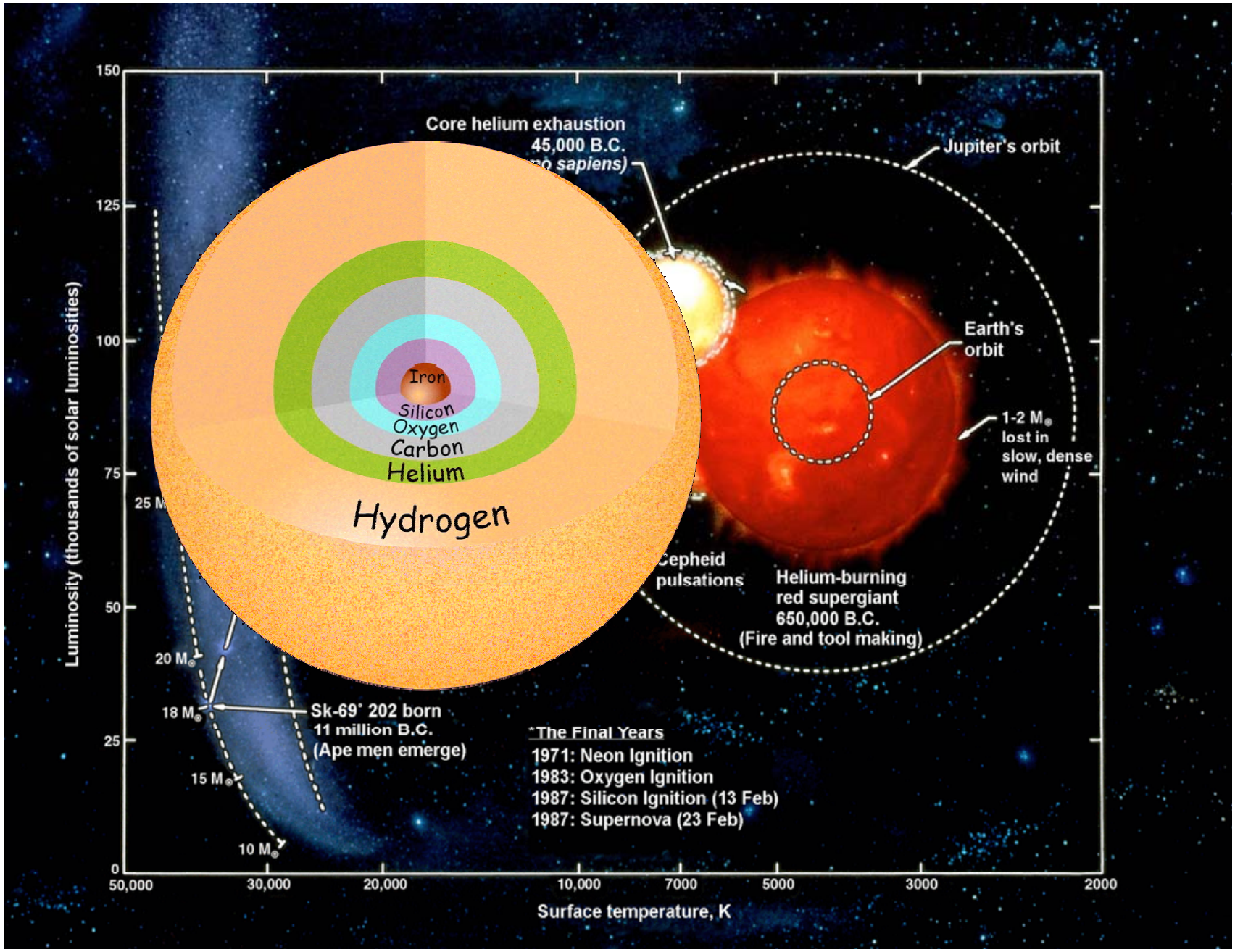
E.B.

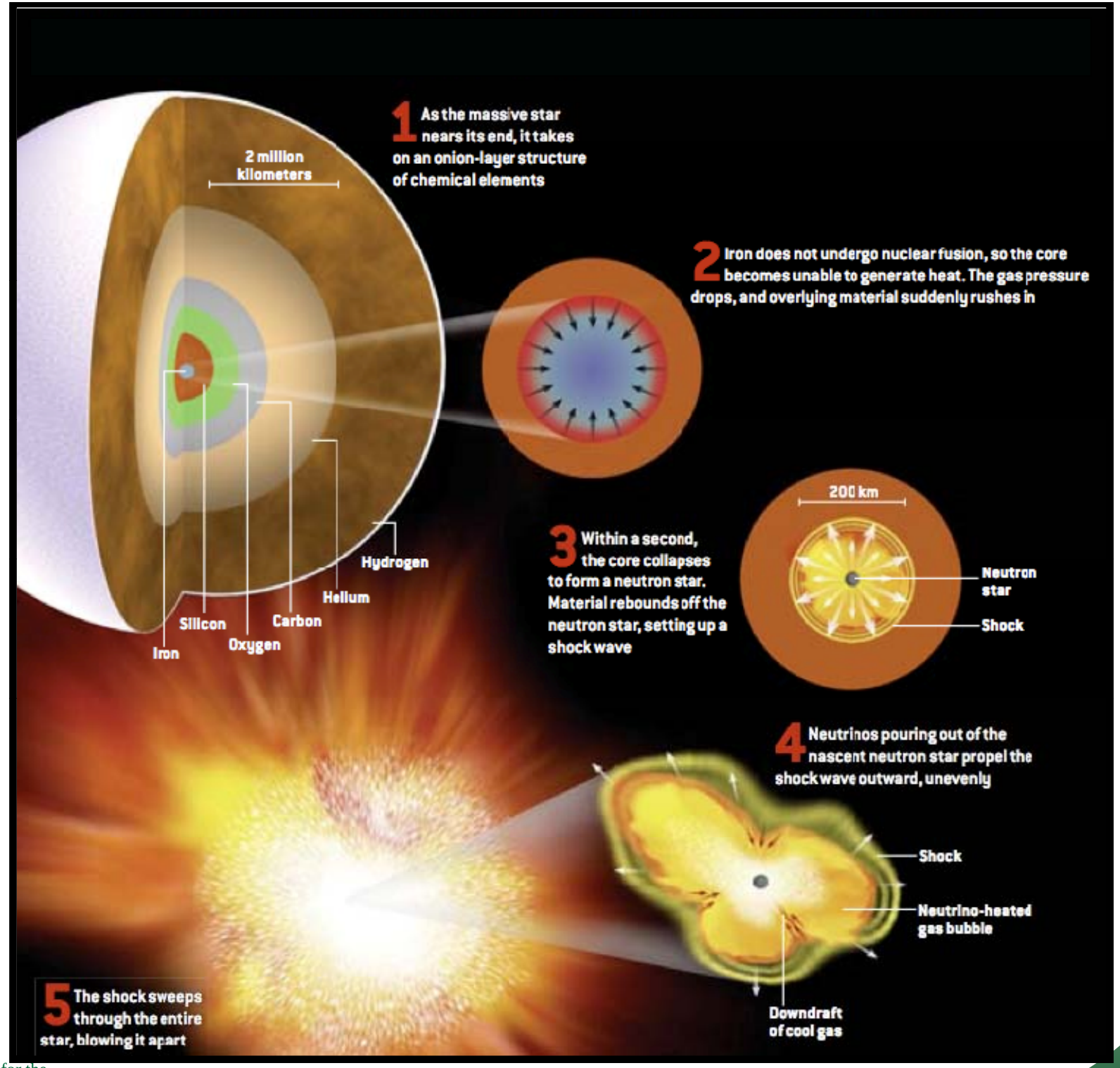
plural supernovas or supernovae; any of a class of violently exploding stars whose luminosity after eruption suddenly increases millions or even billions of times its normal level.

Supernova types

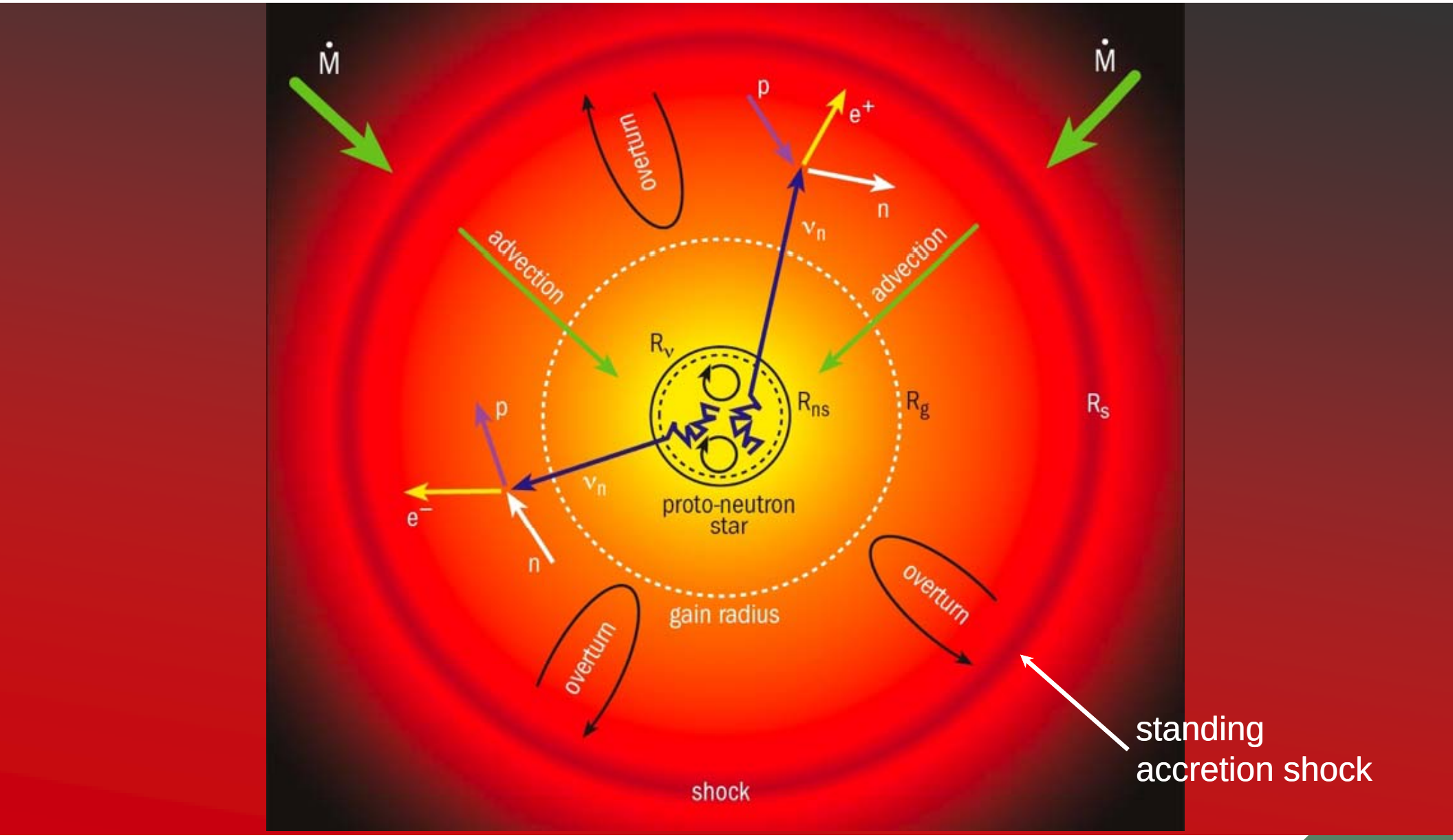


Core collapse

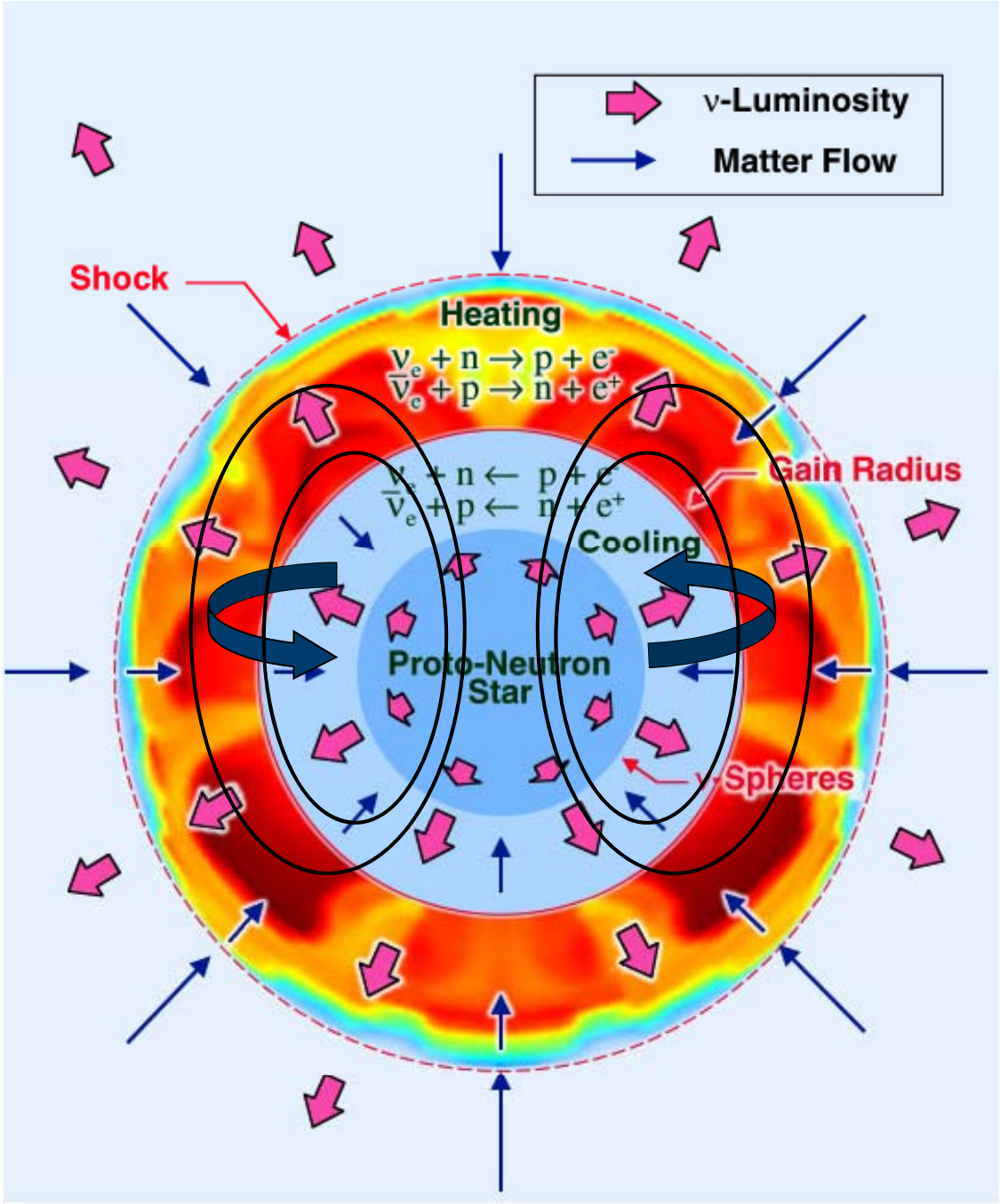



1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements
2 million kilometers
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in
3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave
200 km
Neutron star
Shock
4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly
Shock
Neutrino-heated gas bubble
Downdraft of cool gas
5 The shock sweeps through the entire star, blowing it apart

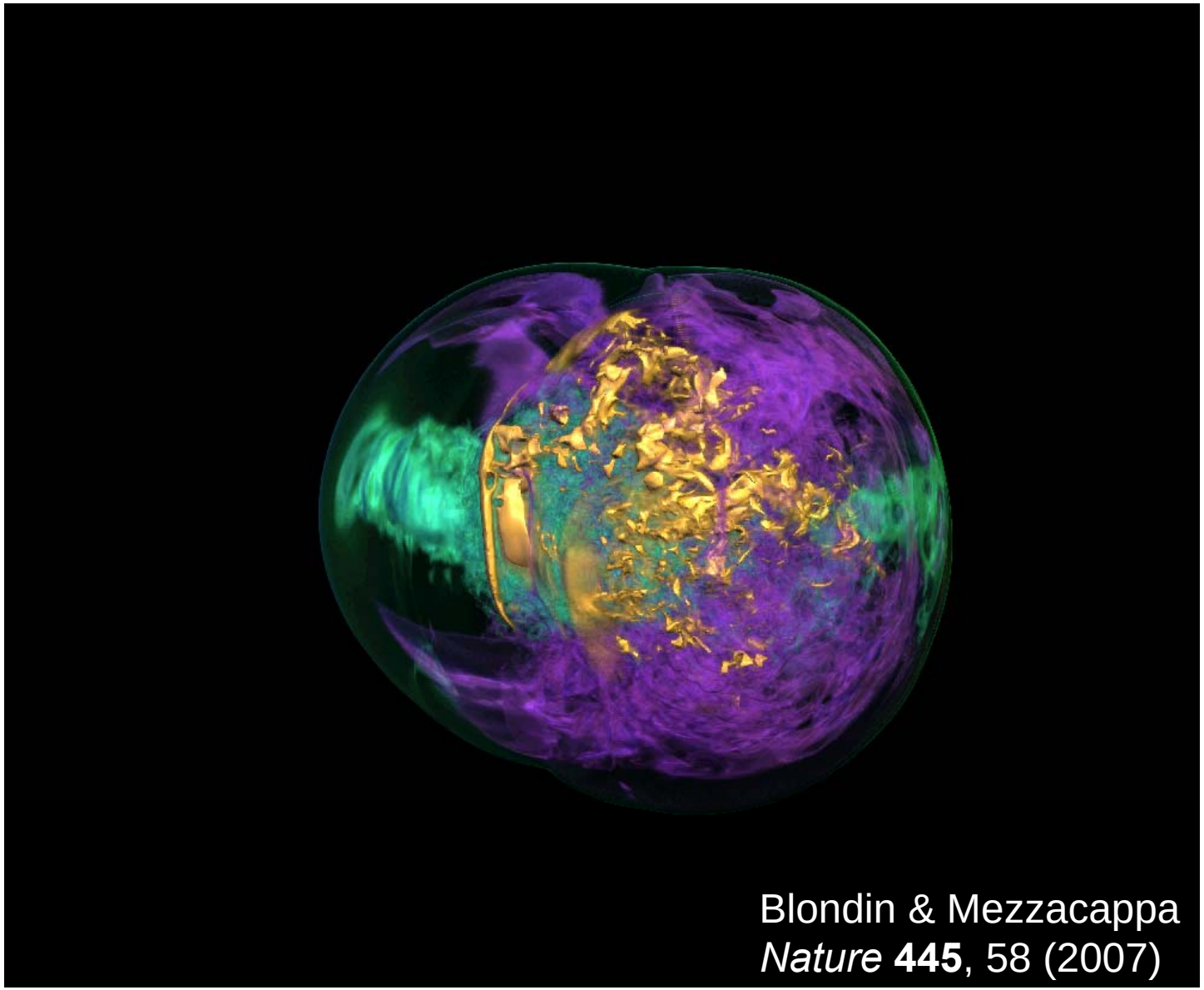
Shock Stall


Ṁ
Ṁ
p
e+
n
overturn
advection
advection
νn
Rν
Rns
Rg
Rs
p
e−
νn
n
proto-neutron
star
gain radius
overturn
overturn
shock
standing
accretion shock

Already a panoply of physics to model...



... and now: a discovery from computation



Visualization: K. Ma (UC Davis)

A standing accretion shock is unstable to non-radial perturbations: the Standing Accretion Shock Instability (SASI).

The SASI has non-axisymmetric modes that are linearly unstable

⇩

must be computed in 3D

Current Workhorse

mCHIMERA

Ray-by-ray MGFLD transport (E↙)
3D (magneto)hydrodynamics
150 species nuclear network

Possible Future Workhorse

bCHIMERA

Ray-by-ray Boltzmann transport (E↙📦➔)
3D (magneto)hydrodynamics
150-300 species nuclear network

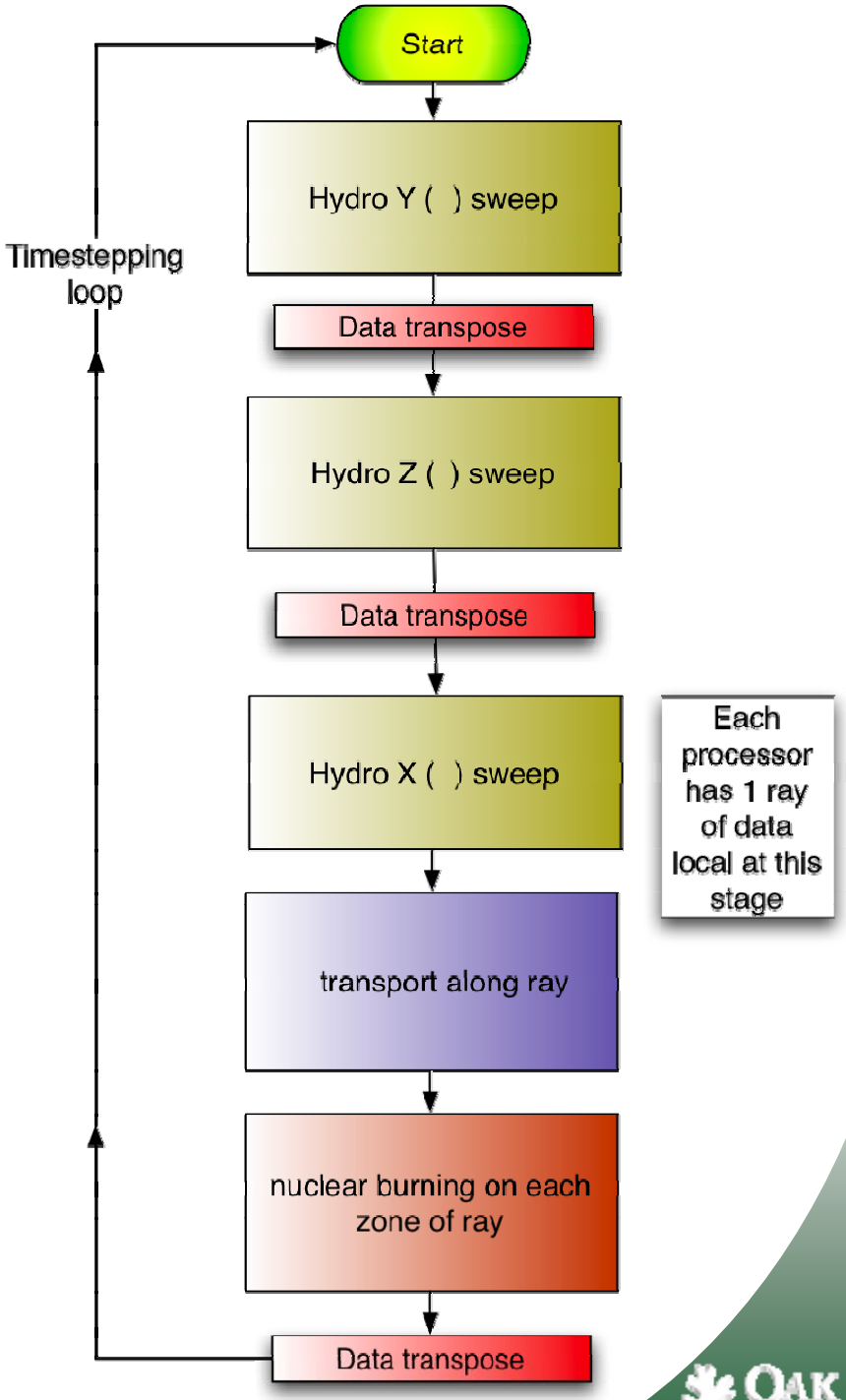
The "Exascale Workhorse"

GenASiS

Full 3D Boltzmann transport (E↙📦➔📦φ)
3D (magneto)hydrodynamics
150-300 species nuclear network
+AMR

CHIMERA Architecture

- CHIMERA has 3 "heads"
  - Hydrodynamics (MVH3)
  - Neutrino Transport (MGFLD-TRANS)
  - Nuclear Kinetics (XNET)
- Data transpose for the directionally-split hydrodynamics accomplished by ALLTOALL over subcommunicators
- Preponderance of FLOPs are performed on "local" data

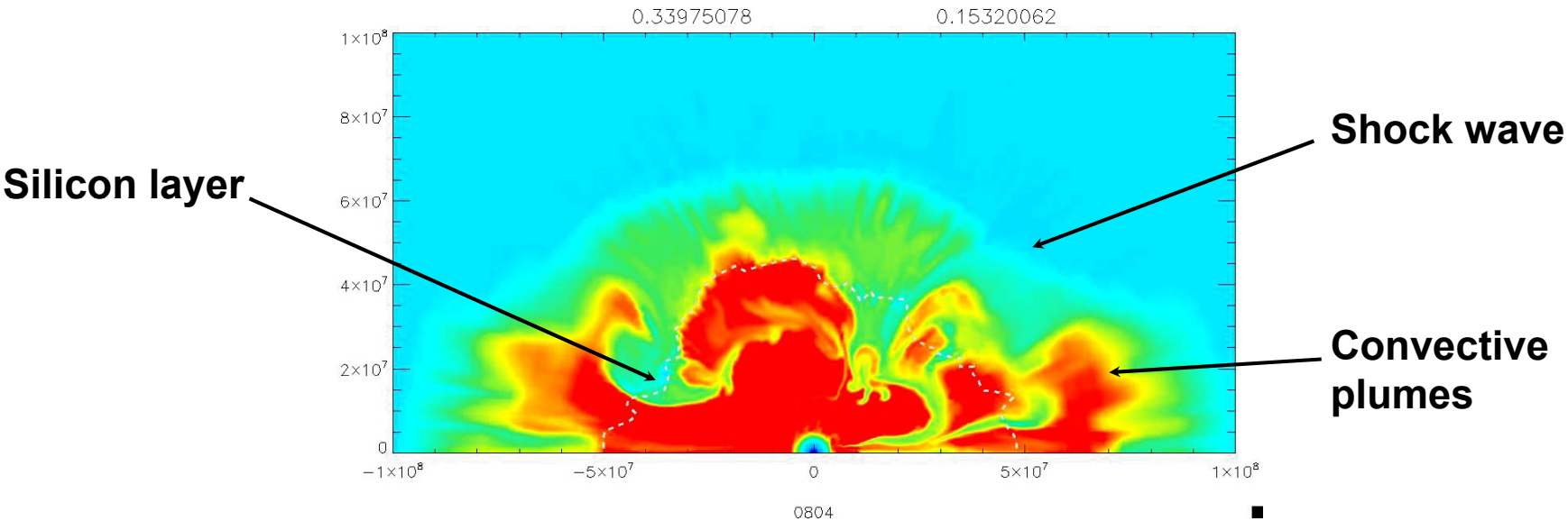


mCHIMERA

New developments

- **Multicore enhancements**
  - **CHIMERA has a lot of unrealized parallelism**
    - **nuclear kinetics**
      - **Jacobian build**
      - **dense linear system solution**
    - **neutrino transport**
      - **Jacobian build**
      - **preconditioning and solving sparse linear system**
  - **At present, we are trying several naïve approaches**
    - **threaded libraries**
    - **simple loop-level threading**

Results: 2D Simulations

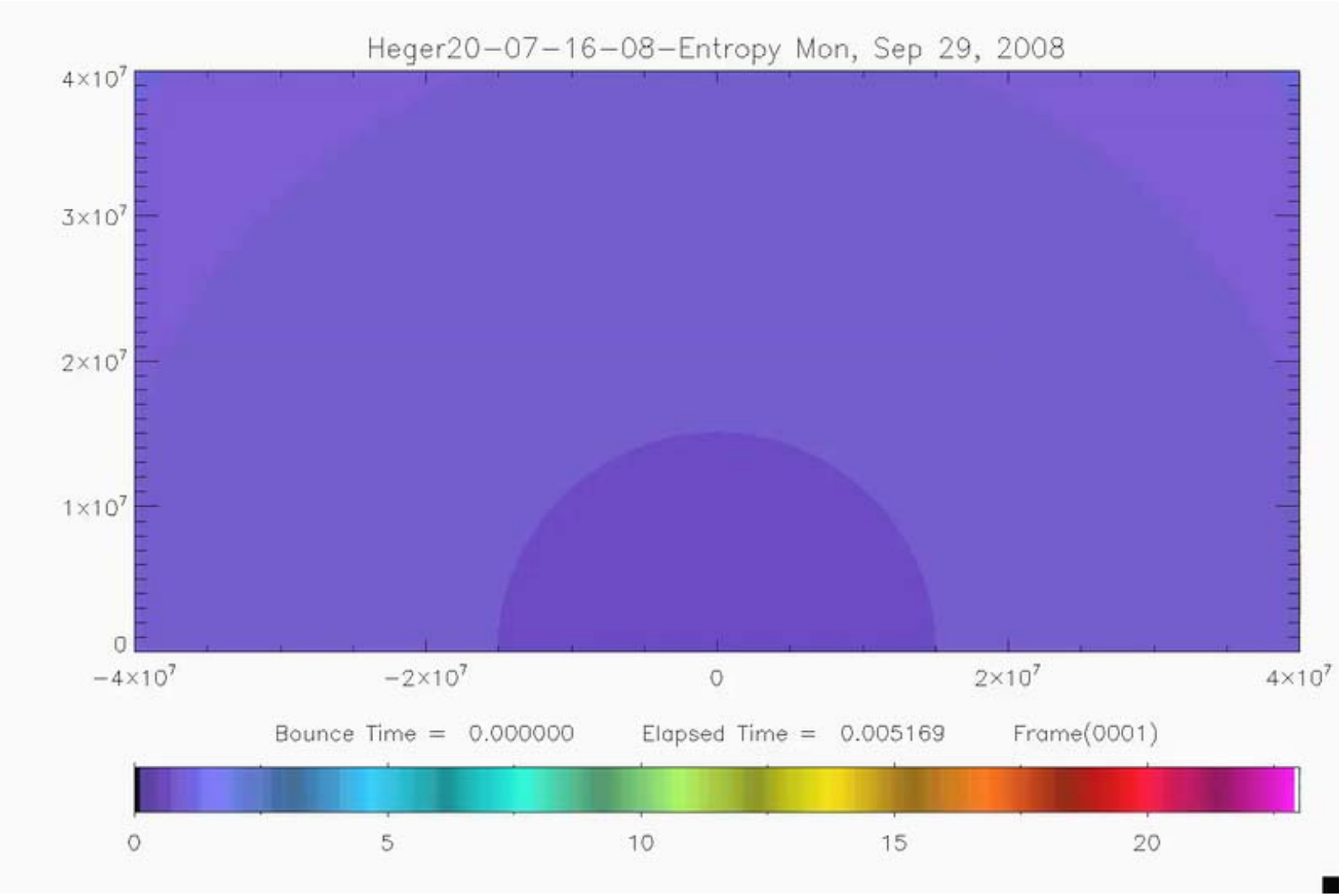


11-Solar-Mass Star

- **Shock powered in part by neutrino (radiation) heating from below, aided by convection.**
- **Improved/additional neutrino interactions increase the neutrino heating.**
- **Shock distorted into cigar shape in part by the shock instability (SASI), which precipitates shock's arrival in silicon and oxygen layers (marked by white dashed line), where nuclear burning can occur behind the shock, further powering it.**
- **Density ahead of the shock decreases rapidly when it reaches the oxygen layer (less for the shock to plow through).**

Bruenn et al., *J. Phys. Conf. Ser.*, **46**, 393 (2006)
Mezzacappa et al., *AIP Conf. Proc.*, **924**, 234 (2007)
Messer et al., *J. Phys. Conf. Ser.*, **78**, 012049 (2007)
Messer et al., *J. Phys. Conf. Ser.*, **125**, 012010 (2008)

20 M⊙ progenitor



Confluence of neutrino heating with improved neutrino interactions, convection, the SASI, nuclear burning, and drop in density lead to an explosion.

First 3D simulations underway

- **CHIMERA-3D currently running on the NCCS XT4 at ORNL**
- **Maiden voyage stats**
  - **304 radial zones, 152 zones in θ, 76 zones in ϕ**
  - **20 energy groups up to 404 MeV to resolve neutrino spectra**
  - **16 species nuclear network (n,p,14 α nuclei)**

  - **11552 processors on jaguar**
  - **roughly 4 TB generated so far (10's of TB for full run)**
  - **set to start similar run on kraken (NICS)**

The future

- A suite of progenitors and weak interaction physics to be run
  - convergence studies are difficult at this scale, but **must** be performed
- Larger nuclear network
  - providing good isotopic information and a more reliable energy release
- MHD
- Parallel development of bCHIMERA

Summary

- **Improved neutrino interaction physics + convection + SASI + nuclear burning + sufficient simulation time leads to explosions across a range of stellar progenitor models in 2D simulations.**
- **The inherently three-dimensional nature of both convection and the SASI demands three-dimensional simulations**
- **CHIMERA is producing the world's first 3D, multiphysics core-collapse supernova simulations.**
- **Much to do and many cpu-hours yet to burn...**