SUPERNOVAE
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Luca Zampieri
INAF-Astronomical Observatory of Padova

II. Explosion mechanisms

Evolution of a massive star

Main sequence phase: core H burning

In stars nucleons are assembled in different nuclear configurations, releasing binding energy that mantains hydrostatic equilibrium.

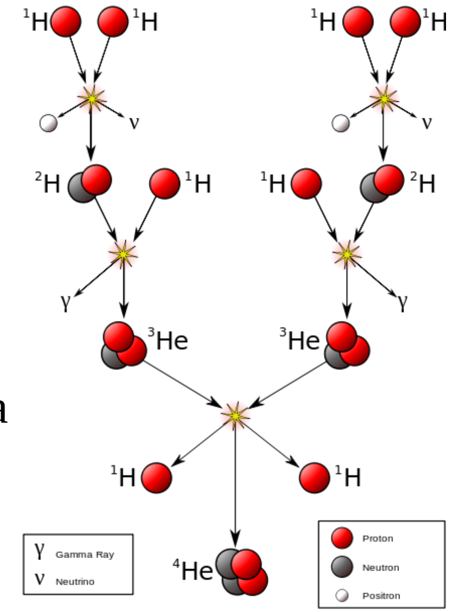
Masses of bound nuclei (*mb*) are smaller than the sum of the masses of the free individual nucleons (*mn*). The difference *Dm=mn-mb* is a measure of the nuclear binding energy: $Eb=Dmc^2$

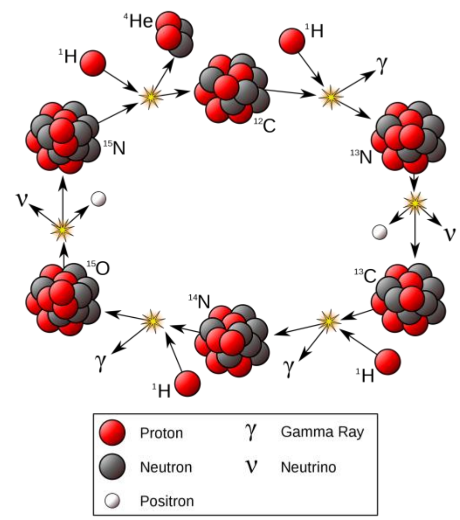
After the first phase of gravitational contraction from a cold and dim molecular cloud lasting ~0.01 – 100 Myr (Iben 1965), a protostar with masses > 0.08 Msun reaches a central temperature of 1.0e7 K and begins to burn Hydrogen into Helium (**Main Sequence phase**):

*A) proton-proton chain (*low M stars*)*: p + p → d + β+ + ν
d(p,γ)3He
3He(3He,2p)4He (pp1 chain)
→ 26 MeV

B) *CNO cycle* (high M stars): 12C(p,γ)13N
13N(β+ν)13C(p,γ)14N(p,γ)15O(β+ν)15N(p,α)12C (CNO1)

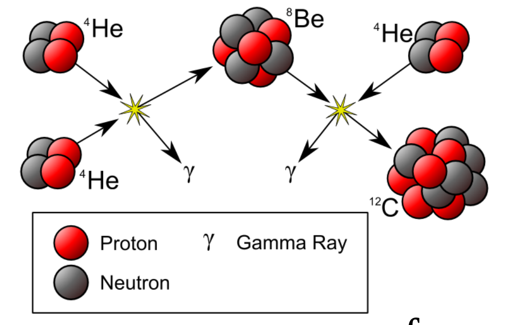
MS lifetime: $t = E/L = fMc^2/L \propto M/L \propto M^{-2.5}$ assuming $L \propto M^{3.5}$





Giant phase: core He burning and beyond

Once H is exhausted, the He-rich core can again gravitationally contract toward a new equilibrium configuration. Depending on its mass, a star can either become a stable He WD or reach sufficiently high temperatures (1.0e8 K, required by the higher Coulomb barrier) to fuse He to Carbon.



A) Triple-α reaction: 4He + 4He → 8Be

8Be + 4He → 12C + β+ + β- → 7 MeV

B) C-α reaction: 12C + 4He → 16O + γ → 7 MeV

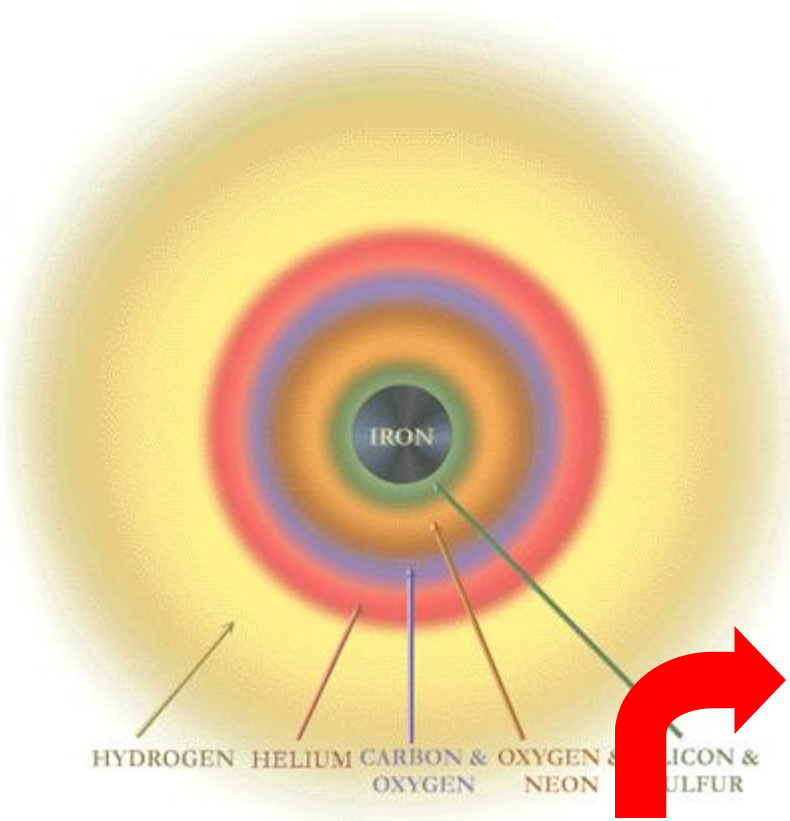
The He burning phase is shorter because He fusion produces less energy per gram of fuel than H fusion (hence more fuel is needed to provide the same L).

He burning results in a CO-rich core. He exhaustion forces the core to contract. Stars with masses up to 8 Msun are not able to achieve sufficient temperatures to ignite C (that requires 0.6 – 1 GK).

M < 8 Msun stars end their lives as CO WDs, representing stellar remnants of planetary size that are supported by the pressure of degenerate electrons.

M > 8 Msun stars ignite further core burning stages (C, O, Ne, Mg, Si) up to the formation of 56Fe, among the most tightly bound species (*Eb=8.8* MeV per nucleon).

Late stages: beyond Si burning, core collapse and explosion



Evolutionary Stages for 25 Solar Mass Star

Stage	Temperature (K)	Density (g/cm^3)	Duration
Hydrogen Burning	4×10^7	5	7×10^6 yrs
Helium Burning	2×10^8	700	5×10^5 yrs
Carbon Burning	6×10^8	2×10^5	600 yrs
Neon Burning	1.2×10^9	4×10^6	1 yr
Oxygen Burning	1.5×10^9	10^7	6 months
Silicon Burning	2.7×10^9	3×10^7	1 day
Core Collapse	5.4×10^9	3×10^9	1/4 sec
Core Bounce	2.3×10^{10}	4×10^{14}	milliseconds

Si is continuing to burn in a shell around the core and continually increases its mass. At this stage *the Fe core is supported by electron degeneracy pressure*.

T and *rho* are so high that *nuclear statistical equilibrium* (NSE) is established (equilibrium between strong and electromagnetic interactions/photodisintegration).

Abundances deduced using statistical mechanics. They depend only on *T*, *rho* and neutron excess: *eta=1-2Ye*,where *Ye=ne/(∑i ni mi)* is the electron mole fraction (*ne*, *ni* and *mi* → electron density, i-th nuclide density and relative atomic mass, respectively).

Core collapse

When the core exceeds ~1.4 Msun, it has no other energy source to support the pressure and it becomes unstable to gravitational collapse.

The infall dynamics depends sensitively on two parameters: (i) the electron mole fraction, *Ye*, and (ii) the entropy per baryon, *s*.

For a small value of s, NSE favors a composition of iron peak nuclei. A large value of s implies that many photons are available per baryon, which favors the photodisintegration of heavier nuclei into free nucleons.

During contraction, as *rho* increases, *electrons are captured onto nuclei*, (e−, νe). Hence *Ye* decreases and electrons that were contributing to the pressure are removed. At the same time, as *T* increases, *s increases and* e− *become relativistic*.

- Photodisintegration:

  $\gamma + {}^{56}\mathbf{Fe} \rightarrow \mathbf{13\ {}^{4}He + 4n}$

- Neutronization:

  $p^{+} + e^{-} \rightarrow \mathbf{n + \nu_e}$

- The EOS becomes dominated by relativistic electrons and softens (Gamma=4/3)

All these effects cause the infall to turn into a collapse (of the innermost 0.5-0.8 Msun)

Core bounce, prompt shock and neutrino burst

Within a fraction of a second, from a size of several thousand km the core collapses to a proto-NS of several tens of km radius.

In the collapsing core, *rho* is so high that neutrinos have significant interactions with matter (inverse β-decay, electron-neutrino scattering, elastic and inelastic scattering on nuclei; Bruenn and Haxton 1991) and neutrino transport effects become important (Lentz et al. 2012).

- **t ~0.1 s** (*rho* ~ 1.0e12 g/cm^3): The neutrino diffusion time becomes larger than the dynamical time (*neutrino sphere*) → neutrinos become trapped (Bethe 1990)
- **t ~0.11** s (*rho* ~ 1.0e14 g/cm^3): The inner core (M ~0.5-0.8 Msun) reaches nuclear densities and bounces, driving a shock wave through the infalling matter. This **prompt shock** propagates outward, but loses severely energy by dissociating Fe
- **t ~0.12** s: When the prompt shock reaches the neutrino sphere, additional e-captures on free protons also remove energy from the shock, giving rise to a strong burst of electron neutrinos (**prompt νe burst;** ~ 1.0e53 erg/s for ~10–20 ms)
- **t ~0.2** s: **The shock stalls** at a radius of ~100–200 km

Neutrino diffusion

Physical conditions in the proto-NS (defined by the radius of the energy-integrated electron neutrino sphere, where $tau_{nu} = 1$) and below the prompt shock

- Neutrinos and antineutrinos of all flavors (electron, muon and tau) are produced

  $e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$ electron-positron annihilation
  $\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,tau} + \bar{\nu}_{\mu,tau}$ neutrino-antineutrino annihilation
  $N + N \rightarrow N + N + \nu_{\mu,tau} + \bar{\nu}_{\mu,tau}$ nucleon bremssthralung

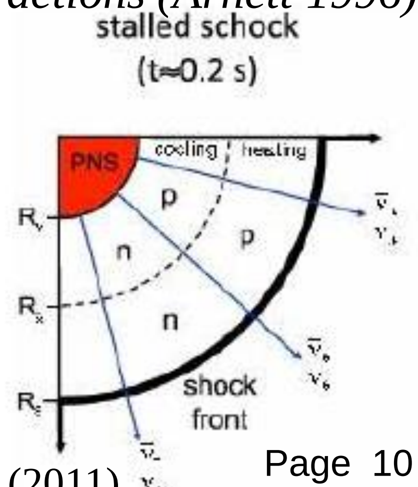
- Interactions with leptons (scattering or neutral current), nucleons (charged-current), nuclei (scattering) cause them not to escape freely but to diffuse outwards

- *Electron neutrino/antineutrino cross section for nucleon interactions (Arnett 1996):*

  $s = 2.0e\text{-}44\ (E/511\ keV)^2\ cm^2$

- *Neutrino diffusion time (E=150 MeV, R=10 km)*

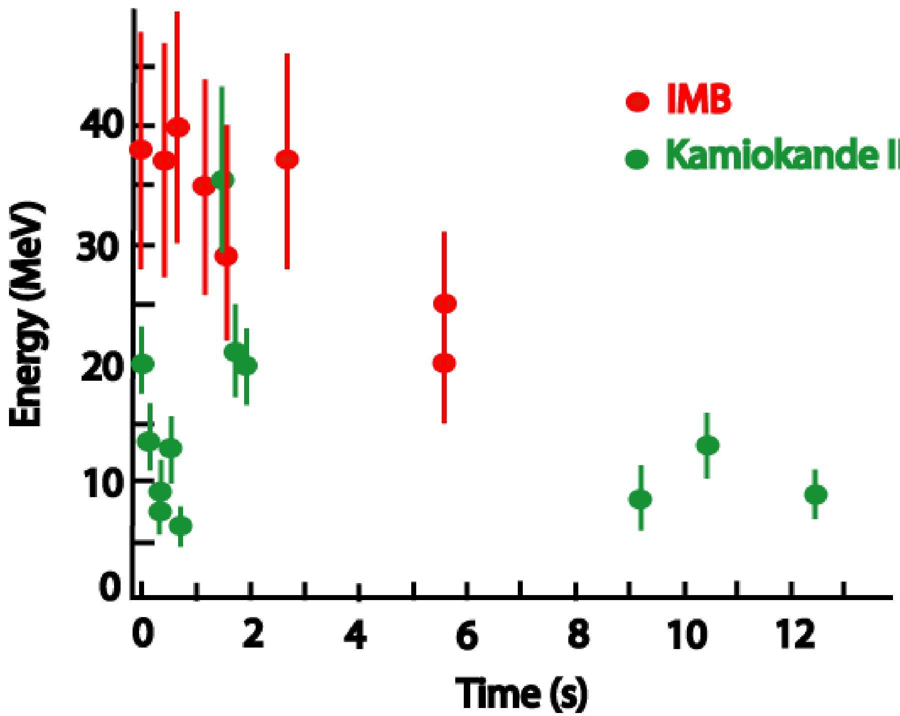
  $n = rho/mn = 6.0e37\ cm^{-3}$
  $lambda = 1/(n\ s) = 9\ cm$
  $tau = R/lambda >> 1$
  $tdiff = R\ tau/c = R^2/(lambda\ c) = 4\ s$



Jose' and Iliadis (2011)

Neutrinos from SN 1987A

A few hours before the light from SN 1987A reached Earth, 11 *electron antineutrinos* were recorded by the KamiokaNDE-II detector (Hirata et al. 1987), 8 by the Irvine-Michigan-Brookhaven (IMB) detector (Bionta et al. 1987), and 5 by the Baksan Neutrino Observatory (Alexeyev et al. 1988). Number and energies of detected neutrinos, and measured burst duration in agreement with theoretical predictions.



Neutrino events from SN 1987A (courtesy of Dick McCray)

Delayed shock, neutrino-driven wind and explosion

The *gain radius Rx* divides the region between the proto-NS and the shock in 2 parts:

1) Dominance of cooling by neutrino emission: $p + e^- \rightarrow n + \nu_e$
$n + e^+ \rightarrow p + \bar{\nu}_e$

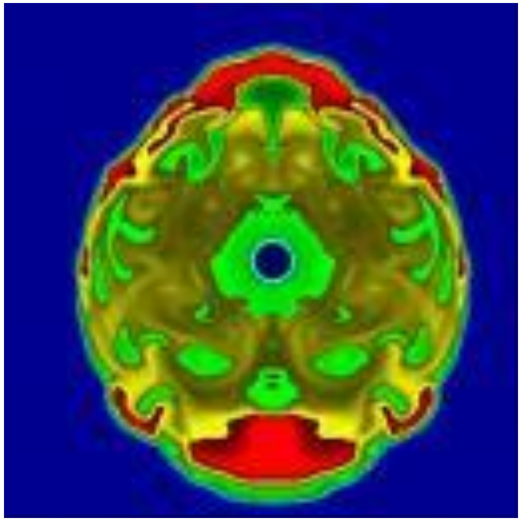
2) Dominance of heating via neutrino absorption: $n + \nu_e \rightarrow p + e^-$
$p + \bar{\nu}_e \rightarrow n + e^+$

Energy deposition in the latter region keeps the pressure high and rejuvenates the shock, causing the supernova explosion (**delayed shock**; Wilson 1985; Bethe and Wilson 1985; Mayle and Wilson 1988, Wilson and Mayle 1993). *Only ~1% of the total gravitational binding energy is required to initiate a powerful explosion.*

Strong neutrino fluxes drive a flow of protons and neutrons, inducing convective overturn from above the proto-NS (**neutrino-driven wind**; Duncan et al. 1986).

Advanced, self-consistent core-collapse models have difficulties in producing an explosion. The problem is highly complex, *involving energy-dependent neutrino transport in three dimensions*, *a convectively unstable region near a compact hot and dense object*, *possible diffusive instabilities*, magneto-rotational effects, and so on.

Core-collapse: hydrodynamics of the explosion



Colgate and White (1966) were the first to propose that core-collapse supernovae may be neutrino-driven. Two decades later Wilson discovered that delayed neutrino-driven explosions could be obtained (Wilson 1985; Bethe & Wilson 1985).

State-of-the-art simulations today continue to explore neutrino-driven explosion in the context of 2D and 3D models (e.g. Burrows et al. 2006, 2007; Marek & Janka 2009; Bruenn et al. 2009; Suwa et al. 2010; Takiwaki et al. 2011)

Multidimensional hydrodynamical instabilities: *convection* in the hot-bubble region increases efficiency of nu heating behind the shock (Herant et al. 1992, 1994; Burrows et al. 1995; Janka & Muller 1996; Muller & Janka 1997), and another large-scale instability, the *standing accretion-shock instability* (SASI; Blondin et al. 2003; Blondin & Mezzacappa 2006;) has a similar beneficial effect.

Core-collapse: hydrodynamics of the explosion

Both instabilities help to keep the accreted material in the gain region for a longer time before it is advected deeper into the cooling region (effectively increasing the adv. time)

$\tau_{adv} > \tau_{heat}$

Advection time-scale through gain region > Heating time-scale required to unbind material between gain radius and shock (Janka & Keil 1998; Thompson 2000; Janka et al. 2001; Buras et al. 2006a; Thompson et al. 2005; Murphy & Burrows 2008)

Detailed studies of the multidimensional hydrodynamics of the explosion (e.g. Muller et al. 2012) must deal with (e.g. Lentz et al. 2012):

* Neutrino transport and heating
* Large-scale hydro instabilities
* Magnetic field and rapid rotation
* Oscillations of the proto-NS star

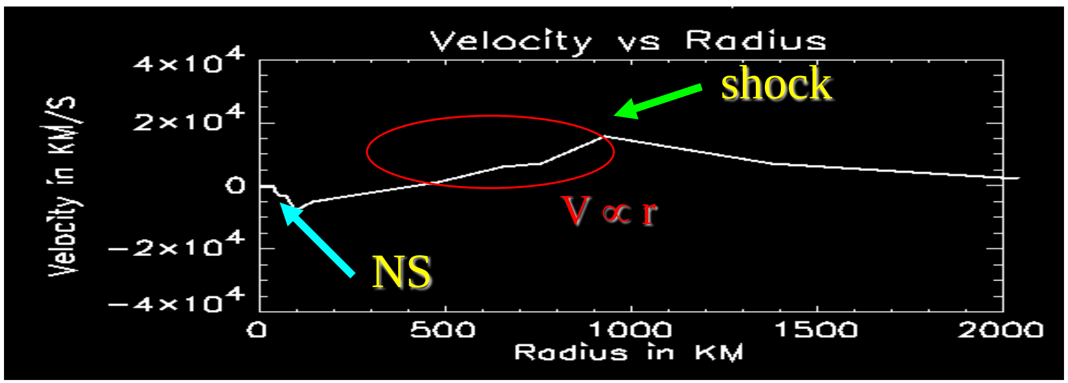
Successful explosion not yet finally and unambiguously established on the basis of state-of-the-art neutrino hydrodynamics simulations in 2D

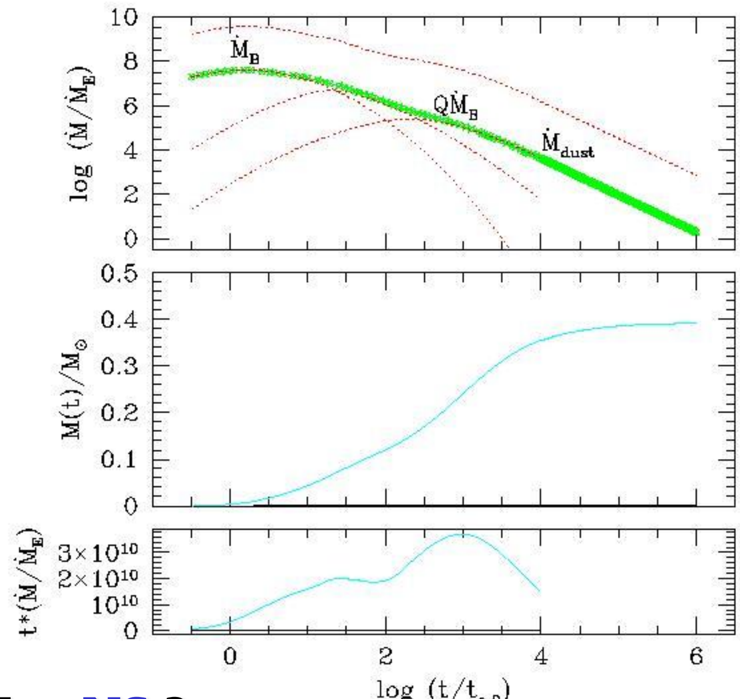
Fallback and BH formation

Fallback and BH formation

- After shock passage, ejecta are in homologous expansion: $V \propto r$
- Low velocity, inner part of the expanding envelope (inside the He layer) may remain gravitationally bound → **fallback** (Woosley & Weaver 1995; Colpi et al. 1996; Zampieri et al. 1998)

The energy deposited by the shock wave in the inner shells is lost in accelerating the layers on the top → the velocity increases outwards



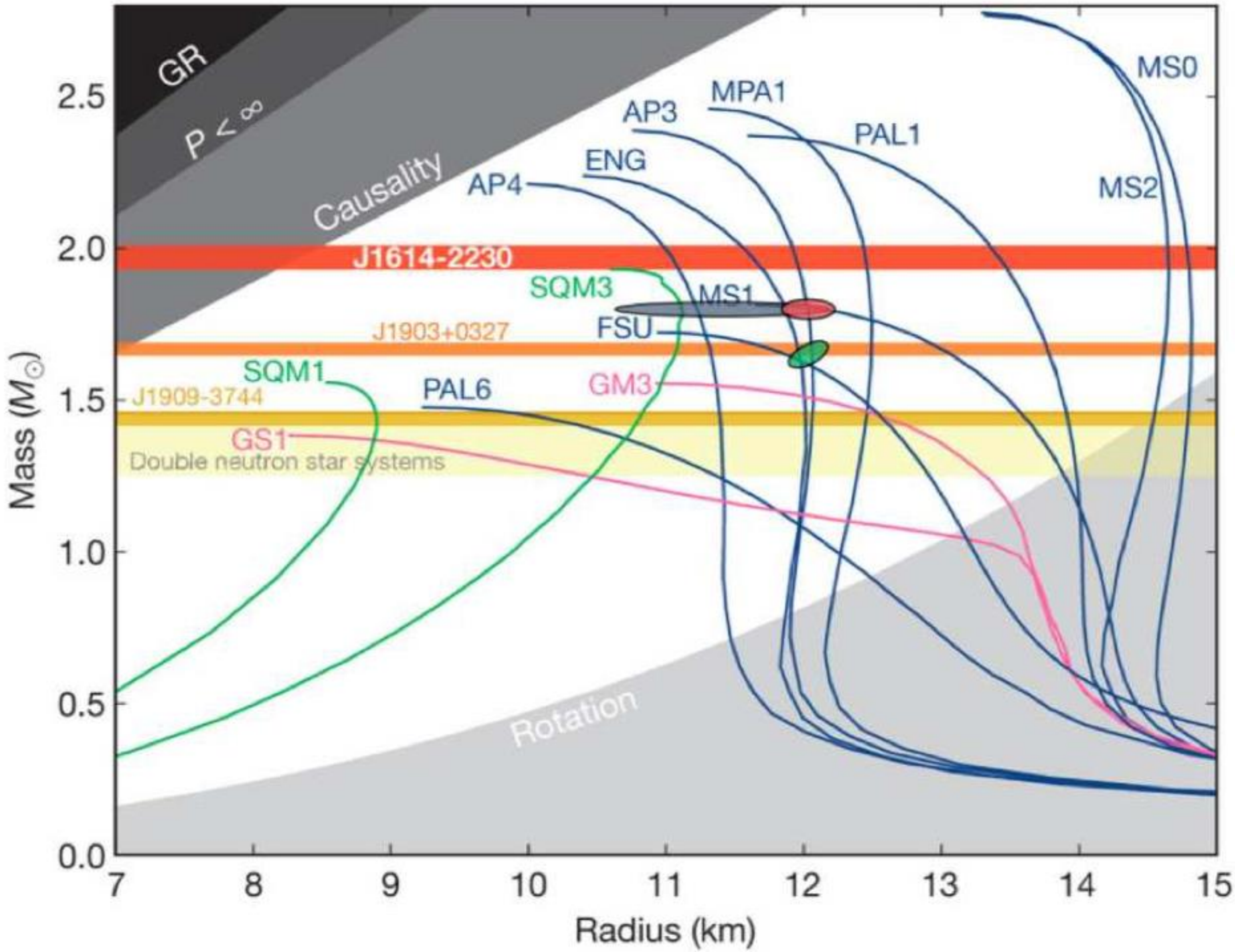


$M_{rem} = M_{core} + M_{fb}$ → **BH** or **NS** ?

$M_{rem} < M_{cr}$ → **NS**

$M_{rem} > M_{cr}$ → **BH**

Fallback (and direct collapse) determines the mass distribution of stellar BHs



GR
P < ∞
Causality
Rotation
J1614-2230
J1903+0327
J1909-3744
Double neutron star systems
AP4
ENG
AP3
MPA1
PAL1
MS0
MS2
MS1
FSU
GM3
SQM3
SQM1
PAL6
GS1
Mass ($M_\odot$)
Radius (km)
0.0
0.5
1.0
1.5
2.0
2.5
7
8
9
10
11
12
13
14
15

Formation and distribution of NSs and BHs

Mrem = Mcore + Mfb → **BH** or **NS** ?

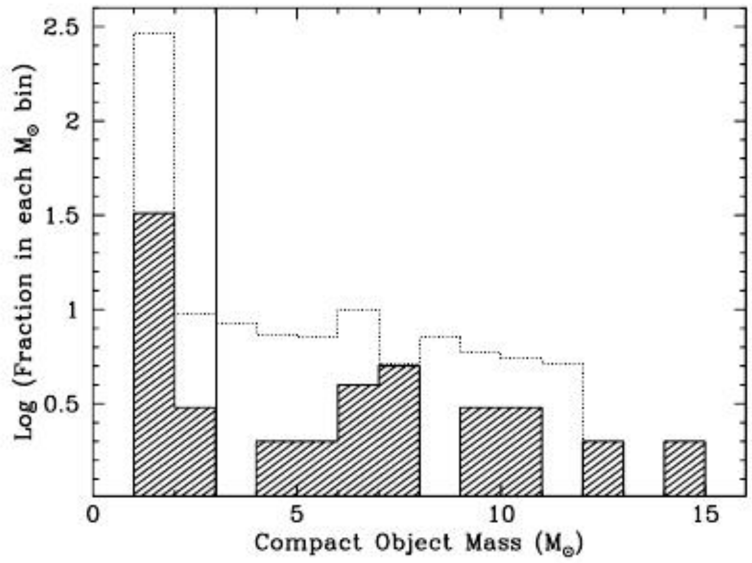
(Woosley & Weaver 1995, ApJS; Fryer 1999, ApJ)			
	8-19 M_0	19-25 M_0	25-40 M_0
M_{core}	1.4 M_0	1.6-1.8 M_0	2.0 M_0
M_{fb}	0	0.1-0.3 M_0	> 1.0 M_0
M_{rem}	1.4 M_0	1.7-2.1 M_0	> 3.0 M_0
M_{cr}	1.8-2.2 M_0 (Akmal et al. 1998, PRC)		
	NS	?	Fallback BH

What is the max observed NS mass? **1.97 +/- 0.04 Msun** (Demorest et al. 2010)

What is the max BH mass? **80 Msun** at Z=0.01 Zsun (Belczynski et al. 2010)

If Mb is the maximum mass of the progenitor that can produce a NS:

$$Xbh = \int_{Mb} f(M)dM / \int^{Mb} f(M)dM$$ relative fraction of BHs to NSs



Observed mass distribution of compact objects in X-ray binaries (shaded histogram; Casares 2006), compared to the theoretical distribution computed in Fryer & Kalogera (2001)

Supernovae and Gamma-Ray Bursts

Gamma-Ray Bursts

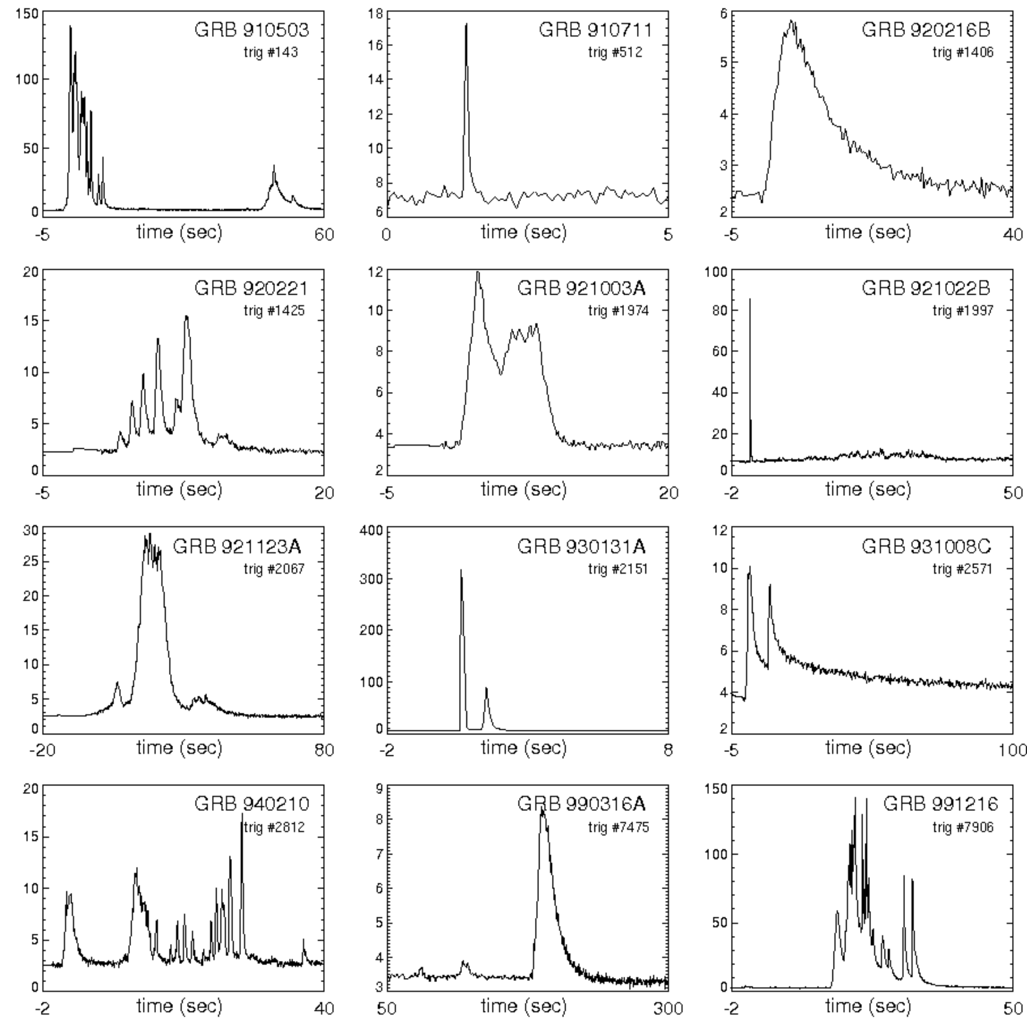
Brief, intense flashes of electromagnetic radiation with typical photon energies (~100 keV) in the γ-ray domain

The most luminous electromagnetic events in the Universe, isotropically distributed on the sky. No repeated burst has been detected from the same source (Gehrels et al. 2009)

Usually followed by a longer-lived afterglow emitted at longer wavelengths (X-rays, UV, optical, IR and radio)

GRB light curves show very complex and diverse patterns. Two broad categories have been established

	duration	**peak energy**
Short (hard)	0.3 s	360 keV
Long (soft)	20-30 s	220 keV



12 bright GRBs detected by BATSE/CGRO

Long GRB afterglows

GRB 970228: First X-ray (Costa et al. 1997) and optical (van Paradijs 1997) afterglows discovered in 1997 → direct measurement of GRB redshift using optical spectroscopy

GRB 980425 and SN 1998bw: The GRB-supernova connection (Galama et al. 1998; Iwamoto et al. 1998)

Supernova, *apparently of Type Ic*, also observed in GRB 030329–SN 2003dh (Stanek et al. 2003) and GRB 031203–SN 2003lw (Malesani et al. 2004)

Eexp = 1.0e52 erg → *hypernovae*

Current models require the acceleration of tiny amounts of matter to ultrarelativistic speeds, as well as a beamed emission focalized into a very small fraction of the sky (e.g. Woosley and Bloom 2006) → *Magnetar* or *Collapsar*?

Thermonuclear ignition of CO WD

A different mechanism for Type Ia SNe

Absence of H emission Balmer lines → H mass < 0.1 Msun

Si II, Ca, Mg, S, O (P Cygni) emission features near maximum light
→ Incomplete burning of material moving at high speeds (1.0e4 km/s)

Two weeks after maximum, permitted Fe II lines
→complete nuclear processing of the inner region to Fe-peak elements

A month after maximum, forbidden emission lines from Fe II, Fe III and Co III
→ light curve tail powered by 56Co decay

The high/low amount of 56Fe/intermediate mass elements point to a thermonuclear explosion as the origin of the outburst of Type Ia SNe

H depleted fuel is naturally provided by a CO WD

He WDs ruled out because explosion is too energetic. O-Ne-(Mg) WDs ruled out because they are expected to collapse (efficient e- capture on 24Mg)

Evidence for an old progenitor system comes also from the fact that Type Ia SNe are observed in all types of galaxies, while CC SNe are found only in late type galaxies.

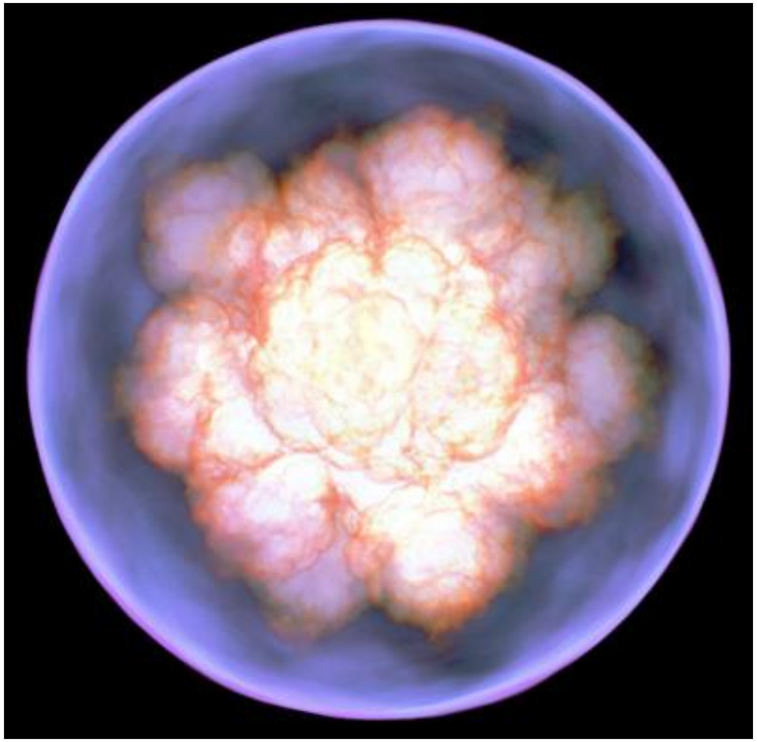
Ignition regimes

The explosion is triggered when the CO WD reaches 1.4 Msun by accretion from a companion star (or merging) and becomes unstable (*Chandrasekhar limit*) → C ignition

C ignition in a degenerate environment depends on the density, temperature, chemical composition and velocity profiles. Two possibilities:

burning front/wave moves *supersonically* → *detonation*
burning front/wave moves *subsonically* → *deflagration*

Image by F. Roepke



- **Prompt detonation**

Pure detonation at the WD center that propagates outward (Arnett 1969). A detonation wave prevents expansion of the layers ahead of the burning front → fuel almost totally incinerated into Fe-peak elements (fails to account for intermediate-mass el.)

- **Pure deflagration**

Fuel layers can react to the advancing front by expanding (Nomoto et al. 1976) → burning quenched when the WD is still gravitationally bound. Large amounts of unburnt C and O (> 0.57 Msun) left behind (Roepke et al. 2007)

Ignition regimes: delayed detonation

- **Delayed detonation**

A deflagration front propagates and pre-expands the star. Subsequently, the deflagration wave switches into a detonation (Ivanova et al. 1974) → synthesis of intermediate-mass elements, while providing the required energy budget

The model accounts for the expected light curves and photospheric expansion velocities **(**Hoeflich and Khokhlov 1996)

Main uncertainty: mechanism driving the deflagration–detonation transition.
May naturally take place once the flame reaches the so-called distributed burning regime (Roepke and Niemeyer 2007), at *rho* ~ 1.0e7 g/cm3, when turbulence affects the laminar flame structure

http://www.nersc.gov/assets/ScienceAtNERSC/_resampled/SetWidth230-Supernova-1.jpg

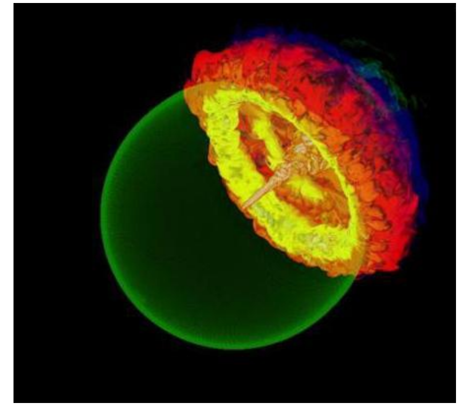
Ignition regimes: delayed detonation

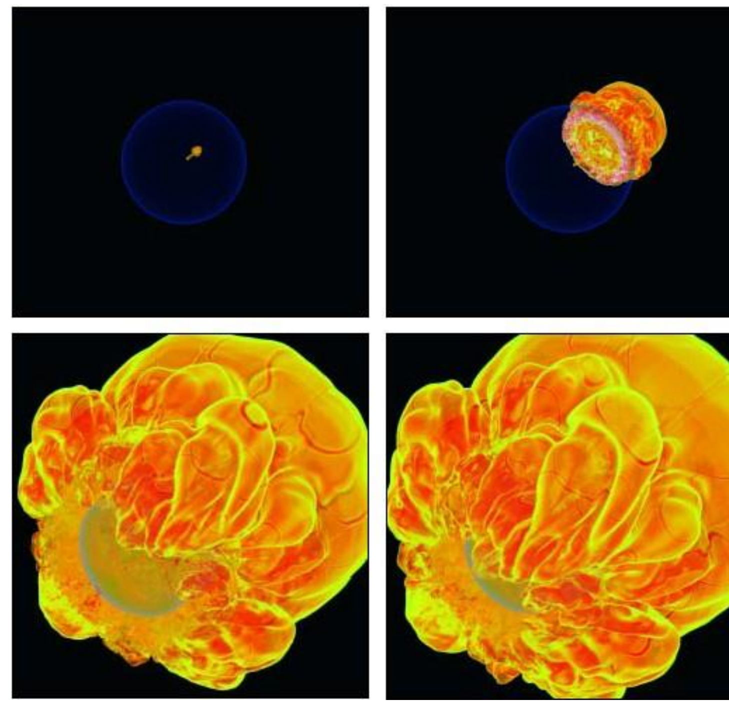
- **Gravitationally confined detonation**

Asymmetric deflagration flame ignitions, pushing burnt fuel towards the WD surface. The collision of these ashes on the far side may generate a detonation wave (Plewa et al. 2004)

- **Pulsational delayed detonation**

Initial deflagration wave pre-expands the star. The burning front is quenched and fails to unbind the star. During recontraction, compressional heating at the interface between burnt and unburnt material ultimately triggers a detonation (Maeda et al. 2010)





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