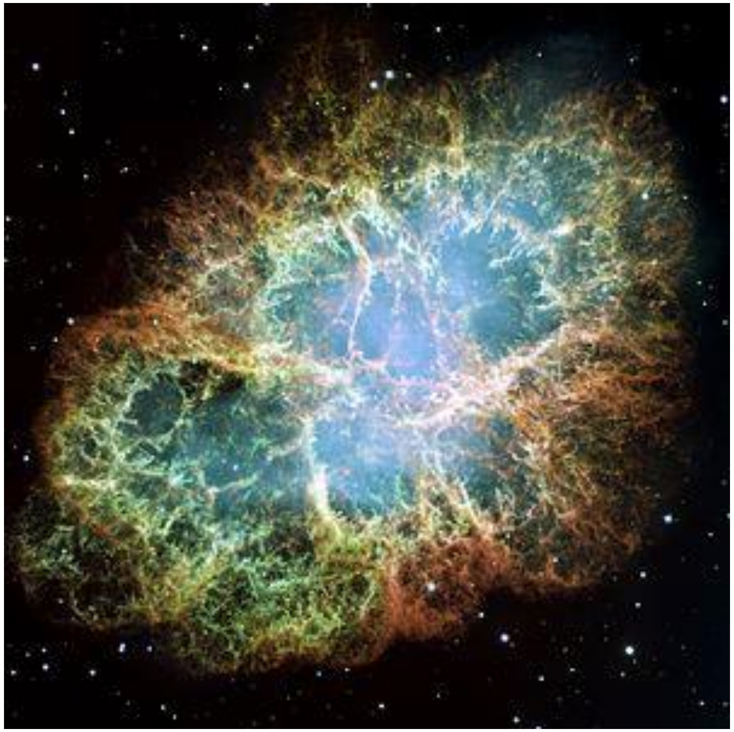
Explosion Energies, Ages and Densities of Galactic Supernovae.



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- Beginning: 5 Gyr ago, start H burning (Main Sequence) 30% fainter
- Now: 5 Gyr, middle aged: H-burning in the core
- +4 Gyr: change to Red giant (H shell burning and He burning)
- The END (+3 Gyr): Rapid mass loss, transition to a hot white dwarf inside a planetary nebula

The Supernova, collapse vs thermonuclear

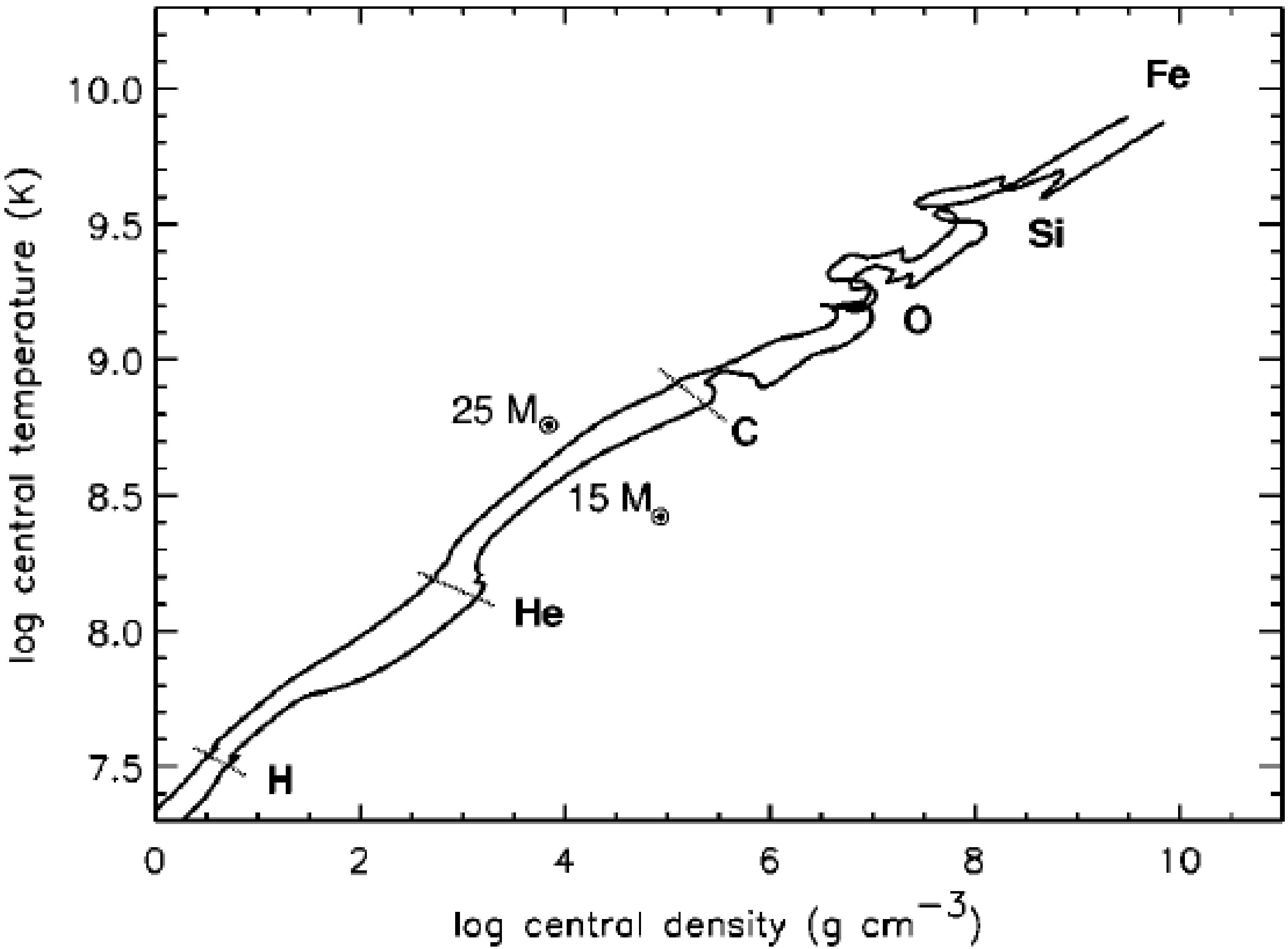
- SN from massive stars: gravitational collapse of the stellar core.
- These give Type II, Ib, Ic SN

- Type Ia SN are driven by the unstable (explosive) thermonuclear burning of a white dwarf

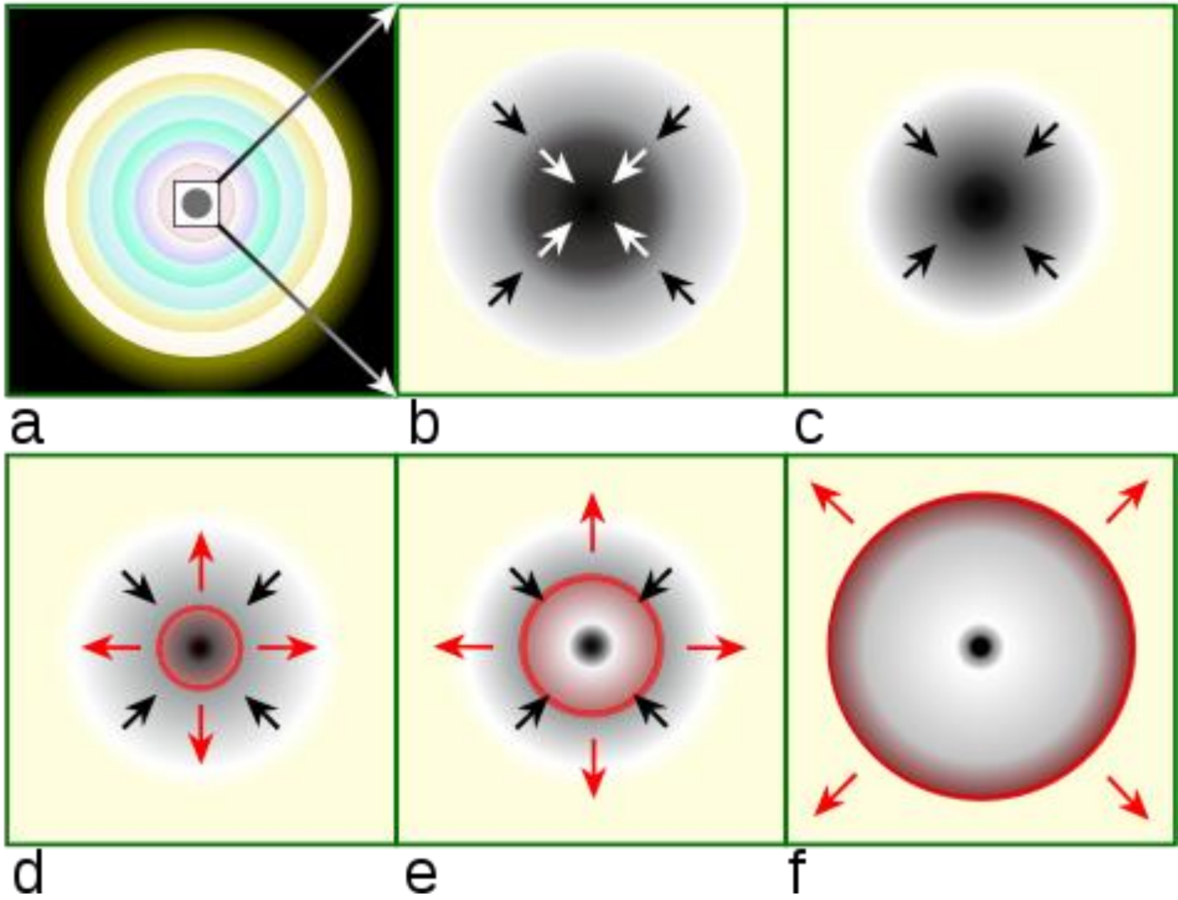
Massive stars

- A high mass star (15*Msun, 20,000*Lsun, 5*Rsun)
- Evolution lasts 11 million years instead of 12 Gyr (for Sun)
- Main sequence phase 10 Myr, giant phase 1 Myr
- At 11 Myr, the supernova explosion
- The supernova remnant lasts ~ 100,000 yr.
- The neutron star fades after ~ 1 million yr.

Change of central density and central temperature with time (Woosley et al 2002)



Core Collapse type



- time sequence:

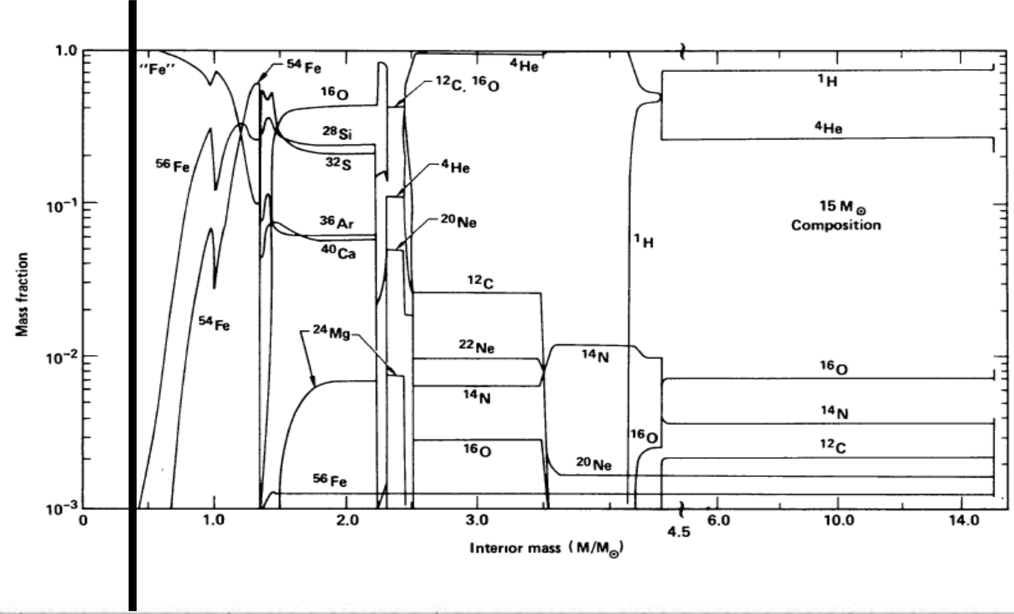
- (a) nuclear burning ends
- in the core
- (b) the core is unstable
- and collapses.
- (c) The inner part is compressed into neutrons.
- (d) core hits nuclear density and bounces, creating an outward-propagating shock.
- (e) the shock halts outward motion because of infalling matter,
- but it is re-invigorated by neutrino energy from the core.
- (f) The revived shock blasts away the stellar envelope.

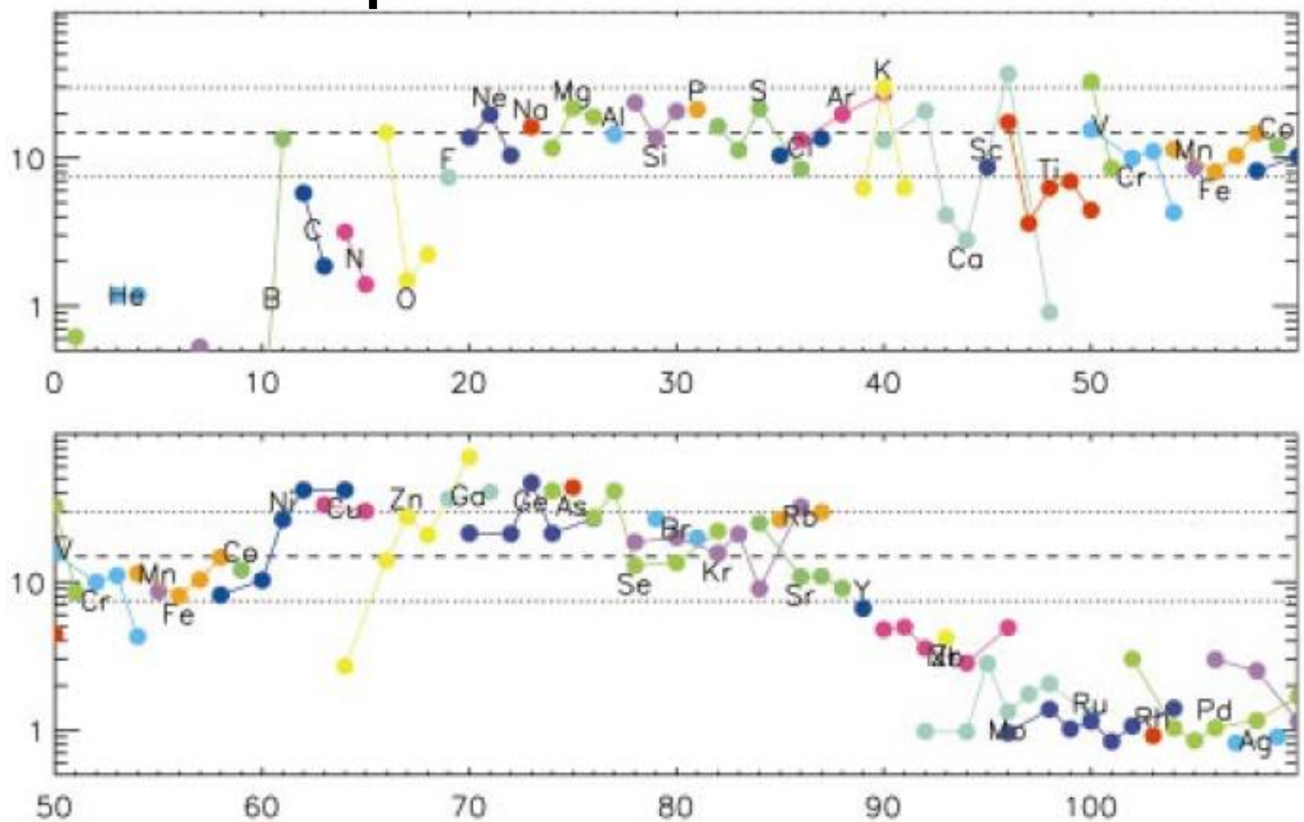
Mass in the star below the "mass cut" is trapped in the compact object

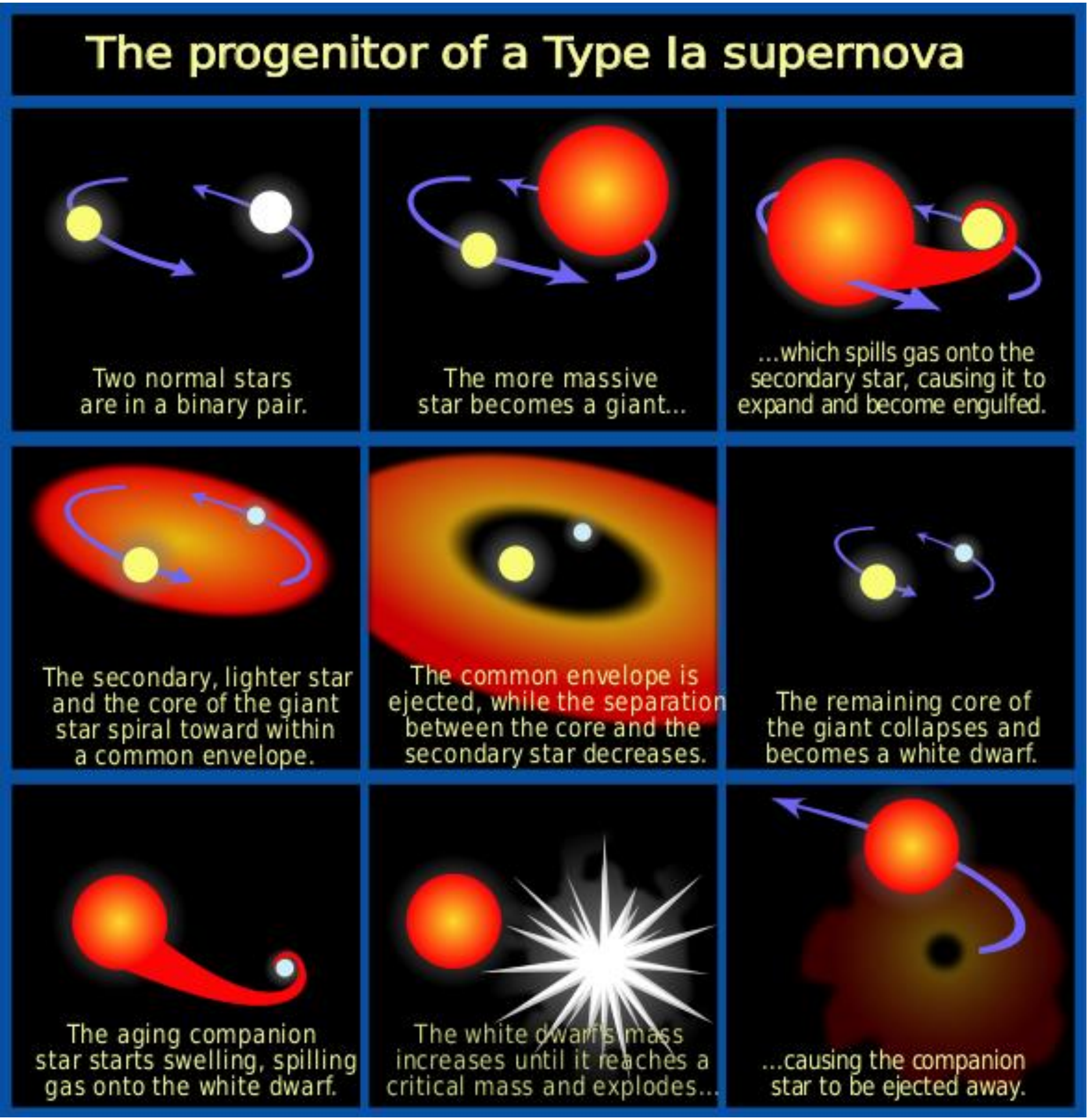
The shock converts elements above the mass cut into a range of products.

Caused by a wide range of burning density/temperature and short timescales.

In the outer parts of the star, the shock is too cool to cause nuclear burning





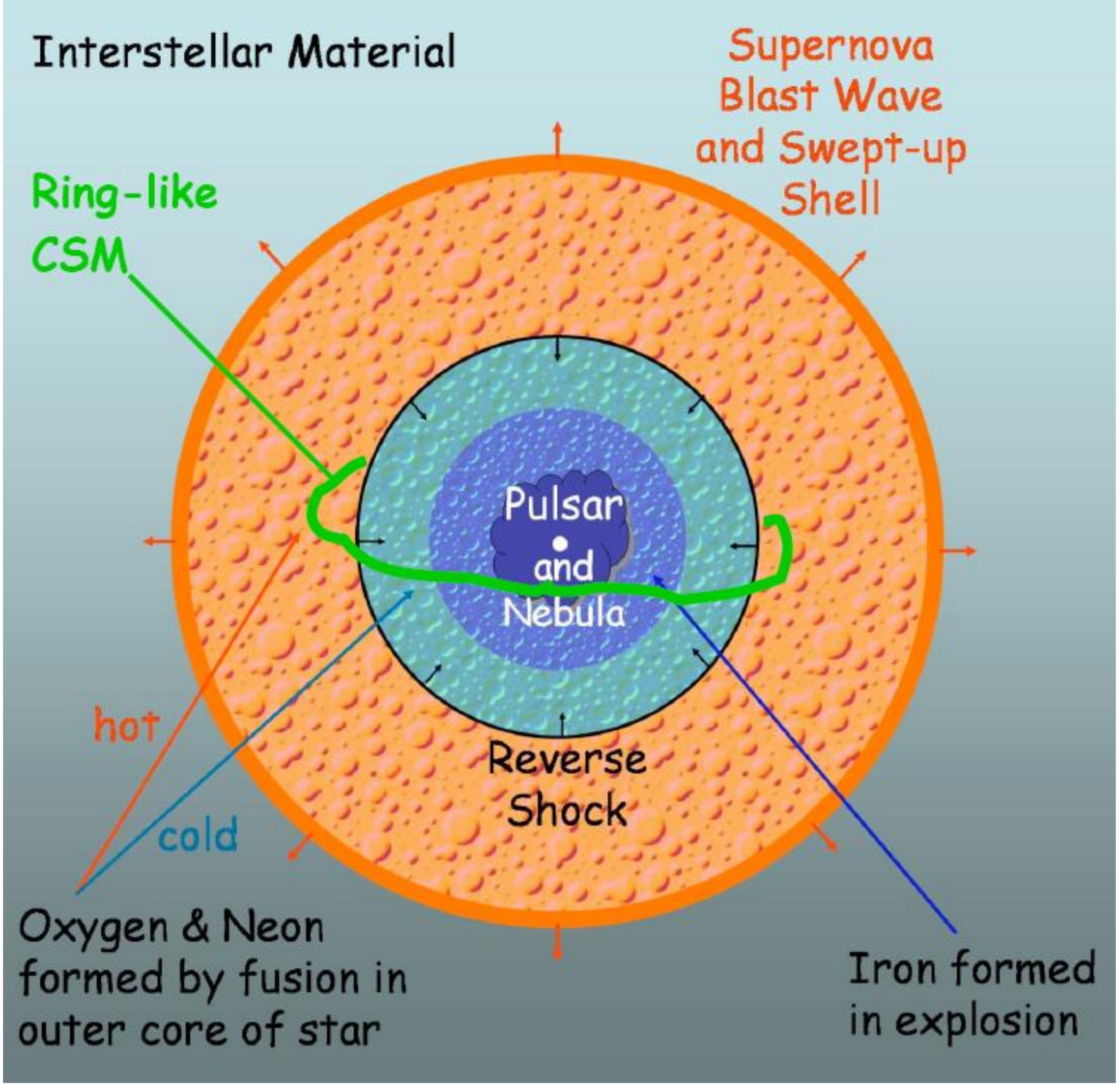


Another favored model for the formation of a Type Ia explosion involves the merger of two white dwarf stars

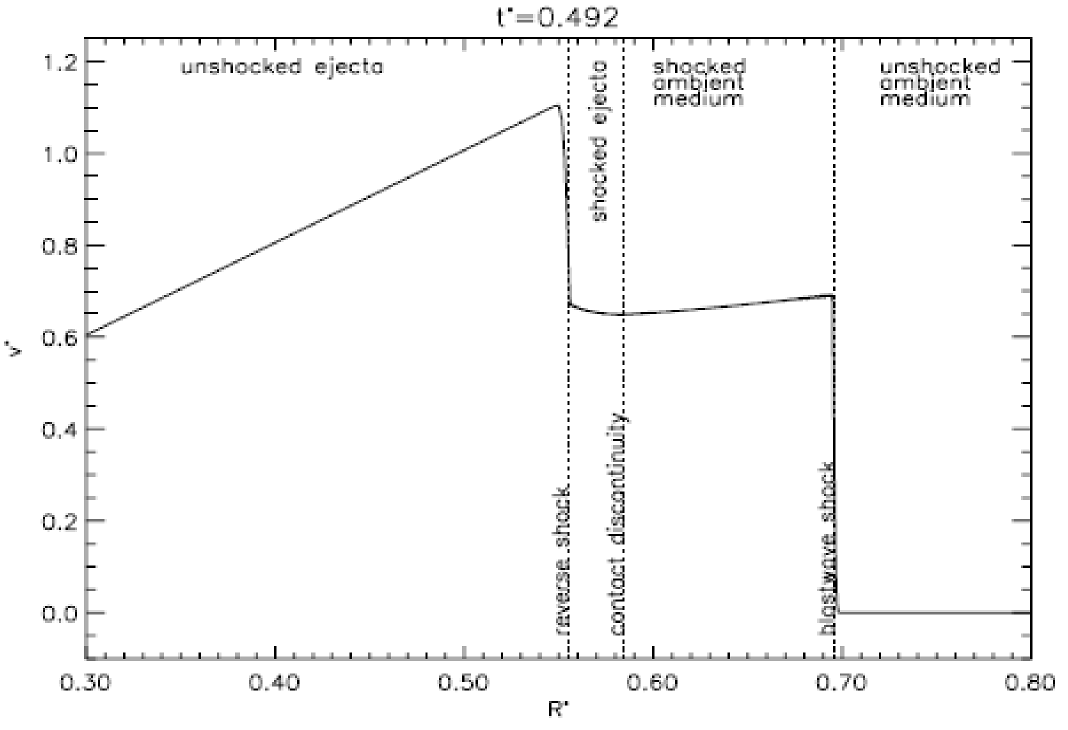
Implications of SNRs

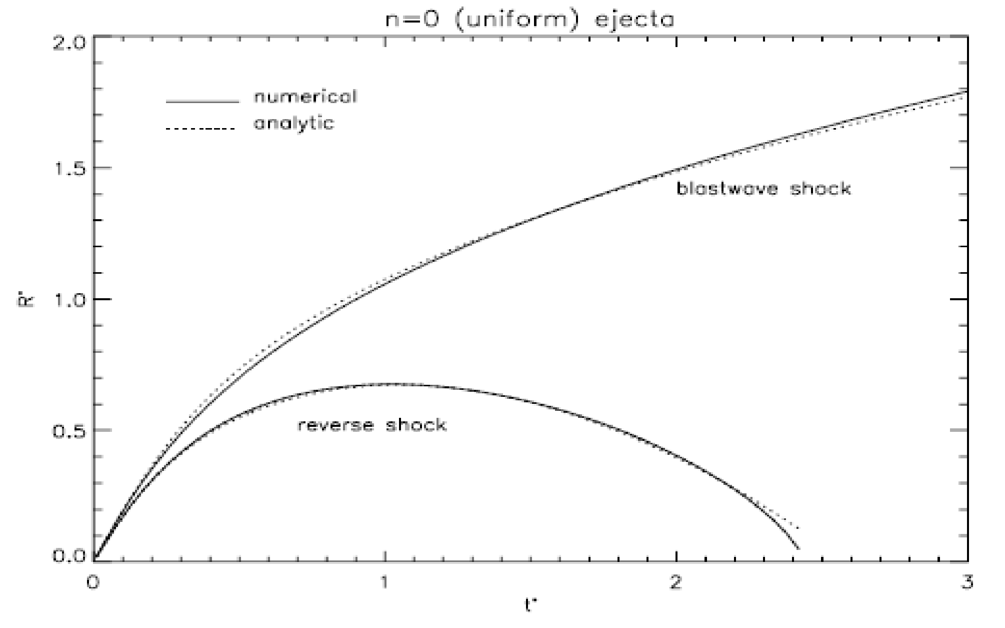
- A SNR heats and accelerates interstellar gas: Converging flows drives the next generation of star/planet formation.
- The shock wave accelerates particles to high energies, producing cosmic rays.
- Nucleosynthesis is detected by x-rays from the hot gas, and tells us about the explosion mechanism.
- SNRs are a laboratory for the study of the shock physics, chemical composition, thermal states, density structure, and particle acceleration.

Prototype of a SNR from a massive star

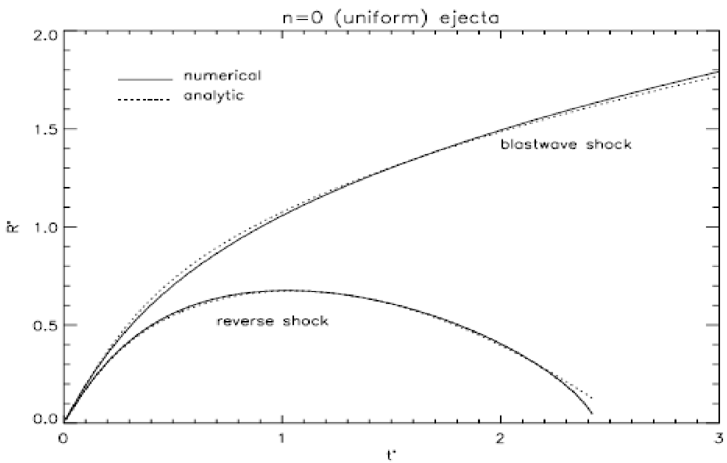


The structure of a spherical SNR using a hydro code (Truelove and McKee 1999) prior to reverse shock hitting the center.





Work done by DL at UC since 2015: extend TM99 calculations. Include electron-ion equilibration by Coulomb collisions. Calculate emission measures of FS gas and of RS gas. Calculate kT of FS gas and of RS gas .



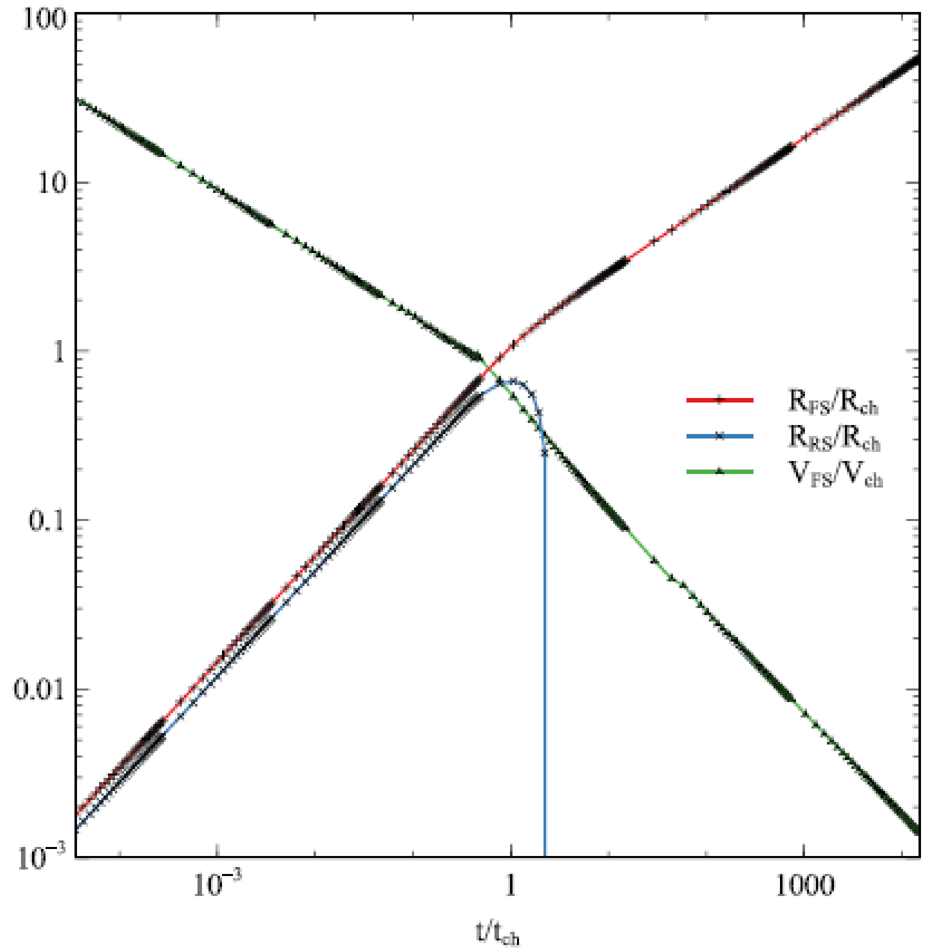
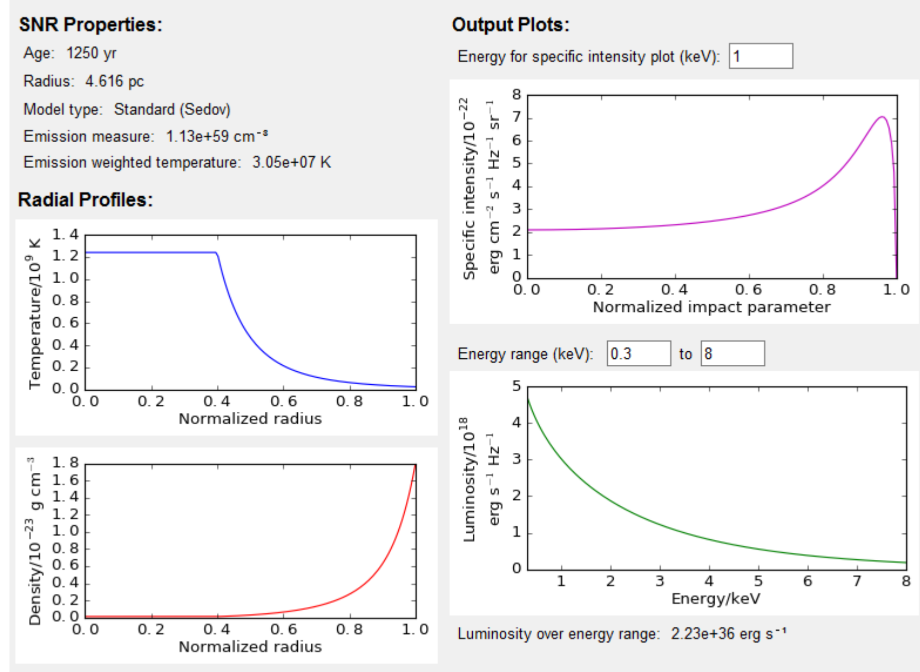


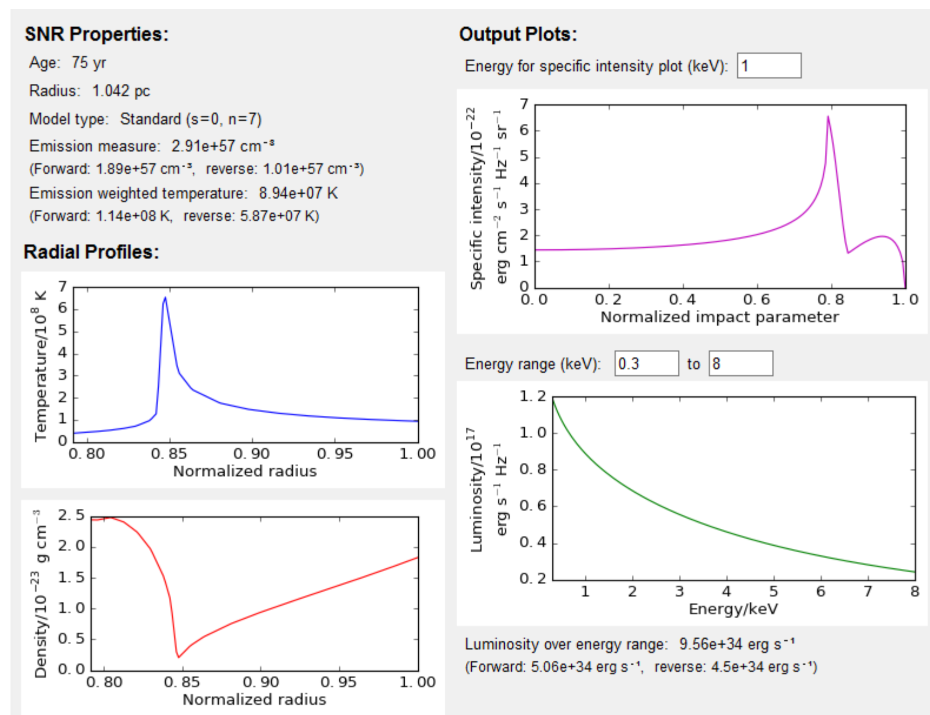
Figure 3. Forward-shock radius R_{FS} and velocity V_{FS}, and RS radius R_{RS} extracted from the hydrodynamic simulations for $s = 0$, $n = 8$. Quantities are plotted in units of characteristic radius or velocity as a function of characteristic time, t/t_{ch}.

Example emission measures(EM) and kT of FS gas and of RS gas.

Upper: Sedov model (zero ejected mass)

Lower: ejecta-dominated phase for SNR with 1 solar mass ejected.





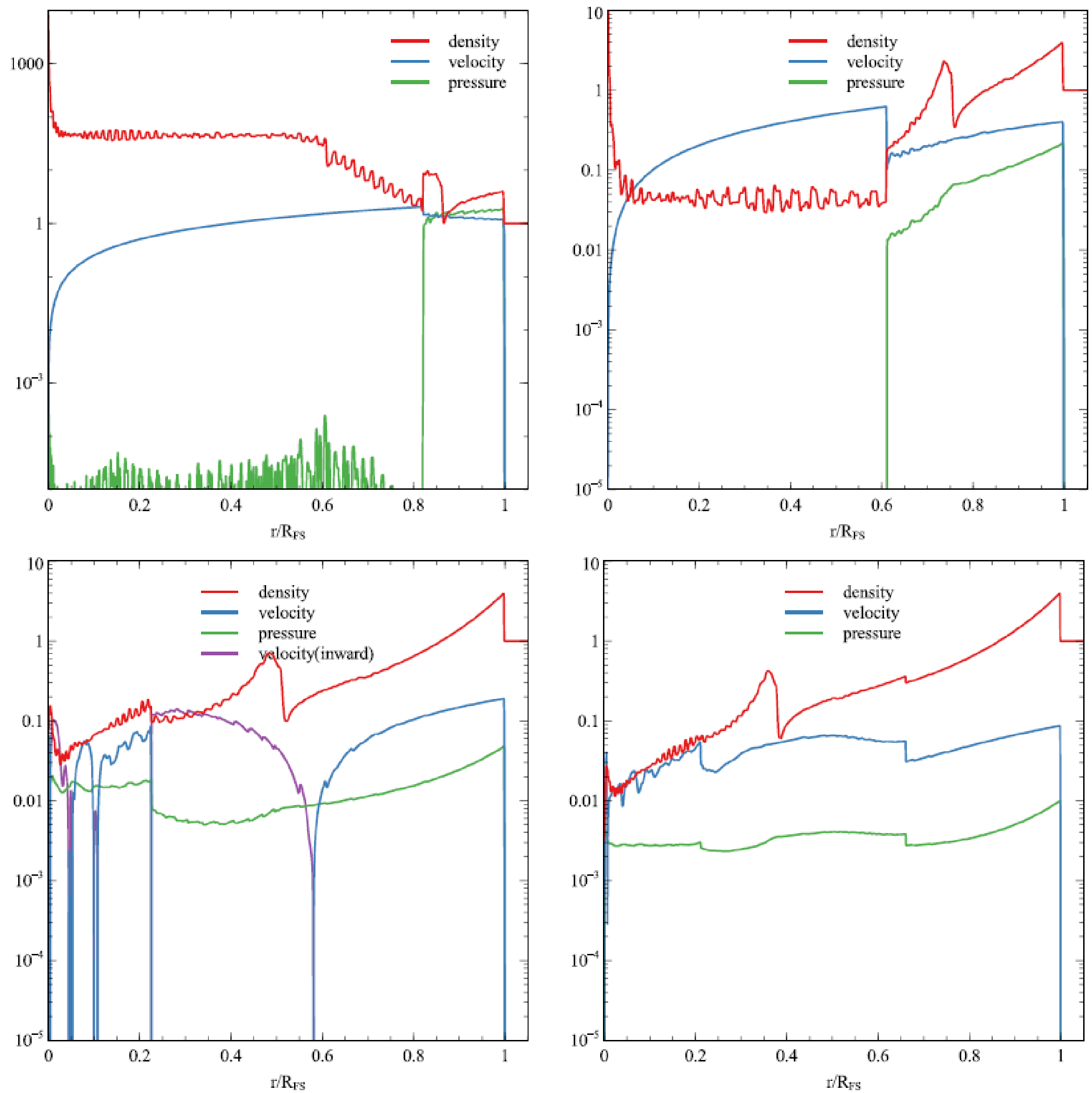


Figure 2. Snapshots of the interior structure for $s = 0$, $n = 8$ from hydrodynamic simulations at four characteristic times: $t/t_{\rm ch} \simeq 0.10$ with $R_{\rm FS}/R_{\rm ch} \simeq 0.27$ (top left), $t/t_{\rm ch} \simeq 1.1$ with $R_{\rm FS}/R_{\rm ch} \simeq 1.1$ (top right), $t/t_{\rm ch} \simeq 3.1$ with $R_{\rm FS}/R_{\rm ch} \simeq 1.8$ (bottom left), and $t/t_{\rm ch} \simeq 10$ with $R_{\rm FS}/R_{\rm ch} \simeq 2.9$ (bottom right). The density, velocity, and pressure are scaled to their characteristic values, and are plotted vs. radius in units of the FS radius ($r/R_{\rm FS}$). Inward gas velocities are plotted in purple in the bottom left panel.

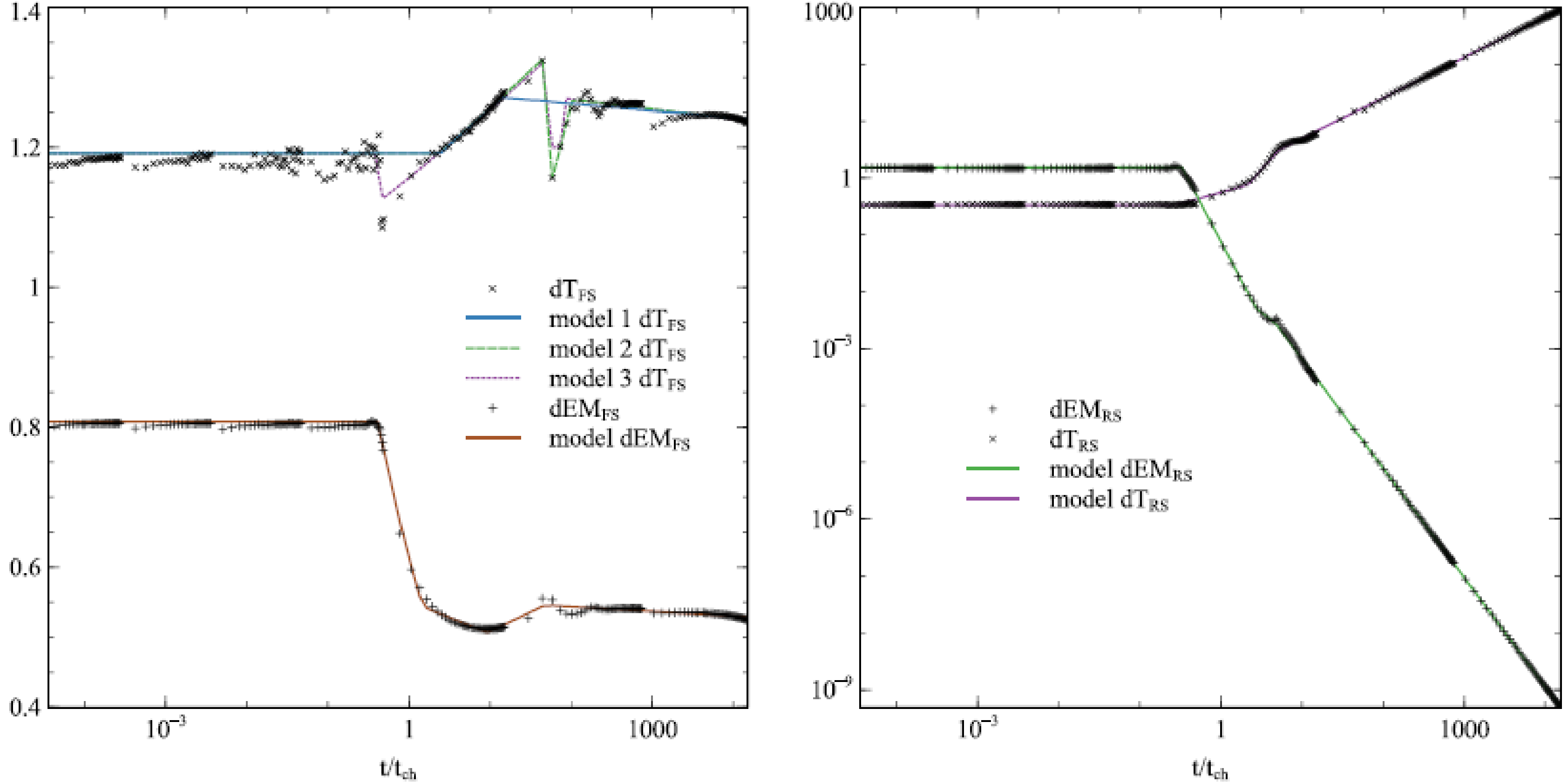


Figure 4. Extracted quantities from the hydrodynamic simulations for $s = 0$, $n = 8$ as a function of characteristic time, t/t_{ch}. Left: dimensionless temperature dT_{FS} and dimensionless emission measure dEM_{FS} of forward-shocked gas. Right: dimensionless temperature dT_{RS} and dimensionless emission measure dEM_{RS} of reverse-shocked gas. The function fits to dT_{FS}, dEM_{FS}, dT_{RS}, and dEM_{RS} vs. t/t_{ch} are shown by the lines labeled model.

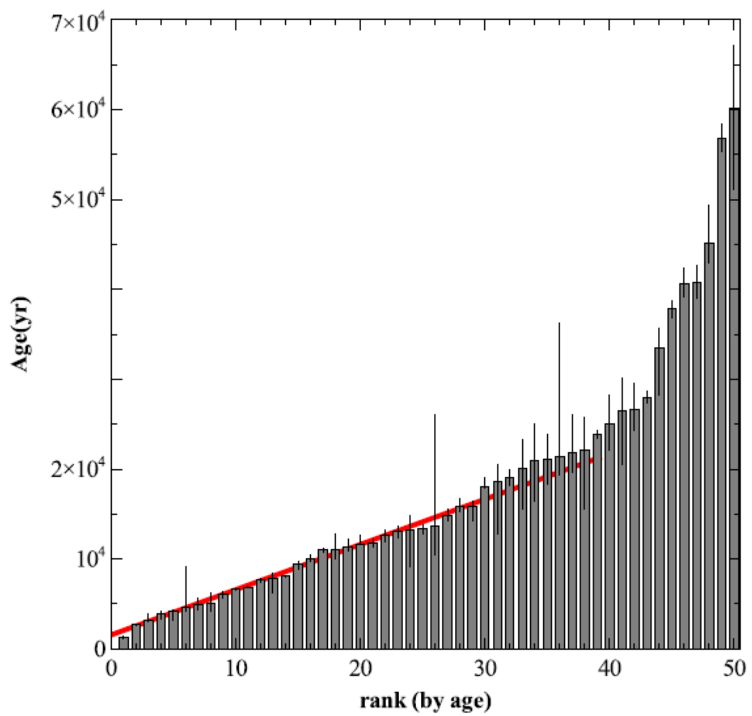
Model X-ray observations, which give kT and EM of shocked gas.

60 LMC SNRs (Leahy 2017):

Mean energy 5.0e50 erg, 1 sigma dispersion 0.5 in log(E)

Mean density 0.1/cm^3

Birthrate 1/500yr (sample complete).



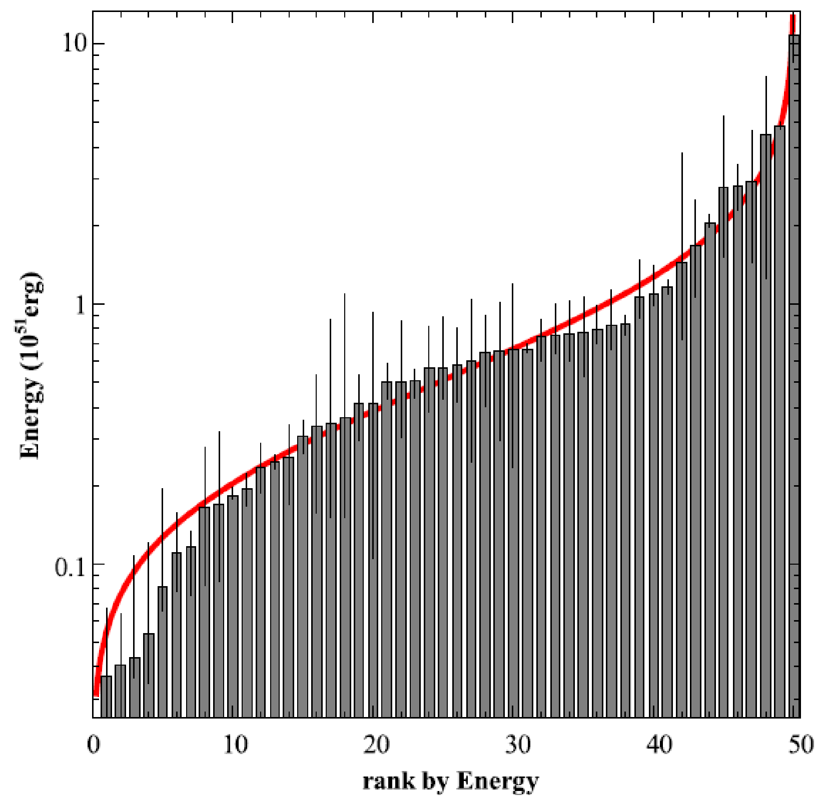


Figure 2. Cumulative distribution of explosion energies (histogram with error bars) for the LMC supernova remnant sample. The horizontal axis is the cumulative number of SNRs with energies less than or equal to the energy of a given SNR, and the vertical axis is the energy of that SNR. The solid curve is a fit for the probability distribution expressed as a log-normal distribution

15 Galactic SNRs with new distances (Leahy & Ranasinghe 2018):

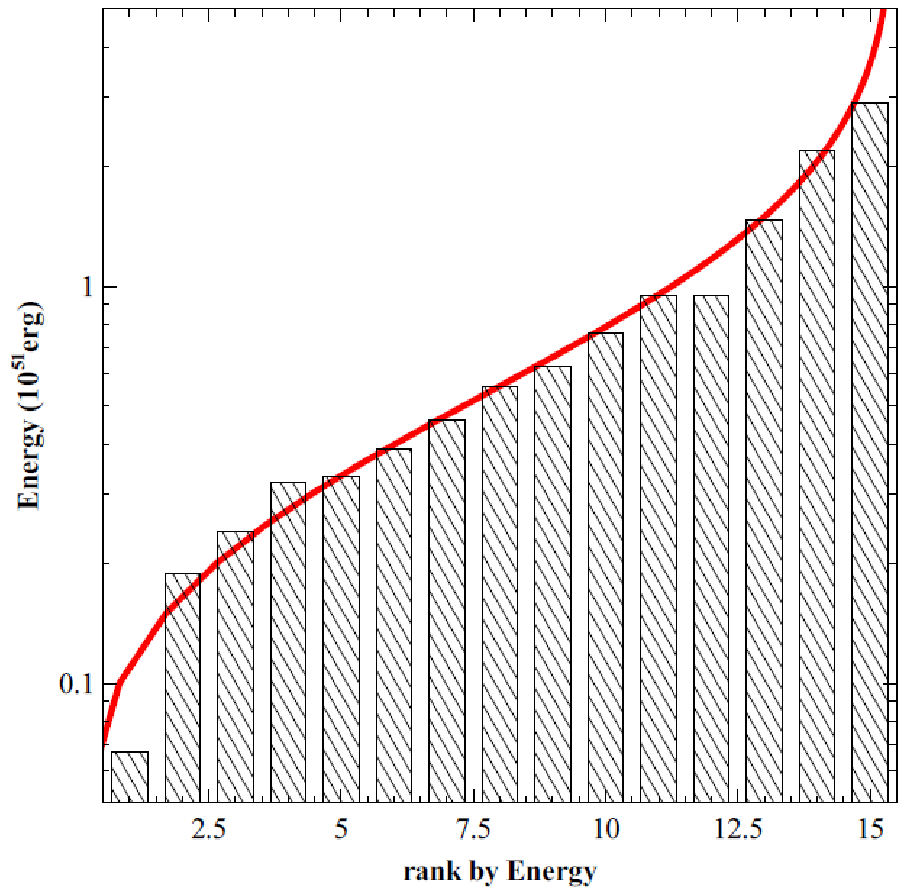
SNRs are in the inner Galaxy.

Mean energy 5.4e50 erg (similar to LMC) , 1 sigma dispersion 0.45 in log(E)

Mean density 0.26/cm^3 (higher than LMC)

Birthrate 1/300yr (inaccurate from incomplete sample).

- 43 Galactic SNRs (Leahy+ 2020) from inner and outer Galaxy
- Mean energy 2.2e50 erg (lower than prev. 2 samples) , 1 sigma dispersion 0.48 in log(E)
- Mean density 0.07/cm^3 (similar LMC)
- Birthrate 1/300yr (sample is still incomplete).



Summary

A program to understand basic properties of Supernova Remnants:

1. Hydrodynamic calculations of evolution with realistic ejecta density profiles and ISM density profiles
2. Extract observable quantities (kT, EM, radius and velocity) from simulations.
3. Write software to interpolate observables as a function of input physical parameters.
4. Create and inverse model that can calculate the physical parameters given observational parameters.
5. Apply to a large number of observed SNRs to get properties of SN explosions.

15 Galactic SNRs (Leahy & Ranasinghe 2018):

Models explored extensively

Several interesting individual cases

Table 4. SNR Model Results

SNR	model type[a] (fs or rs)	s	n	M_{ej} ($M_\odot$)	Age (yr)	Energy (10^{51}erg)	n_0(s=0) (cm^{-3})	ρ_s(s=2) ($M_\odot$s/(km yr))
G18.1-0.1	fs	0	7	1.4	5400	0.189	0.92	n/a
G21.5-0.9	rs	0	9	5	470	0.56	1.01	n/a
G21.8-0.6	fs	0	7	1.4	9700	0.33	0.078	n/a
G27.4+0.0	fs	0	12	10	2500	0.32	1.08	n/a
G28.6-0.1	fs	0	7	1.4	14700	0.95	0.028	n/a
G29.7-0.3	rs	0	9	5	890	0.46	0.43	n/a
G31.9+0.0	rs	0	9	10	9000	0.39	4.5	n/a
	WL	n/a	n/a	n/a	8700	0.39	2.6	n/a
G32.8-0.1	fs	0	7	1.4	7500	0.067	0.018	n/a
G33.6+0.1	fs	2	7	20	780	2.9	n/a	6.3×10^{-8}
G34.7-0.4	fs	0	7	5	9100	2.2	1.52	n/a
	WL	n/a	n/a	n/a	9200	2.2	0.86	n/a
G39.2-0.3	fs	0	7	5	6200	0.24	0.32	n/a
G41.1-0.3	fs	2	7	1.4	1300	0.95	n/a	9.5×10^{-7}
G43.3-0.2	fs	0	7	1.4	3250	1.69	1.17	n/a
	WL	n/a	n/a	n/a	3100	1.82	0.66	n/a
G49.2-0.7	fs	0	9	10	16000	0.76	0.021	n/a
G54.1+0.3	fs	0	7	5	2200	0.63	0.113	n/a

[a]Model type: fs is forward shock model; rs is reverse shock model ; WL is the model of White & Long (1991) with Coulomb equilibration added.