AN EXTRAORDINARY JOURNEY INTO THE TRANSIENT SKY:

from restless progenitor stars to explosive multi-messenger signals

A conference in honour of
Enrico Cappellaro, Massimo Della Valle, Laura Greggio, Massimo Turatto

Padova, Italy, April 1-4, 2025

Core-Collapse Supernova Theory in 2025
Progress and Puzzles

Hans-Thomas Janka
Max Planck Institute for Astrophysics
Garching, Germany

D. Milisavljevic et al.,
JWST Survey of Cas A

Max-Planck-Institut
für Astrophysik

SFB 1258 | Neutrinos
Dark Matter
Messengers

TUM LMU
ORIGINS
Excellence Cluster

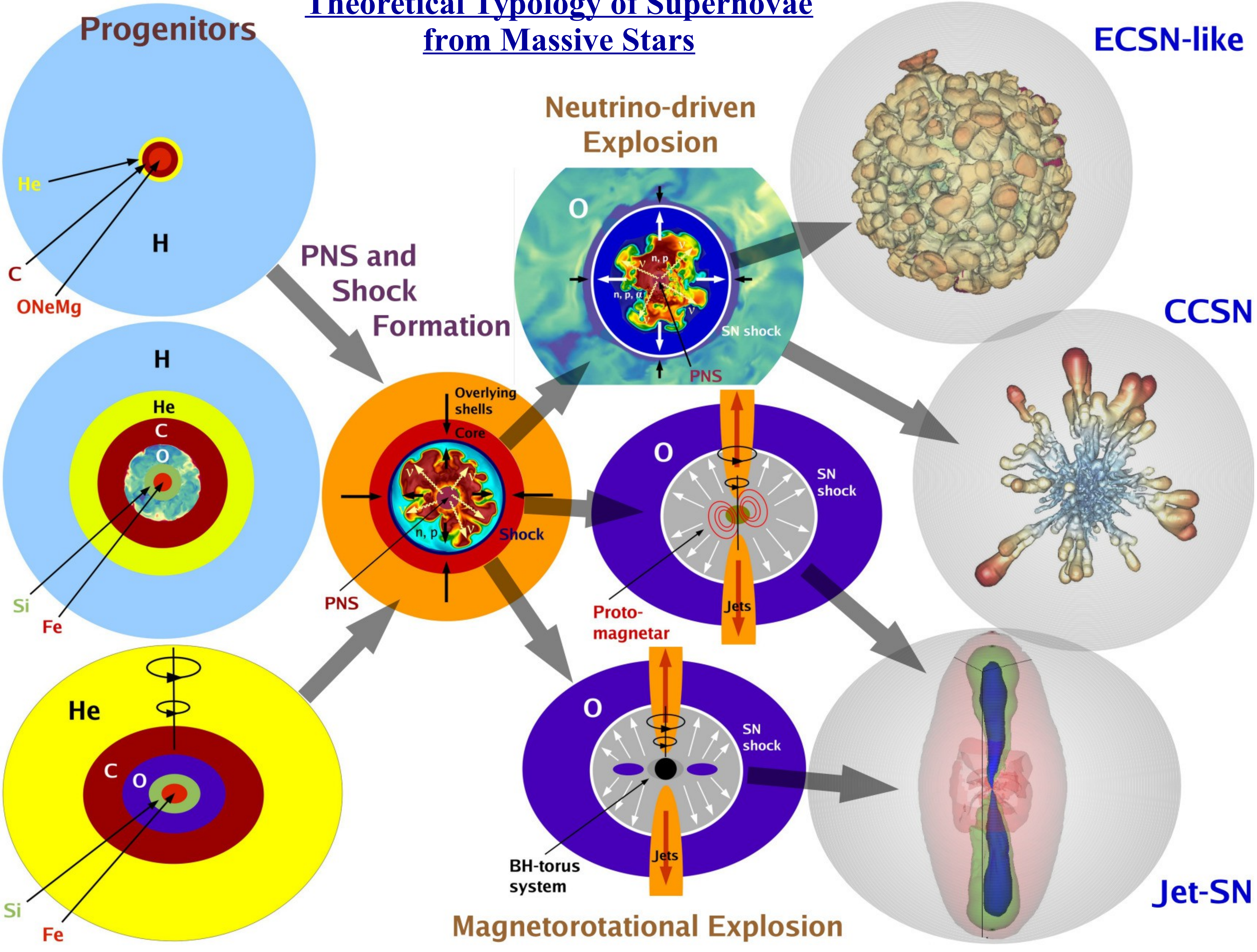
Outline

- **The latest developments:**
  Self-consistent long-term supernova (SN) simulations in 3D to study neutrino-driven explosions

- **Some insights and puzzles:**
  Stellar "explodability", SN nucleosynthesis, and SN 1987A neutrinos

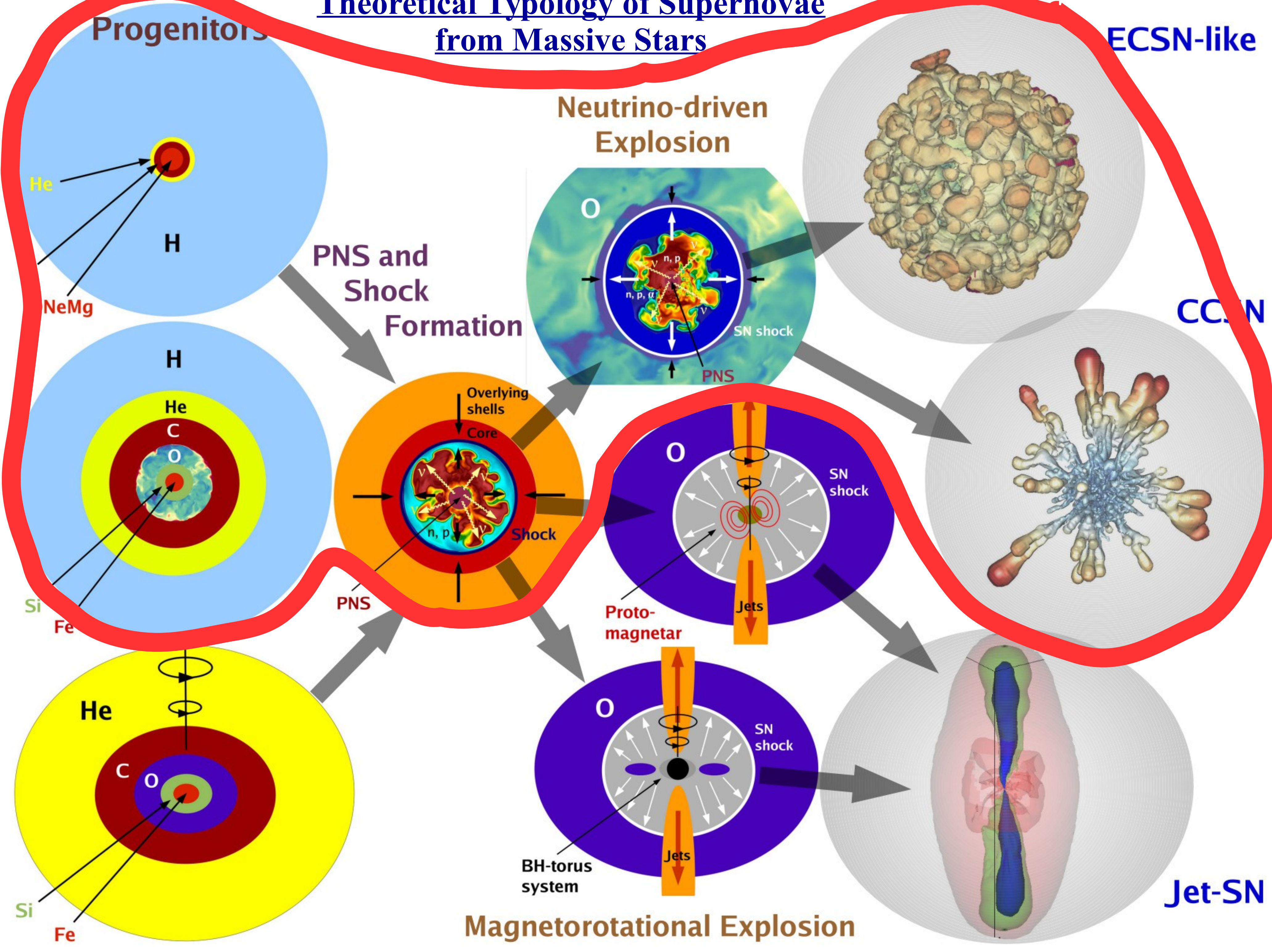
- **An appetizer:**
  Cassiopeia A as a unique laboratory for CCSN physics
  (see also Salvatore Orlando's poster and 2-min. presentation!)

Theoretical Typology of Supernovae from Massive Stars



HTJ & A. Bauswein, in Handbook of Nuclear Physics (Springer-Nature, 2023); arXiv:2212.07498

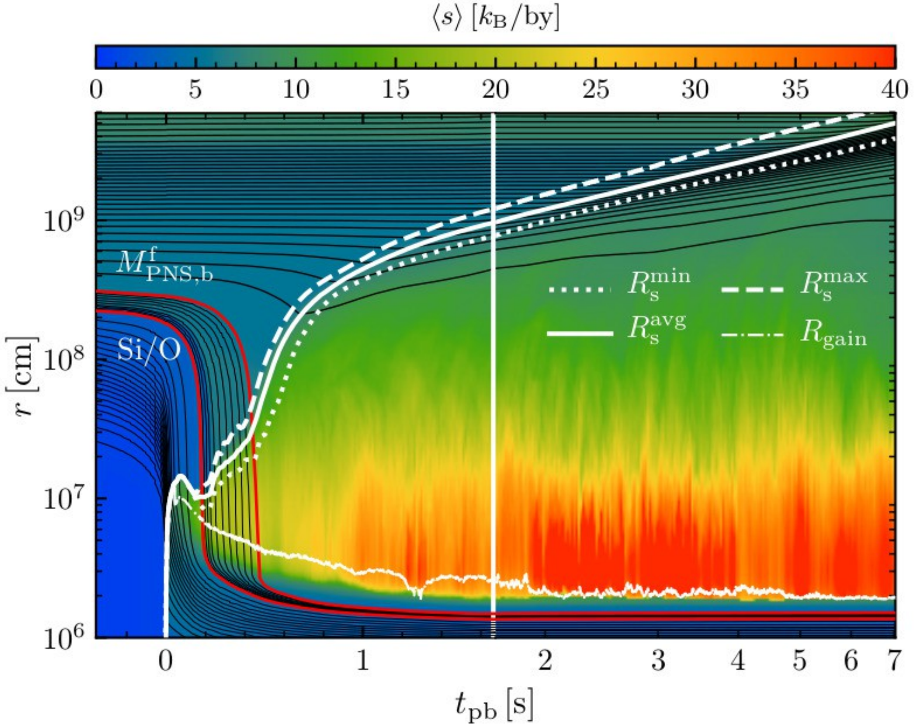
Theoretical Typology of Supernovae from Massive Stars

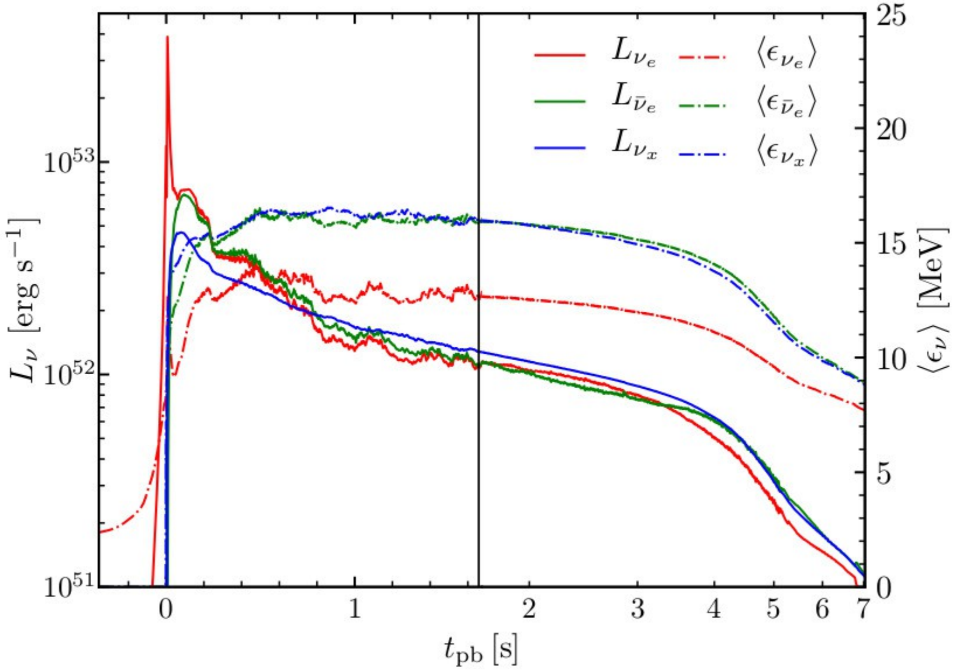


HTJ & A. Bauswein, in Handbook of Nuclear Physics (Springer-Nature, 2023); arXiv:2212.07498

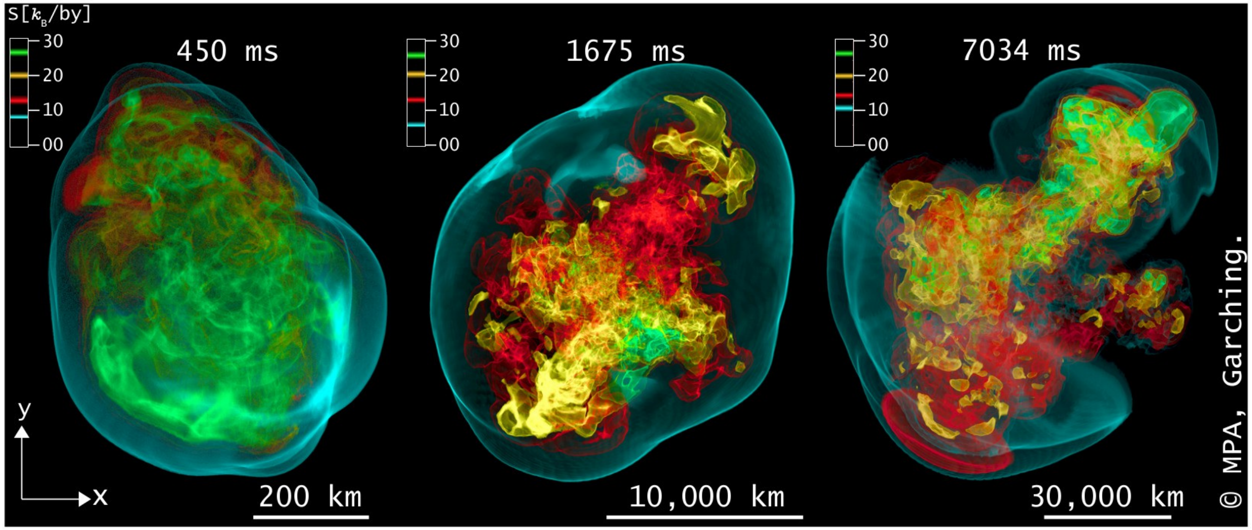
3D Explosion of ~19 M_{sun} Star

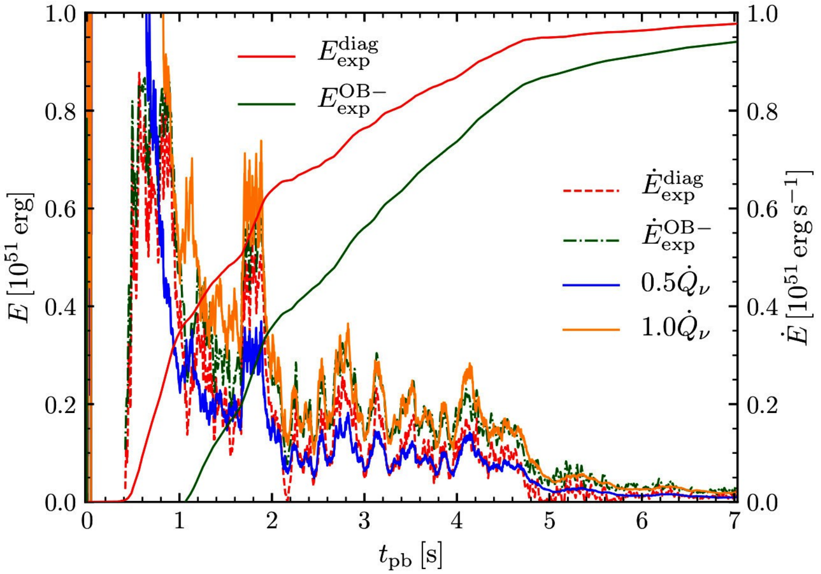
Explosion energy saturates at 10^{51} ergs after 7 seconds





R. Bollig et al., ApJ 915 (2021) 28

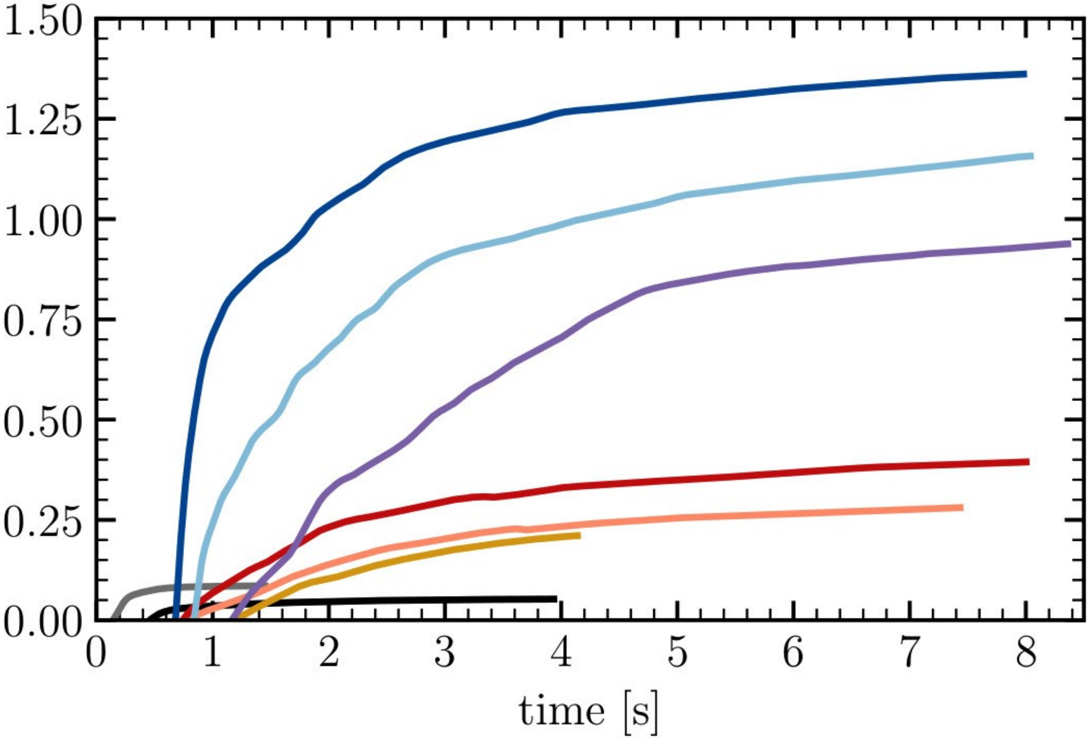


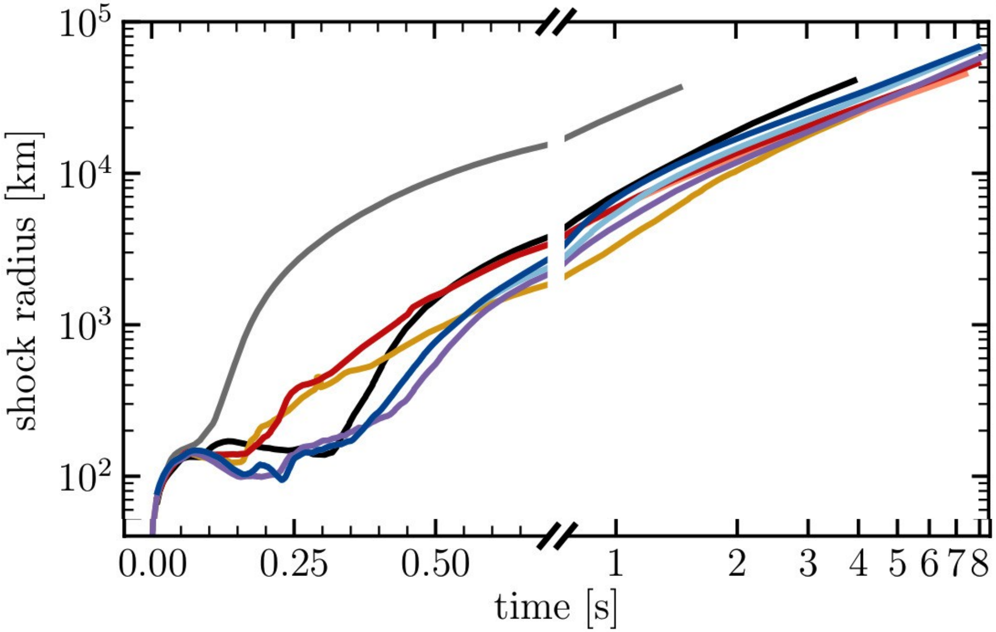


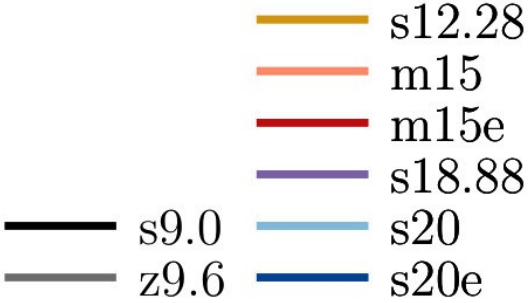
Evolution of 3D Self-consistent CCSN Explosions Towards Energy Saturation

Daniel Kresse
(MPA) Postdoc

(D. Kresse, PhD Thesis, TUM, 2023;
HTJ & D. Kresse, A&SS 369 (2024) 80)







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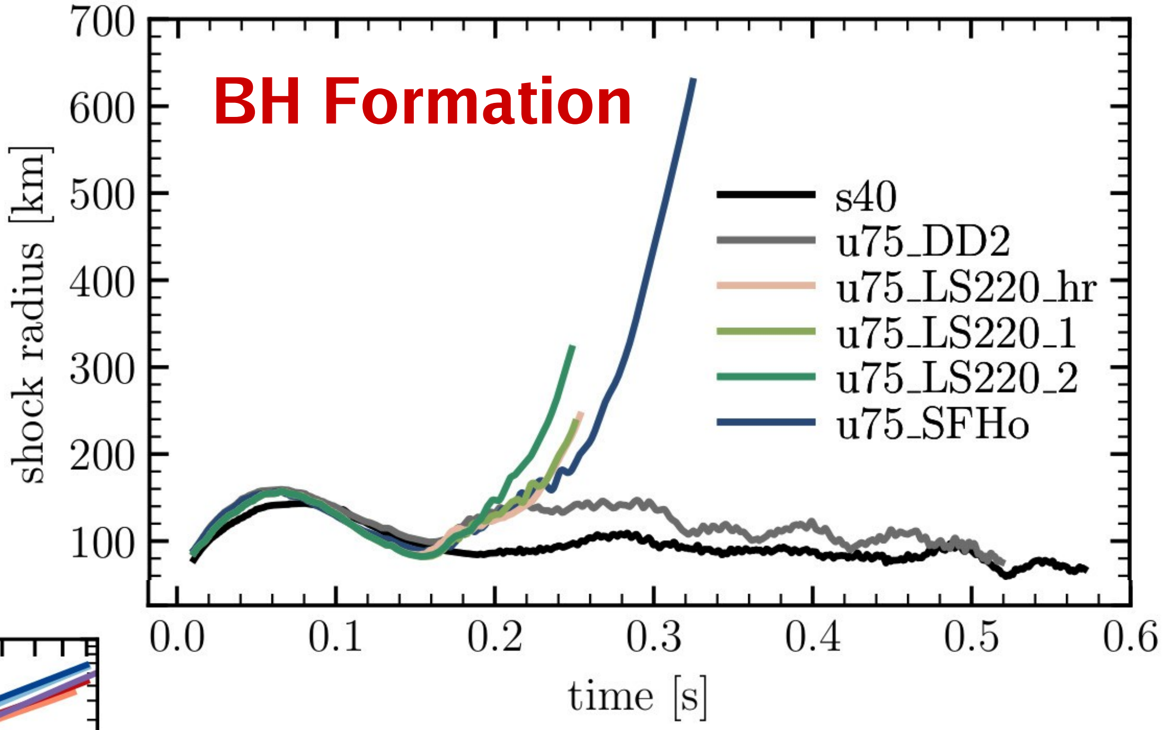
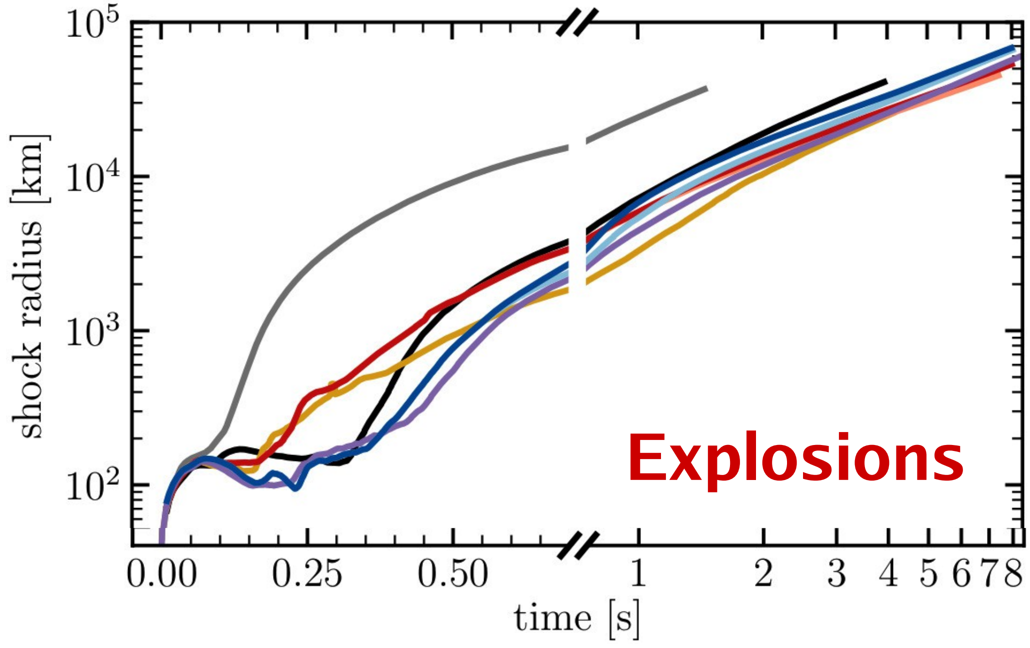




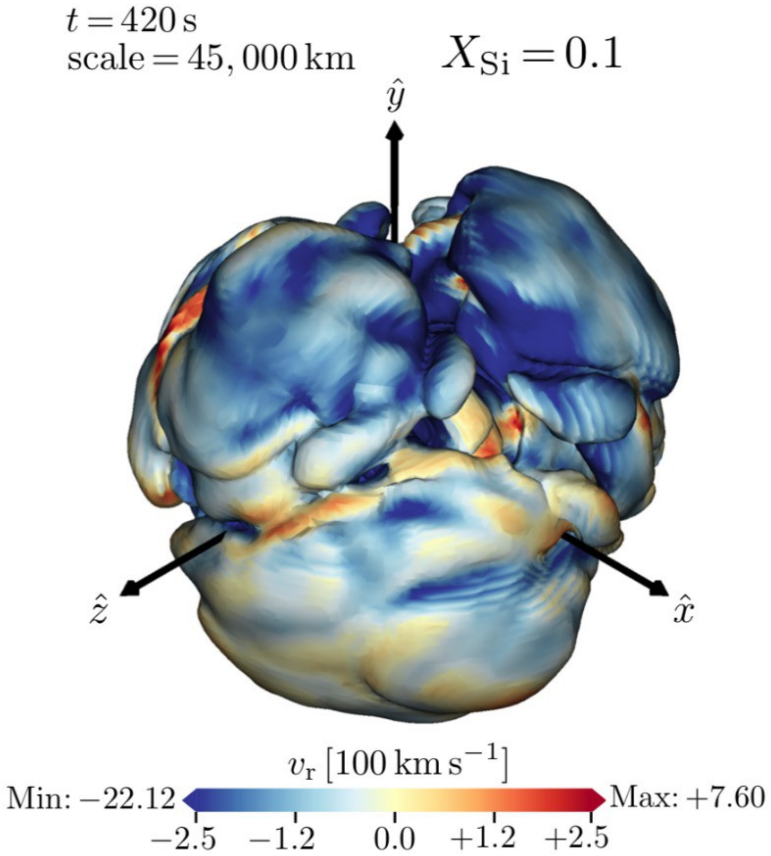
3D self-consistent, ab-initio simulations with state-of-the-art physics yield successful explosions

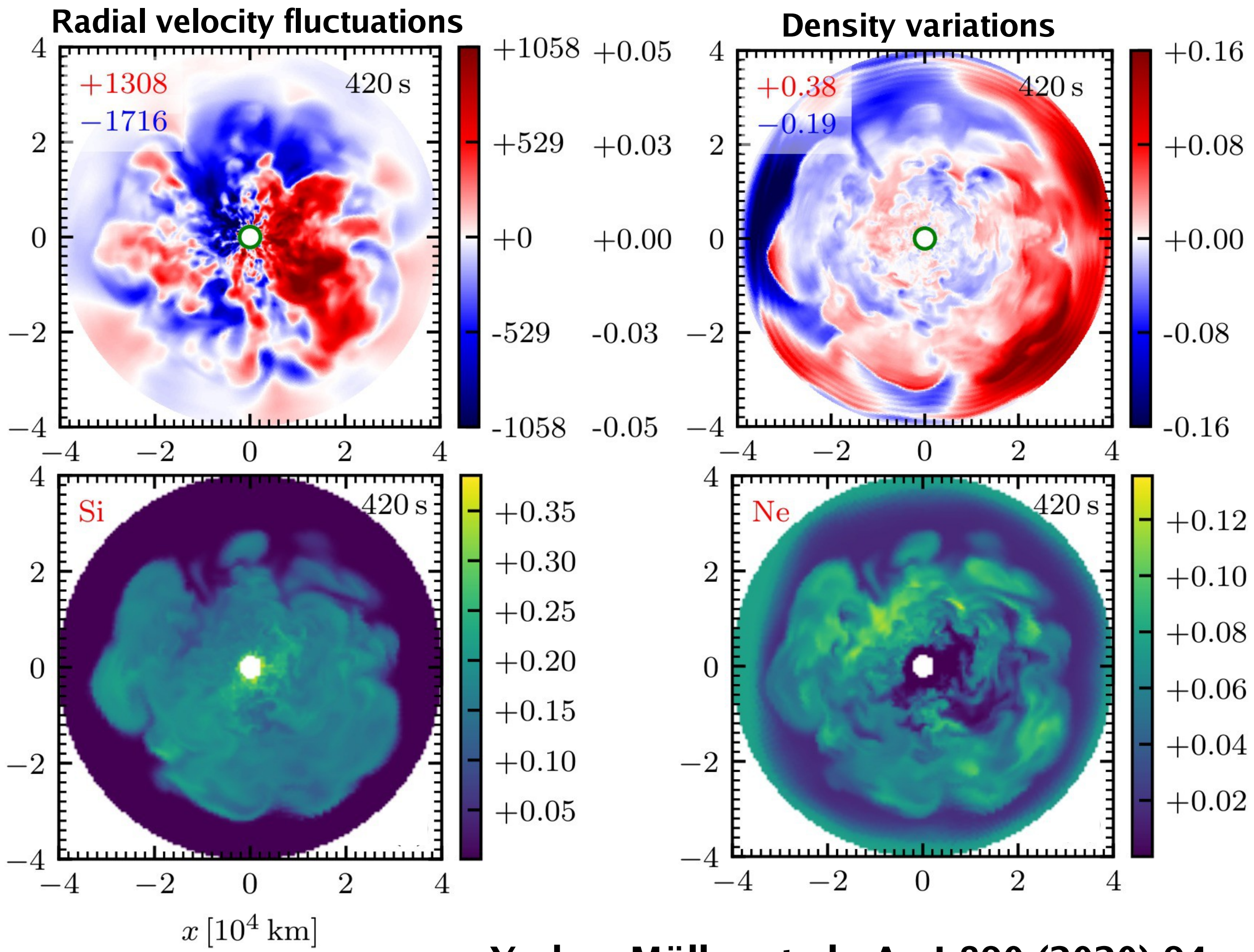
BUT:

Pre-collapse 3D asymmetries in progenitor stars are crucial for the explosion of Garching models

Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

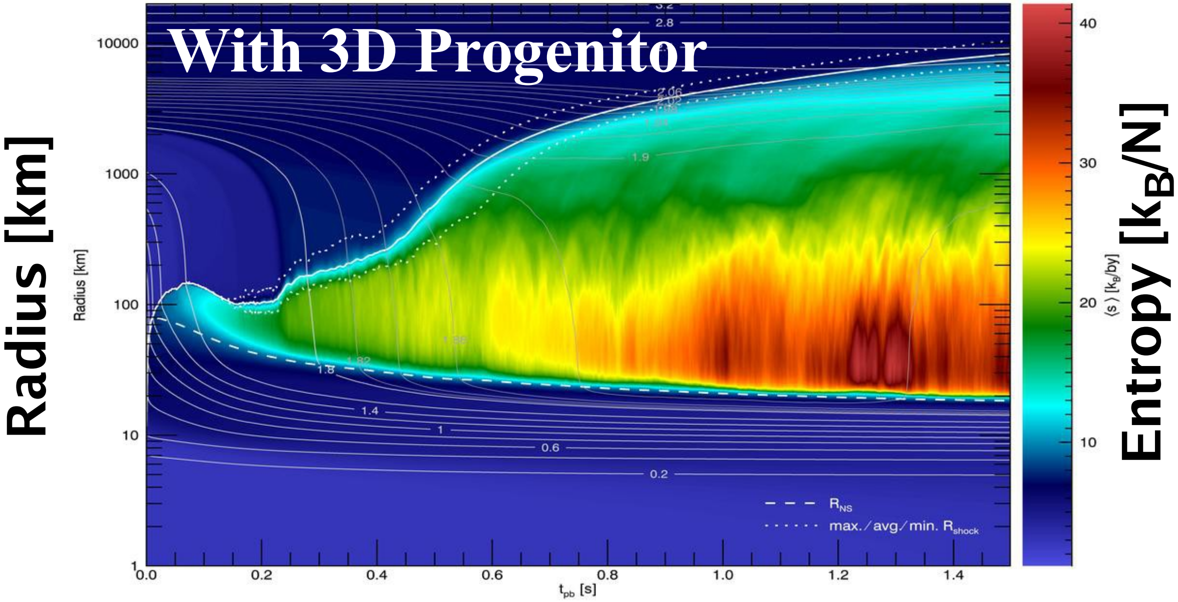
Flash of Ne+O burning in a shell merger creates large-scale asymmetries in density, velocity, Si/Ne composition

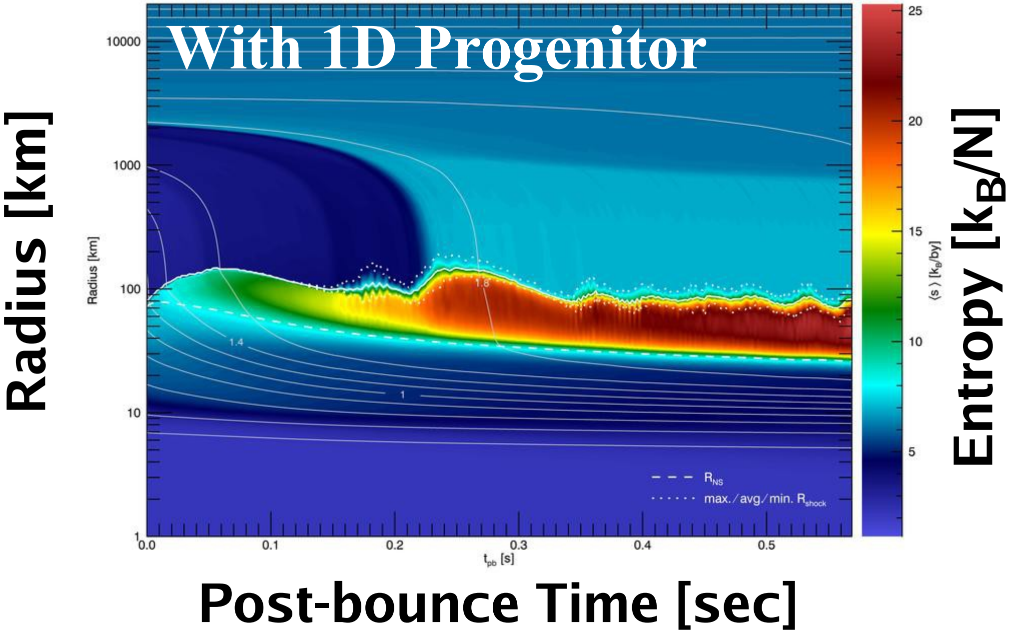


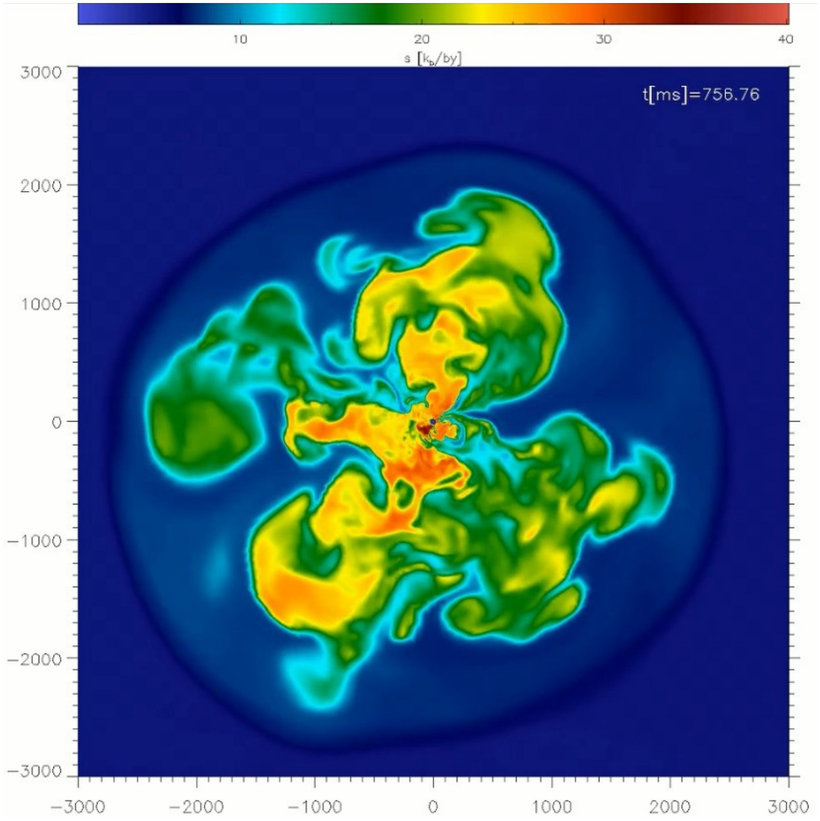


Yadav, Müller et al., ApJ 890 (2020) 94

3D Explosion of ~19 M_{sun} Star after Neon-oxygen-shell Merger







Pre-collapse perturbations in convectively burning O-shell aid explosion because they stir strong postshock convection.

R. Bollig et al., ApJ 915 (2021) 28

Neutrino-driven Explosion Models and "Explodability" of Massive Stars

3D Core-Collapse SN Explosion Models

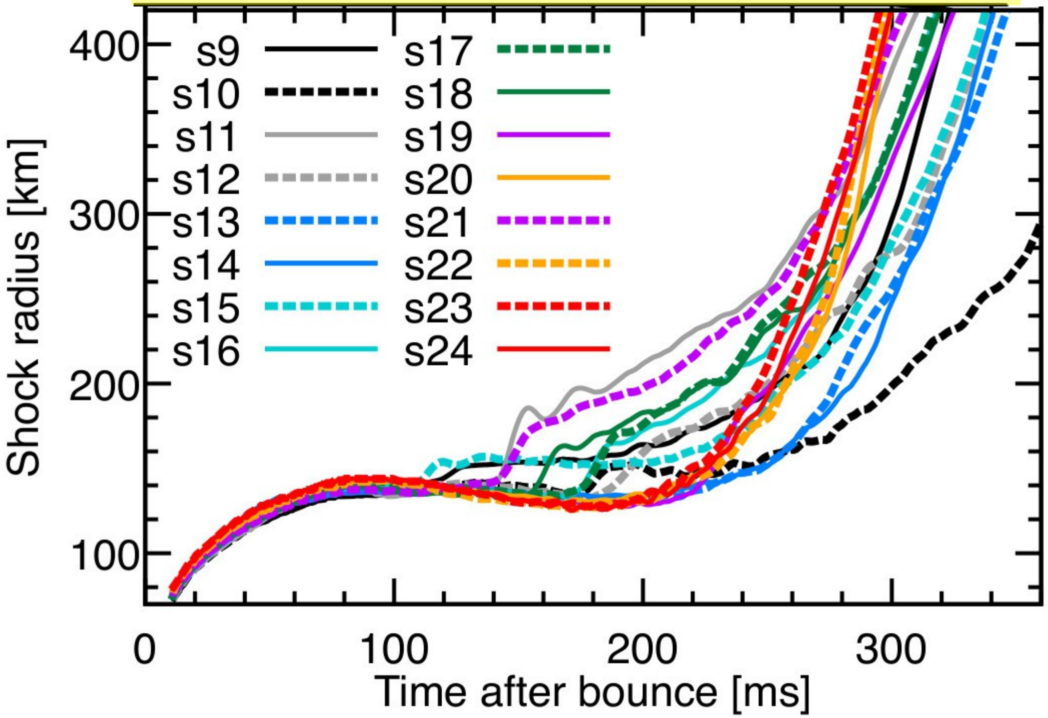
More than half a dozen groups are active in 3D CCSN modeling:

Garching, Monash/QUB, Oak Ridge, Fukuoka, Tokyo, Caltech, Princeton/Berkeley, MSU/Stockholm

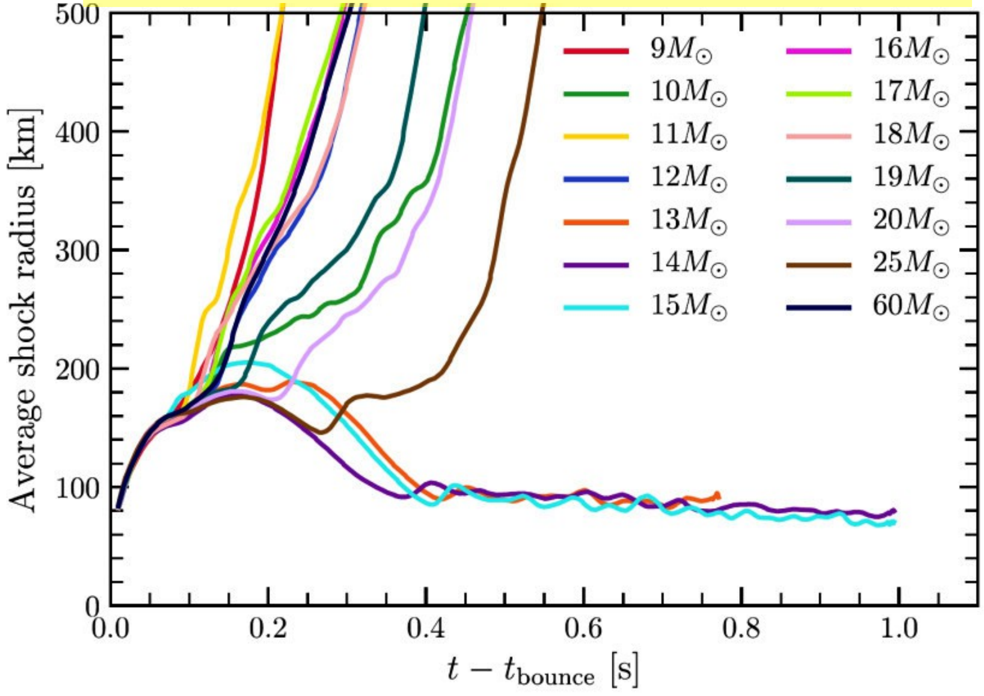
3D simulations differ in many aspects of numerics, physics inputs, seed perturbations. They qualitatively and quantitatively differ in their outcomes.

3D code comparison is highly desirable.

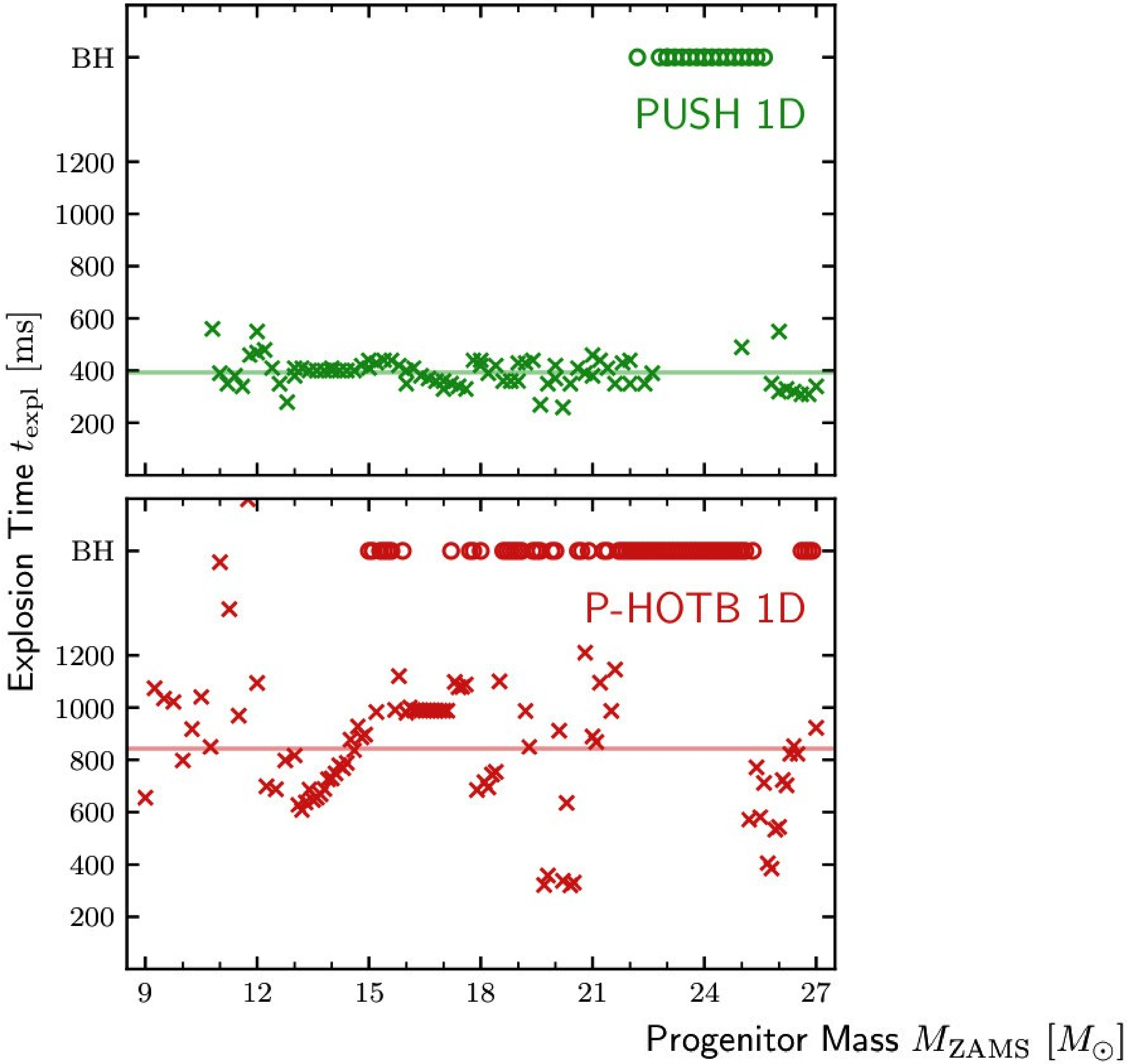
Nakamura+, MNRAS 536, 280; 3D-MHD, LS220 EoS, progenitors: Sukhbold+2016



Burrows+2020, MNRAS 491, 2715; 3D-Hydro, SFHo EoS, progenitors: Sukhbold+2018

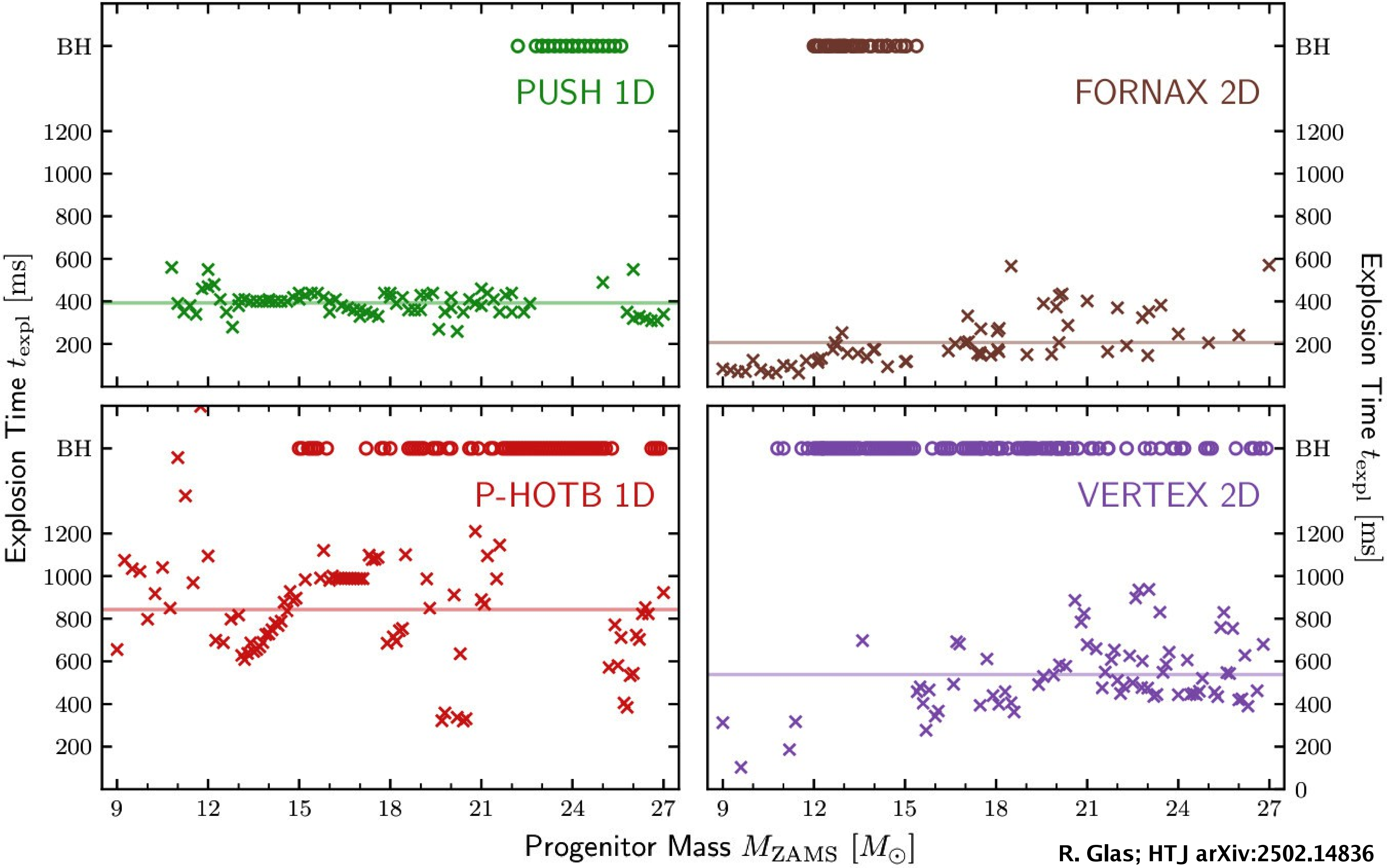


Neutrino-driven Explosions:
1D "Engine" vs. 2D/3D Simulations



R. Glas; HTJ arXiv:2502.14836

Neutrino-driven Explosions: 1D "Engine" vs. 2D/3D Simulations



R. Glas; HTJ arXiv:2502.14836

Summary: Neutrino-driven SNe

Results that can be taken with confidence within known physics:

- Explosions are powered by neutrino energy deposition.
- Neutrino-driven explosions can explain many properties of observed supernovae and supernova remnants.

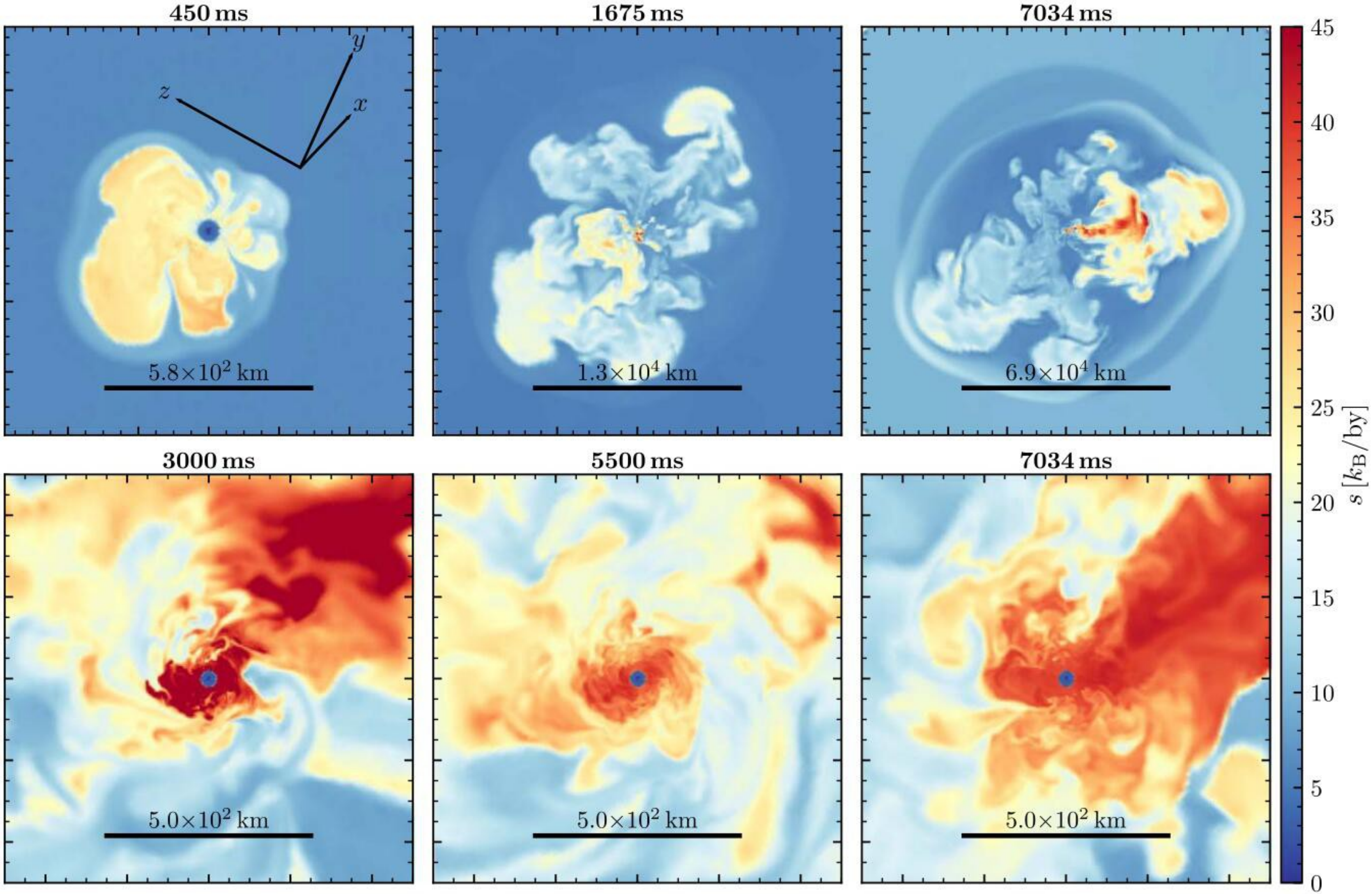
Many open issues and unsolved questions, e.g.:

- CCSN results from different groups differ significantly.
- Progenitor models are 1D (not 3D) and code-dependent.
- Microphysics needs to be settled: Equation of state of NS matter; fast neutrino flavor conversion
- Role of rotation and magnetic fields
- “Explodability” systematics of massive stars is still uncertain

Neutrino-determined Nucleosynthesis in the innermost CCSN Ejecta

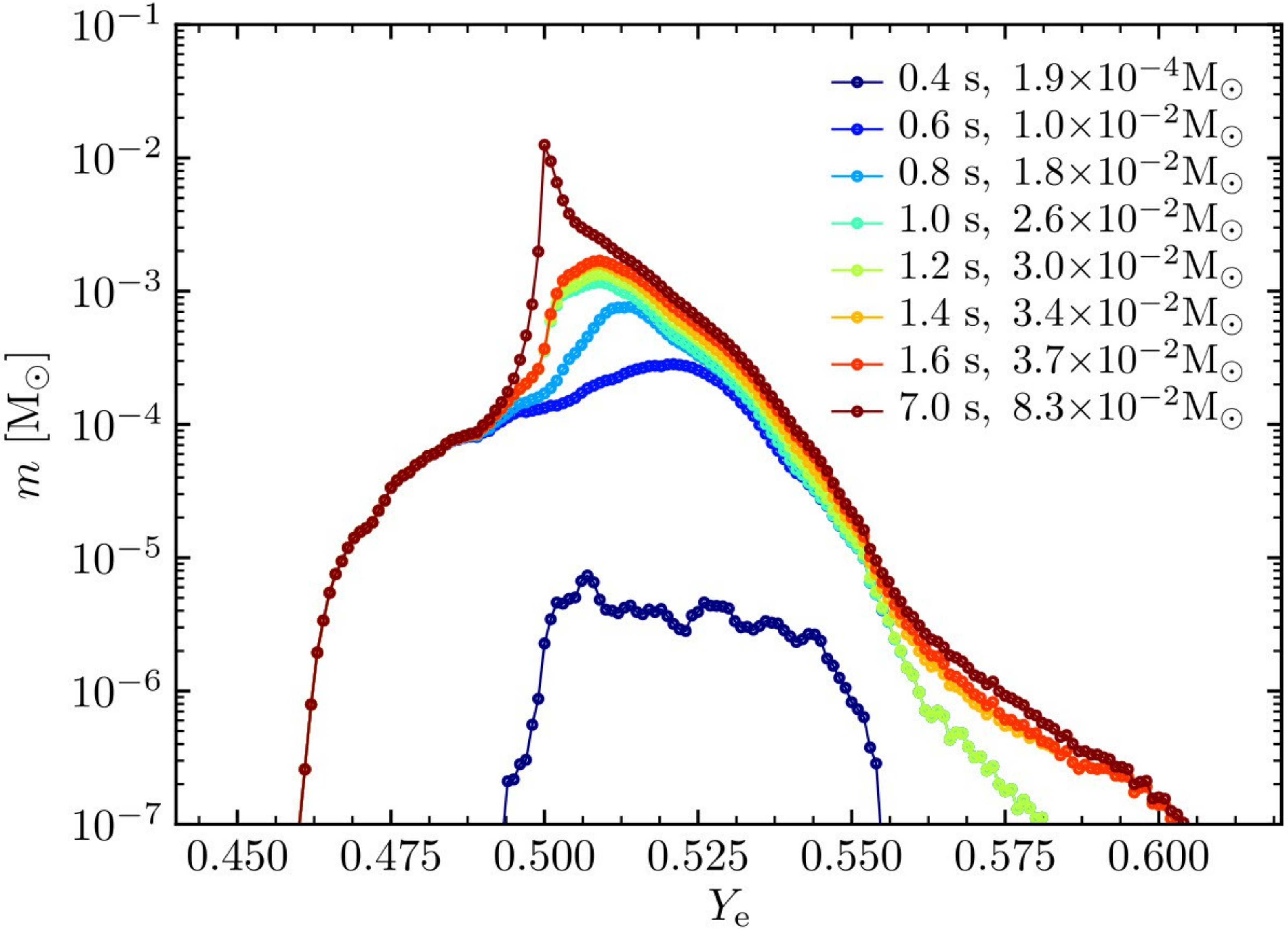
Neutrino-heated Ejecta in 3D CCSN Models

Long-lasting accretion downflows are re-ejected after absorbing neutrinos. They increase the explosion energy over seconds and contribute to production of radioactive isotopes (e.g. ^{56}Ni, ^{44}Ti).



Neutrino-heated Ejecta in 3D CCSN Models

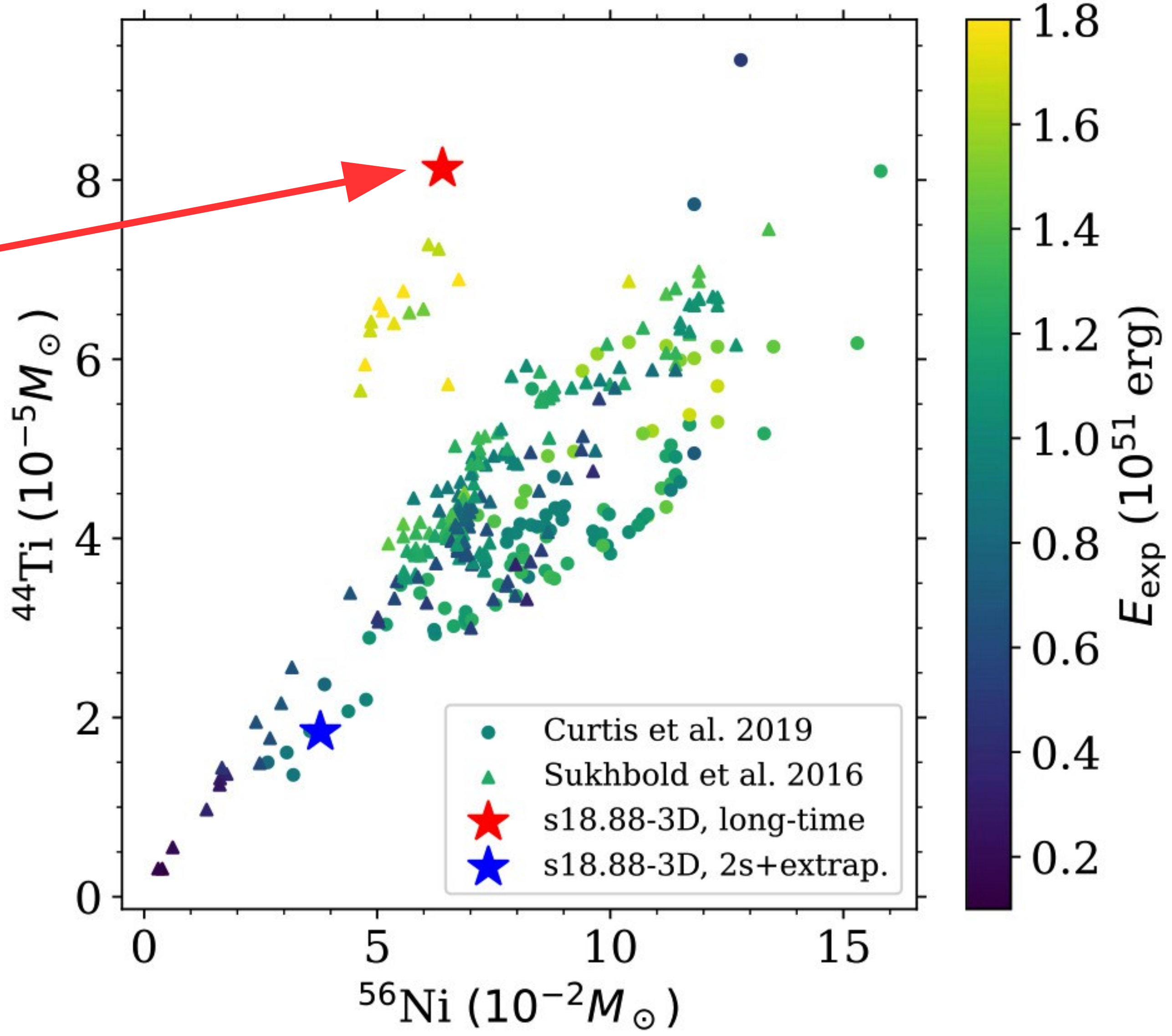
Neutrino-heated ejecta possess wide distributions of neutron-to-proton ratios (or Y_e) as well as entropies at each time.



3D Explosion of ~19 M_{sun} Star: Nucleosynthesis of ^{56}Ni and ^{44}Ti

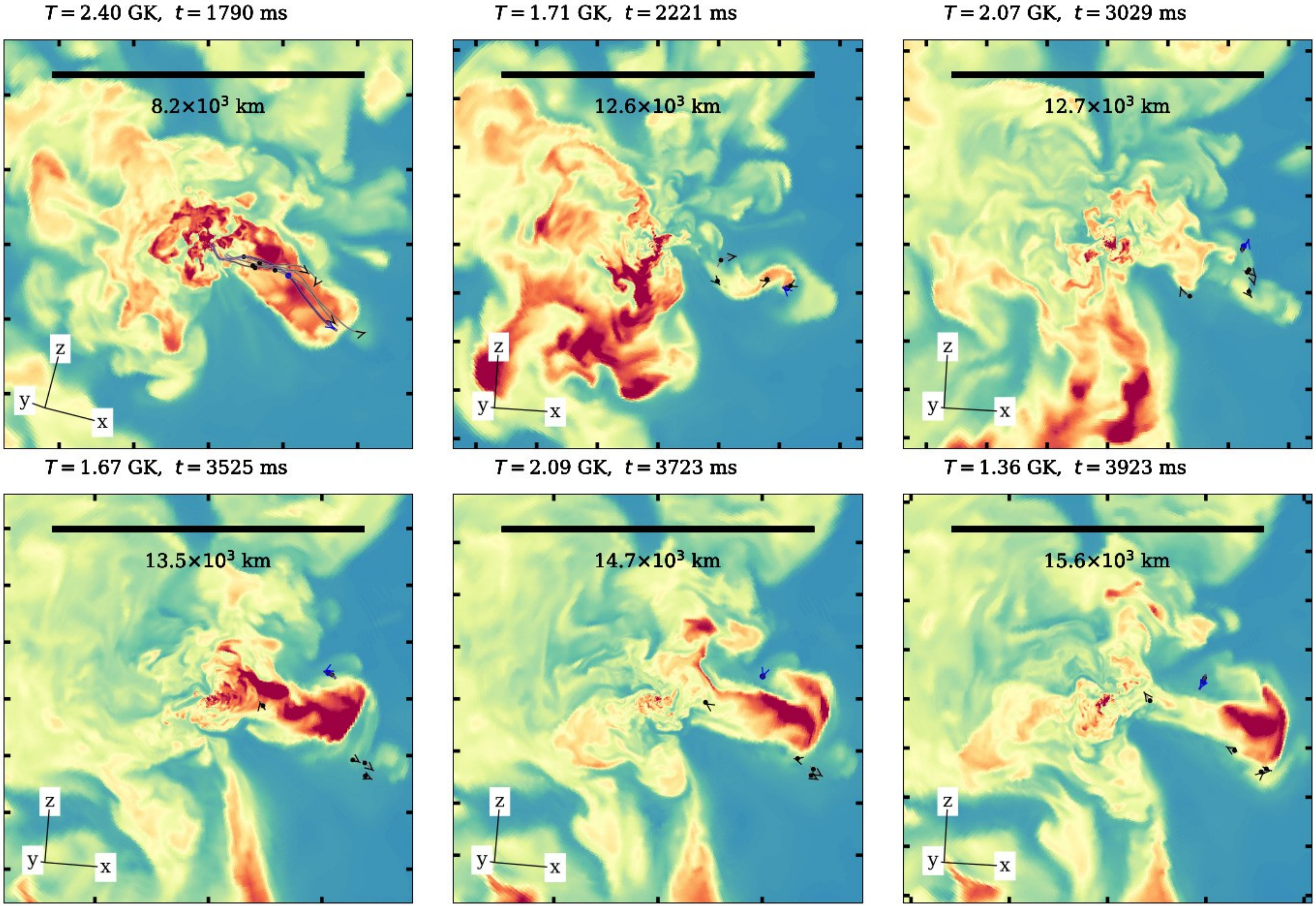
- **Neutrino-driven explosion with energy of ~10^{51} erg**
- **Ejecta contain 0.064 M_{sun} of ^{56}Ni and $8.13 \cdot 10^{-5}$ M_{sun} of ^{44}Ti**
- **3D explosions produce more ^{44}Ti than 1D models with the same ^{56}Ni yield**
- **No ^{56}Ni problem, no underproduction of ^{56}Ni in this neutrino-driven explosion**

Sieverding et al., ApJL 757 (2023) L25



3D Explosion of ~19 M_{sun} Star

Long-lasting aspherical downflows and outflows around the neutron star determine nucleosynthesis conditions in innermost ejecta



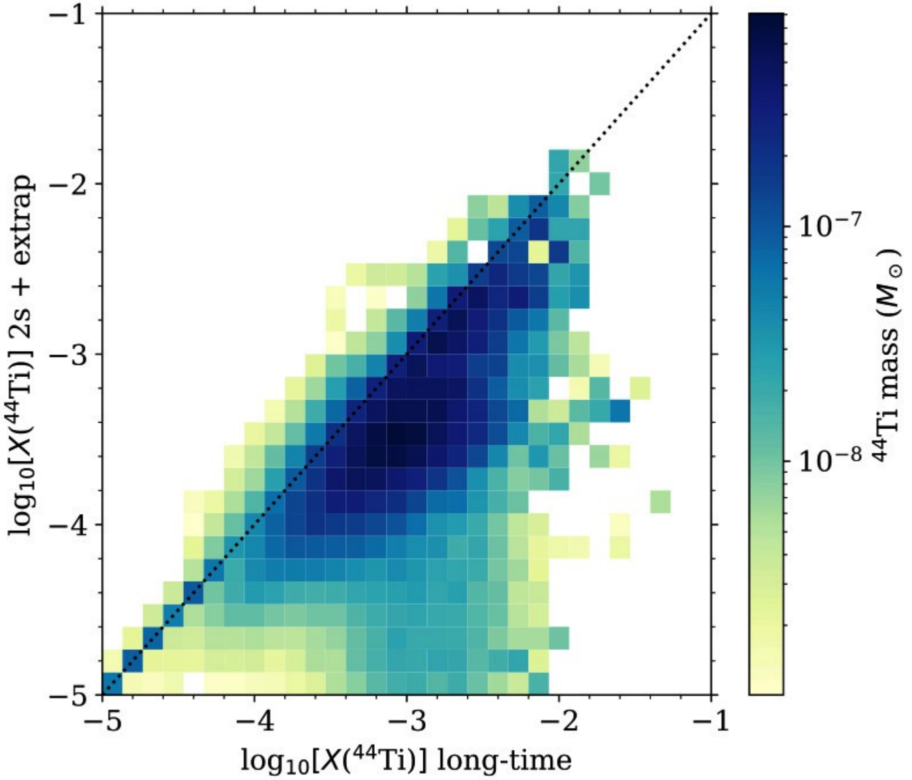
Sieverding et al., ApJL 757 (2023) L25

3D Explosion of ~19 M_{sun} Star: Nucleosynthesis of ^{56}Ni and ^{44}Ti

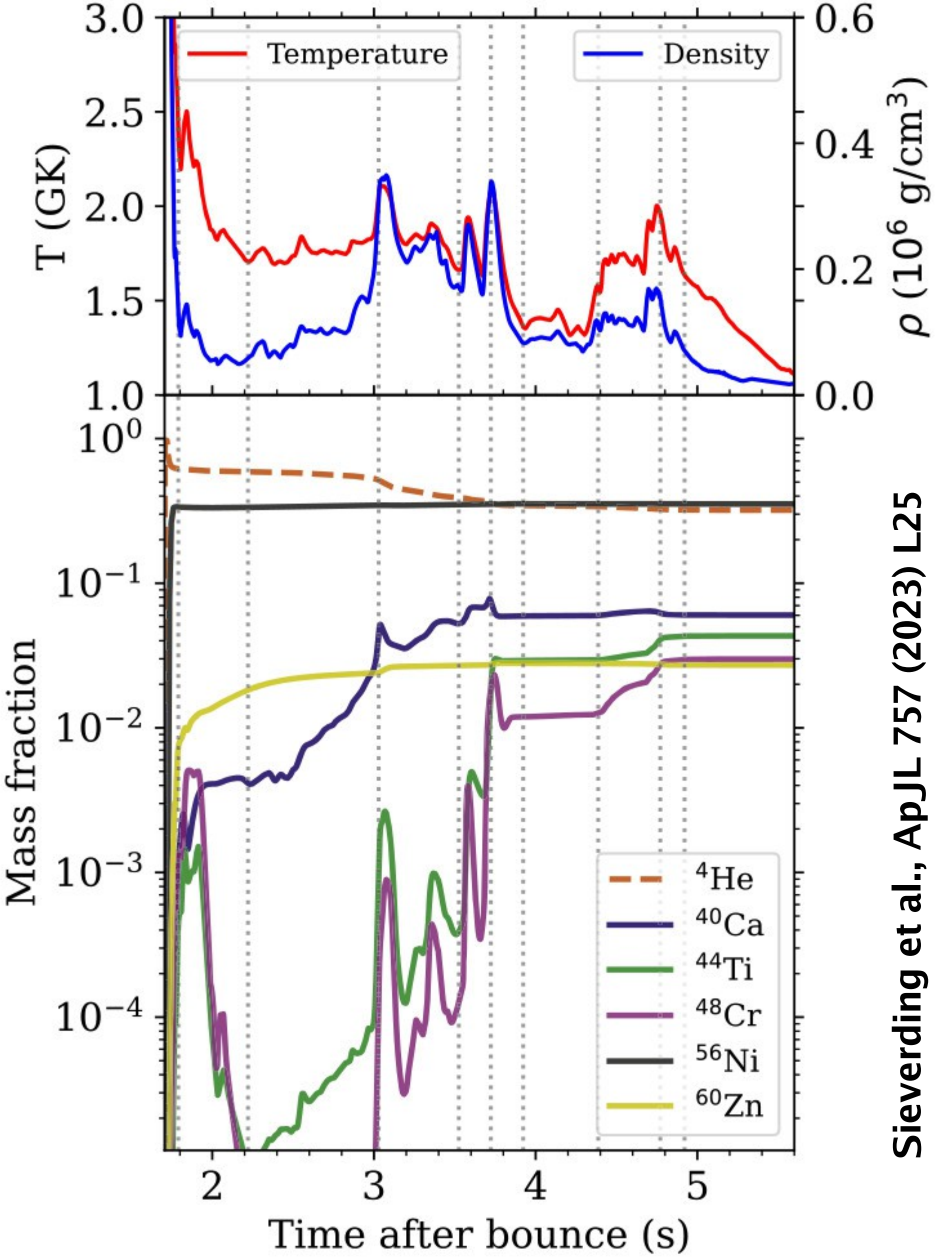
3D ejecta have non-monotonic temperature (and density) evolution due to secondary shocks and compression waves

— >more ^{44}Ti in alpha-rich freeze-out.

Ejecta until 2 seconds p.b. plus monotonic extrapolation



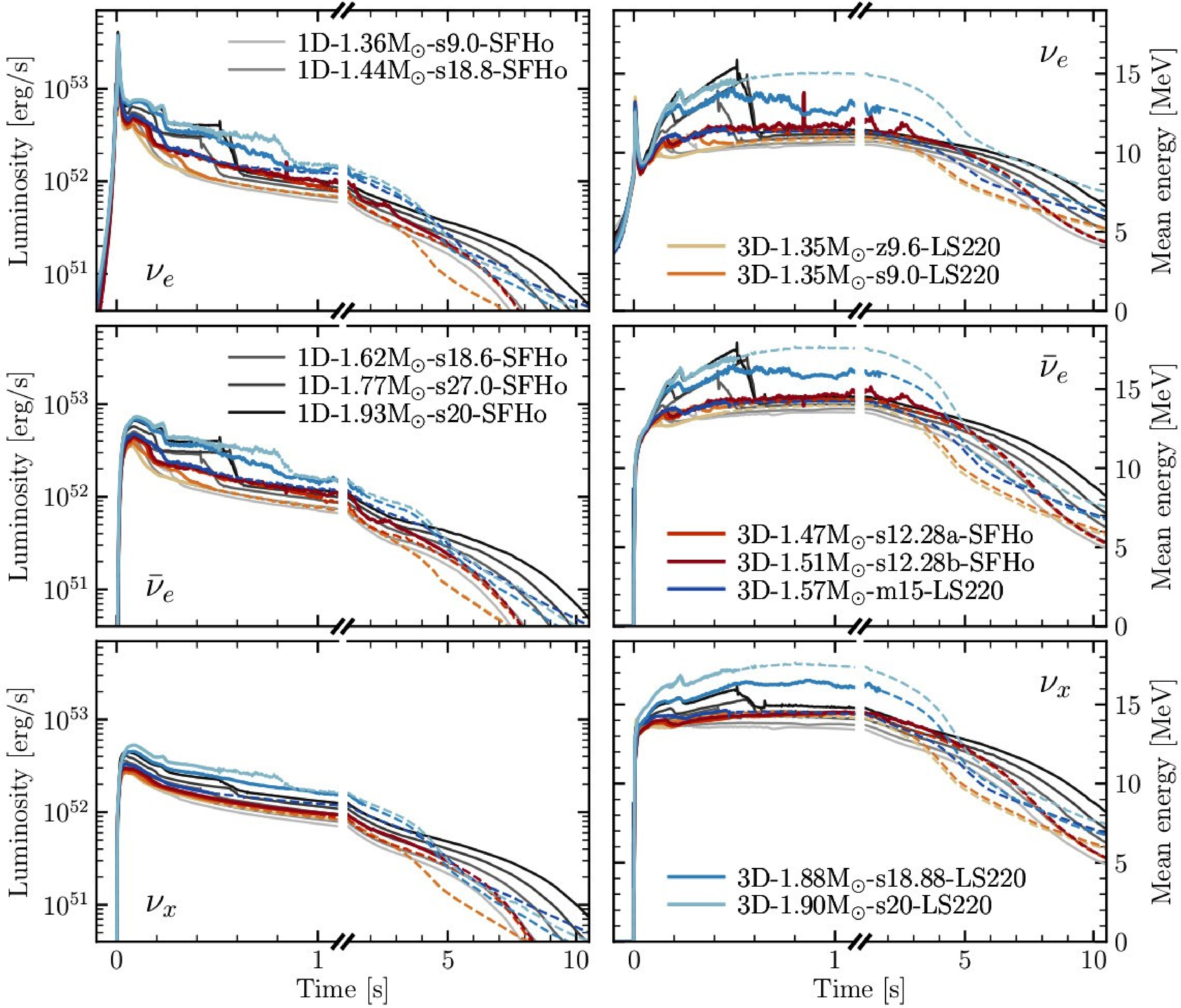
Ejecta until 2 seconds p.b. followed for long-time hydrodynamic evolution in 3D



Sieverding et al., ApJL 757 (2023) L25

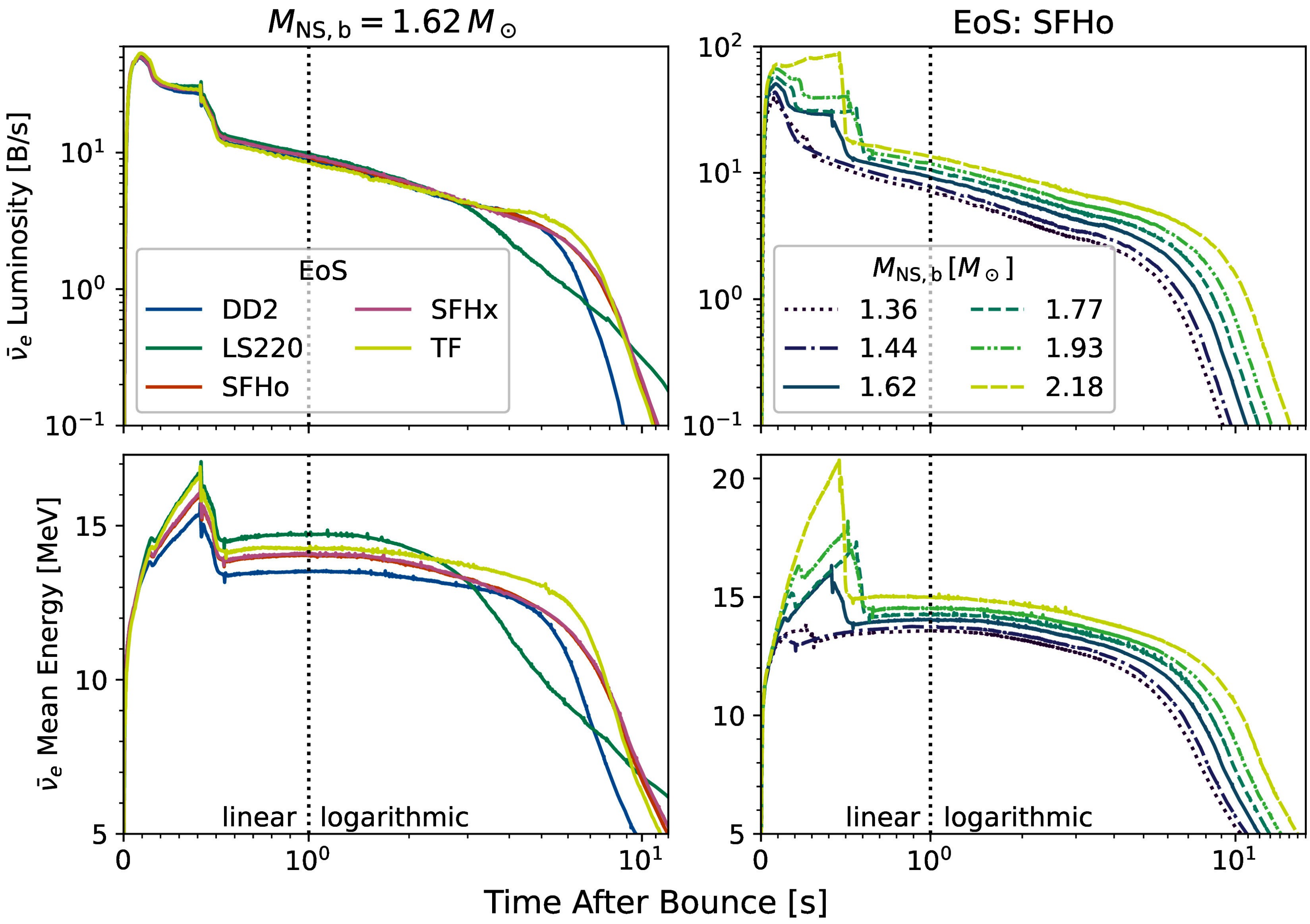
CCSN Neutrino Signals:

PNS Cooling and
SN 1987A Neutrinos

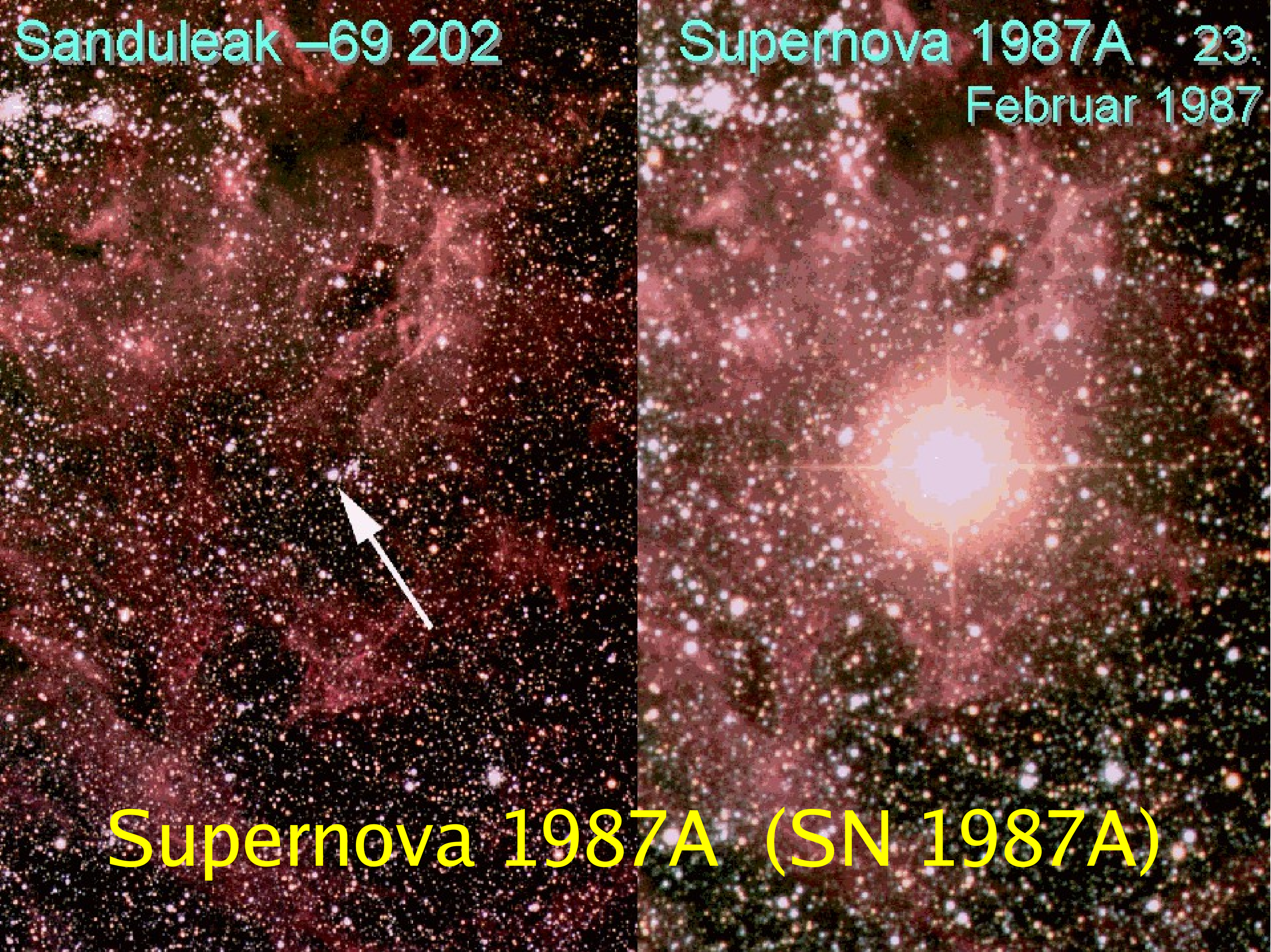


D. Kresse; HTJ arXiv:2502.14836

State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

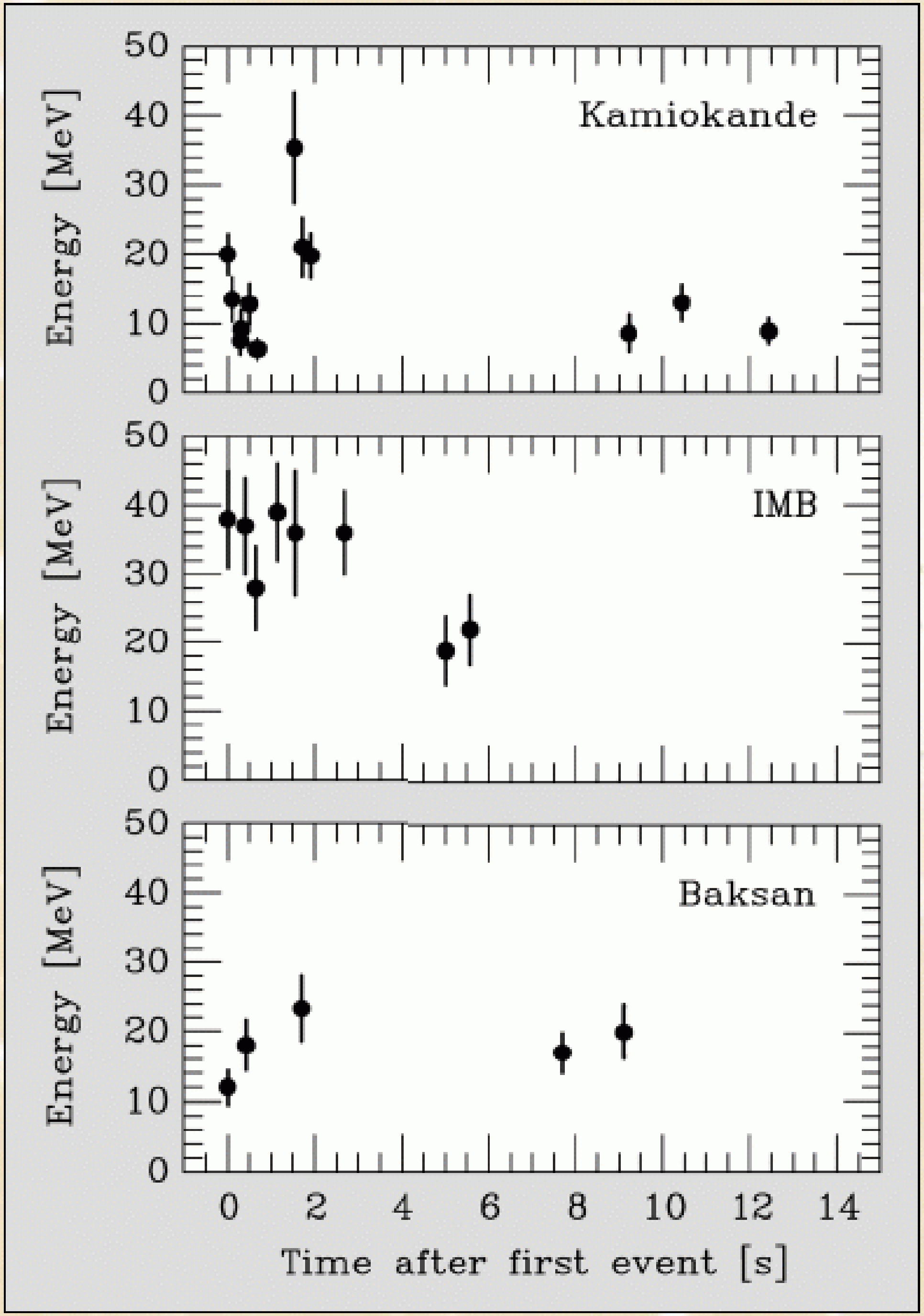


(M. Heinlein, PhD Thesis, TUM 2025)



Supernova 1987A (SN 1987A)

Neutrino Burst of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

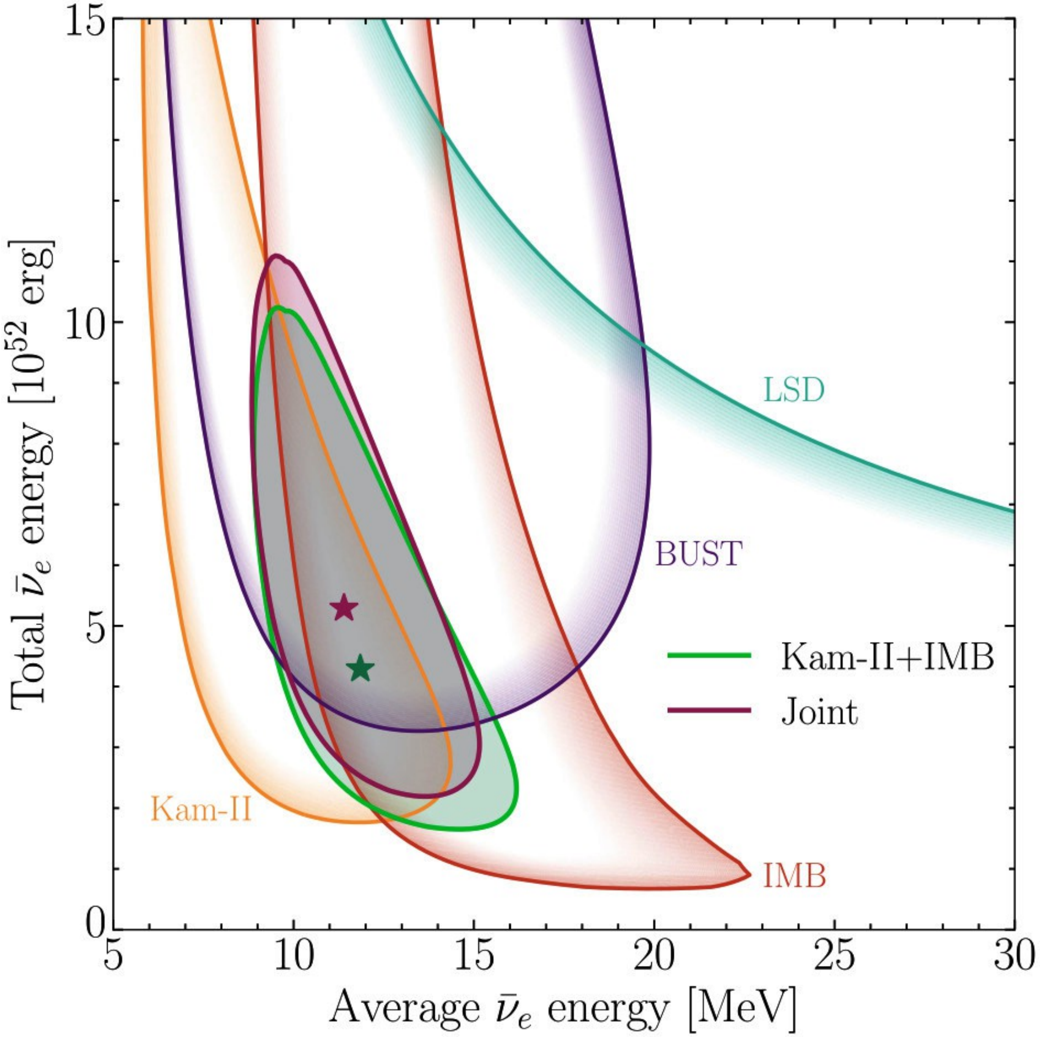
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

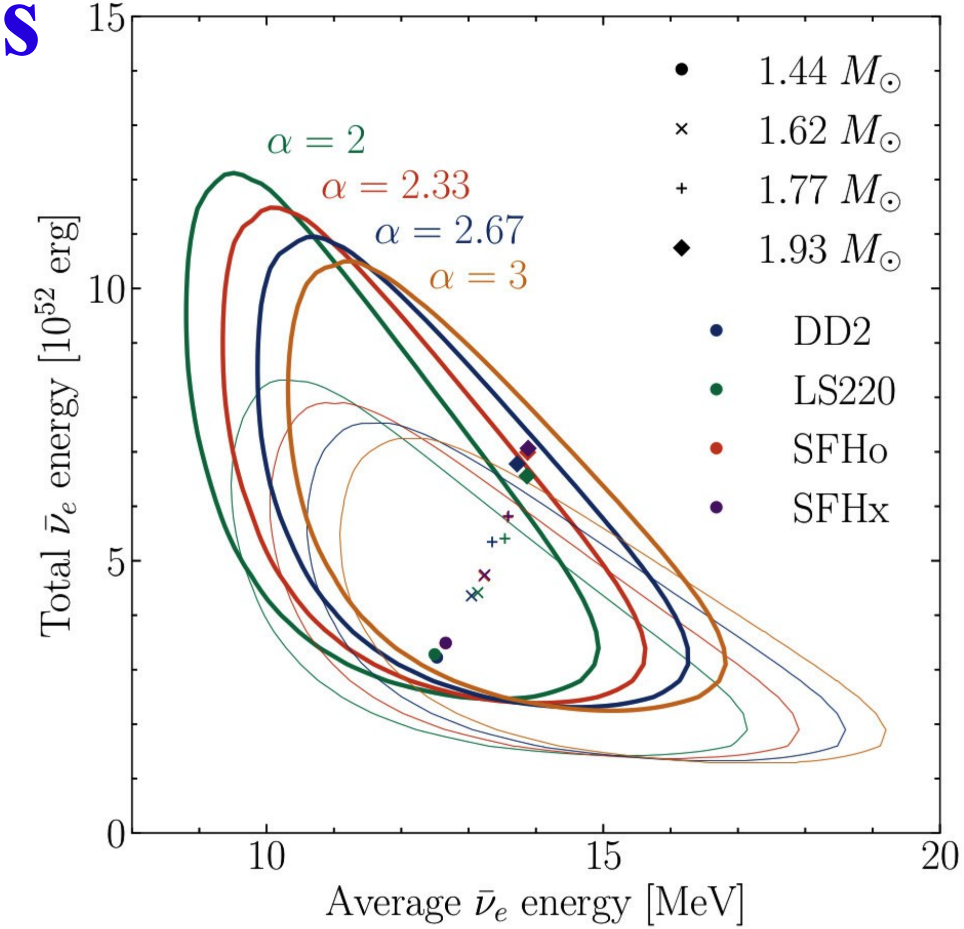
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

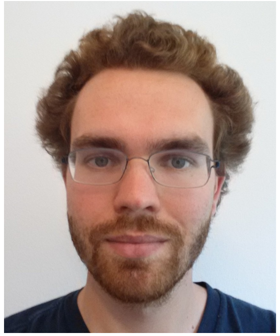
State-of-the-art Proto-NS Cooling Models vs. SN1987A Neutrinos

Models are compatible with confidence region of all experiments combined





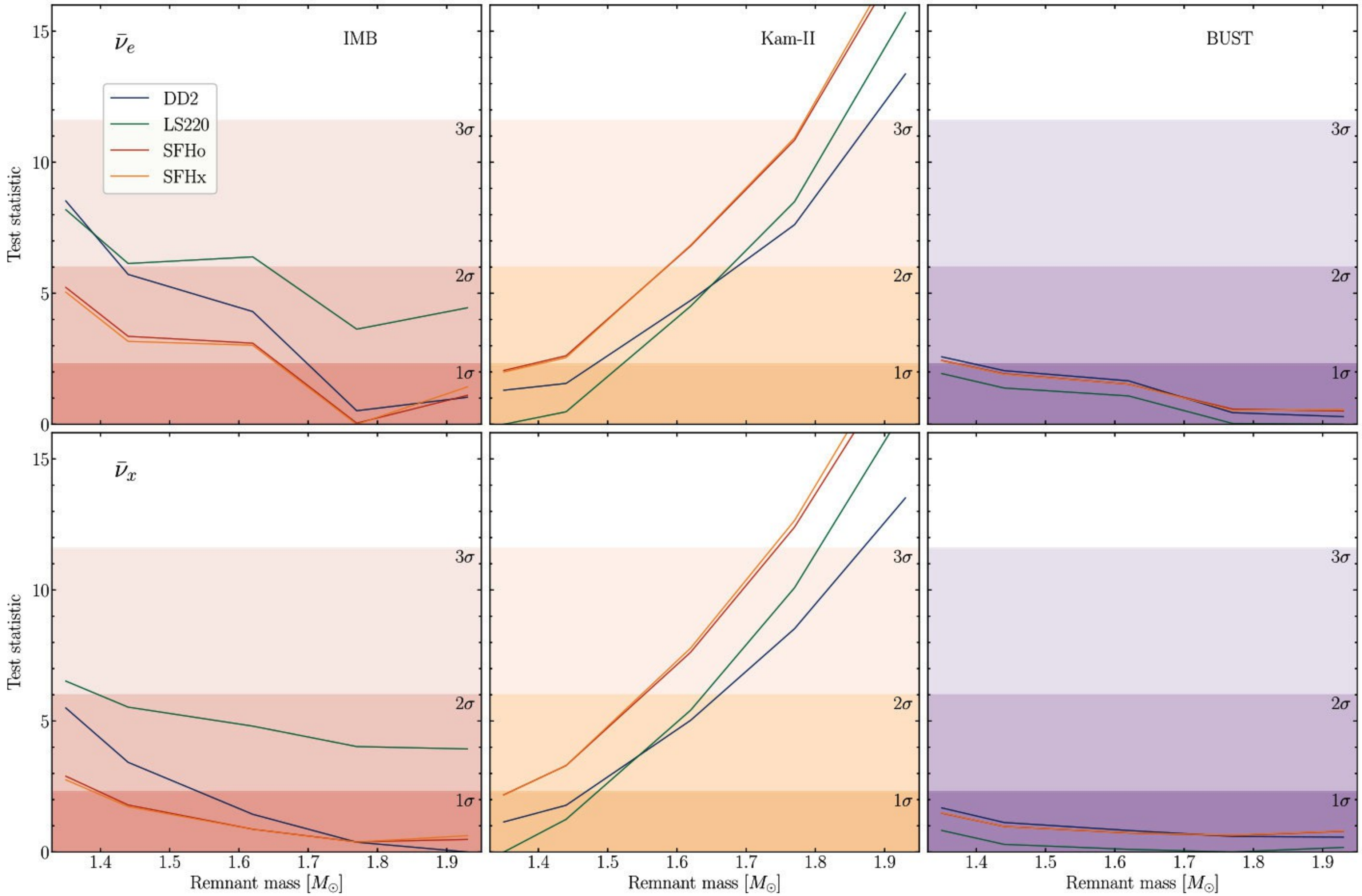
Damiano Fiorillo (DESY), Postdoc



Malte Heinlein (MPA), PhD

**(M. Heinlein, Master Thesis, TUM 2022;
Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)**

State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos



State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

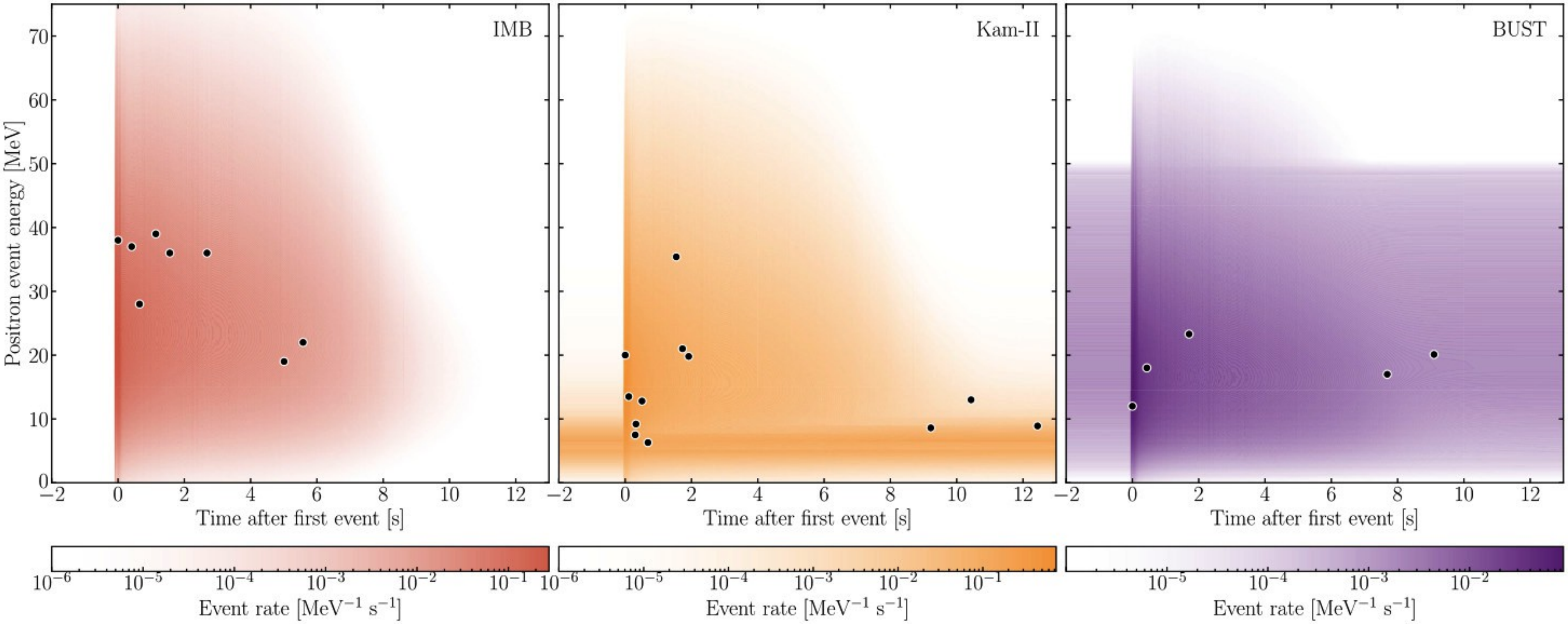
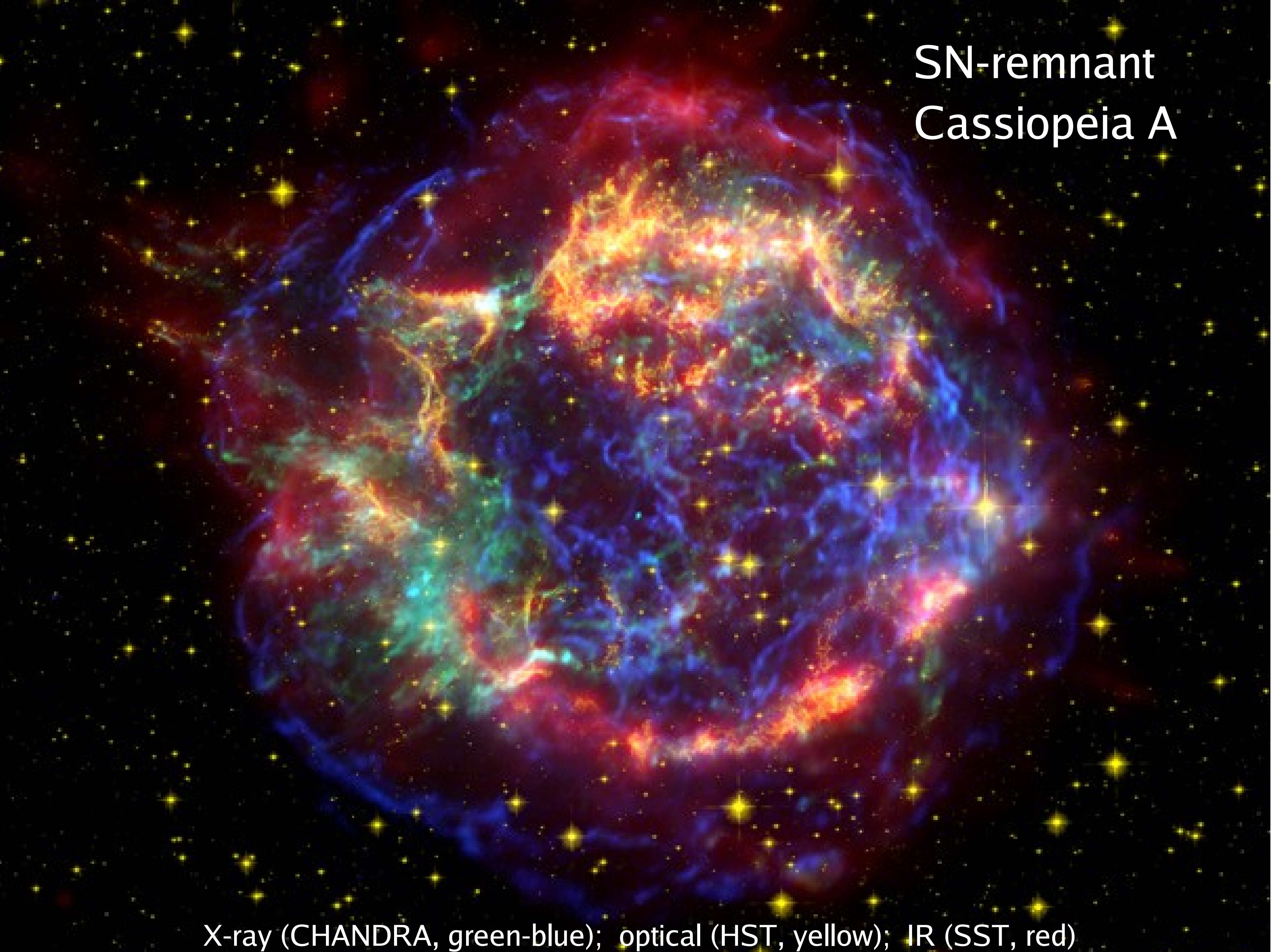


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

**(M. Heinlein, Master Thesis, TUM 2022;
Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)**

SNR Cassiopeia A
as a
Laboratory for SN Physics

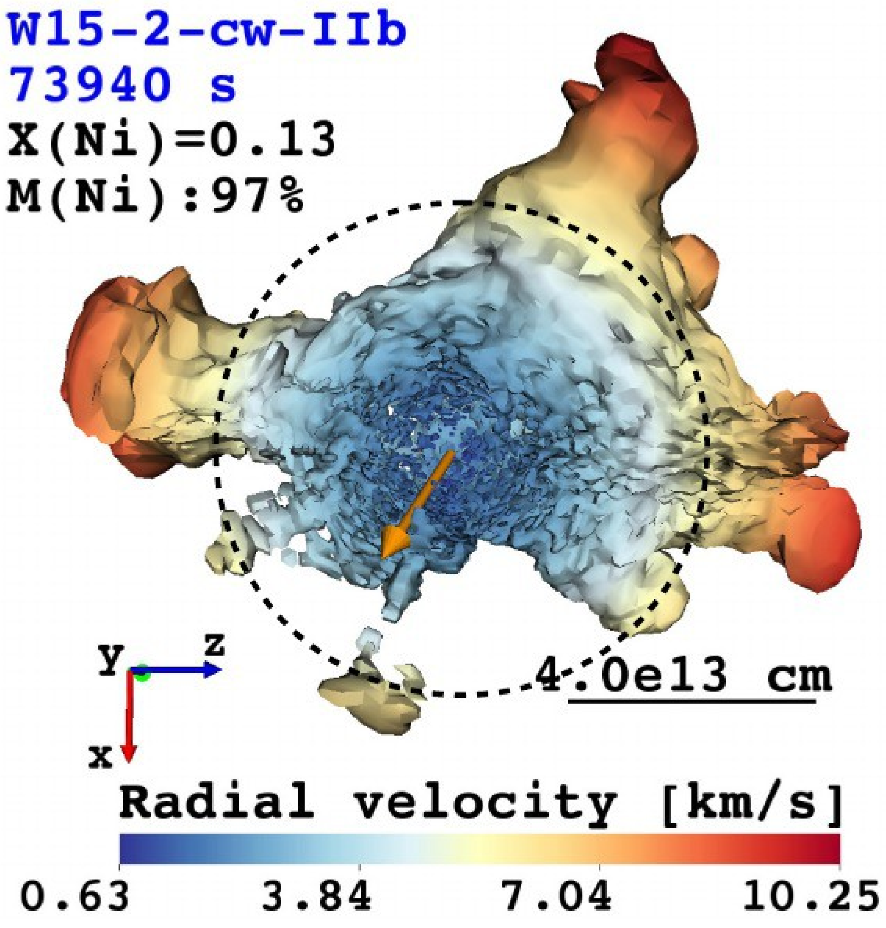
SN-remnant Cassiopeia A



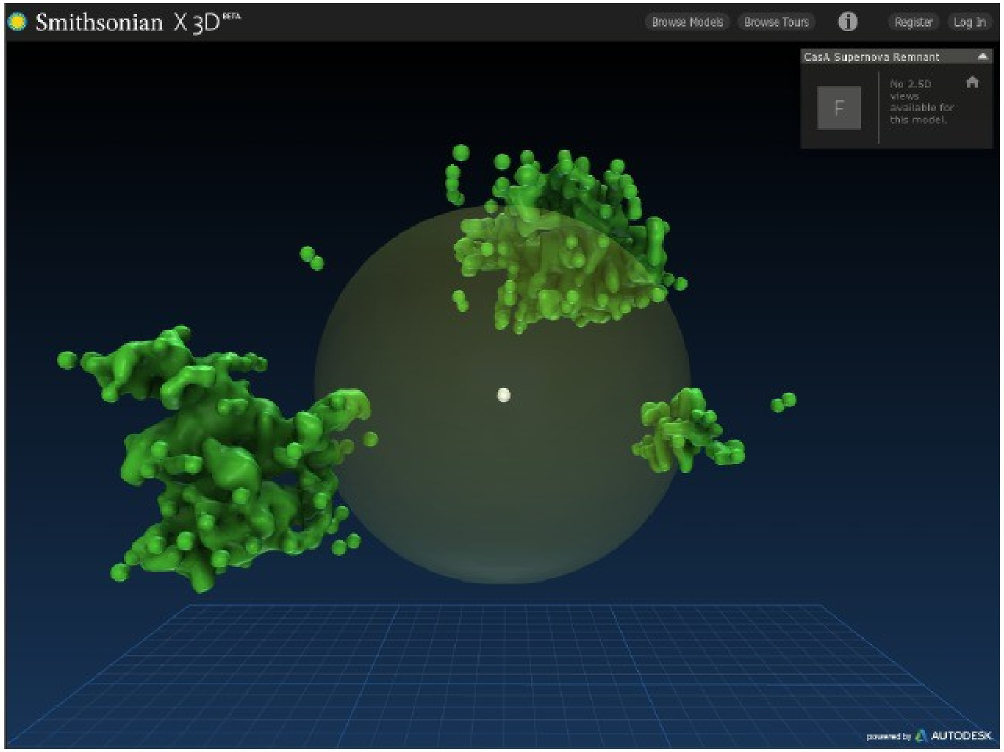
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

Chemical Asymmetries in CAS A Remnant

Iron in Cas A is visible in three big "fingers" in the remnant shell that is heated by reverse shock from circumstellar medium interaction.



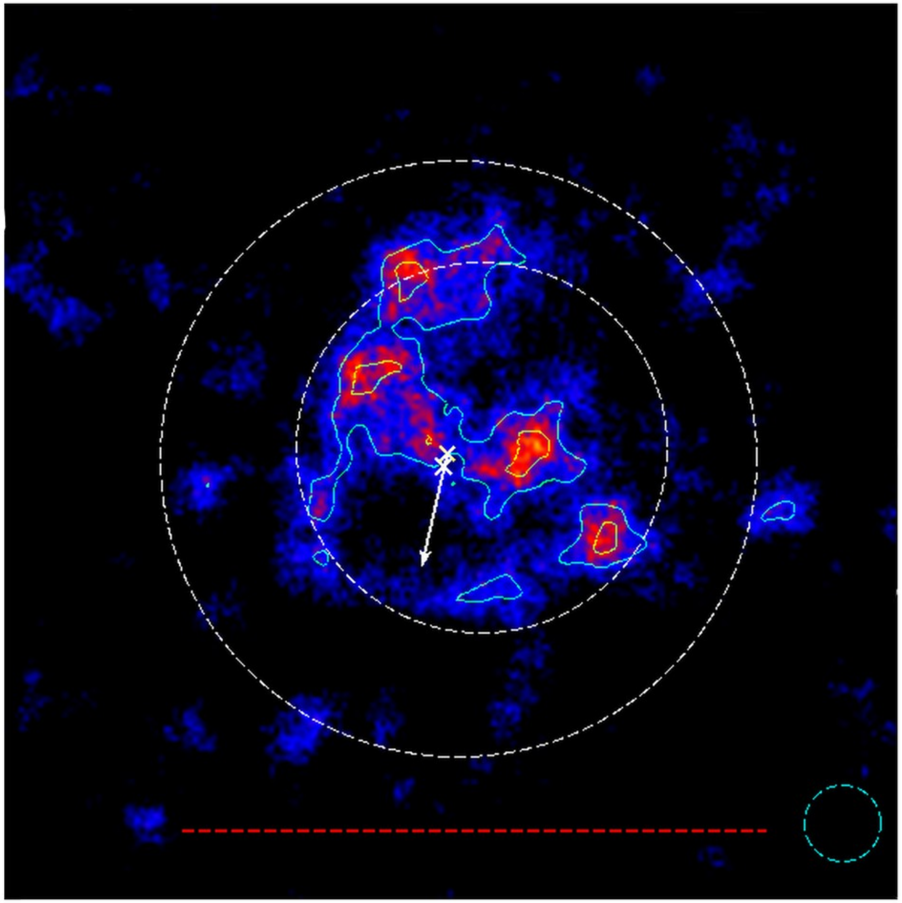
Hot, shocked iron (observed)



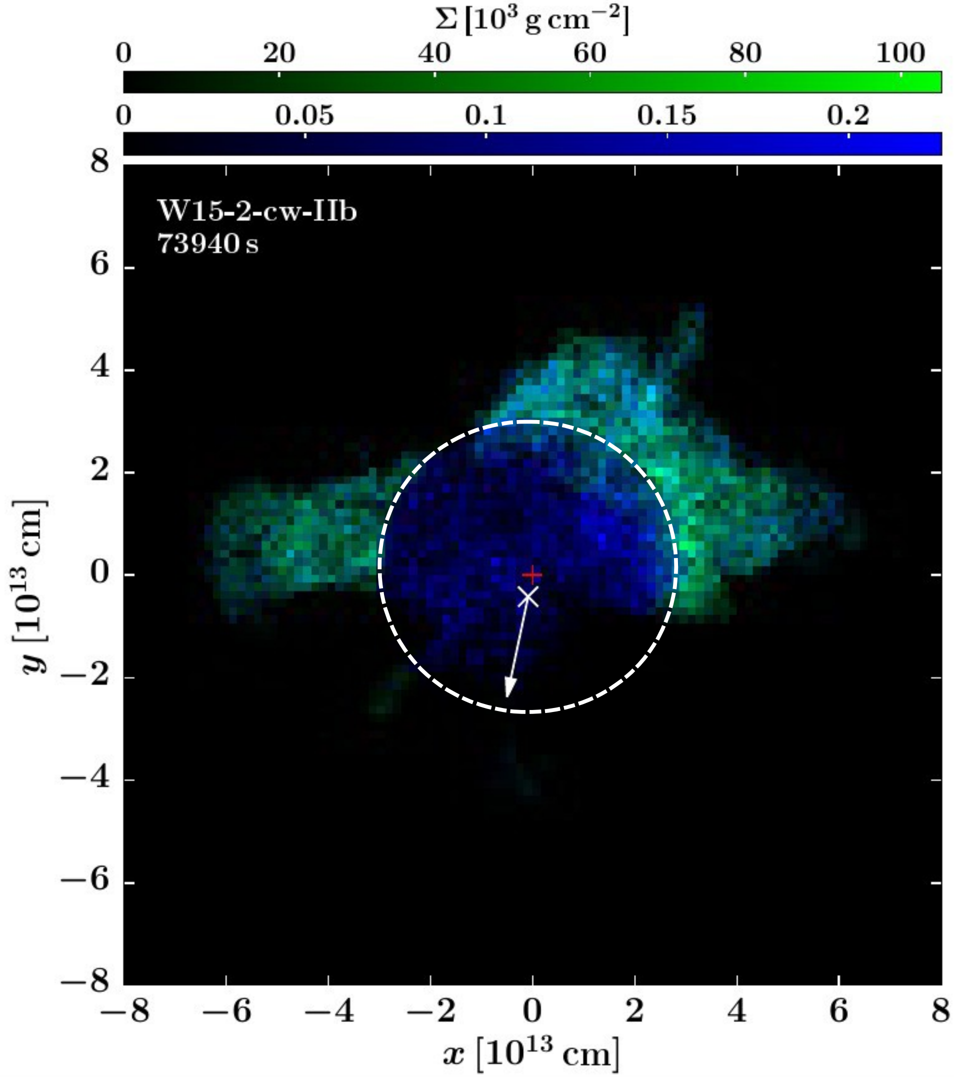
No 2.5D views available for this model.

Wongwathanarat et al., ApJ 842 (2017) 13

Neutron Star Recoil and Nickel/Iron & ^{44}Ti Distributions



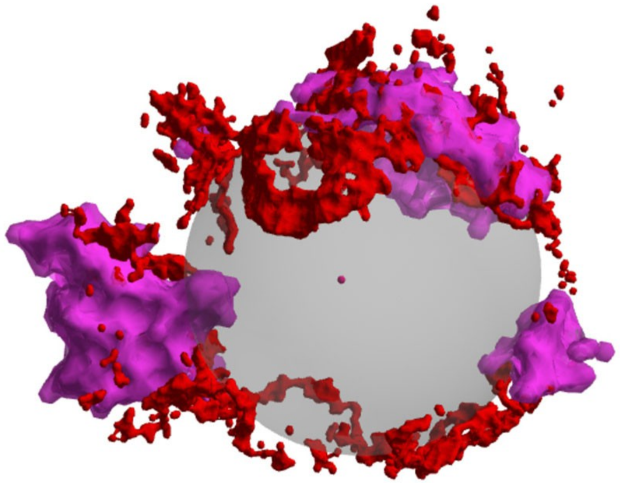
Grefenstette et al., Nature 506 (2014) 340



Wongwathanarat et al., ApJ 842 (2017) 13

Elemental Asymmetries in SNR Cas A

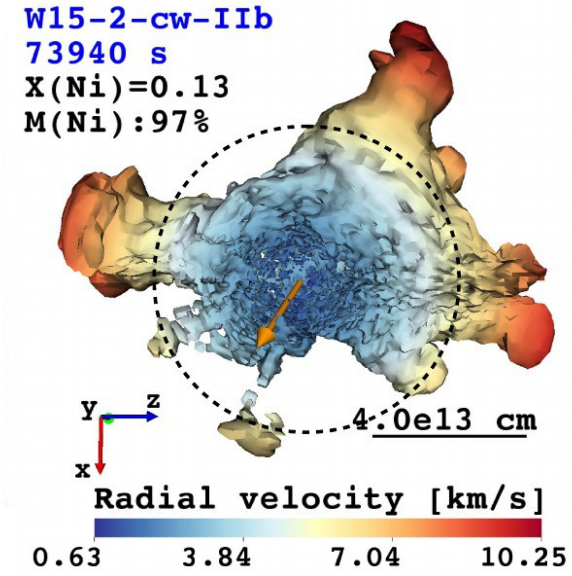
Cas A as remnant of a stripped-envelope SN is unique lab for SN physics



Red: Ar, Ne, and O (optical)

Purple: Iron (X-ray)

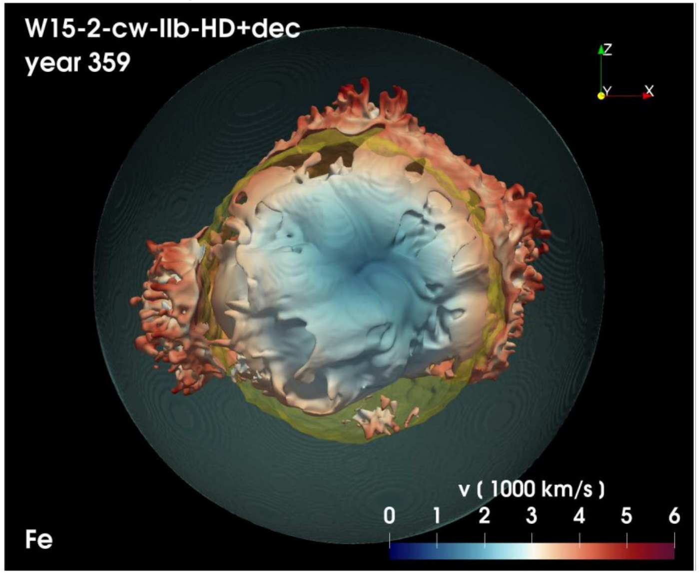
Credit: Robert Fesen and Dan Milisavljevic, using iron data from DeLaney et al. (2010)



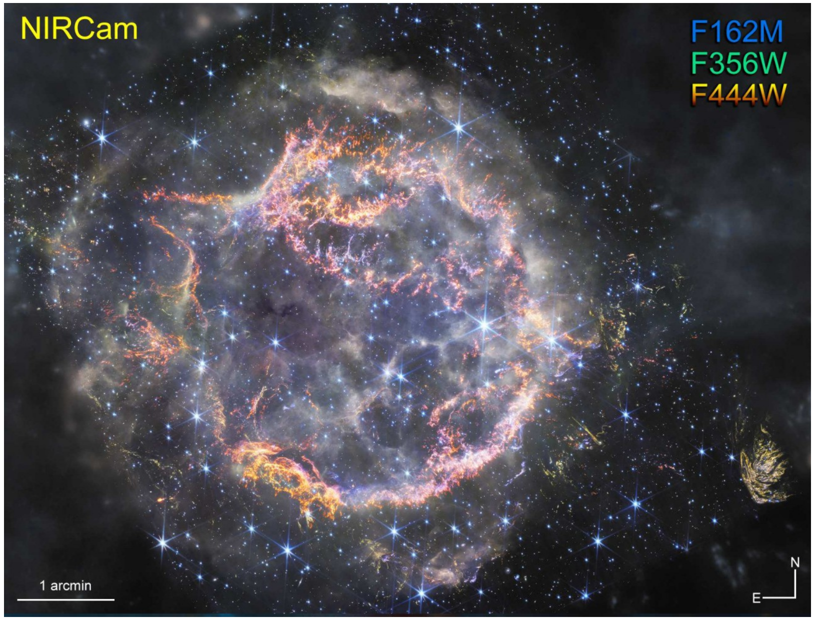
Wongwathanarat et al., ApJ 842 (2017) 13

CAS A simulation at ~360 years

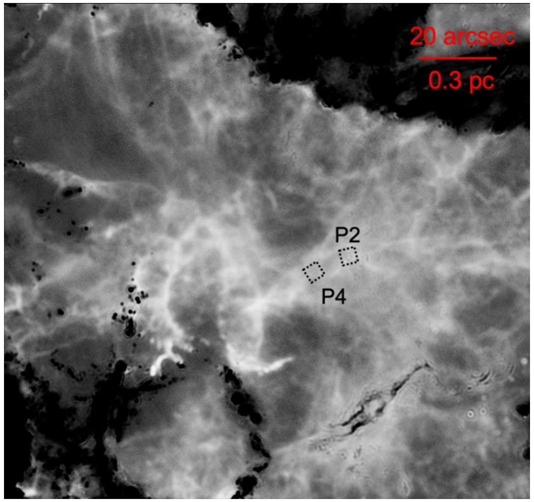
Orlando, Wongwathanarat, HTJ+, A&A 645 (2021) 645



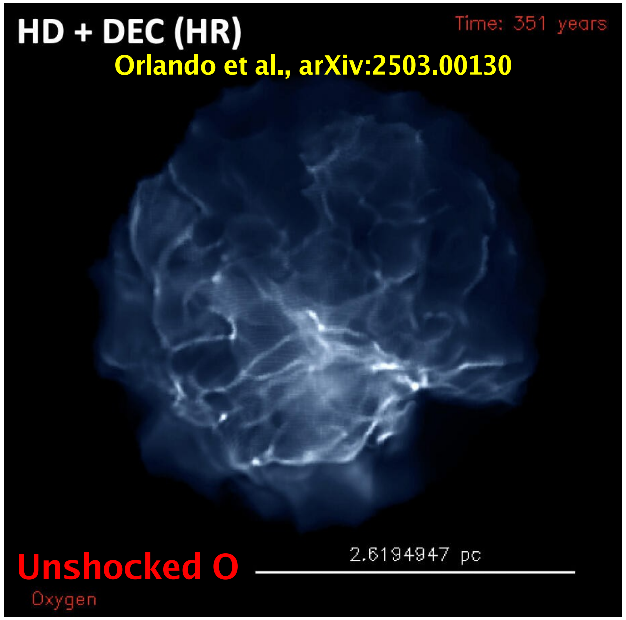
Fe-isosurface @ 5% Fe peak density; radial velocity color coded



D. Milisavljevic et al., JWST Survey of Cas A; ApJL 2024



Unshocked O inside main shell

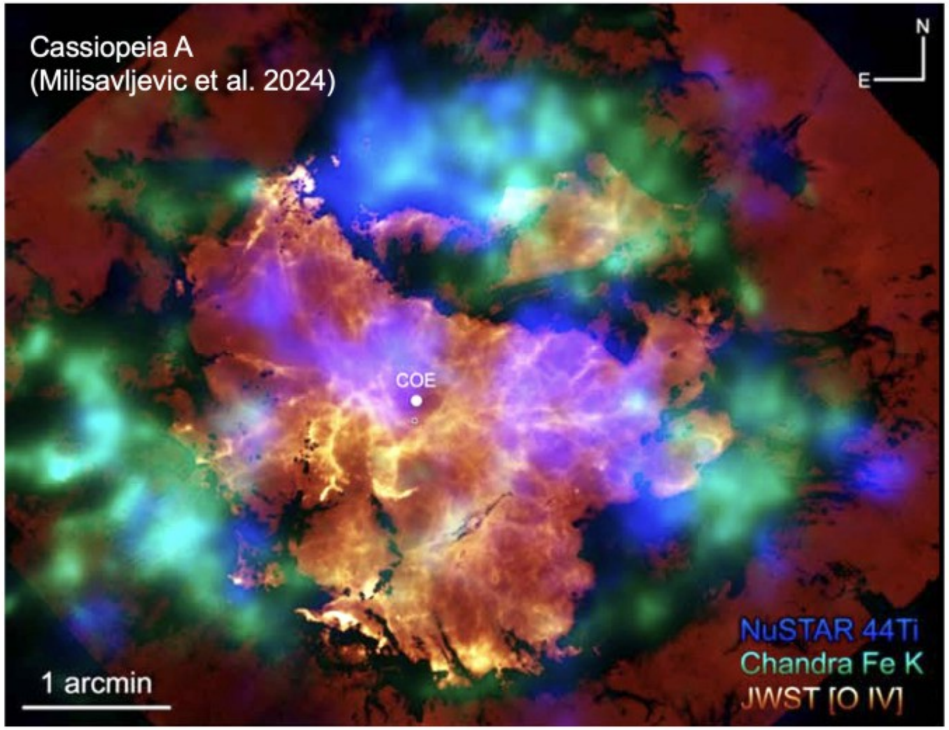


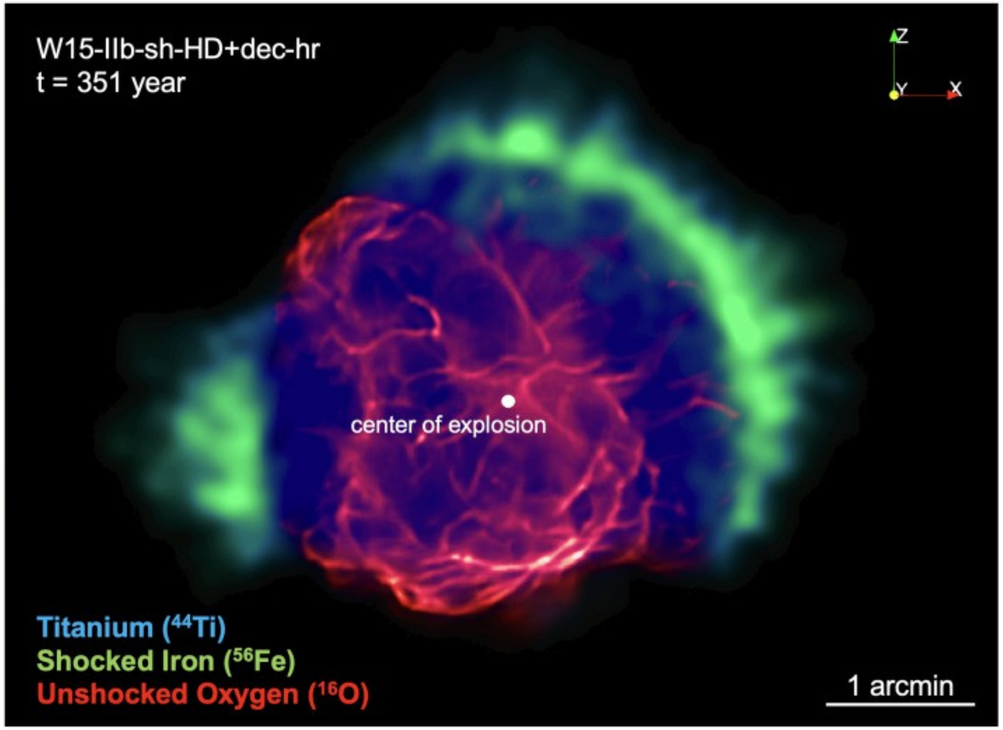
Orlando et al., arXiv:2503.00130

Unshocked O

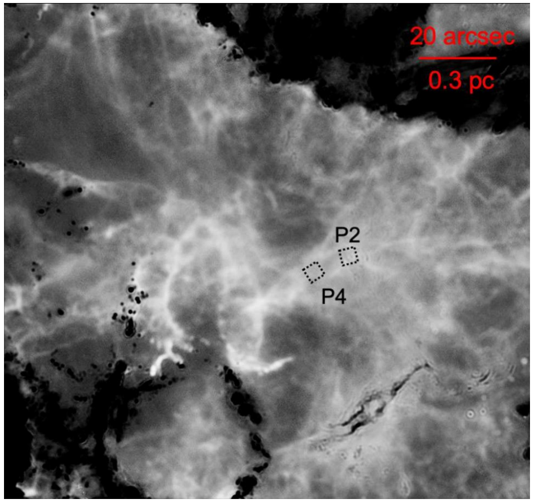
Elemental Asymmetries (Fe, Ti, O) in SNR Cas A

Orlando et al., A&A, in press, arXiv:2503.00130

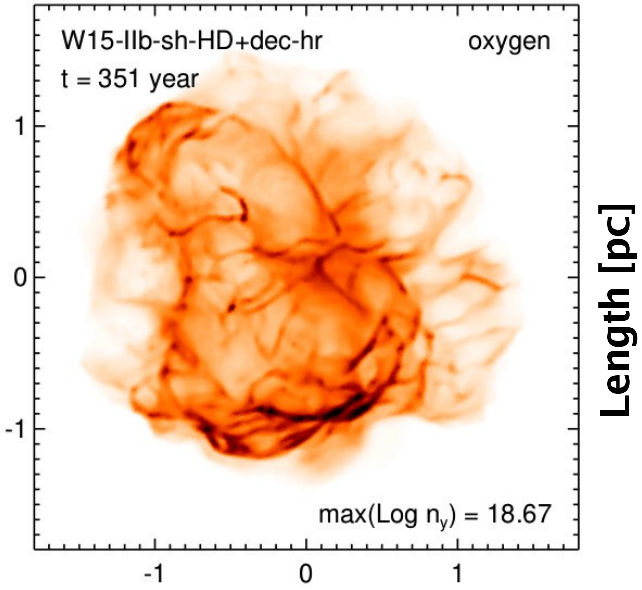




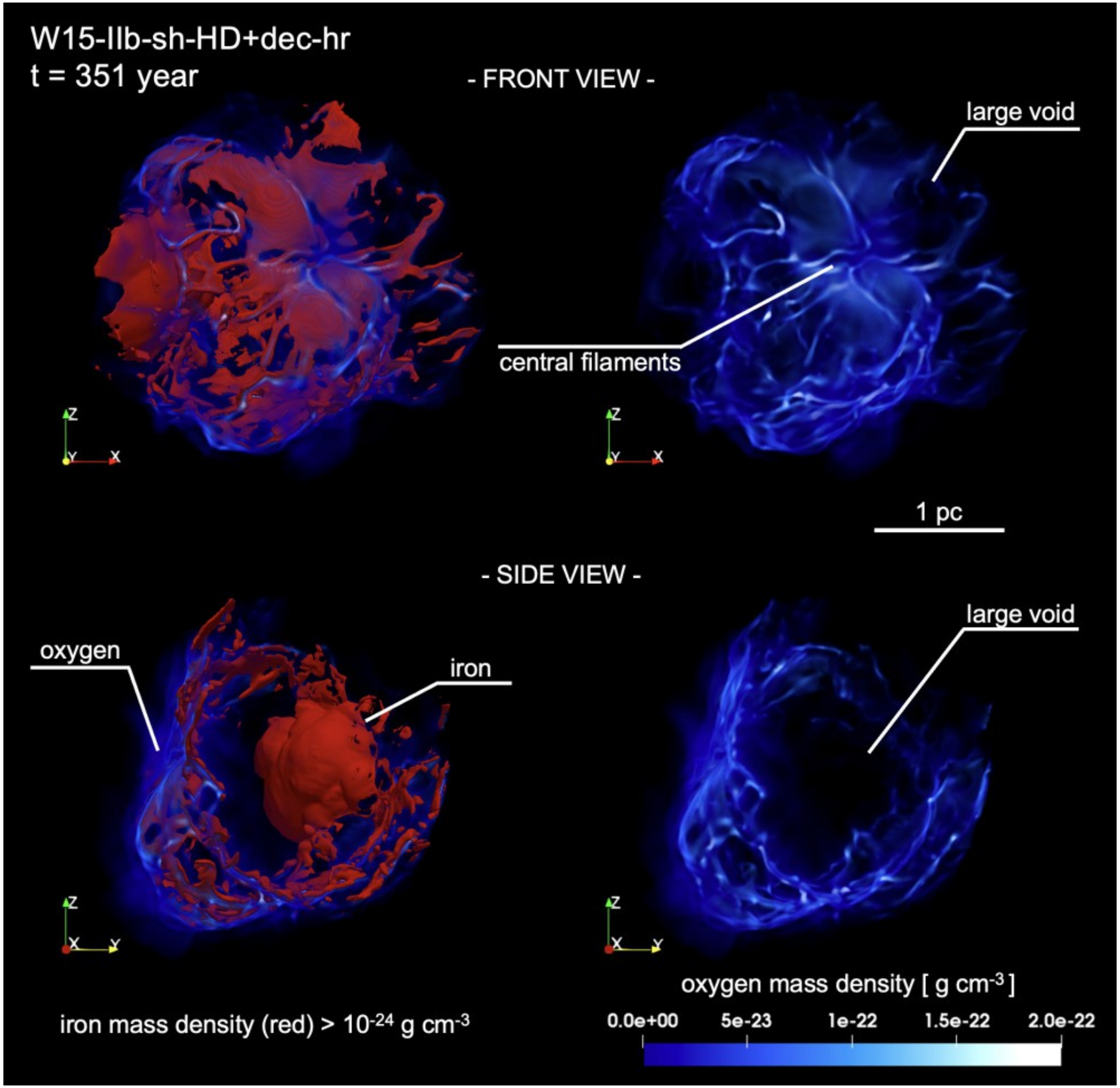
D. Milisavljevic et al., JWST Survey of Cas A; ApJL 2024



Unshocked O inside main shell



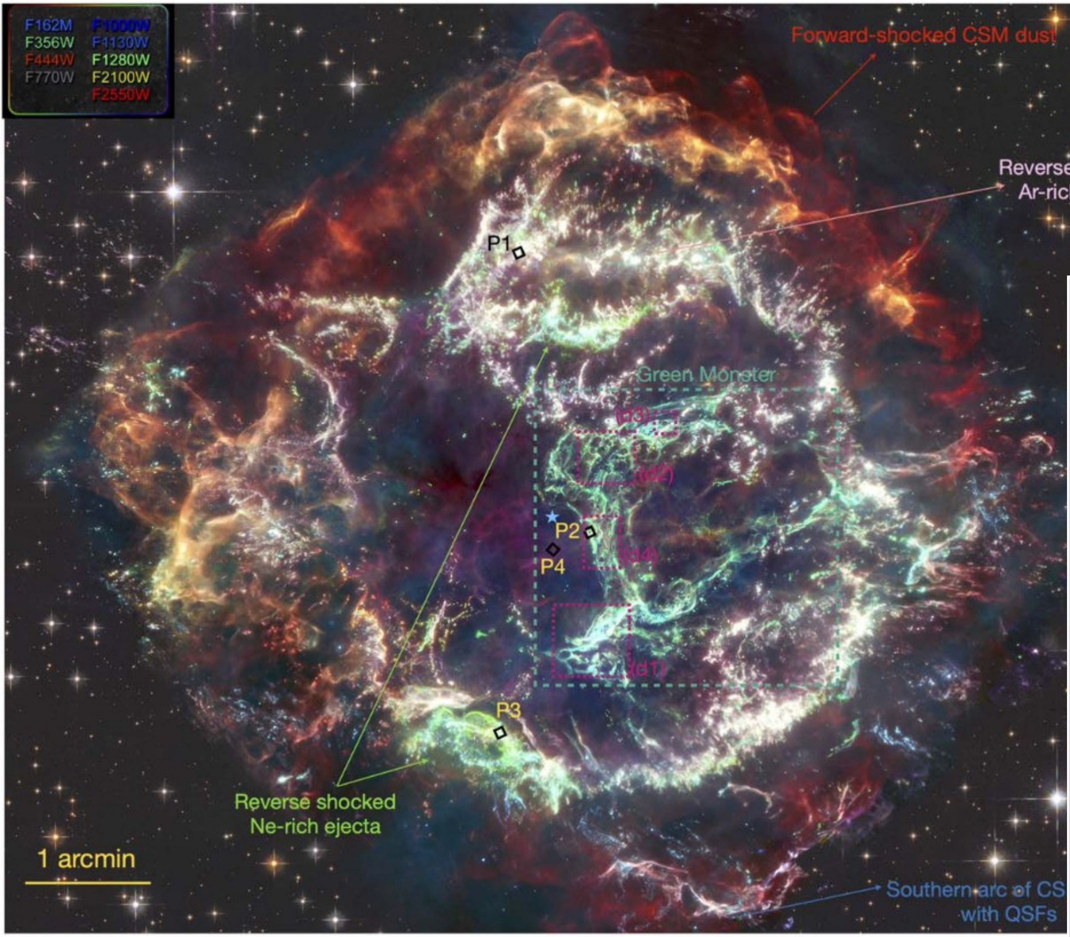
Iron Bubbles and Oxygen Web in the Unshocked Interior of SNR Cas A

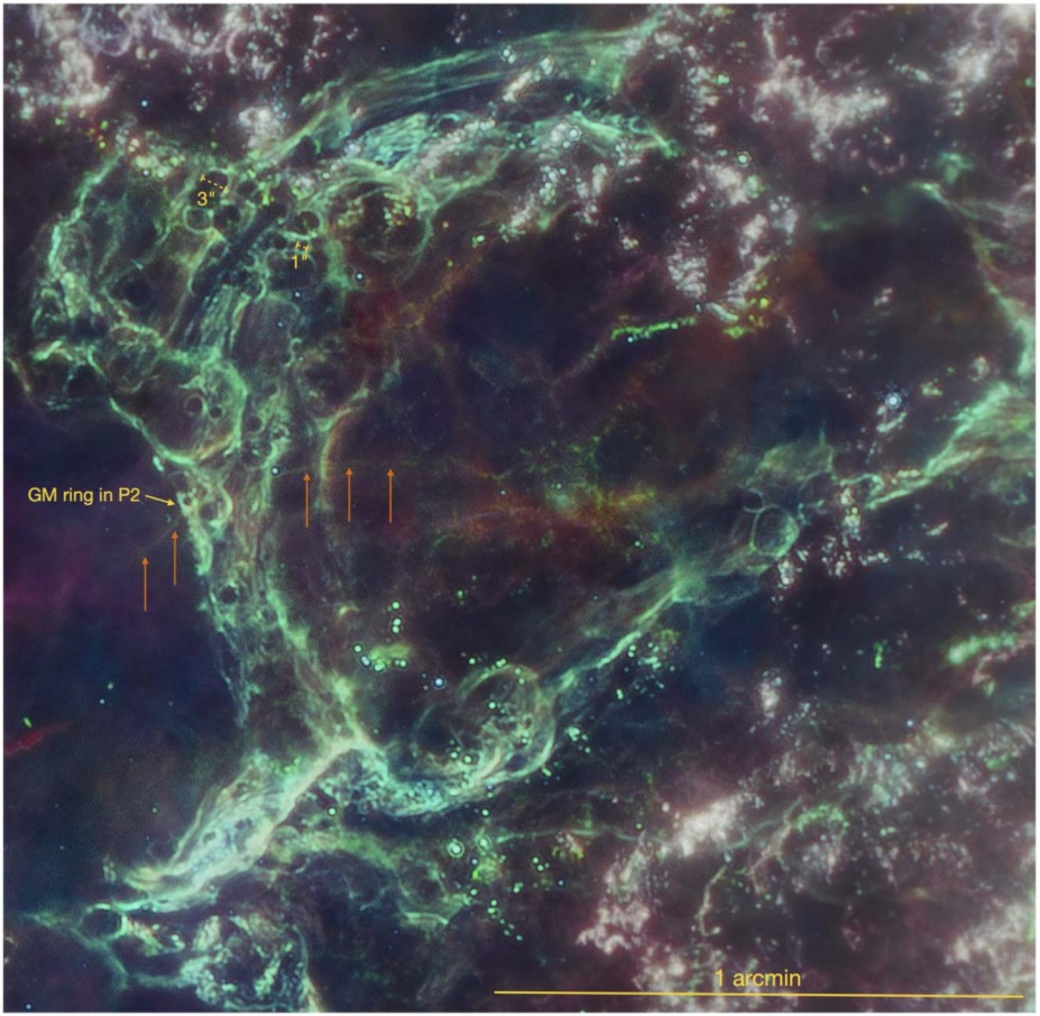


Orlando et al., A&A, in press, arXiv:2503.00130

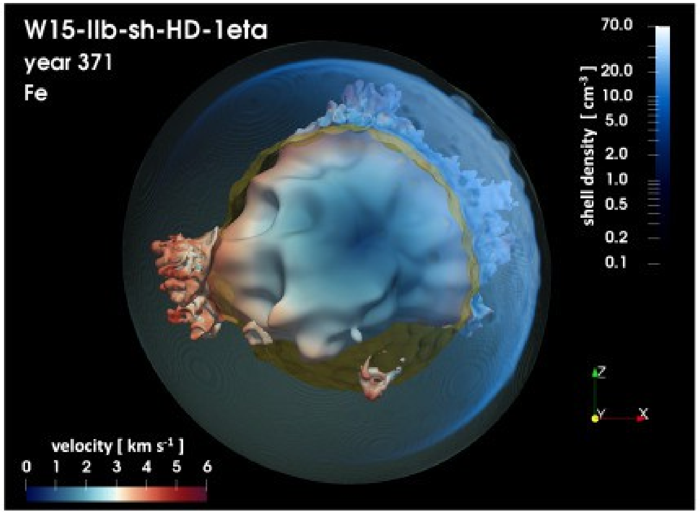
Cas A with JWST: "Green Monster" CSM Structure

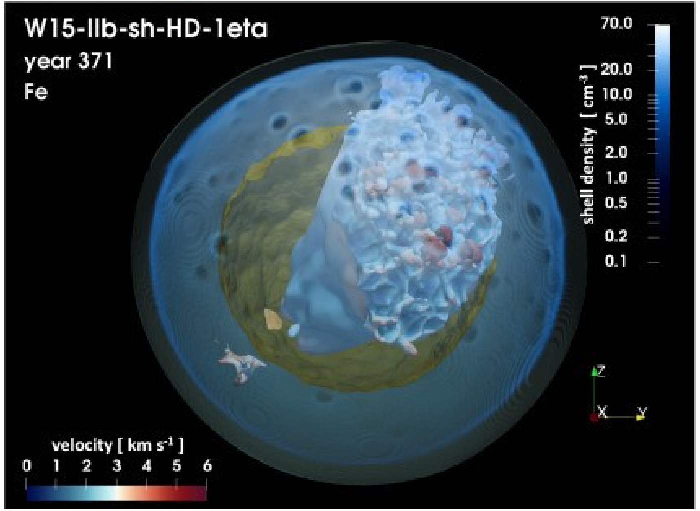
Ejecta interaction with a partial dense and thin CSM shell: holes with rings

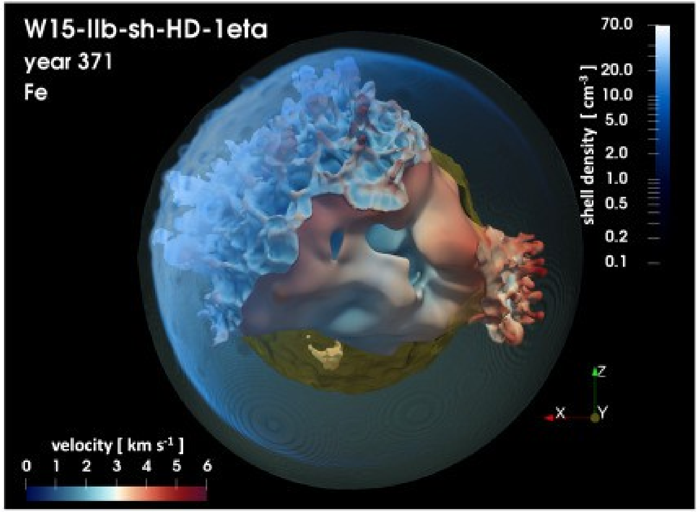




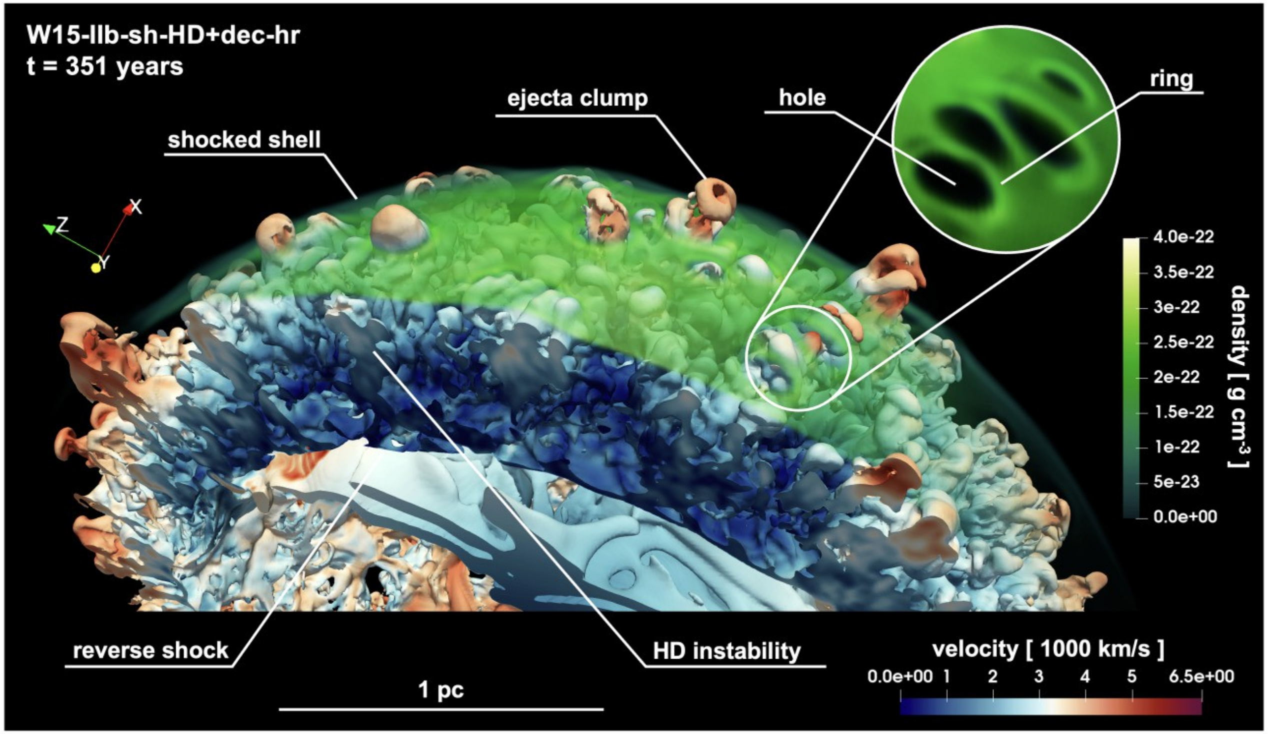
De Looze et al., ApJL 976 (2024) L4;
Milisavljevic et al., JWST Survey of Cas A, ApJL 965 (2024) L27



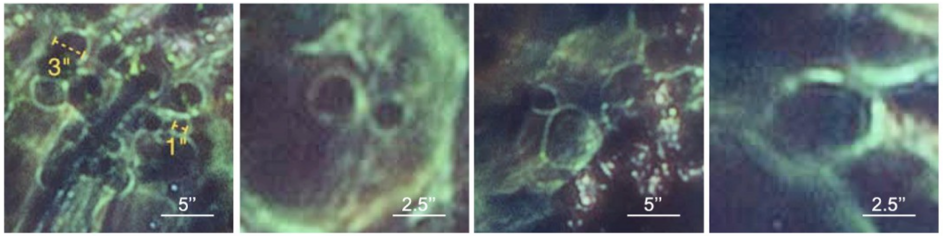




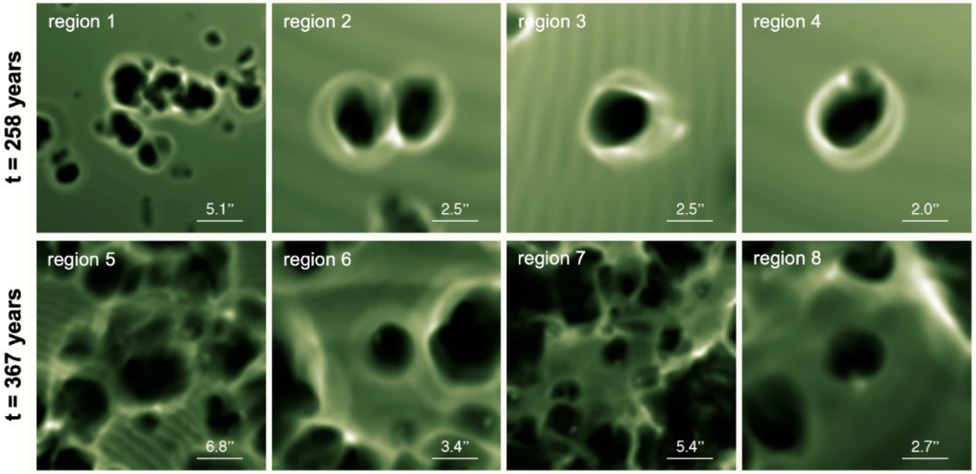
Orlando et al., A&A 666 (2022) A2



”Green Monster” in Cassiopeia A (JWST; De Looze et al. 2024)



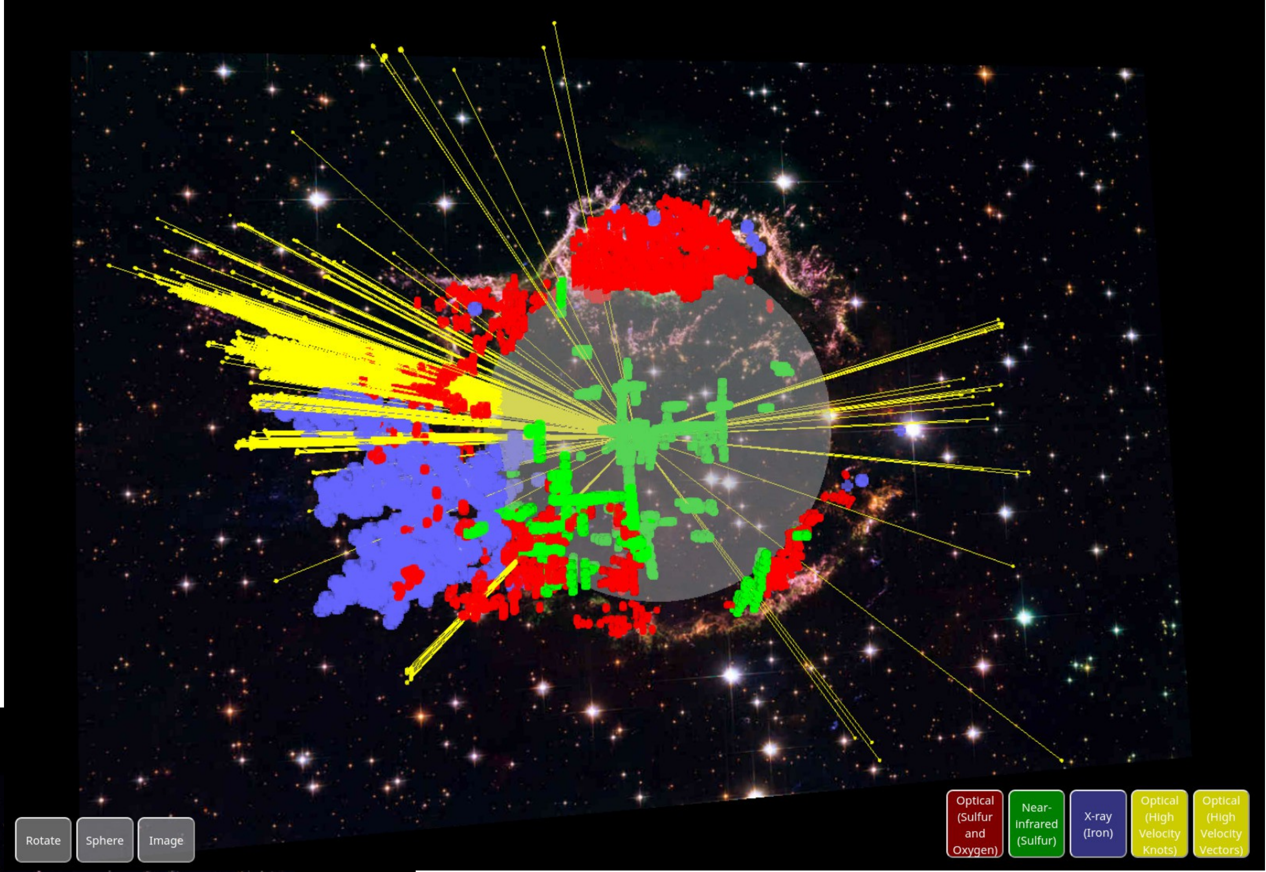
model W15-IIb-sh-MHD+dec-rl-hr

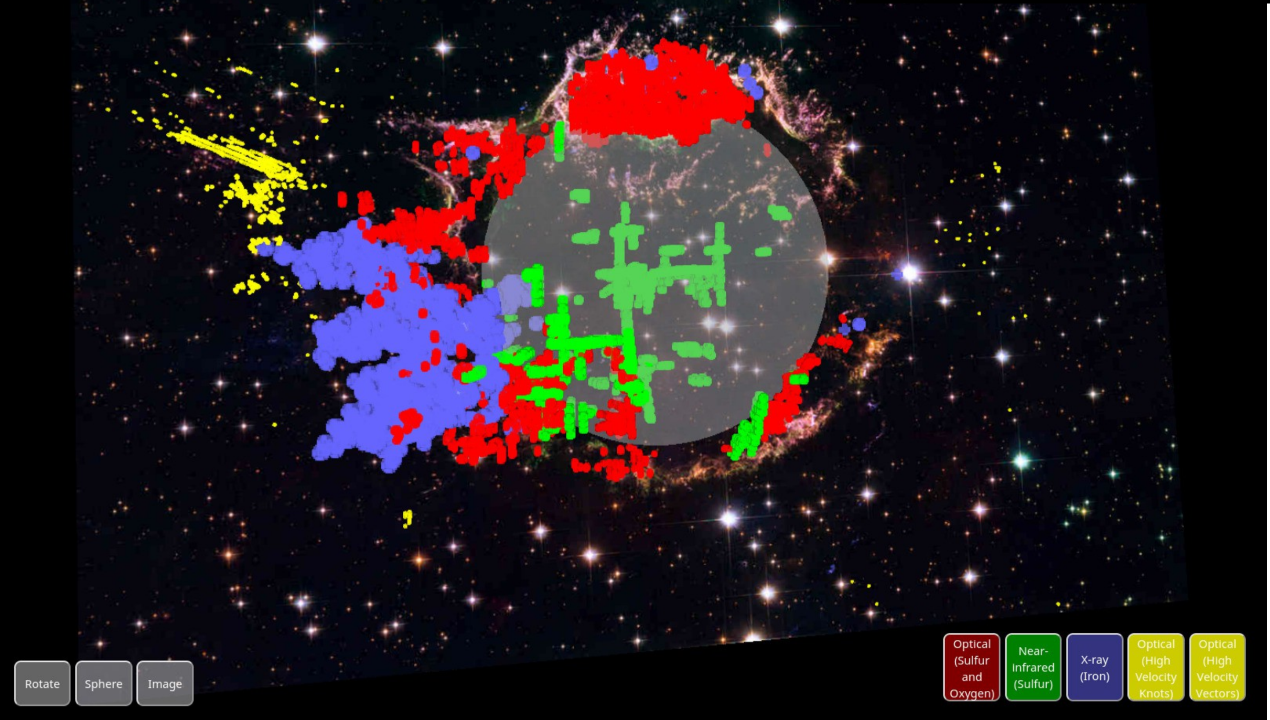


**Orlando et al.,
A&A, in press, arXiv:2503.14455**

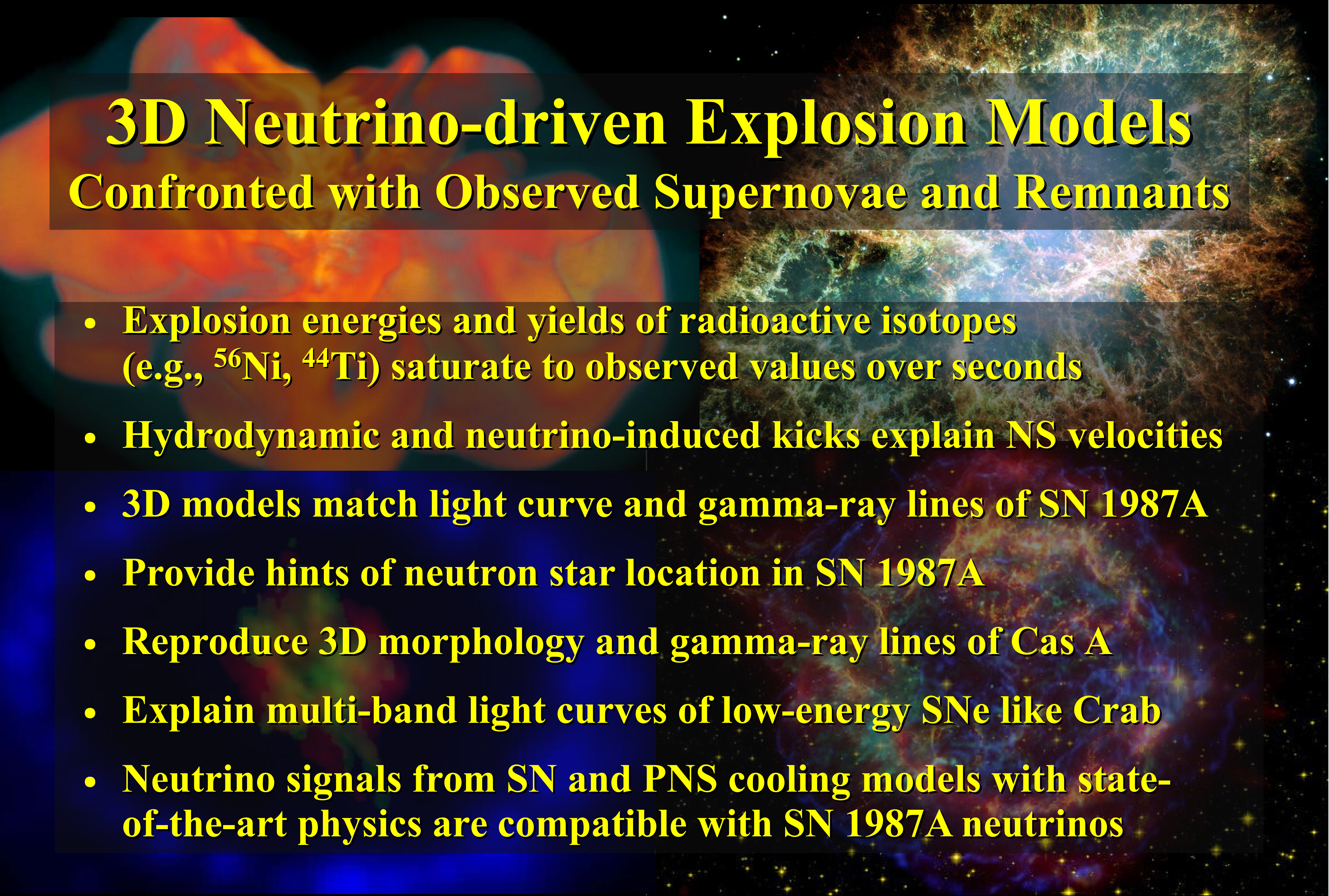
Cas A "Jets" ?

Sulfur, silicon rich knots, moving with speeds up to ~15,000 km/s





Danny Milisavljevic, Purdue Univ.
https://www.physics.purdue.edu/kabooom/casa-webapp/model.html



3D Neutrino-driven Explosion Models

Confronted with Observed Supernovae and Remnants

- Explosion energies and yields of radioactive isotopes (e.g., ^{56}Ni, ^{44}Ti) saturate to observed values over seconds
- Hydrodynamic and neutrino-induced kicks explain NS velocities
- 3D models match light curve and gamma-ray lines of SN 1987A
- Provide hints of neutron star location in SN 1987A
- Reproduce 3D morphology and gamma-ray lines of Cas A
- Explain multi-band light curves of low-energy SNe like Crab
- Neutrino signals from SN and PNS cooling models with state-of-the-art physics are compatible with SN 1987A neutrinos