Stars & Computers

The Computational Challenges in Simulating a Star Prior to its Thermonuclear Explosion

Brendan Boyd [1,2] Alan Calder [1,2] Dean Townsley [3]
Michael Zingale [1]

[1]Department of Physics and Astronomy, Stony Brook University

[2]Institute for Advanced Computational Science, Stony Brook University

[3]Department of Physics and Astronomy, University of Alabama

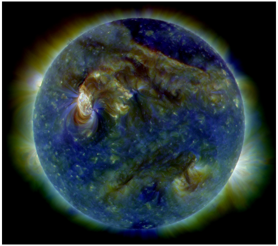
Stony Brook University

Outline

- **Astronomy** - How to Blow Up a Star
- **Simulations** - A Look into Hydrodynamics
- **Computational Challenges** - Sensitivities and Expenses
- **The Research** - What is the Convective Urca Process?
- **Summary**

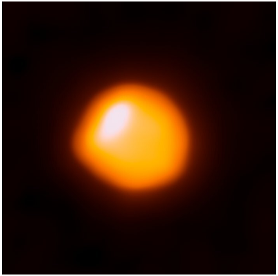
Stars

- Large, stable fusion machines



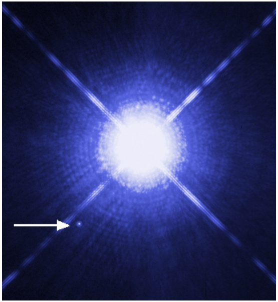
The Sun: Burning Hydrogen

(NASA/SDO/AIA)



Red Giant: Burning Helium (mostly)

(ESO/NAOJ/NRAO/E. O'Gorman/P. Kervella)



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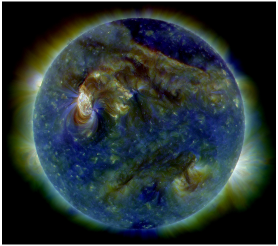
Stars

- Large, stable fusion machines
- Fusion/Burning balances Gravity



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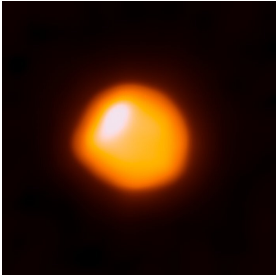

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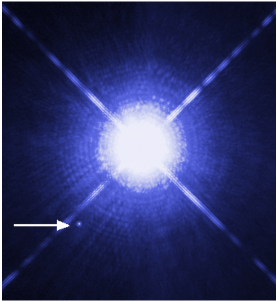

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Stars

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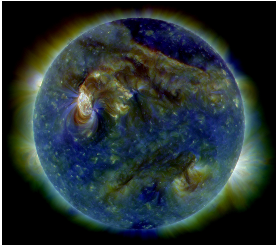
- Fusion/Burning balances Gravity
- 3 basic stages of a Sun-like Star



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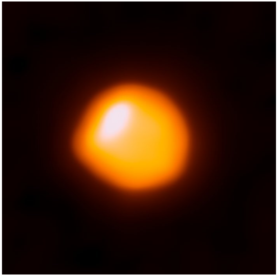

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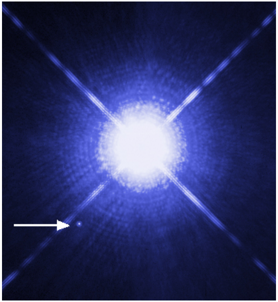

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High-Z Supernova Search Team/HST/NASA

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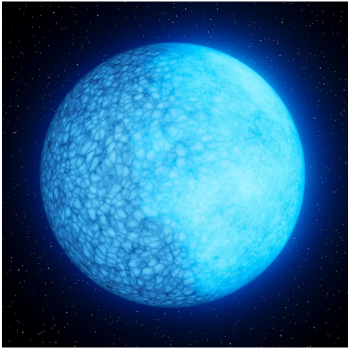
- Observations/theory suggest a White Dwarf blowing up

High-Z Supernova Search Team/HST/NASA

White Dwarfs

- End of life for Sun-like stars



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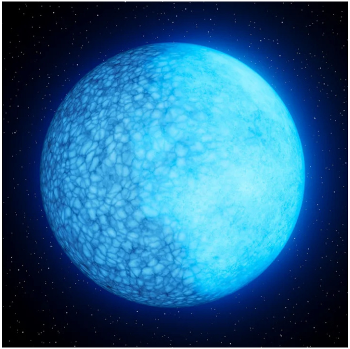

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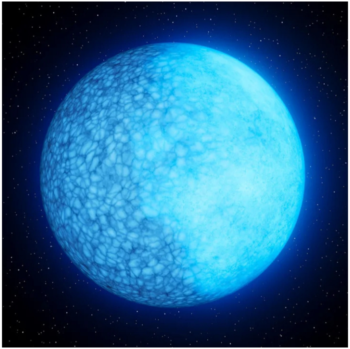

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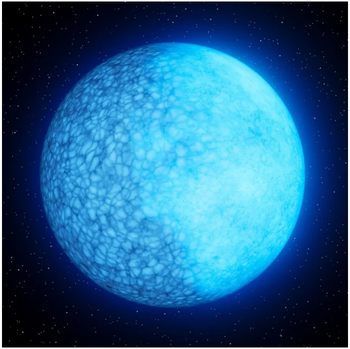

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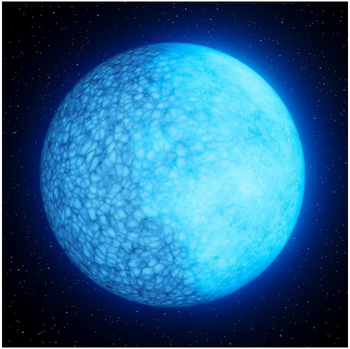

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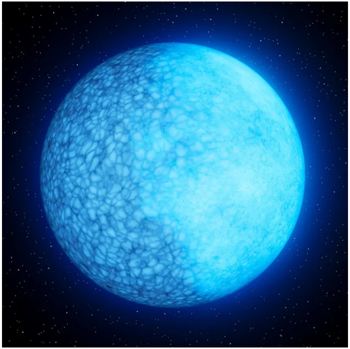

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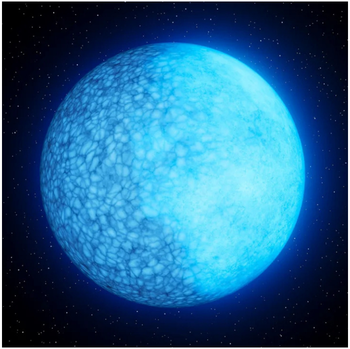

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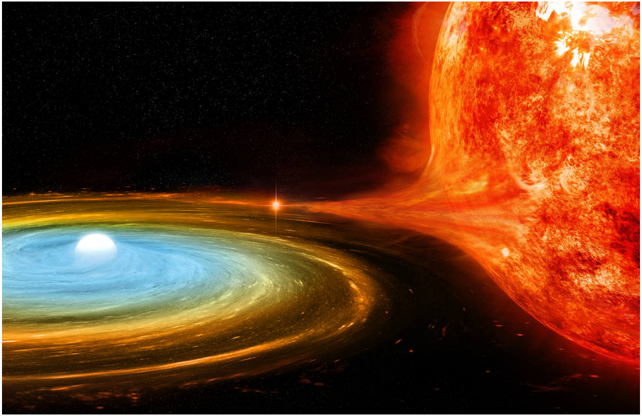
How can it explode???

Binary Systems

- Roughly half the stars are a part of multi-star systems
- Close stars can transfer mass
- Closer stars can collide/merge

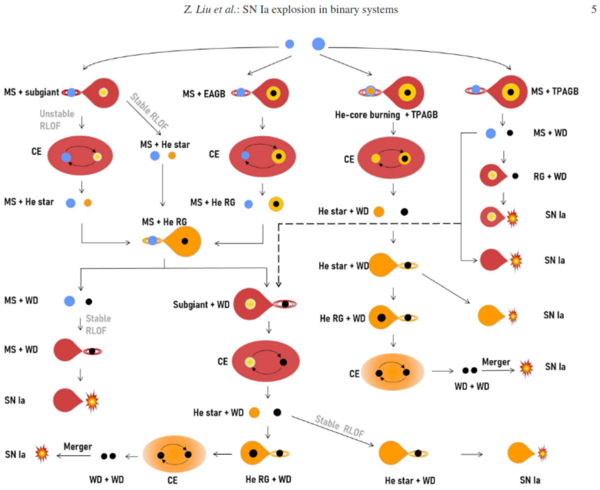
Jim Spinner



NASA/CXC/M. Weiss

How to Blow up a White Dwarf?

It's complicated



Z. Liu et al. 2023

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- Progenitor System
  - 1 White Dwarf and 1 Sun-like Star? (SD)
  - 1 White Dwarf and 1 Red Giant? (SD)
  - 2 White Dwarfs? (DD)
  - Something more exotic?

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- Progenitor System
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  - Something more exotic?
- Ignition Mechanism
  - Nuclear runaway on outside that induces runaway on the inside? (Double Detonation)
  - Colliding white dwarfs starting runaway? (Violent Mergers)
  - Nuclear runaway near the center? (deflagration-to-detonation)
  - And many more

Double Detonation

Nuclear runaway on outside induces runaway on the inside (Double Detonation)

https://www.youtube.com/watch?v=mYXtIuozJ_E

Credit: Michael Zingale et al. 2023 (CASTRO)

Violent Merger

Colliding white dwarfs start explosion (Violent Mergers)

`https://www.youtube.com/watch?v=0AAPwsST9WQ&t=16s`

Credit: M. P. Katz et al. 2016 (CASTRO)

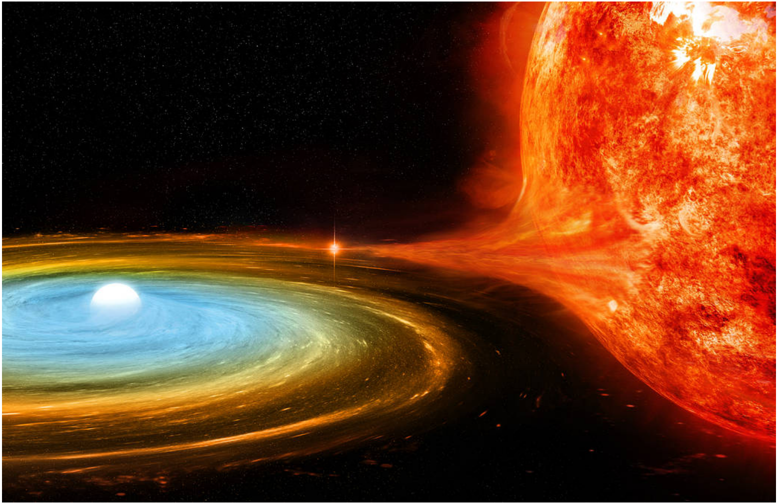
Deflagration to Detonation

Nuclear runaway near the center (deflagration-to-detonation)

https://vimeo.com/168228220

Credit: G. C. Jordan et al., 2007 (FLASH)

Why does this explode?



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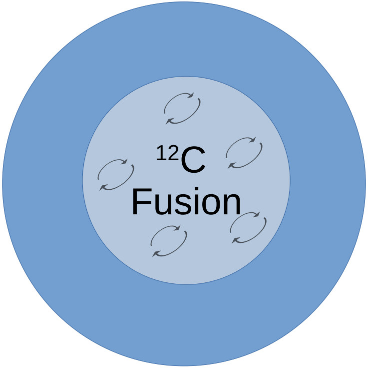
Simmering Phase of White Dwarf

- More Mass == Hotter & Denser core
- Carbon starts burning
- 1,000-10,000 years of convection, "simmering"
- Eventually hot enough to explode

ESA/Justyn Maund/Queens University Belfast



A Brendan Boyd Original

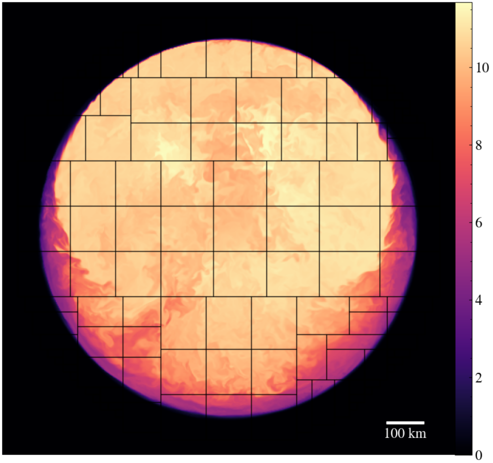
What's in a Simulation

- Unpeel some of the layers
- Challenges and hurdles
  - Physical
  - Computational

https://youtu.be/N4_-qf3BfKM

Hydrodynamics: Modeling Fluids

- Divide domain into "cells" - Finite Volume Method



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  - Density
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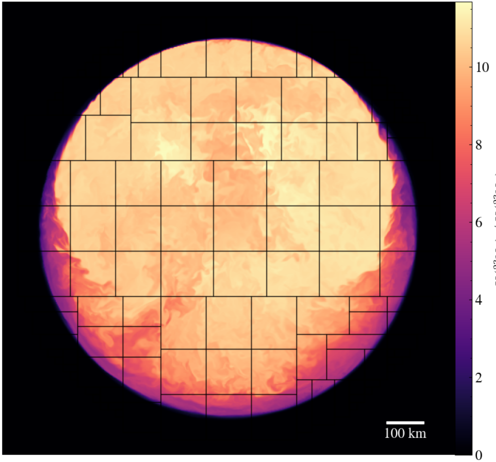
  - etc.



Hydrodynamics: Modeling Fluids

- Divide domain into "cells" - Finite Volume Method
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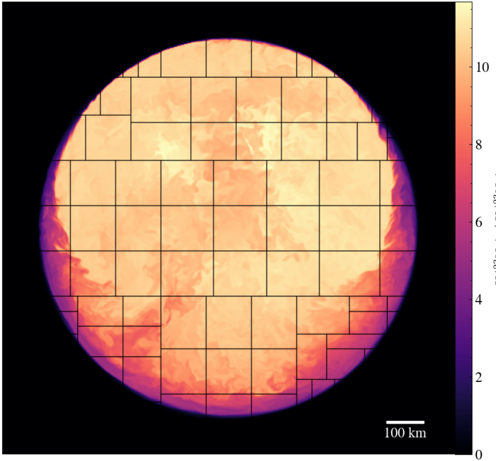
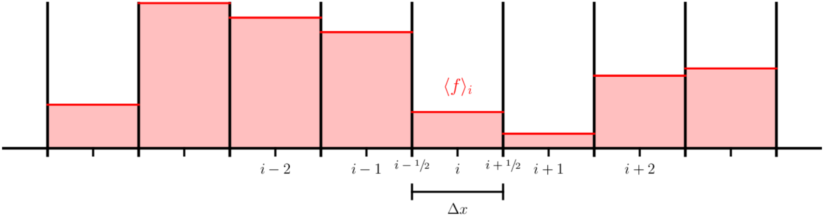
- Apply Conservation Laws
  - Mass
  - Momentum
  - Energy



Hydrodynamics: Advancing in Time

- Cells interact at boundaries



[1]

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Hydrodynamics: Advancing in Time

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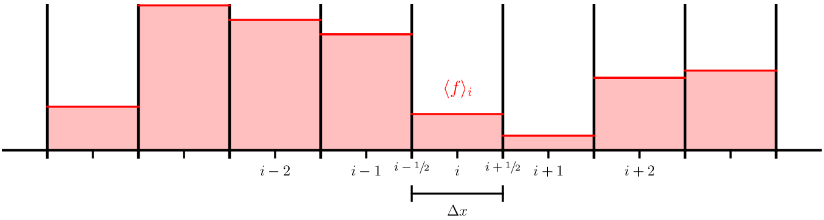

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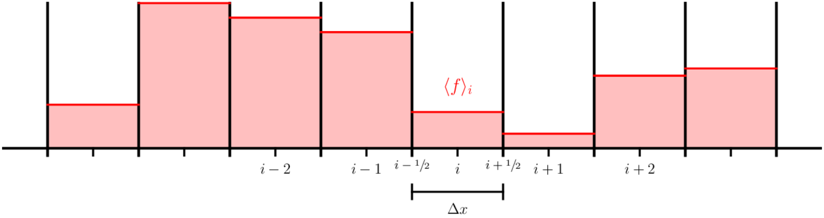
- Cells interact at boundaries
- Conservation laws allow us to predict next state
- Limits to prediction, never want to advance a fluid past one cell
  - fluid moving 2 cells/second. Limit our **timestep** to 1/2 second



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Speed of Sound

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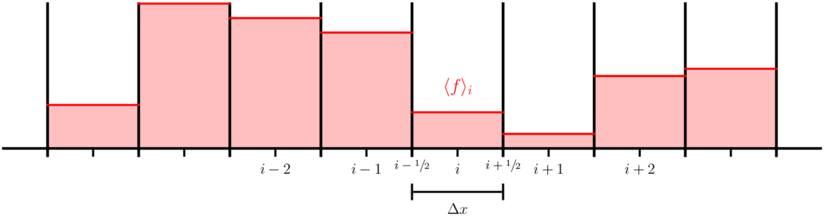

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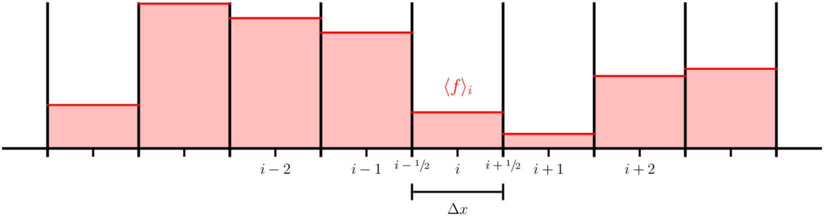

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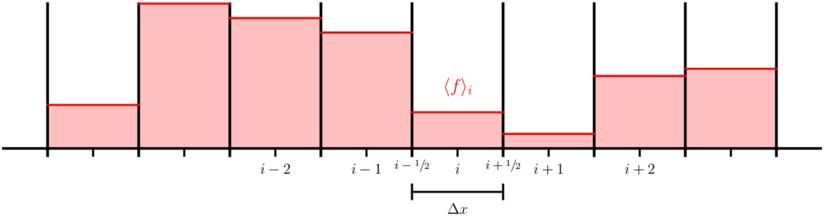

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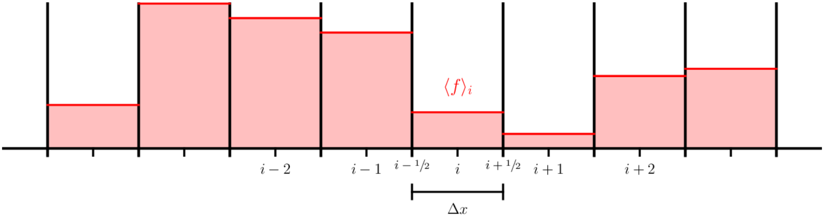

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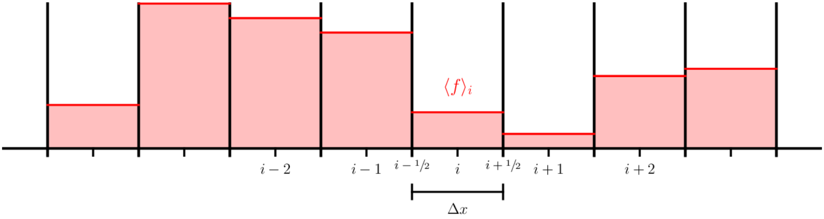
- Speed of sound can limit our timestep



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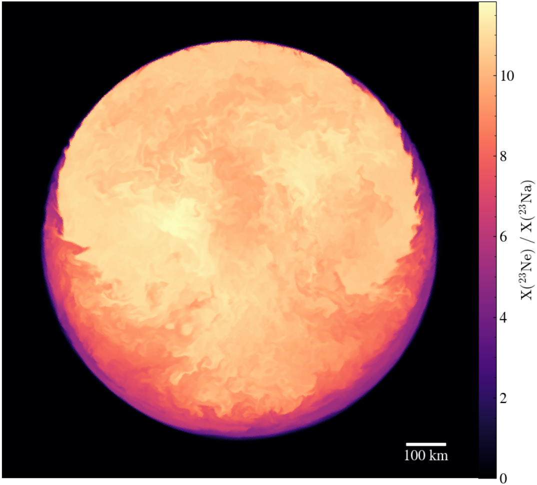
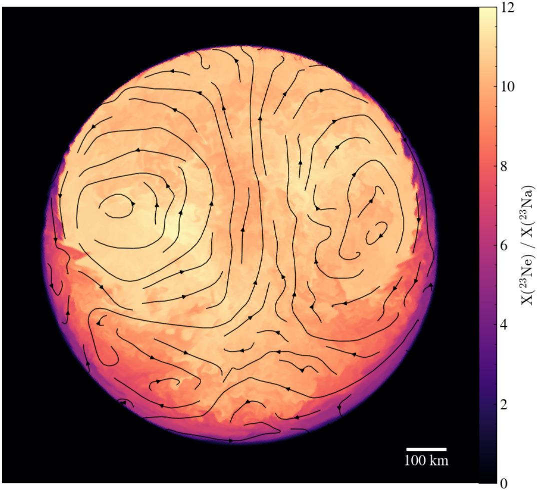
Hydrodynamics: Low Mach Regime

- Mach Number = "Fluid Speed" / "Speed of Sound"
- Low Mach means sound speed limits our timestep



Example: White Dwarf Convection

- Convection is slow & White Dwarf has high sound speed
- Mach number $\sim 10^{-3}$



MAESTROeX: Low Mach Hyrdo Code

- Solve altered equations, effectively filtering out sound waves
- Assumes Mach number $\lesssim 0.2$

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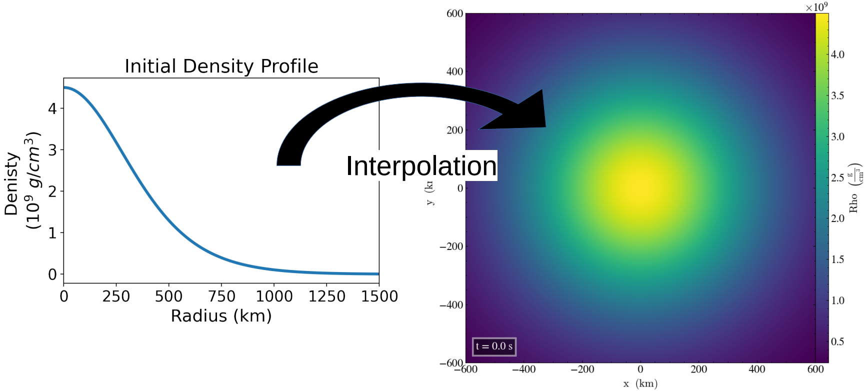
- Solve altered equations, effectively filtering out sound waves
- Assumes Mach number $\lesssim 0.2$
- Built on AMReX Framework
  - Mesh Framework
  - Linear solvers
  - MPI+X parallelism

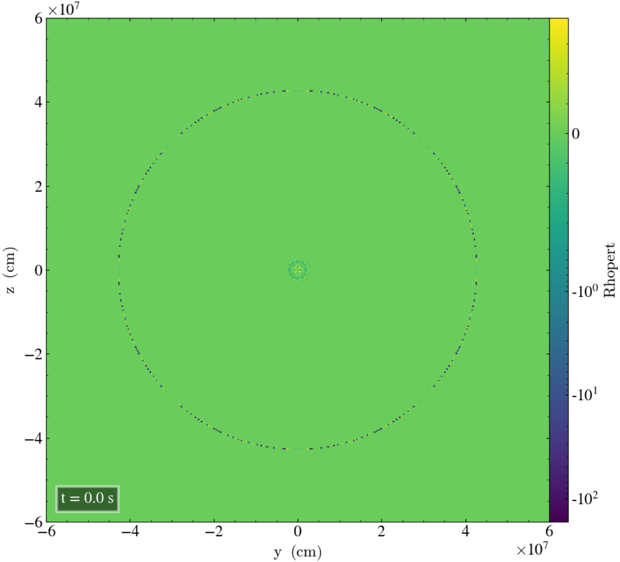
Initial Sensitivities

Unfortunately Low Mach Hydro is very sensitive to small perturbations
Example:



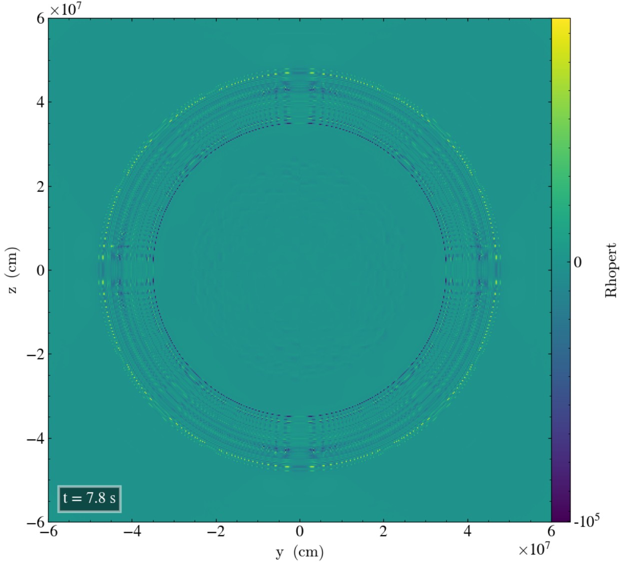
Initial Sensitivities

Small errors in outside. Relative error of $\sim 10^{-7}$



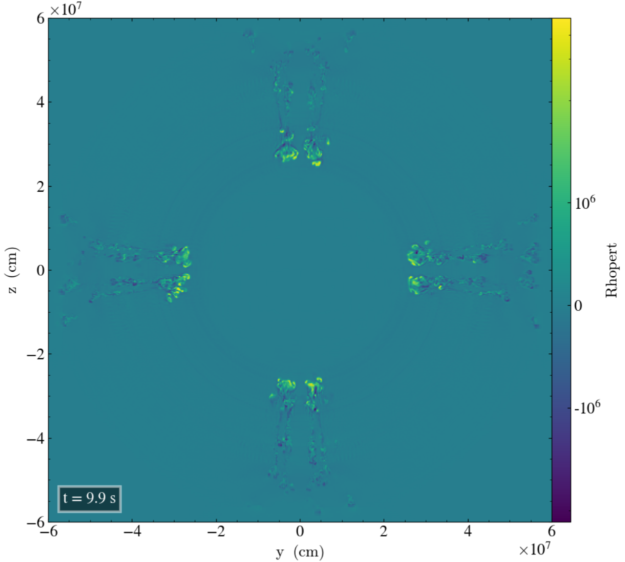
Initial Sensitivities

Grow to relative error of $\sim 10^{-4}$



Initial Sensitivities

Grow to weird unphysical plumes



Small errors can build up quickly.

Computational Resources

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Computational Resources

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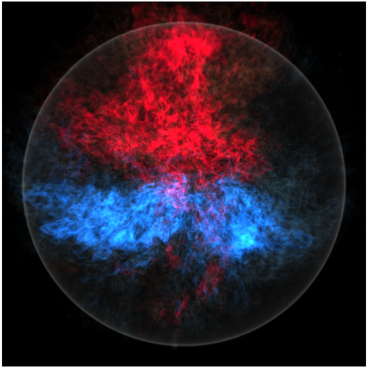
- 3D Hydrodynamic simulations are expensive :(
- Utilize 512 cpus
- 100,000+ timesteps, over a million cpu-hours
- A few hours of convection (simmering phase lasts thousands of years)

`https://youtu.be/apmQmt8hqig`

Simulation Recap

- Simulations of convecting white dwarf



Radial Velocity: Red marks fluid rising away from the center. Blue marks fluid falling inward to the center.

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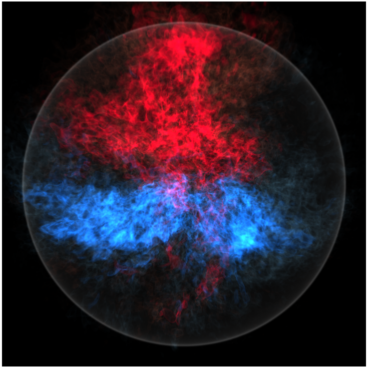

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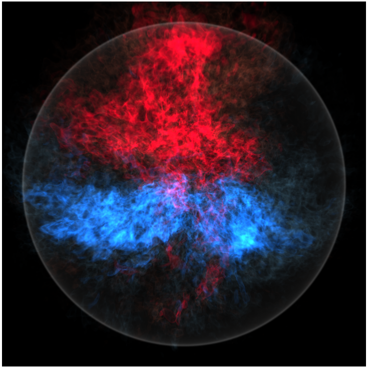

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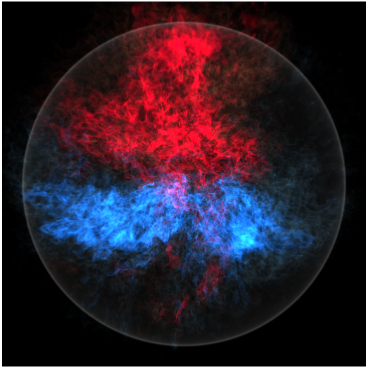
- Working in Low Mach regime
- Simulations highly sensitive to small errors/perturbations
- 3D are resource intensive, but necessary to capture the physics



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Urca Process

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Urca Process

- Relation between two nuclear reactions

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- Relation between two nuclear reactions

$$
\begin{aligned}
{}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^{-} + \bar{\nu}_e \\
{}^{23}\mathrm{Na} + e^{-} &\rightarrow {}^{23}\mathrm{Ne} + \nu_e
\end{aligned}
\tag{1}
$$

Convection

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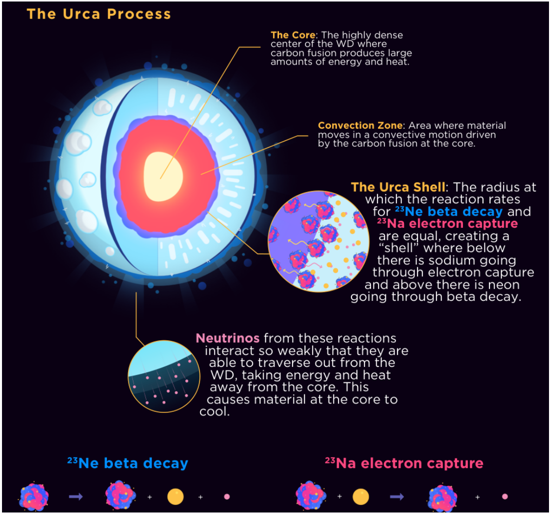
Urca Process

- Relation between two nuclear reactions

$$\begin{aligned} {}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^- + \bar{\nu}_e \\ {}^{23}\mathrm{Na} + e^- &\rightarrow {}^{23}\mathrm{Ne} + \nu_e \end{aligned} \tag{1}$$

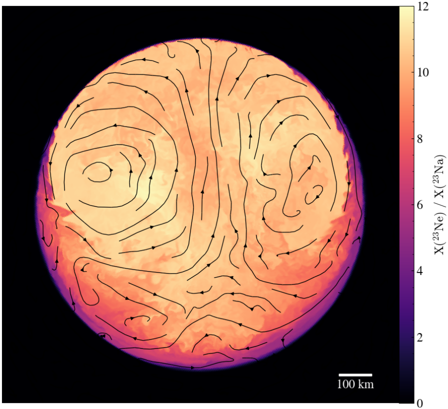
- ν_e are neutrinos. Take energy away from star

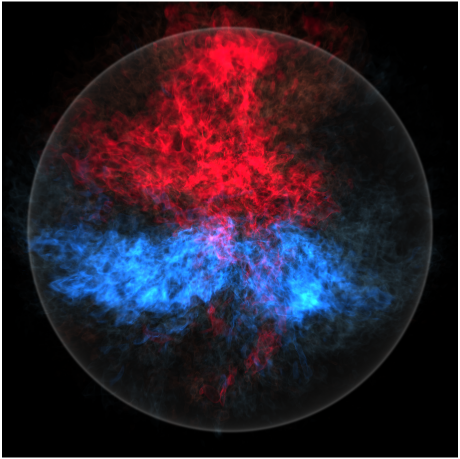
The Convective Urca Process



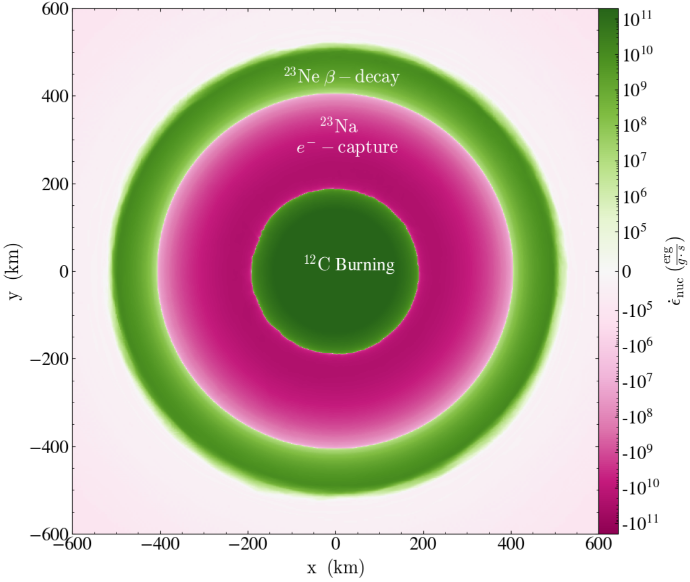
Kian Hayes (Benedictine College)

Movies again

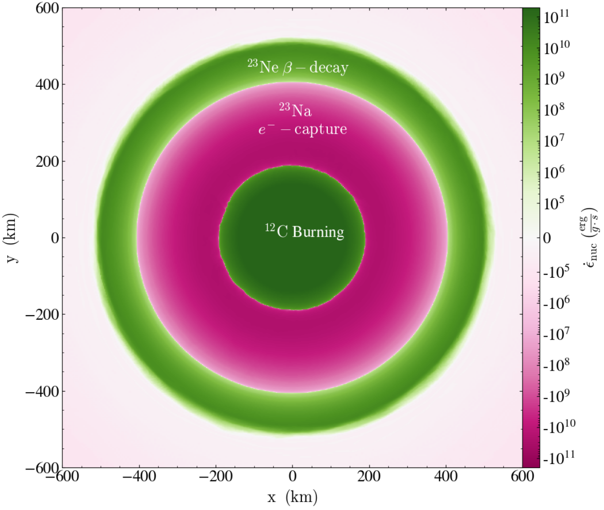




Energy Generation

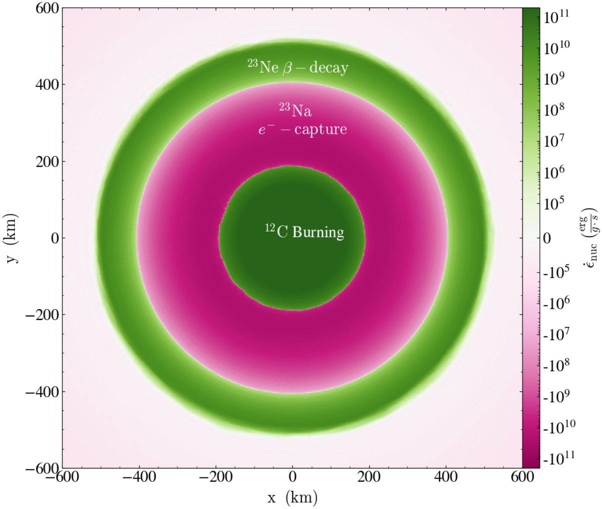


Energy Generation



Specific Nuclear Energy Generation Rate

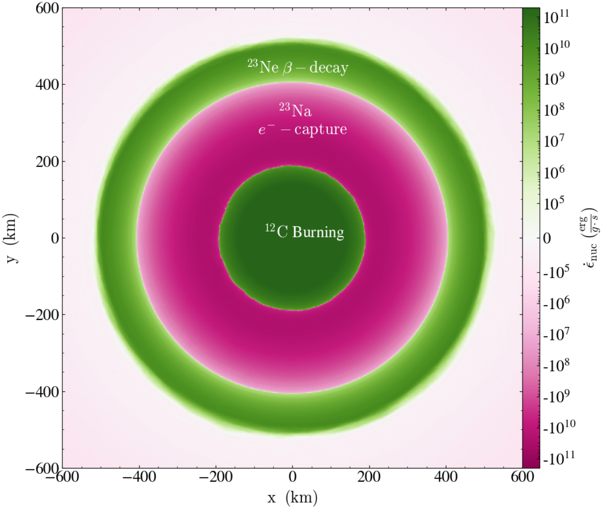
- Total Energy Generated: $2.85 \times 10^{43}\ erg/s$



Specific Nuclear Energy Generation Rate

Energy Generation

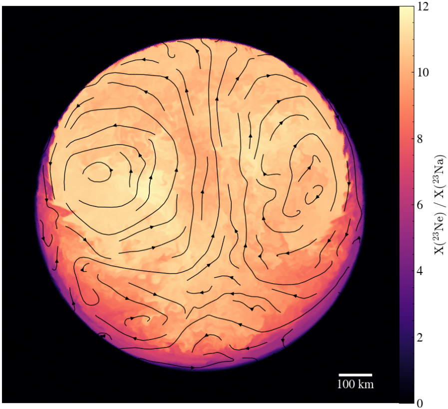
- Total Energy Generated: 2.85×10^{43} erg/s
- Total Energy loss to ν_e: 3.62×10^{42} erg/s



Specific Nuclear Energy Generation Rate

Future Work

- More Urca pairs. e.g. $^{21}\mathrm{F}$-$^{21}\mathrm{Ne}$
- Investigate other densities and temperatures
- What happens at times closer to supernova?
  - Use this as "initial conditions"?



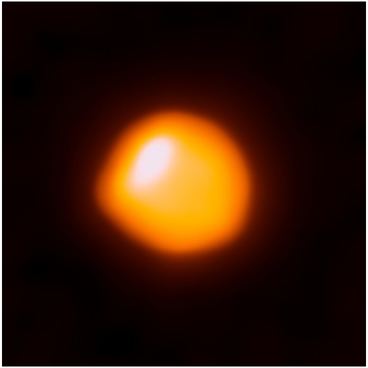
Summary

- Figuring out How to Blow Up Stars
- Hydrodynamic Simulations
- Troubles in Low Mach
- Convective Urca

Thank you for listening!

Why Computational Astrophysics?

- Systems hard to resolve observationally
- Timescales too short/long
- Systems are complex (non-linear)
- Simulations are testbeds



(ESO/NAOJ/NRAO/E. O'Gorman/P. Kervella)

Role of these Simulations

- Inform theory on convective Urca
- How to incorporate into 1D stellar evolution codes
- Observational signatures of the simmering phase