Supernovae

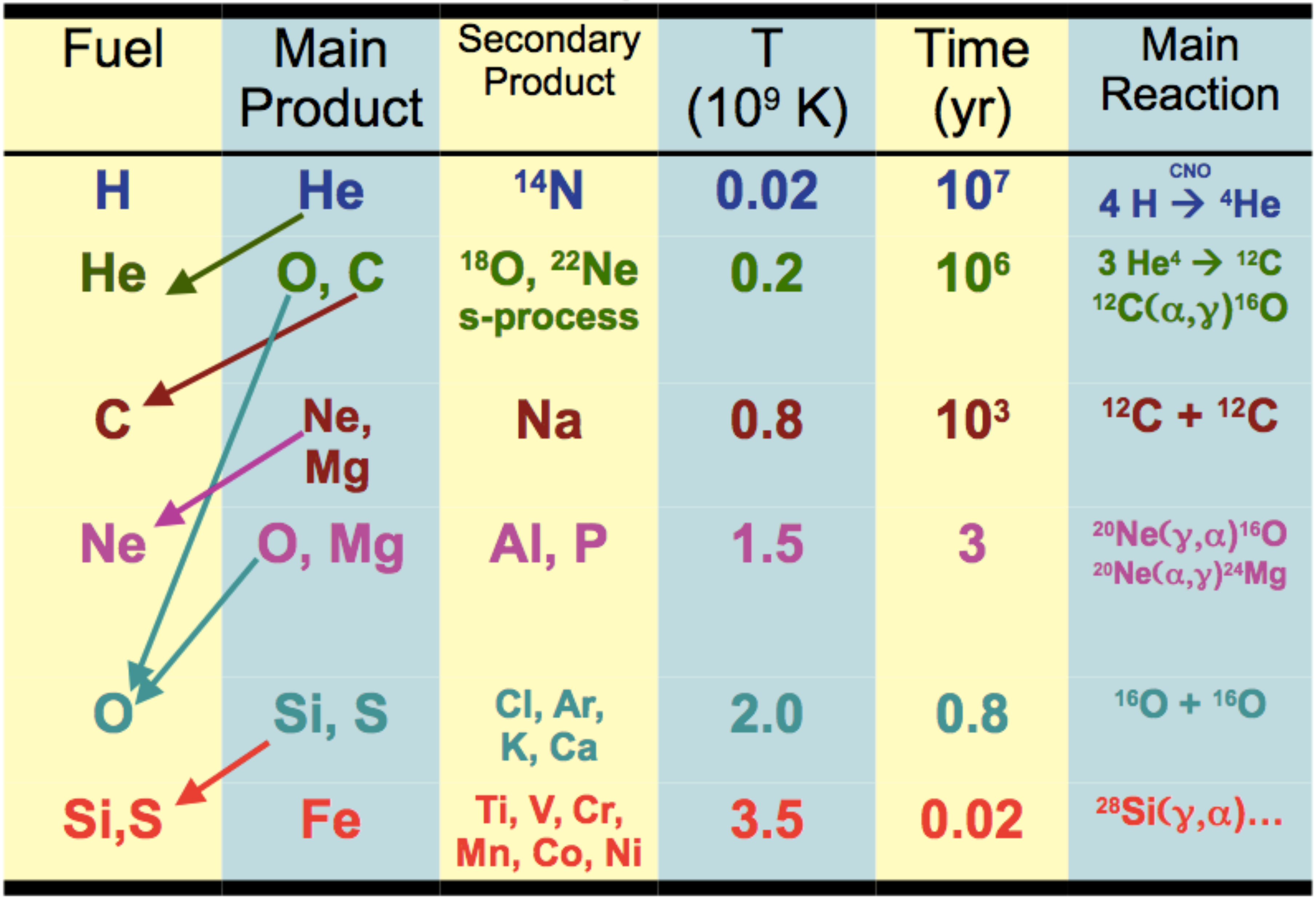
Fates of Different Mass Objects

	Initial Mass ($M_\odot$)	Final Evolutionary State
	<0.01	planet
	$0.01<M_*<0.08$	brown dwarf
Low	$0.08<M_*<0.25$	He white dwarf
	$0.25<M_*<8$	CO white dwarf
	$8<M_*<12$	ONeMg white dwarf
High	$12<M_*<30\text{-}40$	Type II SN → ns,bh
	$30\text{-}40<M_*<100\text{-}130$	bh
	$M_*>130$	no remnant

Core collapse SN may be driven by photodissociation and/or electron capture, pair driven pulsations, or pair instability

Nuclear burning stages

(20 $M_\odot$ stars)



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

SUPERNOVA TYPES

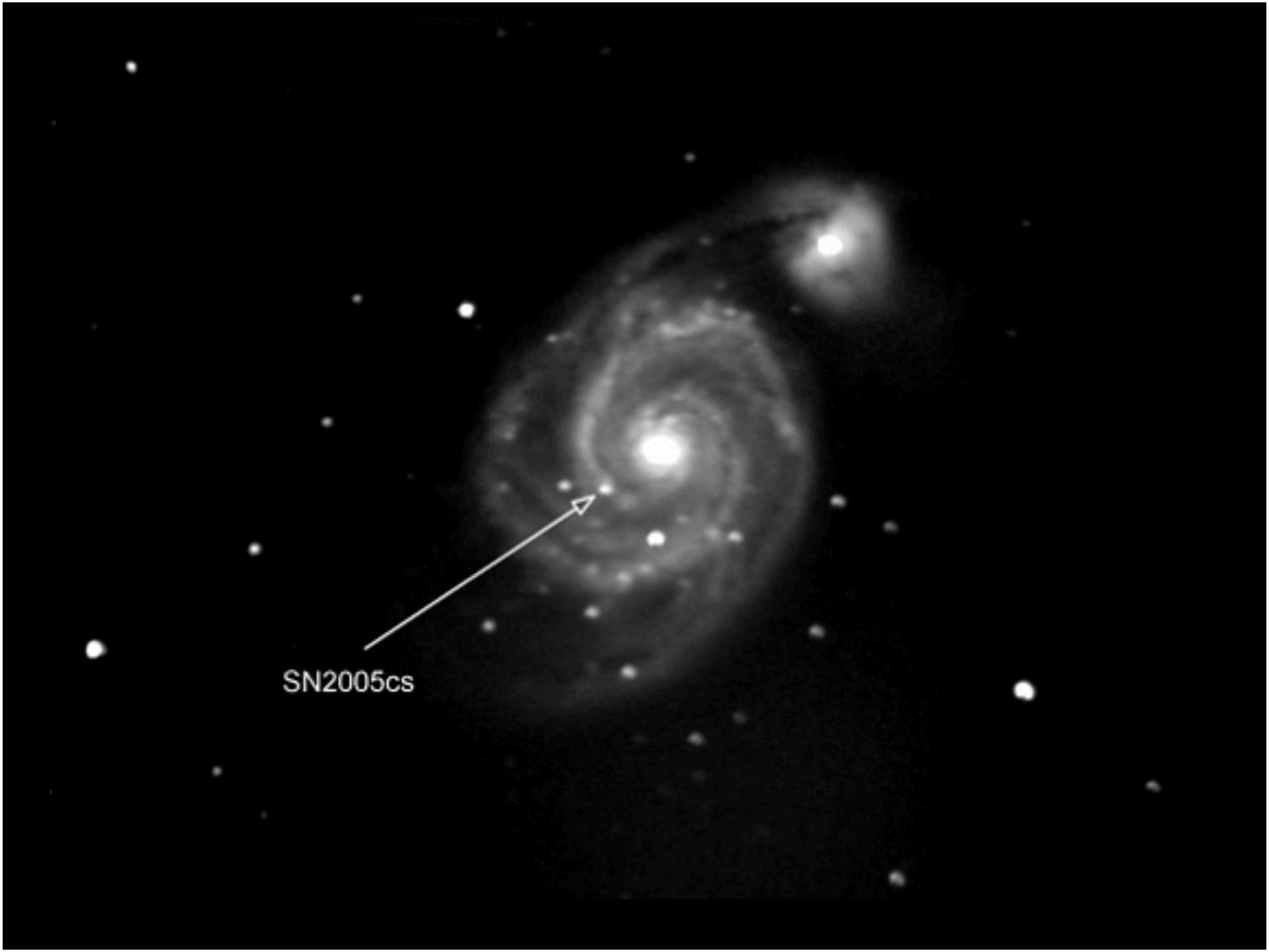
Type I and Type II Supernovae (SN) are among the most energetic stellar events in the Universe. *Type I SN* are the results of the explosions in white dwarf binary star systems and Type II SN are the deaths of massive stars. Both types of SN involve the release of more energy the Sun produces in its entire lifetime! (A Type II SN has a peak luminosity $10^{11}\ L_{\odot}$ and lasts for several months--it produces more than 100 times the energy produced by the Sun over its lifetime.) Here, we spend most of our time looking at Type II SN, although we discuss *Type I SN* as well because of their importance for Cosmology, the study of the origin and evolution of the Universe.

Interesting tidbits about Type II SN:

- 99 % of the energy comes out as neutrinos
- ~1 % of the energy goes into kinetic energy of the ejected material
- only 0.01 % of the energy goes into the photons. Even this tiny amount of visible energy allows Type II SN to stand out against the background light of entire galaxies (next slide)!

Type I and Type II SN are impressive and interesting, they, however, are interesting for other reasons as well.

- *SN produce most of the heavy elements* found in the Universe
- *Type I SN are standardizable candles*, giving the first believable evidence the expansion rate of the Universe is increasing.
- *Type II SN can trigger star formation* and halt star formation
- ....


SN2005cs

Supernovas are divided into classes based upon the appearance of their spectra: ***hydrogen lines are prominent in Type II*** supernovas; ***hydrogen lines are absent in Type I*** supernovas.

This tells us that the progenitor stars either had hydrogen in their outer envelopes or did not have hydrogen in their outer envelopes. ***Type II supernovae are associated with the collapse and explosion of the cores of massive stars*** while ***Type I supernovae are associated with the explosion of massive white dwarfs*** in white dwarf binary star systems.

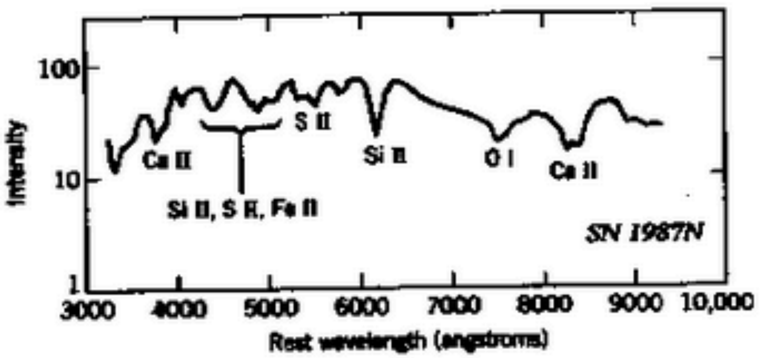


FIGURE 19–12. Type I supernova spectrum; note the lack of hydrogen lines.

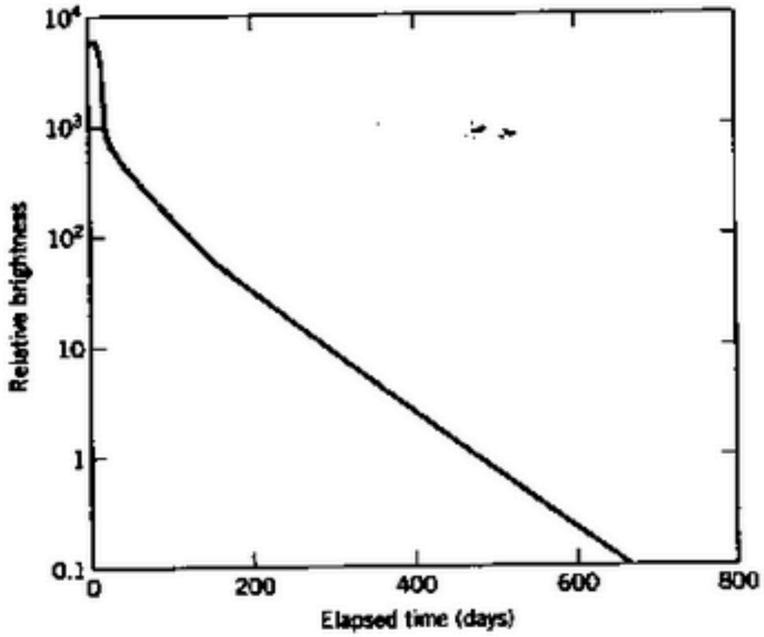


FIGURE 19–13. Type I supernova light curve.

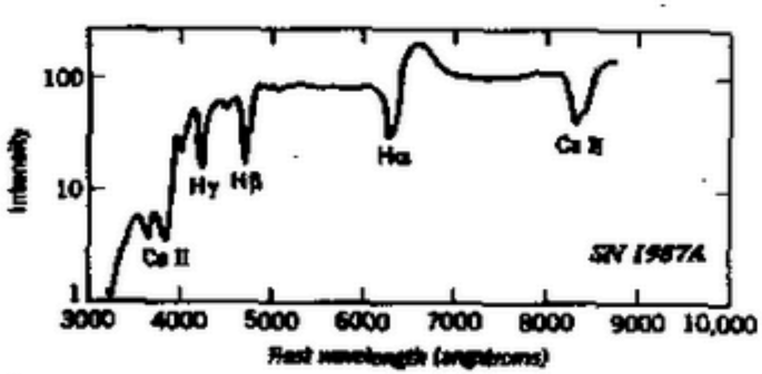


FIGURE 19–14. The spectrum of SN 1987A, a Type II supernova; note the presence of hydrogen lines.

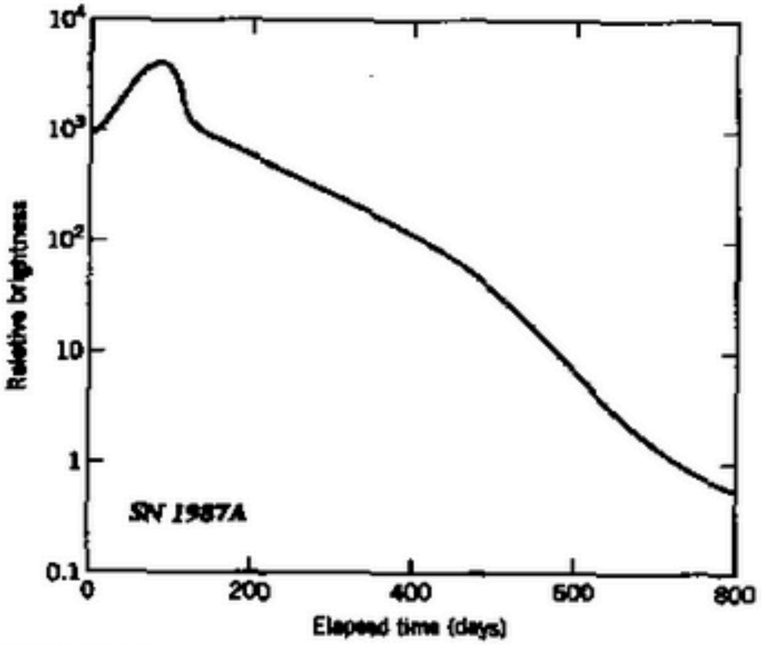


FIGURE 19–15. Type II supernova light curve.

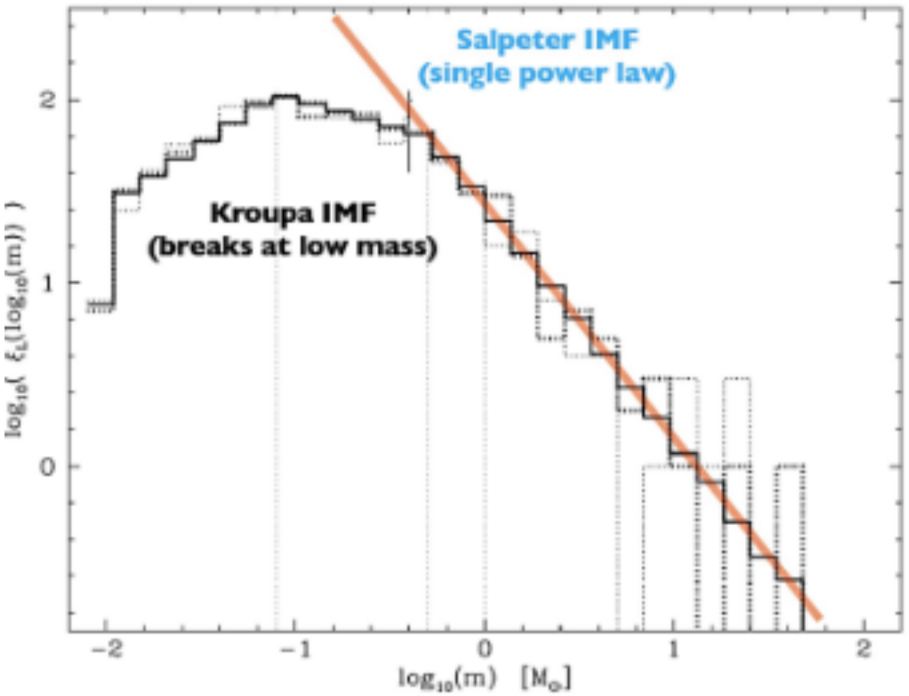
Supernova designation (year)	Constellation	Apparent magnitude	Distance (light years)	Type	Galaxy	Comments
SN 185	Centaurus	−4 (?)[24]	9,100[25]	Ia (?)	Milky Way	Surviving description sketchy; modern estimates of maximum apparent magnitude vary from +4 to −8. The remnant is probably RCW 86, some 8200 ly distant,[26] making it comparable to SN 1572. Some researchers have suggested it was a comet, not a supernova.[27][28]
SN 386	Sagittarius	+1.5	14,700	II	Milky Way	"suggested SN",[29] candidate remnant could be G11.2-0.3.[30][31] There are three suggestions and doubtful if SN at all or classical nova or something else.[32]
SN 393	Scorpius	−0	3,400	II/Ib	Milky Way	"possible SN",[29] could also be classical nova or something else[32]
SN 1006	Lupus	−7.5[33]	7,200	Ia	Milky Way	Widely observed on Earth; in apparent magnitude, the brightest stellar event in recorded history.[34]
SN 1054	Taurus	−6[35]	6,500	II	Milky Way	Remnant is the Crab Nebula with its pulsar (neutron star)
SN 1181	Cassiopeia	0	8,500		Milky Way	"possible SN",[29] probably no SN but activity at WR-star[36]
SN 1572	Cassiopeia	−4.0	8,000	Ia	Milky Way	Tycho's Nova
Kepler's Supernova	Ophiuchus	−3	14,000	Ia	Milky Way	Kepler's Star; most recent readily visible supernova within the Milky Way
Cas A, ca. 1680	Cassiopeia	+5	9,000	IIb	Milky Way	Apparently never visually conspicuous, due to interstellar dust; but the remnant, Cas A, is the brightest extrasolar radio source in the sky

Abstract

We present supernova rate measurements at redshift 0.1–1.0 from the Stockholm VIMOS Supernova Survey (SVISS). The sample contains 16 supernovae in total. The discovered supernovae have been classified as core collapse or type Ia supernovae (9 and 7, respectively) based on their light curves, colour evolution and host galaxy photometric redshift. The rates we find for the core collapse supernovae are $3.29_{-1.78\,-1.45}^{+3.08\,+1.98} \times 10^{-4}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}\ h_{70}^{3}$ (with statistical and systematic errors respectively) at average redshift 0.39 and $6.40_{-3.12\,-2.11}^{+5.30\,+3.65} \times 10^{-4}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}\ h_{70}^{3}$ at average redshift 0.73. For the type Ia supernovae we find a rate of $1.29_{-0.57\,-0.28}^{+0.88\,+0.27} \times 10^{-4}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}\ h_{70}^{3}$ at $\langle z \rangle = 0.62$. All of these rate estimates have been corrected for host galaxy extinction, using a method that includes supernovae missed in infrared bright galaxies at high redshift. We use Monte Carlo simulations to make a thorough study of the systematic effects from assumptions made when calculating the rates and find that the most important errors come from misclassification, the assumed mix of faint and bright supernova types and uncertainties in the extinction correction. We compare our rates to other observations and to the predicted rates for core collapse and type Ia supernovae based on the star formation history and different models of the delay time distribution. Overall, our measurements, when taking the effects of extinction into account, agree quite well with the predictions and earlier results. Our results highlight the importance of understanding the role of systematic effects, and dust extinction in particular, when trying to estimate the rates of supernovae at moderate to high redshift.

A proposed ***IMF*** is the ***Salpeter Initial Mass Function*** shown to the right and compared to data,

$$\frac{dN}{dM} = \xi_o M^{-2.35}$$



The ***observed IMF*** rolls over around ***0.5 $M_\odot$***. The constant in the ***IMF*** is determined by observations. For example, suppose we see a galaxy with ***2×10^{11}*** stars over the mass range ***0.1 M_s*** to ***100 M_s***. *How can we find ξ_o?*

Integrate the ***IMF*** to find $\boldsymbol{\xi_o}$.

$$\frac{dN}{dM} = \xi_o M^{-2.35} \rightarrow \int_0^{2\times10^{11}} dN = \xi_o \int_{0.1M_s}^{100\,M_o} M^{-2.35} dM$$

Integrating we find

$$\int_0^{2\times10^{11}} dN = 2\times10^{11} = \frac{\xi_o}{-1.35} M^{-1.35}\Big|_{0.1M_s}^{100\,M_s} \rightarrow \xi_o = 1.2\times10^{10} M_s^{1.35}$$

and the ***IMF*** is

$$\frac{dN}{dM} = 1.2\times10^{10} M_s^{1.35} M^{-2.35}$$

Suppose I want to use the **IMF** to find the rate of Type II SN, **How could I go about this problem?**

Integrate from *8 $M_\odot$* to ***100 $M_\odot$***. This gives us the total number of stars with mass greater than *8 $M_\odot$* born into the galaxy from its conception,

$$N_{>8} = 1.2\times 10^{10} M_s^{1.35}\left(\frac{1}{-1.35(100M_s)^{1.35}} - \frac{1}{-1.35(8M_s)^{1.35}}\right)$$

$$\rightarrow N_{>8} = 3.8\times 10^{8}$$

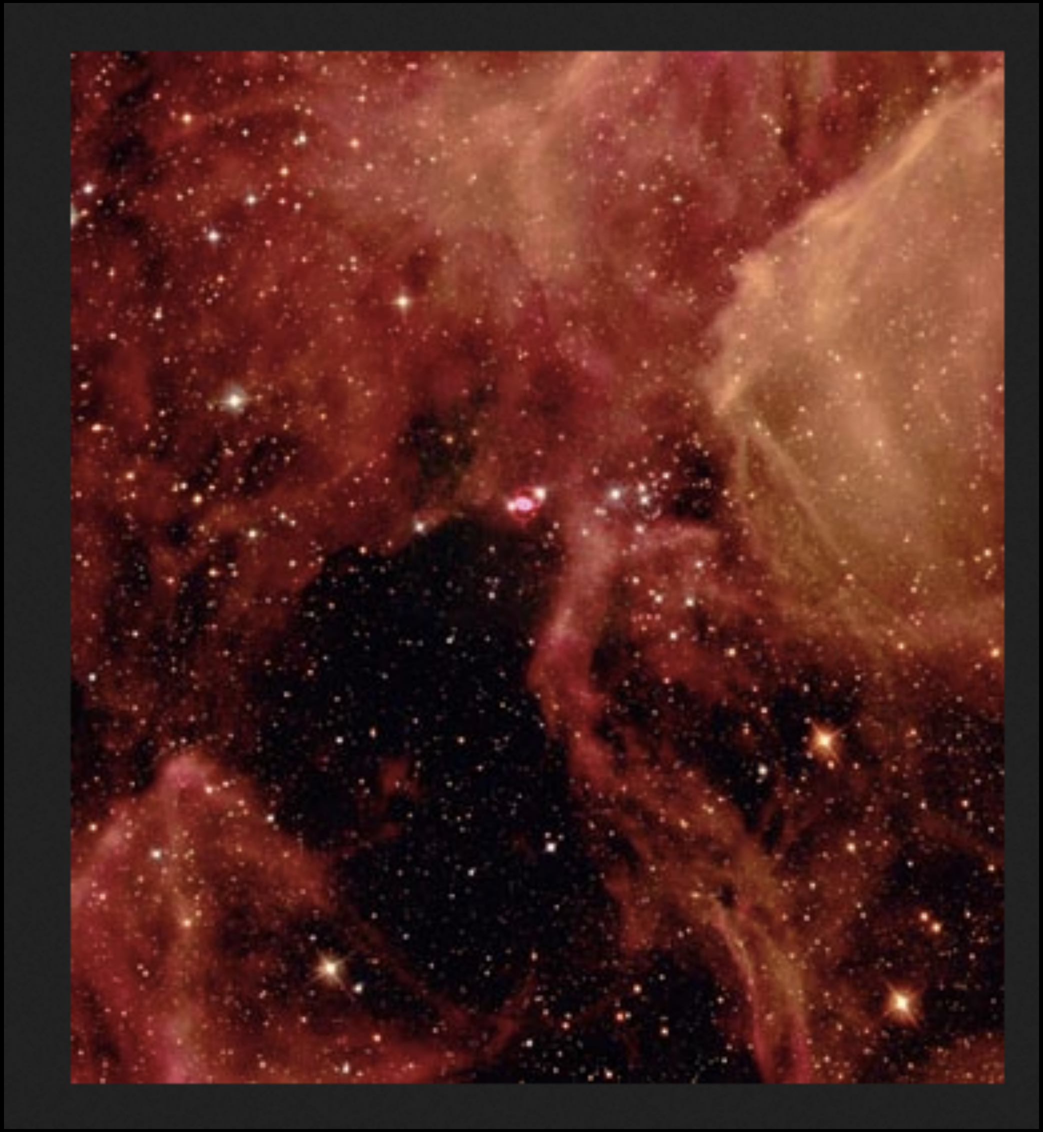
Given this, What is the rough Type II SN rate? An ***8 $M_\odot$*** star lives for around *30 million years*. Use this to estimate the SN rate as *1/500 per year.*

Suppose I want to use the **IMF** to find the # of ***50 M***$_\odot$ black holes have formed in our Galaxy? **How could I go about this problem?**

Integrate from ***50 M***$_\odot$ to ***100 M***$_\odot$,

$$N_{>8} = 1.2 \times 10^{10} M_s^{1.35} \left(\frac{1}{-1.35(100 M_s)^{1.35}} - \frac{1}{-1.35(50 M_s)^{1.35}} \right)$$

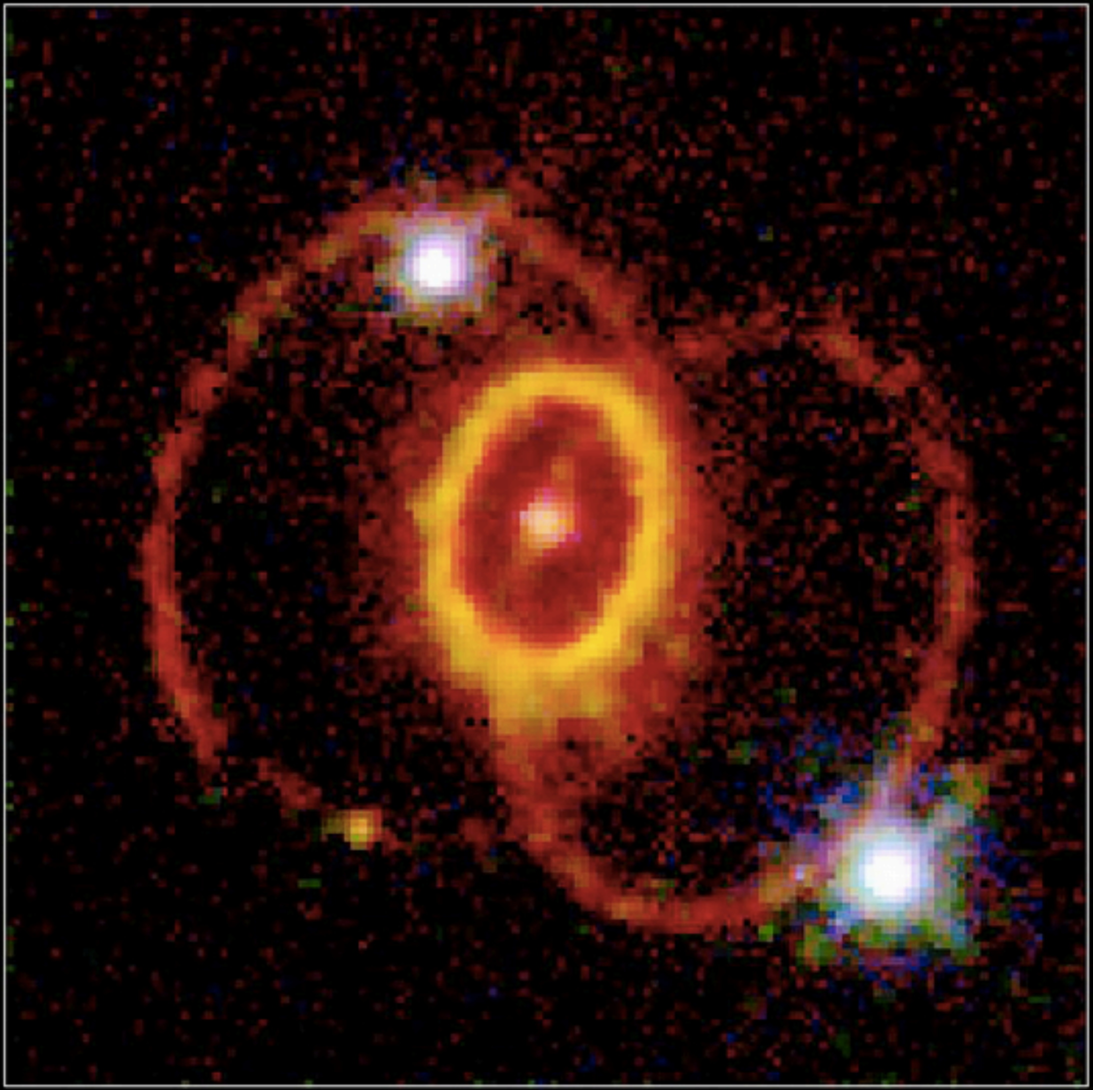
SN 1987A: CASE STUDY



As detected by Terrestrial observers, SN1987A went off on February 23, 1987 at 07:35:02.4. However, as its home, the Large Magellanic Cloud, is ~ 169,000 light years from the Earth, it actually went off 169,000 years before February 23, 1987. SN1987A, due to its proximity, was the brightest supernova in the last 383 years and since it was visible to the naked eye it is referred to as a historical supernova. Importantly, it is the only historical supernova to have gone off in modern (technological) times and so is the most well-studied supernova of all time. SN 1987a has taught us many things about supernova outbursts. Here, we look at some of the issues SN1987A helped to clarify.

Supernova 1987A is the bright star at the centre of the image, near the Tarantula nebula.

Supernova 1987A Rings



Hubble Space Telescope

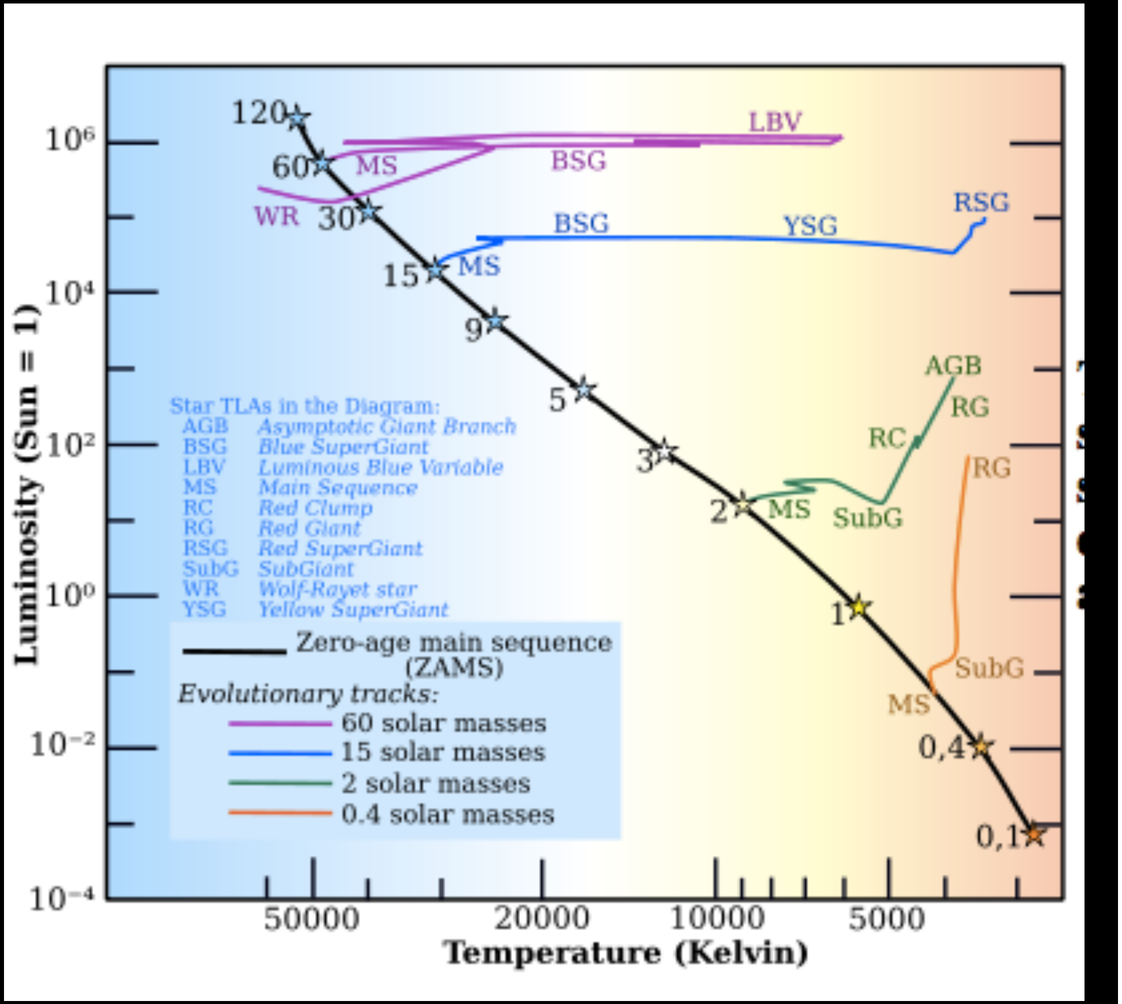
Wide Field Planetary Camera 2

SPACE
TELESCOPE
SCIENCE
INSTITUTE

Sk -69 202

SN 1987a during outburst and Sk -69 202 before outburst

The designation Sk means that Nick Sanduleak catalogued the star. The -69 is the approximate declination for the star and the 202 means that it is the 202nd star in the catalogue.



Properties of SK -69 202:

- $L_* \sim 100{,}000\ L_\odot$
- Sp. Cl. = B3 I supergiant
- $T_{eff} \sim 16{,}000$ K
- $M_* \sim 20\ M_\odot$
- $R_* \sim 3 \times 10^{12}$ cm

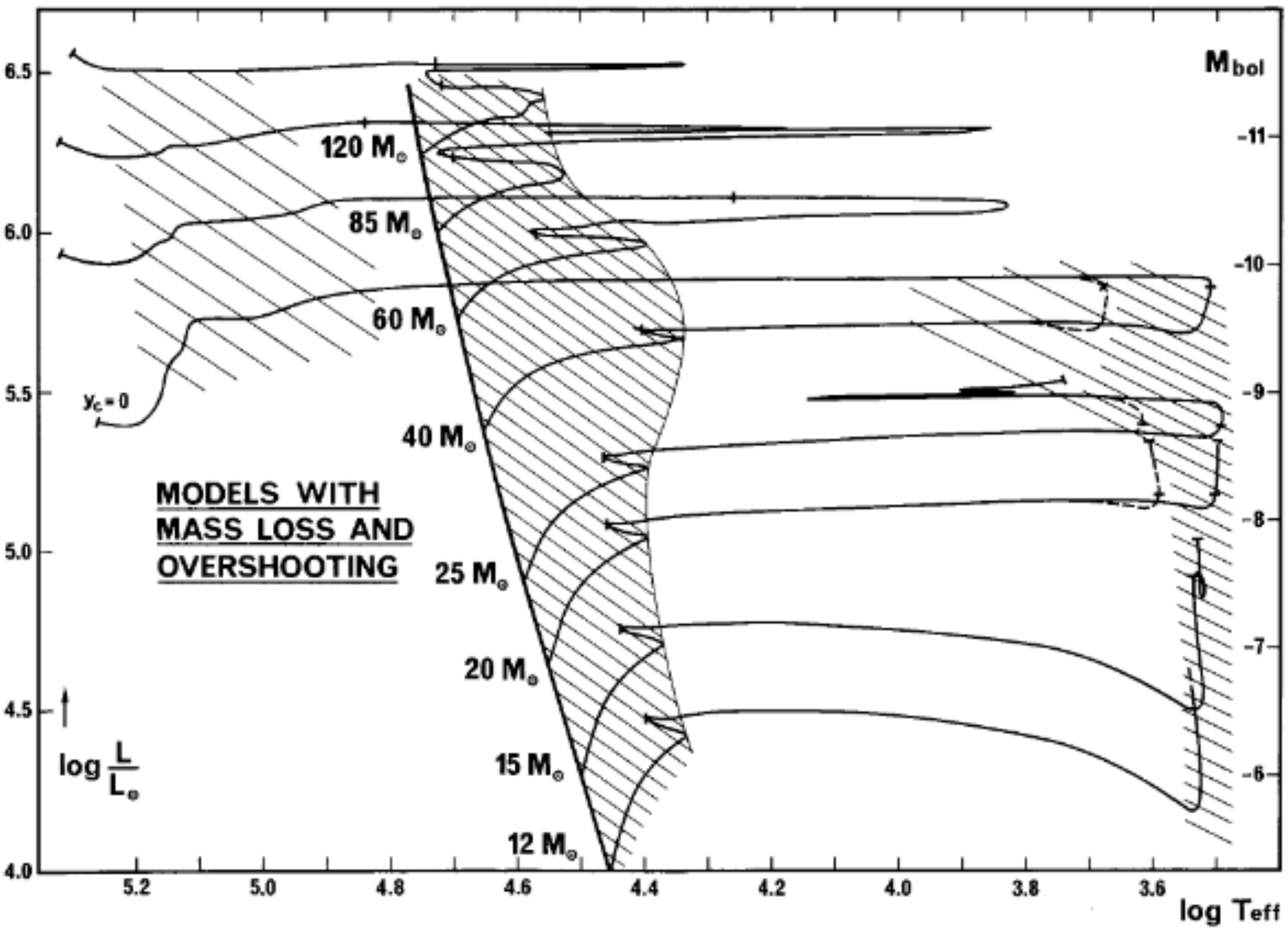


Figure 12.3. Evolution tracks of massive stars ($12 - 120\ M_\odot$) calculated with mass loss and a moderate amount of convective overshooting ($0.25\,H_P$). The shaded regions correspond to long-lived evolution phases on the main sequence, and during core He burning as a RSG (at $\log T_\mathrm{eff} < 4.0$) or as a WR star (at $\log T_\mathrm{eff} > 4.8$). Stars with initial mass $M > 40\,M_\odot$ are assumed to lose their entire envelope due to LBV episodes and never become RSGs. Figure from Maeder & Meynet (1987, A&A 182, 243).

SK -69 202 was a blue supergiant whereas the typical TYPE II supernova is produced by a red supergiant. The inference that TYPE II supernovae are produced by red supergiants was also based on theoretical modeling of the light curves of supernovae and numerical simulations of massive stars.

Possible solutions to this puzzle were produced rather early on when theorists noted that blue supergiants could in fact produce TYPE II supernova if some additional effects were included in the calculations. It was found that if one considered the fact that the stars in the LMC seem to have fewer heavy elements than the stars in our Galaxy and if one included the effects of stellar winds in the evolutions, then one could make evolved stars loop back into the hot portion of the HR diagram. That is, evolved stars could appear as blue supergiants! Tis question is still investigated as recent work has suggested that the blue supergiant Sk -69 202 may have been produced by a merger.

So, although the observation that a blue supergiant exploded was initially puzzling, it turned out that such an observation could be accomodated by theory and suggested why SN 1987a's lightcurve was odd for a Type II SN.

Set-up:

The interior of *SK -69 202* just before the outburst is like that of a red supergiant. The core of the star is 1.3-2 $M_{\odot}$ but is around the size of the Earth and composed of iron with density around ***10^9 g cm^{-3}***. and temperature several ***10^9 K***. The core is surrounded by the shell sources ignited after each phase of core burning ran to completion. The outer envelope of the star is 90 % hydrogen and roughly 10 % helium (as is the rest of the Universe). Because iron is the last element which can be profitably used as fuel for the fusion process, something catastrophic is poised to happen.

The core is not degenerate and starts to contract heating and becoming more dense as it has done before but now something bad is poised to happen

Outburst Mechanism:

- When the temperature exceeds around 10^{10} K, photons have typical energy ~ 3 MeV (3 kT). Photons in the blackbody tail at ~8 MeV may photodisintegration iron. The process does not go to completion, about 10% helium is broken out of the iron. This steals thermal energy from the gas and collapse accelerates.

$$^{56}_{26}Fe + \gamma \rightarrow 13\,^{4}_{2}He + 4n$$

- the density goes up above ~ 10^9 g cm^{-3}, the Fermi. This steals electrons and further accelerates the collapse.

$$e^{-} + A(Z,N) \rightarrow A(Z-1,N+1) + \upsilon_e$$

- As collapse accelerates, the temperature and density continue to rise and the emission of neutrinos by the pair process accelerates.

Core Collapse:

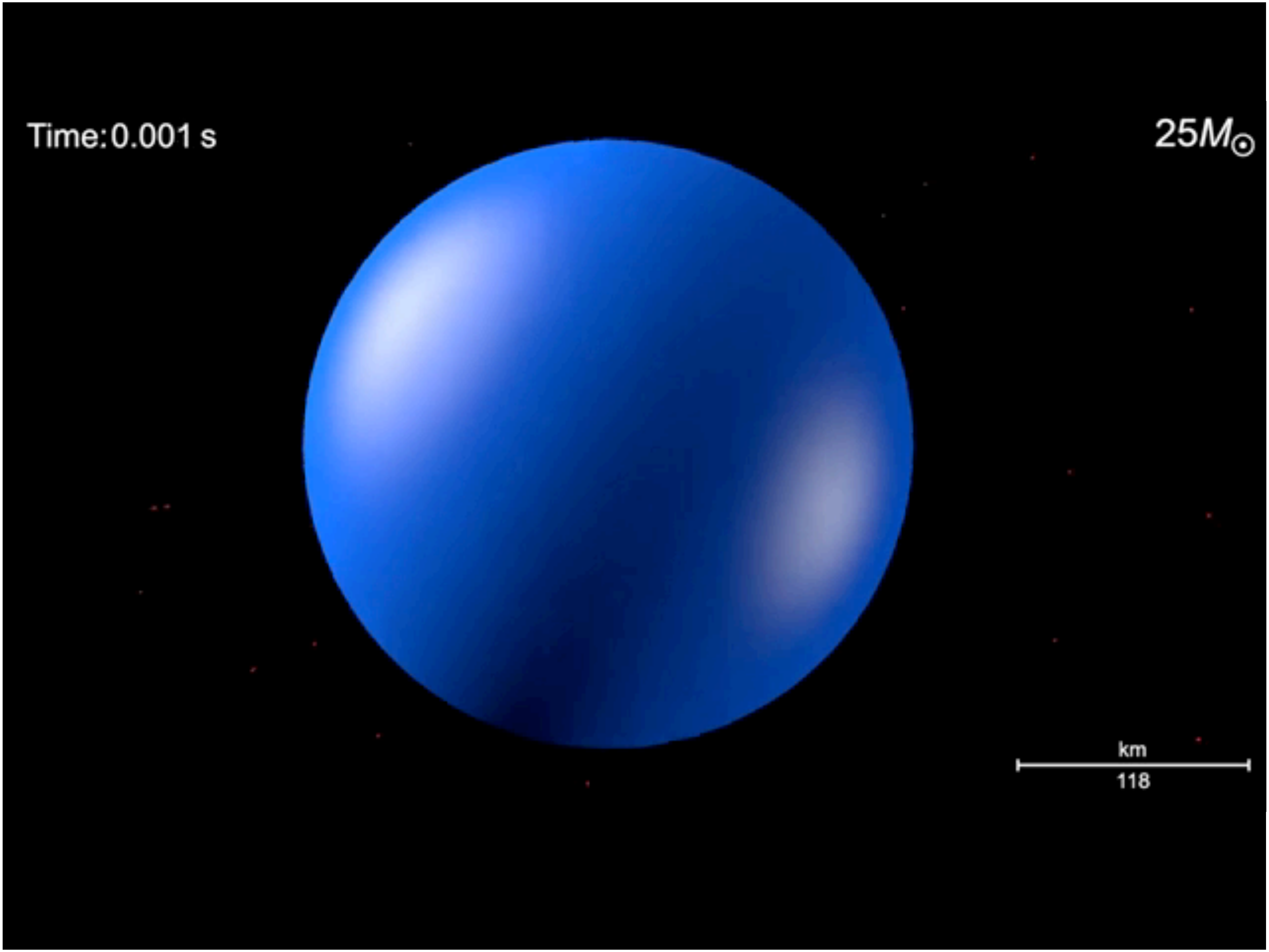
Time Scale: The collapse once initiated is very quick. The collapse time is roughly a tenth of a second!

Some Details

- The collapse is inside-out in that the denser regions collapse more quickly than the less dense regions.
- For the star this means that the inner core collapses in less than a second but that the outer burning shells and the envelope of the star (being less dense) not realizing that the core is gone are suspended above the collapsing core.
- They do not take part in the event until the explosion begins in earnest.

- The inner core collapses unimpeded until another threshold is reached (a new way to generate pressure – Main Sequence stars; normal gas and radiation pressure – Red Giants and Asymptotic Giants and Superbiants can use degenerate electron pressure as well as gas pressure).
- When the density of the core becomes roughly around the density of the nucleus of an atom, ***10^{14} g cm^{-3}*** (the protons and neutrons in the star, in a sense, are touching) ===> pressure increases greatly because of neutron and proton degeneracy and the nuclear force which is normally attractive (==> fusion and finding together of nuclei) becomes repulsive at high densities! These cause the pressure of the core to increase strongly.

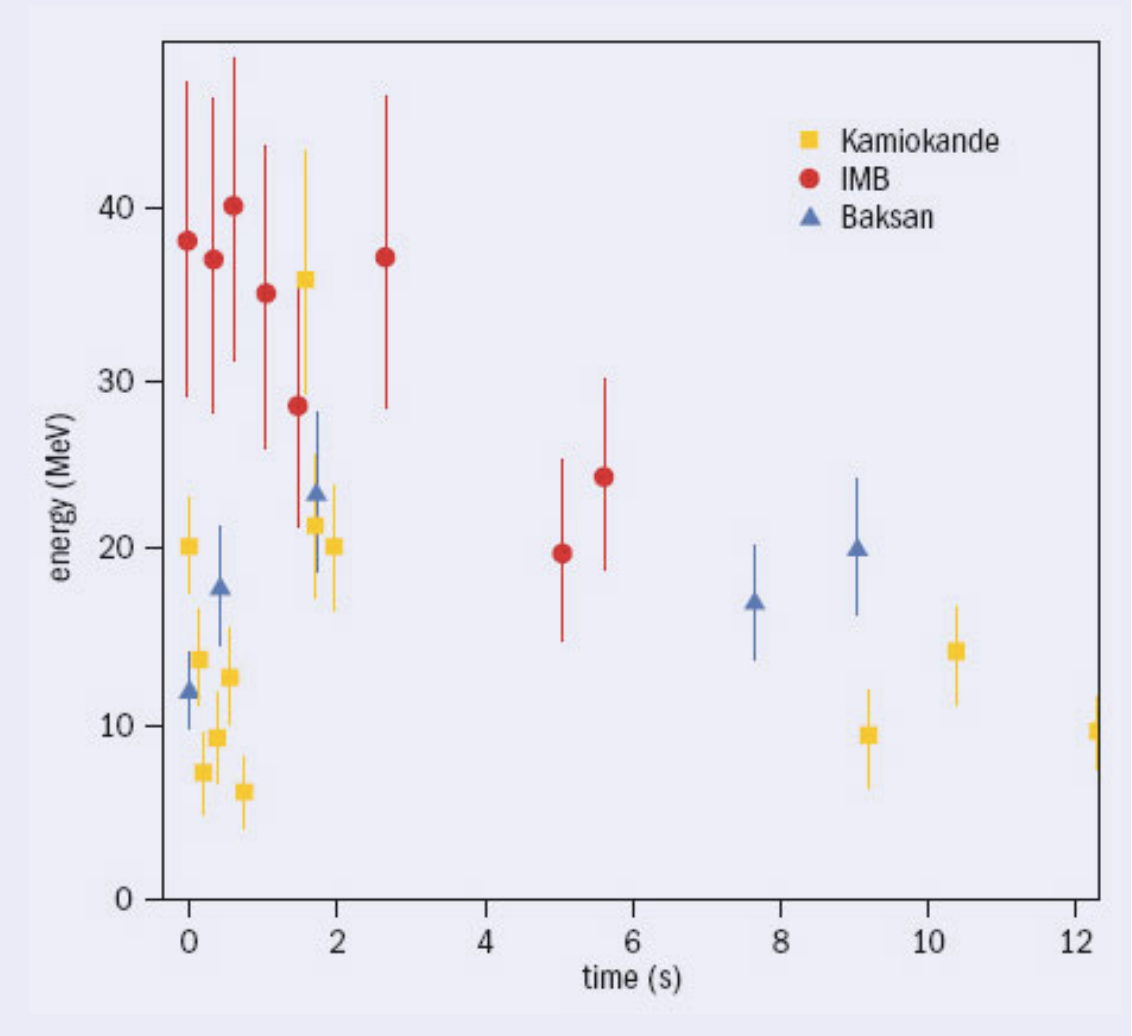
- The core is now like a steel ball. The higher lying layers have a chance to catch-up and they fall onto the hard core of the star.
- Because the outer layers accelerate to high speeds as they fall onto the core (~ tenth the speed of light or so), they have large kinetic energies.
- When they are forced to come to a halt at the core, this energy is converted into heat which drives a shock wave back into the star -- it is this shock wave which causes the explosion.
- Up to here, the scenario has been modeled quite nicely on the computer. However, the details of how the shock wave is generated and fed causing the ejection of the outer layers of the star have never been convincingly demonstrated. This is an active field of research.
- We discuss the passage of the shock wave through the star in the unit on ***Nucleosynthesis***.


Time:0.001 s
$25M_\odot$
km
118

Neutrinos:

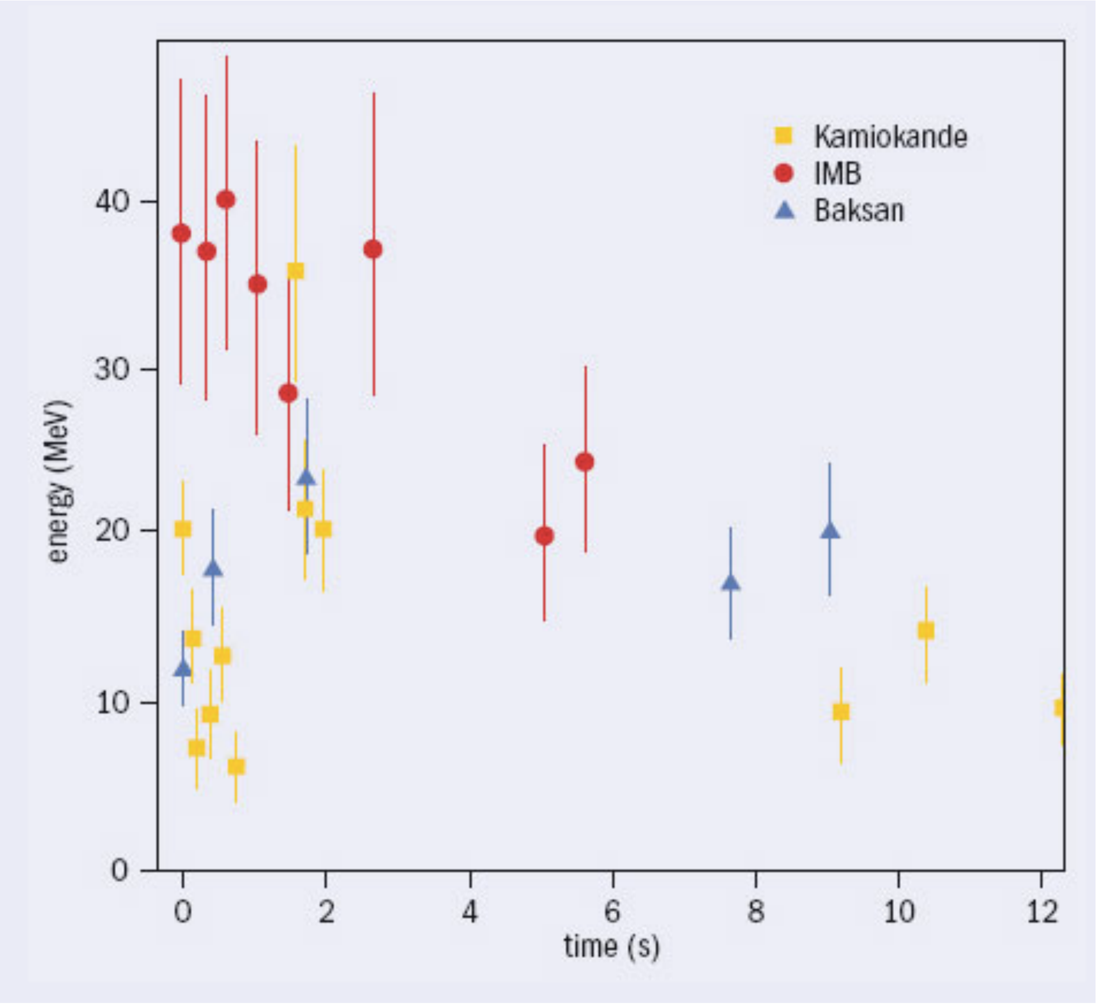
- A prediction of all models for Type II SN outbursts is that, the dominant source of energy loss is neutrino emission.
- The star sheds an amount of energy in neutrinos roughly equal to the increase in the energy it gains from the compression due to gravity. This is a huge amount of energy. This is more than 100 times the energy the Sun will radiate in its entire lifetime!
- **This is a strong theoretical prediction and must be true if our theories are to be taken seriously**
- The Kamiokande, IMB, and Baksan experiments saw ~20 events.
- 20 events are what we would expect for SN1987a which radiated ~ ***5 x 10^{53} ergs*** in neutrinos, **around 5 x 10^{58}** neutrinos at the source (the LMC) with ~ 2.4 x 10^{11} neutrinos passing through every square centimeter on the Earth.

Neutrinos observed from SN1987A:



The neutrino detection is strong corroboration that our basic model for Type II SN is correct.

The neutrino detection may be used to place a limit on the neutrino mass, in principle. Can we use SN1987a to do so?



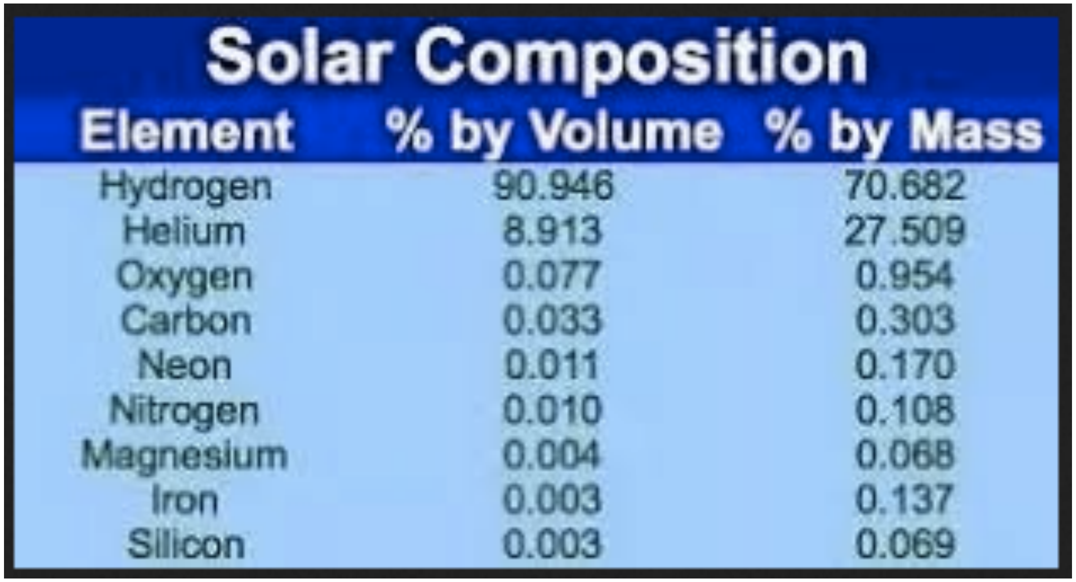
If we assume that neutrinos of all energies start their journey at the same time then we might be able to do so. If neutrinos have mass, then they travel at speeds that depend on their masses (unlike massless particles such as photons). As a result, more energetic neutrinos would arrive before ower energy neutrinos.

The current limit is 5.8 eV from SN1987a, compared to that obtained from tritium decay of 0.8 eV.

- The neutrinos are produced by the core collapse (the initial phase of the SN outburst) and so are expected to lead the optical fireworks by anywhere from hours to days (depending upon the type of progenitor star). The neutrinos led the optical outburst of SN1987A by several hours.
- The ***neutrinos were detected on 23.316 February 1987***
- The optical SN was not detected on 23.316 February but was seen ***on 23.443 February ===> the*** **optical brightening lagged the neutrino outburst by 0.074 to 0.127 days or 1.8 to 3 hours**
- Typical Type II SN are expected to show a lag of several days between the neutrino outburst and the optical display. The short lag is entirely consistent *with the fact that* ***Sk-69 202*** was a smallish blue supergiant and not a humongous red supergiant

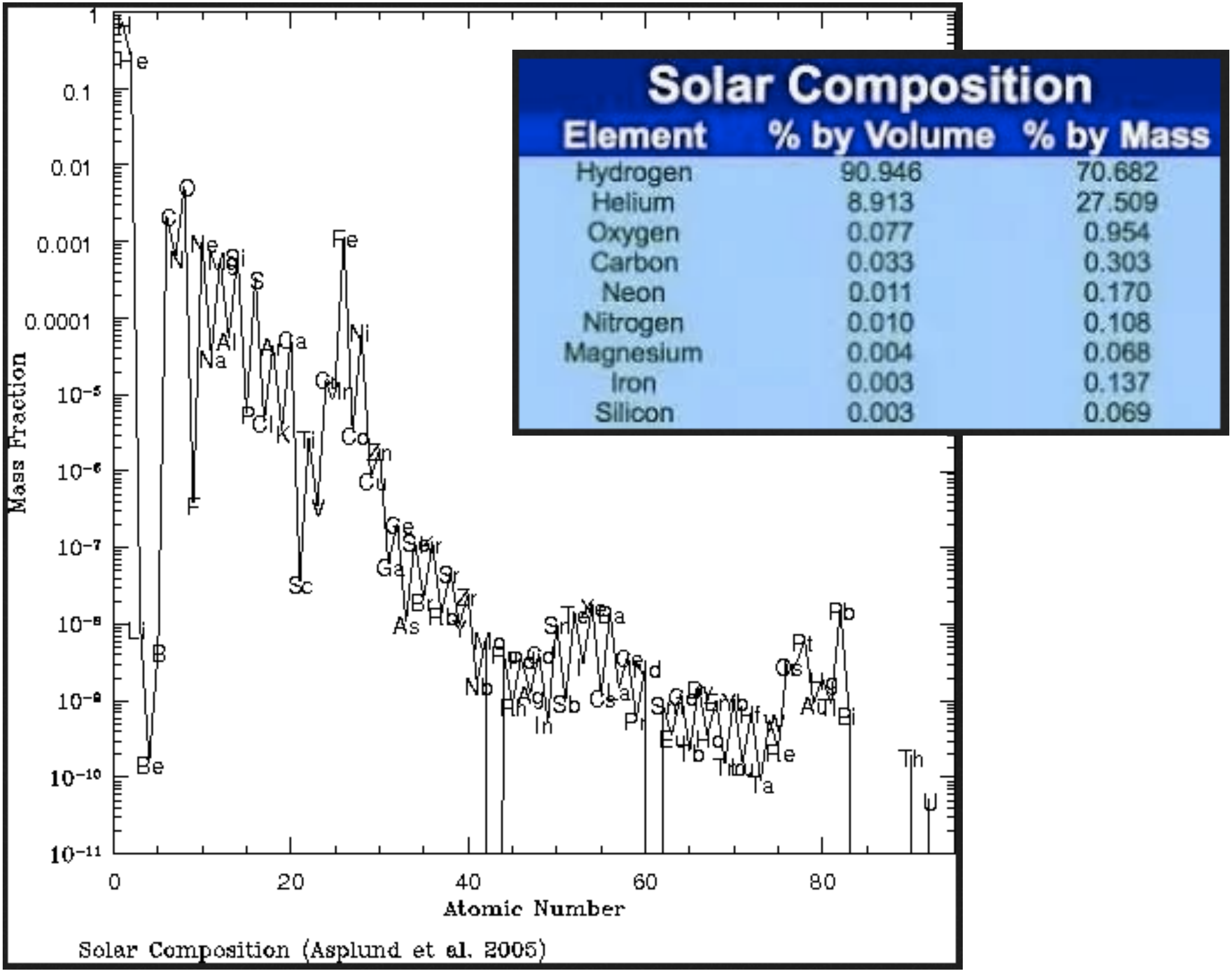
Stellar Nucleosynthesis:

The goal of *stellar nucleosynthesis* is to explain the chemical composition of the Universe and of the Sun, in particular



Solar Composition

Element	% by Volume	% by Mass
Hydrogen	90.946	70.682
Helium	8.913	27.509
Oxygen	0.077	0.954
Carbon	0.033	0.303
Neon	0.011	0.170
Nitrogen	0.010	0.108
Magnesium	0.004	0.068
Iron	0.003	0.137
Silicon	0.003	0.069



Solar Composition (Asplund et al. 2005)

Solar Composition

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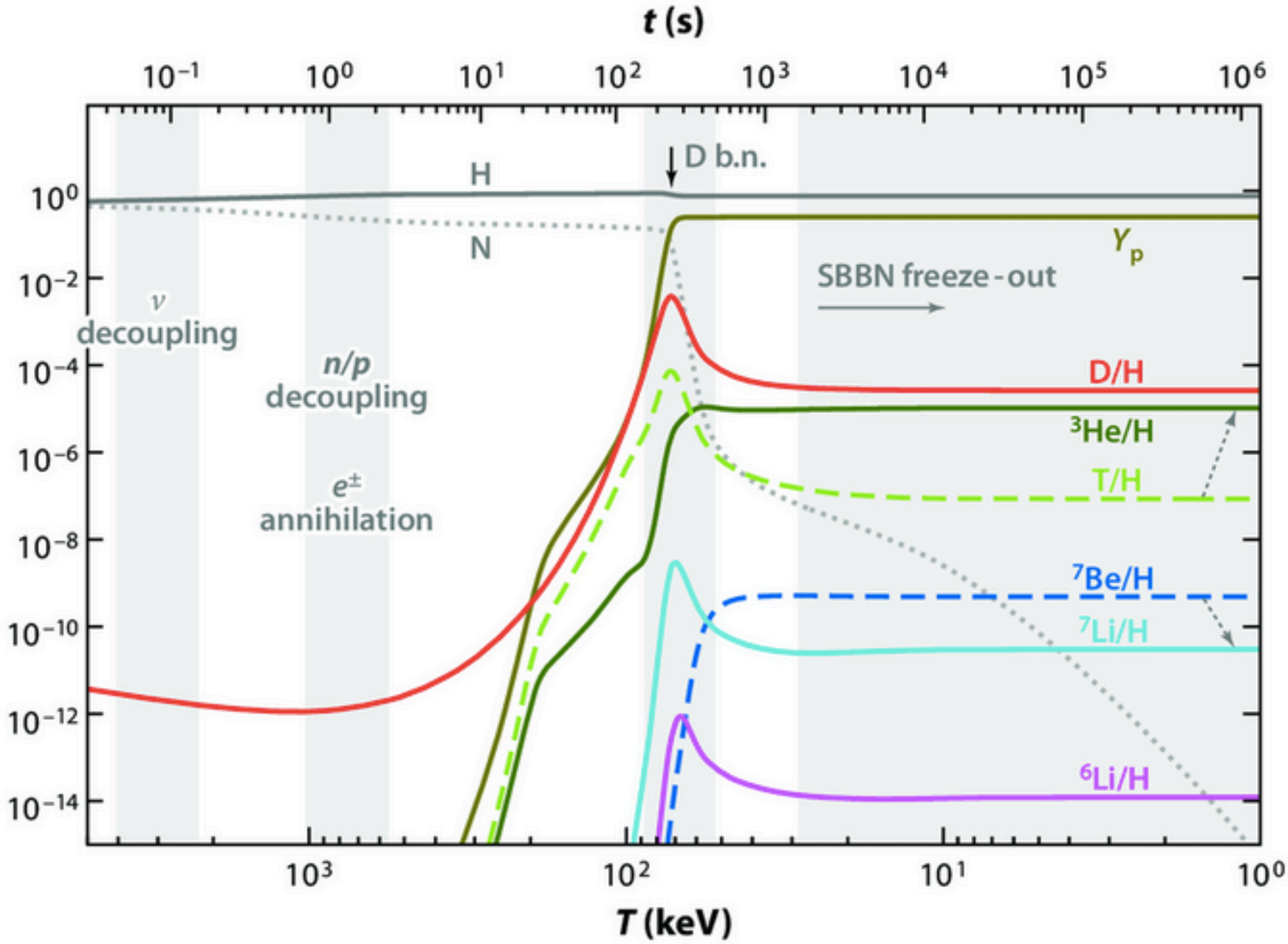
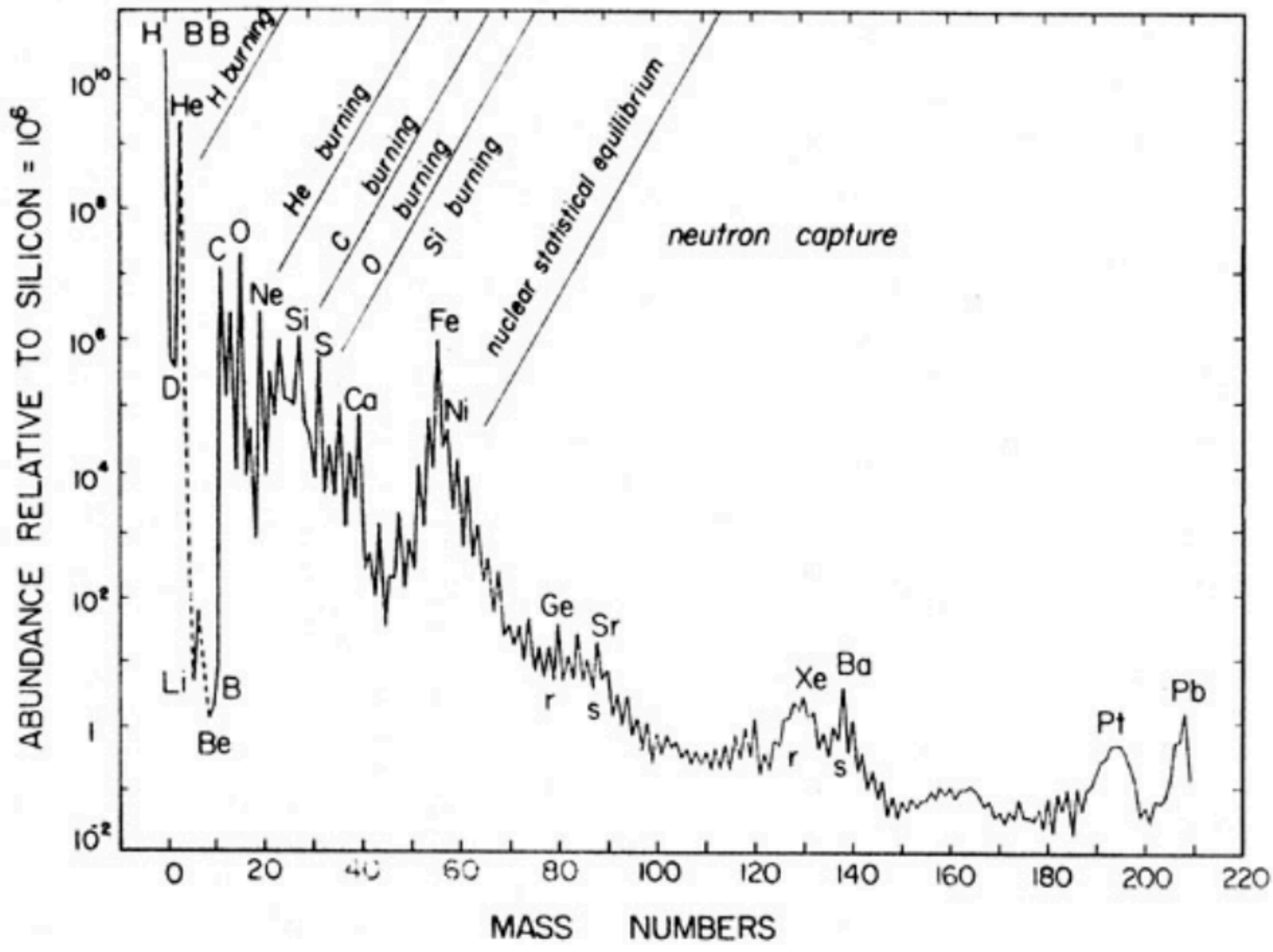


1.: Standard Big-Bang nucleosynthesis of the most abundant primordial nuclei, taken from [9].


ABUNDANCE RELATIVE TO SILICON = 10^6
10^{10}
10^8
10^6
10^4
10^2
1
10^{-2}
MASS NUMBERS
0
20
40
60
80
100
120
140
160
180
200
220
H
BB
He
H burning
He burning
C burning
O burning
Si burning
nuclear statistical equilibrium
neutron capture
D
Li
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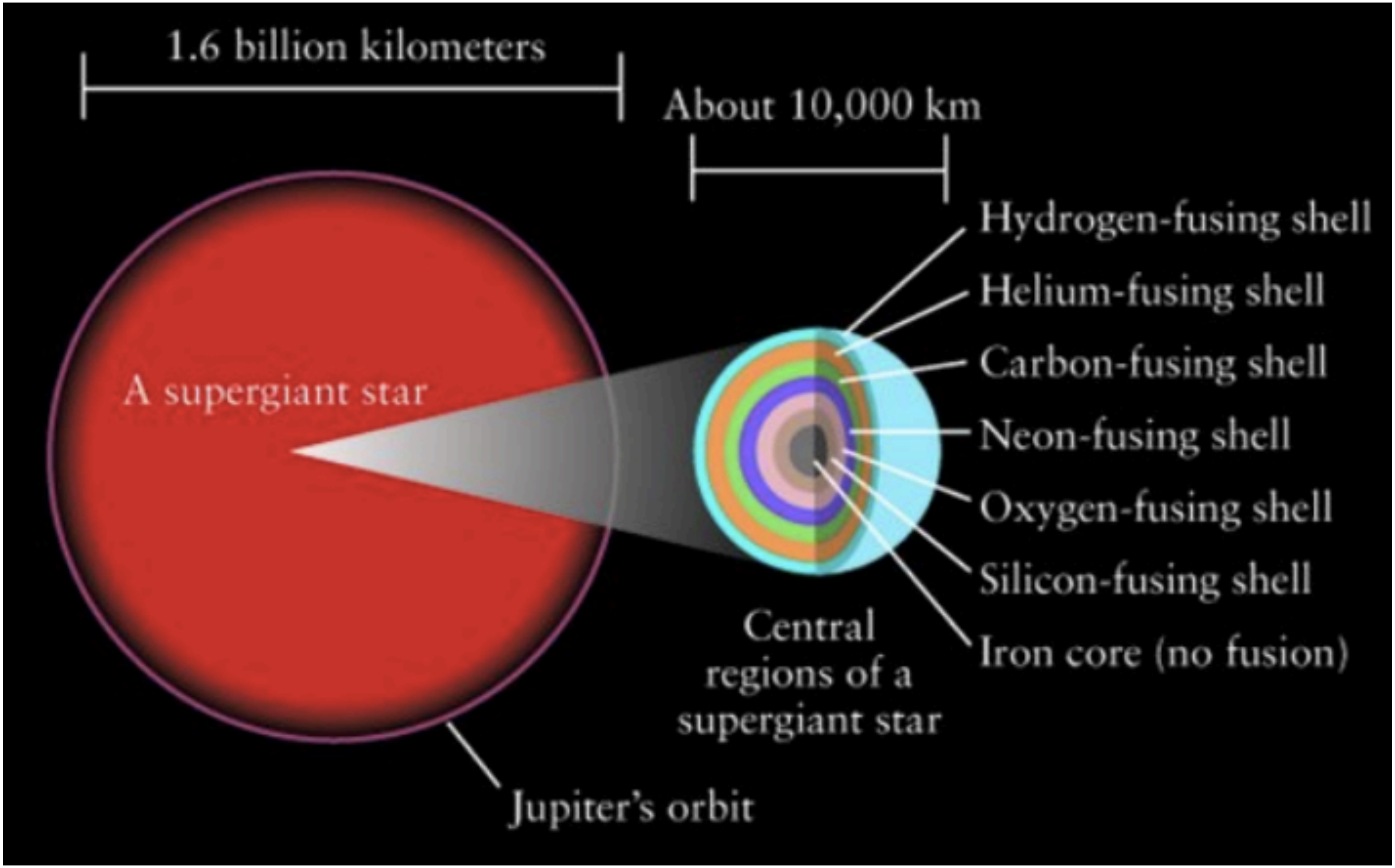
Pt
Pb



Pre-collapse Structure

Type II, core-collapse supernovae, produced at the end of the life of a massive star, play a dominant role in galactic chemical evolution, producing elements up to the iron-peak elements into the Universe. The iron-peak elements are produced in the shock heated material near the core. Outside of the hot shock, there is no nuclear processing and the outer layers simply ejected, the layers with elements produced in the star during its lifetime through a succession of burning phases, including the bulk of the C, O, Ne, and Mg. Additionally, s-process elements synthesized in the AGB shell-burning layers, elements such as Cu and Ge are also ejected in the supernova.

What are the r-process and s-process?

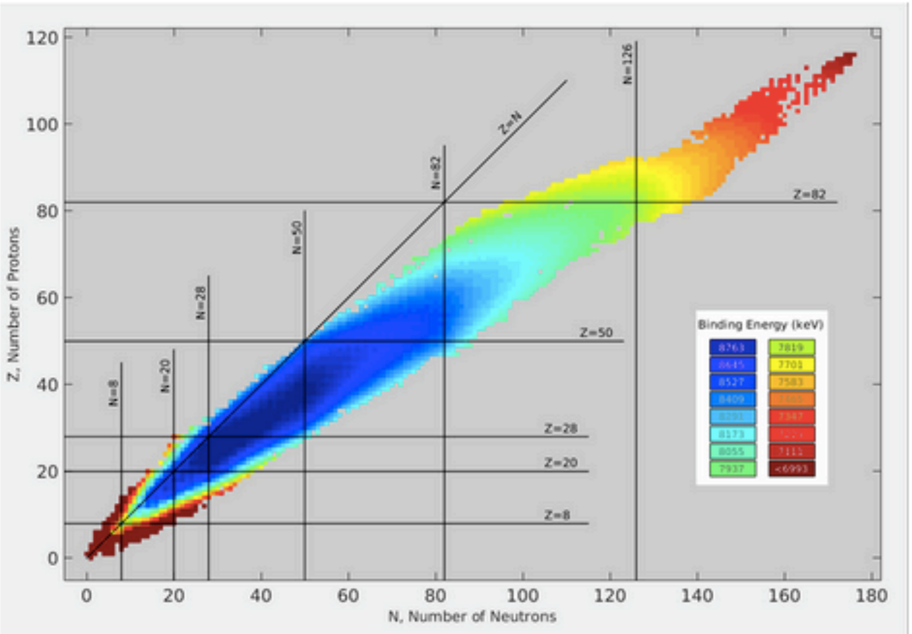


Chart of nuclides (isotopes) by binding energy, depicting the valley of stability. The diagonal line corresponds to equal numbers of neutrons and protons. Dark blue squares represent nuclides with the greatest binding energy, hence they correspond to the most stable nuclides. The binding energy is greatest along the floor of the valley of stability.

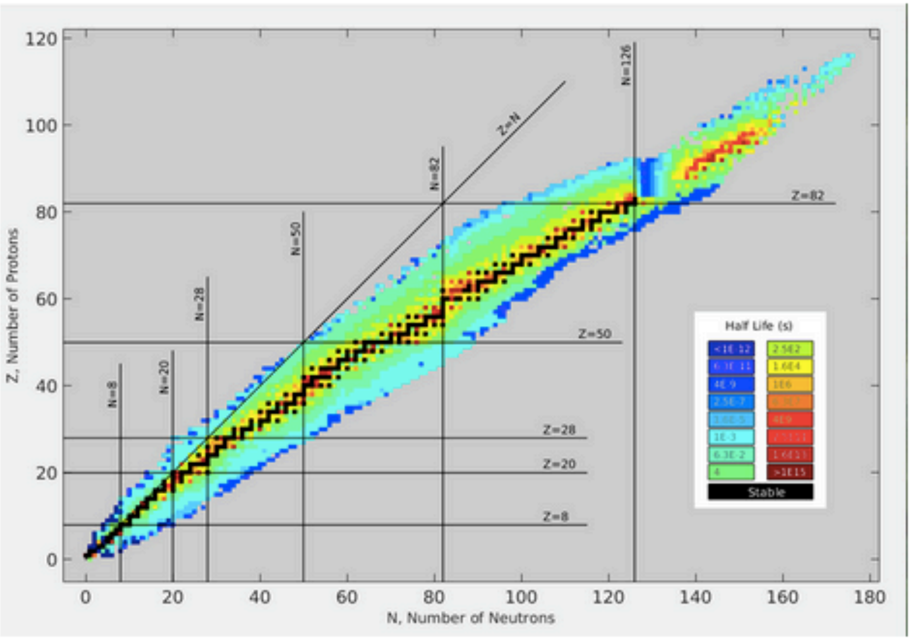
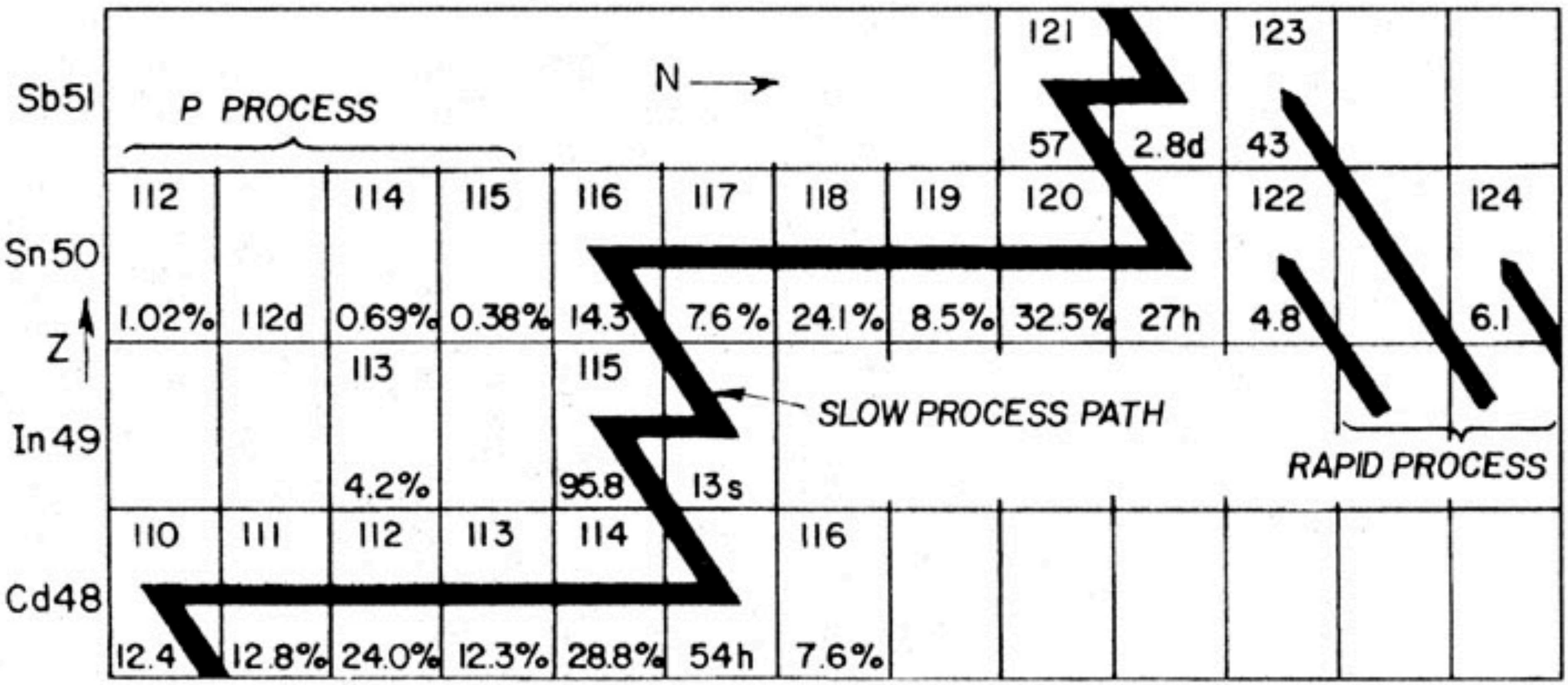


Chart of nuclides by half life. Black squares represent nuclides with the longest half lives hence they correspond to the most stable nuclides. The most stable, long-lived nuclides lie along the floor of the valley of stability. Nuclides with more than 20 protons must have more neutrons than protons to be stable.

Valley of β-Stability

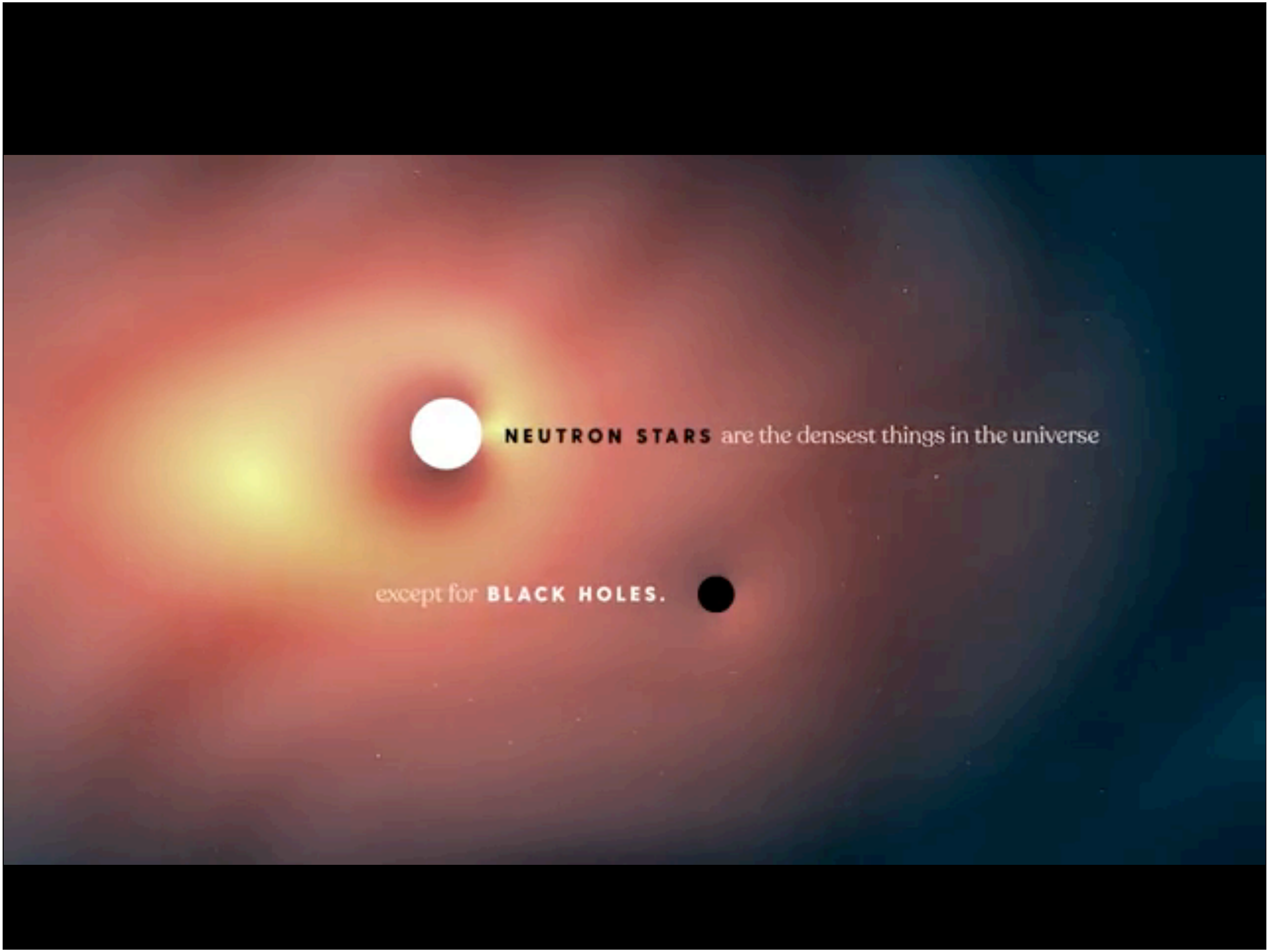


Neutron Capture Nucleosynthesis:

- *r-process: rapid capture of neutrons (ns mergers, SN)*
- *s-process: slow capture of neutrons (AGB shells)*

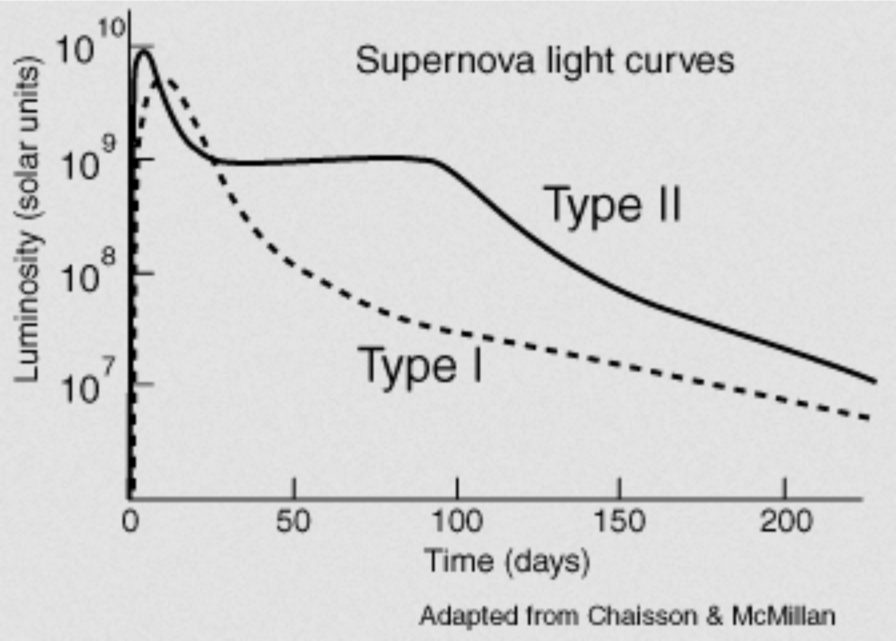
Type II supernovae were once thought to also be the primary site for synthesis of other elements beyond the the iron peak as well due to something known as the ***r-process***. However, currently, neutron star mergers, not core-collapse supernovae, are thought to be the primary site of ***r-process***, this, however, is far from certain.

Supernovae may still play a large role in first-peak r-process abundances and/or the r-process elements in the universe.



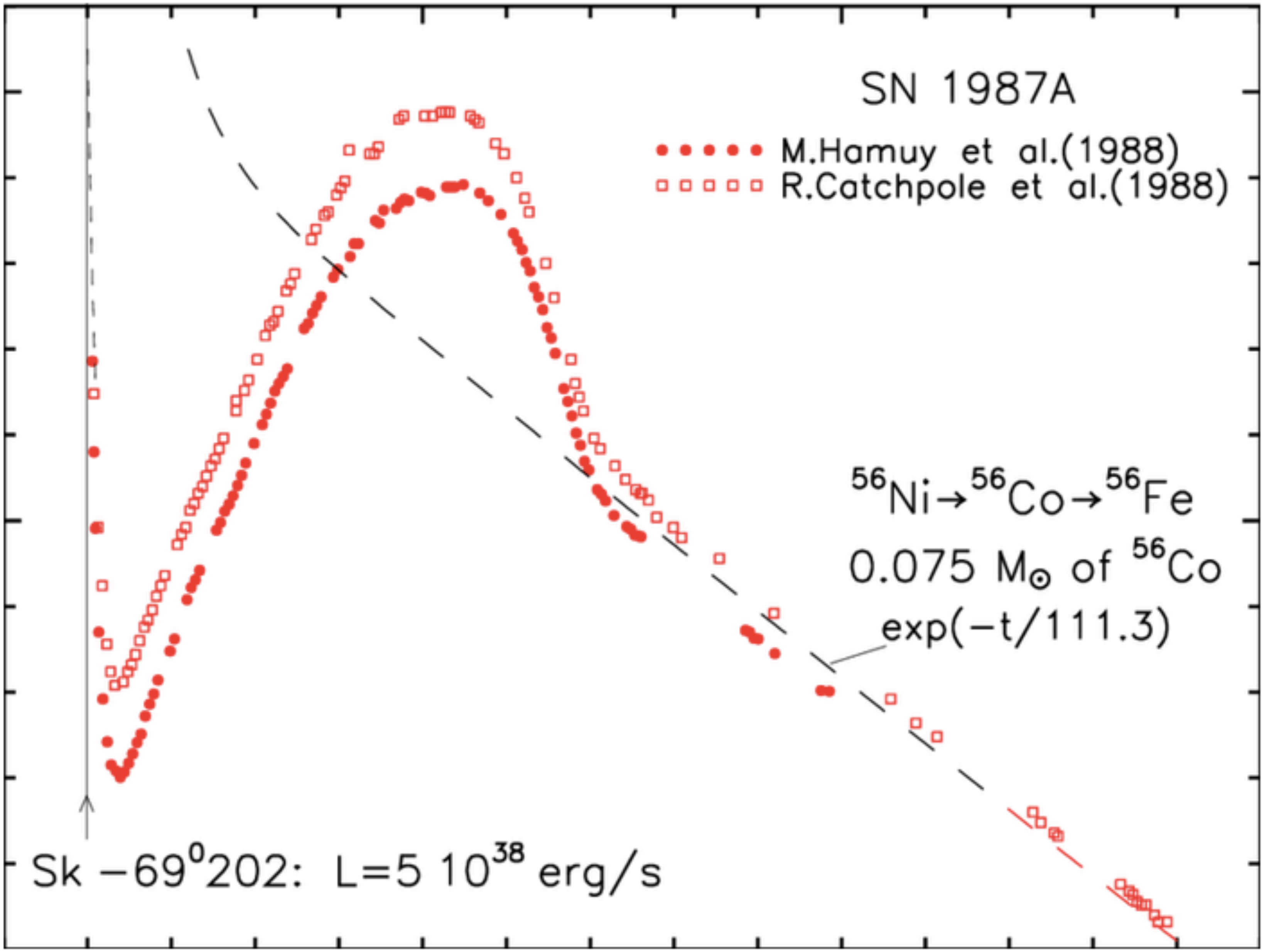
NEUTRON STARS are the densest things in the universe

except for **BLACK HOLES.**

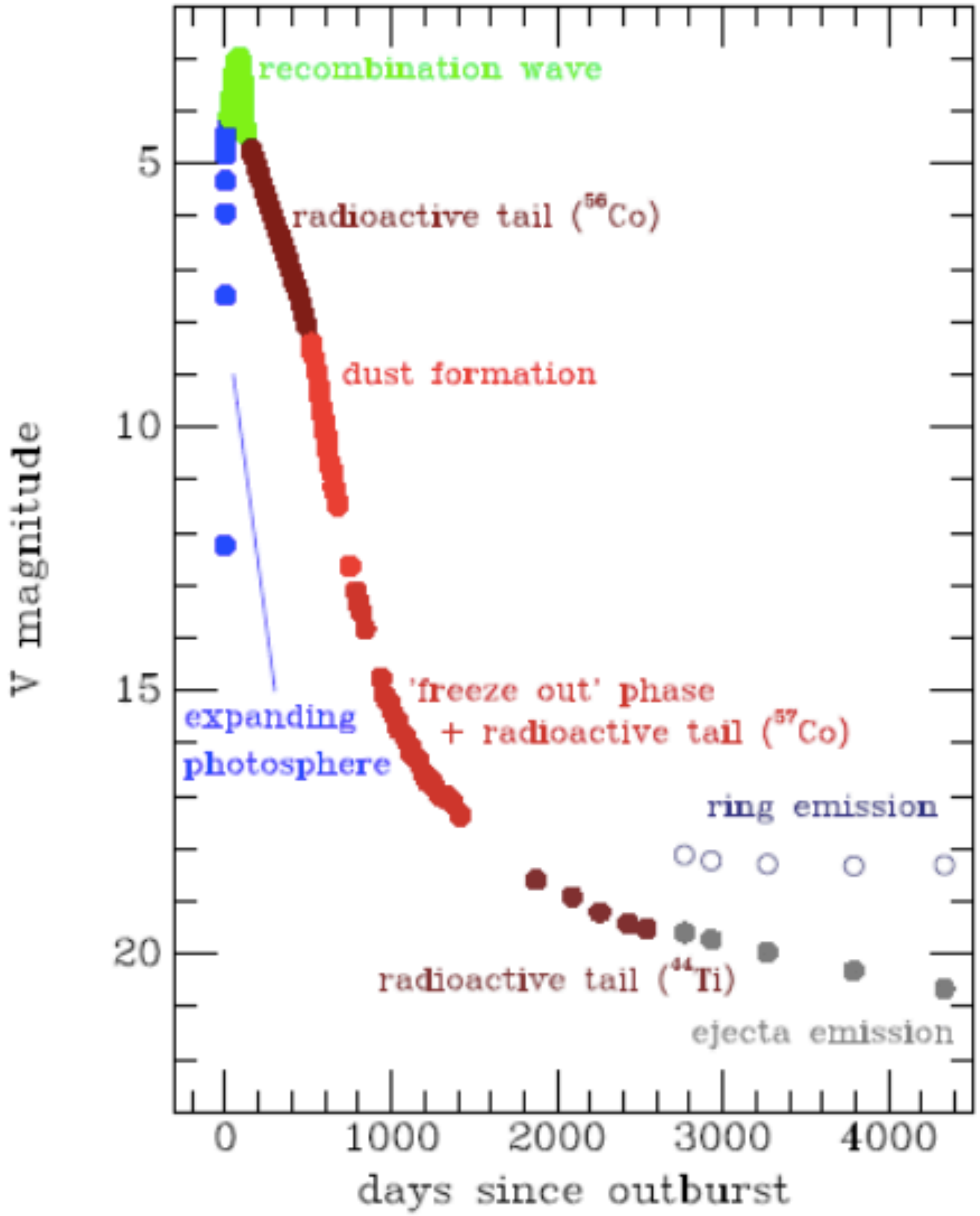


Type I vs Type II Lightcurves:

Both show rapid rises but differ strongly in the mid-time range. The difference is a consequence of the progenitor size, Type I are small (wds) and so initial expansion leads to large relative volume changes while Type II are large (RSGs) and so initial expansion does not lead to large relative volume changes.

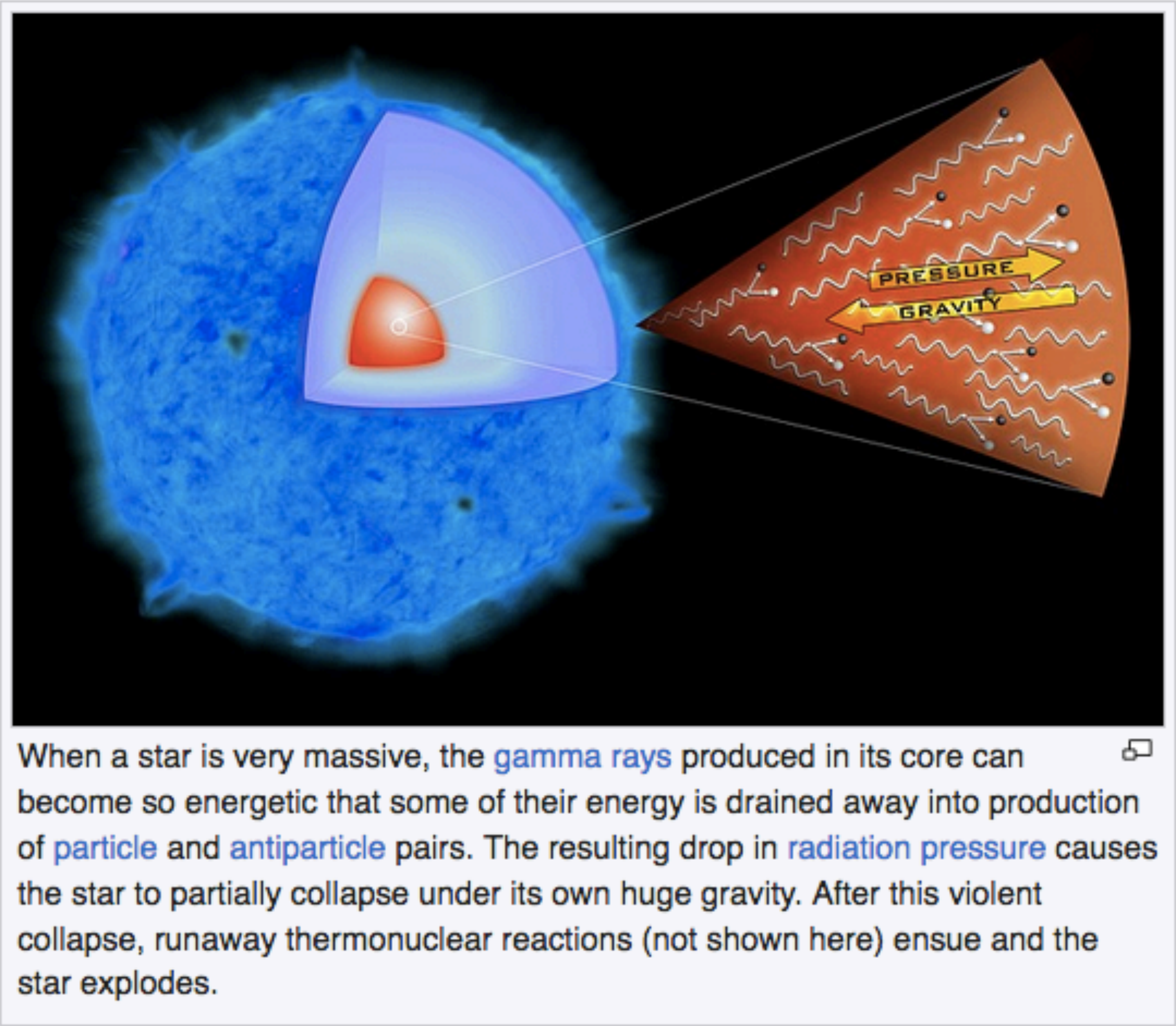


The bolometric light curve of SN 1987A exploded on February 23, 1987. Time is measured from the moment of the shock wave breakout. At t ≈ 90 days, the SN 1987A luminosity attains a maximum of ≈ 10 42 erg/s that by a factor of 2,000 exceeds the luminosity of the progenitor, blue supergiant Sk-69 o 202. The shock wave breakout " tail " is shown by a nearly vertical dashed line at t ≈ 0. (Adapted from Ref. 19).



Light curve of SN 1987A over the first 12 years. The figure marks some of the most important events in the history of the supernova (from Leibundgut & Suntzeff 2003).

Pair Instability Supernovae



When a star is very massive, the gamma rays produced in its core can become so energetic that some of their energy is drained away into production of particle and antiparticle pairs. The resulting drop in radiation pressure causes the star to partially collapse under its own huge gravity. After this violent collapse, runaway thermonuclear reactions (not shown here) ensue and the star explodes.

Massive, hot stars, $M > 100\ M_{\odot}$, have central temperatures > $3\times10^{8}K$, photons produced in the stellar core are primarily in the form of very high energy-level gamma rays. The pressure from these gamma rays fleeing outward from the core helps to hold up the upper layers of the star against the inward pull of gravity. If the level of gamma rays (the energy density) is reduced, then the outer layers of the star will begin to collapse inwards.

Gamma rays with sufficiently high energy can interact with nuclei, electrons, or one another to form electron-positron pairs, and these pairs can also meet and annihilate each other to create gamma rays again, all in accordance with Albert Einstein's mass-energy equivalence equation $E = mc^2$.

At the very high density of a large stellar core, pair production and annihilation occur rapidly. Gamma rays, electrons, and positrons are overall held in thermal equilibrium, ensuring the star's core remains stable. By random fluctuation, the sudden heating and compression of the core can generate gamma rays energetic enough to be converted into an avalanche of electron-positron pairs. This reduces the pressure. When the collapse stops, the positrons find electrons and the pressure from gamma rays is driven up, again. The population of positrons provides a brief reservoir of new gamma rays as the expanding supernova's core pressure drops.

As temperatures and gamma ray energies increase, more and more gamma ray energy is absorbed in creating electron–positron pairs. This reduction in gamma ray energy density reduces the radiation pressure that resists gravitational collapse and supports the outer layers of the star. The star contracts, compressing and heating the core, thereby increasing the rate of energy production. This increases the energy of the gamma rays that are produced, making them more likely to interact, and so increases the rate at which energy is absorbed in further pair production. As a result, the stellar core loses its support in a runaway process, in which gamma rays are created at an increasing rate; but more and more of the gamma rays are absorbed to produce electron–positron pairs, and the annihilation of the electron–positron pairs is insufficient to halt further contraction of the core, resulting in a supernova

100 to 130 $M_\odot$

These stars are large enough to produce gamma rays with enough energy to create electron-positron pairs, but the resulting net reduction in counter-gravitational pressure is insufficient to cause the core-overpressure required for supernova. Instead, the contraction caused by pair-creation provokes increased thermonuclear activity within the star that repulses the inward pressure and returns the star to equilibrium. It is thought that stars of this size undergo a series of these pulses until they shed sufficient mass to drop below ***100 $M_\odot$***, at which point they are no longer hot enough to support pair-creation. Pulsing of this nature may have been responsible for the variations in brightness experienced by ***η Carinae in 1843***, though this explanation is not universally accepted.

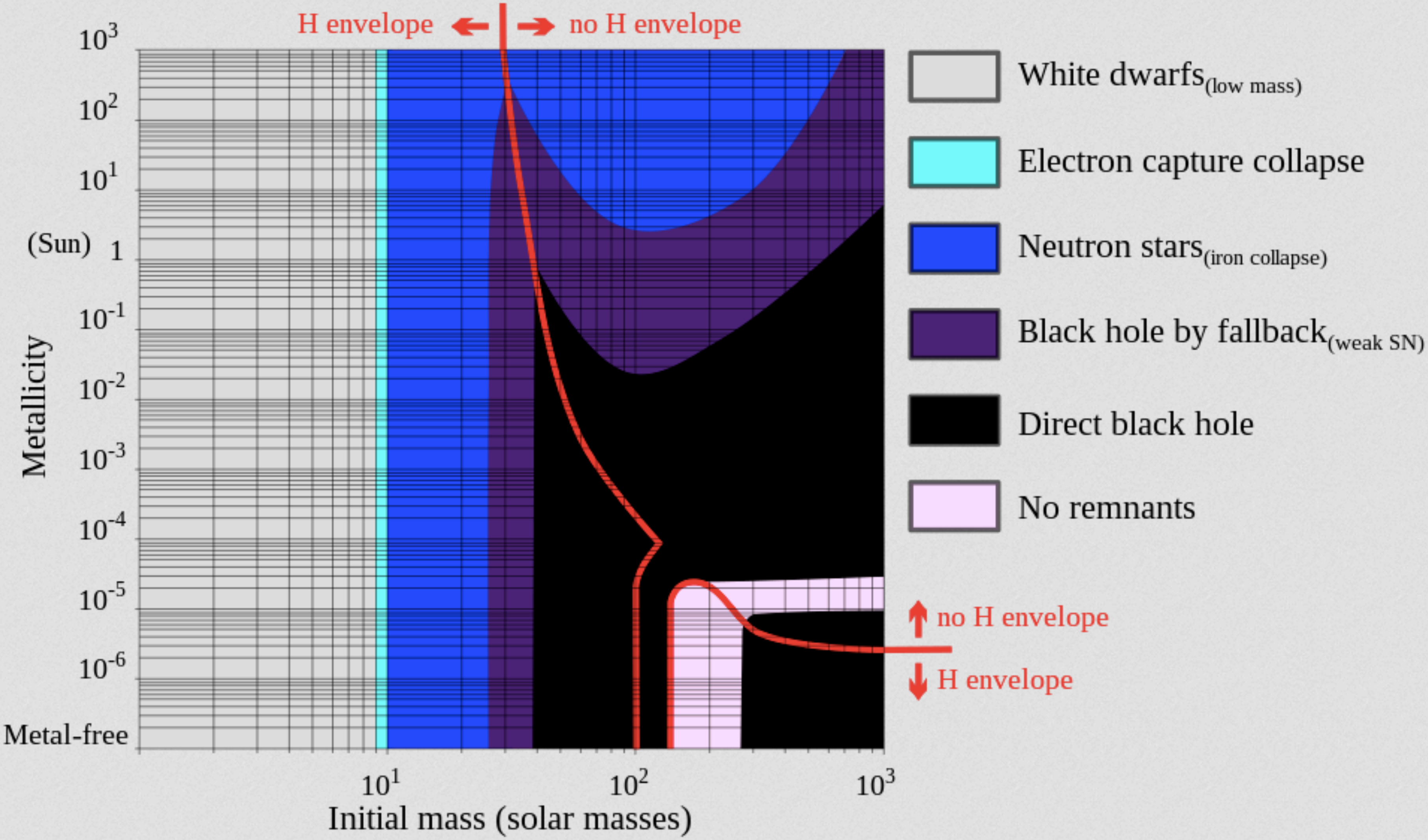
130 to 250 $M_\odot$

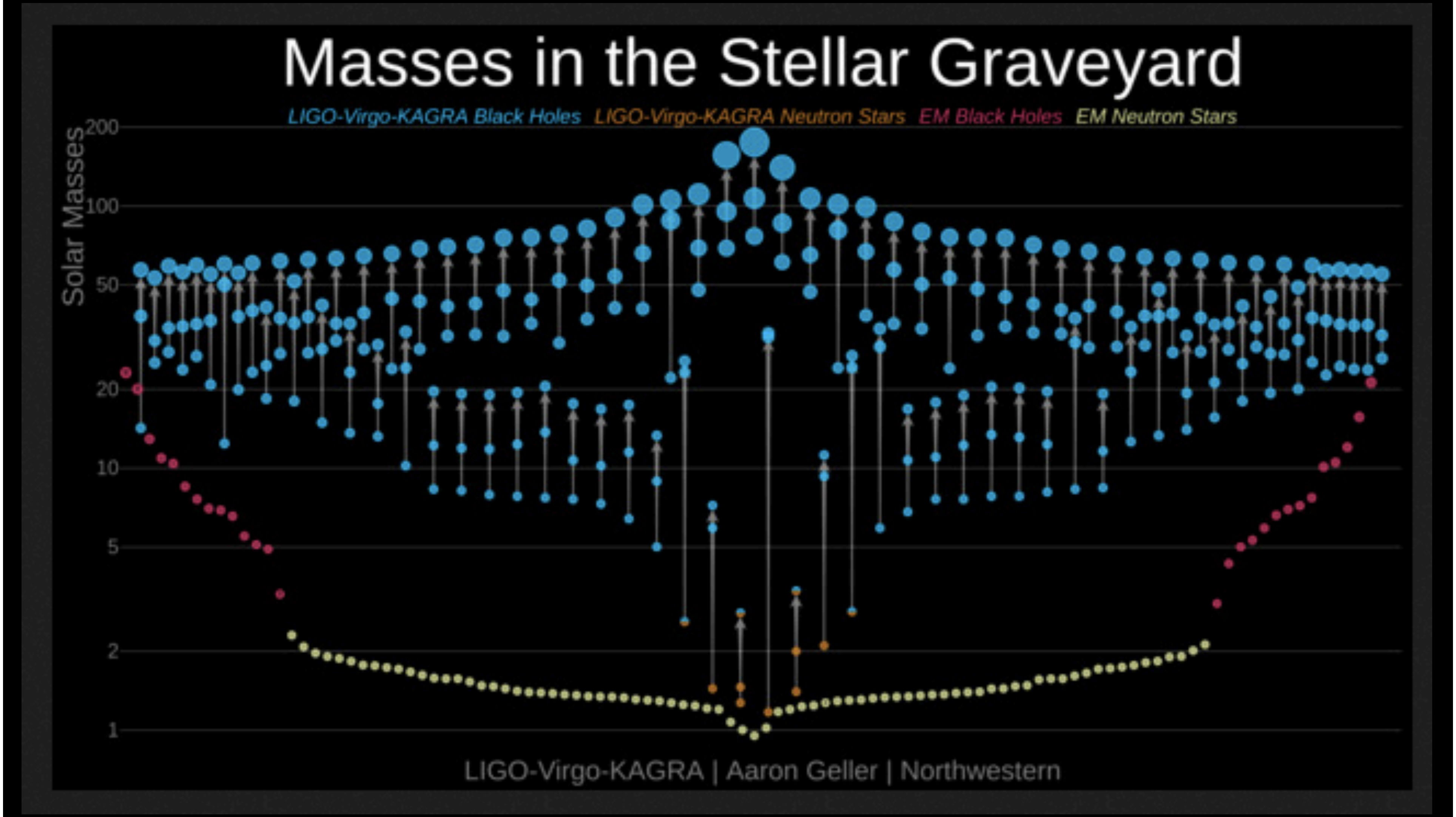
For very high-mass stars, with mass ***130-250 $M_\odot$***, a true pair-instability supernova can occur. In these stars, the first time that conditions support pair production instability, the situation runs out of control. The collapse proceeds to efficiently compress the star's core; the overpressure is sufficient to allow runaway nuclear fusion to burn it in several seconds, creating a thermonuclear explosion. *With more thermal energy released than the star's gravitational binding energy, it is completely disrupted; no black hole or other remnant is left behind. This is predicted to contribute to a "mass gap" in the mass distribution of stellar black holes*. This "upper mass gap" is to be distinguished from a suspected "lower mass gap" in the range of a few solar masses.

>250 $M_\odot$

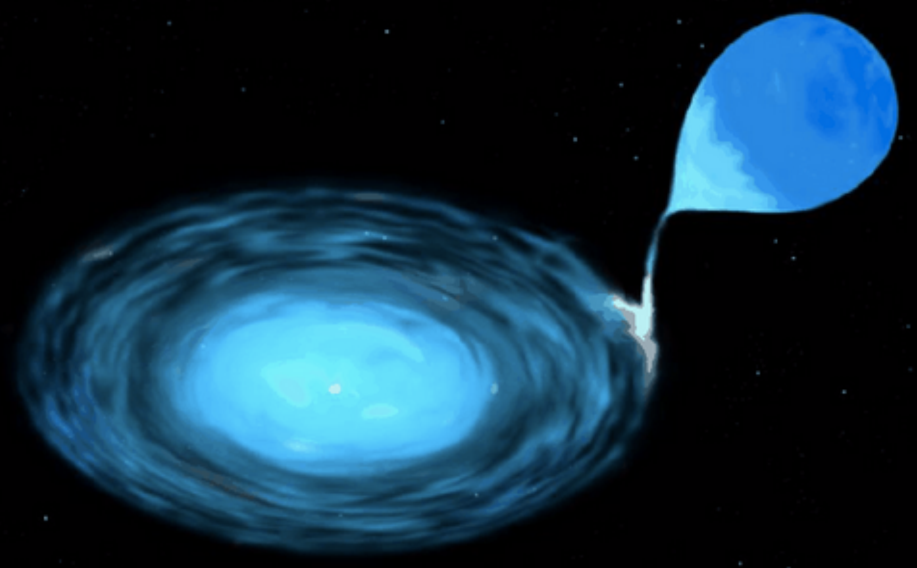
A different reaction mechanism, photodisintegration, follows the initial pair-instability collapse in stars of at least ***250 $M_\odot$***. This endothermic (energy-absorbing) reaction absorbs the excess energy from the earlier stages before the runaway fusion can cause a **hypernova explosion**; the star then ***collapses completely into a black hole***.

Remnants of massive single stars




Masses in the Stellar Graveyard

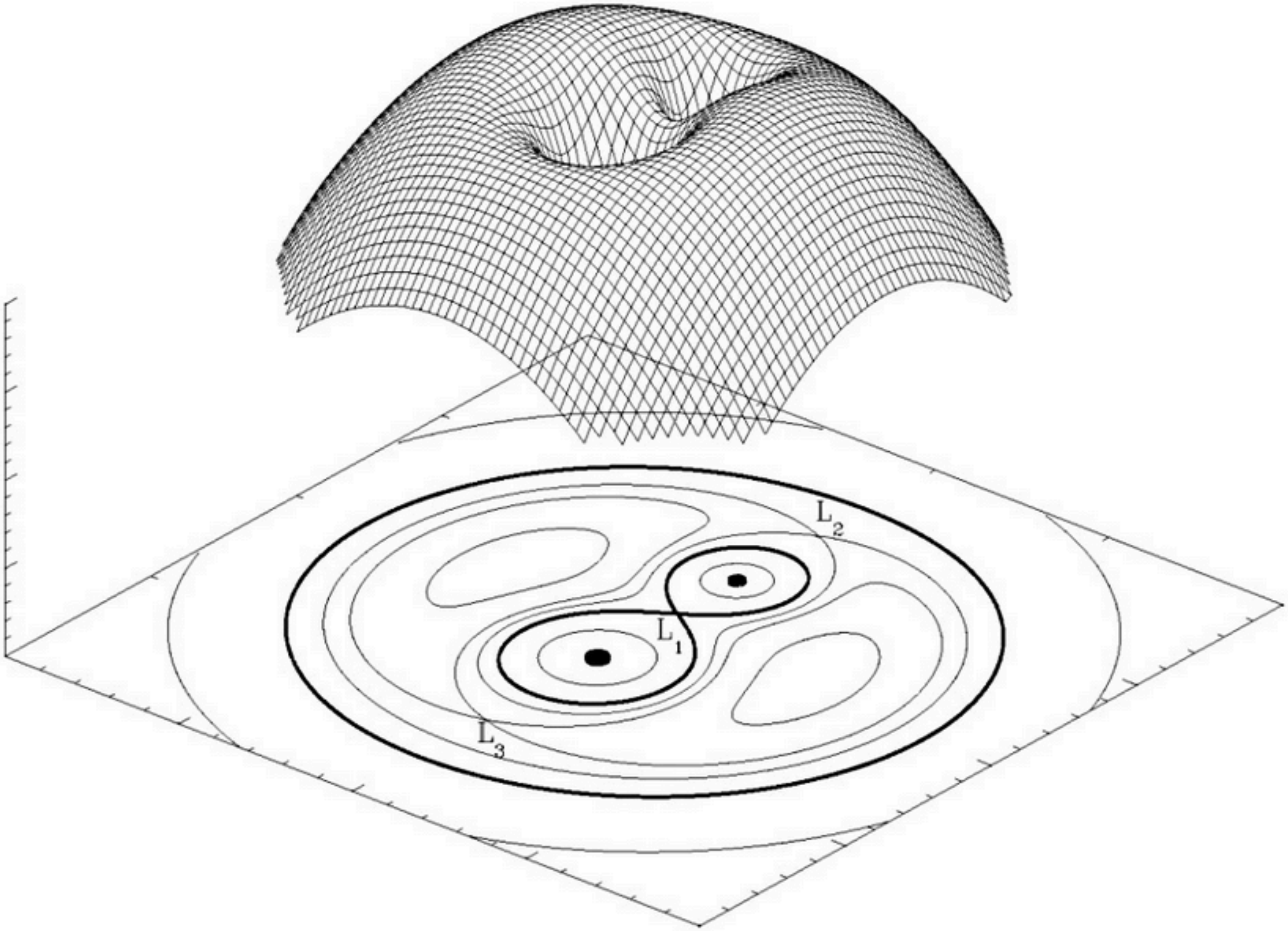
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



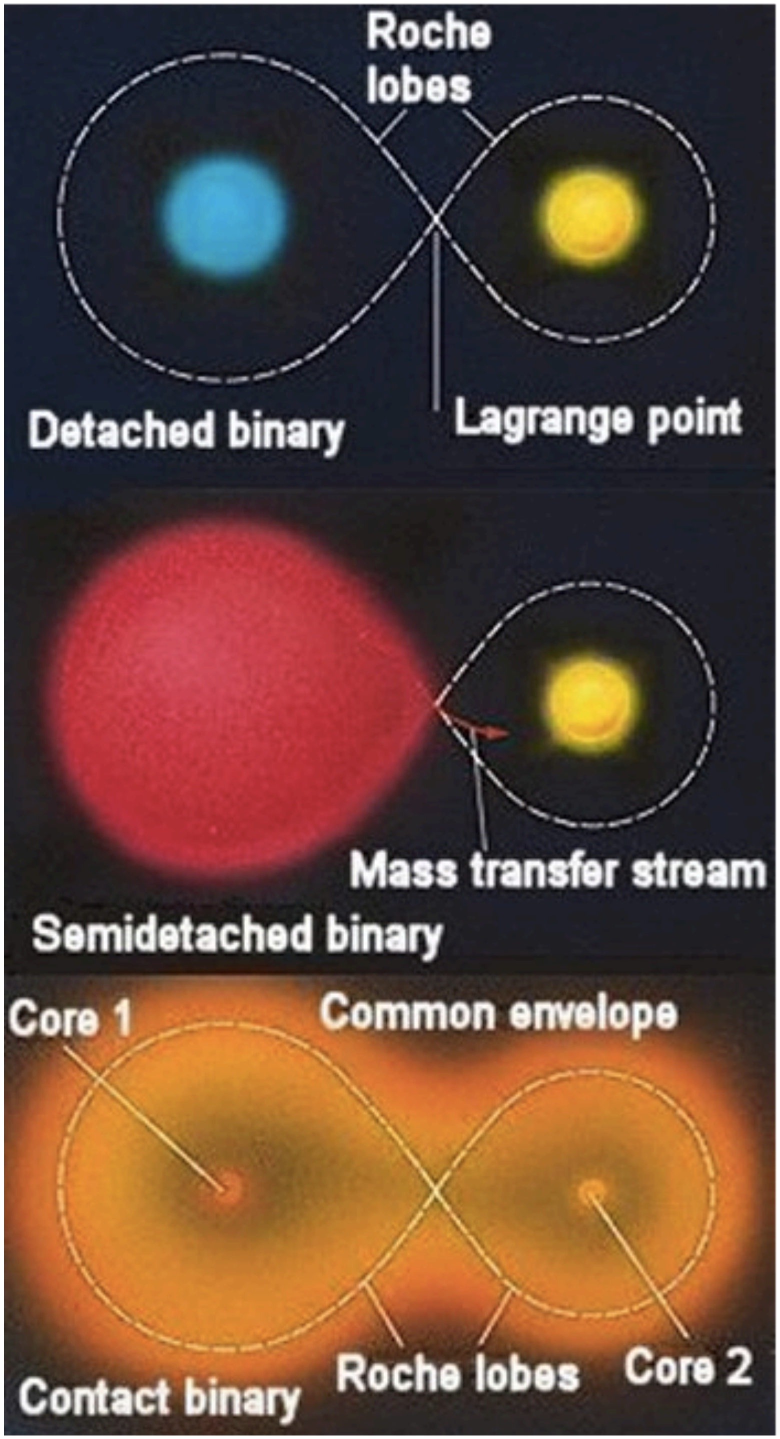
The common lore is that Type Ia SN occur in close binary systems composed of a white dwarf and a normal companion star. The particular type of binary systems are referred to as ***Cataclysmic Variables (CVs)***.

CVs are short orbital period (hours to days) binary star systems composed of a white dwarf and a low mass main seqeunce star (in general, sometimes the companion star is a red evolved star). As their name implies, ***CVs*** are sites for cataclysmic events. However, the events are not so cataclysmic as to destroy the binary star systems (in general). The events lead to rapid increases in the luminosities of the systems. There are three main types of ***CVs***, Dwarf Novae, Recurrent Novae, and Classical Novae. Also, many ***CVs*** are strong sources of x-ray emission, and *CVs* may be the progenitors of *Type I Supernovas*.

Mass Transfer in CVs: The systems must have short orbital periods (hours to a few days) or else the stars will be too far apart to exchange significant amounts of mass. Let's define some things.

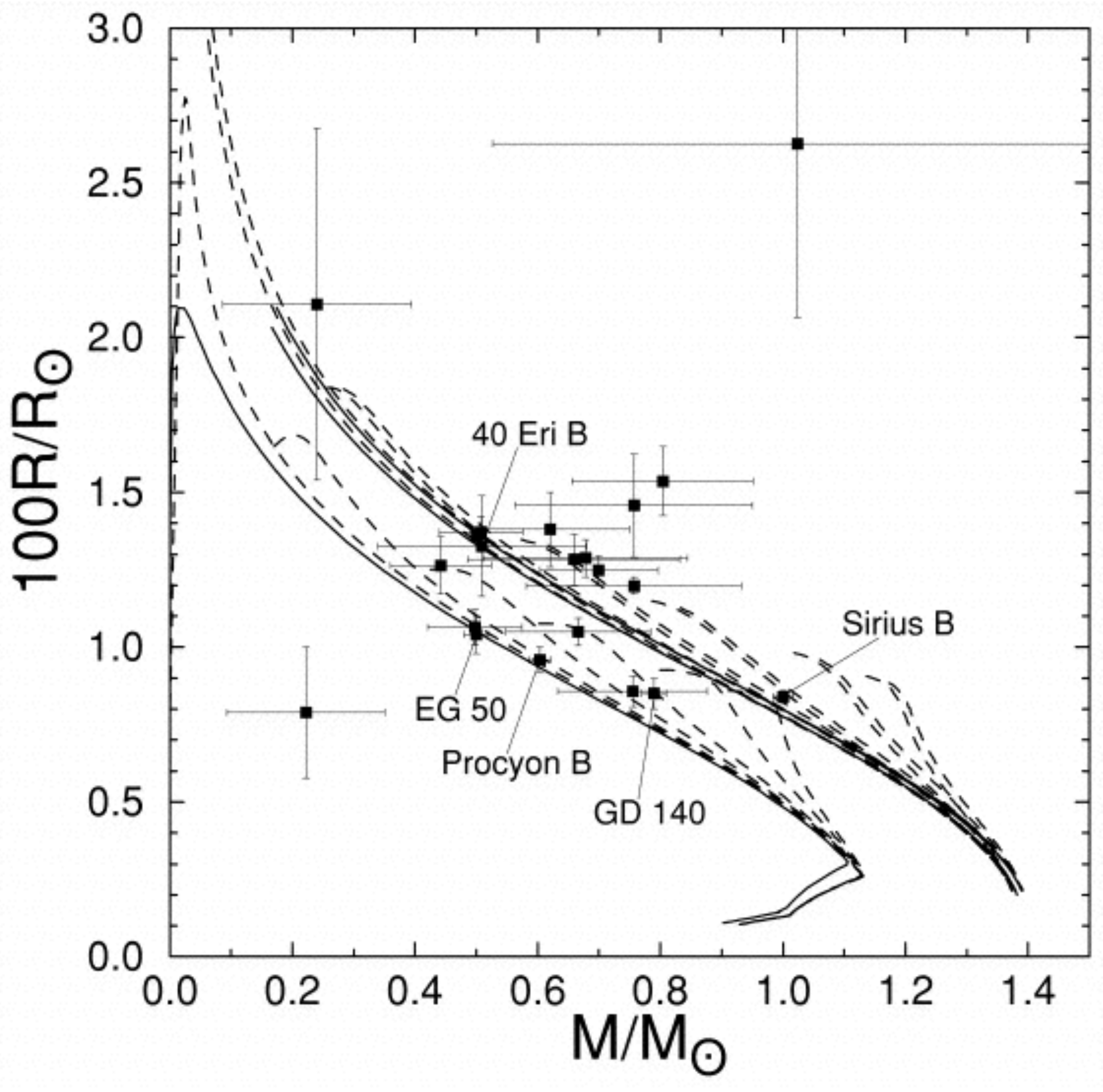


Consider 2 point masses in circular orbits. Compute and plot equipotential surfaces in the frame where the stars are stationary. 3 critical points are shown, the 3 lowest Lagrange points. The heavy solid line (the figure 8) mark the Roche lobes for stars 1 and 2.



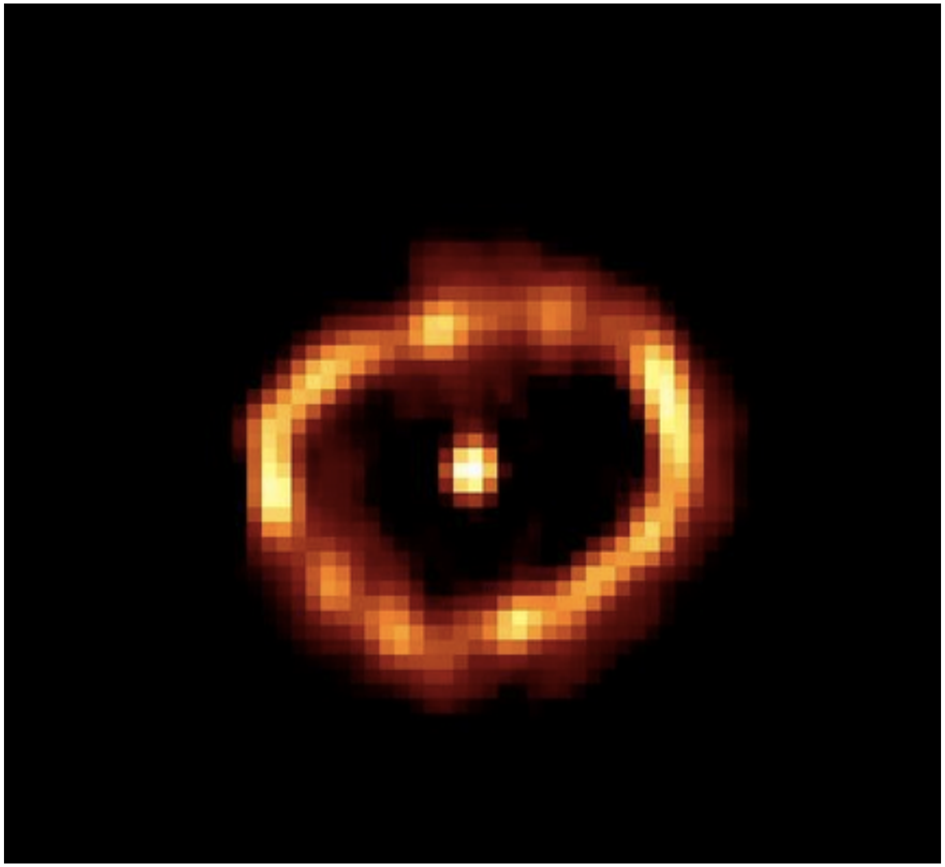
Based on the relationship of the stars to their Roche lobes, we can define 3 types of binary systems:

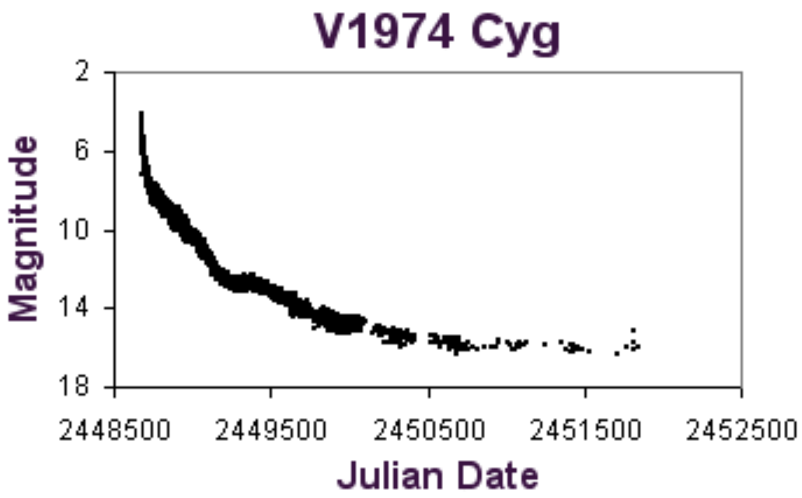
- ***Detached systems***, both stars are within their Roche lobes
- ***Semi-detached systems***, one star overflows its Roche lobe
- **Contact systems**, both stars overflow their Roche lobes forming a system with a common envelope



Comparison of theoretical white dwarf mass-radius relationshops and observed white dwarfs. The upper curves are pure helium and pure carbon white dwars. The lower curve is for a pure iiron white dwarf.

For slow accretion rates, ***$< 10^{-11}$-$10^{-10}\,M_{\odot}y^{-1}$***, the material radiates the energy gained as it falls onto the white dwarf. The material accreted compresses further due to the weight of continued added material. The compression causes the temperature and pressure of the accreted material to increase but only slowly. After around 10,000 to 100,000 years of accretion, the conditions become right for nuclear burning. The ignition of the nuclear burning is not gentle because of the high densities. The ignition of the burning leads to an explosion (either because the material is degenerate or the ignition occurs in a thin mass shell, ***10^{-5}-$10^{-6}\,M_{\odot}$***). The thermonuclear explosion causes the nuclear burning shell to be ejected leading to a **Classical Nova outburst** and no increase in mass the ***CO*** core.

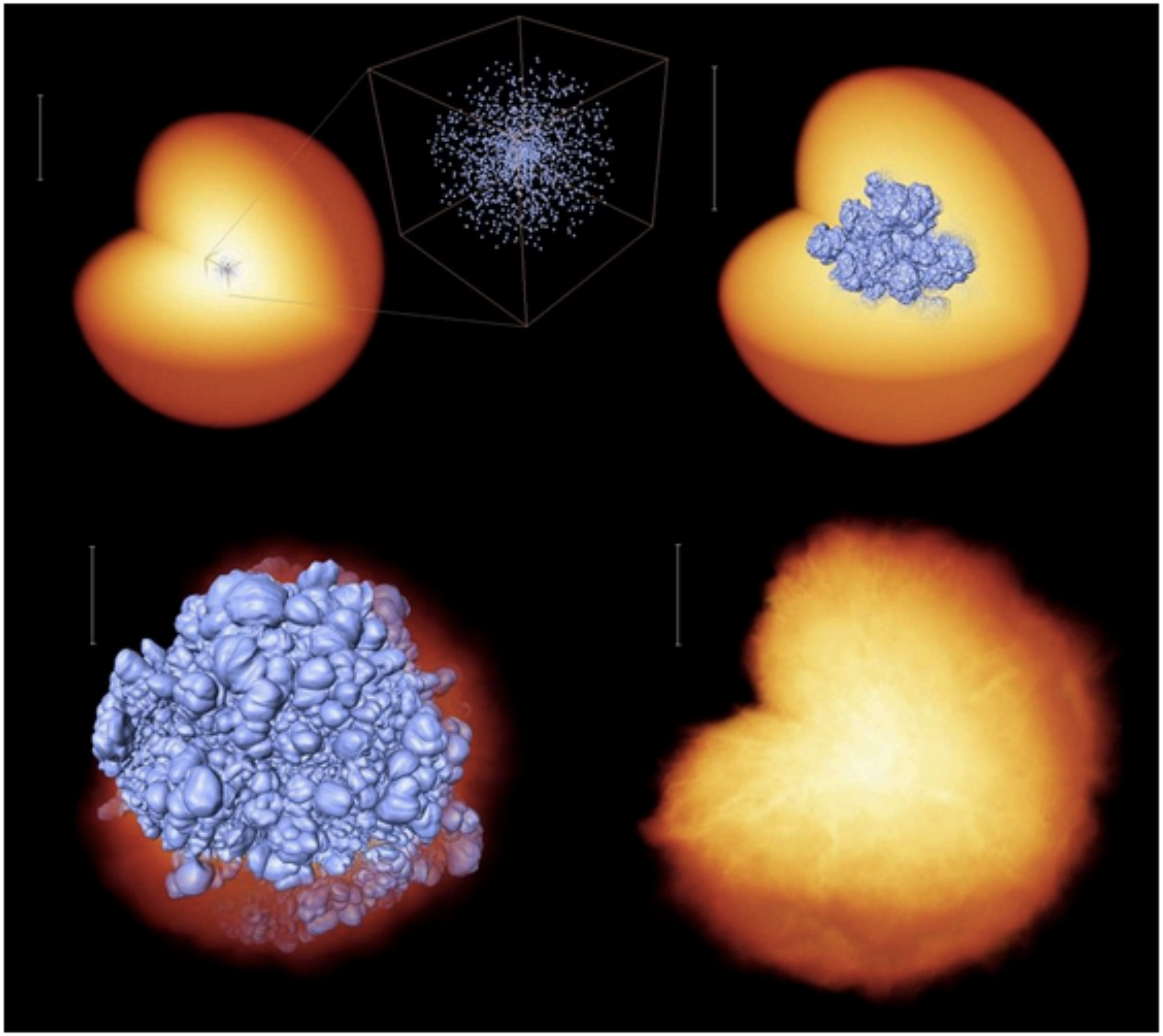




Visual light curve of V1974 Cyg from the AAVSO International Database; August 31, 1991 to August 13, 2002.

For fast accretion rates ***$>10^{-(7-8)} M_{\odot} y^{-1}$***, the material does not have time to lose its energy it gained as it falls onto the white dwarf. In this case when the conditions needed for the onset of nuclear burning are reached, the material is not degenerate and the ignition is gentle, there is no explosion. The ashes of hydrogen burning then settle onto a helium burning layer whose ashes then settle onto the core of the white dwarf increasing its mass. This gentle increase in the mass **of the white dwarf eventually causes the white dwarf to approach the *Chandrasekhar Limit*.** For a CO white dwarf this leads to ignition of C which causes the entire white dwarf to rapidly undergo a thermonuclear outburst which incinerates the star. This leads to a ***Type I SN.***

Although this occurs near the Chandraskehar Limit most workers think the explosion is not caused by collapse that ensues after the Chandraskehar limit is exceeded but rather it happens because the gas reaches high enough densities and temperatures to ignite C.



-Evolution of the thermonuclear supernova explosion simulation. The zero level set associated with the thermonuclear flame is shown as a blue isosurface and the extent of the WD is indicated by the volume rendering of the density. The upper left panel shows the initial set up and the close-up illustrates the chosen flame ignition configuration. The subsequent two panels illustrate the propagation of the turbulent flame through the WD and the density structure of the remnant is shown in the lower right panel.

Comment: The gravitational binding energy of a white dwarf is

$$U_g \approx -0.6\frac{GM^2}{R} = -3\times10^{51}erg$$

The energy available from carbon burning is

$$U_{nuc} \approx 0.0012Mc^2 = 3\times10^{51}erg$$

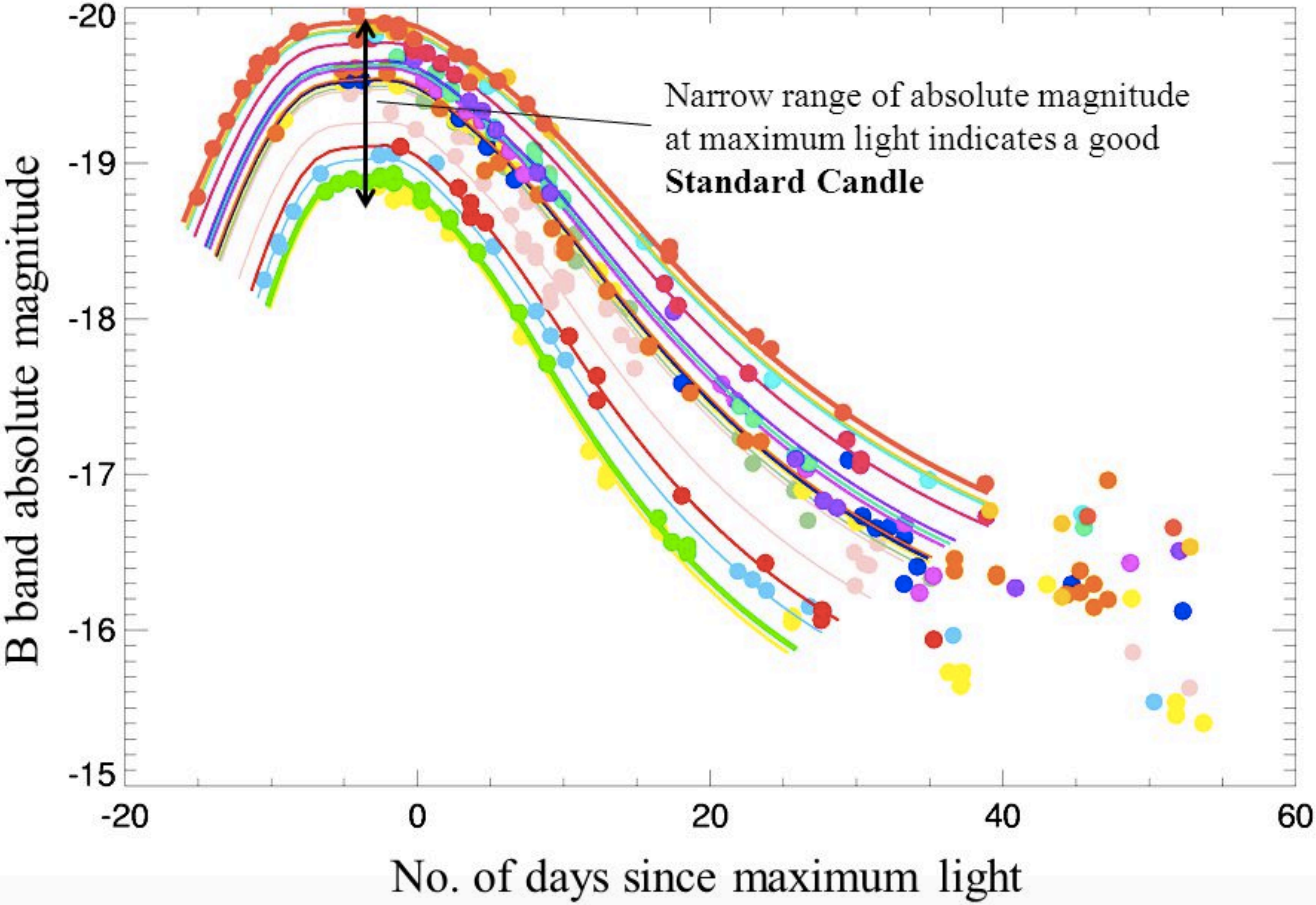
This is close, but enough energy to unbind the white dwarf and cause explosion.

What about Ne-Mg white dwarfs?

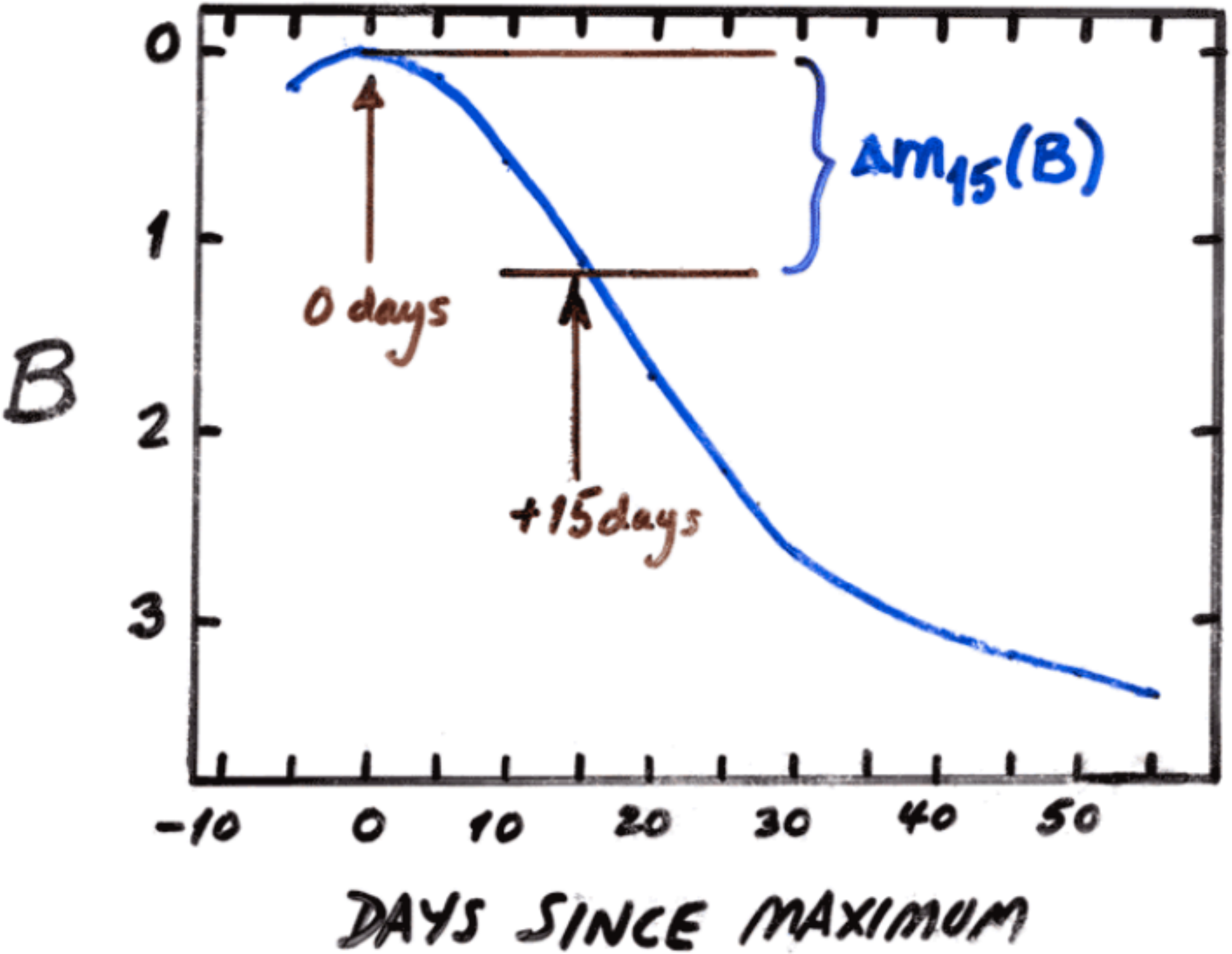
Because the ignition of carbon in ***Type I SN*** occurs when the white dwarf is near the ***Chandrasekhar limit***, the progenitor stars for ***Type I SN*** have nearly the same properties. This led to the suggestion that *Type I SN* should all appear to be similar in appearance prompting the suggestion that ***Type Ia SN*** may serve as ***standard candles***. This is as opposed to ***Type II SN*** where the progenitor stars are thought to have widely differing properties.

It turns out that ***Type Ia SN*** are not ***standard candles*** but are things referred to as ***standardizable candles***. We now discuss what is meant by ***standardizable candles***.

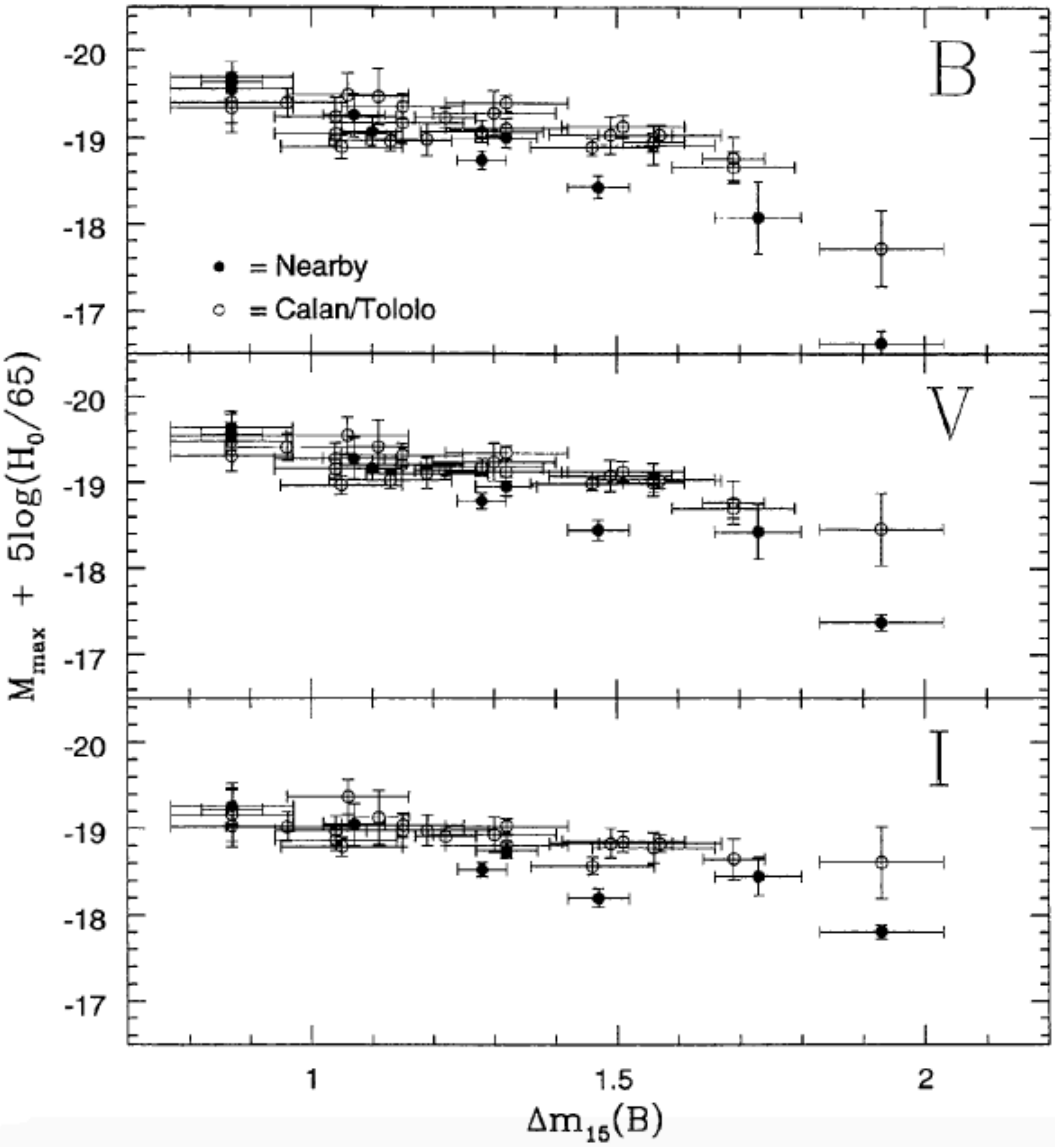
Some examples of Type I supernova light curves

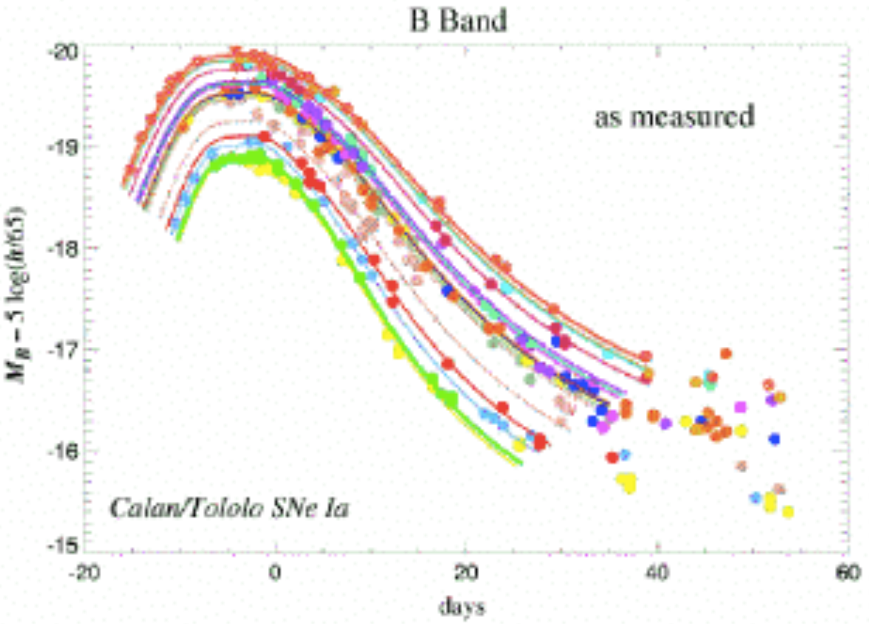


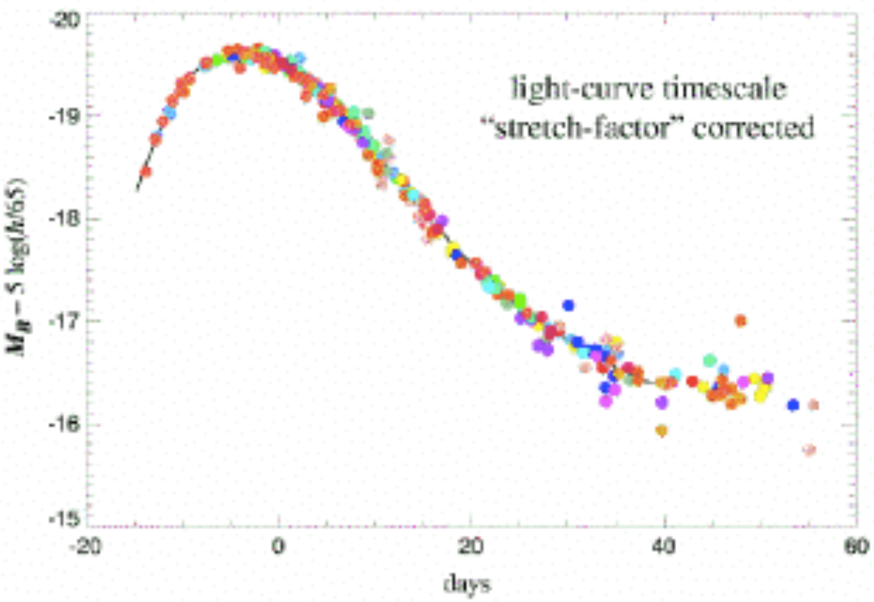
Narrow range of absolute magnitude at maximum light indicates a good **Standard Candle**



0
1
2
3
B
0 days
+15 days
Δm₁₅(B)
-10
0
10
20
30
40
50
DAYS SINCE MAXIMUM


B
V
I
● = Nearby
○ = Calan/Tololo
-20
-19
-18
-17
1
1.5
2
$M_{max} + 5\log(H_0/65)$
$\Delta m_{15}(B)$


B Band
as measured
Calan/Tololo SNe Ia
M_B − 5 log(h/65)
-20
-19
-18
-17
-16
-15
-20
0
20
40
60
days


light-curve timescale
"stretch-factor" corrected
M_B − 5 log(h/65)
-20
-19
-18
-17
-16
-15
-20
0
20
40
60
days

Perlmutter & Schmidt (2003)