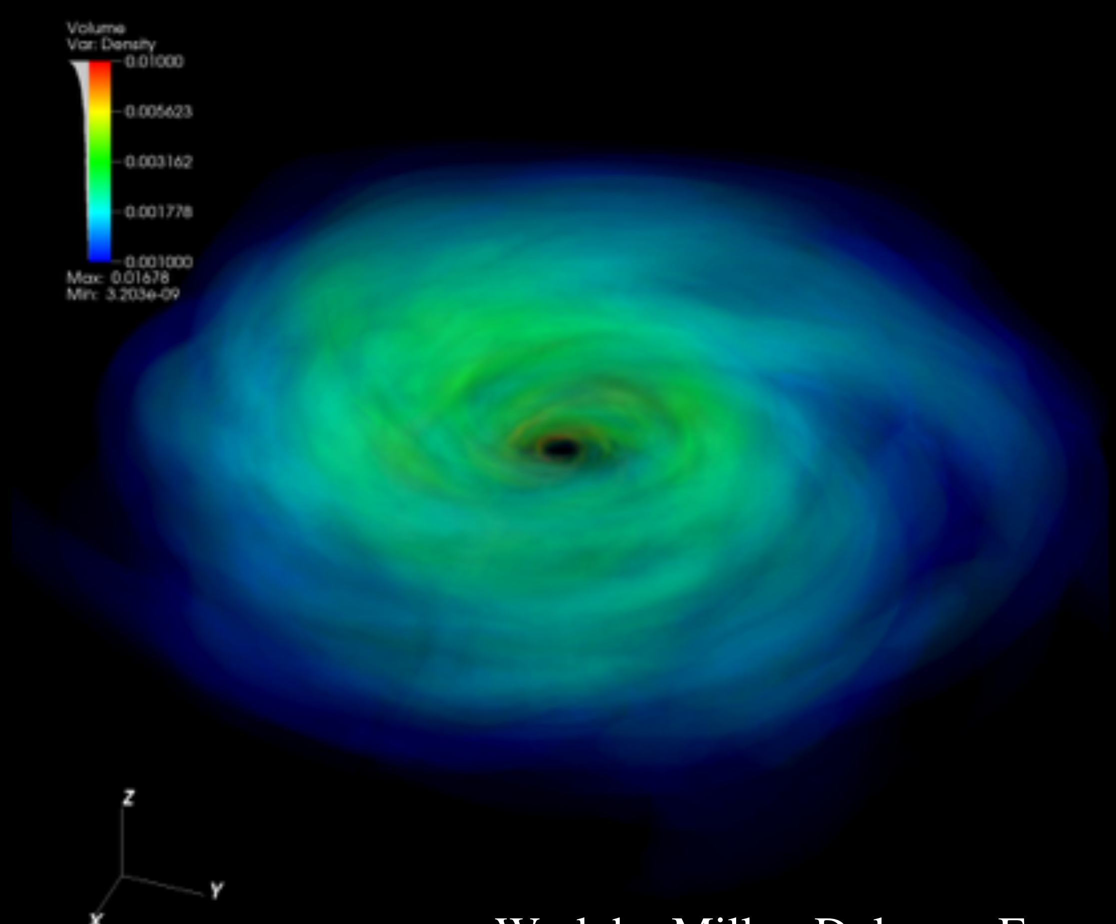
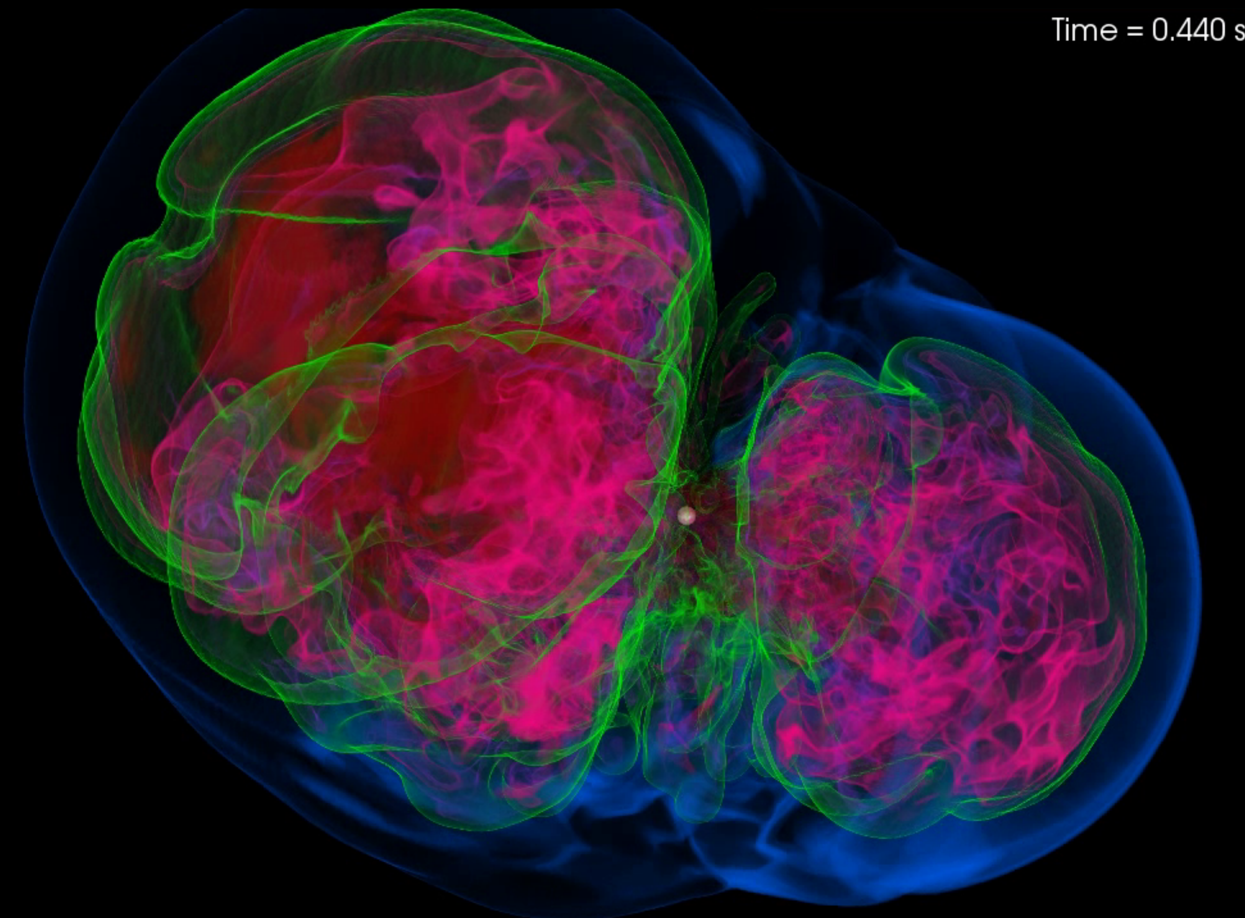
Towards Exascale Astrophysics for





Work by Miller, Dolence, Fryer, … Work by Burrows, …

Mergers and Supernovae

William Raphael Hix (ORNL/U. Tennessee)
for the SciDAC-4 TEAMS collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

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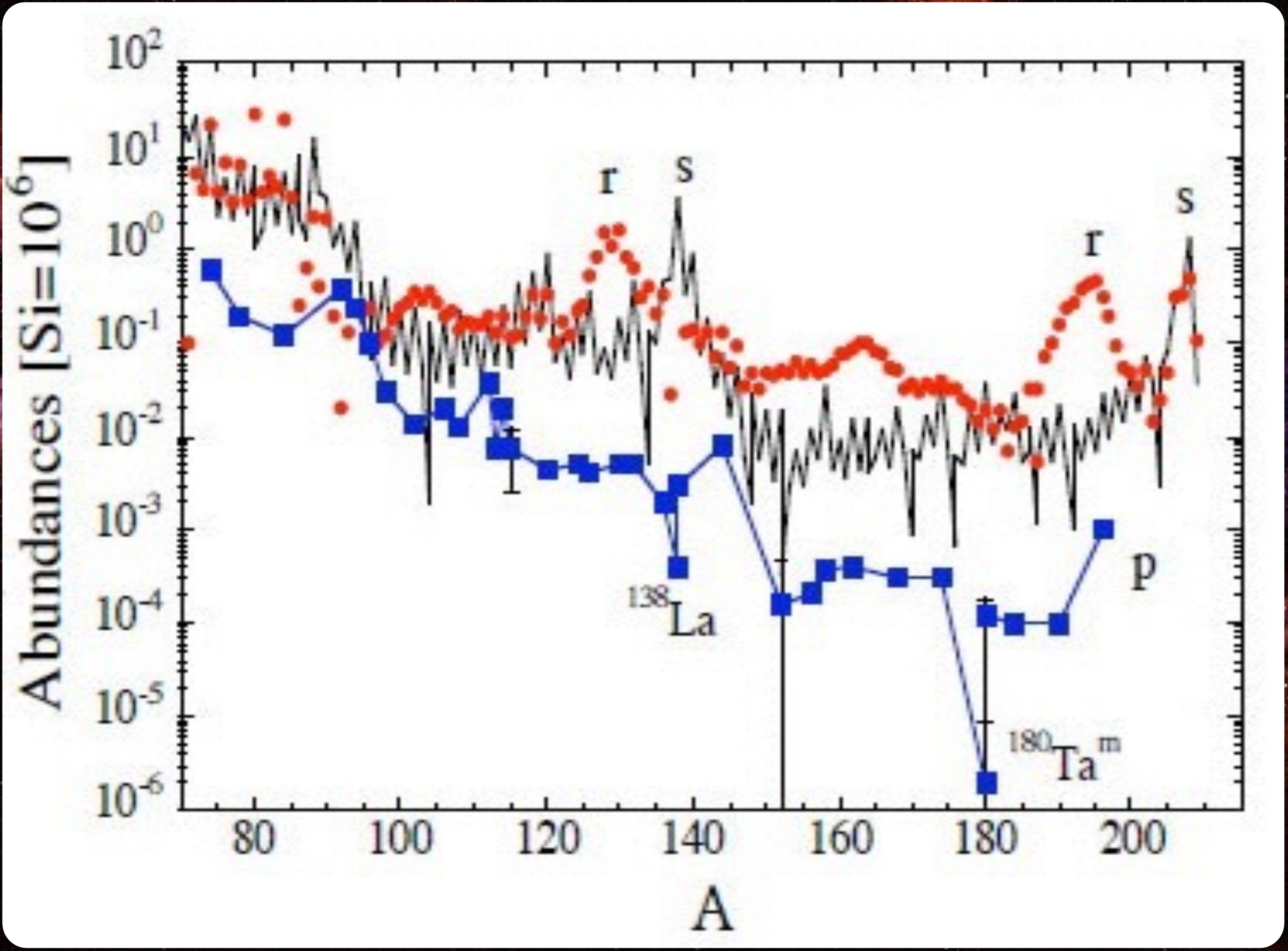
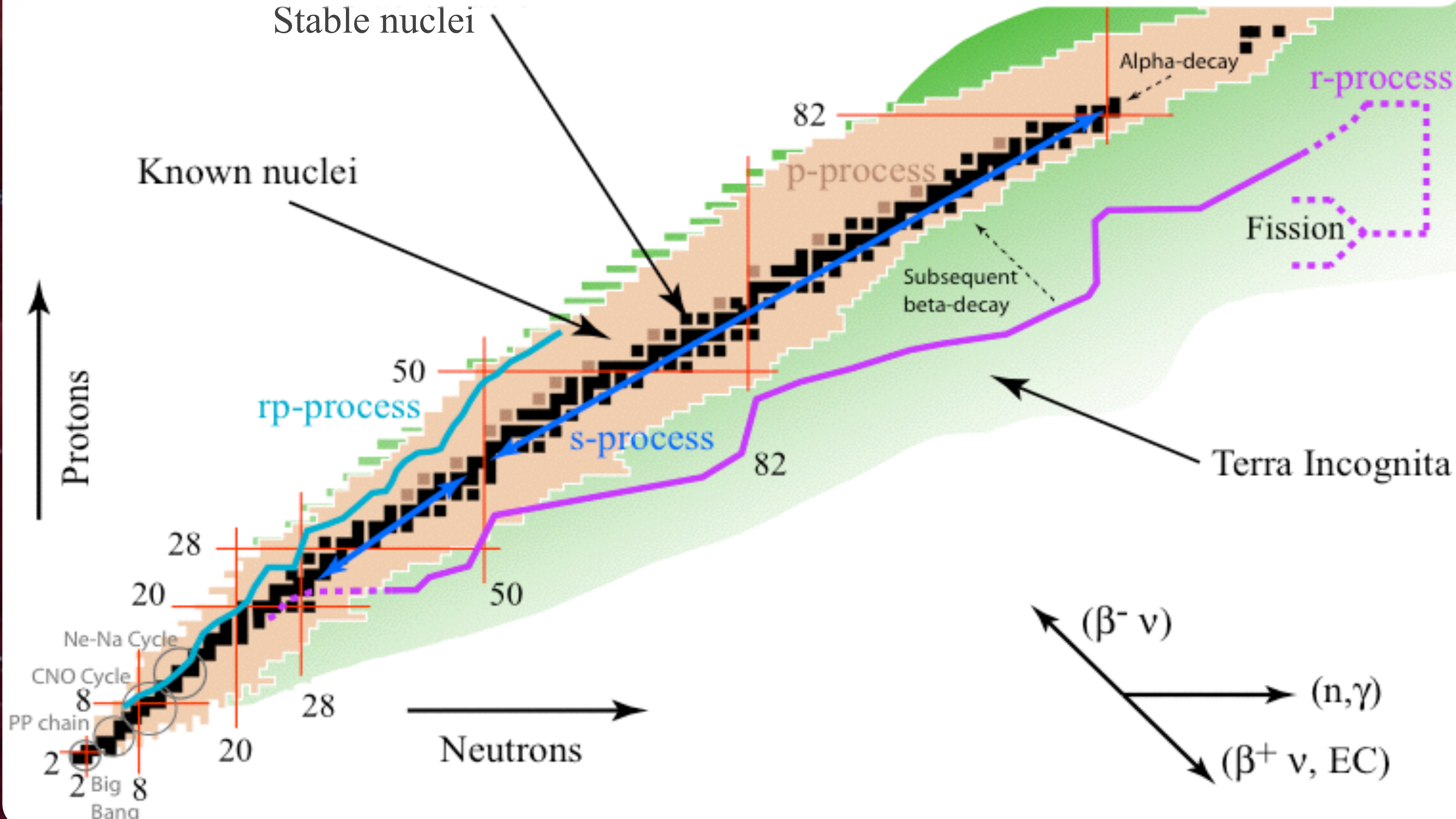
R-PROCESS & P-PROCESS

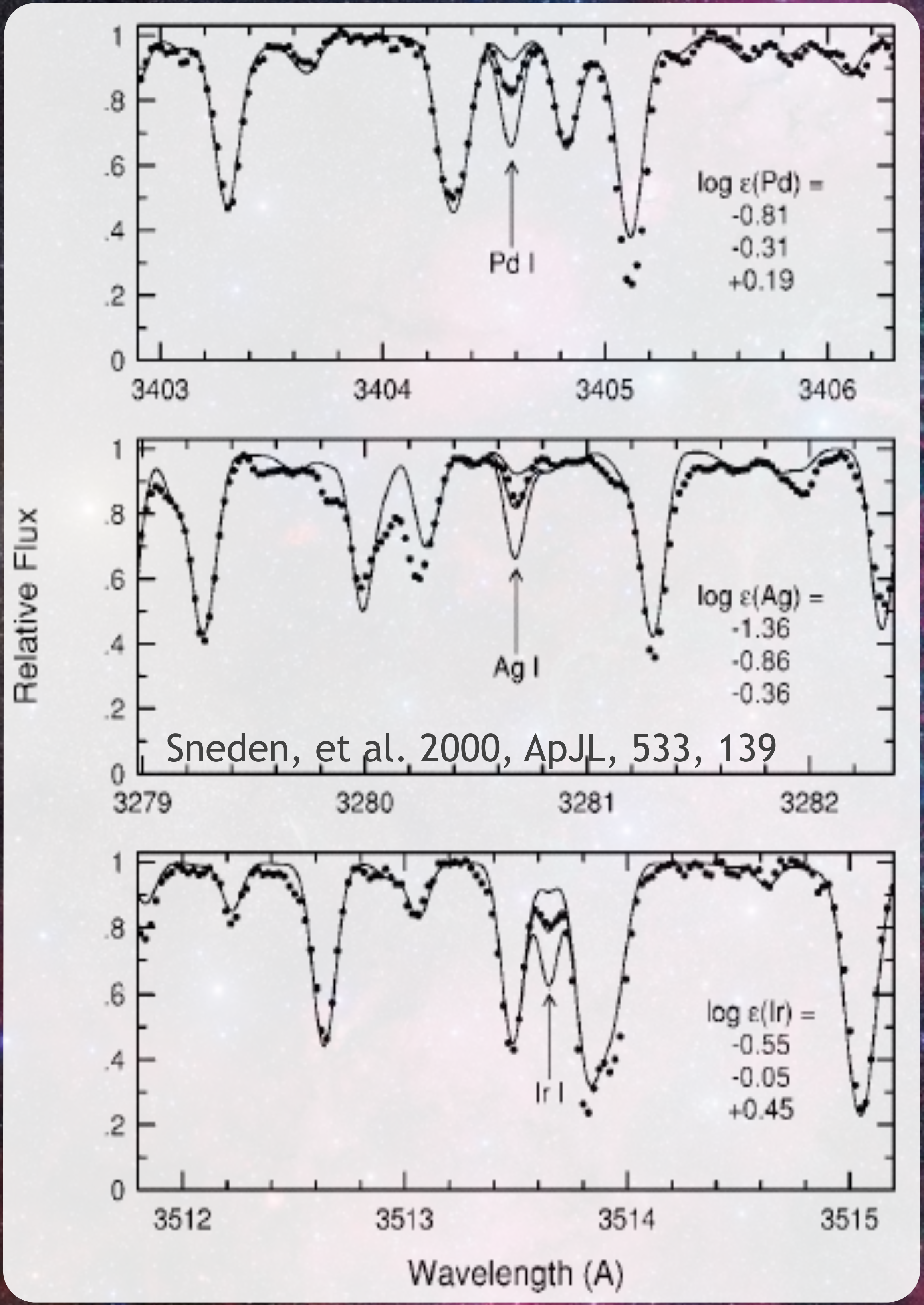


Processes and Sites

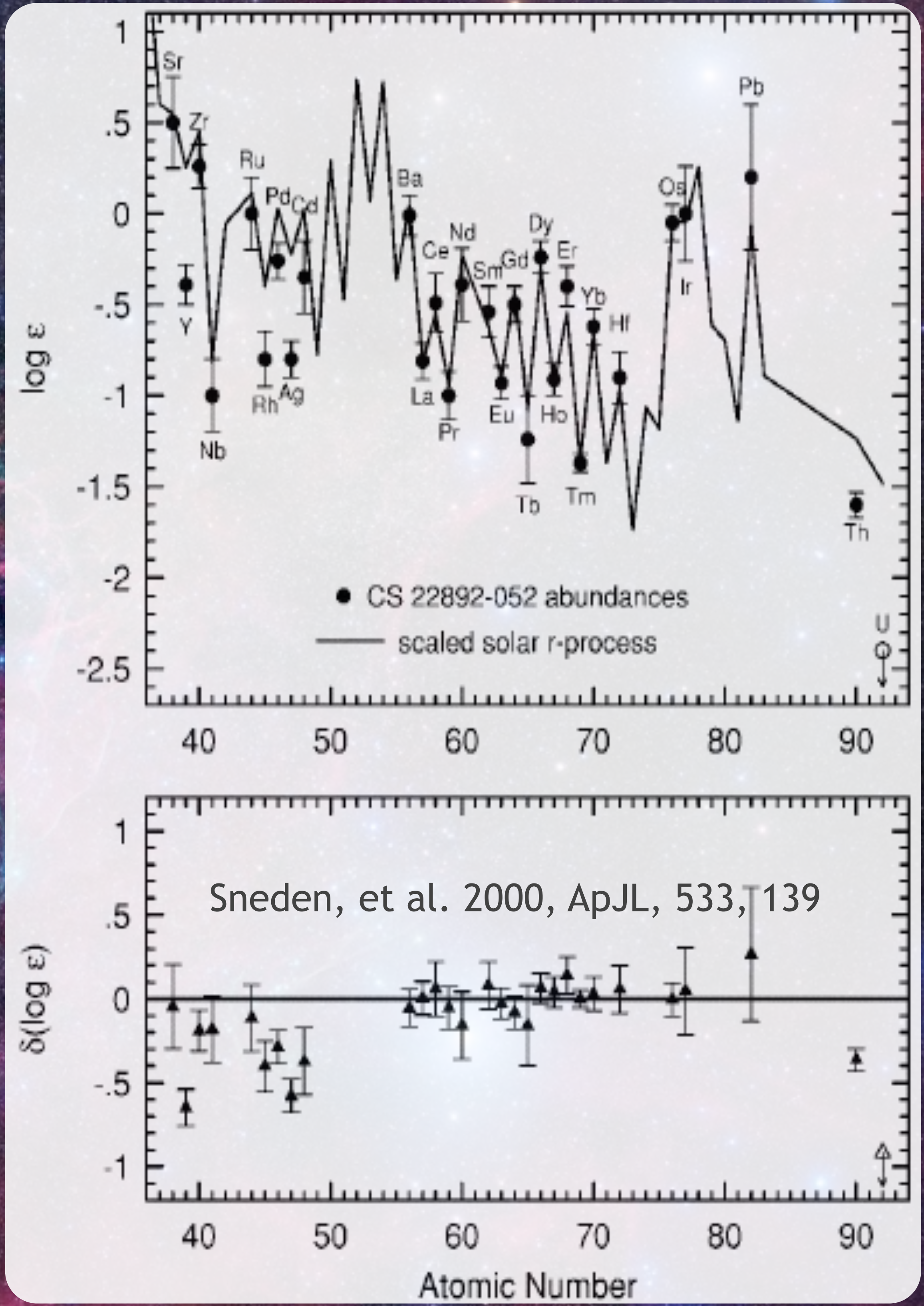


Understanding our nuclear origins means understanding processes that transmute nuclei and the sites where these processes occur.

r-process Elements in old stars



Sneden, et al. 2000, ApJL, 533, 139



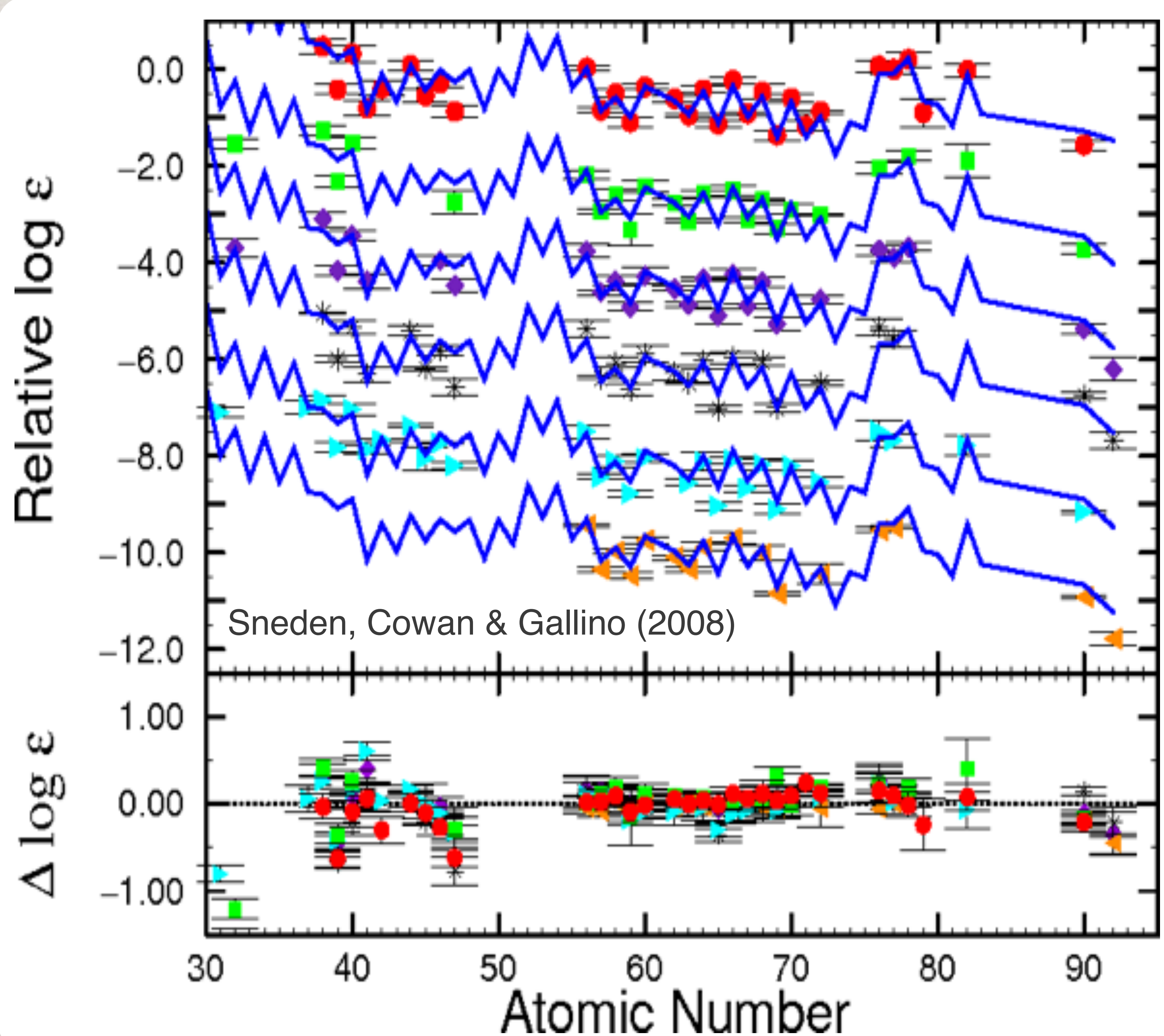
Sneden, et al. 2000, ApJL, 533, 139

Universal R-process?

This similarity between the r-process abundances in the Sun and in some of the Galaxy's oldest stars was not an isolated example.

For $Z > 55$, the R-process abundances are very similar, whether they come from a single event, like the low metallicity stars, or are the sum of many events over billions of years.

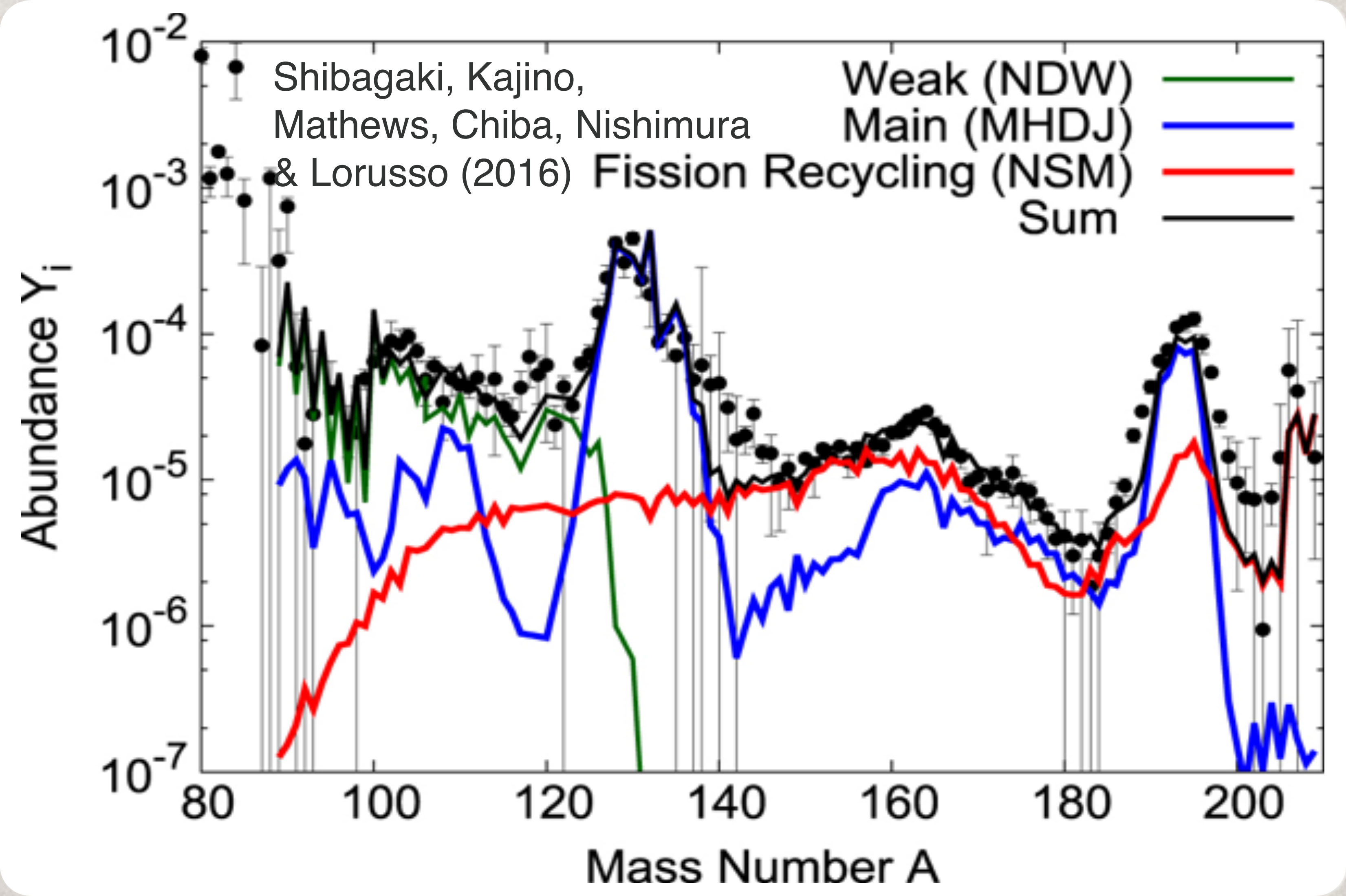
This universality does not seem to apply for $Z < 50$.



Multiple sites?

The variability of the weak r-process (Z < 50) in contrast to the universality of the main r-process (Z > 55) suggests to many that more than one r-process site is needed to explain the observations.

With ordinary supernovae struggling to maintain sufficient neutron-richness, because of neutrino interactions, they are generally ruled out for the main r-process.

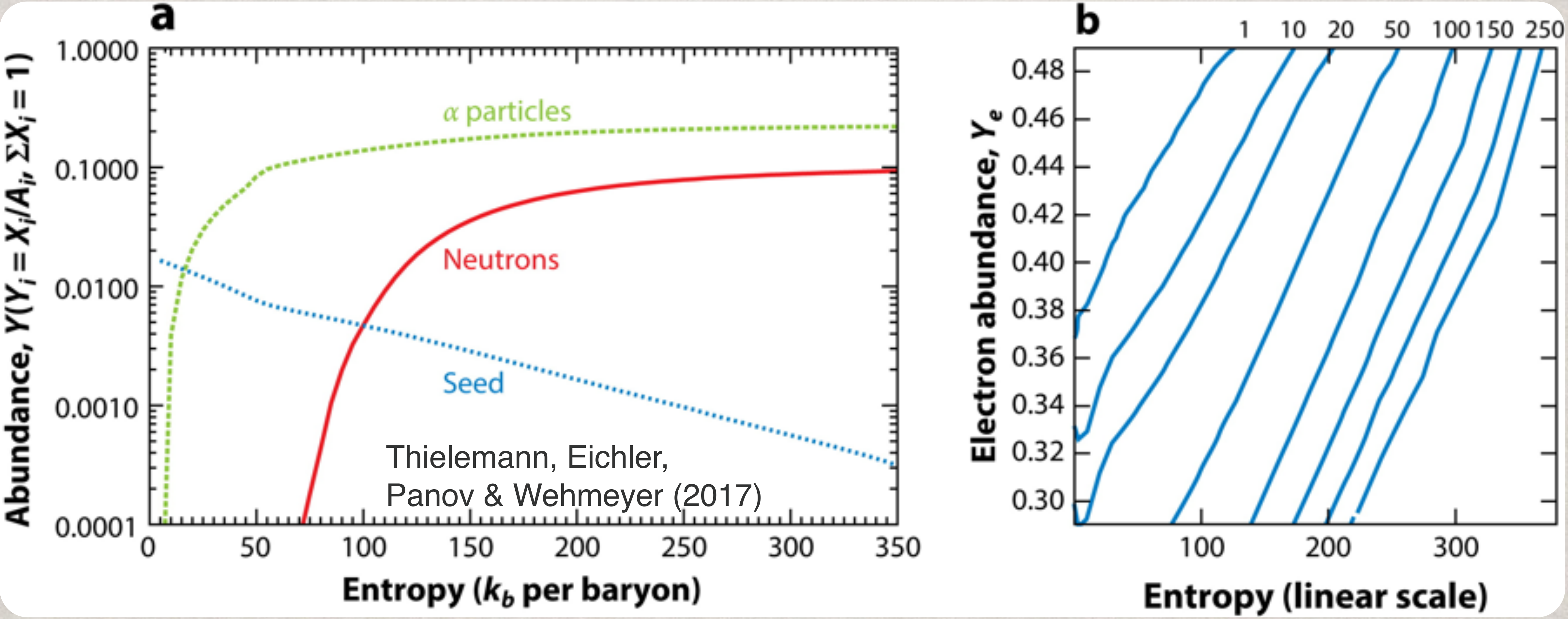


This generally leaves exotic supernovae and neutron star mergers (or both) as the site of the main r-process.

Recipe for the R-process

Making the heaviest nuclei via rapid neutron capture requires roughly 150 free neutrons for each *seed* heavy nucleus (typically A > 60).

Because ^{4}He is immune to neutron captures, its presence, even in large quantities, does not diminish the neutron/seed ratio.



Thielemann, Eichler, Panov & Wehmeyer (2017)

Thus, a similar neutron/seed ratio can be achieved in less neutron-rich conditions by increasing the entropy or otherwise increasing ^{4}He.

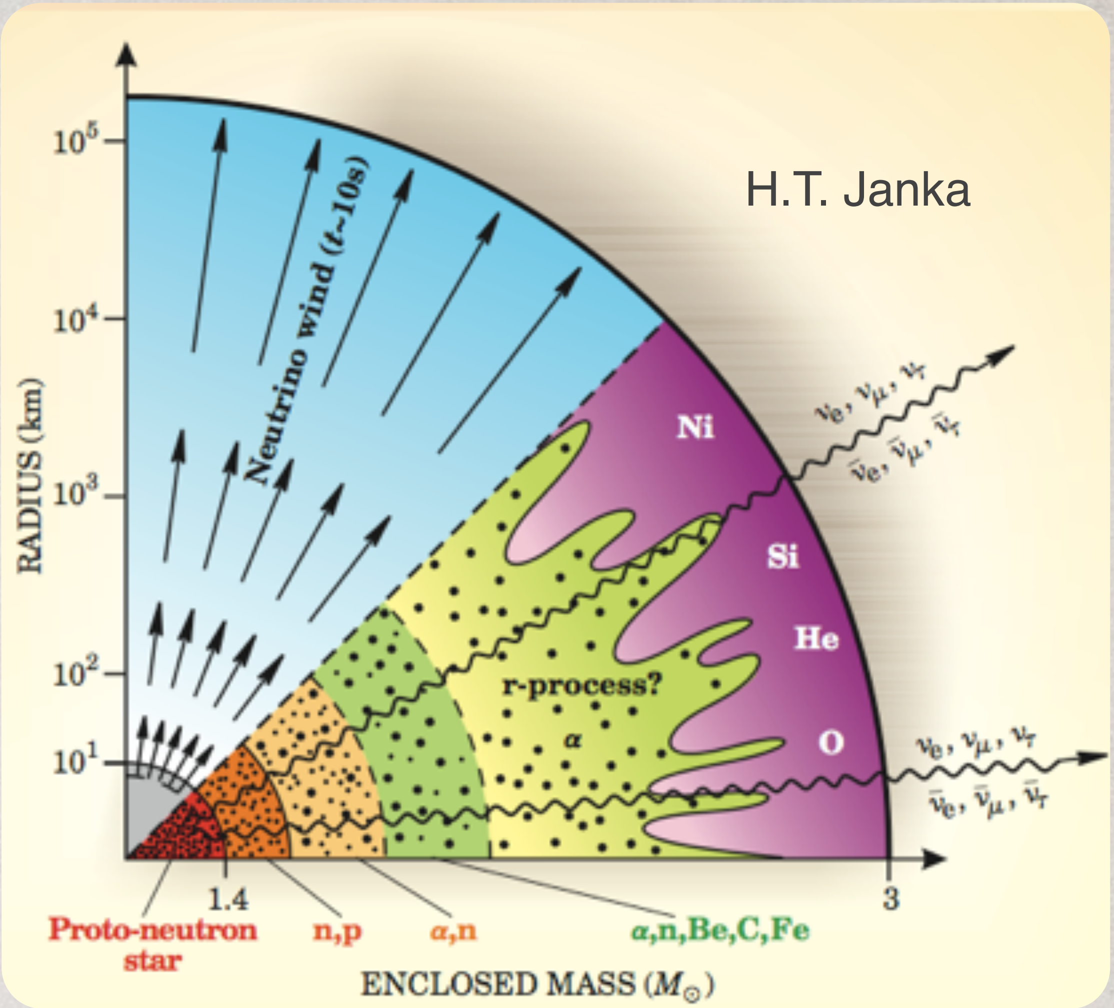
Site of the r-process

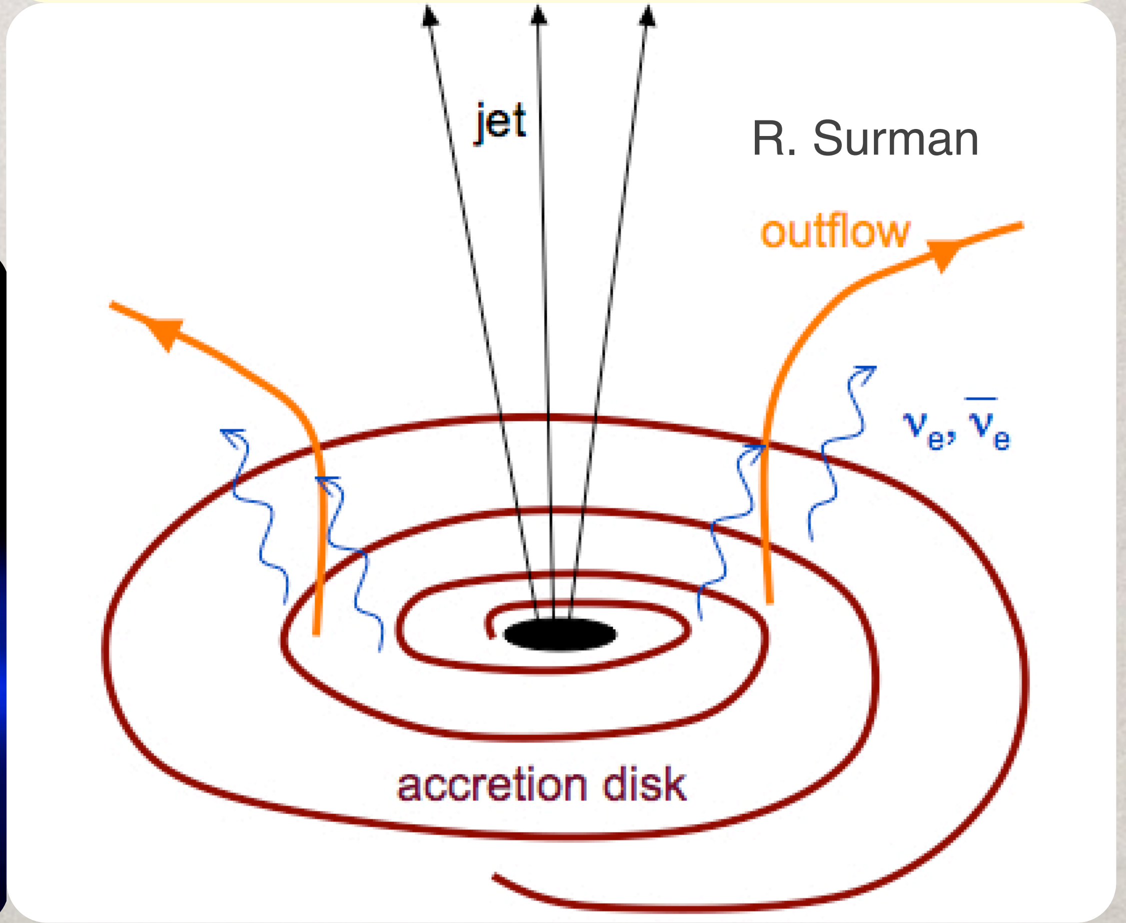
Formation of r-process requires neutron-rich, high entropy matter such as may occur in

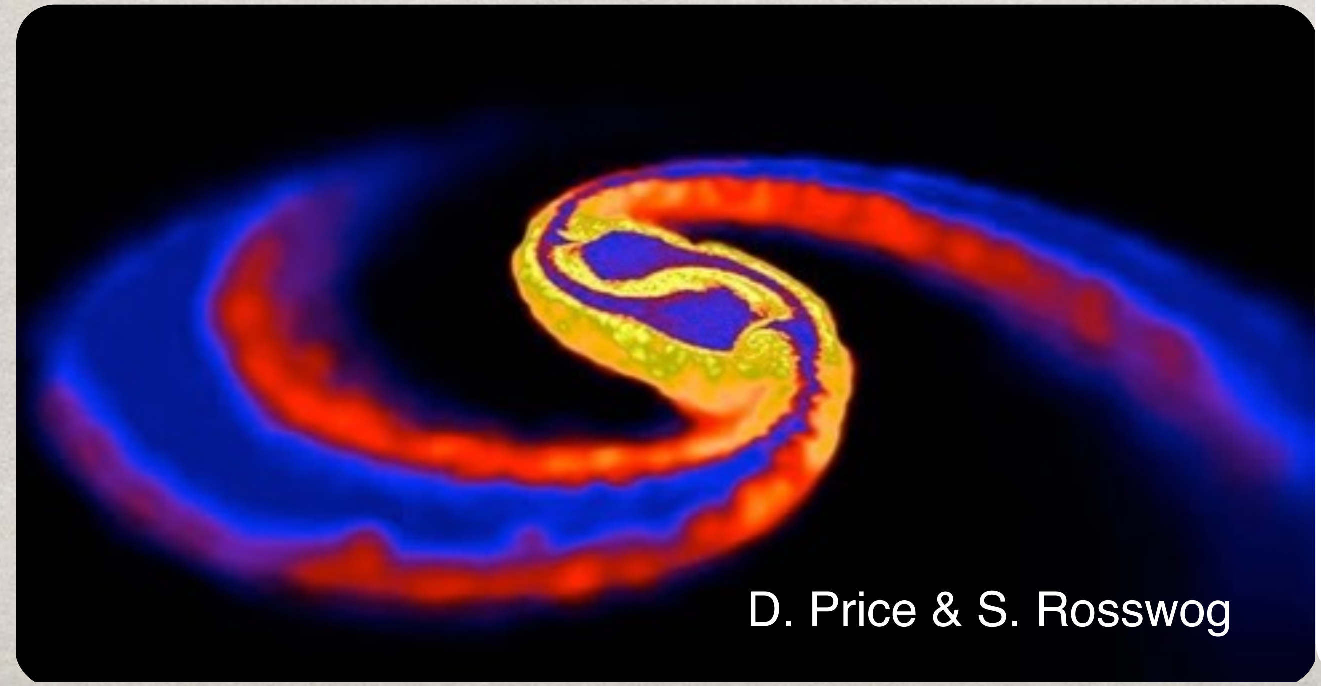
1) PNS wind in an SN,

2) in a wind from an accretion disk around a black hole,

3) or in a neutron star merger.





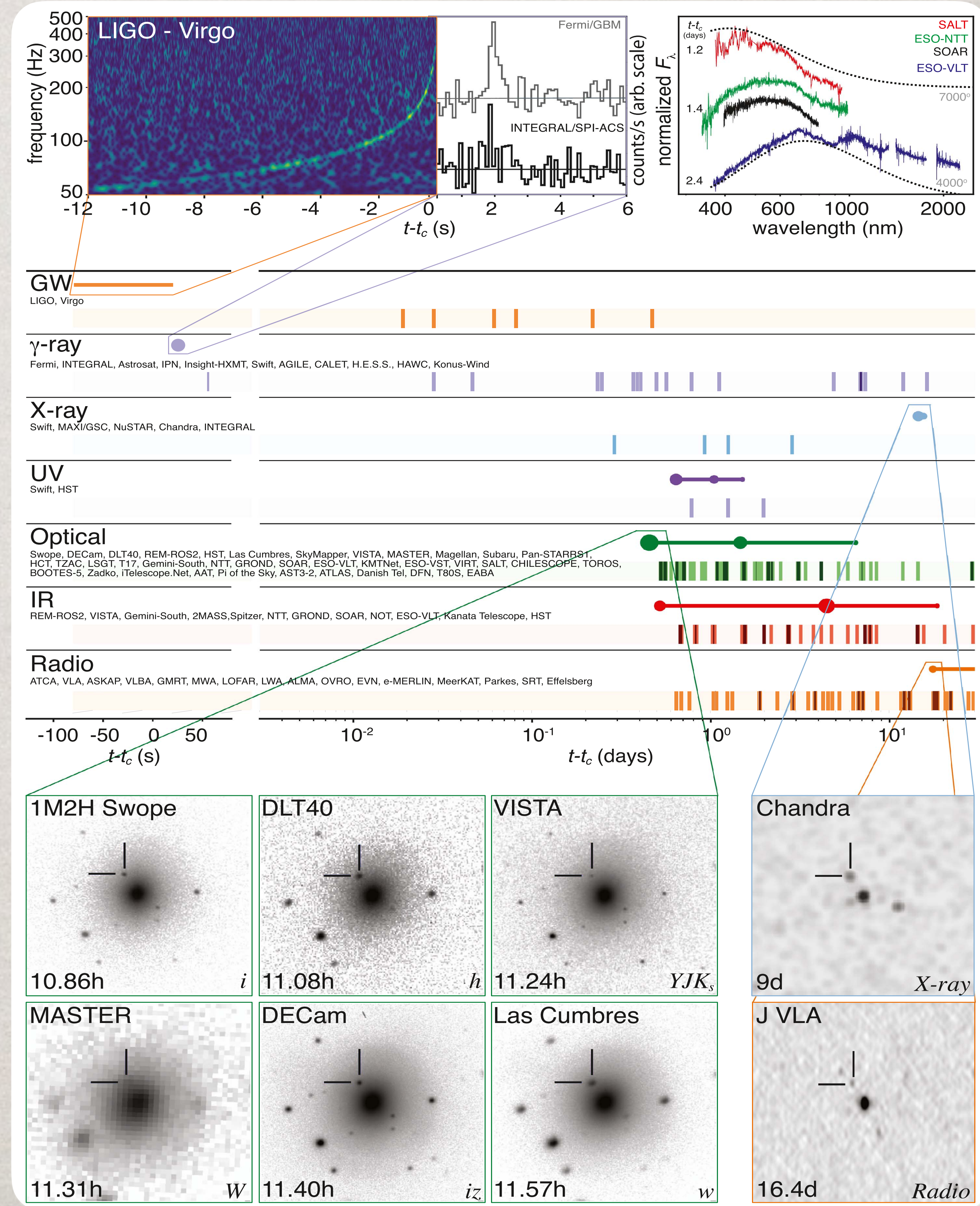


Seeing the r-process?

Observations of GW170817 and GRB 170817a confirmed the long suspected connection between short GRBs and neutron star mergers.

They also launched a extensive multi-wavelength observational campaign, which provided observations of the second ever *kilonova*, with expected red (high opacity) and unexpected blue (low-opacity) components.

This high opacity component is consistent with heavy r-process production, but interpretation of the quantity and composition of the ejecta are model-dependent.



TEAMS Goals

The overall goal of the TEAMS collaboration is to explore as many of the proposed sites of the r-process (and p-process), with much higher physical fidelity using the coming generation of exascale computers.

Iron Core-Collapse Supernovae: FORNAX (Princeton), CHIMERA, FLASH

Oxygen-Neon Core-Collapse: CHIMERA (ORNL), FORNAX, FLASH

MHD-driven Supernovae: FLASH (MSU), FORNAX

Neutron Star Decompression: WhiskyTHC (Princeton), FLASH/CLASH

Black Hole Accretion Disks (NSM or Collapsar): FLASH/CLASH (UCB), bhlight (LANL)

Epstein, Colgate & Haxton Mechanism (in the supernova shocked He layer of stars): CHIMERA (ORNL), FORNAX

Compute multi-D supernova progenitors: Maestro (Stony Brook/LBNL).

Compute photon signatures using Sedona (UCB), Cassio & SUPERNU (LANL).

TEAMS Goals II

Reaching our goals for improved physical fidelity with near-exascale simulations requires improvements not just in our astrophysics, but also in our nuclear physics.

To this end, TEAMS includes expertise in nuclear physics and nucleosynthesis.

Nuclear Equation of State for Supernovae and Neutron Stars:
Steiner (UTK)

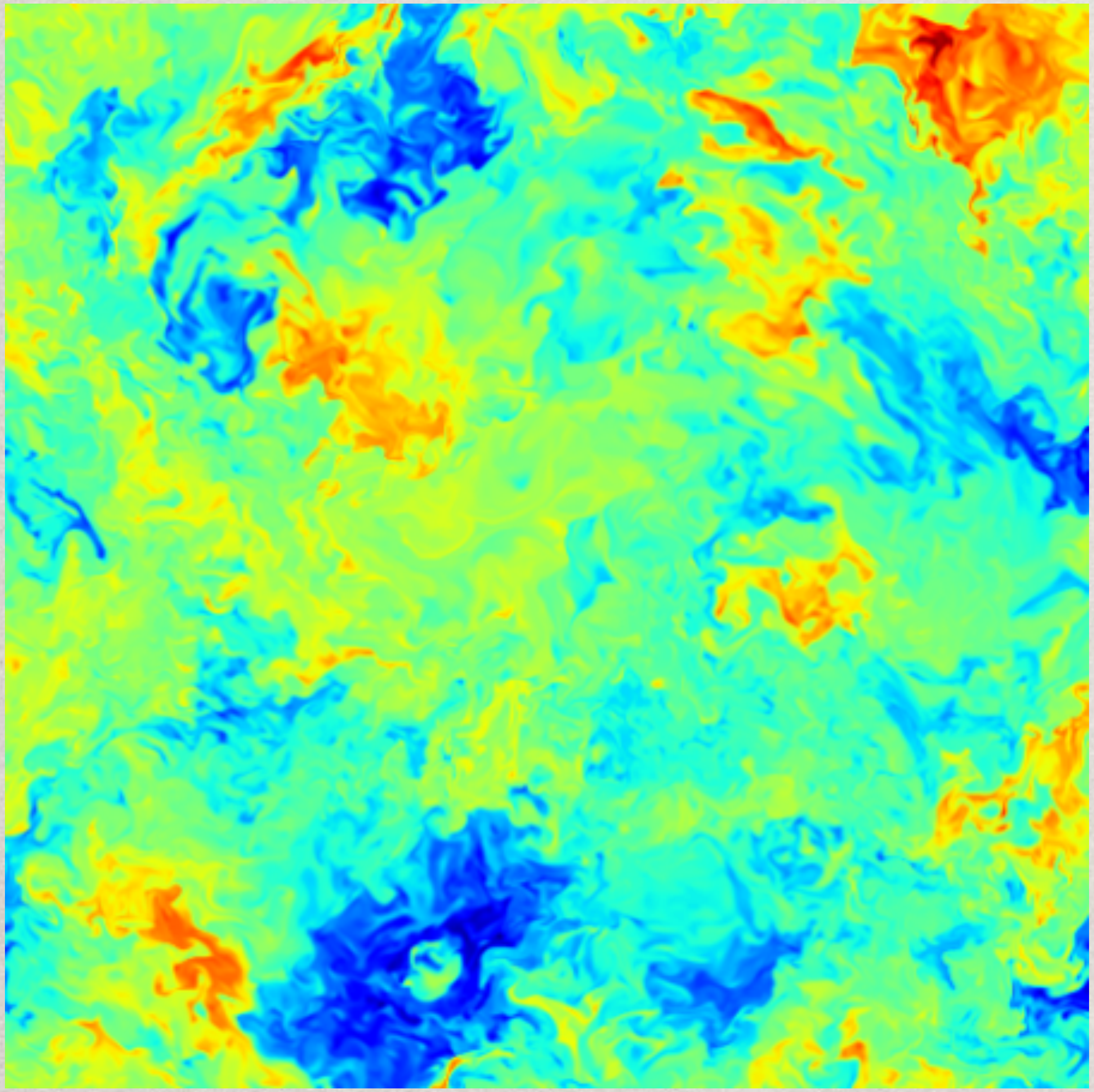
Consistent Neutrino Opacities:
Reddy(UW) and Roberts (MSU)

Nuclear Physics Uncertainty Quantification for the r-process:
Surman (Notre Dame)

Astrophysical Uncertainty Quantification for Nucleosynthesis:
Surman (Notre Dame), Hix (ORNL), and Fryer (LANL).

WhiskyTHC

http://www.astro.princeton.edu/~dradice/whiskythc.html

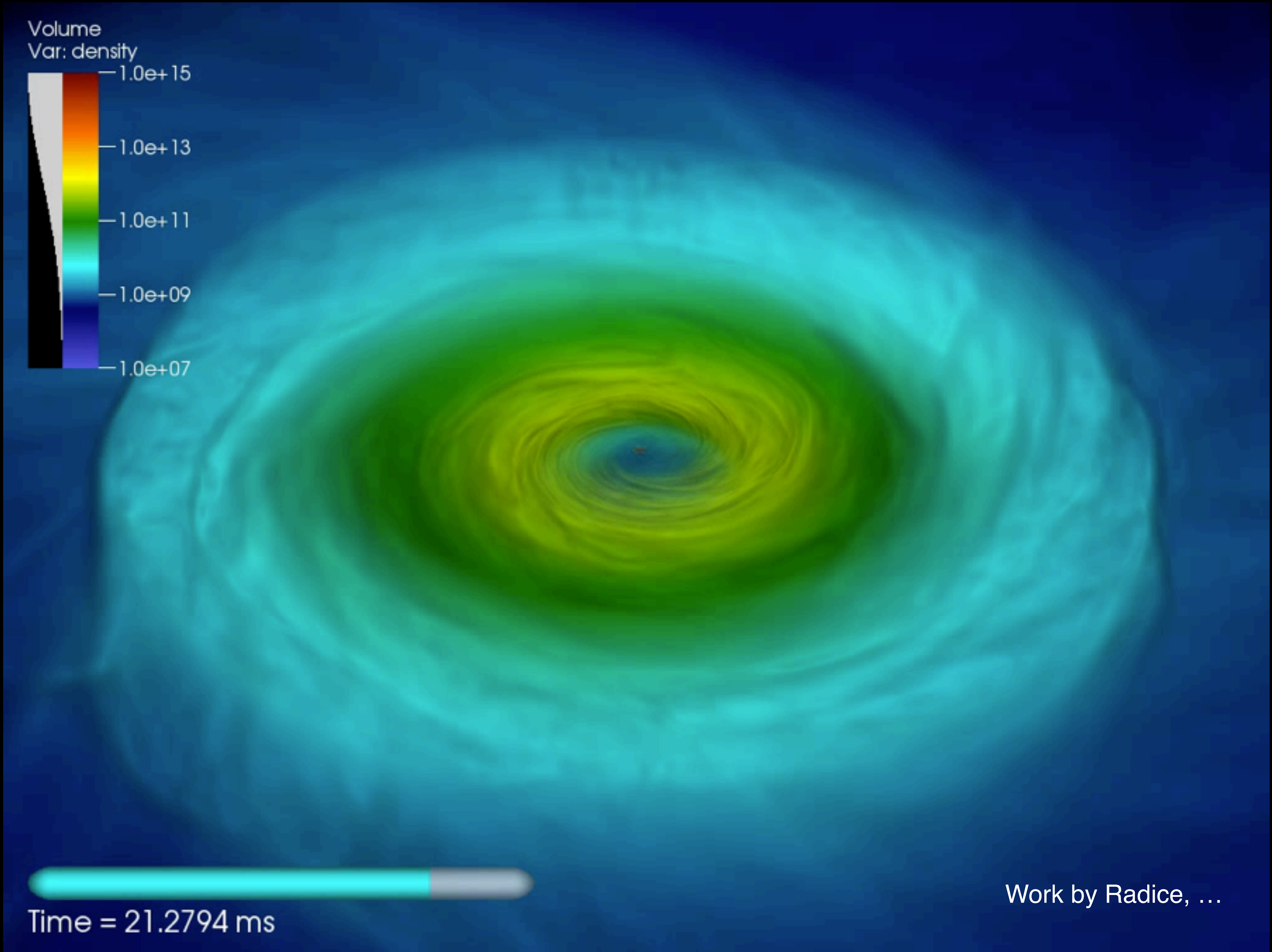


- Full-GR, dynamical spacetime*
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics

  THC: Templated Hydrodynamics Code
- Open source!

* using the Einstein Toolkit metric solvers

Merger Simulations



Work by Radice, …

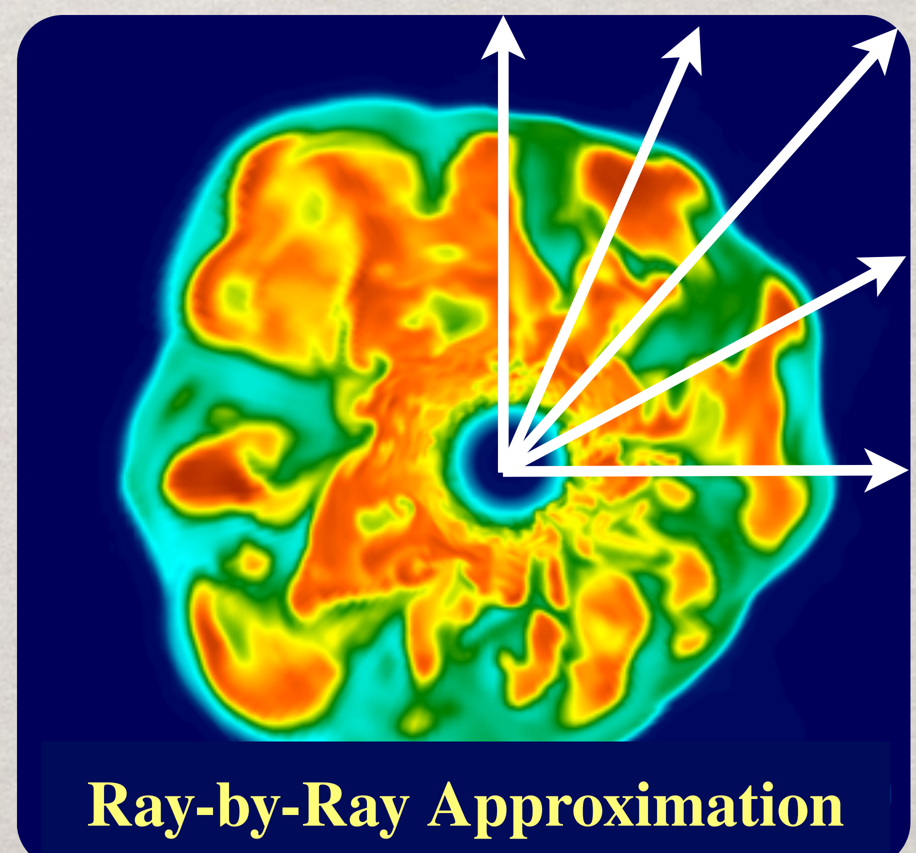
CHIMERA

CHIMERA has 3 “heads”

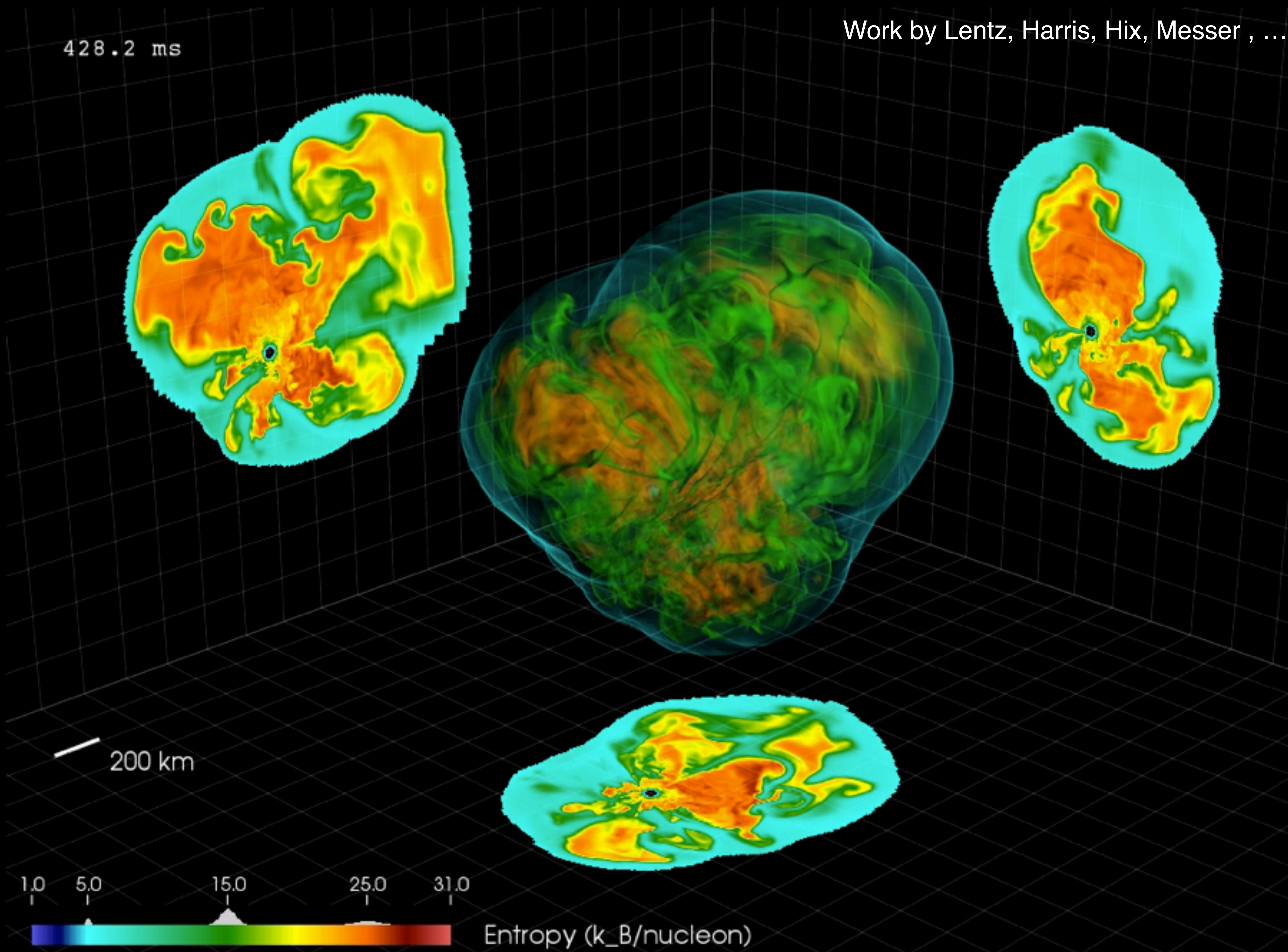
- Spectral Neutrino Transport (MGFLD-TRANS, Bruenn) in Ray-by-Ray Approximation
- Shock-capturing Hydrodynamics w/ radial adapt. (VH1, Blondin)
- Nuclear Kinetics (XNet, Hix & Thielemann)
- Plus Realistic Equations of State, Newtonian Gravity with Spherical GR Corrections.

Models use a variety of approximations

- Self-consistent models use full physics to the center.
- Leakage & IDSA models simplify the transport.
- Parameterized models replace the core with a specified neutrino luminosity.



Supernova Simulations

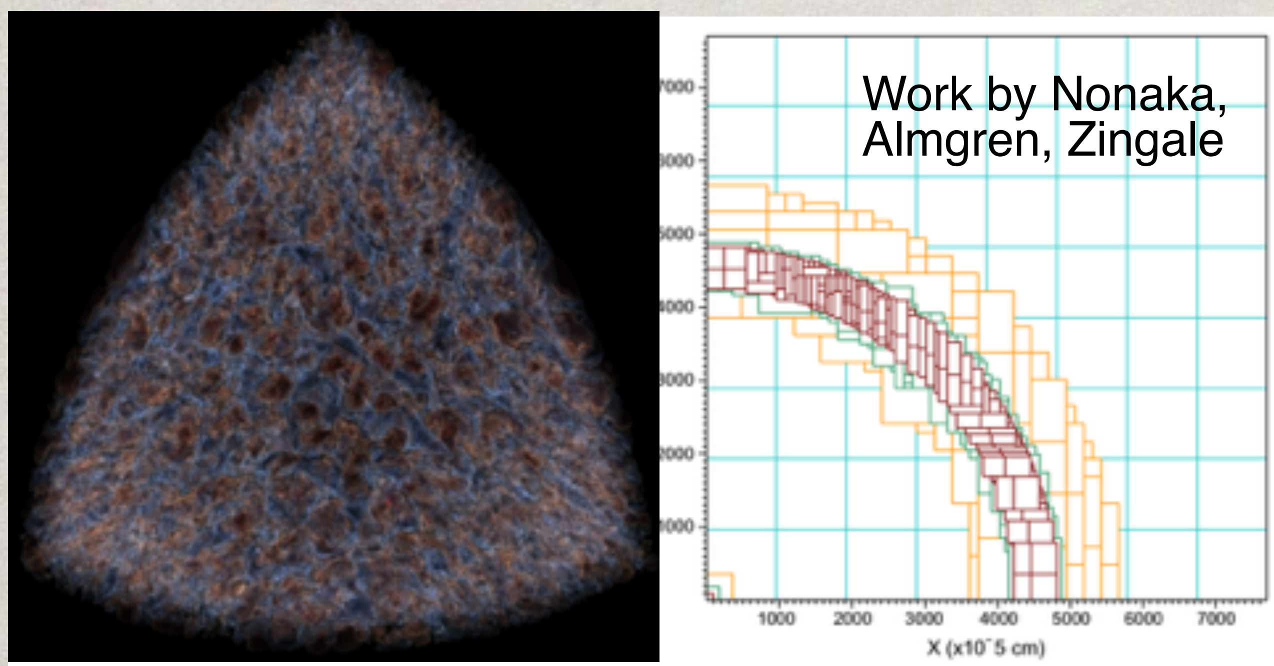


Low Mach Number Methods for Astrophysical Phenomena

Many astrophysical phenomena are characterized by subsonic flow in a stratified atmosphere. By combining low Mach number modeling techniques with adaptive mesh refinement (AMR), researchers can efficiently integrate long-time dynamics that are too expensive for compressible solvers.

We have migrated the existing MAESTRO code to use the exascale-ready software framework AMReX in order to enable detailed high-resolution simulations on high-performance architectures.

With the AMReX software framework, researchers are now able to study low Mach number, stratified astrophysical phenomena using state-of-the art linear solvers, grid hierarchy management, load balancing and intra-node optimization. AMReX uses a hybrid approach to parallelism.



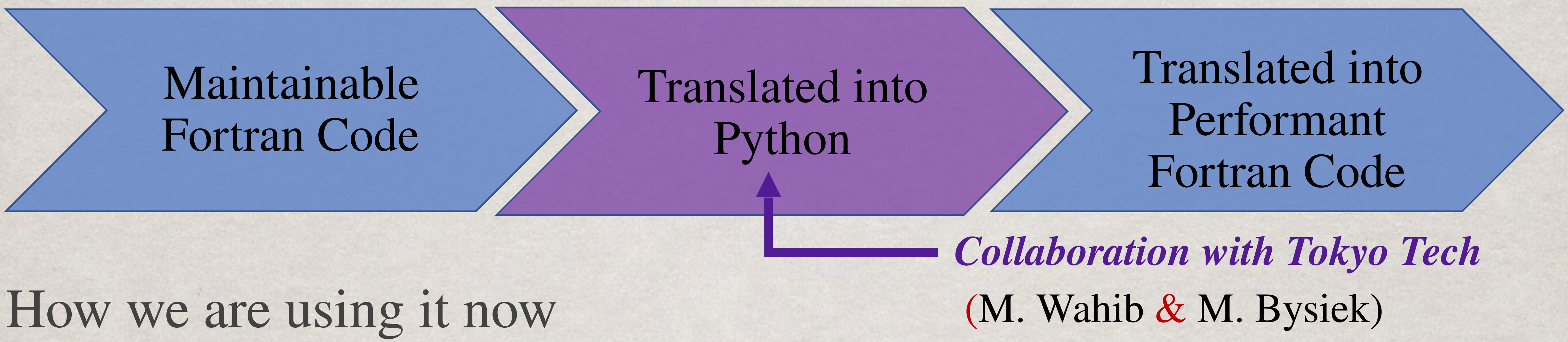
(Left) Convective plumes driven by nuclear burning in a helium layer on the surface of a sub-Chandra white dwarf. (Right) AMR focuses computational resources in regions of interest.

Current algorithmic developments including improved hydrostatic mapping, rotating stars, and efficient coupling to a compressible code framework for post-ignition studies.

Performance Portability at Kernel Level

The technology

Work by Chawdhary & Dubey



How we are using it now

- Convert raw code into function calls, avoid explicit indexing
- At translation, inline the functions, transpose data structures

More platform specific optimizations in the backend.

The big win: No dependence on DSL, there is always executable code

No need to rewrite the code in another language

TEAMS WILL …

… compute models of world-class physical fidelity for the majority of potential r-process and p-process sites, including Neutrino-driven Iron and Oxygen-Neon Core Collapse, Magneto-Hydrodynamic-Driven Supernovae, Neutron Star Mergers and Accreting Black Holes, and their progenitors, taking advantage of advances in HPC.

… compute observable signatures of these models in photons, neutrinos and gravitational waves.

… build world-class implementations of the essential nuclear microphysics.

… quantify the nuclear and astrophysical uncertainties in our nucleosynthesis predictions.

… continue to exploit advances made by our computational science colleagues to improve the simulations.

… request astronomical amounts of **supercomputer time**.