# Multi-Messenger Diagnostics Probing the Supernova Engine

- Issues with our Understanding of Supernovae (asymmetries and mixing)
- Diagnostics of these asymmetries
  - Compact Remnants
  - Shock Breakout
  - Ejecta Remnants

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NNSA
National Nuclear Security Administration
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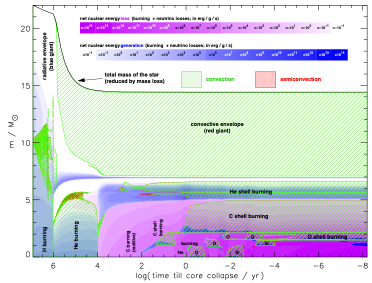
# The holistic approach – connecting all diagnostics

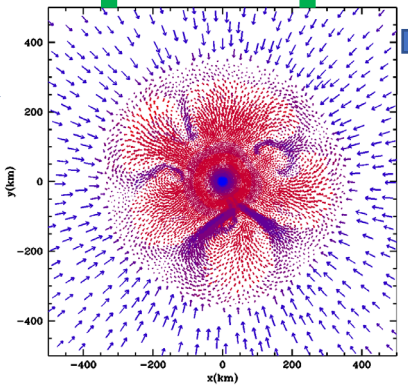
All phases require detailed stellar models: e.g. engine (core-properties), blastwave (stellar structure), remnant (winds).




Nuclear burning, Implicit hydrodynamics with subgrid models, diffusive transport, …

Gravitational Waves

Neutrinos



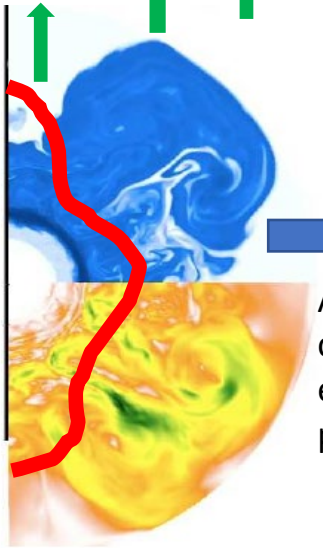

Supernova Engine: Physics includes dense nuclear matter, neutrinos, general relativity, magneto-hydrodynamics and turbulence, nuclear reactions

Characterize Explosion Properties: v(θ,t), Composition

Compact Remnants

Nucleosynthetic Yields

Shock Breakout

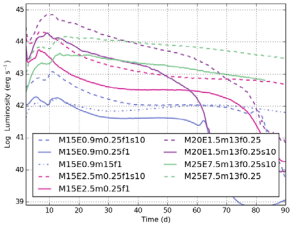


Propagation of Blastwave out of star: Radiation Hydrodynamics and turbulence, nuclear burning

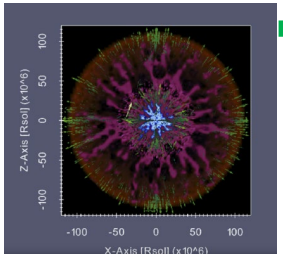
Again characterize explosion properties

Light-Curves and Spectra

Gamma-rays




Supernova Emission: Radiation Transport, Atomic Physics, NLTE effects, plasma physics, dust

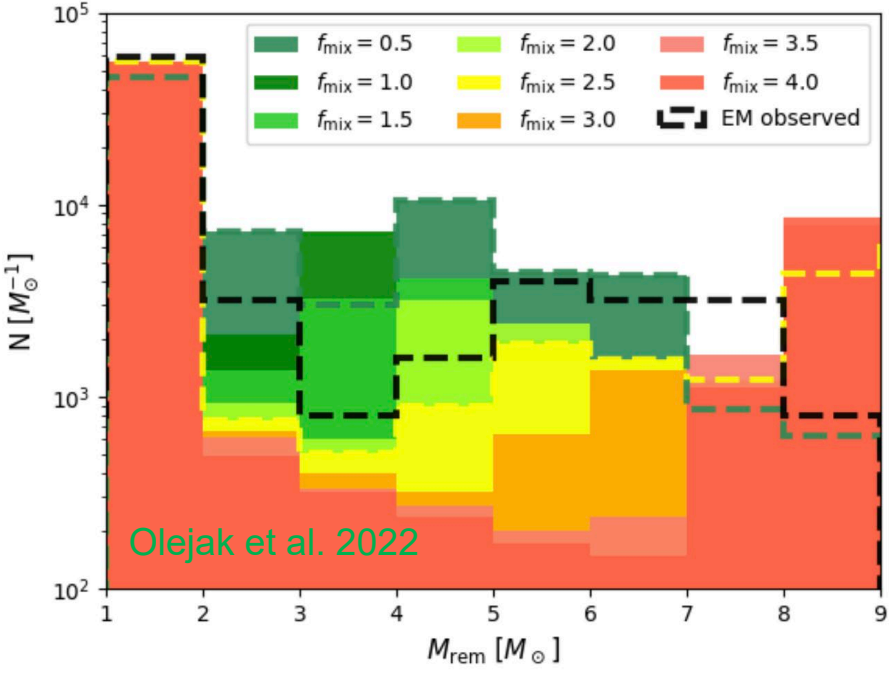


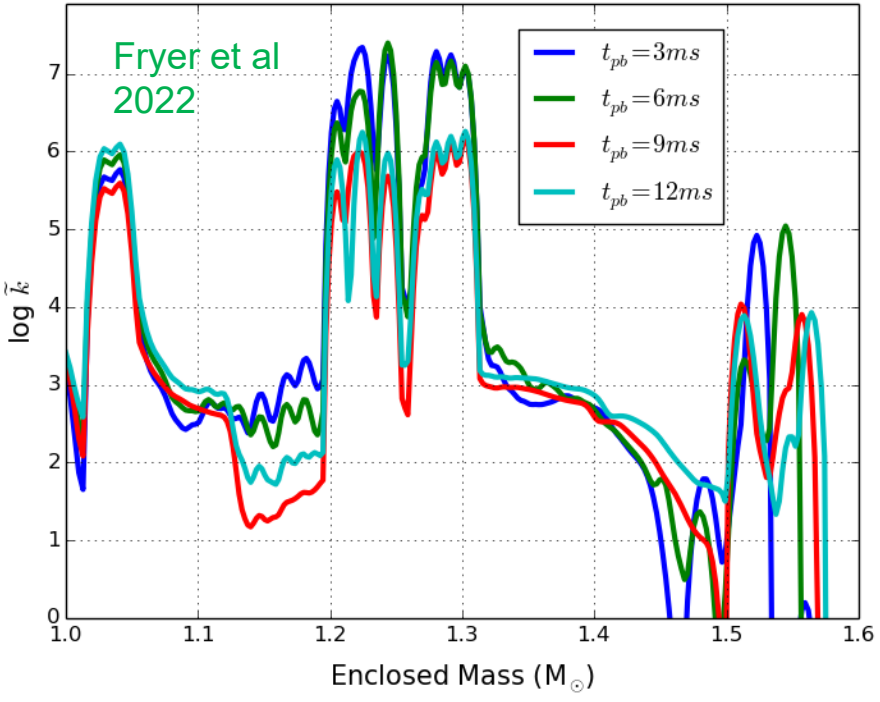

Propagation through circumstellar medium: turbulence, cosmic ray acceleration

Remnant Observations

# Remnant Distribution Depends on Growth of Convection

- Although GWs from a Galactic SN could probe convection directly, we don't have to wait that long. GWs from mergers constrain the compact remnant mass distribution.

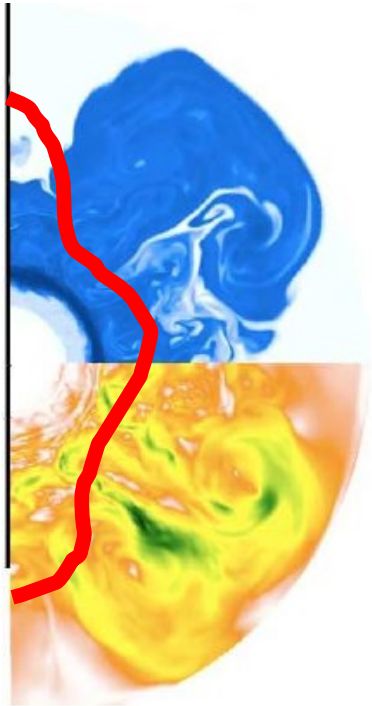


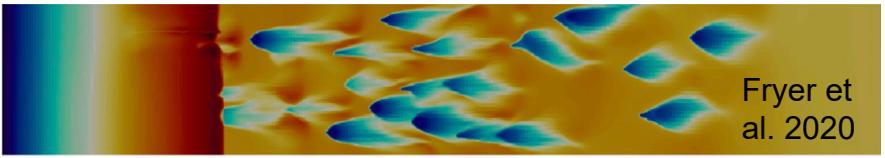




- The remnant distribution is affected by the growth of convection in the supernova engine.
- We leverage fluid dynamics expertise to determine this affect.

# Shock Breakout

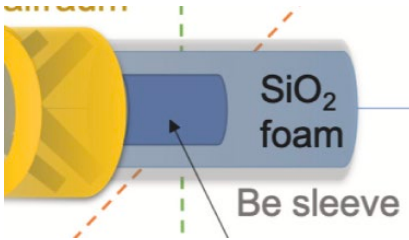
Theory Work:
Analytics now incorporating asphericities (Irwin et al. 2021)
Shocks through stars (Tsang et al. 2022, Hix Talk)
Shocks in Winds (e.g. Fryer et al. 2020)
Predictions for Observations (e.g. Bayless et al. 2022)!

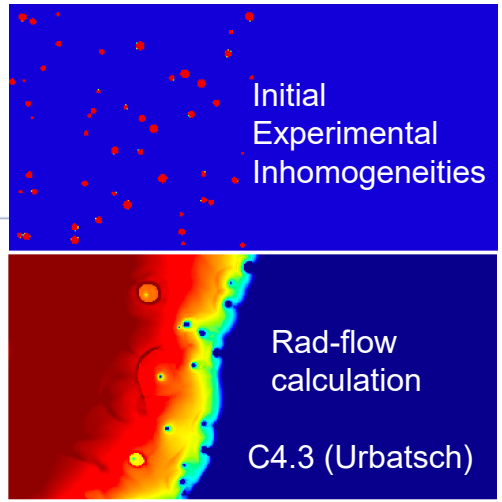





NASA has played a huge role in understanding these events:

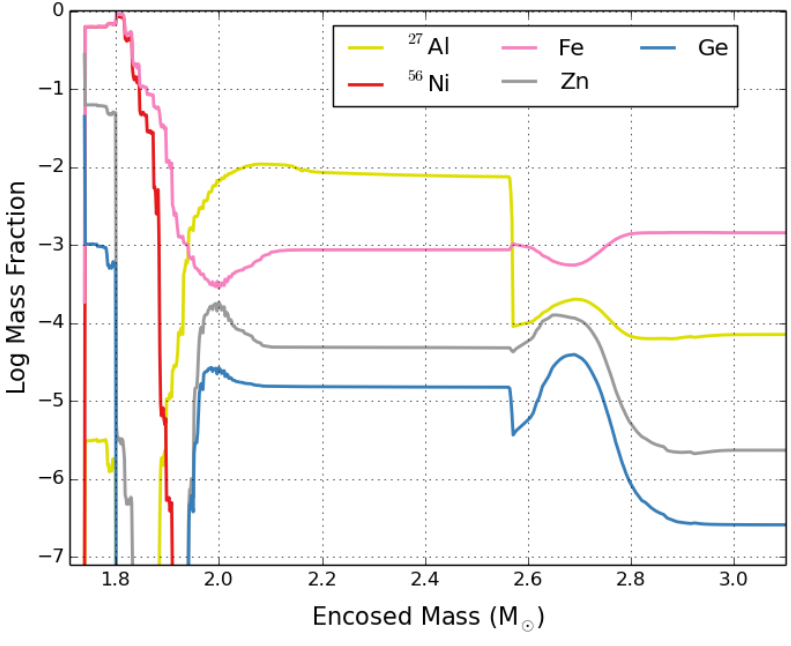
- 2008D with Swift (Soderberg et al 2008)
- Alp & Larsson (2020) have found potential candidates in XMM
- UltraSat (ISA) is a wide-field UV satellite that will detect the UV emission. It will measure the UV flux, proving the prevalence of shock breakout.

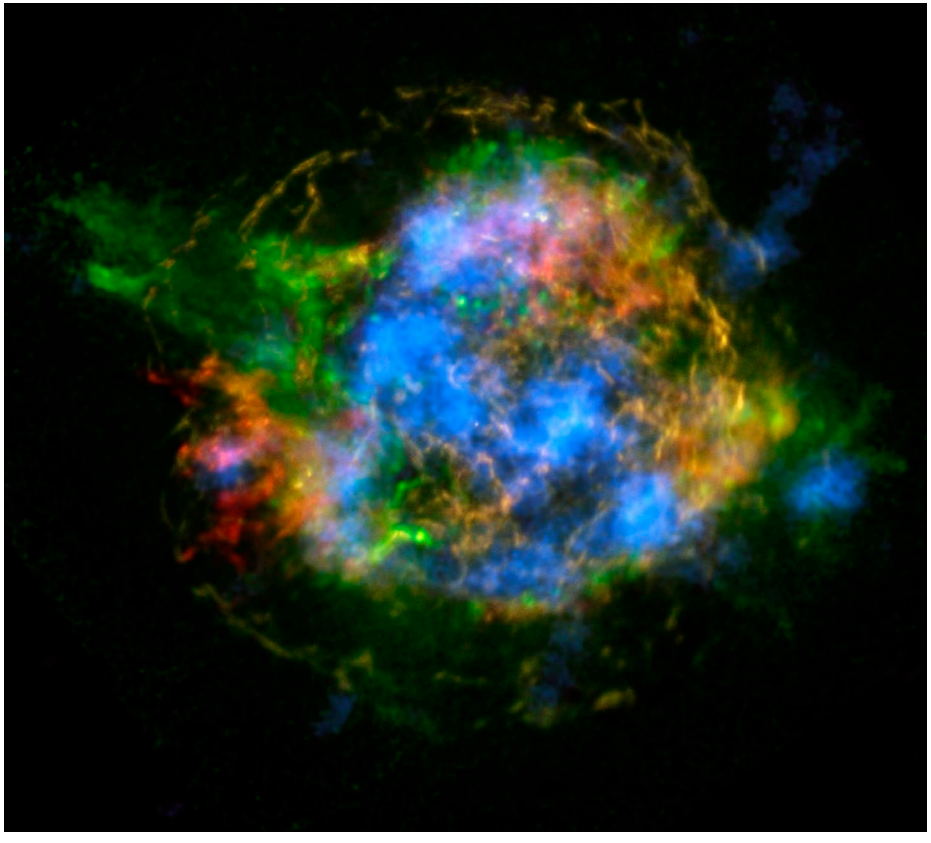


# Cassiopeia A: Chandra, NuSTAR, JWST…

- Observations of $^{44}$Ti provided key support for the convective engine.
- But many questions remain unanswered (e.g. why is the iron not collocated with the $^{44}$Ti).

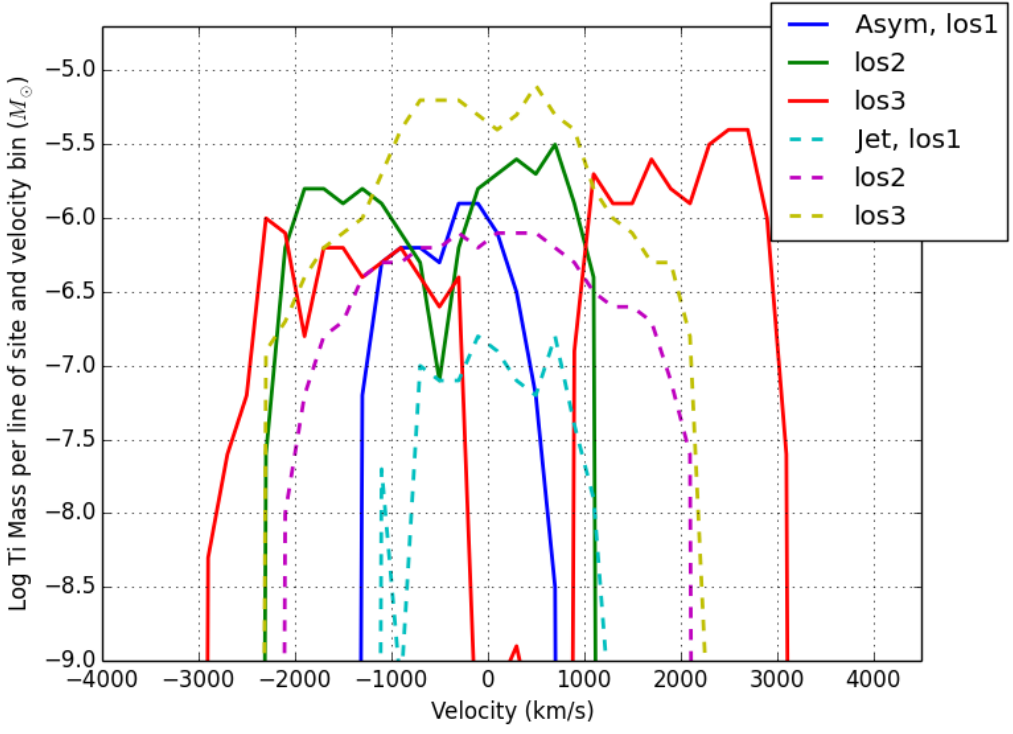


- Combining Chandra, NuSTAR and JWST (Milisavjlevic observations) and data is key.

# What is Multi-Messenger?

- Multi-Messenger does not require concurrent.
- Multi-Messenger does not require different particles.
- Multi-messenger means different sources, i.e. different probes or different diagnostics.
- Theorists are working to bridge different simulations and different physics expertise and fields to calculate these diagnostics.
- NASA can play a huge role in providing multi-messenger diagnostics for supernovae.




Line profiles could be resolved to constrain the convective engine.