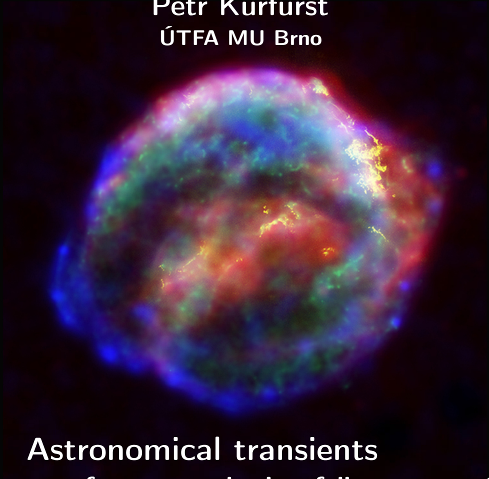
SNe: physical properties and progenitor types

Petr Kurfürst
ÚTFA MU Brno



Astronomical transients

Selected chapters from astrophysics, fall semester, 2022

Thermonuclear SNe: electron degeneracy

- # of quantum states of an electron in a volume V, between momenta $p, p + \mathrm{d}p$ (degeneracy $g = 2$): $2\,\dfrac{4\pi p^2\,\mathrm{d}p\,V}{h^3} \equiv \dfrac{V\,p^2\,\mathrm{d}p}{\pi^2\hbar^3}$
- *Pauli exclusion principle*: electrons occupy all quantum states within the Fermi sphere radius $p = p_F$ (in momentum space), with energy $\epsilon = \epsilon_F$
- # of electrons in these states (with $\epsilon_F = \sqrt{p_F^2 c^2 + m_0^2 c^4}$):

$$N = \frac{V}{\pi^2\hbar^3}\int_0^{p_F} p^2\,\mathrm{d}p \quad \Rightarrow \quad p_F = (3\pi^2)^{1/3}(N/V)^{1/3}\hbar$$

- **Nonrelativistic (NR) electron degeneracy**, $p_F \ll m_0 c$, $\epsilon_F = p_F^2/2m_e$:
  - **Energy** in the whole Fermi volume (from the 1st Eq.):

$$E(\mathrm{NR}) = \frac{V}{2m_e\pi^2\hbar^3}\int_0^{p_F} p^4\,\mathrm{d}p = \frac{V\,p_F^5}{10 m_e \pi^2\hbar^3}$$

  - **Pressure** (P: $E = 3/2PV$ statistical physics! & from the 2nd Eq):

$$P(\mathrm{NR}) = \left(3\pi^2\right)^{2/3}\frac{\hbar^2}{5m_e}n_e^{5/3} \quad (T \text{ independent!})$$

  - M - R **relation** (using a polytropic solution):

$$M(\text{NR case}) = \text{const.} \times R^{-3} \approx 1.7 \times 10^{60}\,R^{-3}\ (\text{cgs})$$

Thermonuclear SNe: electron degeneracy

- Following the M - R relation → with an M increasing, the **room for free electrons shrinks** (due to the *Heisenberg's uncertainty principle*) → **their momenta increase**, approaching $v_e \to c$:
- **Ultrarelativistic (UR) electron degeneracy**, $p_F \gg m_0 c$, $\epsilon_F = c p_F$:
  - **Energy** in the whole Fermi volume (from the 1st Eq.):

$$E(\mathrm{UR}) = \frac{3}{4}(3\pi^2)^{1/3}\hbar c\, N \left(\frac{N}{V}\right)^{1/3}$$

  - **Pressure** (P: $E = 3PV$ statistical physics! & from the 2nd Eq):

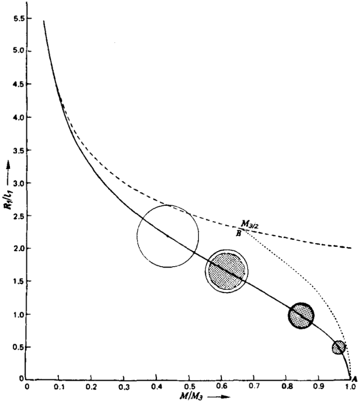
$$P(\mathrm{UR}) = \frac{\hbar c}{8\pi}\left(\frac{3}{8\pi}\right)^{1/3} n_e^{4/3} \quad (T \text{ independent!})$$

  - M - R **relation** (using a polytropic solution):

$$M(\mathrm{UR\ case}) \equiv M_{\mathrm{Ch}} = \mathrm{const.} \approx 1.44\, M_\odot$$

Thermonuclear SNe: electron degeneracy

- Following the M-R relation → with an M increasing, the **room for free electrons shrinks** (due to the *Heisenberg's uncertainty principle*) → **their momenta increase**, approaching $v_e \rightarrow c$:
- **Ultrarelativistic (UR) electron degeneracy**, $p_F \gg m_0 c$, $\epsilon_F = c p_F$:



Credit: Chandrasekhar 1983

Thermonuclear SNe

- **Consequence of degeneracy of WD matter:**
  - **WDs**: degenerate matter → $P \neq P(T)$ → **no expansion**
  - **no self-regulation** of stellar nuclear reactor: no cooling by expansion → **strong** increase in reaction rate → **further increase in** T
  - **thermonuclear runaway** (TNR): self-accelerating cycle → **unlimited growth of reaction rate** → until fuel exhausted or degeneracy lifted
- **Basic SN Ia characteristics:**
  - **rise time** ∼19 days; **max** L: $L_{\mathrm{bol,max}} \approx 10^{43}\,\mathrm{erg\,s^{-1}} = 10^{9.4}\,L_\odot$
  - **total** $E_{\mathrm{rad}} \approx 10^{49}\,\mathrm{erg}$, **total** $E_{\mathrm{kin}} \approx 10^{51}\,\mathrm{erg} \Rightarrow E_{\mathrm{kin}} \approx 10^2\,E_{\mathrm{rad}}$
  - **maximum emission** in V and B bands, **fade away** → d, w, or months
  - no **H, He** lines in spectra, strong features of intermediate elements (**S, Si**) and iron group (**Ni, Co, Fe**)
  - **no direct observations** of progenitor systems, progenitors' nature elusive
  - **spectral lines shift** → **high velocities** $\approx 10^4\,\mathbf{km\,s^{-1}}$

Thermonuclear SNe

- **Properties of type Ia SNe**: (cf. also the F. Röpke's lecture on SF 2017
- **Contribution to Galaxy chemical evolution** (Arnett 1982, Röpke+ 2013):
  - **TN** explosion **reactions**: $2\,^{12}\mathrm{C} + 2\,^{12}\mathrm{O} \rightarrow\ ^{56}\mathrm{Ni}$, quickly transformed to expansion E_{kin}, followed by $^{56}\mathrm{Ni} \rightarrow\ ^{56}\mathrm{Co}$ ($\epsilon^{0}_{\mathrm{Ni}} = 4.78 \times 10^{10}\,\mathrm{erg\,g^{-1}\,s^{-1}}$) and $^{56}\mathrm{Co} \rightarrow\ ^{56}\mathrm{Fe}$ ($\epsilon^{\gamma,0}_{\mathrm{Co}}/\epsilon^{+,0}_{\mathrm{Co}} = 6.444/1.512 \times 10^{9}\,\mathrm{erg\,g^{-1}\,s^{-1}}$) decays
  - **SNe Ia** produce $\approx 0.5 M_{\odot}$ of Fe per 1 event
  - **CC SNe** produce $\approx 0.1 M_{\odot}$ of Fe per 1 event
  - **$\sim$2/3 of Fe in the local! universe** made by **SNe Ia**
- **SN Ia cosmology** tests "world model": "revolution" by HZT, SCP projects - Riess 1998, Perlmutter 1999
  - SNe distances incosistent with any universe dominated by gravity
  - can only be fitted by model **involving Λ**
  - **expansion accelerates**
- precise SN Ia distance measurements → major task
- dark energy → major challenge to theory

Thermonuclear SNe

- **Energy release of SNe Ia**:
- **Nuclear energy of material**:
  - initial TNR ejecta - dense and opaque to radiation
  - takes ∼days before all E produced in interior by ^{56}Ni decay reaches the surface → it shapes light curve and peak of L
  - **simplifying assumption**: mass of produced $^{56}\mathrm{Ni} \approx 0.6\,M_\odot \Rightarrow$ LC picture around peak of L powered by ^{56}Ni decay beyond doubt
  - **evolution of Ni/Co/Fe ratio** ← most frequent decay chains:

$$^{56}\mathbf{Ni} \xrightarrow{\tau_{1/2}=8.8\,\mathrm{d}} {}^{56}\mathbf{Co} \xrightarrow{\tau_{1/2}=78.8\,\mathrm{d}} {}^{56}\mathbf{Fe};$$

$$^{57}\mathbf{Ni} \xrightarrow{\tau_{1/2}=35.6\,\mathrm{d}} {}^{57}\mathbf{Co} \xrightarrow{\tau_{1/2}=271.8\,\mathrm{d}} {}^{57}\mathbf{Fe};$$

$$^{55}\mathbf{Co} \xrightarrow{\tau_{1/2}=17.5\,\mathrm{h}} {}^{55}\mathbf{Fe} \xrightarrow{\tau_{1/2}=1000\,\mathrm{d}} {}^{55}\mathbf{Mn}$$

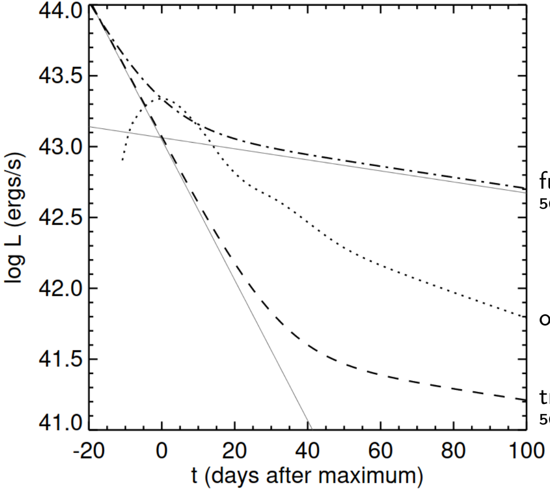
- **Simplified BB early phase luminosity** (Arnett's law, $R_\star = 1$):

$$L(1,t) = \sum_X \epsilon_X^0 M_X^0 \,\mathrm{e}^{-t^2/\tau_m^2} \int_0^t \mathrm{e}^{t'^2/\tau_m^2} \frac{2t'}{\tau_m^2} \,\mathrm{e}^{-t'/\tau_X}\,\mathrm{d}t',$$

where X = radionuclide, τ_m = effective diffusion timescale

Thermonuclear SNe

- **Energy release of SNe Ia**:
- **Nuclear energy of material**:



full trapping of decay energy

^{56}Co decay line

observed bolometric LC

trapping of only e^{+} decay energy

^{56}Ni decay line

Credit: Leibundgut & Suntzeff 2003

Thermonuclear SNe

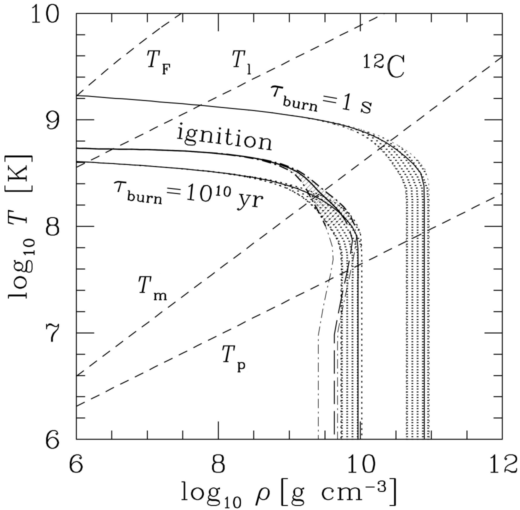
- **Are SNe Ia "standard candles"?**:
  - **no**, even if most observed SNe Ia are "regular"
  - **significant variations** among "regular" SNe Ia → peak brightness ∼ order of magnitude → large errors, if uncorrected: stretch parameter $s{=}(\Delta m_{15} + 0.6)/1.7$, used for time-rescaling $t'{=}(t - t_{B_{\mathbf{max}}})/[s(1+z)]$ (Nobili+ 2003)
  - empirical "Phillips relation" between $M_{B,\mathrm{max}}$ and LC shape (see the 1st lecture): $M_{B,\mathrm{max}} =$-21.726 + 2.698Δm_{15}, no theoretical background!
- **Major tasks:**
  - precise theoretical understanding of WLR
  - dependence on environment, metallicity?
  - different progenitor/explosion mechanisms?
- intrinsically **multi-D processes** ⇒ **multi-D models** → explosion mechanisms, connection to progenitor structure and evolution, nuclear processes, etc.

Thermonuclear SNe

- Progenitors of TN SNe: what WDs make type Ia SNe?
  - **WDs of different ChC** → depending on stellar mass: **He, CO, ONe**
- Favored progenitor scenario: CO WD
  - **most abundant** + **TN burning** leads most likely to **SN Ia-like event**
- He WDs?
  - would **show He in spectra?**
  - produce IGE but **lack of IME** in spectra (Woosley+ 1986)
- ONe WDs?
  - "traditional picture": **core collapse** induced by electron captures onto ^{20}Ne and ^{24}Mg before explosive burning ignites (Gutierrez+ 1996) + TN explosion unlike SN Ia (Marquardt+ 2015)
  - **but:** very high central densities needed to initiate gravitational collapse (Jones+ 2016b)
  - anyway: ONe WDs less abundant than CO: small fraction (if working)
  - alternative: CONe hybrid WDs (Denissenkov+ 2015): from off-center C ignition in core of AGBs (strongly depends on parameterization of mixing processes)

Thermonuclear SNe

- **Ignition of TN SNe:**
- primary ignition by **$^{12}C + ^{12}C$ reaction**



Credit: Gasquez+ 2005

- reaction rate depends on thermal energy of ions → Coulomb barier penetration → nuclei fusion
- lower T, higher ρ: strongly coupled Coulomb system → liquid or a solid
- high T, low ρ: ions → Boltzmann gas

(uncertainties...)

$T_F = T$ of electron degeneracy

$T_l = T$ of ion liquid appearance

$T_m =$ melting T of ion crystal

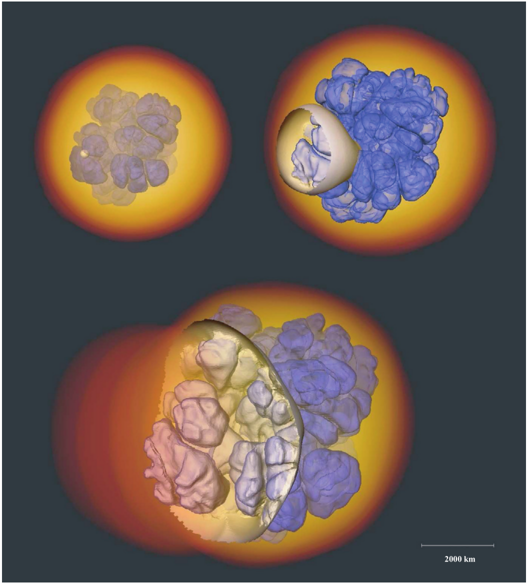
$T_p = T$ of ion plasma

Thermonuclear SNe

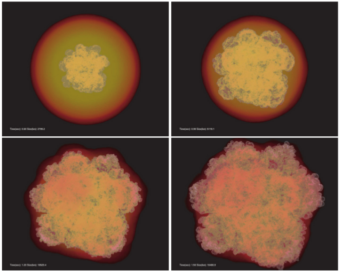
- **Ignition of TN SNe:**
- ρ_{central} grows → energetic evolution of WD core is driven by compressional heating and neutrino cooling (Woosley & Weaver 1986)
- @ $\rho_{\text{central}} \sim 2 \times 10^9\,\text{g}\,\text{cm}^{-3}$ nuclear energy production wins over ν-cooling → **C-burning starts**
- after C ignition → energy outward transportation from the core driven by convective motions
- after ∼century of convective C-burning → hotspot(s) form in turbulent environment → **TNR deflagration ignites** (likely off-center at radius $\sim 50\,\text{km}$), nonlinear instabilities amplify effects! (Röpke+ 2007)
- **ignition of detonation**:
  - direct (pre-existence of a shock wave)
  - spontaneous (pre-shock-free) → Zel'dovich gradient mechanism = shallow T gradient with subsequent self-ignition, etc. (Zel'dovich 1970)

⇒ **strong shock wave** propagates through the star compressing the fuel

Thermonuclear SNe



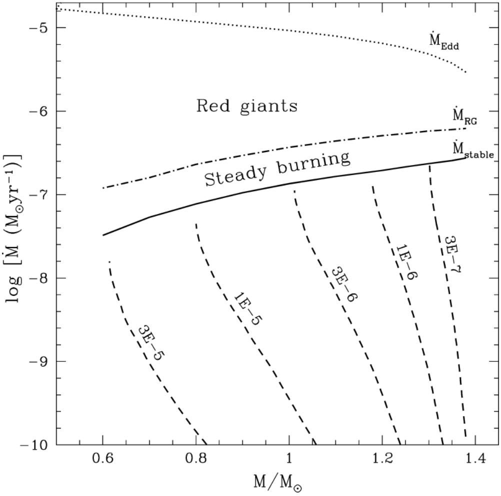
Credit: Röpke 2017



- deflagration simulation @ 0.6, 0.9, 1.2, and 1.5 s after ignition
- delayed detonation 3D sim @ 0.72 (t-l), 0.80 (t-r), and 0.90 s (b) after deflagration ignition (blue); detonation front (white) and density (yellow/orange) of the exploding WD

Thermonuclear SNe

- **Scenarios for Ch/sub-Ch/super-Ch TN SNe:**
- **Single degenerate channel:**

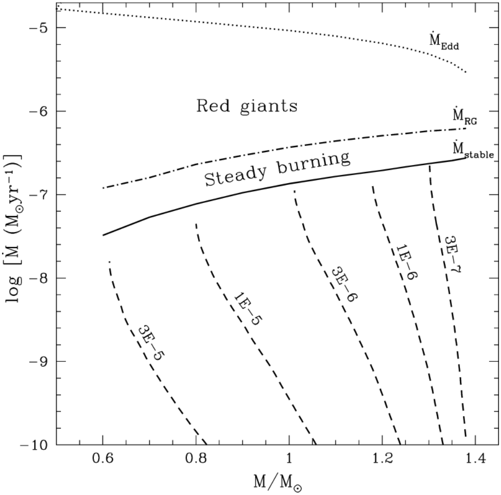


Credit: Nomoto+ 2007

- WD accretes from MS or RG
- accretion rates have to be tuned to allow to accrete to M_{Ch}:
  - low rates → nova eruptions → WD loses more matter than accreted (?)
  - too high rates → formation of extended He-rich envelope
  - moderate accretion rates → degenerate He-shell → detonation → secondary CO core (Nomoto 1982) before M_{Ch} reached → sub-Chandrasekhar explosion (Woosley & Weaver 1994)

Thermonuclear SNe

- **Scenarios for Ch/sub-Ch/super-Ch TN SNe:**
- **Single degenerate channel:**



Credit: Nomoto+ 2007

- WD accretes from MS or RG
- accretion rates have to be tuned to allow to accrete to M_{Ch}:
  - somewhat higher rates → lead to stable hydrostatic burning → accreted material: CO
  - WD may reach the M_{Ch} → Chandrasekhar mass model (Hoyle & Fowler 1960; Arnett 1969, Hansen & Wheeler 1969)
  - stable mass transfer to form M_{Ch} WD highly nontrivial (e.g., Nomoto & Iben 1985)
  - spin up/spin down → nonnegligible effects

Thermonuclear SNe

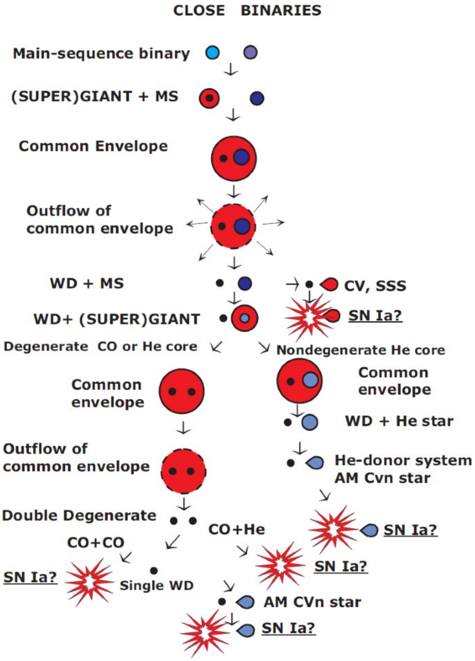
- **Scenarios for Ch/sub-Ch/super-Ch TN SNe:**
- **Single degenerate channel:**
- ignition in **sub-M_{Ch} WDs less natural** than in M_{Ch} WDs → detonation ignition not spontaneous
- **other process is necessary**, some possibilities:
  - double detonation scenario → accretion of He-rich layer on top of CO WD → detonation in massive enough He-layer drives a shock wave into the CO core → triggers a secondary detonation in the core
  - violent WD inspiral/mergers → violent tidal interaction, unstable mass transfer → detonation **before** the actual merger (Guillochon+ 2010; Pakmor+ 2010, 2013) in one of the (still intact) WDs
  - the previous may also potentially trigger the double detonation scenario

Thermonuclear SNe

- **Scenarios for Ch/sub-Ch/super-Ch TN SNe:**
- **Double degenerate channel:**
- 2 CO WDs **merge** → advantage: system naturally contains almost no H, He
- **merger process** possibilities:
  - less massive companion tidally disrupted → forms accretion disk around primary → high accretion rate onto primary CO WD → gravitational collapse (e.g., Saio & Nomoto 1985, 1998) or Ch/sub-Ch TN explosion (Jones+ 2016a)
  - strong mass transfer in inspiral and tidal interaction phase before the secondary is completely disrupted onto the yet sub-Ch primary → detonation → violent merger scenario (Pakmor+ 2010)
  - merger in the final stage of CE phase from post-AGB core and WD companion (Kashi & Soker 2011)
  - example of super-M_{Ch} WDs → WD mergers (model of $0.9M_\odot + 1.1M_\odot$ → good candidate for SN Ia → produce $0.62M_\odot$ of ^{56}Ni)

Thermonuclear SNe

- **Scenarios for Ch/sub-Ch/super-Ch TN SNe:**



Credit: Postnov & Yungelson 2014

Thermonuclear SNe

- **Major computational caveats for TN SNe:**
  - nuclear reactions **not in TE as in stellar evolution** ⇒ fluid dynamical effects propagate in time as a combustion front
  - nuclear reactions occur in **rapidly expanding material** → **EOS extremely complex** (involved as a table)
  - metallicity of ZAMS progenitor of WD has significant impact on Y_e in nuclear statistical equilibrium → **metallicity reduces the brightness of thermonuclear supernovae**
  - numerical simulations required to solve full system in 3D - **extremely computationally costly**
  - **scaling problems** → **thickness of a combustion wave** (waves?) → involving relevant (or even fundamental) nonlinearities - RT, KH instabilities, turbulence, etc.

CC SNe: Stellar evolutionary tracks

Evolution of $1 - 2\, M_\odot$ stars Evolution of $2 - 8\, M_\odot$ stars

$Z = Z_\odot$ (cf. the lectures of S. Phinney on 35HUJI & Ch. Fryer on SF, 2017)

https://rainman.astro.illinois.edu/ddr

Based on Hurley 2000 SSE code

CC SNe: Stellar evolutionary tracks

Evolution of $8 - 11\,M_{\odot}$ stars

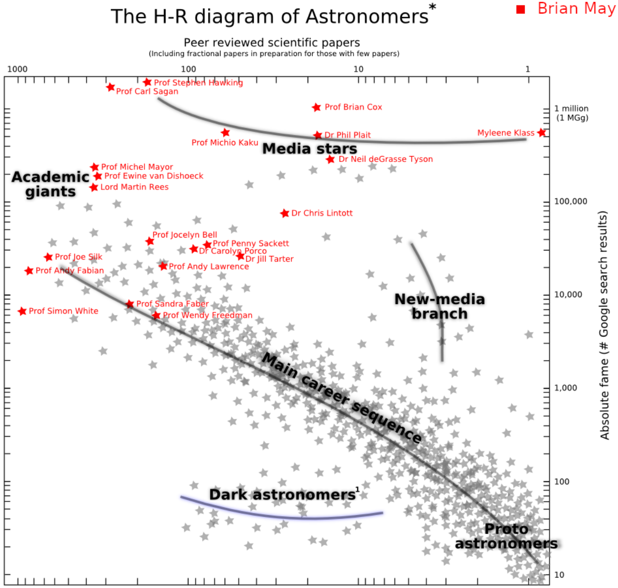
$Z = Z_{\odot}$

Evolution of $15\,\&\,25\,M_{\odot}$ stars

https://rainman.astro.illinois.edu/ddr

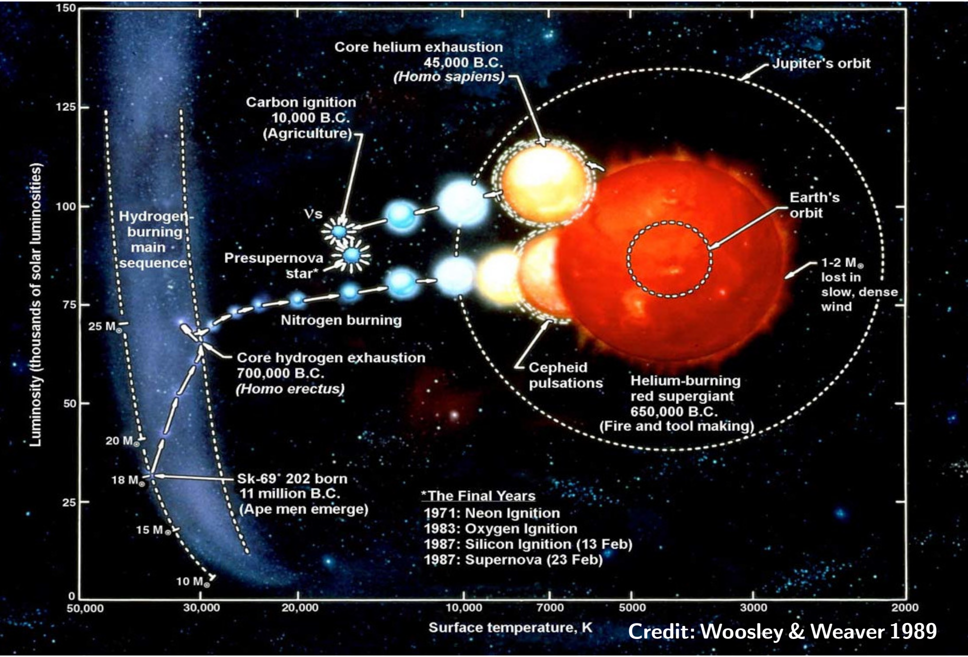
Based on Hurley 2000 SSE code

CC SNe: Stellar structure and evolution



■ Brian May

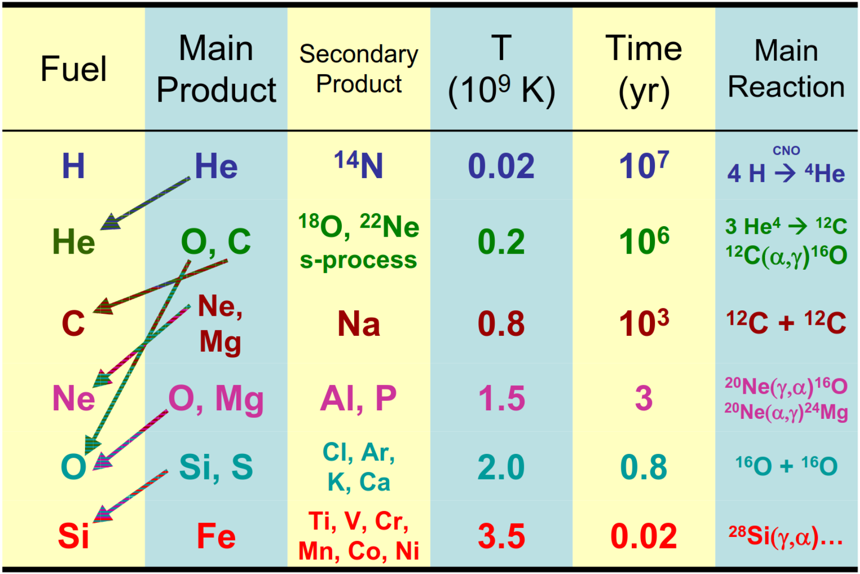
* Includes associated others. Apologies to Hertzsprung and Russell. ¹ Productive but generally invisible.
NOTE: As in astronomy, the numbers are correct to a factor of a few. Most of the grey points are purely representative.
P.S. This was made in 2010 as a joke: http://www.strudel.org.uk/blog/astro/000943.shtml. See http://tinyurl.com/astroHR for a follow-up AAS poster based on real data



Credit: Woosley & Weaver 1989

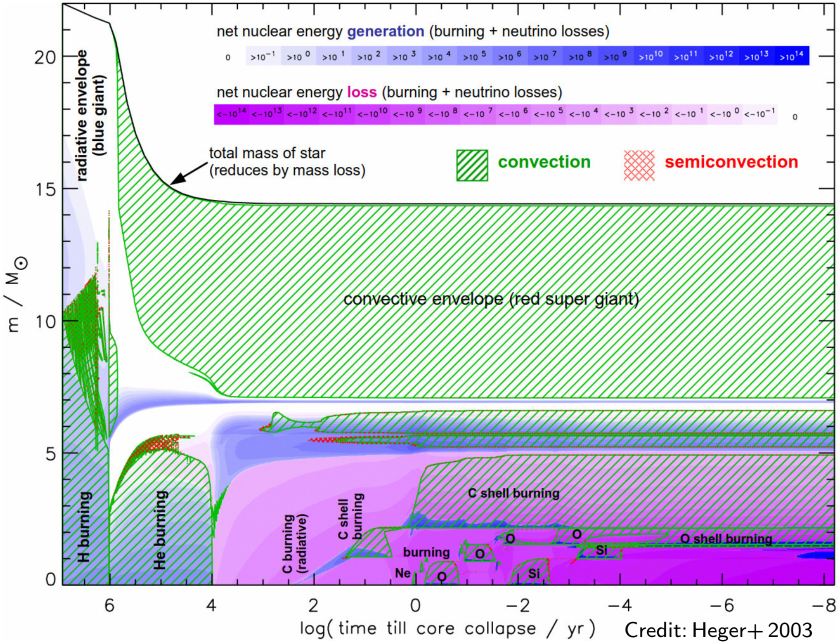
CC SNe: Nuclear burning stages

20 $M_\odot$ star



Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	**He**	**^{14}N**	**0.02**	**10^7**	**$4\,\mathrm{H} \xrightarrow{\text{CNO}} {}^4\mathrm{He}$**
He	**O, C**	**^{18}O, ^{22}Ne s-process**	**0.2**	**10^6**	**$3\,\mathrm{He}^4 \rightarrow {}^{12}\mathrm{C}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$**
C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}\mathrm{C} + {}^{12}\mathrm{C}$**
Ne	**O, Mg**	**Al, P**	**1.5**	**3**	**$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$**
O	**Si, S**	**Cl, Ar, K, Ca**	**2.0**	**0.8**	**$^{16}\mathrm{O} + {}^{16}\mathrm{O}$**
Si	**Fe**	**Ti, V, Cr, Mn, Co, Ni**	**3.5**	**0.02**	**$^{28}\mathrm{Si}(\gamma,\alpha)\ldots$**

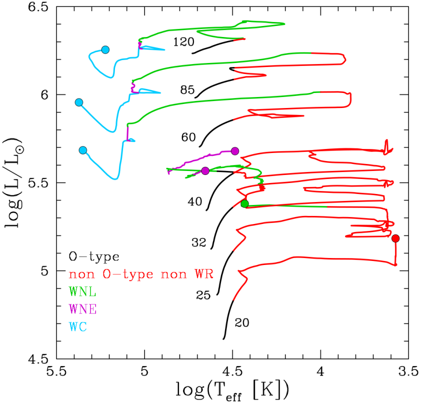
CC SNe: Stellar evolution (Kippenhahn diagram for a 22 $M_\odot$ star)



Credit: Heger+ 2003

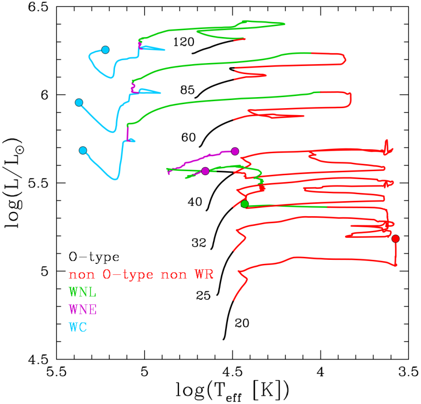
CC SNe: Stellar evolution

- **We roughly distinguish four cases of M_{init}** (Meynet & Maeder 2017):
- **(1) The mass range of stars between 9 and 20 $M_\odot$** → end their life as RSGs at $Z_\odot$ (see previous slide)
  - will produce in general **type IIP SNe** (see Filippenko 1997)
- **(2) The mass range of stars between ~20 and 25 $M_\odot$** → cross the HR gap, being for a while a RSG, then evolve back to the blue, ending their life as YSGs, BSGs or even WR stars
  - expected to produce **type IIL**, **type IIb SNe** in general and sometimes even **type Ib** (see the 25 $M_\odot$):



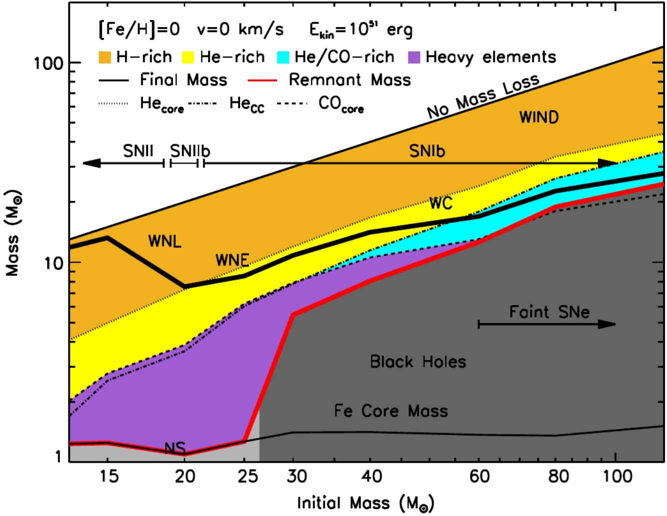
CC SNe: Stellar evolution

- **We roughly distinguish four cases of $M_{\rm init}$** (Meynet & Maeder 2017):
- **(3) The mass range of stars between 25 and ∼140-150 $M_\odot$** → end their life as WR stars (see previous slide)
  - may produce **BH** with **no SN event** (all the matter swallowed) or **Ibc SNe** (see the tracks from 32 $M_\odot$ to 120 $M_\odot$):



- **(4) The mass range of stars with $M_{\rm init} > 150\, M_\odot$** → may encounter the pair instability strip during the advanced stages of their evolution
  - produce PPISN or PISN ← pulsations → in some circumstances the complete destruction of the star → Pair Creation SN; PCSN (Heger & Woosley 2002):

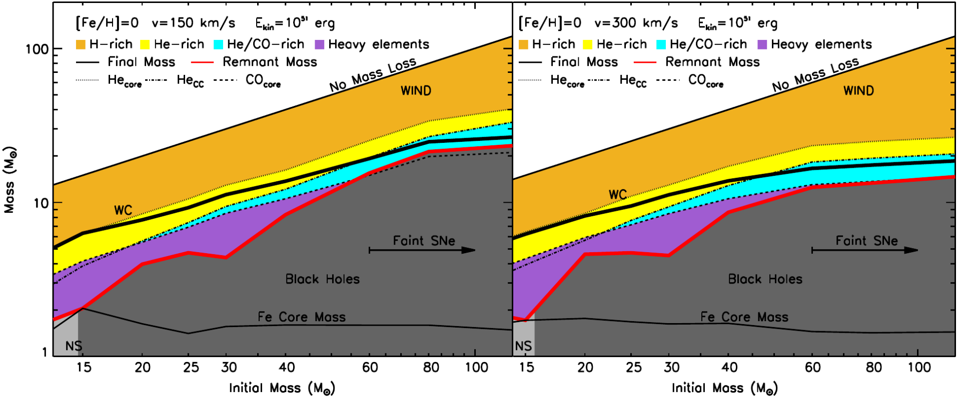
CC SNe: generation of $Z_\odot$ nonrotating massive stars



Credit: Limongi 2017

Limiting masses for the various SN types; the initial mass-remnant mass relation for 1 foe explosions

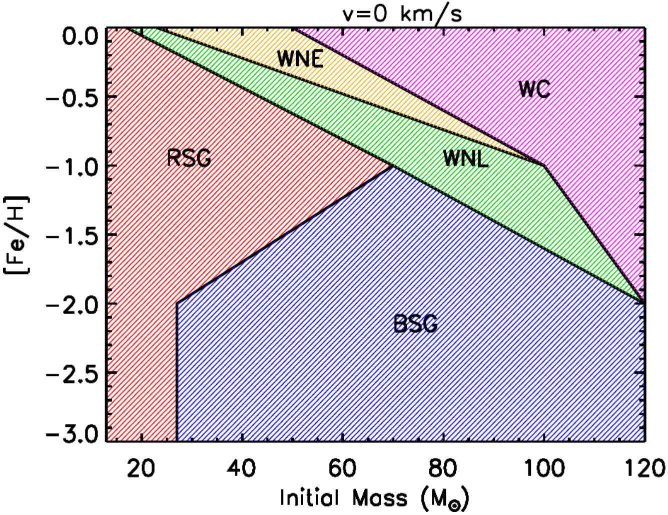
CC SNe: generation of $Z_\odot$ rotating massive stars



Credit: Limongi 2017

Limiting masses for the various SN types; the initial mass-remnant mass relation for 1 foe explosions

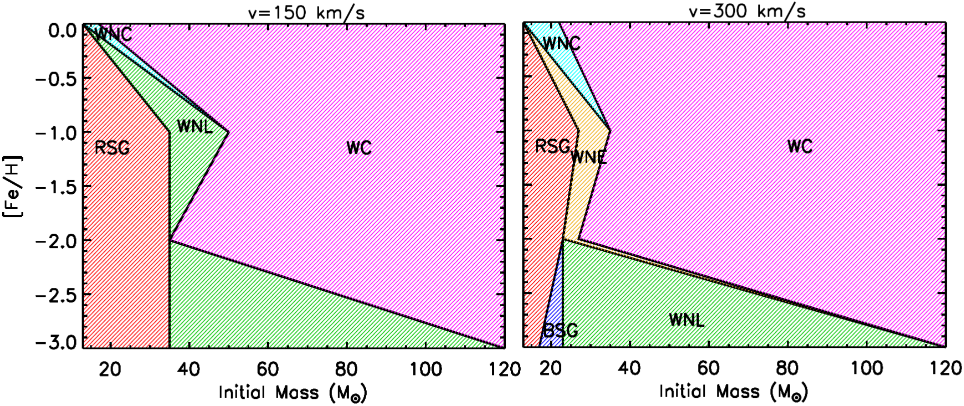
CC SNe progenitors by initial mass vs. metallicity



Credit: Limongi 2017

Predicted SN progenitors for nonrotating models at various Z

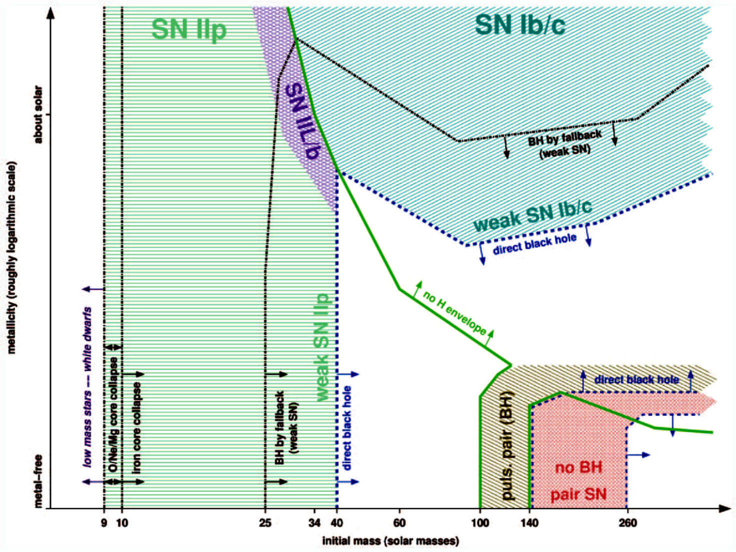
CC SNe progenitors by initial mass vs. metallicity



Credit: Limongi 2017

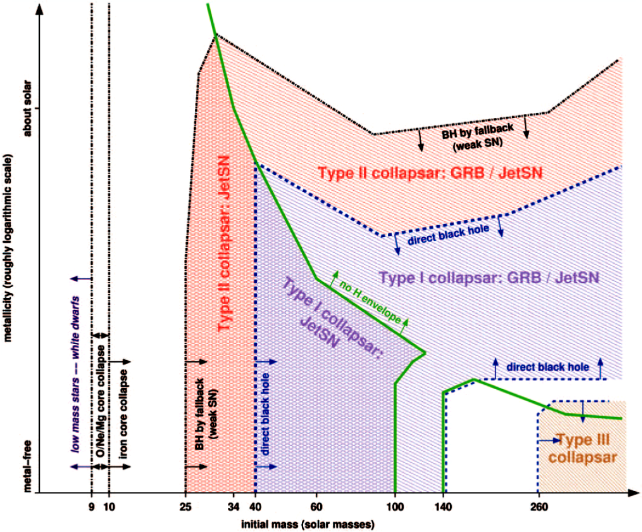
Predicted SN progenitors for rotating models at various Z

CC SNe types by initial mass vs. metallicity



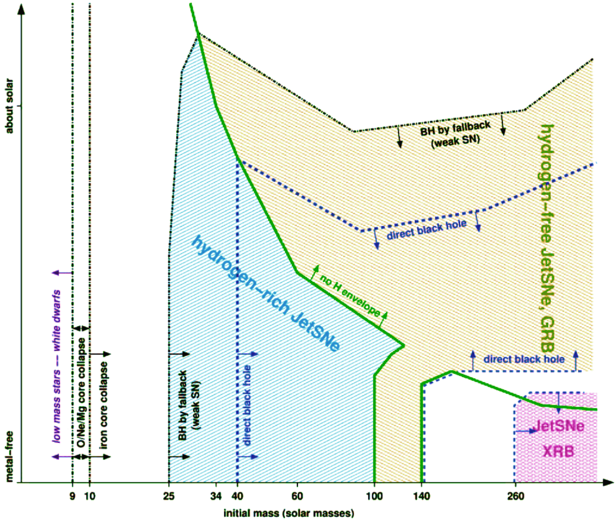
Credit: Heger+ 2003

CC SNe types by initial mass vs. metallicity



- **collapsar types** Credit: Heger+ 2003

CC SNe types by initial mass vs. metallicity



- **jet-driven types of SNe**

Credit: Heger+ 2003

CC SNe:

- **'Canonical' anatomy of a Fe core collapse:** (to the current knowledge) (e.g., Couch 2017; Pejcha 2020, etc.)
- stars more massive than about 8-10 $M_\odot$ go through multiple epochs of core and shell burning of ever heavier elements ultimately culminating in Si 'burning' to form cores of Fe
- The complex, quasi-equilibrium Si shell burning continues to grow Fe cores up to the effective M_{Ch}
- The collapse of the **critical-mass Fe core** rapidly accelerates, driven principally by photodissociation of Fe-peak nuclei and by electron captures:

$$p + e^- \rightarrow n + \nu_e$$

- Both processes drive core ρ and T higher and higher → the inner core ($\sim$0.4 - 0.6 $M_\odot$) collapses homologously, while the outer core collapses supersonically
- The rapid infall proceeds until the central ρ exceeds that of nuclear matter, $\rho_{\rm nuc} \sim 2 \times 10^{14}\,{\rm g\,cm^{-3}}$

CC SNe:

- **'Canonical' anatomy of a Fe core collapse:** (to the current knowledge) (e.g., Couch 2017; Pejcha 2020, etc.)
- stars more massive than about 8-10 $M_\odot$ go through multiple epochs of core and shell burning of ever heavier elements ultimately culminating in Si 'burning' to form cores of Fe
- The complex, quasi-equilibrium Si shell burning continues to grow Fe cores up to the effective M_{Ch}
- The collapse of the **critical-mass Fe core** rapidly accelerates, driven principally by photodissociation of Fe-peak nuclei and by electron captures:

$$p + e^- \rightarrow n + \nu_e$$

- Both processes drive core ρ and T higher and higher → the inner core ($\sim$0.4 - 0.6 $M_\odot$) collapses homologously, while the outer core collapses supersonically
- The rapid infall proceeds until the central ρ exceeds that of nuclear matter, $\rho_{\rm nuc} \sim 2 \times 10^{14}\,{\rm g\,cm^{-3}}$

CC SNe:

- **'Canonical' anatomy of a Fe core collapse:** (to the current knowledge) (e.g., Couch 2017; Pejcha 2020, etc.)
- The nature of instabilities in a region semi-transparent to neutrinos $\rightarrow$ great challenge to theory
- The evolution of the stalled shock now bifurcates into two possible channels: the central object **collapses** into a black hole (failed SN?) **or** the combined action of neutrinos and instabilities **overturns** the accretion into explosion
- The shock propagating through the star heats up the stellar interior above $\sim 5 \times 10^9$ K stimulating a nuclear burning to iron-group elements
- After the shock breakout, we observe the hot and expanding ejecta as a CC SN, part of the light comes from the radioactive decay of the newly synthesized elements, especially ^{56}Ni
- The asymptotic SN energy $\sim 10^{51}$ ergs, is $\sim$1% of the NS binding energy ($\rightarrow$ neutrinos) while the radiated energy is $\sim$0.1% of this

CC SNe:

- **Other channels:**
- **EC SN** of the "transitional range" progenitor ($\sim$8 to 10 $M_\odot$) between TN SN and Fe CC SN, with a degenerate O+Ne+Mg core
- EC SNe undergo only the first phase of the CC SNe → driven by the electron capture reactions in a degenerate O+Ne+Mg core
- EC SNe form NS, however, the process is less energetic → fainter than the "regular" CC SNe
- A pair-instability supernova **(PISN)** → driven by the production of free electrons and positrons in the collision between atomic nuclei and energetic gamma rays
- PISN can only happen in stars with a mass range from around 130 to 250 $M_\odot$ and low to moderate Z
- stars of $\sim$100 to 130 $M_\odot$ PPISN undergo a series of pulses until they shed sufficient mass to drop below 100 $M_\odot$ → low T to support pair-creation → likely followed by a "normal" CC SN

CC SNe:

- **neutrinos:**
- neutrino physics importance → (Burrows 1998, Fryer 2009)
- EOS plays an important role in number of aspects of SN explosion:
  - bounce
  - convection in core
  - neutrino emission and opacities
- rotating stars produce a disk around PNS → how does this affect a neutrino transport?
- collective neutrino oscillations →
- alternate engines → exist, but most invoking magnetic fields, magnetars, collapsars or similar mechanisms →
- these do not explain normal SNe → likely → exotic SNe or GRBs

CC SNe:

- **GWs:**
- as massive objects move around, the changes in space-time propagate as GWs ⇒ produced in system with rapidly moving quadrupole moment
- advanced LIGO: measurements up to 200 - 215 Mpc
- most sources seen to 100 kpc
- source simplifications:
    - mild (normal) rotation and no rotation: rotating quadrupole
    - higher rotation → bar modes
    - highest rotation → fragmentation ⇒ (better understand the convective GW signal)
- we can (even with advanced LIGO) probe the convective signal only for Galactic SNe

CC SNe:

- **A lot of future work:**
- progenitors
- EOS and neutrino physics
- transports and turbulence
- magnetic fields
- advancing neutrino and GW signals
- LCs → understand uncertainties + more accurate models
- nucleosynthesis → beat down uncertainties

Various rate of SN events within various galaxies ?

- MW → last SN: 1604 (1680?), M31 → last SN: 1885A
- NGC 6946 (fireworks galaxy, $D = (6.9 \pm 3.4)$ Mpc) SNe: 1917A, 1939C, 1948B, 1968D, 1969P, etc.