Simulating Supernovae with Supercomputers

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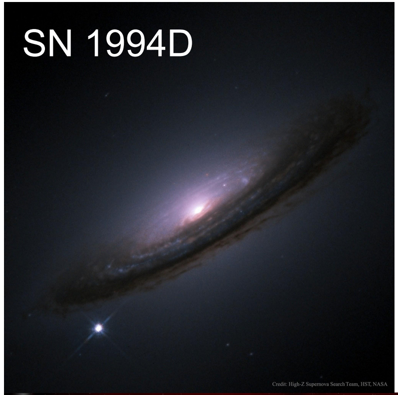
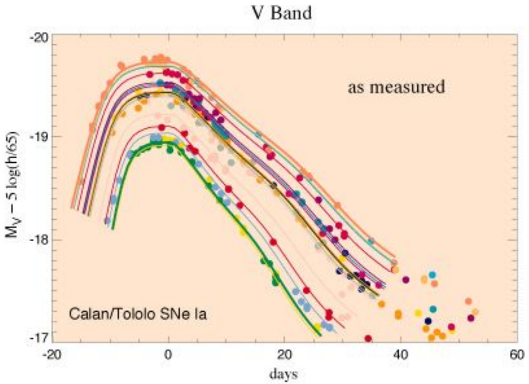
What are Type Ia Supernovae?

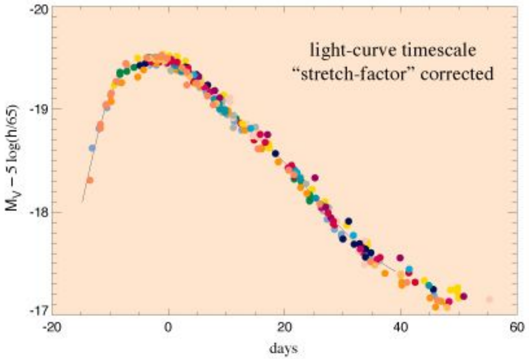


- Peak luminosity can rival host galaxy
- Luminosity powered by decaying Ni^{56}
- Spectra: Si, Ca, Fe (but not H)
- Brighter lightcurves are broader → standardizable



Origins Require Simulations

- ~1 $M_\odot$ degenerate C^{12}/O^{16}
- Several scenarios:
  - Accreting WD with M_{Ch}
  - WD + WD mergers
  - Accreting WD with $M < M_{Ch}$



(Perlmutter, et al. 1997)

Single White Dwarf Progenitor Model for SNIa

Determining the influence of electron captures and beta decays in convective white dwarf cores is a challenging problem!

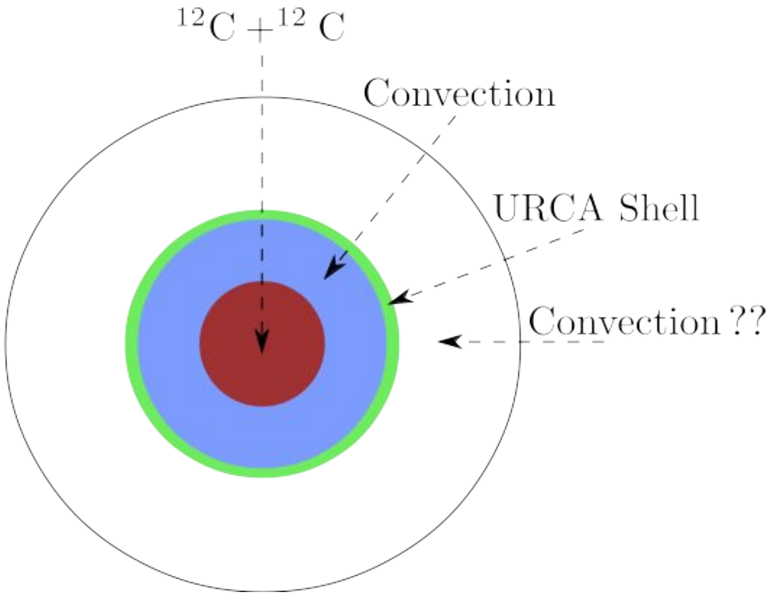
- Problems with existing methods:
  - Long timescales needed - many hours of convection
  - Accurate convection needed
  - 1-D Lagrangian codes do not properly model convection
  - Reactions expensive in 3-D
- The new approach:
  - Use low-Mach hydrodynamics for long timescales in 3-D
  - Use GPU accelerated reaction networks
- Results:
  - First 3-D simulations of the convective Urca process for SNIa progenitors

Why We Need 3-D Simulations ...

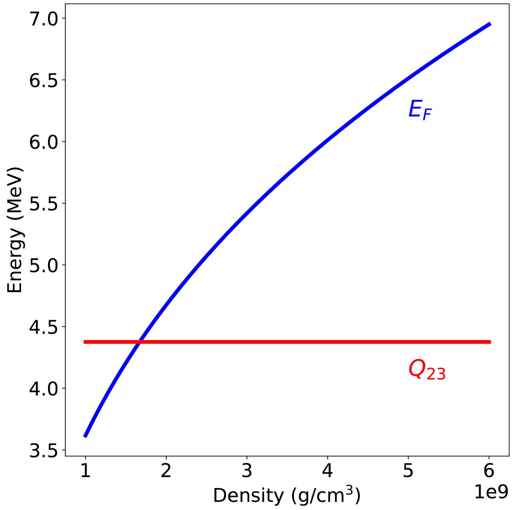
$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{4}\mathrm{He} + ^{20}\mathrm{Ne}$$
$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow \mathrm{p} + ^{23}\mathrm{Na}$$
$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow \mathrm{n} + ^{23}\mathrm{Mg}$$
$$^{12}\mathrm{C} + ^{4}\mathrm{He} \rightarrow ^{16}\mathrm{O}$$
$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-}$$

$$^{23}\mathrm{Na} + e^{-} \rightarrow \nu_e + ^{23}\mathrm{Ne}$$
$$^{23}\mathrm{Ne} \rightarrow e^{-} + \overline{\nu}_e + ^{23}\mathrm{Na}$$

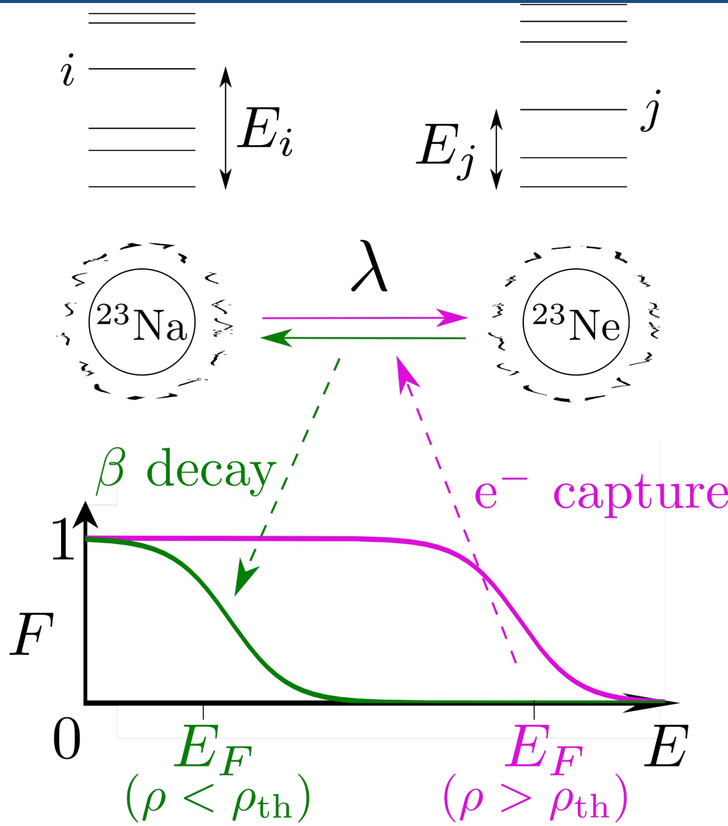
Urca reactions are cyclic



Where Does the Energy for Urca Cycles Come From?



- Highly degenerate matter
- Q-value comparable to E_F
- E_F = Q at E.C. threshold
- E.C. vs. beta decay
- Neutrinos escape freely
- Energy loss and transport
- Convective coupling needs 3-D



$$^{23}\mathrm{Na} + e^- \rightarrow \nu_e + {}^{23}\mathrm{Ne}$$

$$^{23}\mathrm{Ne} \rightarrow e^- + \overline{\nu}_e + {}^{23}\mathrm{Na}$$

Low Mach Hydrodynamics with MAESTROeX enables 3-D Simulations

$$\frac{\partial(\rho X_k)}{\partial t} = -\nabla \cdot (\rho X_k \boldsymbol{U}) + \rho \dot{\omega}_k$$

$$\frac{\partial \boldsymbol{U}}{\partial t} = -\boldsymbol{U} \cdot \nabla \boldsymbol{U} - \frac{\beta_0}{\rho} \nabla \left(\frac{\pi}{\beta_0} \right) - \frac{\rho - \rho_0}{\rho} g \boldsymbol{e}_r$$

$$\frac{\partial(\rho h)}{\partial t} = -\nabla \cdot (\rho h \boldsymbol{U}) + \frac{\mathrm{D} p_0}{\mathrm{D} t} + \rho H_{\mathrm{nuc}}$$

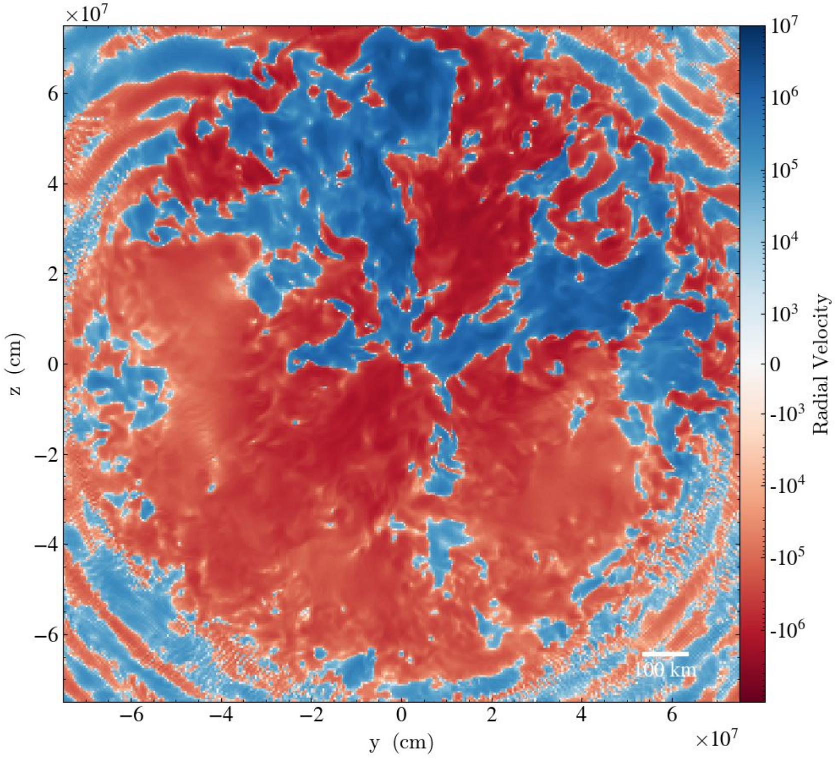
velocity constraint

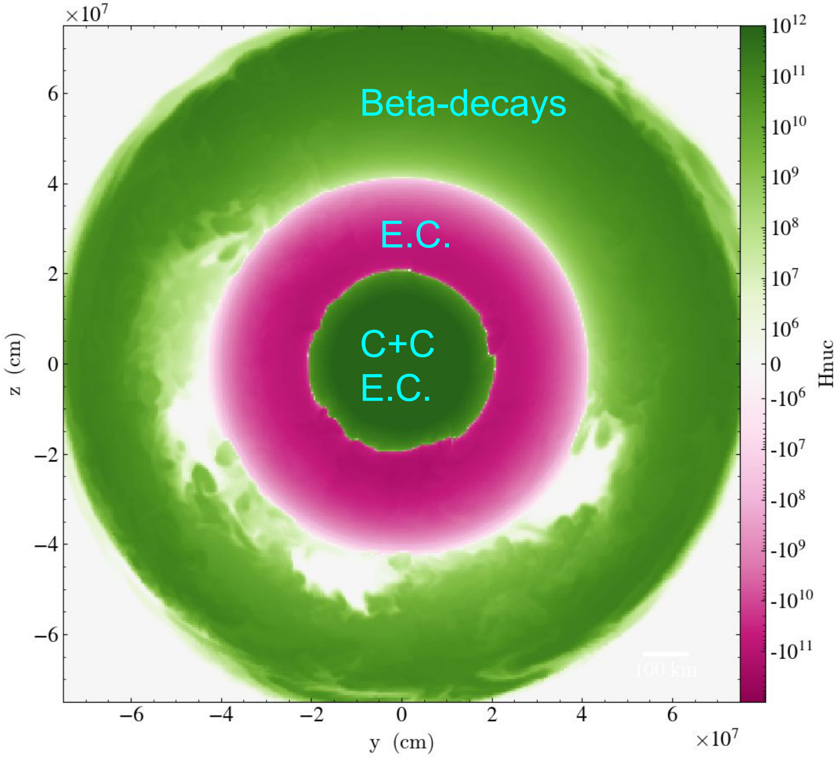
$$\nabla \cdot (\beta_0 \boldsymbol{U}) = \beta_0 \left(S - \frac{1}{\overline{\Gamma}_1 p_0} \frac{\partial p_0}{\partial t} \right)$$

- Pressure split into base state + perturbation
- Low Mach approximation valid for Ma << 1
- Velocity constraint with heating, compressibility
- Initial conditions in hydrostatic equilibrium
- Longer timesteps!
- Urca simulations can take ~0.2 second timesteps at 1km resolution
- Compressible CFL timestep < 0.1 milliseconds

https://github.com/amrex-astro/maestroex

Convection Determines Energy Generation From Urca Reactions





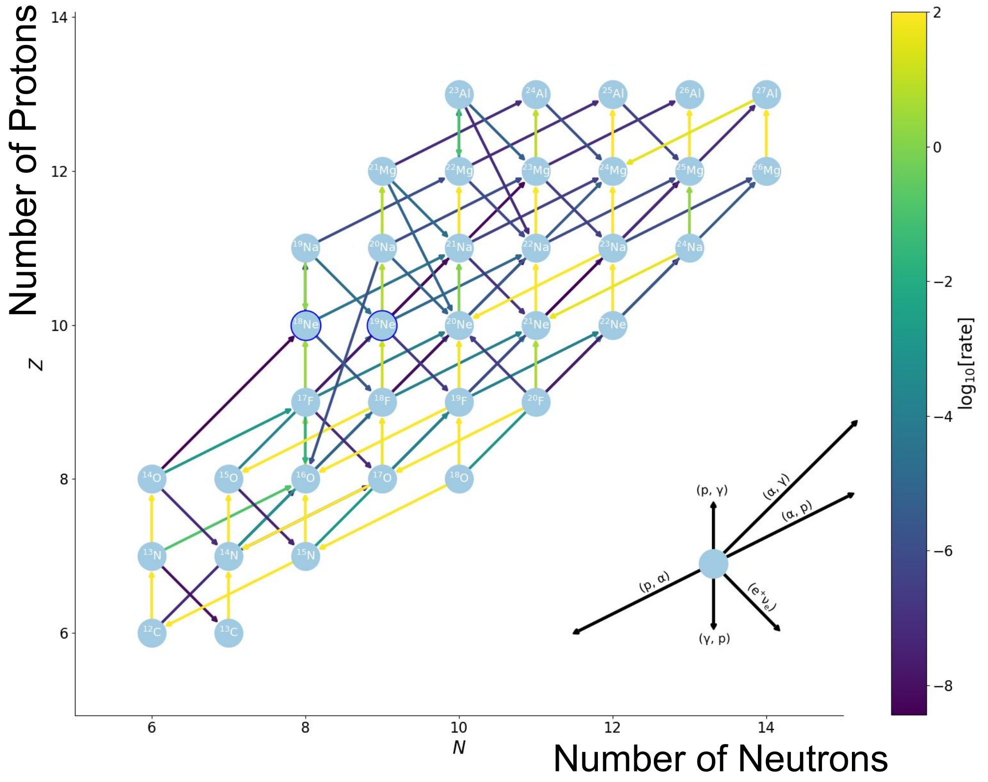
Automating Reaction Networks Speeds Development

- Python interface to nuclear rate databases
- Database searching and filtering
- Network visualization
- Symbolic ODE representation
- Code generation
  - Python
  - Fortran / CUDA Fortran

Shown:

- Hydrogen burning in XRB conditions
- Hot-CNO → rp-process breakout
- Collaboration with Kiran Eiden, SBU

Willcox & Zingale, JOSS 2018



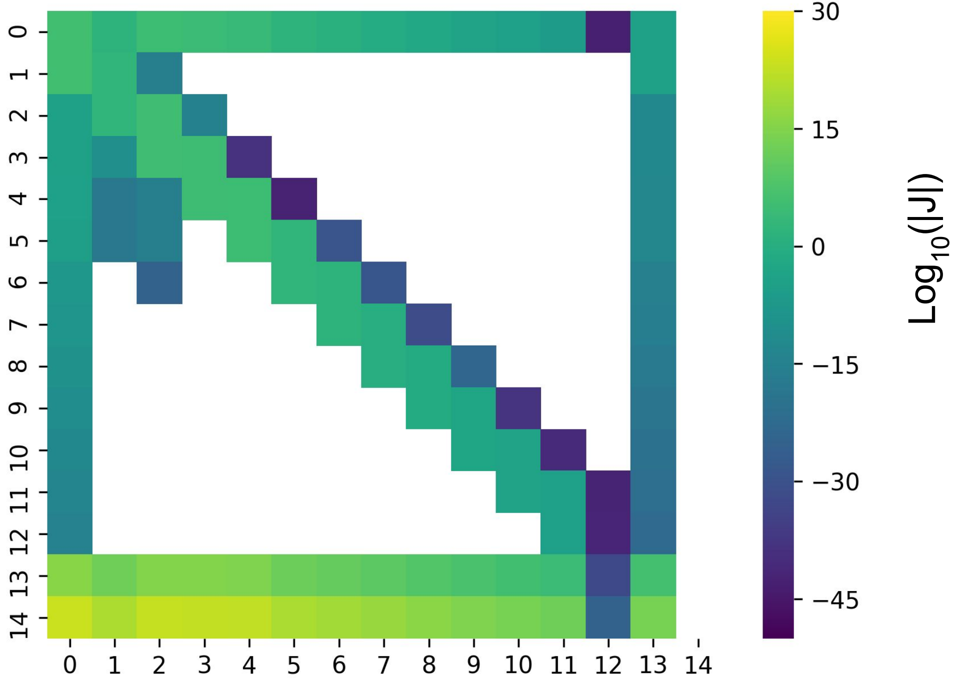
We Need Implicit ODE Solvers for Stiff Reaction Networks!

- **Shown:**
  - $Log_{10}(|J|)$
  - 13-isotope He^4-burning network
  - ODE system: X, T, e

- Diagonally dominant in species
- He^4 interacts with everything strongly
- Nuclear reaction rates *very* T-sensitive

- ~60 orders of dynamic range!
- Very stiff
- Ratio max/min eigenvalues ~ 10^{26}

currently used for simulating X-ray bursts, more on that later ...



GPU Accelerated Reactions Enable Science on OLCF Summit

VODE:

- Variable order, implicit multi-step

GPU Implementation:

- First: ported VODE to CUDA Fortran
- 1 GPU thread per ODE system
- Single GPU kernel launch
- NVIDIA P100 10x faster than ideal 10-core scaling on POWER8 chip.
- *New*: We ported VODE and our reaction networks to CUDA C++. (Katz, et al. to appear in SC20)

$$\dot{y} = f(t, y) \qquad y \in \mathbb{R}^N$$

$q = 1, \ldots, 5$

variable order

$$\sum_{i=0}^{q} \alpha_{n,i} y_{n-i} + h_n \beta_{n,0} \dot{y}_n = 0$$

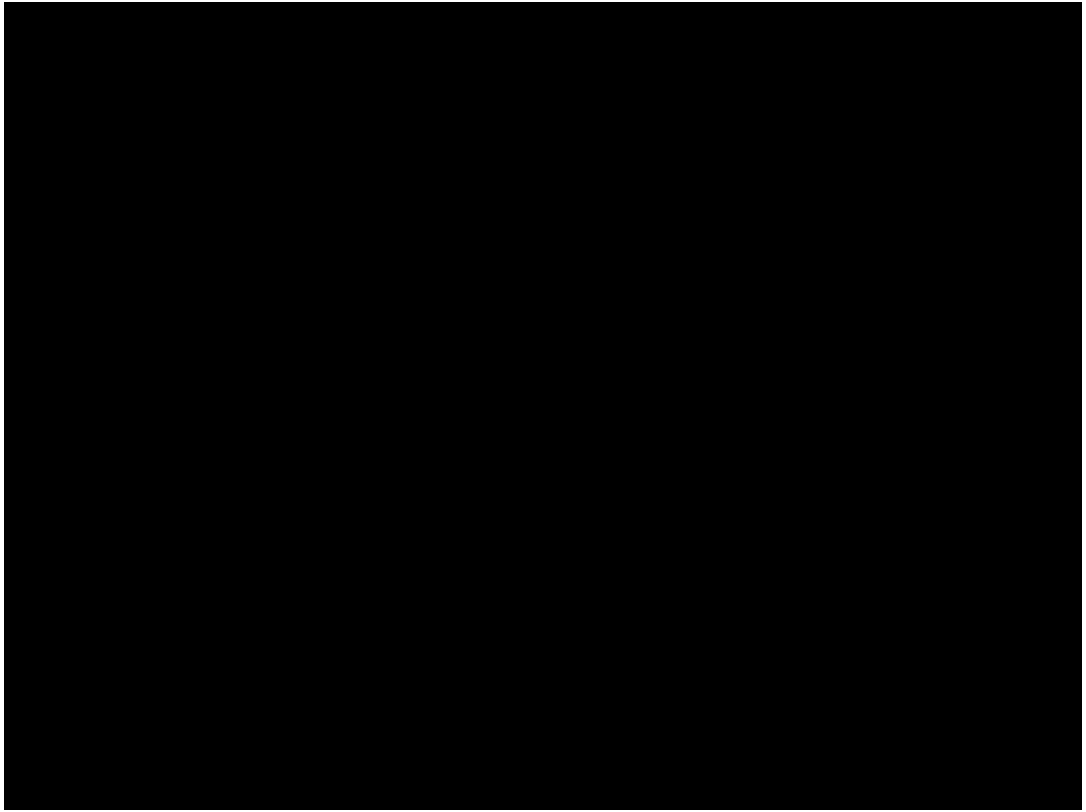
current stepsize

determined by current & prior stepsizes

$$J(t, y) = \frac{\partial f(t, y)}{\partial y}$$

Newton + linear solve

GPU Accelerated Reactions to Assist WD Merger Simulations



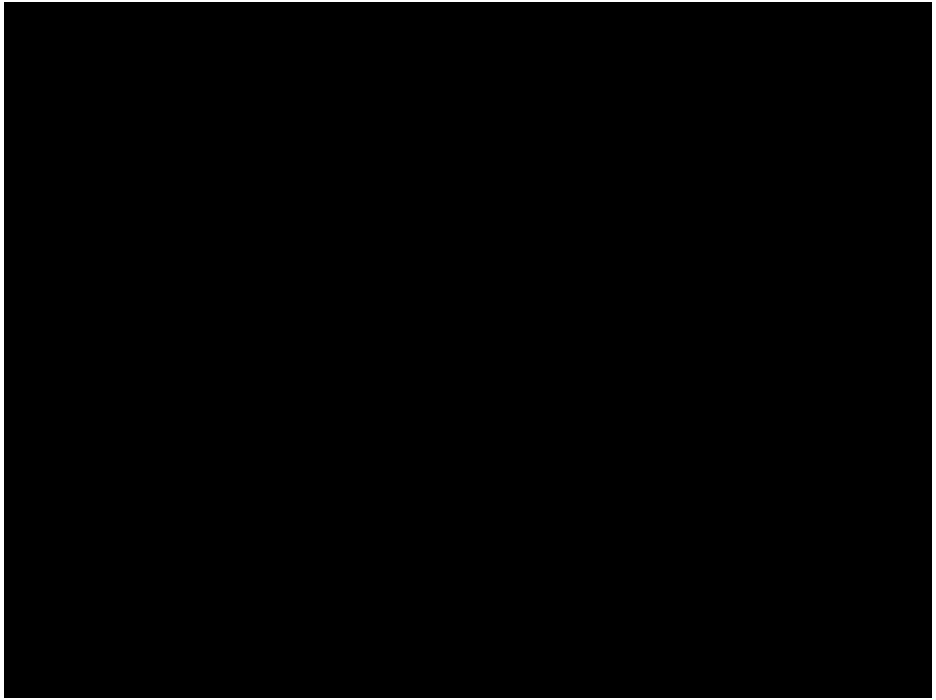
- Merger of 0.9 + 0.6 Msol WD
- WD merger model for SNIa
- Left: Castro simulation by Max Katz, (SBU/NVIDIA)
- Current: Maria Barrios Sazo (SBU) adding MHD
- Will benefit from GPU accelerated reactions, shared across codes.

https://github.com/amrex-astro/Castro

https://github.com/starkiller-astro/Microphysics

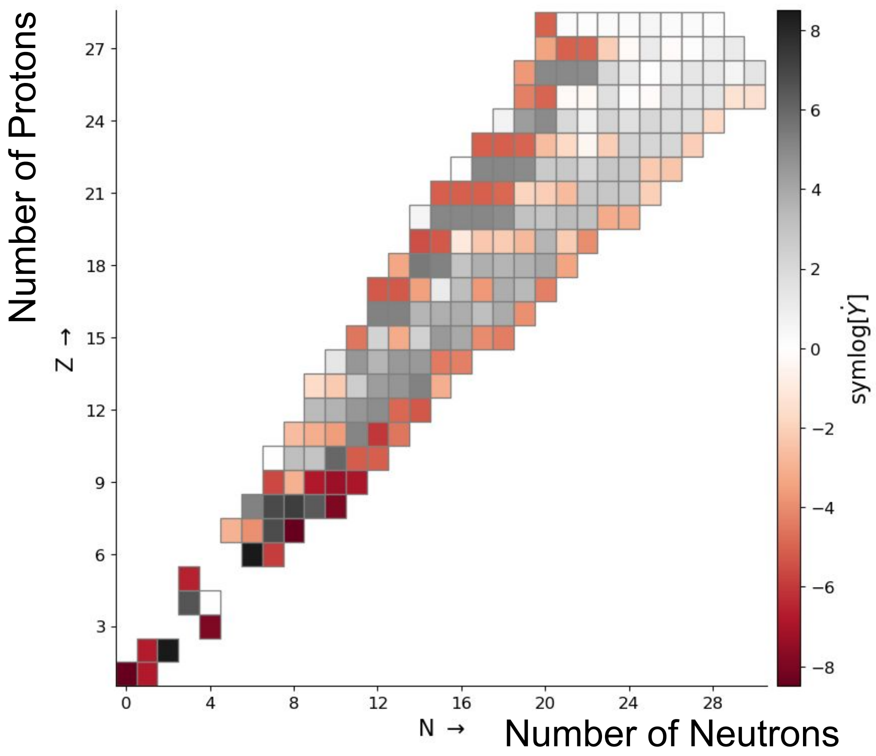
Accelerated Reactions Enable X-Ray Burst Simulations

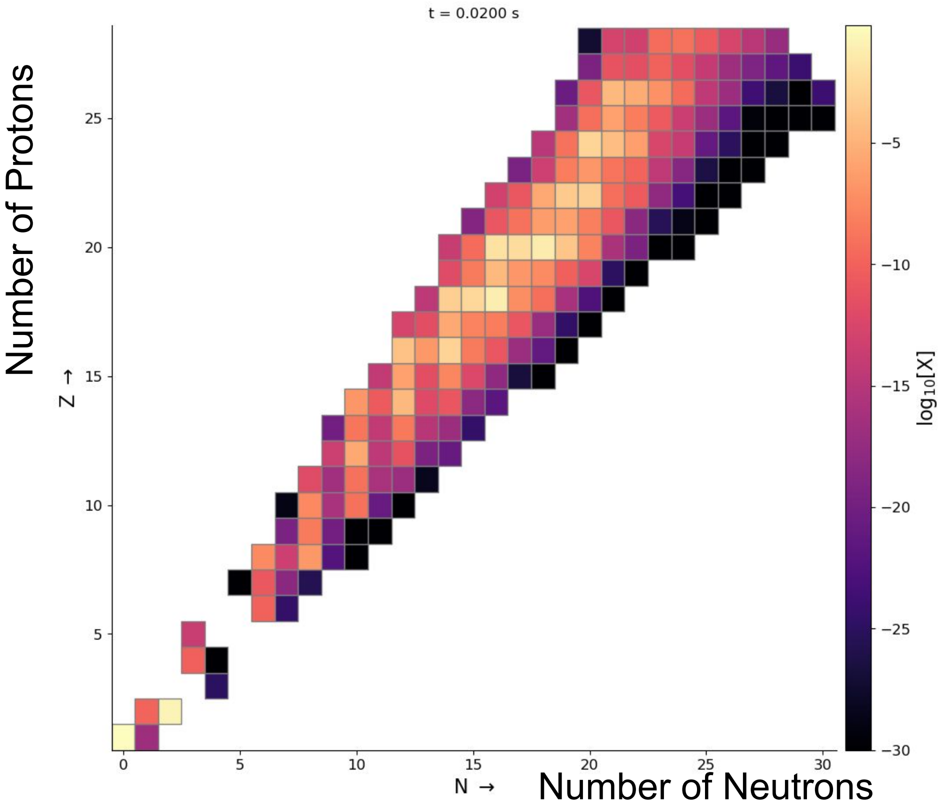
- Flame evolution on NS surface
- First simulation to resolve both lateral and vertical scales in the XRB flame
- Physical mixing across flame surface
- 2D geometry + rotation
- He^4 burning reaction network
- Allows measurement of flame speed
- *Now*: reactions on GPUs let us run flame simulations with realistic burning rates (no “boosting”!)



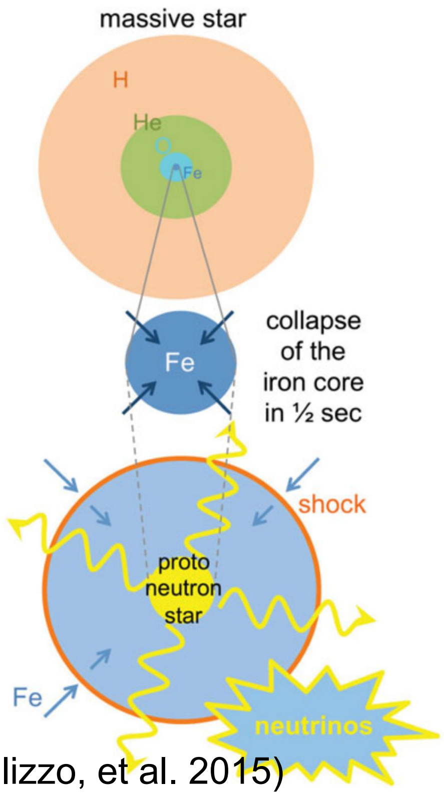
(Eiden, et al. 2019)

Automated Network Generation Will Enable Larger Networks





Future Opportunities Include Core Collapse Supernovae



(Foglizzo, et al. 2015)

- Massive star Fe core collapses → PNS/BH
- 10^{53} ergs gravitational energy
- 10^{51} ergs explosion energy
- PNS incompressible at nuclear densities → shock
- Simulations needed to determine shock revival mechanism
- Castro coupled to Thornado for two-moment radiation transfer
- *Current*: collaborating with Adam Peterson (CCSE) to develop numerical GR solver with AMR to couple to these simulations.

Conclusions & Outlook

Determining the influence of electron captures and beta decays in convective white dwarf cores is a challenging problem!

- Developed new code-generation tools for arbitrary reaction networks
- Developed GPU accelerated reaction network integration
- Implemented Urca reactions modeling into low-Mach hydrodynamics code MAESTROeX

- Impact:
    - First 3-D simulations of the convective Urca process for SNIa progenitors
    - GPU accelerated reactions enable other science explorations (X-ray bursts)
    - Arbitrary reaction networks will allow us to explore nuclear physics sensitivities in XRB
    - GPU developments to benefit ongoing work on CCSNe modeling

With Many Thanks To Collaborators ...

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