Lecture 1: Evolution of Massive Stars

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ICTS Summer School on Gravitational-Wave Astronomy 2022
Lectures on Core-Collapse Supernovae

Recommended Review

- Woosley, Weaver & Heger 2002, Rev. Mod. Phys. 74, 1015 (Stellar Structure and Evolution)

Recap (Hopefully): Stellar Structure Equations

Stellar evolution is governed by:

- The continuity equation (expressing mass conservation),
- The equation of hydrostatic equilibrium (or more generally the Euler of fluid dynamics for momentum conservation),
- The equation of energy conservation,
- An equation for the energy flux carried by radiation or convection in terms of, temperature gradients and/or other gradients.
- Rate equations for the change of the composition (mass fractions) due to nuclear reactions,
- Sometimes: Equations for the transport of angular momentum,
- An equation of state for the pressure in terms of density, temperature, and composition.

On secular evolutionary time scales, these equation need to be solved in spherically symmetric models. 2D models for secular evolution are restricted to certain evolutionary phases. Fully dynamical 3D simulations are only possible over short time scales.

Recap (Hopefully): Stellar Structure Equations

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho} ,$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} ,$$

$$\frac{\partial l}{\partial m} = \epsilon_{\mathrm{n}} - \epsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho} \frac{\partial P}{\partial t} ,$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \nabla ,$$

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho} \left(\sum_j r_{ji} - \sum_k r_{ik} \right) , \quad i = 1, \ldots, I .$$

(Kippenhahn, Weigert & Weiss, Stellar Structure and Evolution, Springer 2012)

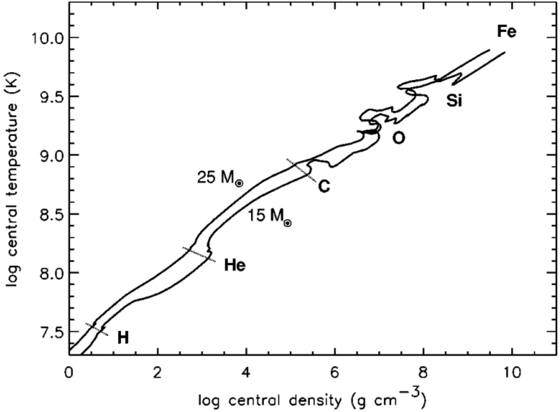
Influence of Stellar Mass

Some features of stellar structure can already be gleaned from simplified models such as polytropes with $P = K\rho^{1+1/n}$ or even one-zone models where we estimate derivatives based on central and surface values of ρ, T, P, ...
For polytropes of a given composition, one can derive that for a perfect gas or radiation-dominated equation of state (see tutorials),

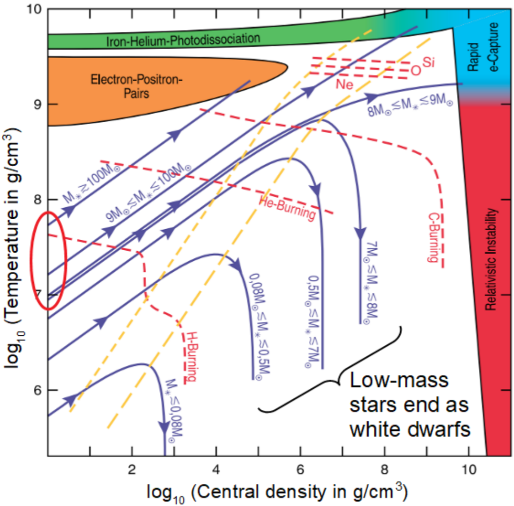
$$\frac{T_\mathrm{c}^3}{\rho_\mathrm{c}} \propto M^2.$$

This holds qualitatively for stars on the main sequence, and if stars were just to contract adiabatically, it would hold throughout their evolution. Nuclear burning, neutrino cooling, and the emergence of a more complex shell structure cause deviations from $T_\mathrm{c}^3/\rho_\mathrm{c} = \mathrm{const.}$. Nonetheless, many basic features of the mass-dependence of stellar evolution can be understood by using $T_\mathrm{c}^3/\rho_\mathrm{c} \approx \mathrm{const.}$ and charting the trajectory of $(\rho_\mathrm{c}, T_\mathrm{c})$ through different equation-of-state regimes.

Evolution of ρ_c and T_c: Realistic Models



Woosley, Heger & Weaver (2002): Real (ρ_c, T_c) trajectories:



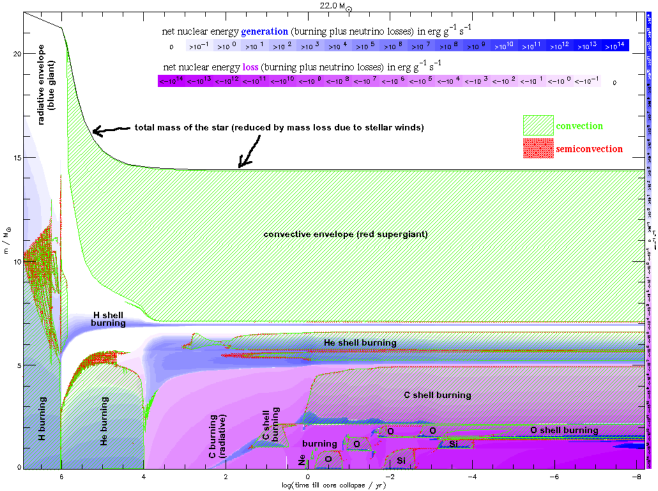
Adapted from Wheeler (1990)

Schematic View

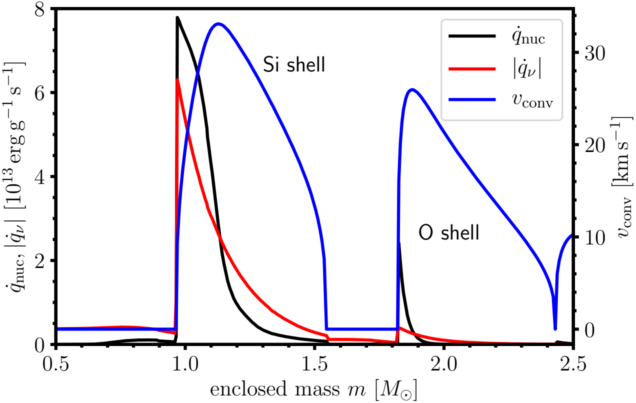
- Single stars of lower mass reach the regime of degeneracy at lower ρ_c and T_c. When this happens, they evolve into inert remnants that are supported by degeneracy pressure (white dwarfs) after H, He, and perhaps C burning or never ignite H burning at all (brown dwarfs).
- Massive stars of about $8 \ldots 100 M_\odot$ avoid degeneracy through most of their evolution. After each burning stage, the core contracts, and another burning process is eventually triggered until an Fe core is formed after after H, He, C, Ne, O, and Si burning.
- There may be a narrow channel around of **electron-capture supernovae** around $9 M_\odot$ in ZAMS mass. These collapse due to electron captures and explode after an ONeMg core is formed.
- For even higher mass, the stars reaches the regime of electron-positron pair creation after C burning. This results in pulsational instability as pair creation reduces the adiabatic index to $\gamma < 4/3$, and can lead to partial mass ejection (**pulsational pair instability supernova**), complete disruption (**pair instability supernova**), or black hole formation. Will be discussed in last lecture.

Shell Structure

- As the core contracts and reaches higher temperatures through the various burning stages, burning processes with lower threshold temperature are ignited in shells further out, producing the characteristic onion-shell structure of supernova progenitors.
- The envelope expands after H core burning; the star becomes a red supergiant. Red supergiants may still go through "blue loops". In case of SN 1987A this probably happened because of binary interaction (Podsiadlowski, Joss, & Rappaport 19989). Most massive stars explode as red supergiants, though.
- The energy generated by advanced burning stages (after He burning) is carried away predominantly by neutrinos, not photons.
- The advanced burning stages usually proceed convectively. The energy generated at the bottom of the burning region is redistributed in the convective region such that it is balanced by neutrino losses.
- H and He core burning are also convective in massive stars.
- The structural evolution of stars is conveniently visualised by Kippenhan diagrams.



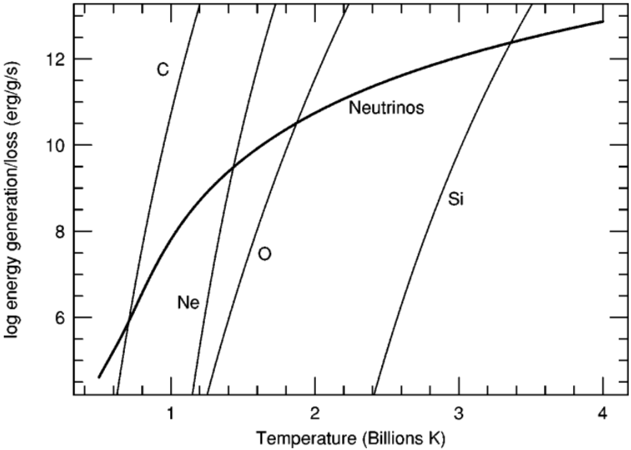
Credit: A. Heger, `https://2sn.org/stellarevolution/explain.gif`



Mueller 2020, Living Reviews in Computational Astrophysics 6, 3

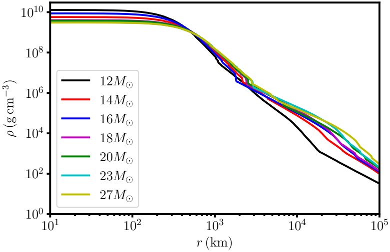
Advanced Burning Stages: Balanced Power

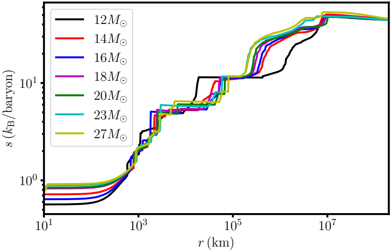
As the nuclear energy generation rates have a much steeper dependence on temperature than the neutrino loss rates, balanced power regulates the temperature and entropy of the burning region within close limits.



Woosley, Heger & Weaver 2002, Review of Modern Physics 74, 1015

The interplay of nuclear energy generation, neutrino losses, and contraction drives the entropy down during later burning stages, resulting in characteristic density and entropy profiles ate collapse. Massive stars tend to have bigger iron cores (both in radius and entropy).





Impact on Supernova Dynamics

The progenitor density profile critically influences the dynamics of collapse and explosion because it determines the accretion rate onto the proto-neutron star, (Woosley & Heger 2015, Mueller 2016)

$$\dot{M} \approx \frac{8\rho}{3}\sqrt{\frac{3GM}{r^3}},$$

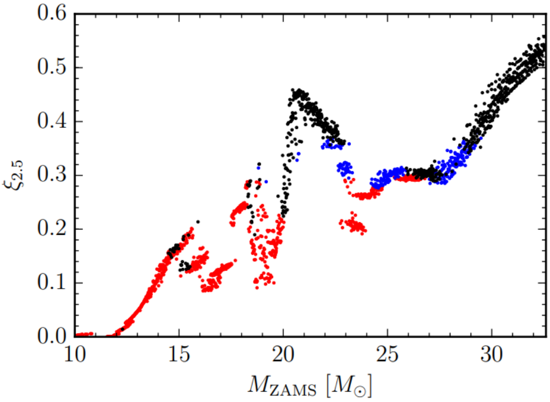
and hence the strength of the "accretion tamp" that acts to contain the supernova shock.
In lieu of the full density profile, global metrics can provide some information on how "explodable" a star is. one such measure is the compactness parameter ξ_M for a given reference mass coordinate M (O'Connor & Ott 2011),

$$\xi_M = \frac{M/M_\odot}{R(m=M)/1000\,\mathrm{km}}.$$

A number of other stellar structure parameters, such as the mass of the Fe-Si core or the binding energy outside the Si/O shell interface tend to be strongly correlated with compactness.

Non-mononicities in Supernova Progenitor Structure

Upon closer inspection, compactness, core size, etc. do not depend monotonically on progenitor mass. This is due to variations in the structure and sequence of shell burning episodes. E.g., the compactness peak is related t to the transition from convective to radiative core C burning. Some chaotic fluctuations are due to the presence or absence of shell mergers.



Mueller et al. (2016)

Time Scales of Advanced Burning Stages

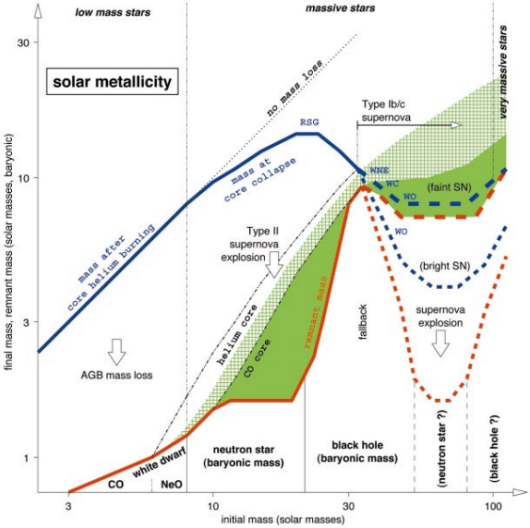
Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O,^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

(Credit: S. Woosley, https://www.ucolick.org/ woosley/ay112-14/lectures/

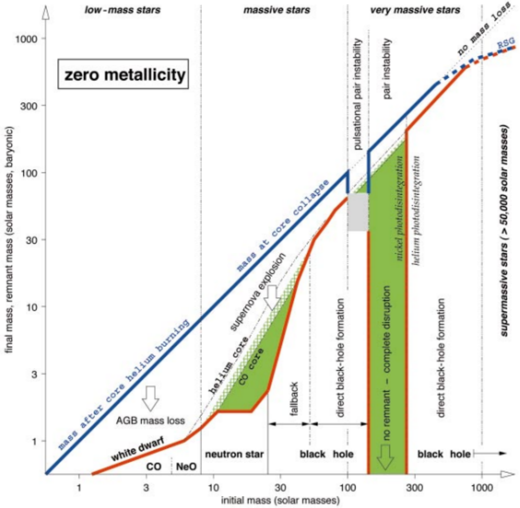
As an important side effect of the transition from photon to neutrino cooling, the time scales for the advanced burning stages become shorter than the thermal time scale of the envelope. As a result, the evolution of the core and envelope effectively decouple. The fate of the star is mostly fixed by the CO core mass/structure after He burning.

Effect of Metallicity & Mass Loss (Single Stars)



Credit: Woosley, Heger & Weaver (2002)

Effect of Metallicity & Mass Loss (Single Stars)



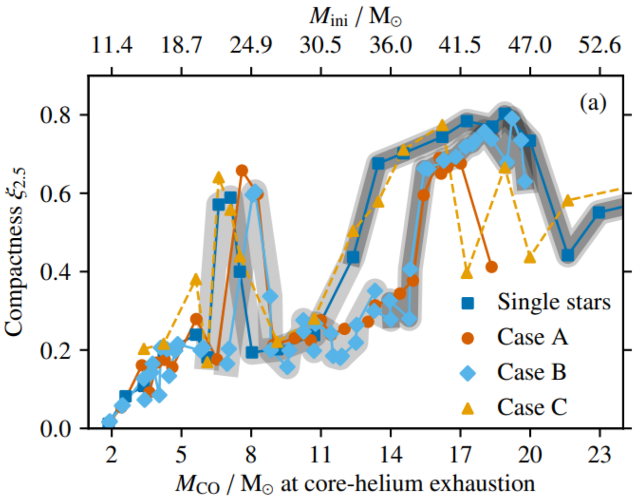
Credit: Woosley, Heger & Weaver (2002)

Effect of Metallicity & Mass Loss (Single Stars)

- Single stars will lose mass by winds, and sometimes by eruptive events (whose origin remains less clear). Wind mass loss is expected to depend on metallicity, though the functional dependence is still not completely clear and less certain for some wind regimes.
- Relatively more mass loss is predicted for more massive stars. At solar metallicity, we expect the more massive stars to completely lose their H and develop into Wolf-Rayet stars. The initial-to-final mass relation becomes non-monotonic.
- There is also a complicated interplay of mass loss with angular momentum transport within stars.
- We expect certain supernova types (pair/pulsation pair instability supernovae/gamma-ray burst supernovae) to be absent or rare at higher metallicity.

Mass Loss: Binaries

The majority of massive stars live in binaries and a large fraction of them will interact with their companion during their lifetime (Sana et al. 2012). As it is difficult to account for the rather large fraction of hydrogen-free supernovae (Ib/c, IIb, see next lectures), most of these "stripped-envelope" supernovae probably come progenitors that underwent binary interactions (Smith 2011).
The most relevant scenario for the subsequent supernova is the loss of the hydrogen envelope by the donor, but other scenarios (e.g., mass accretion or mergers) are also relevant.
To first order, we expect the cores of stripped stars to evolve to collapse similar to single stars of the same He or CO core mass (cp. previous comment on the decoupling of the core and envelope evolution). This is valid for late stripping, but mass transfer on the main sequence (Case A) or on the red giant branch, or the ascent to the red giant branch (Case B) will affect the evolution of the He core (size and final composition) and hence the pre-supernova structure.



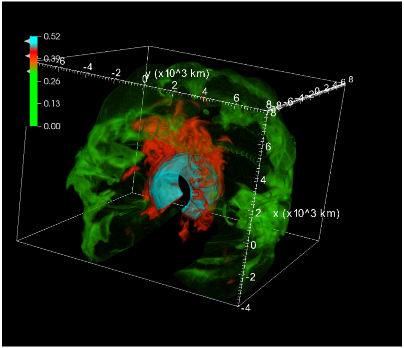
Schneider, Mueller & Podsiadlowski (2021)

Uncertainties: Mixing & Angular Momentum Transport

- 1D stellar evolution models need to treat the transport of composition and angular momentum by convection and other (magneto-)hydrodynamic instabilities by means of a diffusion (or sometimes advection-diffusion) equation.
- State-of-the art codes (e.g., Heger et al. 2000, 2005) include mixing by convection, semi-convection, thermohaline mixing, as well as shear instabilities. Angular momentum transport by magnetic torques computed based on a dynamo model is sometimes also included. (e.g., Heger et al. 2005)
- Some of the effective transport coefficients are still quite debated (e.g., for magnetic torques), and it is unclear how well effective 1D prescriptions model some of the multi-dimensional transport processes.
- One challenge in constructing a "correct" treatment of angular momentum transport in stellar interiors is to simultaneously comply with constraints on measured core spin rate in red giants (from asteroseismology), white dwarf and neutron star spin periods, and also allow for some rapidly spinning supernova progenitors to explain hyperenergetic explosions and gamma-ray bursts.

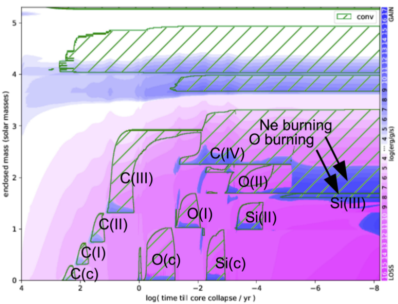
Uncertainties: Mixing

- Challenges in treating mixing in massive stars are less related to the interiors of convective region.
- Mixing at convective boundaries (overshooting, "entrainment"...) and the behaviour of regions with competing stabilising and destabilising entropy and composition gradients are a bigger concern.
- Some of these processes can be studied with 3D (magneto)-hydrodynamic simulations, but these can only cover limited time scales. For the subsequent supernova, it is also important to consider deviations from spherical symmetry in the core region of the star.

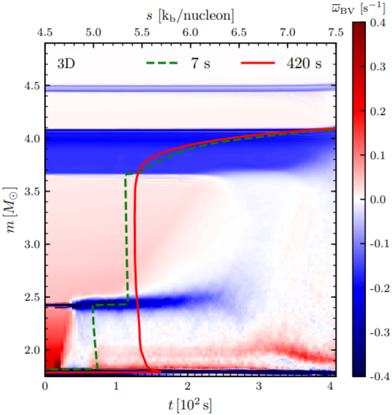


Mueller et al. (2016)

Mixing: Shell Mergers

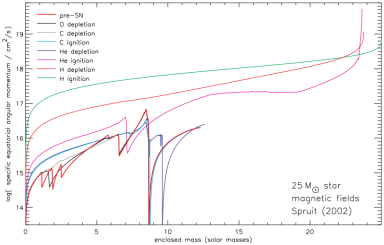


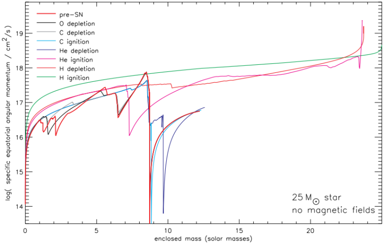
Collins, Müller & Heger (2018): 40% of progenitors between $16 M_\odot$ and $26 M_\odot$ undergo shell merger minutes before collapse



Yadav et al. (2020): 3D simulation of shell merger shortly before collapse

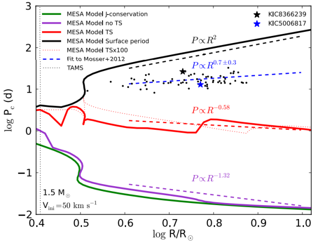
Angular Momentum Transport





Heger et al. (2005)

Modern 1D stellar evolution models (top) of massive stars with magnetic torques (Tayler-Spruit dynamo) predict pre-collapse spin rates that translate into pulsar birth period of tens of milliseconds (Heger et al. 2005) as observed. However, the predicted core spin rate in evolved low-mass stars are still too high (Cantiello et al. 2014). More efficient angular momentum transport mechanisms may be at play.



Cantiello et al. (2014)

Special Evolutionary Channels: Electron Capture Supernovae around $9 M_\odot$ ZAMS mass?

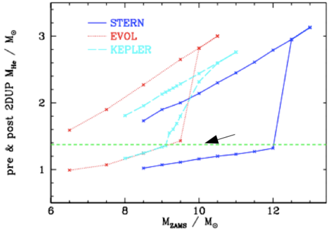
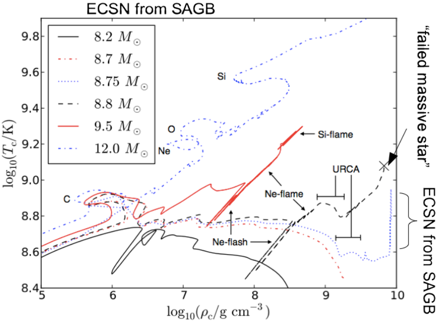


FIG. 2.— Helium core masses for stars of various initial masses, as obtained using different stellar evolution codes (solid line: STERN, dashed line: KEPLER, dotted line: EVOL). The upper part of the line shows the maximum size of the helium core, prior to the second dredge-up. The lower part shows the size of the helium core just after the completion of the second dredge-up and prior to the onset of the TP-AGB. The light dashed horizontal line gives the lower limit for the final helium core mass for which the star may experience an electron-capture supernova.

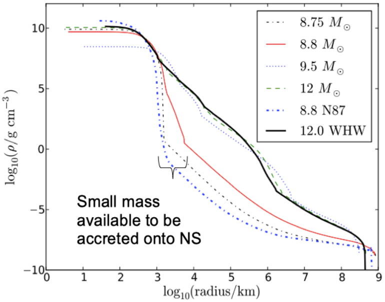
Poelarends et al. (2008)
https://ui.adsabs.harvard.edu/abs/2008ApJ...675..614P



Jones, Hirschi & Nomoto (2013)
https://ui.adsabs.harvard.edu/abs/2013ApJ...772..150J

Width of this channel may be narrow (a few percent of SNe from single stars or even none at all; perhaps more for binaries).
No SN has been clearly identified as ECSN (Crab is a candidate, but its kick velocity argues against that).

Special Evolutionary Channels: Electron Capture Supernovae around $9 M_\odot$ ZAMS mass?



Jones, Nomoto & Hirschi (2013)

- Small mass between O/Ne/Mg core and H shell
- Implies NS mass very close to $1.37 M_{sun}$ (baryonic)
- Explosion energy of a few 10^{49}erg
- Low kick velocity (a few km/s)
- Same explosion dynamics applies if O/Ne WD is brought to Chandrasekhar mass (accretion-induced collapse)
- If He core mass is higher by a few $0.1 M_{sun}$, kick can still be small (tens of km/s)