

Supernovae Type Ia

TYPE IA (THERMONUCLEAR) SUPERNOVA

(NOT TO SCALE)



super-critical accretion onto a white dwarf star

thermonuclear supernova explosion

supernova remnant without a neutron star

Illustration: NASA/CXC/M.Weiss

Reading Material

- ✓ Blondin, S. (2025). *Type Ia supernovae*. In *Reference Module in Materials Science and Materials Engineering*. Elsevier. <https://doi.org/10.1016/B978-0-443-21439-4.00101-2>
- ✓ Liu, Z.-W., Röpke, F. K., & Han, Z. (2023). *Type Ia supernova explosions in binary systems: A review*. *Research in Astronomy and Astrophysics*, 23(8), 82001. <https://doi.org/10.1088/1674-4527/acd89e>
- ✓ Pakmor, R., Seitenzahl, I. R., Ruitter, A. J., Sim, S. A., Röpke, F. K., Taubenberger, S., Bieri, R., & Blondin, S. (2024). *Type Ia supernova explosion models are inherently multidimensional*. *Astronomy & Astrophysics*, 686, A227. <https://doi.org/10.1051/0004-6361/202449637>

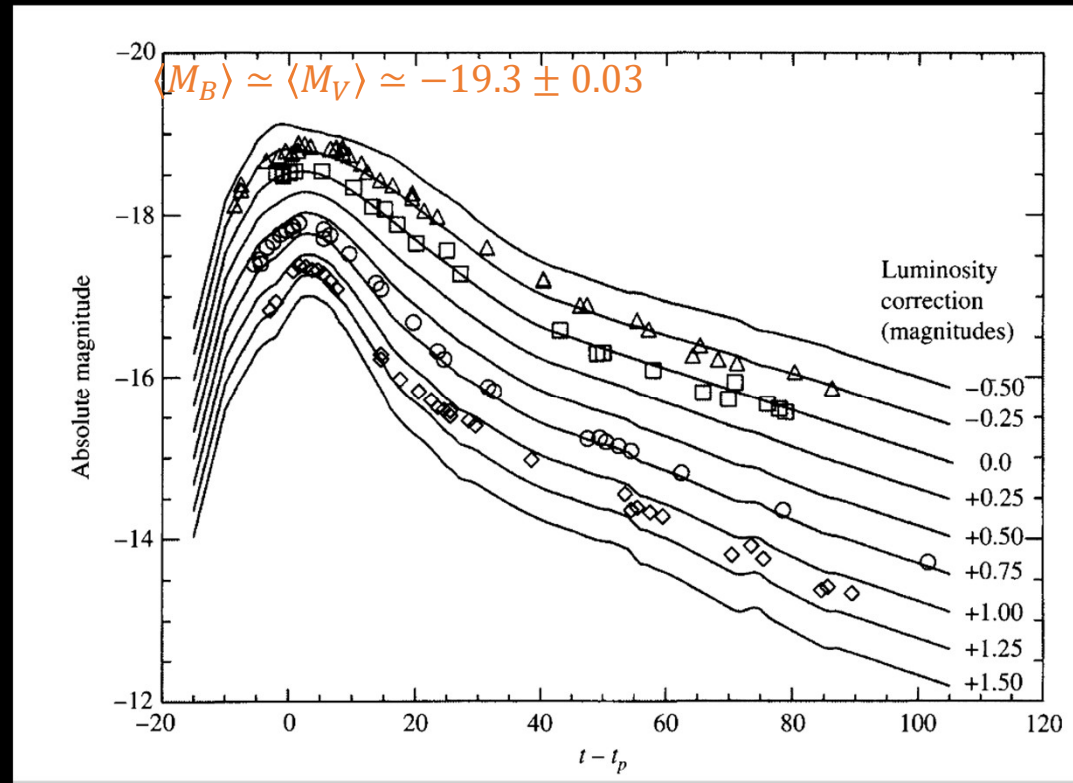
Key points

- ✓ Type Ia supernovae (SNe Ia) are the **thermonuclear explosions** of carbon–oxygen white dwarf (C–O WD) stars in binary systems.
- ✓ They are triggered by the **accretion of material** from a companion star, or by the **merger/collision** with a secondary white dwarf.
- ✓ Total energy output $\approx 10^{44} J$
- ✓ Their high luminosities ($L_{\text{peak}} \approx 10^{36} \text{J s}^{-1} \sim 3 \times 10^9 L_{\odot}$) and the brightness–light-curve shape relation enable them to be **standard candles** for precise cosmological distance measurements (observable - with JWST- up to redshifts 2.3-2.5)
- ✓ SNe Ia are the **main producers of iron** and play a fundamental role in the chemical evolution of galaxies.
- ✓ While observations confirm the basic picture (powered by radioactive decay of ^{56}Ni), key uncertainties remain about the companion and explosion mechanism.
- ✓ **Multiple progenitor channels** are likely required to explain the observed diversity.

SN Ia Basic Observational facts/constraints

1. No hydrogen or helium lines in the spectra
 2. No direct detection of exploding star or the nature of the binary companion (but firm non-detections of giant companion in some cases)
 3. Occurrence of type SN Ia in early type galaxies (ellipticals) which host old populations
 4. Rapid evolution of LC → indirect evidence for a relatively compact companion
- Progenitor must be a WD

Type Ia Supernovae lightcurves



The decline rate of SN Ia light curves is inversely correlated with peak luminosity → enables their use as standard candles

Typical spectra (at different epochs) of a SNIa

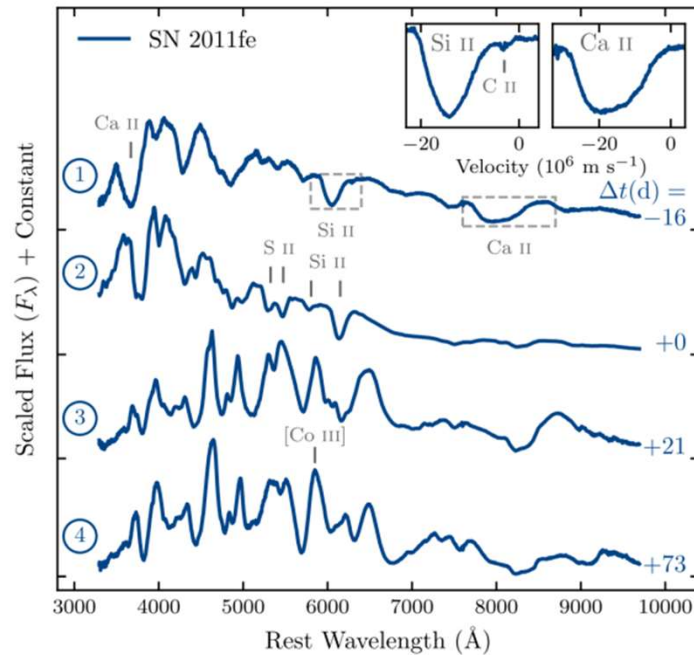
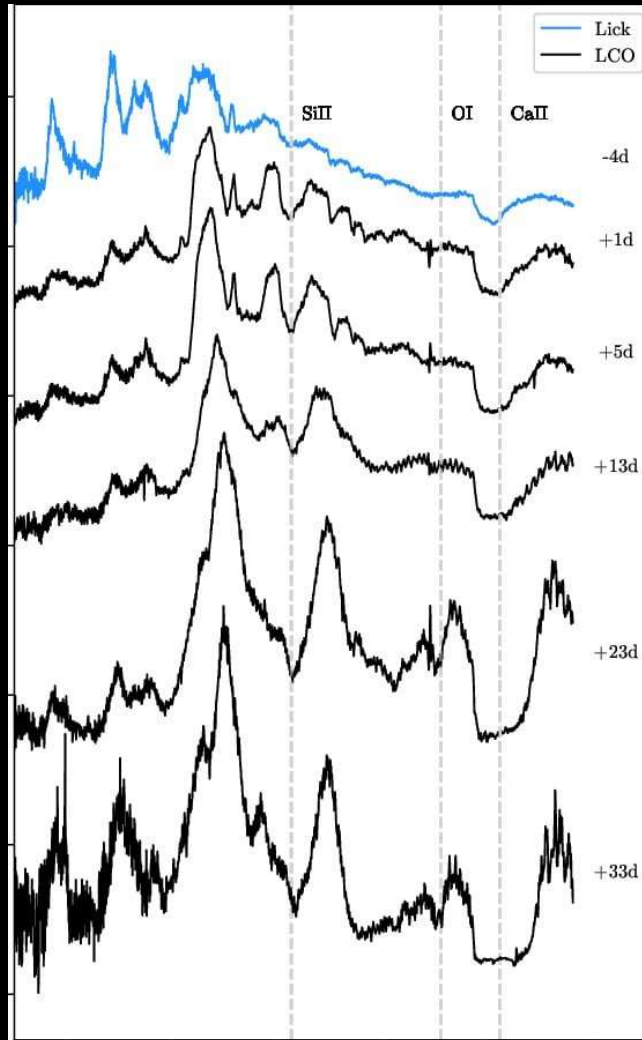


Fig. 4: Spectroscopic evolution of the Type Ia SN 2011fe over the first ~100 days post explosion (data from [Pereira et al. 2013](#)). The right labels give the spectral phase in days from maximum light, and the circled numbers on the left correspond to the phases highlighted in Fig. 3. The tickmarks on the Y-axis give the zero-flux level of each spectrum. A few key spectroscopic features are highlighted in gray. The insets show examples of high-velocity features at early times in the Si II 6355 Å and Ca II near-IR triplet line profiles. A small absorption due to C II 6580 Å (i.e., unburnt carbon) can also be seen in the left inset.

Spectral evolution of a Type Ia SN



Spectral time series of SN 2019eix. Epochs with respect to V band maximum are included on the right. The spectra have been corrected for both Milky Way and host extinction. (The last spectrum in the series has an unusual flat-bottomed Ca feature).

SN Ia : spectral evolution

1. Strong silicon absorption (Si II λ 6355) near maximum light \rightarrow defining spectral feature used for classification
2. Intermediate-mass elements (IMEs) present: Si, S, Ca, Mg in early-time spectra
3. Iron-group elements (IGEs) dominate at later times \rightarrow Fe, Co lines emerge as ejecta expand and cool
4. Large expansion velocities ($\sim 10,000$ km/s) \rightarrow measured from blueshifted absorption features
5. Overall spectral homogeneity, but with observable diversity \rightarrow variations in line strength, velocity, and ionization state

Chandrasekhar limit

- ✓ Carbon–oxygen white dwarfs (C–O WDs) form from stars with initial masses $\sim 2\text{--}8 M_{\odot}$.
- ✓ Supported by **electron degeneracy pressure**, preventing collapse until a critical mass is reached.
- ✓ Maximum stable mass (**Chandrasekhar mass**):

$$M_{\text{Ch}} = 0.197 \left(\frac{hc}{G} \right)^{3/2} \frac{1}{\mu_e m_H} \approx 1.44 M_{\odot} \quad (\mu_e = 2)$$

- ✓ This mass limit explains the **relative homogeneity** of SNe Ia.
- ✓ Most C–O WDs are born with $M < 1 M_{\odot} \rightarrow$ cannot explode.
- ✓ To reach explosion conditions ($\sim 1.4 M_{\odot}$), WDs must:
 - ✓ **Accrete mass from a companion**, or
 - ✓ **Merge with another WD**

Still SNe Ia are now known to show significant diversity.
Many current models favor sub-Chandrasekhar mass explosions (sub- M_{Ch}).

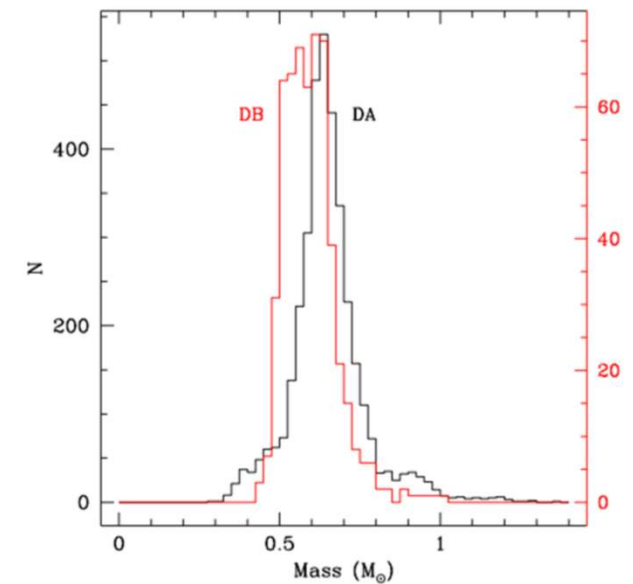


Figure 1. Mass distribution by number for 3636 DAs with $T_{\text{eff}} \geq 13000$ K, $S/N_g \geq 15$ and $\langle S/N \rangle = 31$ in black and 549 DBs with $T_{\text{eff}} \geq 16000$ K, $S/N_g \geq 10$ and $\langle S/N \rangle = 21$ in red.

Basic Explosion physics

- ✓ As a C–O white dwarf approaches the Chandrasekhar mass, core conditions ($T \sim \text{few} \times 10^8 \text{ K}$, density $(\gtrsim 2 \times 10^{12} \text{ kgm}^{-3})$) ignite carbon fusion.
- ✓ Accretion \rightarrow compression \rightarrow heating increases nuclear reaction rates, creating a positive feedback loop.
- ✓ In normal stars, expansion regulates this process. In degenerate matter, pressure is independent of temperature \rightarrow no self-regulation \rightarrow thermonuclear runaway.

- ✓ **Several cooling mechanisms act in the WD:**
 - **Neutrino emission**
 - **Thermal conduction**
 - **Convection**
- ✓ These processes **partially compensate** the temperature increase from nuclear burning
- ✓ The WD begins to **expand** when thermal pressure approaches electron degeneracy pressure
- ✓ **Convection** initially transports energy and helps regulate burning
- ✓ However, cooling and convection are **not efficient enough** to:
 - Remove excess energy fast enough
 - Prevent the development of **strong temperature gradients**
- ✓ **A deflagration (subsonic flame)** forms and propagates via thermal conduction
- ✓ Once ignited, a thermonuclear runaway is unavoidable (including **sub-Chandrasekhar WDs**)

Explosion energetics- expansion

- ✓ Fusion of $\sim 1.4 M_{\odot}$ of C/O \rightarrow iron-group elements releases

$$E_{\text{nuc}} \sim 2 \times 10^{44} \text{ J}$$

- ✓ Energy budget:

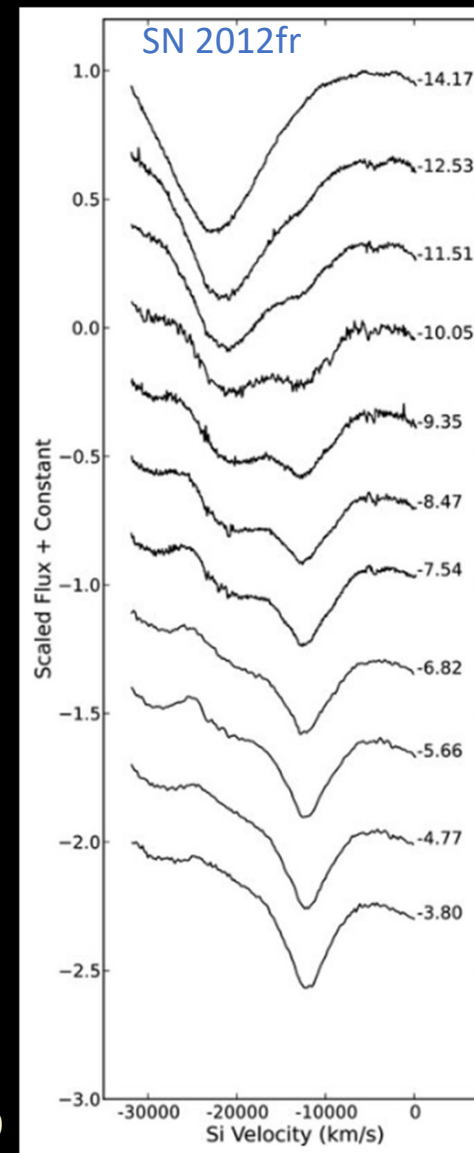
$$E_{\text{nuc}} \approx -E_b + E_{\text{kin}}$$

- ✓ Binding energy for a non-rotating M_{Ch} WD:

$$E_b \sim -5 \times 10^{43} \text{ J}$$

- ✓ Kinetic energy: $E_{\text{kin}} \lesssim 1.5 \times 10^{44} \text{ J}$

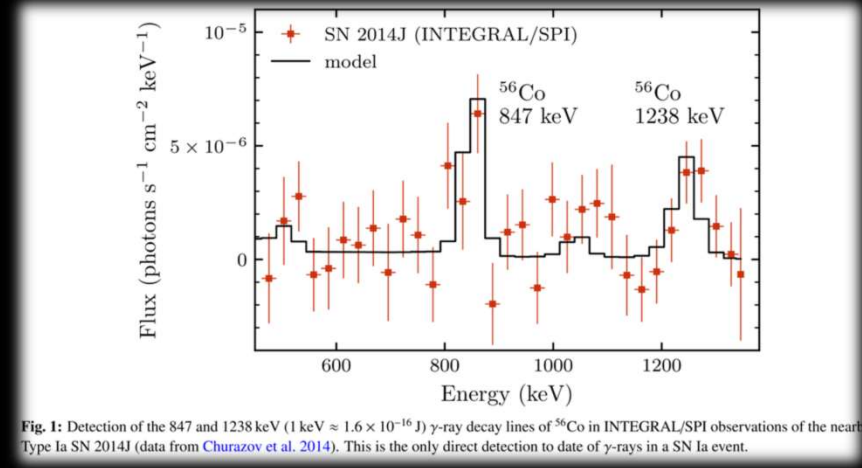
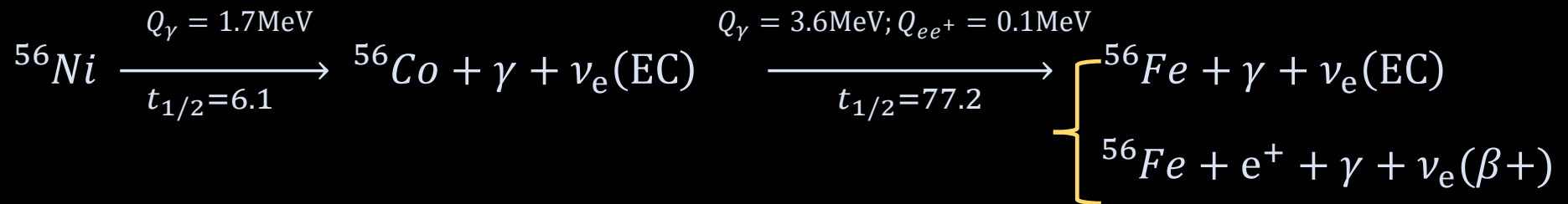
- enough to explain ejecta velocities as high as $\sim 10^4$ km/s (from spectral line blueshifts) $\varepsilon \delta \omega$



- ✓ After a few seconds → **homologous expansion** (self-similar, $v \propto r$)
- ✓ Rapid expansion → **strong adiabatic cooling**
- ✓ **Radius:** $\sim 10^6 \text{m} \rightarrow \sim 10^{12} \text{m}$ (in $\sim 1 \text{d}$)
- ✓ **Temperature** drops from $\sim 10^9 \text{K} \rightarrow \sim 10^3 \text{K}$ (in 1d)
- ✓ Without additional heating → SN would **fade rapidly**

BUT

- ✓ Abundant production of ^{56}Ni
- ✓ Radioactive decay emitting γ -rays and positrons → depositing energy to ejecta



How is ^{56}Ni produced?

- ✓ At $T \gtrsim 5 \times 10^9 \text{K}$ nuclear reactions are fast and reversible
→ matter reaches **nuclear statistical equilibrium** (forward = reverse reactions) – favouring most stable nuclei
- ✓ Composition set only by:
temperature, density, and electron fraction $Y_e (= Z/A)$
→ independent of individual reaction rates
- ✓ Burning drives material to the iron peak (most stable nuclei)
 $Y_e \approx 0.5 \rightarrow ^{56}\text{Ni}$ **dominates**
- ✓ Lower Y_e (*) → neutron-rich isotopes (e.g. ^{58}Ni , ^{54}Fe)
- ✓ As ejecta expand and cool → reactions stop → freeze-out → abundances fixed

(*) at higher densities - M_{Ch} WDs electrons very degenerate → electron capture is favoured → $Y_e \downarrow$ → neutron-rich nuclei favoured

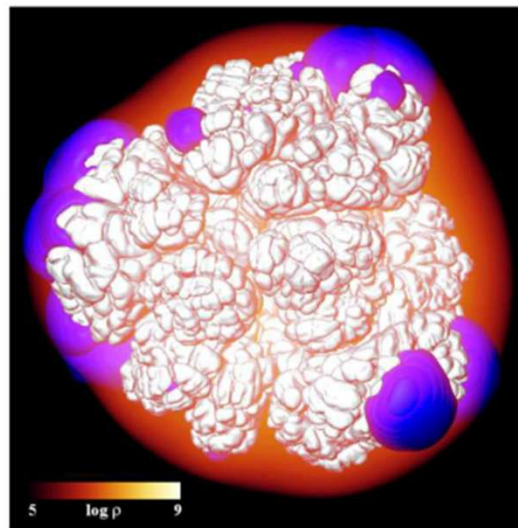
Three basic ingredients for a successful SN Ia model

1. **Explosion energy:** of the order of 10^{44} J to unbind the WD and accelerate the ejecta to characteristic velocities of the order of 10^7 m s⁻¹. This implies the WD must be (almost) entirely burnt to release sufficient nuclear energy from fusion of C-O into heavier elements.
Note: some explosion models (e.g., pure deflagrations) result in too low an explosion energy to completely unbind the WD, in which case a bound remnant is left behind. Such models have been found to be a good candidate for low-luminosity Type Iax events.
2. **Nucleosynthesis:** a ⁵⁶Ni yield in the range 0.1–1.0 M_⊙ (to power the light curve) + several 0.1 M_⊙ of IMEs (to match the spectra) + some stable IGE isotopes (⁵⁸Ni, ⁵⁴Fe) + possible traces of unburnt C-O. This requires thermonuclear burning at a large range of densities.
3. **Chemical stratification:** stable IGEs + ⁵⁶Ni near the center and IMEs in the outer layers. This requires a large (exponentially decreasing) density gradient and weak large-scale mixing during the explosive phase.
Note: the inner ejecta of violent merger models are dominated by the ashes of the incompletely burned secondary WD (O, Ne, Mg), and pure deflagration models predict significant amounts of unburnt C-O material as a result of large-scale mixing during the explosion.

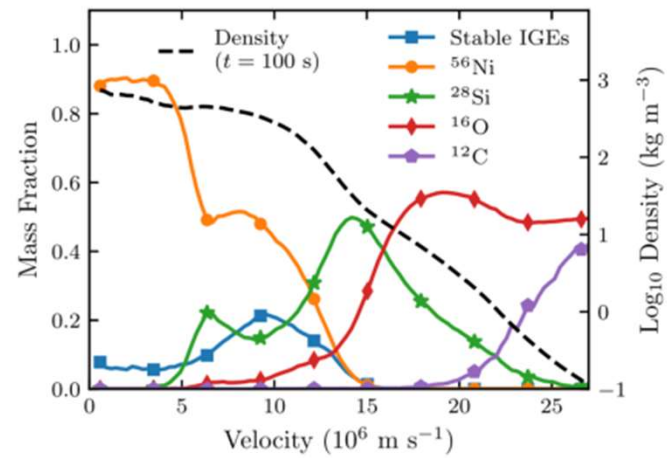
Blondin, S. (2025)

IMEs: Intermediate-Mass Elements Si, S, Ca, Mg, (Ar)

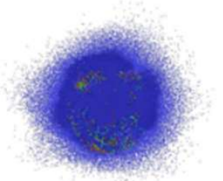
- ✓ Produced when temperatures/densities not high enough to reach NSE
- ✓ Dominant in outer layers of the ejecta



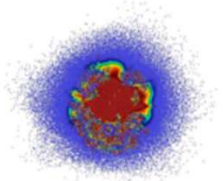
(a) $t = 1$ s



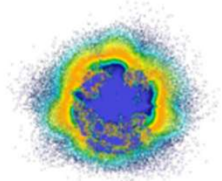
(b) $t = 100$ s



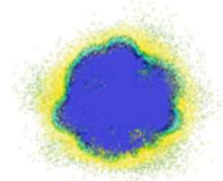
(c) Stable IGEs



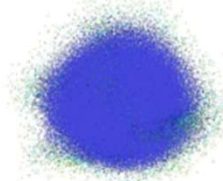
(d) ^{56}Ni



(e) ^{28}Si



(f) ^{16}O



(g) ^{12}C

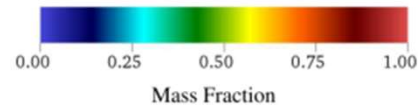


Fig. 2: Example of a 3D M_{Ch} delayed-detonation model (N100; [Seitenzahl et al. 2013b](#)). (a) Density (in $\text{g cm}^{-3} = 10^3 \text{ kg m}^{-3}$; orange color scale), deflagration plumes (white), and detonation front (blue) at $t = 1$ s post explosion. (b) Spherically averaged density (dashed line) and composition profiles for representative isotopes (solid lines) at $t = 100$ s post explosion. The 2D-projected distribution of each isotope is shown in the bottom row in panels (c)–(g). The graphics shown in panels (a) and (c)–(g) are reproduced with permission from [Seitenzahl et al. \(2013b, their Figs. 2 and 4\)](#).

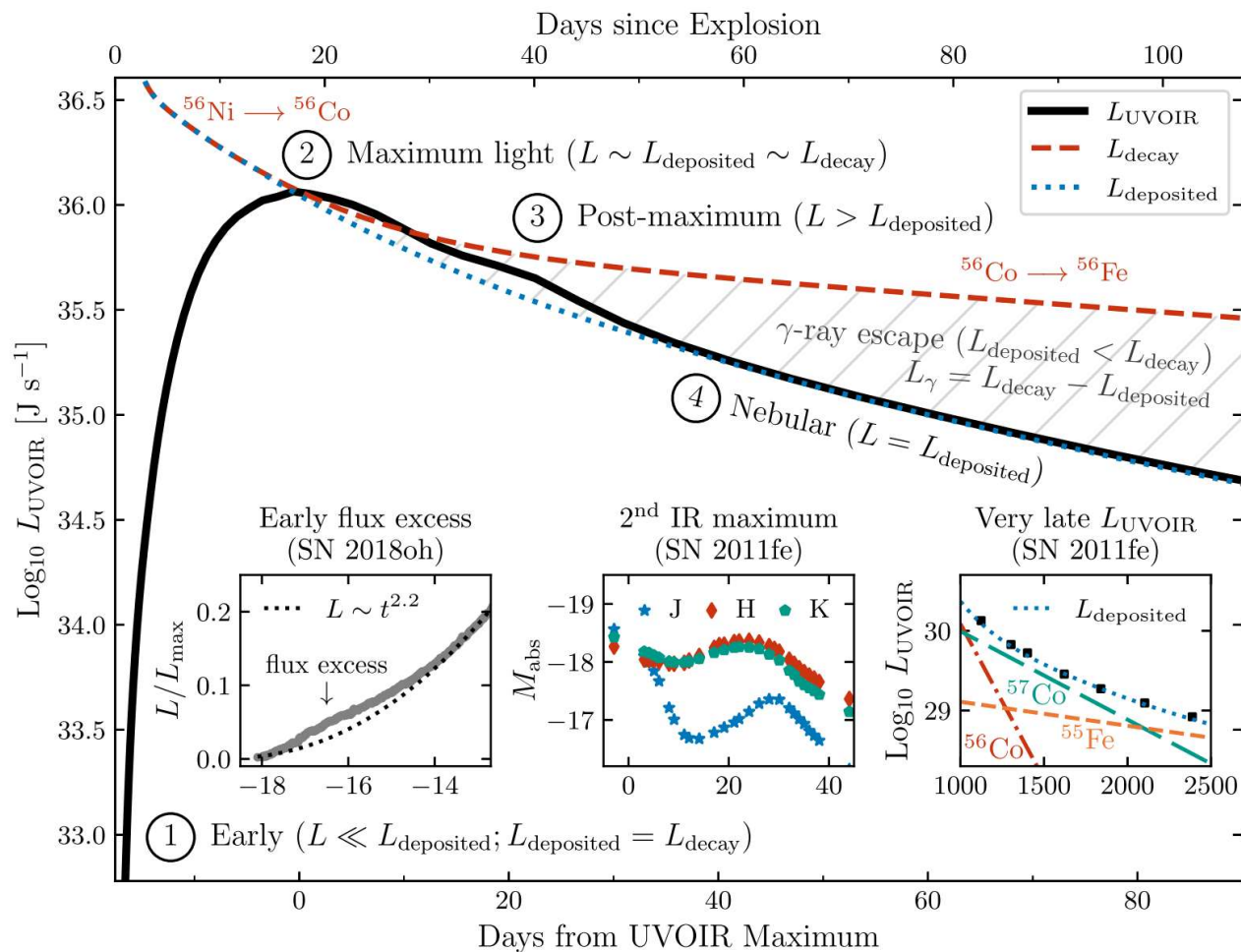


Fig. 3: Luminosity evolution for a SN Ia model with $\sim 0.5 M_{\odot}$ of ^{56}Ni (black solid line; DDC15 model of Blondin et al. 2015). The dashed and dotted lines show the decay luminosity and the deposited decay power, respectively. The hatched area highlights the increasing γ -ray escape past maximum light. The insets give examples of early flux excess (left; data from Dimitriadis et al. 2019), the secondary near-IR maximum (middle; data from Matheson et al. 2012), and the contribution of additional decay chains to the luminosity at very late times (right; data from Tucker et al. 2022). The axis in each case corresponds to days from maximum light.

Early evolution highlights

- ✓ Early emission powered by ^{56}Ni decay, but initially photons are trapped \rightarrow possible short dark phase (~ 1 day)
- ✓ As ejecta expand \rightarrow optical depth decreases \rightarrow photons escape \rightarrow luminosity rises
- ✓ Early light curve (power law):

$$L(t) \propto t^\alpha, \alpha \sim 2$$

but deviations are common, including early flux excess (possibly caused by companion/CSM interaction or surface ^{56}Ni)

- ✓ Early spectra: dominated by IMEs (Si, S, Ca) + sometimes unburnt C, showing P-Cygni profiles
- ✓ High-velocity features (HVFes) common (Ca II, Si II) \rightarrow evidence for asymmetries / outer ejecta structure

Peak luminosity

- ✓ Peak occurs when radioactive energy input equals radiative losses



$$L_{\text{decay}}(t) = L_{\text{Ni}}e^{-t/\tau_{\text{Ni}}} + L_{\text{Co}}e^{-t/\tau_{\text{Co}}}$$

Arnett's rule:

$$L_{\text{peak}} \approx L_{\text{decay}}(t_{\text{peak}})$$

→ **peak luminosity traces ${}^{56}\text{Ni}$ mass**

Valid to ~10–20% accuracy

- ✓ Spectra at maximum: dominated by IMEs (Si, S, Ca)
- ✓ Unburnt carbon signatures typically disappear by peak

Highlights of post-maximum evolution

- ✓ Expansion → decreasing density → declining optical depth
→ ejecta become transparent to γ -rays
- ✓ Increasing γ -ray escape → reduced energy deposition
→ drives the overall luminosity decline
- ✓ Early post-peak: luminosity > instantaneous deposition
→ release of stored thermal energy (~first 30 days)
- ✓ Around ~30–50 days: emission shifts from optical to near-IR
→ due to cooling and Fe/Co line emission (incl. forbidden lines)
→ produces a secondary maximum in JHK bands
- ✓ Brighter SNe Ia decline more slowly
→ width–luminosity (Phillips) relation

Highlights of late time evolution

- ✓ Ejecta become optically thin ($\sim 50+$ days)
→ luminosity \approx instantaneous decay energy deposition in the ejecta (mainly ^{56}Co)
- ✓ At late times, heating is increasingly dominated by positrons from ^{56}Co decay, while γ -rays escape
- ✓ Nebular spectra probe inner ejecta (IGEs)
→ dominated by forbidden lines of Fe and Co
- ✓ ^{56}Ni fully decayed → remaining Ni is stable (e.g. ^{58}Ni)
→ constrains explosion conditions / WD mass
- ✓ Line profiles (shifts, asymmetries, double peaks)
→ probe ejecta geometry and explosion mechanism
- ✓ the time-weighted integral of the UVOIR luminosity is equal to that of the deposited decay power by this time → infer the ^{56}Ni mass

$$\int_0^t t' L_{\text{UVOIR}}(t') dt' = \int_0^t t' L_{\text{dep}}(t') dt' \quad \text{for } t \gg t_{\text{peak}}$$

Observational diversity

- ✓ Basic SN Ia framework explains most events, **but**
 - diversity** in luminosity, decline rate, colors, and spectra
 - partly due to viewing-angle effects in asymmetric explosions
- ✓ High-luminosity (91T-like):
 - higher ionization, more IGEs in outer layers
 - sometimes linked to CSM interaction
- ✓ Low-luminosity (91bg-like):
 - strong Ti II/Cr II absorption, redder colors
 - no secondary NIR maximum
- ✓ Diversity may form a continuous sequence driven by ^{56}Ni mass
 - sets temperature and ionization
- ✓ Additional peculiar sub-classes:
 - Super-luminous (e.g. SN 2009dc; possibly super-MChM_{\rm Ch}MCh)
 - Ia-CSM: strong H lines from dense circumstellar interaction
 - Type Iax: low luminosity, low velocities (partial explosions)

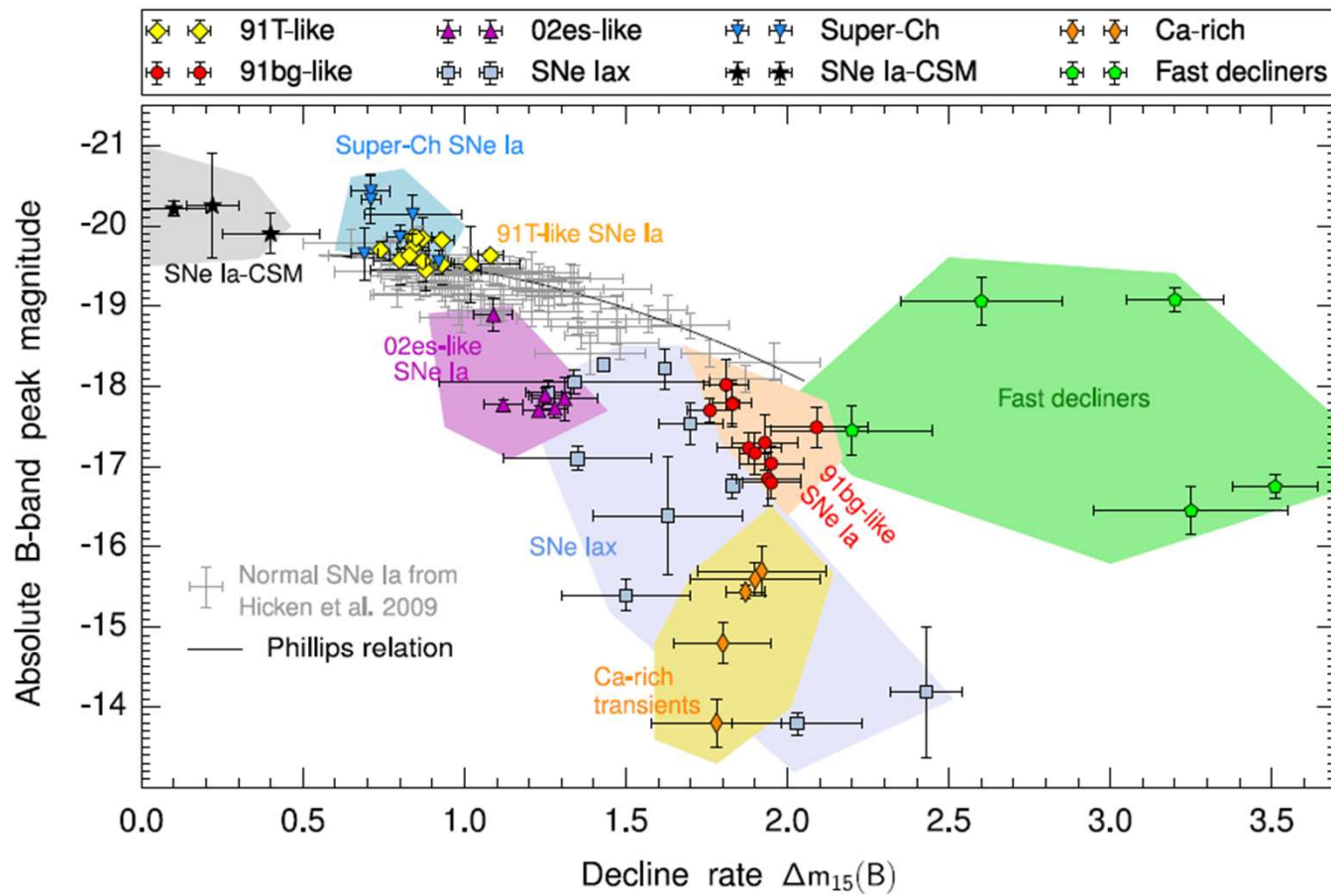


Figure 1. Distributions of normal SNe Ia and different subclasses in the peak luminosity vs. light curve width ($\Delta m_{15}(B)$; Phillips 1993) diagram. The figure is reproduced based on Figure 1 of Taubenberger (2017).

Progenitor scenarios & explosion mechanisms

- ✓ Multiple progenitor channels and explosion mechanisms can produce SNe Ia
- ✓ Classical picture: explosion of a near-Chandrasekhar-mass (M_{Ch}) WD
- ✓ Increasing support for sub- M_{Ch} scenarios:
 - ✓ Double detonations
 - ✓ Violent WD mergers
- ✓ Different models can produce similar observables
 - ejecta properties often weakly sensitive to initial conditions
- ✓ However, some SNe Ia show “smoking-gun” signatures
 - pointing to specific progenitor scenarios

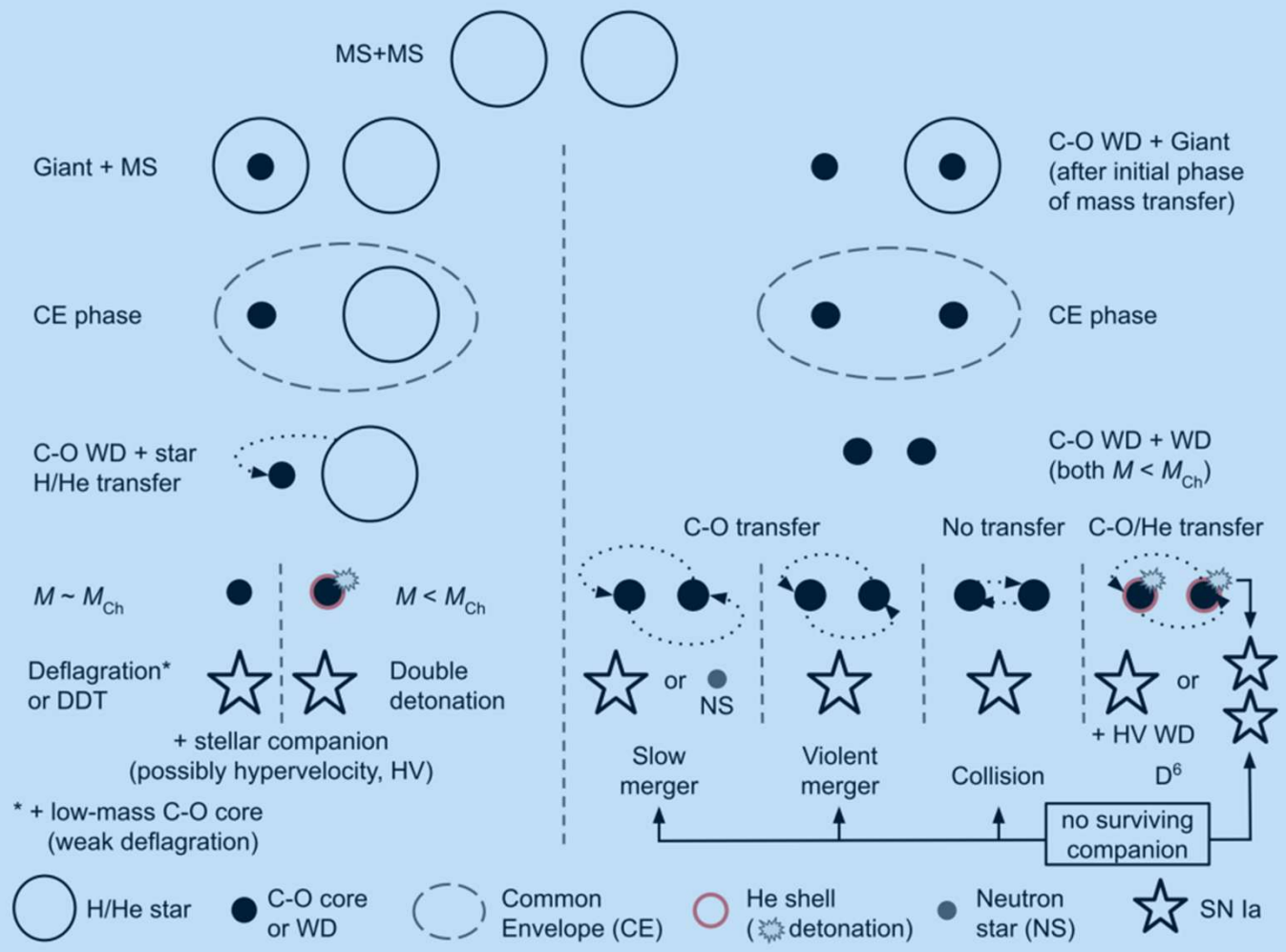


Fig. 7: Schematic view of the six SN Ia progenitor channels presented in this chapter, starting with a main sequence (MS) binary system and proceeding through different evolutionary stages and final outcomes (each separated by a dashed vertical line).

SN Ia Progenitor Scenarios

- Single degenerate model WD + non degenerate star

Scenario 1

- Helium amassed on top of C-O WD becomes degenerate
- When enough He → Helium flash → sends shock wave inwards causing ignition of the degenerate C-O

Scenario 2

- No surface ignition of Helium
- Multiple independent C-O ignition points in core → non-spherical events

Research still in progress

Fine tuned accretion rate required...

Μοντέλα για SNIa

- Double degenerate model WD +WD
 - Two WD orbiting each other
 - gravitational waves
 - loss of energy and angular momentum
 - spiral in (when period < ~14hrs for ~solar mass members)
 - the least massive WD which also has the larger radius will spill over its Roche lobe
 - in a few orbits all its mass is transported to the accretor through a disk (C-O rich material)
 - when mass near the Chandrasekhar limit → nuclear reactions in the interior begin
 - type Ia SN

Correct prediction of SNIa rates in galaxies but computer simulations currently seem to favor formation of a NS rather than a SN explosion

Table 1. Confronting SN Ia scenarios with observations

Scenario ^[1,2]	Core Degenerate (CD)	Double Degenerate (DD)	Double Degenerate (DD-MED)	Double Detonation (DDet)	Single Degenerate (SD-MED)	WD-WD collision (WWC)
Channel by MED	MED built-in.	No MED	MED	No MED (not allowed)	MED (with no peculiar SNe Ia)	No MED
$[N_{\text{exp}}, N_{\text{sur}}, M]$	$[1, 0, M_{\text{Ch}}]$	$[2, 0, \text{sub-}M_{\text{Ch}}]$	$[1, 0, M_{\text{Ch}}]$	$[2, 1, \text{sub-}M_{\text{Ch}}]$	$[2, 1, M_{\text{Ch}}]$	$[2, 0, \text{sub-}M_{\text{Ch}}]$
Presence of 2 opposite Ears in some SNR Ia ^[3]	Explained by the SN inside planetary nebula (SNIP) mechanism.	Low mass Ears if jets during merger (Tsebrenko & Soker 2013).	Requires a short gravitational waves delay time shortly after CEE; unlikely.	No Ears are expected for He WD companion.	OP: ^[4] Ears by jets from accreting WD (Tsebrenko & Soker 2013).	No Ears are expected
Spherical SNRs + low polarisations	Expected in all cases.	Cannot explain.	Expected in all cases.	Cannot explain.	Explained in most cases (with MED).	Cannot explain.
$\approx 1M_{\odot}$ CSM in Keplers SNR	The massive CSM shell might be a PN.	No CSM shell	Requires a short gravitational waves delay time shortly after CEE; unlikely.	Any CSM is of a much lower mass.	OP: ^[4] Can be explained by heavy mass loss from an AGB donor.	No CSM shell
The need to synthesis ^{56}Mn and other elements.	M_{Ch} can do it	Not possible	M_{Ch} can do it	Not possible	M_{Ch} can do it	Unlikely
Main Scenario Predictions	1. Single WD explodes 2. Massive CSM in some cases (SNIP). 3. $M_{\text{WD}} \approx M_{\text{Ch}}$	1. Sufficient WD-WD close binaries 2. $\text{DTD} \propto t^{-1}$ 3. $M_{\text{WD}} < 1.2M_{\odot}$	1. Single WD explodes 2. $M_{\text{WD}} \approx M_{\text{Ch}}$	1. A companion survives 2. Asymmetrical explosion 3. $M_{\text{WD}} < 1.2M_{\odot}$	1. A companion survives 2. $M_{\text{WD}} \approx M_{\text{Ch}}$	Asymmetrical explosion
General Strong Characteristics	1. Explains some SN Ia with H-CSM 2. Spherical explosions 3. Many explosions with $M_{\text{WD}} \approx M_{\text{Ch}}$ 4. Explains large SNe Ia population shortly after CEE	1. Explains very well the delay time distribution (DTD) 2. Ignition easily achieved	Explains very well the delay time distribution (DTD) 2. Many explosions with $M_{\text{WD}} \approx M_{\text{Ch}}$ 3. Spherical explosions	Ignition achieved	1. Accreting massive WDs exist 2. Many explosions with $M_{\text{WD}} \approx M_{\text{Ch}}$ 3. Spherical explosions	Ignition easily achieved
Work for future studies	1. Ignition process 2. Merge during CEE 3. To solidify the claim for M_{Ch} WDs (Bear, & Soker 2018) 4. DTD	1. To derive spherical explosions	1. Ignition process 2. Merge process 3. To solidify the claim for M_{Ch} WDs (Bear, & Soker 2018)	1. To explain the non-detection of helium 2. To find surviving companions	1. Ignition process 2. To explain the DTD and number of SNe Ia 3. To find surviving companions	1. Find a way to account for $> 1\%$ of normal SNe Ia. 2. Examine which peculiar SNe Ia the WWC might account for.
Contribution to normal SNe Ia ^[5]	$\approx 20 - 50\%$	$\approx 20 - 40\%$	$\approx 20 - 40\%$	$\approx 0 - 10\%$	$\approx 0 - 10\%$	$\ll 1\%$
Contribution to peculiar SNe Ia ^[5]	$\approx 0 - 10\%$	$\approx 30 - 70\%$	$\approx 0 - 10\%$	$\approx 10 - 30\%$	$\approx 20 - 50\%$ by the SD scenario without MED	$\approx 1\%$