Supernova Simulation with CHIMERA

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FOR COMPUTATIONAL SCIENCES

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- Ted Lee (UTK)

Outline

- Some supernova science

- Why is it a petascale (and beyond) problem?

- CHIMERA* in context

- CHIMERA architecture

- Some testing results

✳ Conservative Hydrodynamics Including Multi-Energy RAdiation

Supernova modeling marked the genesis of computational astrophysics

THE HYDRODYNAMIC BEHAVIOR OF
SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

"The reason this paper is cited so many times is **because it started the new endeavor of hydrodynamic stellar modeling.** It is ironic that this work started because of an argument with Soviet scientists during the negotiations for the Cessation of Nuclear Weapons Tests in Geneva in 1959. It was claimed by me that the radiation emissions from a supernova might trigger the then proposed detection net for high altitude nuclear explosions that the Soviets were proposing. This objection of a possible false triggering of the system was brushed aside by the Soviet Ambassador Tsarpkin because, 'Who knows what a supernova would look like?'"
- S. Colgate *The Scientist* 12/1/1980
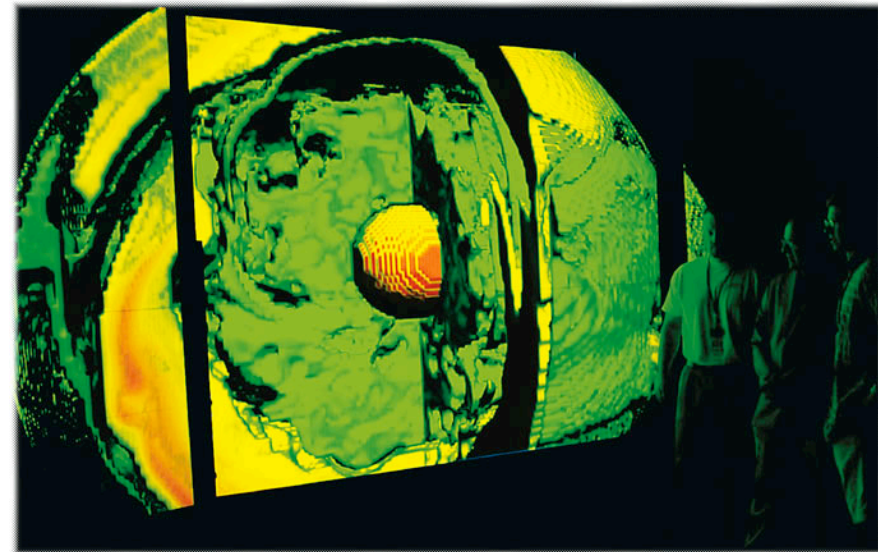
SCIENTIFIC AMERICAN

October 2006

Catastrophysics

WHAT MAKES A STAR BLOW UP?
THE MYSTERY OF A
SUPERNOVA

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.

How to *Blow Up* a Star

By Wolfgang Hillebrandt,
Hans-Thomas Janka
and Ewald Müller

It is not as easy as you would think. Models of supernovae have failed to reproduce these explosions—until recently

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.

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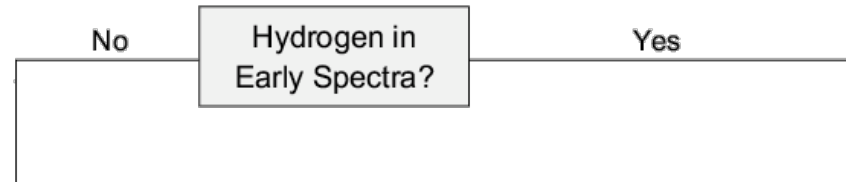have failed to reproduce these explosions—until recently

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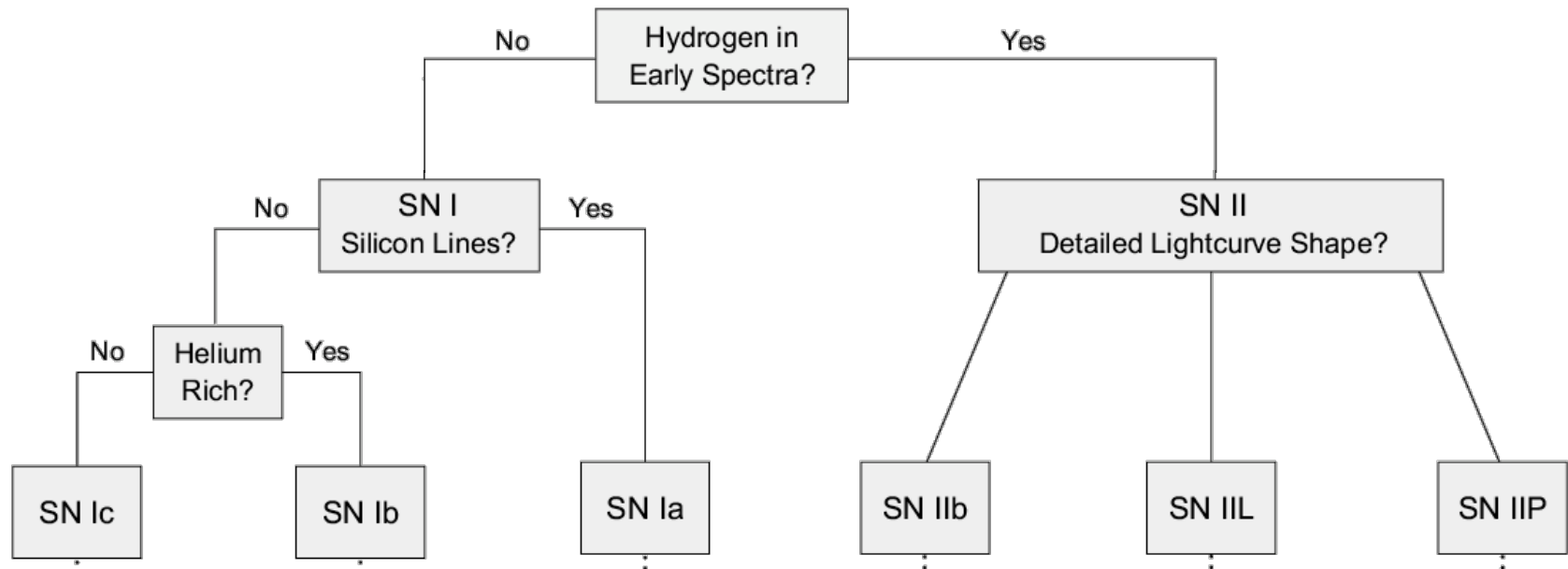
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Supernova Taxonomy

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Taxonomy 2007

The path to explosion
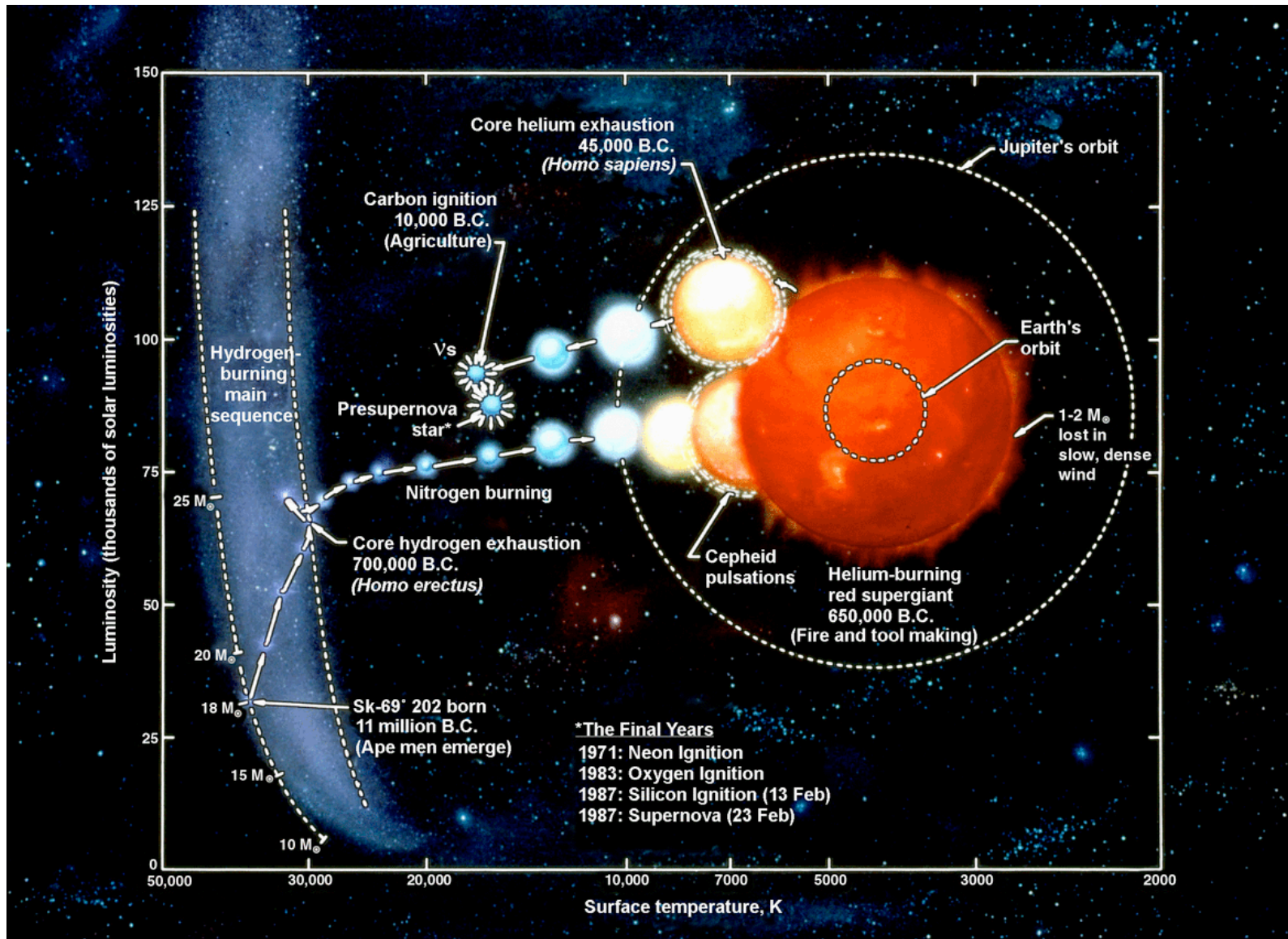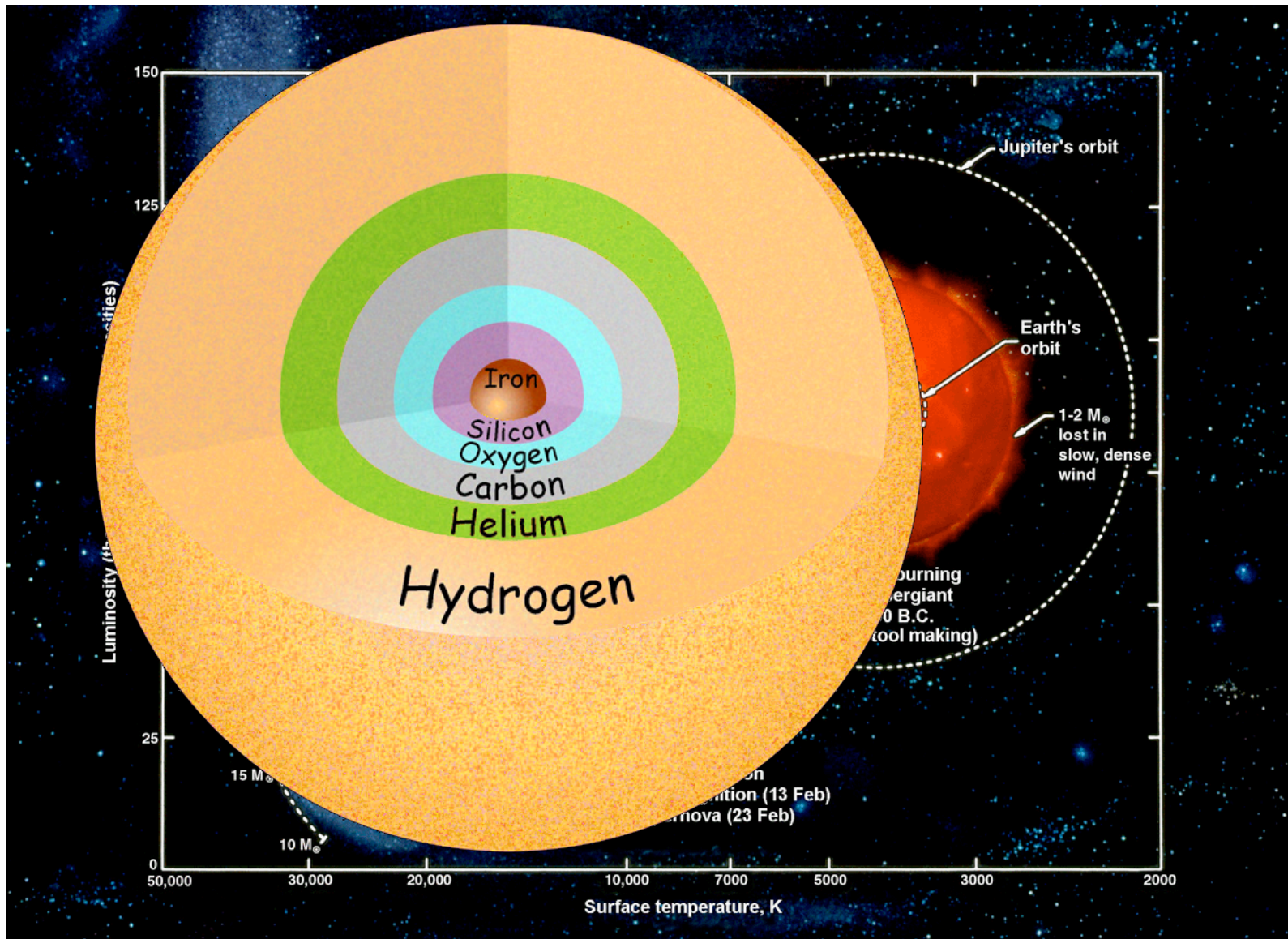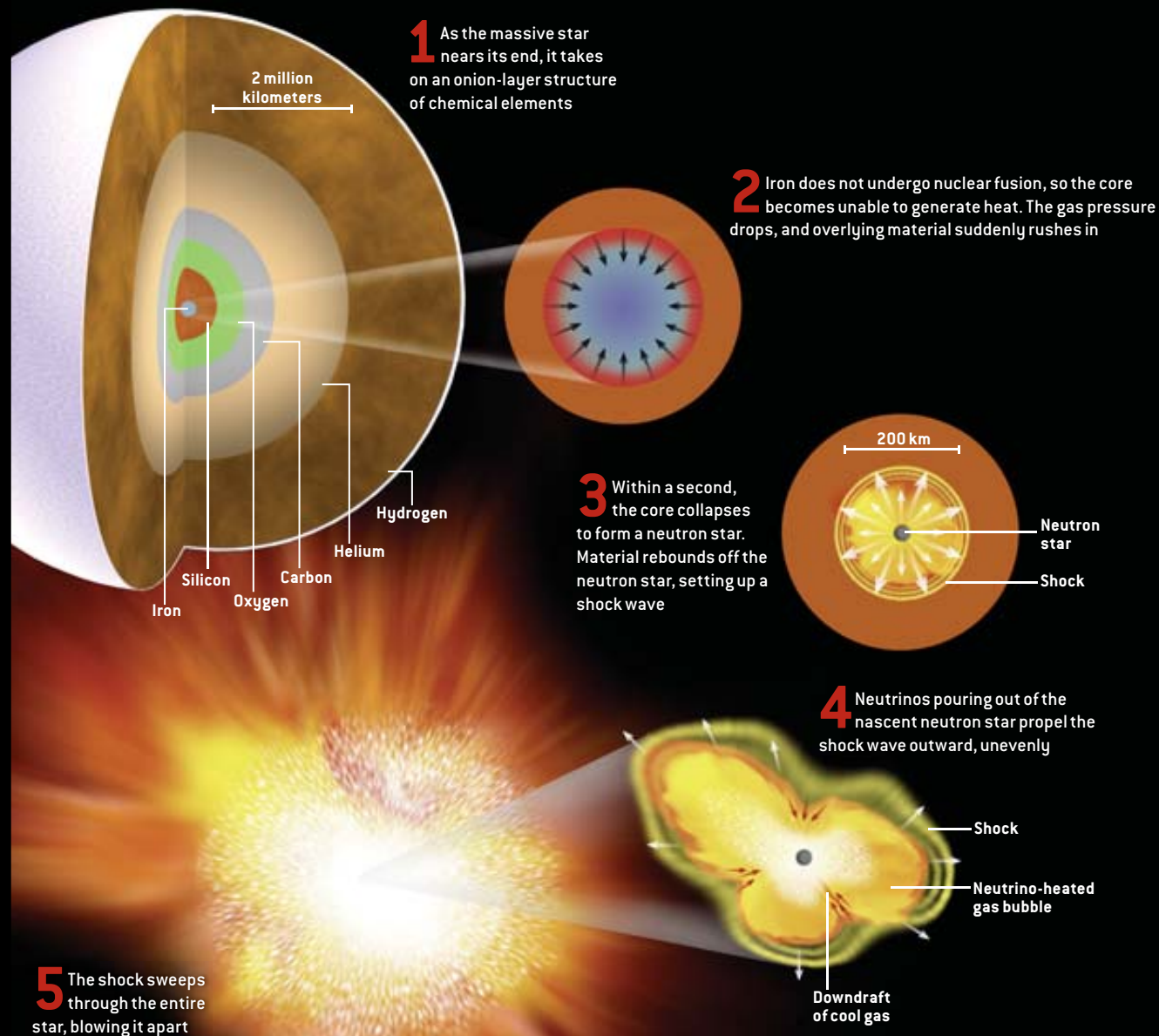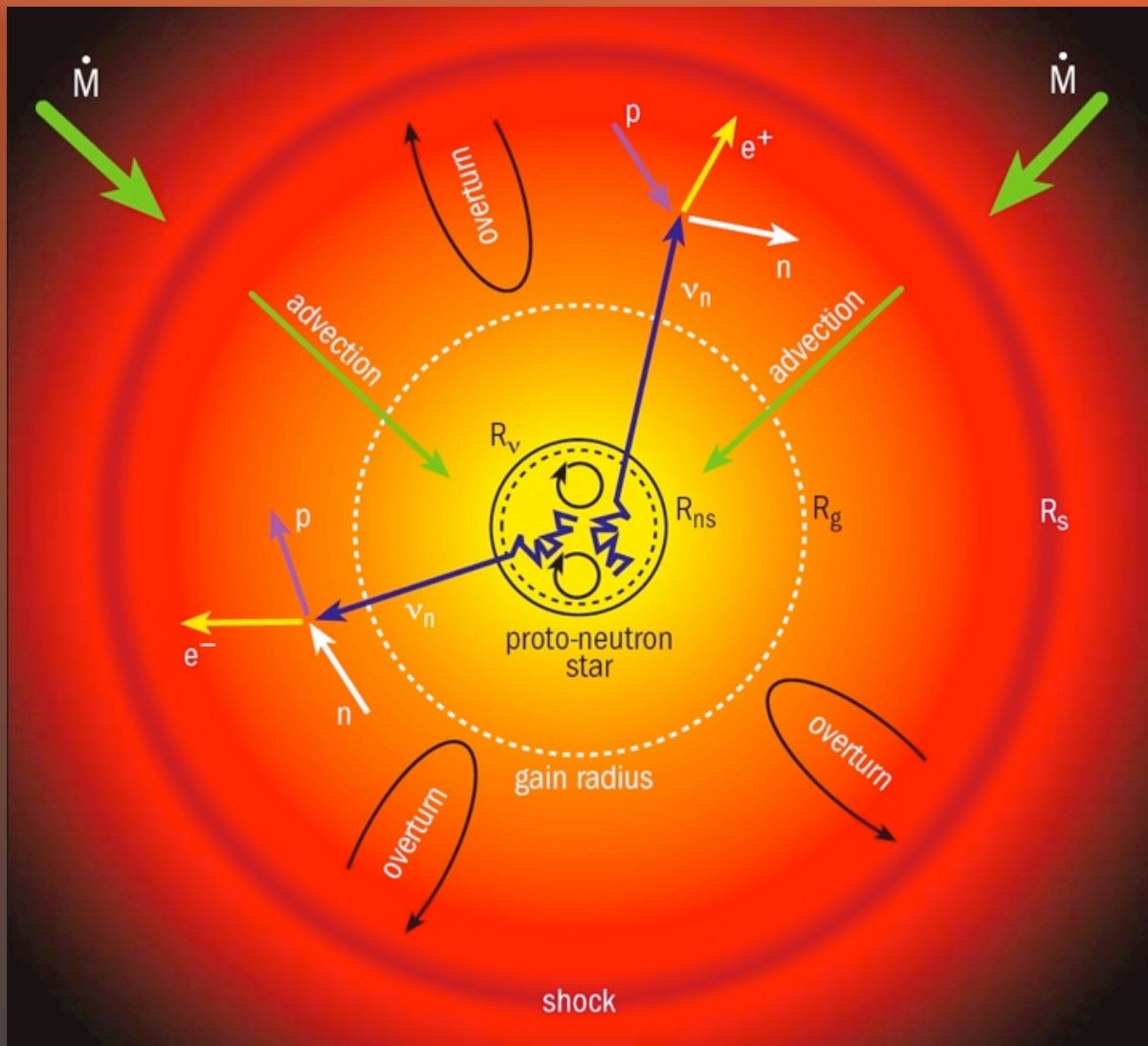
The path to explosion

The other class of supernova involves the implosion of a star at least eight times as massive as the sun. This class is designated type Ib, Ic or II, depending on its observed characteristics.
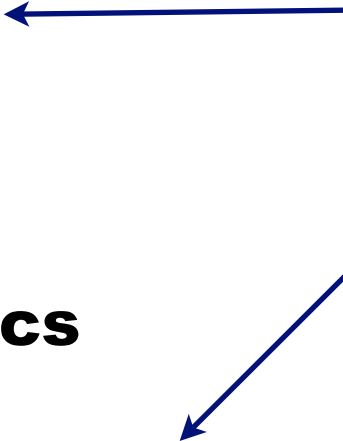
1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 million kilometers

Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen

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

Accretion shock

All the multiphysics presents a daunting software integration task

- Neutrino Transport

- Nuclear kinetics

- Magnetohydrodynamics

- General relativistic gravity

- Dense matter equation of state

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- **Neutrino Transport**

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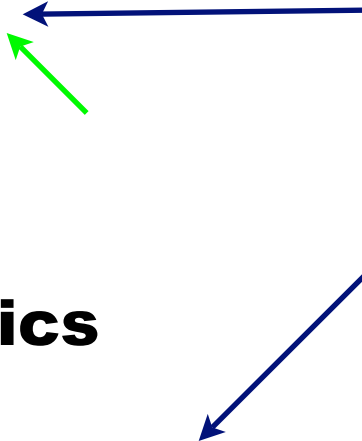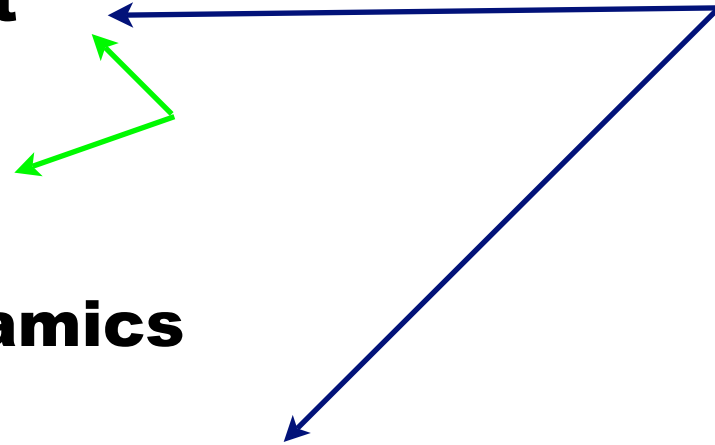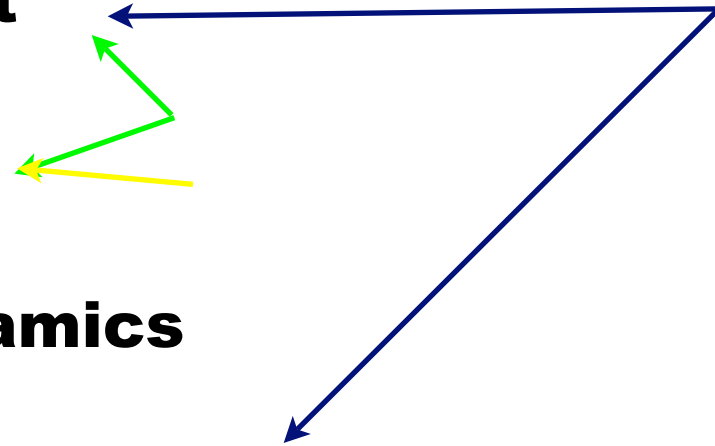- **General relativistic gravity**
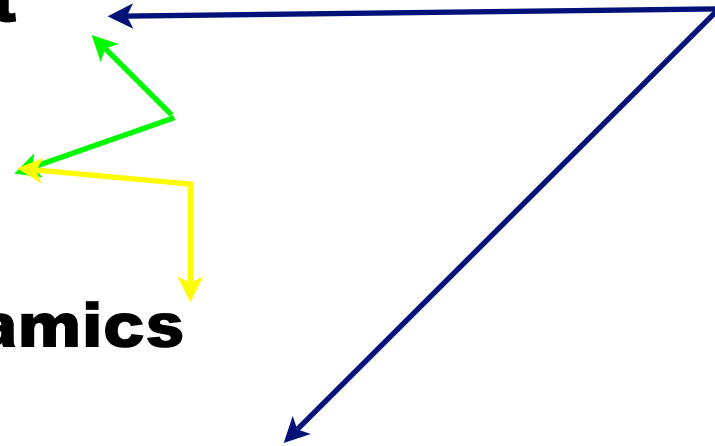
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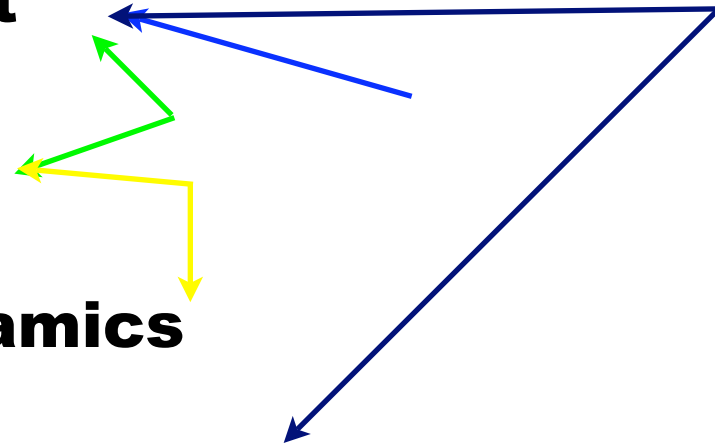
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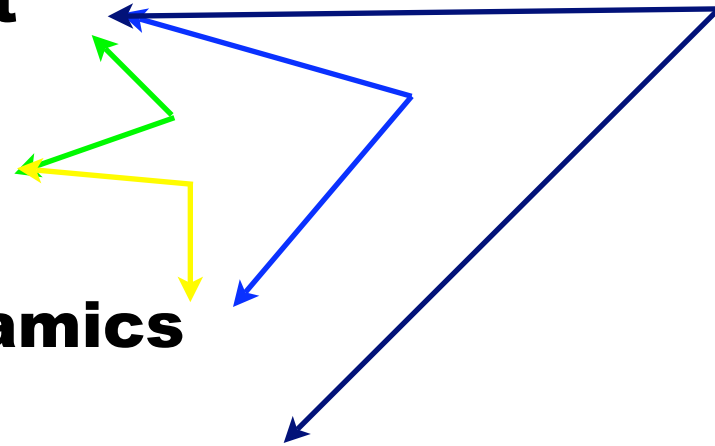
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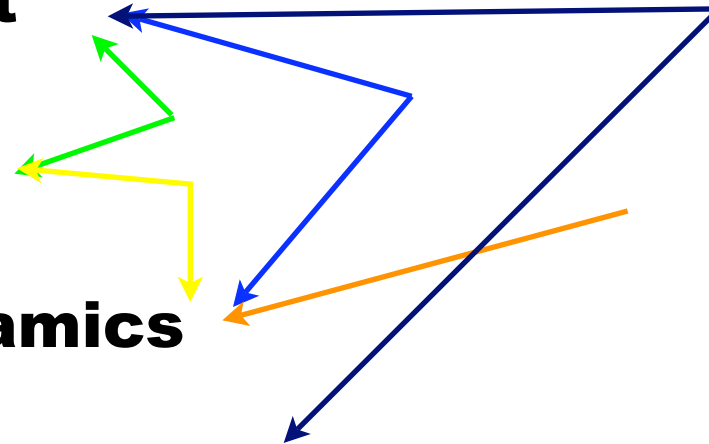
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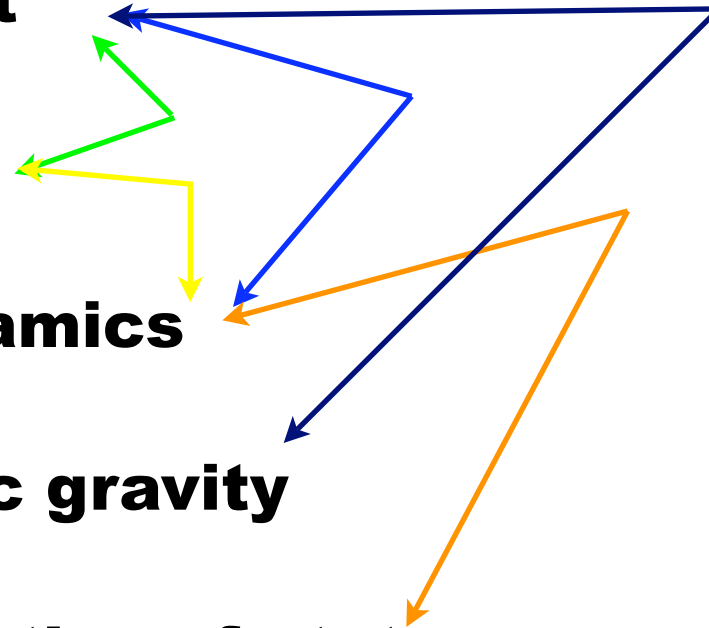
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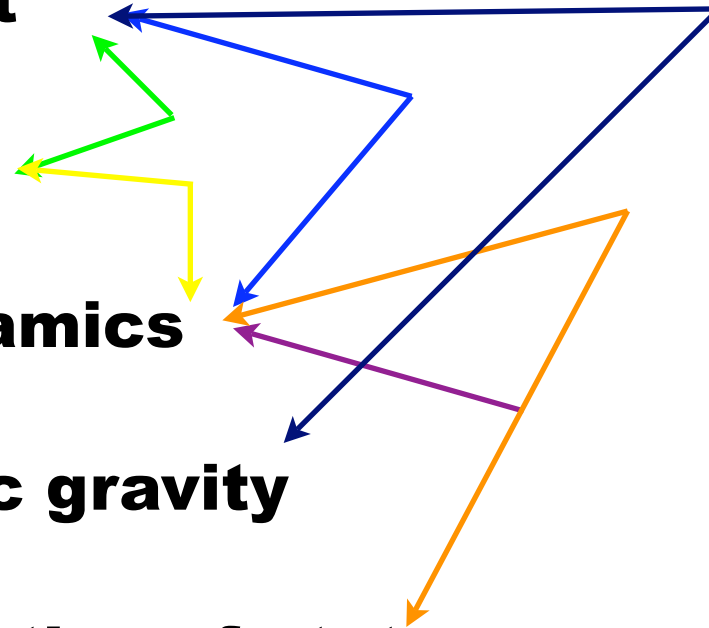
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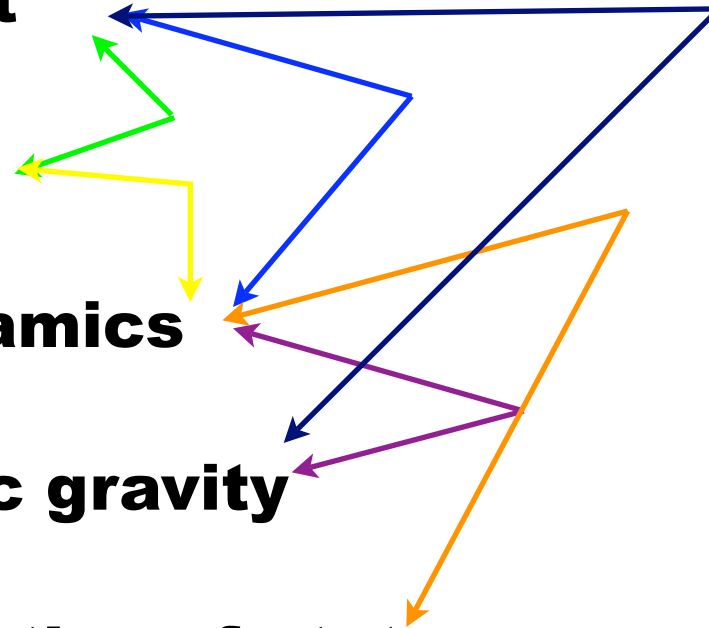- Dense matter equation of state

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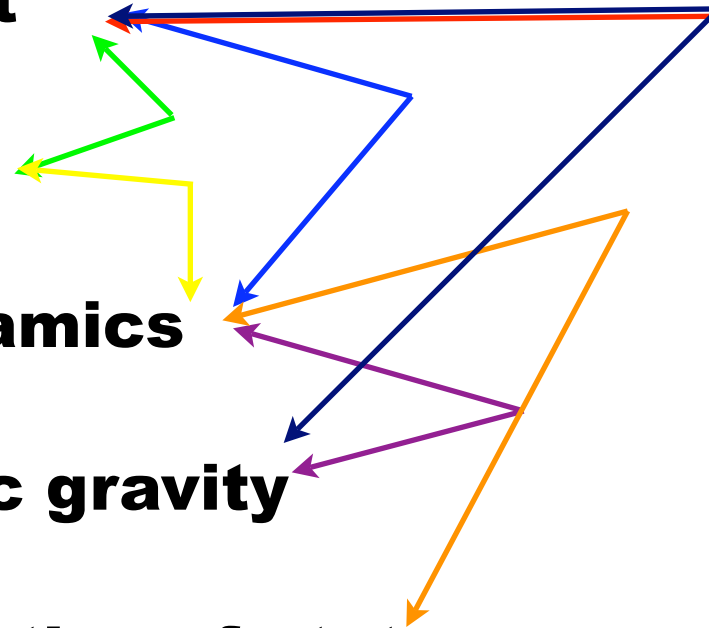
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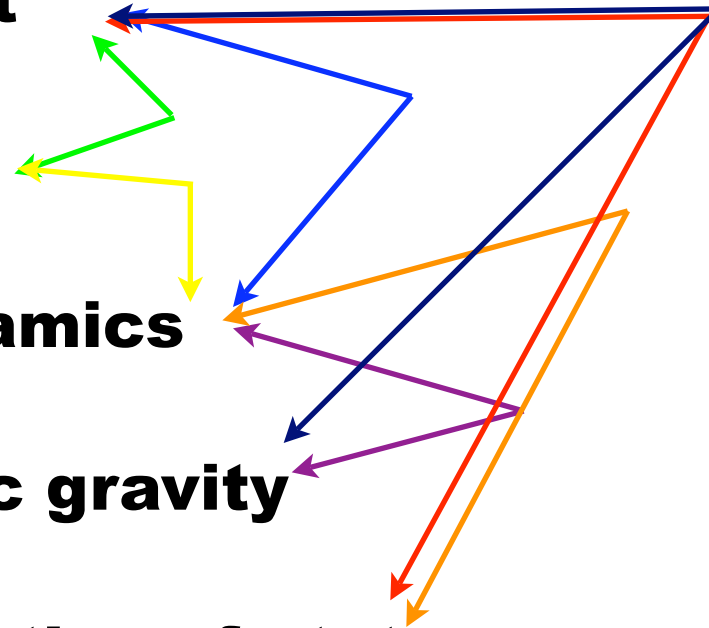
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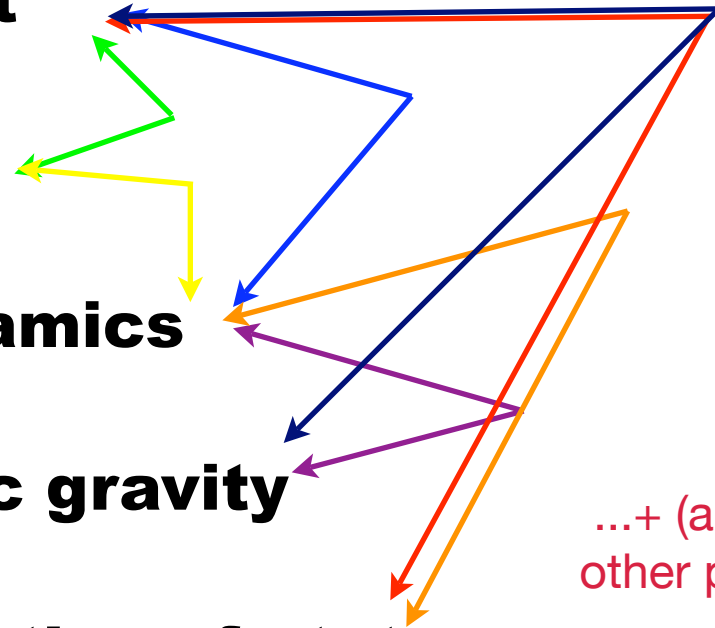
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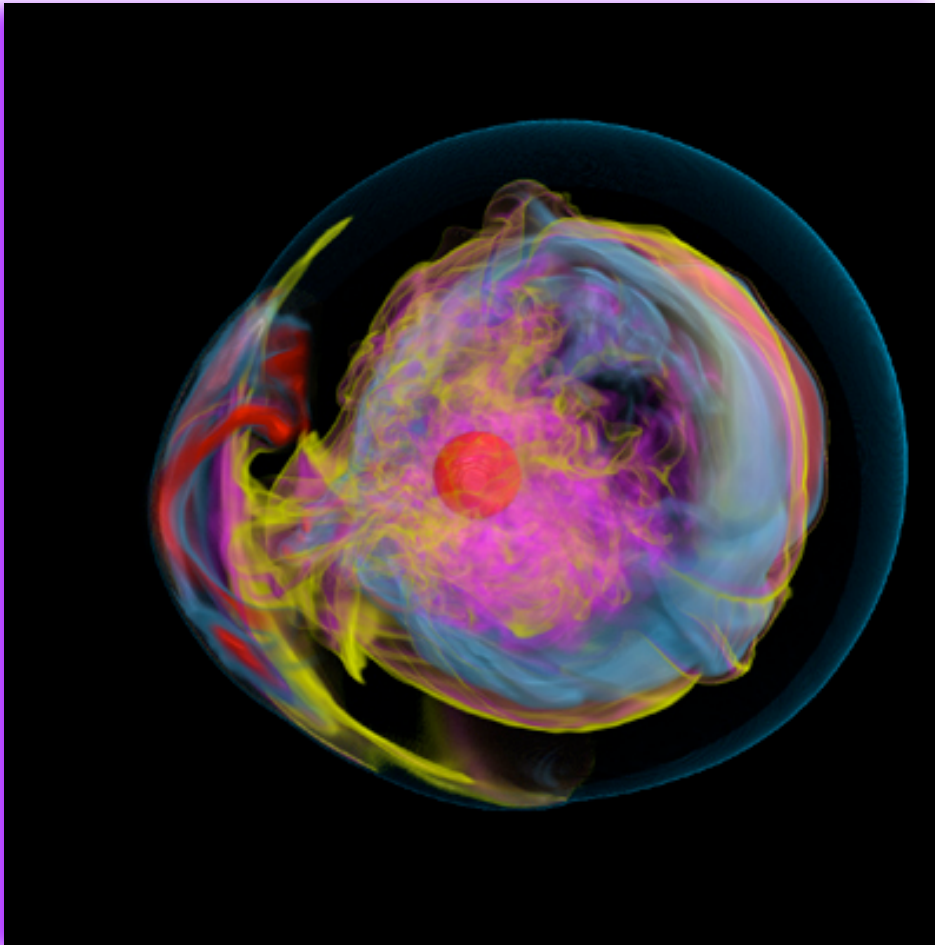# All the multiphysics presents a daunting software integration task

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All the multiphysics presents a daunting software integration task

- **Neutrino Transport**

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...+ (almost every other permutation)

- **Dense matter equation of state**

The real numerical/algorithmic challenge lies in the couplings. Interfaces for each component need to be robust enough to allow for various degrees of approximation.
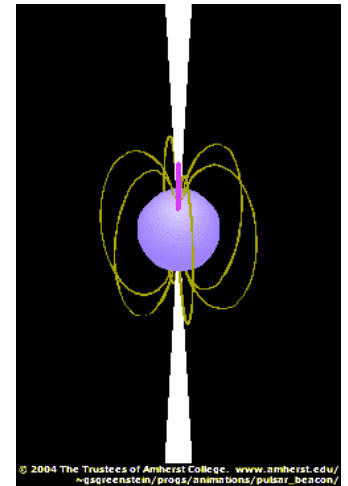
Discovery of the SASI
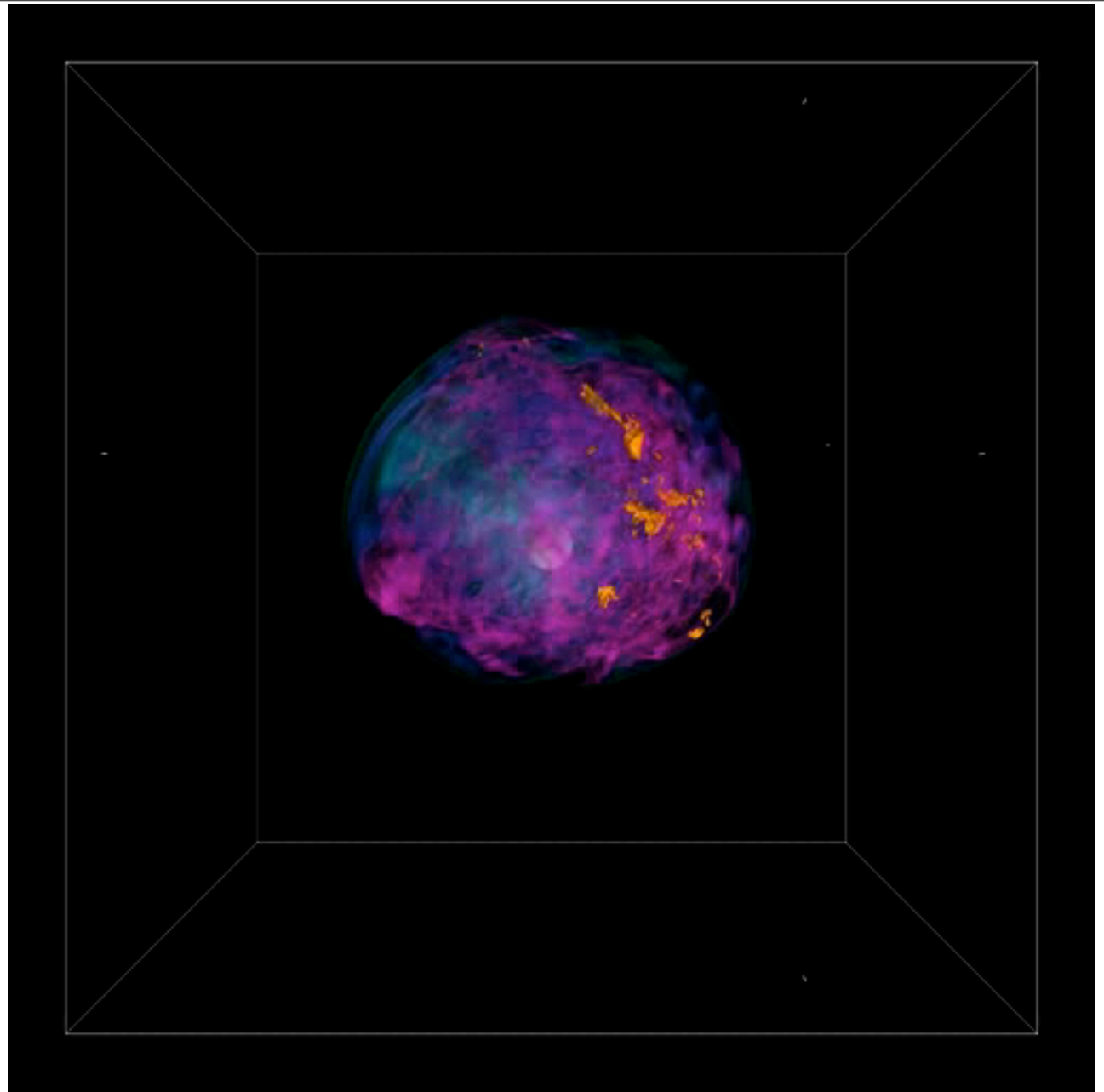## (Standing Accretion Shock Instability)

- Wholly computational discovery

- Instability serves to move the shock outward → explosion?

- Provides 'natural' explanation for neutron star spin up

Blondin & Mezzacappa Nature 445, 58-60 (4 January 2007)

SASI

Current Workhorse

mCHIMERA

Ray-by-ray MGFLD transport (E_ν)
3D (magneto)hydrodynamics
150 species nuclear network
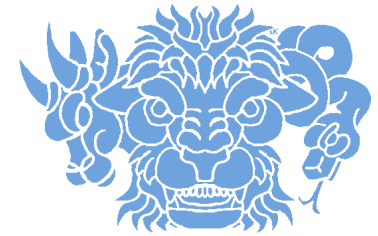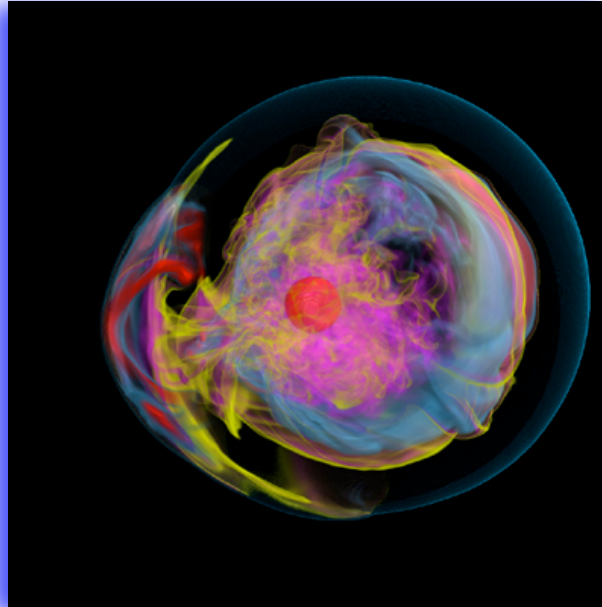
Possible Future Workhorse

bCHIMERA

Ray-by-ray Boltzmann transport (E_ν,θ)
3D (magneto)hydrodynamics
150-300 species nuclear network

The "Ultimate Goal"

GenASiS

Full 3D Boltzmann transport (E_ν,θ,ϕ)
3D (magneto)hydrodynamics
150-300 species nuclear network

- mCHIMERA is, well... a "chimera" of 3 separate, mature codes:
  - VH1 (MVH3)

- Multidimensional hydrodynamics
- http://wonka.physics.ncsu.edu/pub/VH-1/
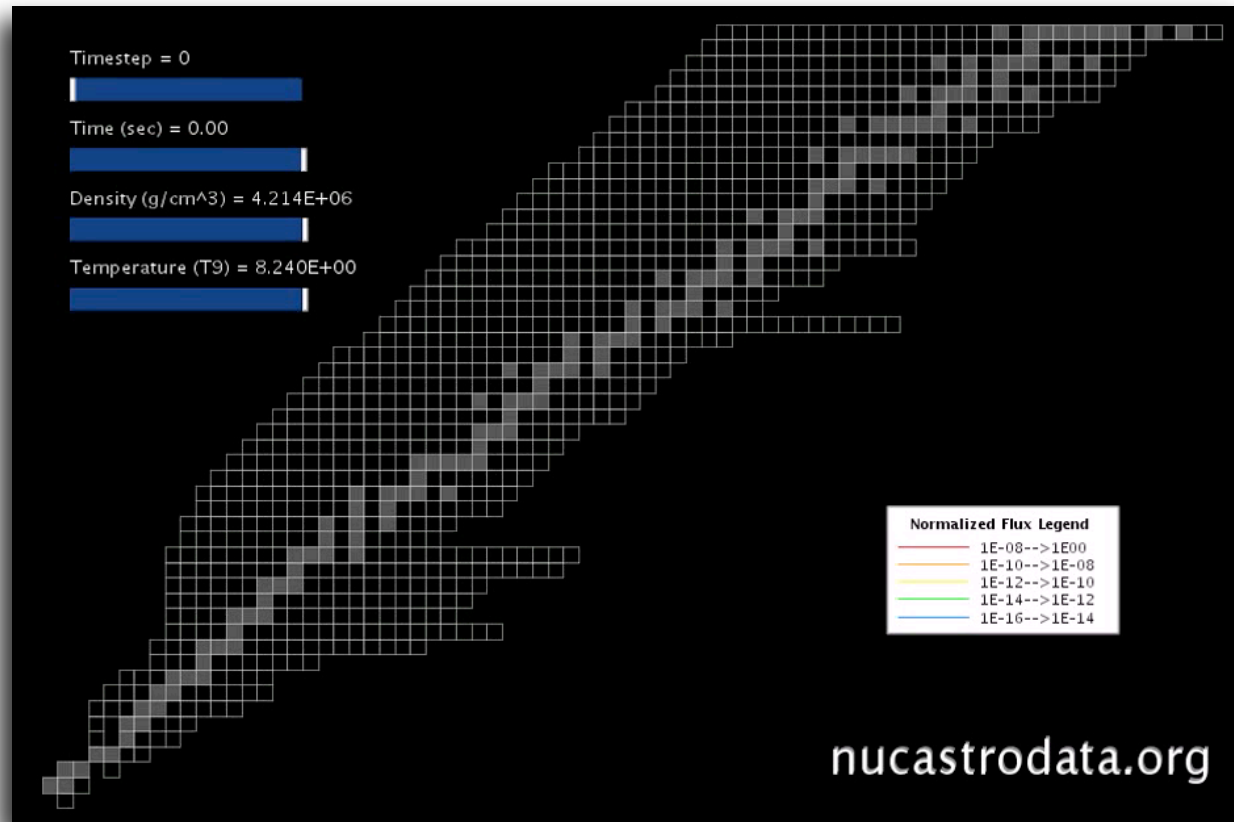- N. B. The CHIMERA version of VH1 is vastly different from the public version
  - non-polytropic EOS
  - 3D domain decomposition
  - **other sausage-like changes**

- MGFLD-TRANS
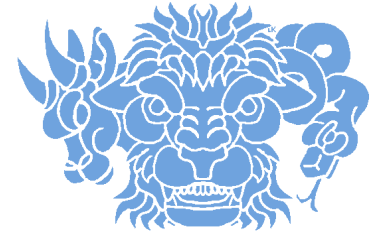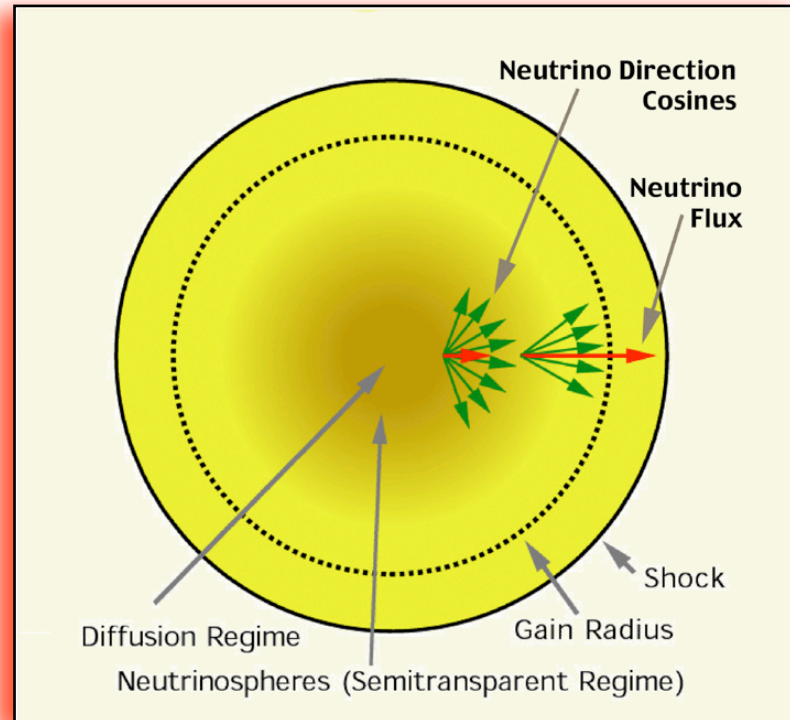
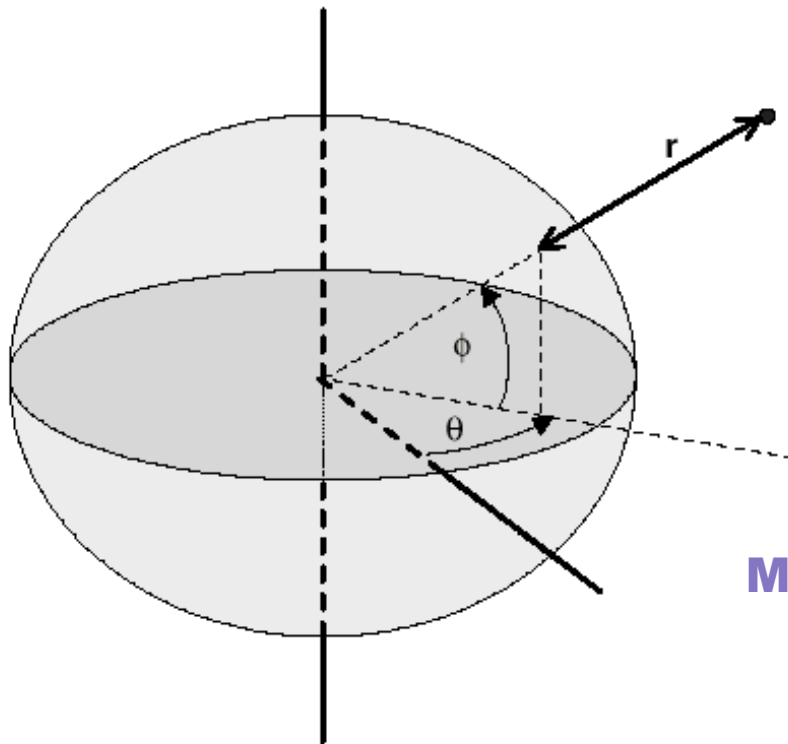- Multi-group (energy) neutrino radiation hydro solver
  - GR corrections
  - 4 neutrino flavors with many modern interactions included
- flux limiter is "tuned" from Boltzmann transport simulations

- XNET

- Nuclear kinetics solver
    - Currently have implemented only an α network
    - 150 species to be included in future simulations
- Custom interface routine written for CHIMERA
- All else is 'stock'

How does CHIMERA work?

VH1/ MVH3

MGFLD-TRANS

XNET

Start

Hydro Y (ϑ) sweep

Data transpose

Hydro Z (ϕ) sweep

Data transpose

Hydro X (r) sweep

ν transport along ray

nuclear burning on each zone of ray

Data transpose

Timestepping loop

Each processor has 1 ray of data local at this stage
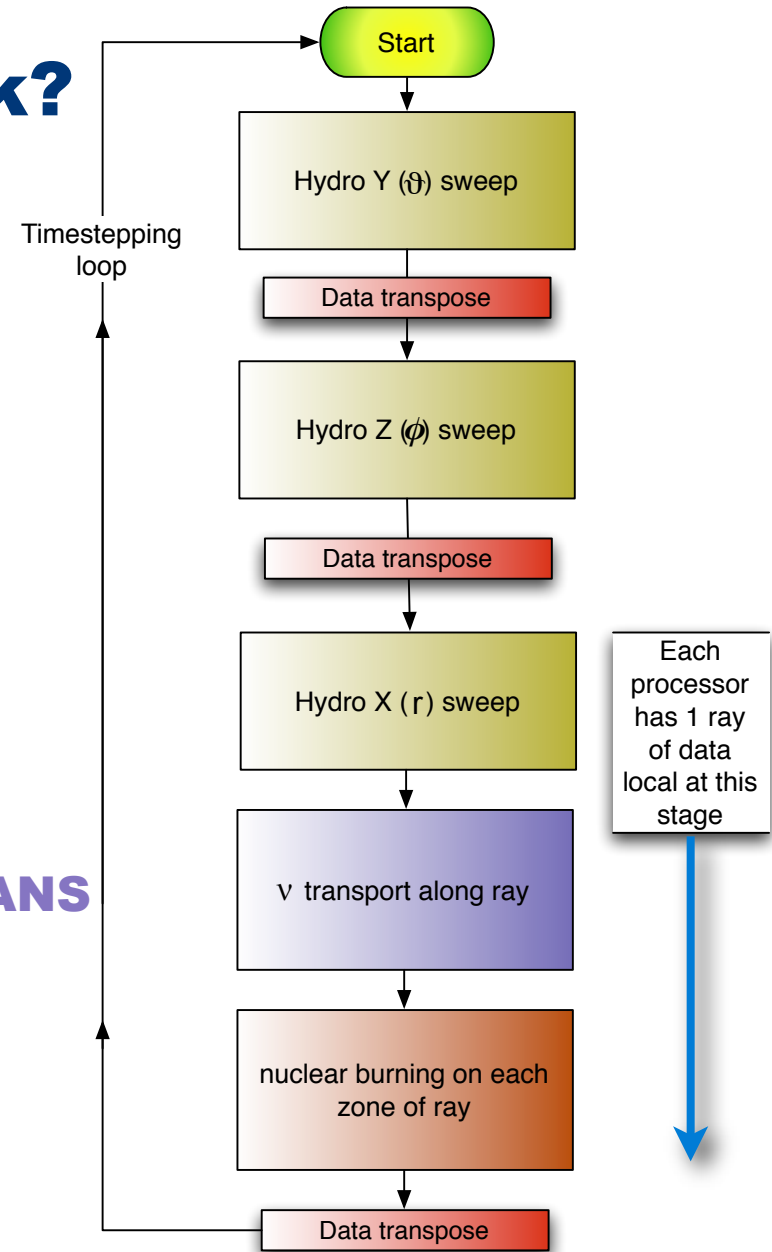
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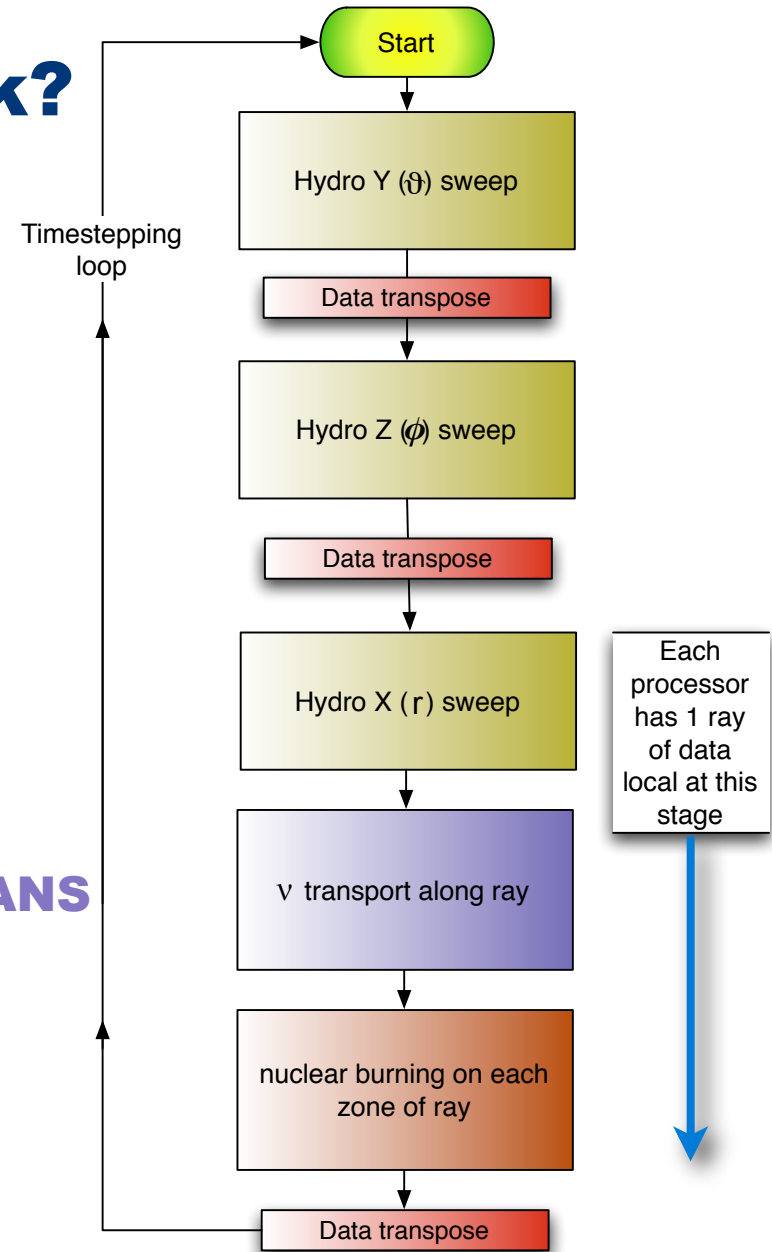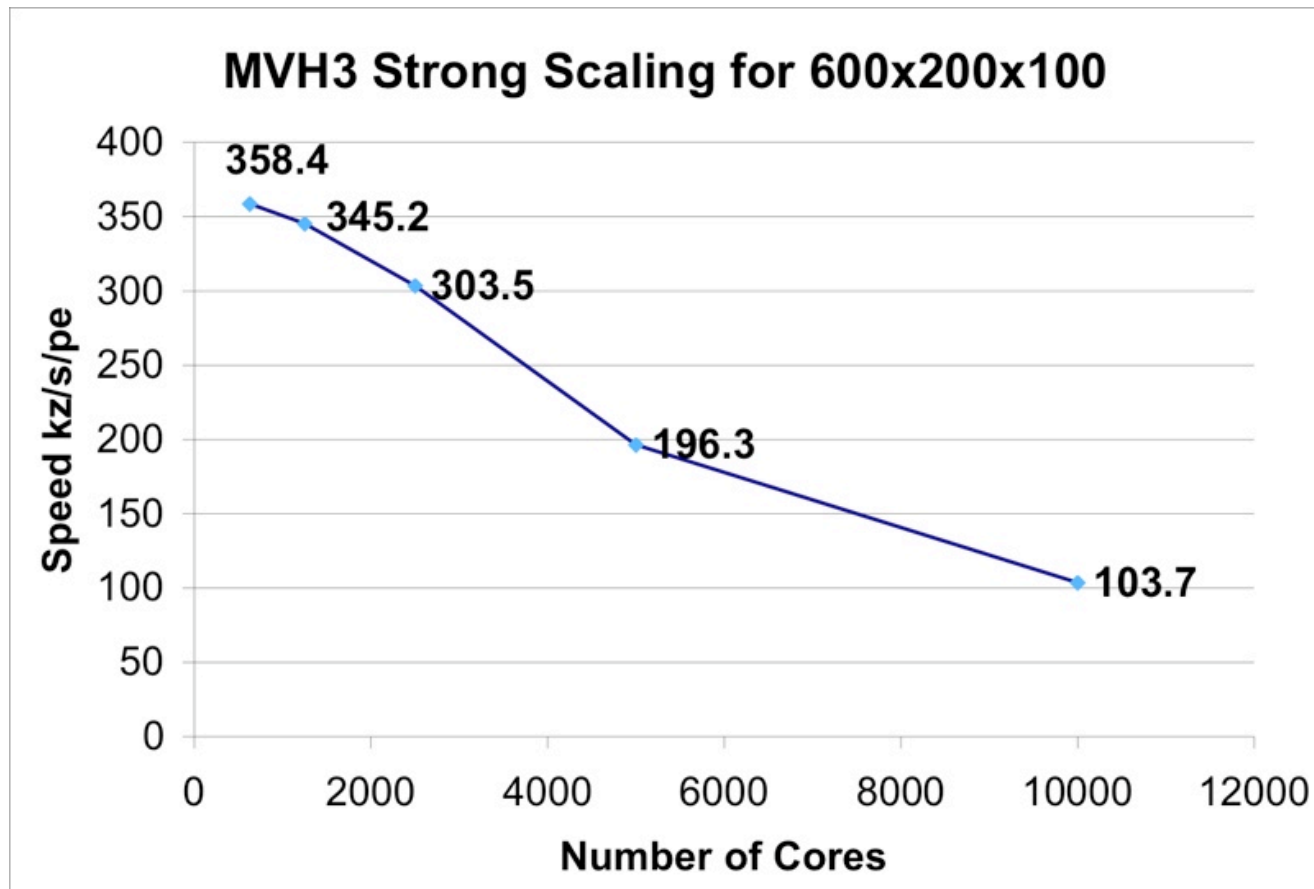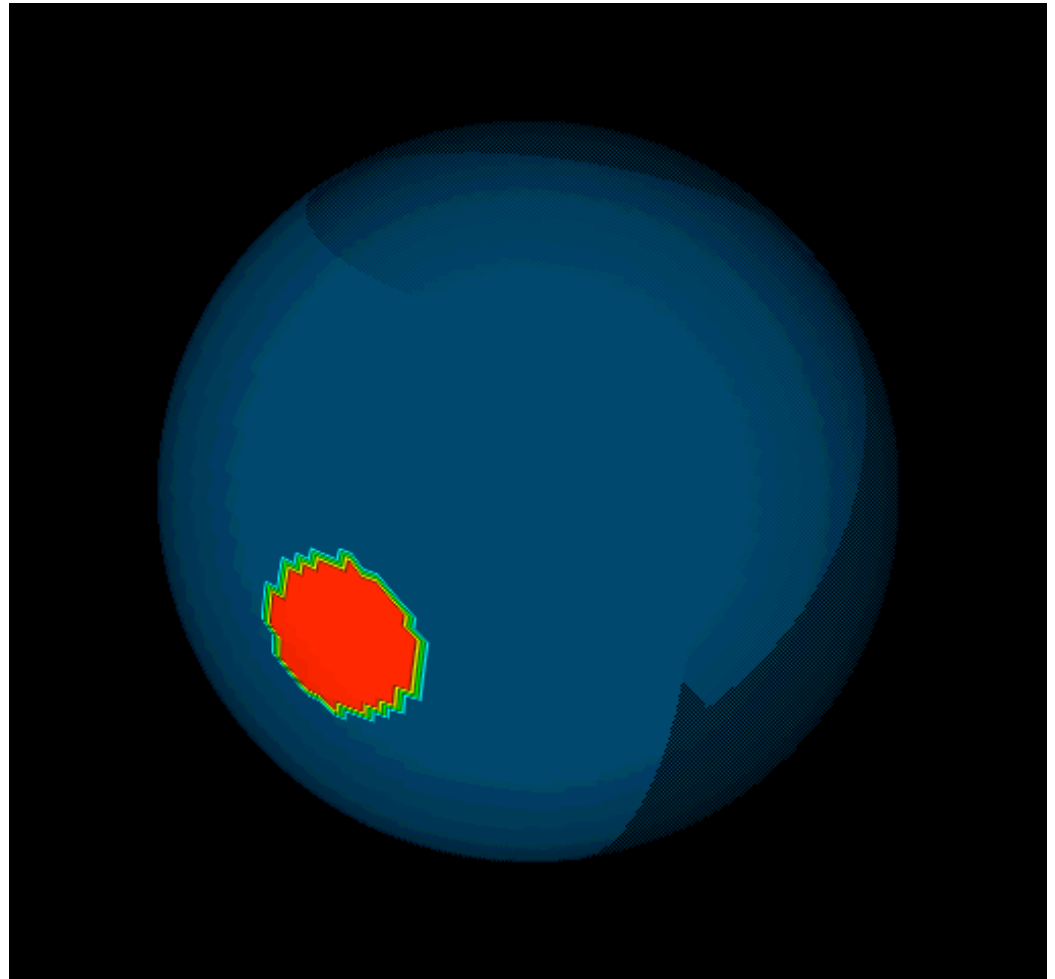
Hydrodynamics Scaling

The hydrodynamics is a negligible component of the overall runtime (e.g. 0.04 s out of ~45 s total at 10K cores)

Other Hydrodynamics issues

- Ray-by-ray transport "constrains" one to use spherical polar coordinates

- Courant and coordinate singularity issues ensue
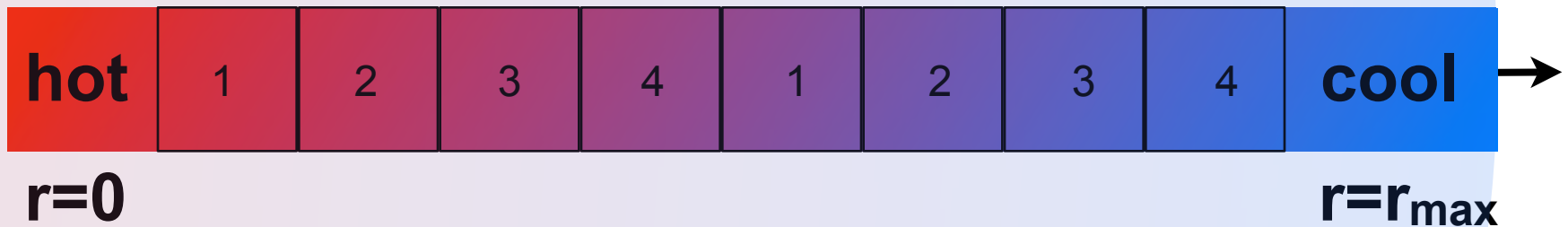

VH-1 hydro with YinYang grid (J. Blondin)

XNET performance and implementation

- XNET runs at ~50% of peak on a single XT4 processor
  - **Roughly 50% Jacobian build / 50% dense solve**

- 1 XNET solve is required per SPATIAL ZONE (i.e. hundreds per ray)

- Best load balancing on a node with OpenMP or a subcommunicator is interleaved

lots of burning   **little burning**

| hot | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | cool | → |

r=0   **r=r$_{max}$**

Transport module

- Transport solution is primarily 1 large-ish sparse solve

- Technology/Implementation for bCHIMERA:
  - **Boltzmann solver already uses threaded "ADI-like" preconditioner (D'Azevedo et al. 2005)**
    - **plan to move this preconditioner to mCHIMERA**
  - **Boltzmann transport solver also already parallelized along a ray, so subcommunicator across a "very-multi"-core socket is viable with little work**

local physics: coupling in angle and energy

radial transport
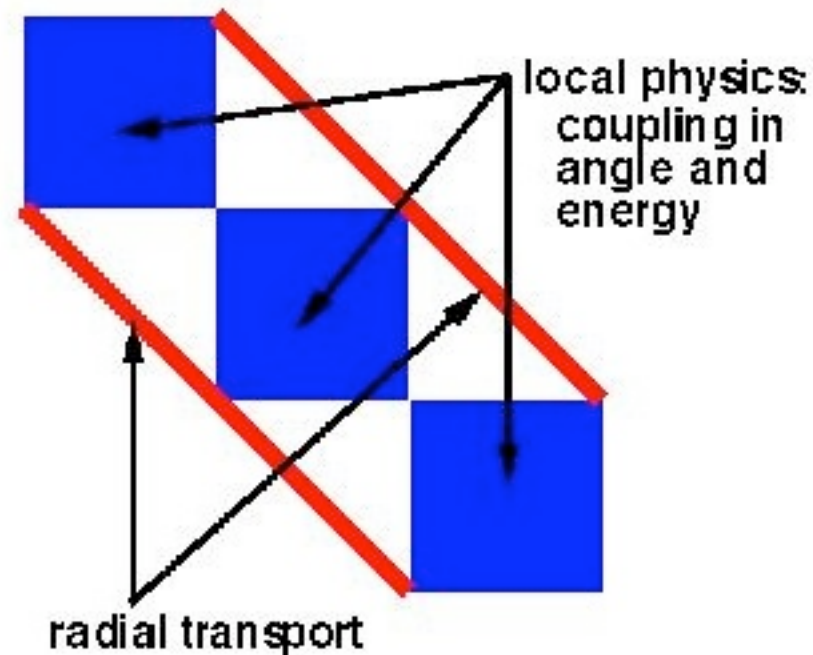
- Diagonal blocks are unsymmetric, ~80x80 for MGFLD, 500x500 for Boltzmann

- Overall system ~8000x8000, ~1% non-zeroes (MGFLD)

2D results
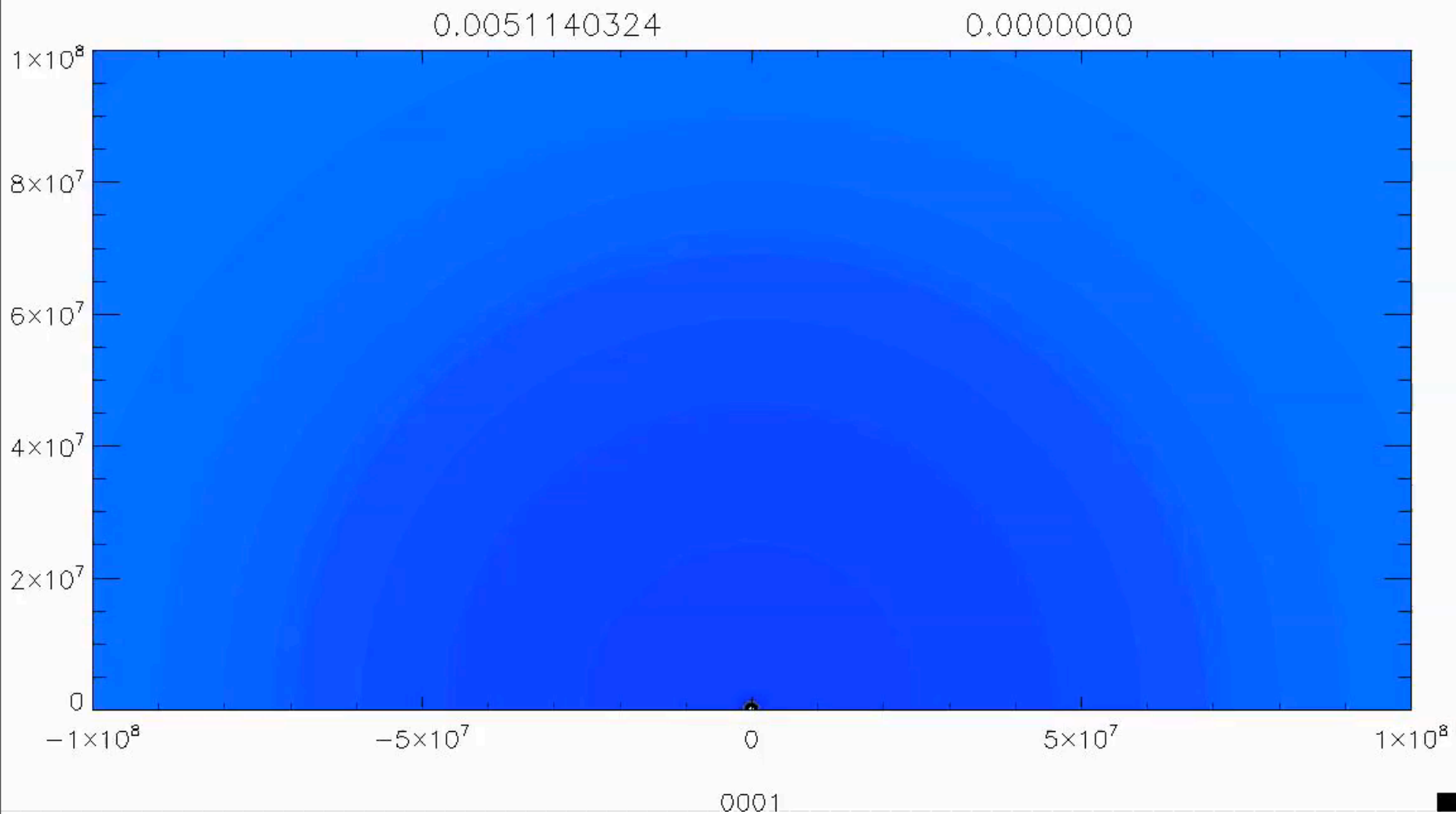
Summary

- The multi-scale and multi-physics characteristics of core-collapse supernova simulation makes it an ideal candidate for petascale (and beyond) computing
    - **huge scale contrasts**
    - **massive amounts of physics to be modeled**
    - **requires modern, sophisticated software infrastructure to make real progress**

- CHIMERA architecture allows realistic supernova simulations to be run on modern and near-future platforms
    - **fine-grain parallelism can be exposed in the neutrino transport and the nuclear burning**
    - **OpenMP? MPI sub-communicators?**
    - **transport module can be swapped out**
    - **nuclear kinetics module can be made more sophisticated (e.g. QSE)**