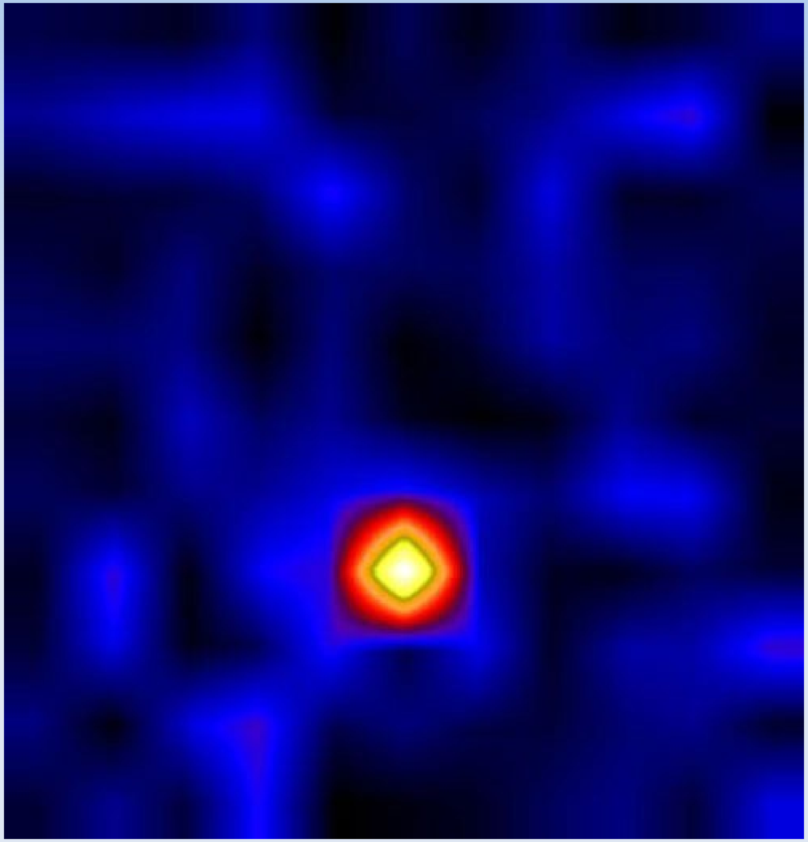
Compact Stars



Lecture 13

Summary of the previous lectures

- I presented pulsars, their dicovery, and observed properties of pulses
- Pulsars are divided into ‘normal’ and millisecond pulsars. The latter are ‘recycled’ by accretion.
- Pulsars radiate on the cost of rotational energy of magnetized neutron star
- Dipole model explains energy extraction mechanism, via stripping of charged particles by electric force from NS star surface
- Lighthouse model is an obligue rotating dipole version, explaining periodiciy of pulses

Summary of the previous lectures

- I also presented gravitational waves. They are waves of spacetime curvature distorsion, originating due to accelerated motion of massive bodies.
- These waves are detected by intereferometers, when test masses are oscillating because of GW passage.
- Astrophysical sources of kHz frequency GWs detectable by ground-based interferometers are compact binaries (black holes and neutron stars).
- Development of numerical relativity algorithms in 21st century made it possible to formulate templates of GW wave forms, which are used now for detections.

Summary of the previous lectures

- I also talked about the supermassive black hole mergers and some observational signatures of their past or future occurrence
- Numerical simulations are now giving robust algorithms to compute the binary black hole merger in vacuum and simulate gravitational wave radiation. „Wet mergers' in gaseous environment are more complex to model.
- Recoil velocity due to gravitational kick occurs when the mass ratio and/or the spin vectors orientation allows for it. The spin flip of BH is possible and follows from the total angular momentum conservation.

Today: supernovae

- Supernova classification, mechnisms of type Ia and core-collapse supernova explosions.
- Spernovae Ia are useful for cosmology. Their observations may be relevant to probe the high-redshift Universe.
- GRBs may also provide tool for estimation of standard cosmological model parameters, via their (E_{peak}-E_{iso}) correlation. They are not standard candles though.

Supernovae

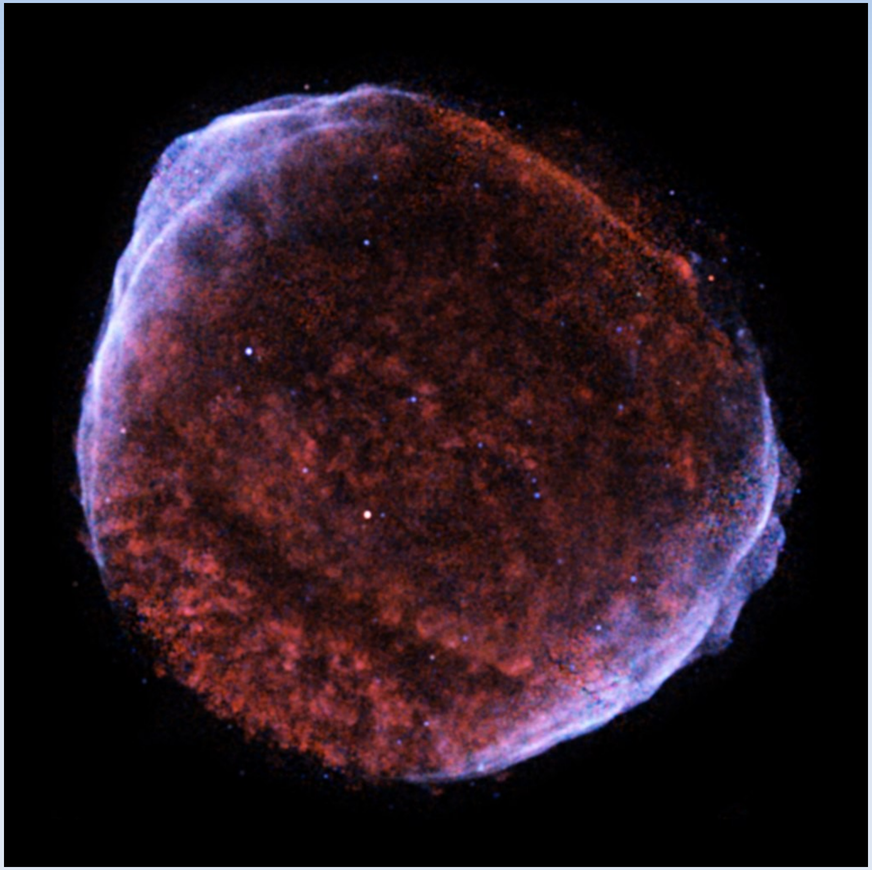
- Supernovae are exploding stars whose luminosity after eruption suddenly increases many millions of times its normal level.
- They are broadly classified into two main types depending on the type of star which explodes.
- The progenitors of a Type Ia supernova (SNIa) is a white dwarf accreting matter from a companion.
- Progenitors of core-collapse supernovae are massive stars at the end of their lives.

Historical Supernovae

- Historically, only seven supernovae are known to have been recorded before the early 17th century.
- The most famous of them occurred in 1054 and was seen in one of the horns of the constellation Taurus. The remnants of this explosion are visible today as the Crab Nebula.
- Other prominent supernovae are known to have been observed from Earth in 185, 393, 1006, 1181, 1572, and 1604.

SN 1006

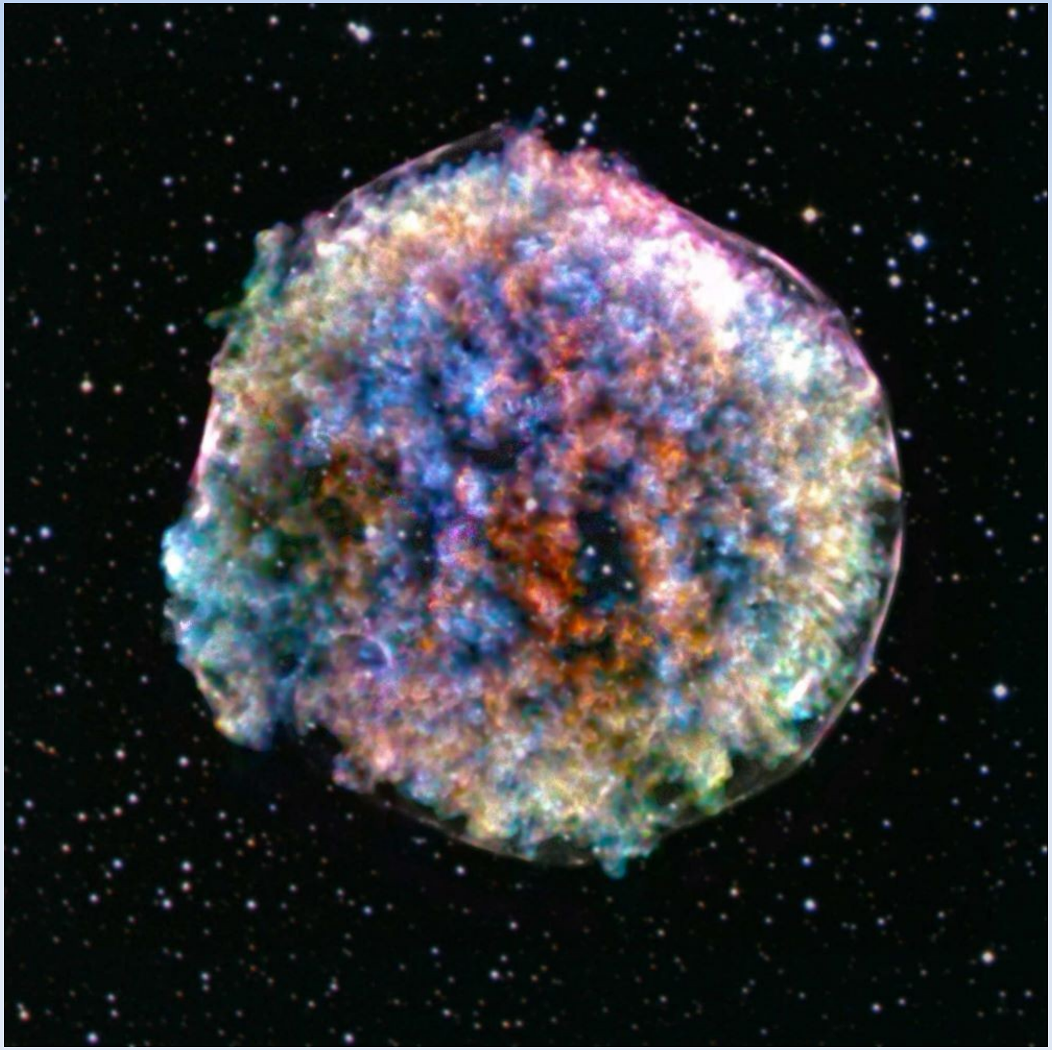
- Likely the brightest observed stellar event in recorded history, reaching an estimated −7.5 visual magnitude.
- Appeared on April 30 - May 1, 1006, in the constellation of Lupus, as "guest star". It was described by observers across China, Japan, modern-day Iraq, Egypt, and Europe.
- The associated supernova remnant from this event was identified in 1965. Its emission ranges from radio to gamma rays
- No associated neutron star neither black hole was found, indicationg the Type I SN nature.



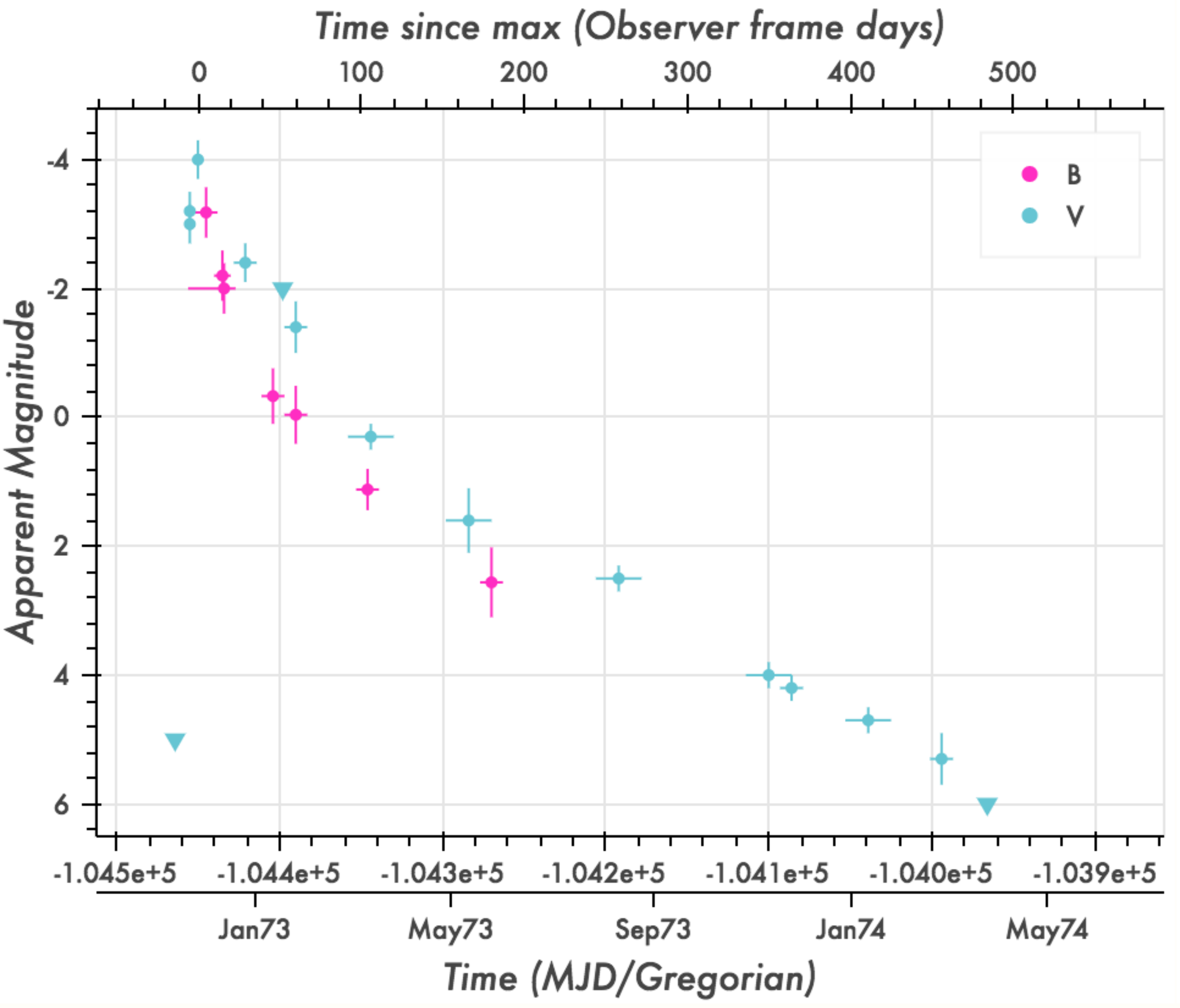
X-ray image of SN 1006 supernova remnant

SN 1572

- X-ray image of the Tycho supernova, also known as SN 1572, located between 8,000 and 9,800 light-years from Earth.
- Tycho is an example of a recent supernova that was visible from Earth in 1572.
- Its supernova remnant has been observed optically but was first detected at radio wavelengths; it is often known as 3C 10.



Reconstructed Tycho SN lightcurve

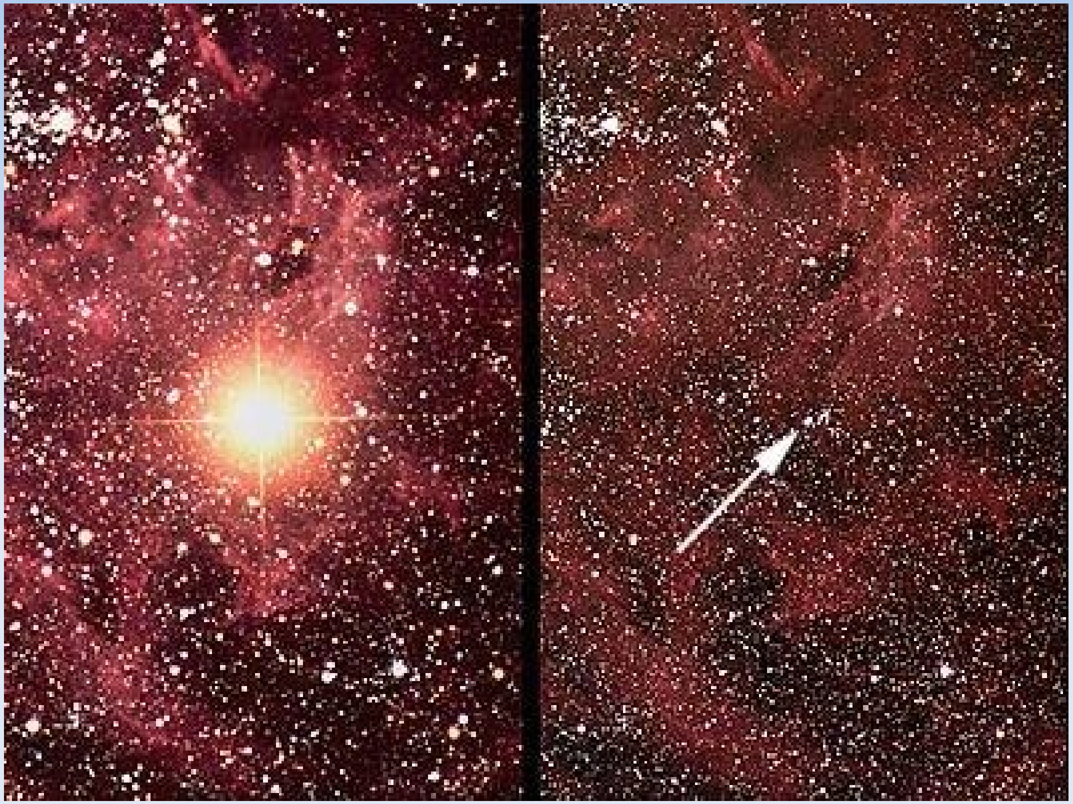


The classification as a type Ia supernova of normal luminosity allows an accurate measure of the distance to SN 1572. The peak absolute magnitude can be calculated from the B-band decline rate to be −19.0±0.3. Given estimates of the peak apparent magnitude and the known extinction of 1.86±0.2 magnitudes, the distance is about 3.8 kpc

Supernovae and novae

- Supernovae resemble novae in several respects.
- Both are characterized by a tremendous, rapid brightening lasting for a few weeks, followed by a slow dimming.
- Spectroscopically, they show blue-shifted emission lines, which imply that hot gases are blown outward.
- The supernova explosion, unlike a nova outburst, is a cataclysmic event for a star, one that essentially ends its active lifetime.

SN 1987A



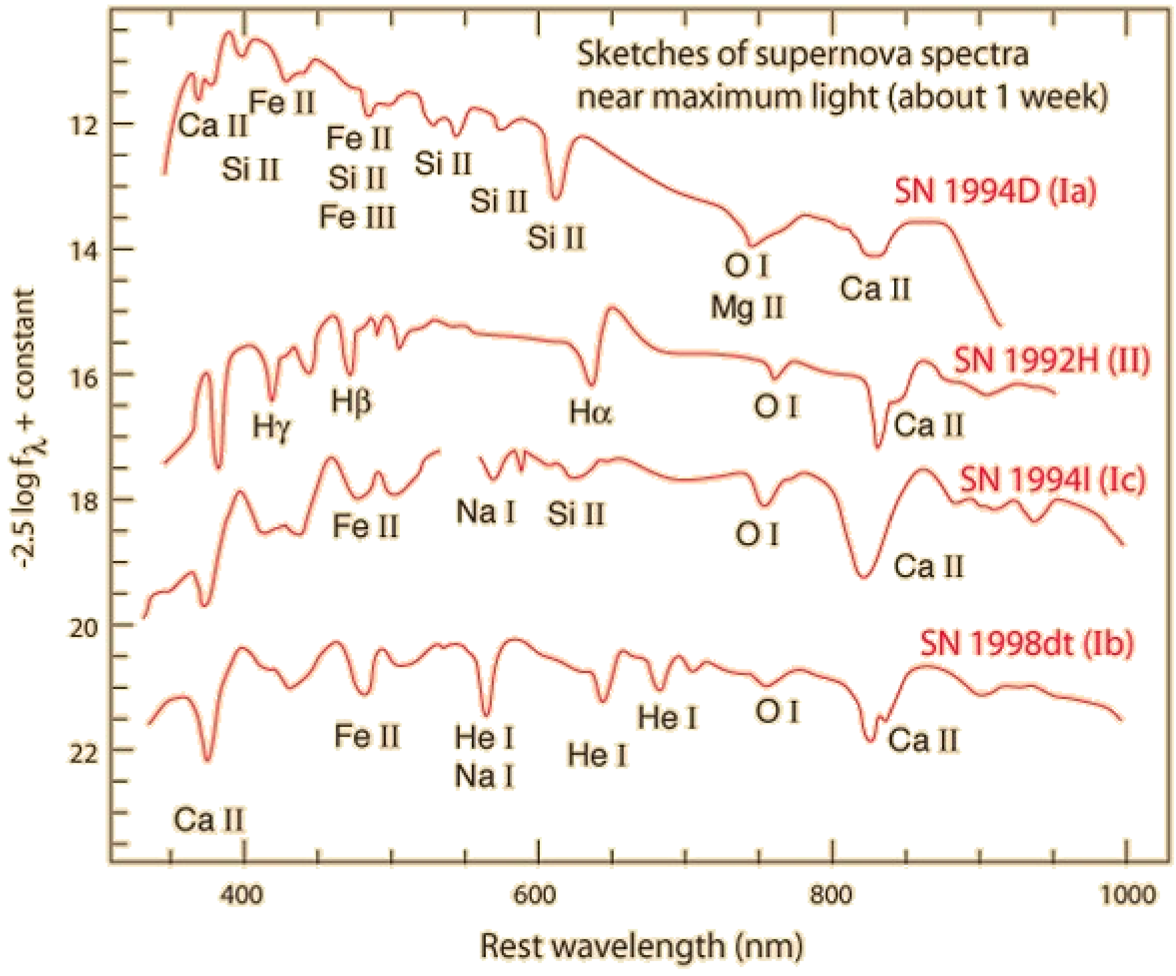
The most famous supernova of recent times is SN1987A. It exploded in the Large Magellanic Cloud, was clearly visible to the naked eye, and is one of the best studied objects outside our own Galaxy.

Credit: David Malin, Anglo-Australian Observatory

Classification history

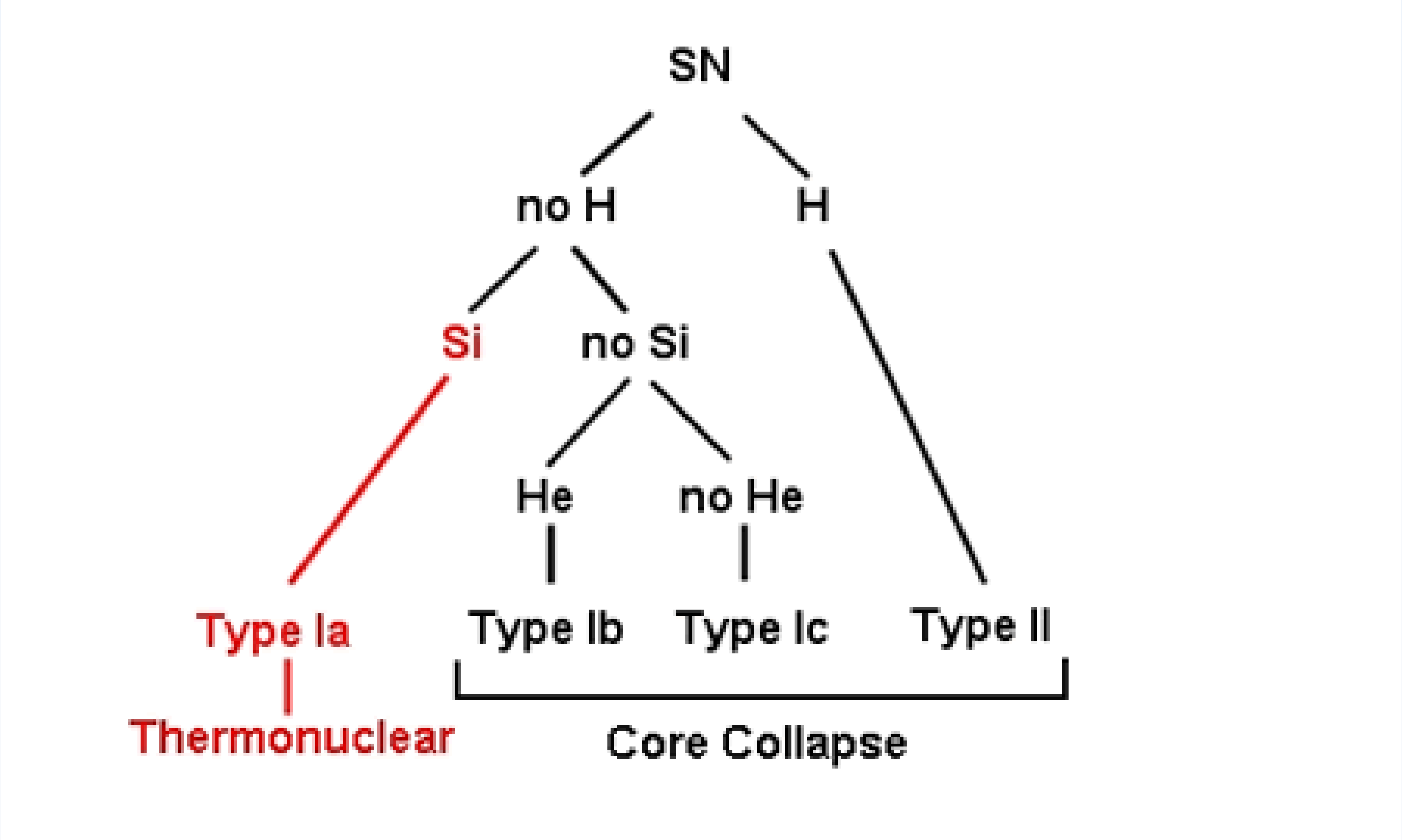
- Supernovae were first categorised in 1941 when Rudolph Minkowski recognised that at least 2 different types existed, those that showed hydrogen (H) in their spectra: Type II, and those that did not: Type I.
- In the mid-1980s as the rate of supernova discoveries increased and data quality improved, Type I supernovae were further sub-divided based on the presence or absence of silicon (Si) and helium (He) in their spectra.
- Type Ia supernovae contain an obvious Si absorption at 6150 A, Type Ib have no Si but show He in emission, and Type Ic display neither Si nor He.
- It was also discovered that while Type Ia supernovae could be found anywhere and in any type of galaxy, Type Ib and Type Ic supernovae occurred primarily in populations of massive stars, similar to Type IIs.

Exemplary spectra of SNe

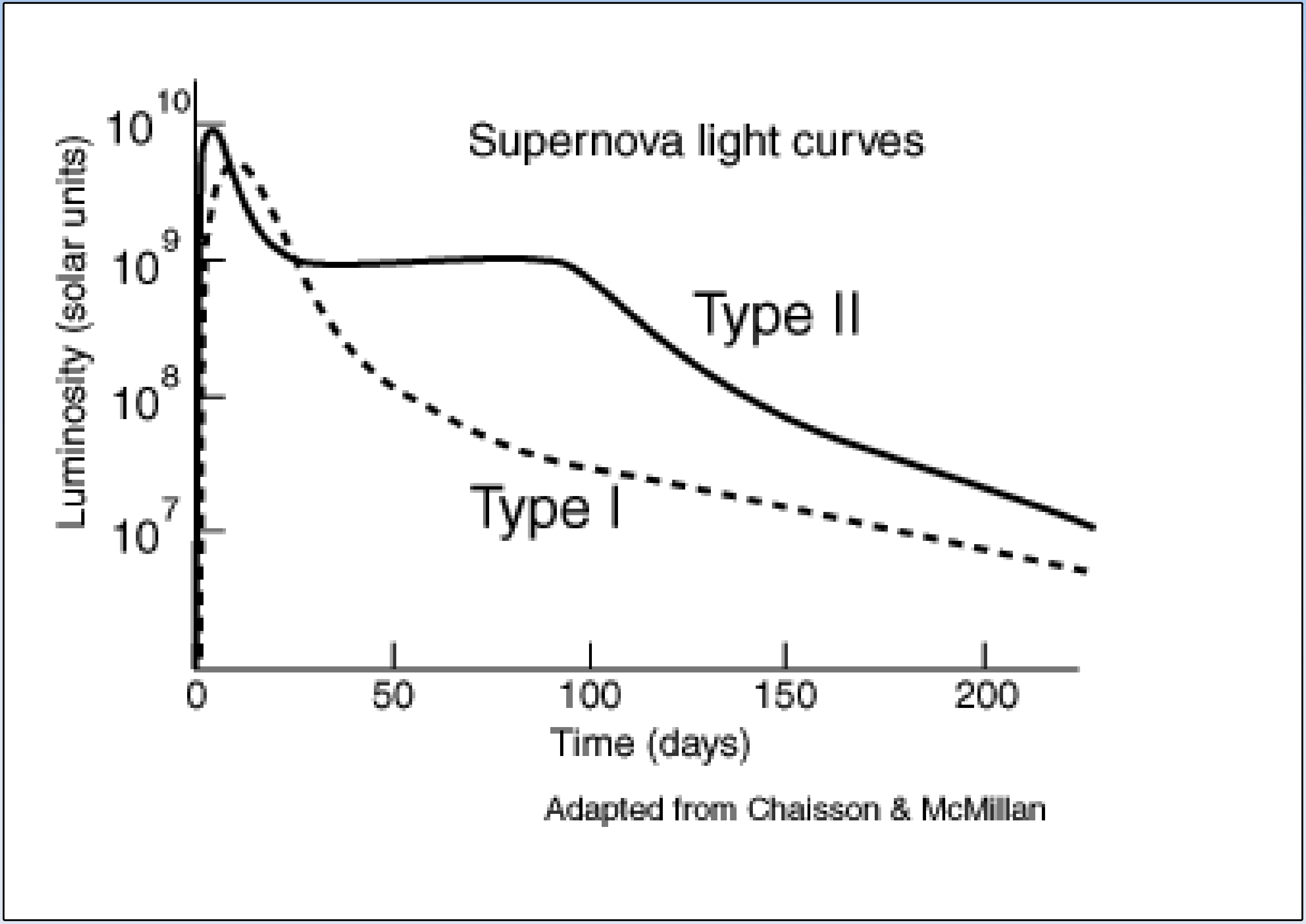


Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Supernovae classification



Types of lightcurves



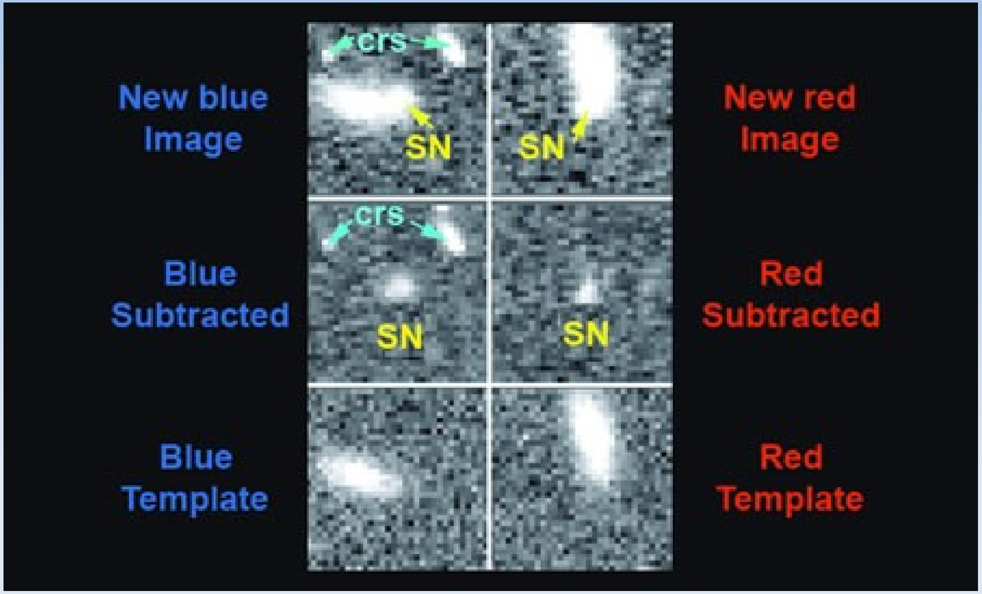
Adapted from Chaisson & McMillan

Supernova searches

- Supernovae are transient objects. They appear suddenly as a bright star (that can outshine an entire galaxy) at a random position in the sky, and fade relatively quickly.
- As they are difficult to find, astronomers have established supernova searches dedicated to locating new supernovae and obtaining rapid and extensive follow-up observations.
- They look for changes in the light distribution of nearby galaxies. With the help of technological advances such as Charged Couple Devices, supernova searches are now conducted with dedicated telescopes and software that systematically scan specific regions of the sky.

Supernova searches

- The same field is re-imaged and compared to the template.
- The timescale for this re-imaging varies depending on the exact nature of the project, but is typically around 2 weeks – the average time it takes for a supernova light curve to rise to maximum.



This means that supernovae are now discovered very early in their evolution and can be followed for longer (before they become undetectable) revealing much more information about the object.

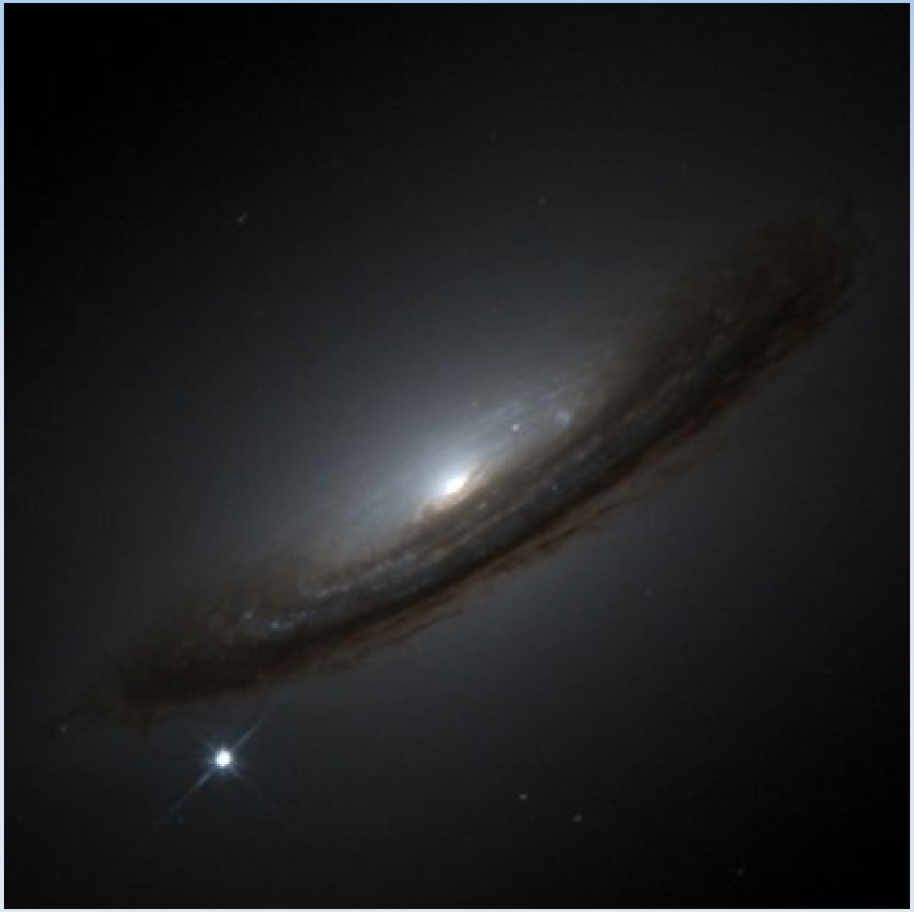
Once each candidate has been checked by eye and a list of objects that appear to be supernovae has been collated, the next step is to obtain spectra to confirm the discovery and (if real) determine the supernova type.

SDSS supernova survey

- The SDSS Supernova Survey ran from 2005 to 2008. The time-domain survey, involving repeat imaging of the same region of sky every other night, weather permitting, to detect and measure light curves for several hundred supernovae through repeat scans of the SDSS Southern equatorial stripe 82 (about 2.5° wide by ~120° long).
- SDSS-II SN discovered and measured multi-band lightcurves for ~500 spectroscopically confirmed Type Ia supernovae in the redshift range z=0.05-0.4.
- The survey also discovered about 80 spectroscopically confirmed core-collapse supernovae (supernova types Ib/c and II).

Type Ia supernova

- SNIa are the result of the explosion of a carbon-oxygen white dwarf in a binary system as it goes over the Chandrasehkar limit, either due to accretion from a donor or mergers.
- They are the brightest of all supernovae with an absolute magnitude of $M_B \sim -19.5$ at maximum.
- They occur in all galaxy types, and are characterised by a Sillicon absorption feature (rest wavelength = 6355 angstroms) in their maximum light spectra.



SN 1994D in NGC 4526.

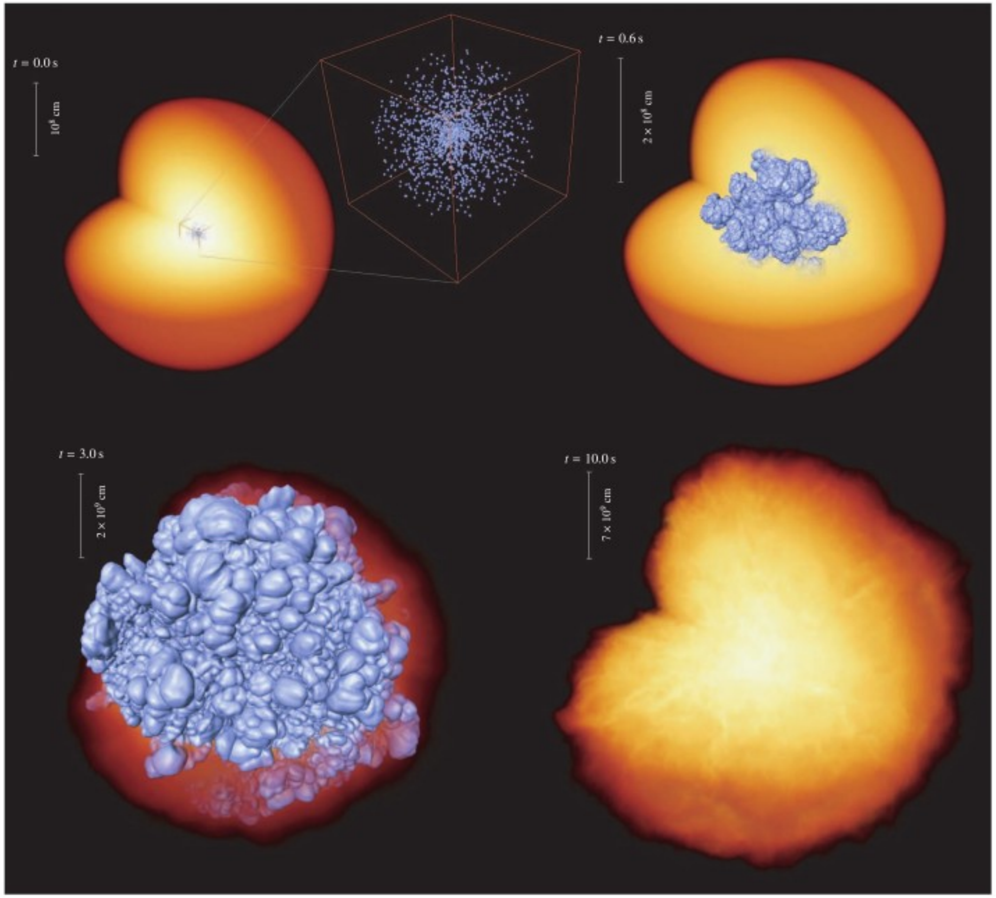
Credit: High-Z Supernova Search Team/HST/NASA

Explosion mechanism

- White dwarf has no hydrogen envelope (no H lines in spectrum).
- Carbon burning heats up the star. Above the burnig region a convective zone forms.
- Dynamical burning can proceed via
  - Deflagration
  - Detonation

Deflagration model

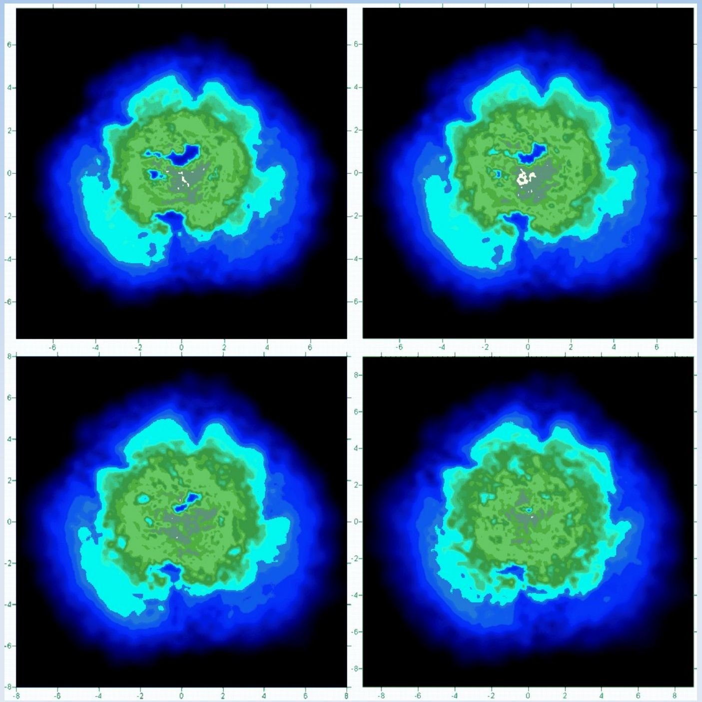
- Models are computed numerically in 3D.
- Parameterized by the flame ignition conditions
- Flame interacts with turbulence and turns on a turbulent cascade
- Energy of explosion falls into the lower end of observed SN Ia luminosities



Simulation of thermonuclear supernova, by Roepke et al. (2007)

Deflagration to Detonation Transition

- Deflagration needed to make the observed Sillicon.
- Even a best-choice pure deflagration model has shortcomings that indicate the need for a different mode of nuclear burning at late times.
- They predict unobserved amounts of carbon and oxygen moving with low velocities. Mass of ejected Ni-56 is too low.
- DDT models proposed to overcome this problem. Suggested transition to detonation at low density.



Snapshots of temperature maps after detonation (Brava & Garcia-Sanchez, 2008)

Various scenarios fo SN Ia

- Single degenerate model. Single white dwarf accretes material from its companion Main Sequence star
- Double degenerate model. In double WD system, the more massive accretes He and C/O from the less massive companion, or tidally disrupts it.

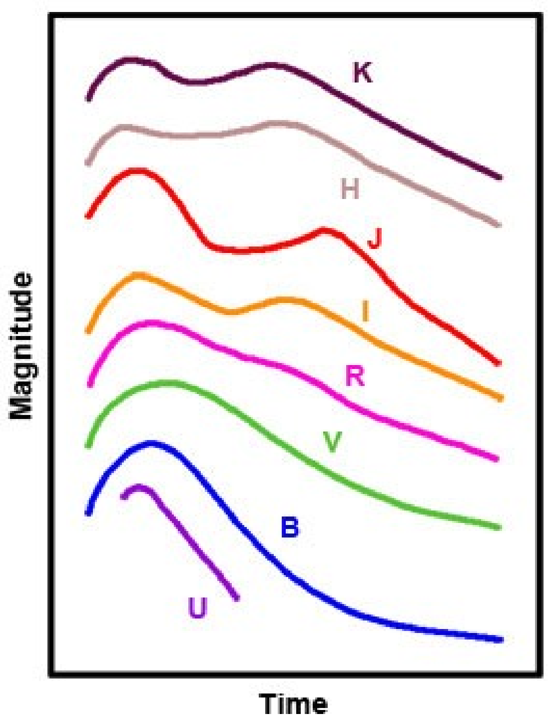
  Single degenerate model woul require most of progenitors to appear as supersoft X-ray sources, before explosion. Statistics does not match the observed SN 1a rates.

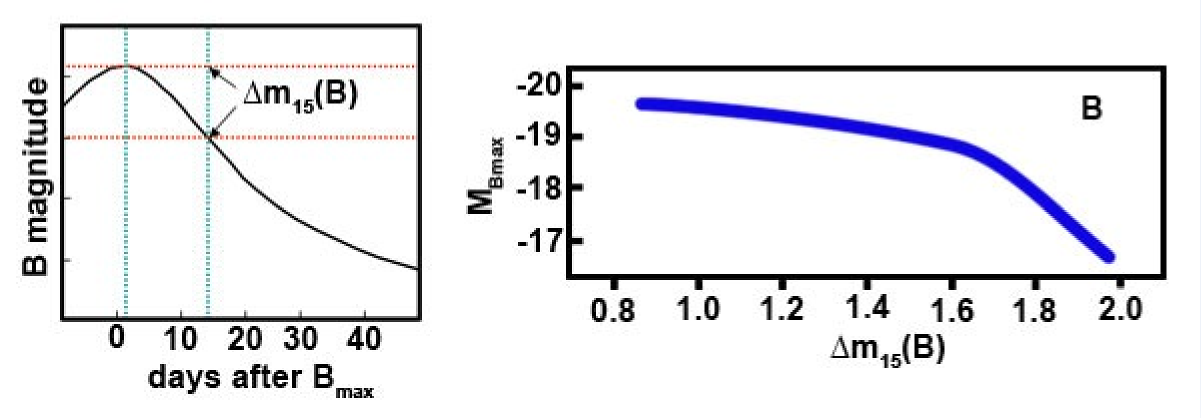
Lightcurves of SN Ia

- Very bright Optical explosion, ~10^{43} erg/s at maximum (can outshine the entire host galaxy by an order of magnitude).
- Reach maximum after 10-15 days. Then decays exponentially. Timescale similar to radioactive decay of Ni-56
- Powered by decay, Ni-56 → Co-56 (τ~9d) and Co-56 → Fe-56 (τ~114d)

SN Ia lightcurve shapes

- A shoulder, which becomes a pronounced secondary maximum, appears from blue colours (U, B, V) to red (R, I) and near-infrared colours (J, H, K).
- The maximum B-band luminosity is linked to how fast the light curve declines in the 15 days following B maximum





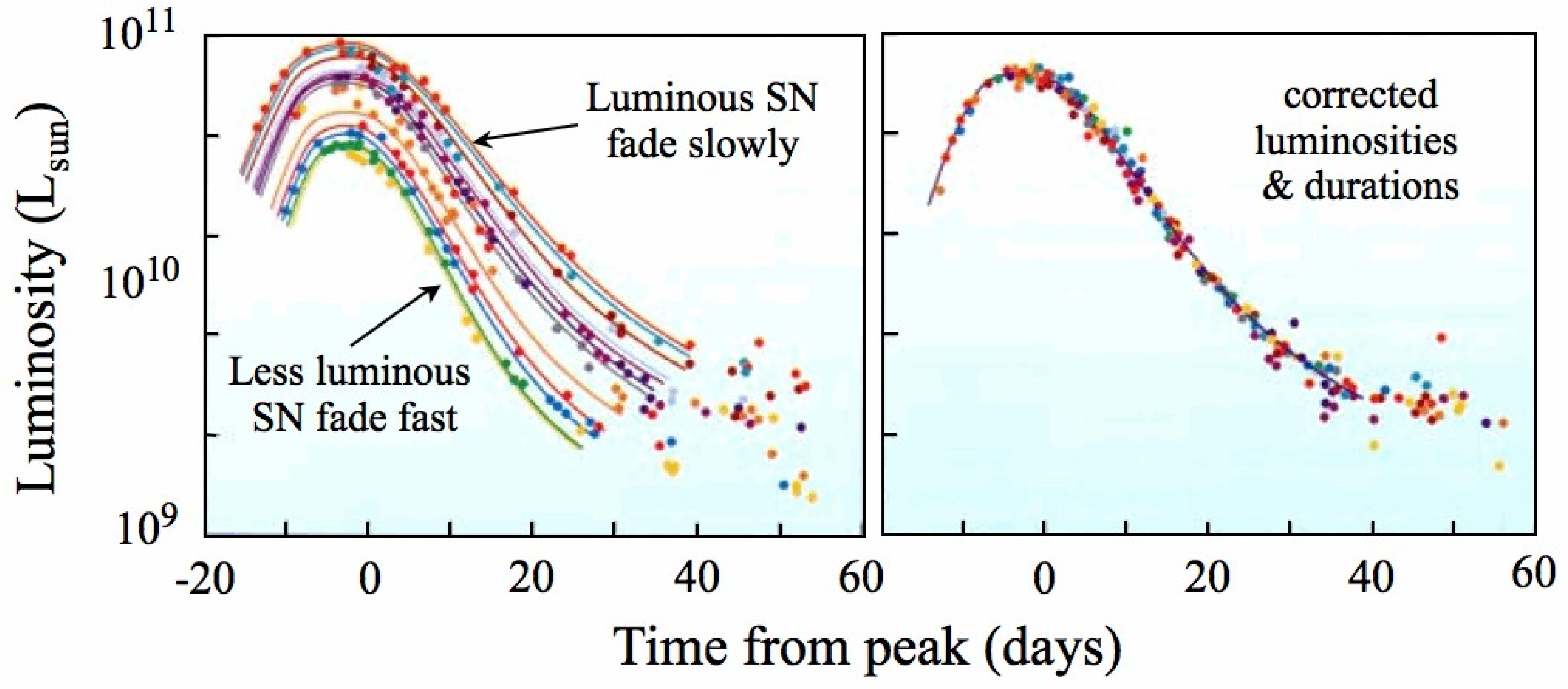
Phillips relation

- Relation between maximum brightness and speed of supernova, determined emipirically.

  $$\boxed{M_{B,max} = -21.726 + 2.698\ \Delta m_{B,15}}$$

  where M is absolute B-band magnitude and Δm is decline in luminosity at 15 days after maximum.
- The origin of this relation is based on physics of radiative transfer and energy deposition. It is generally applicable to any explosion.

Lightcurves corrected by timescale

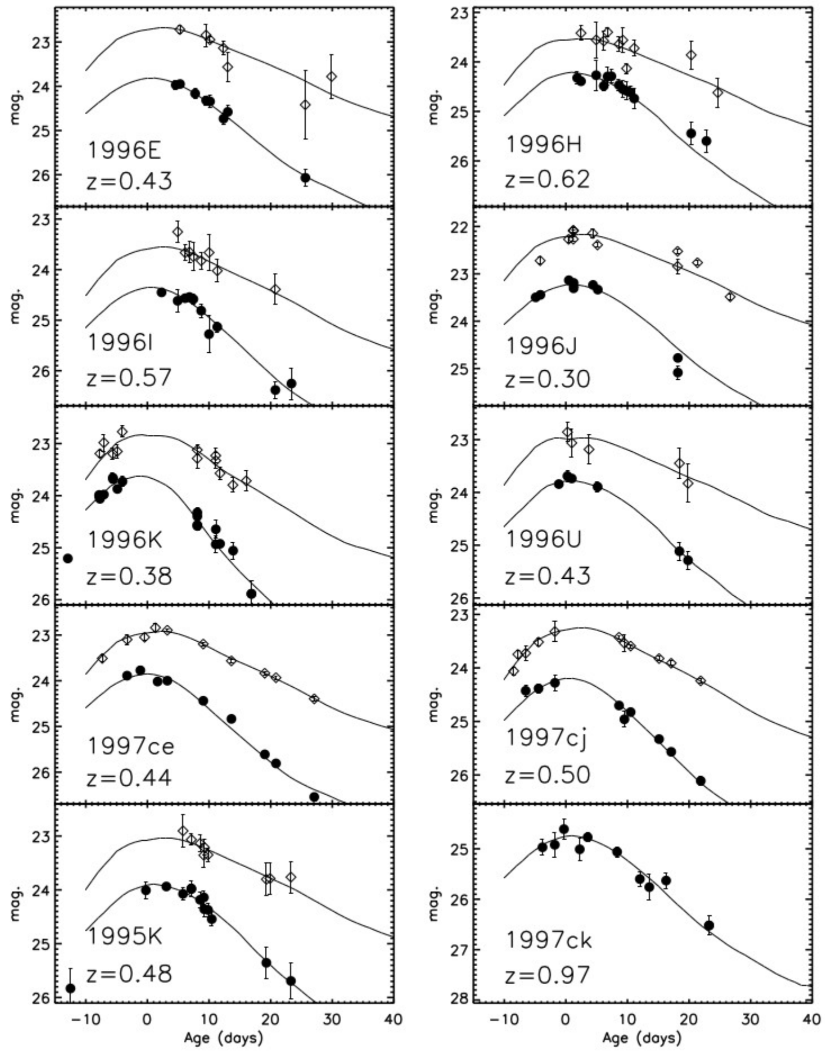


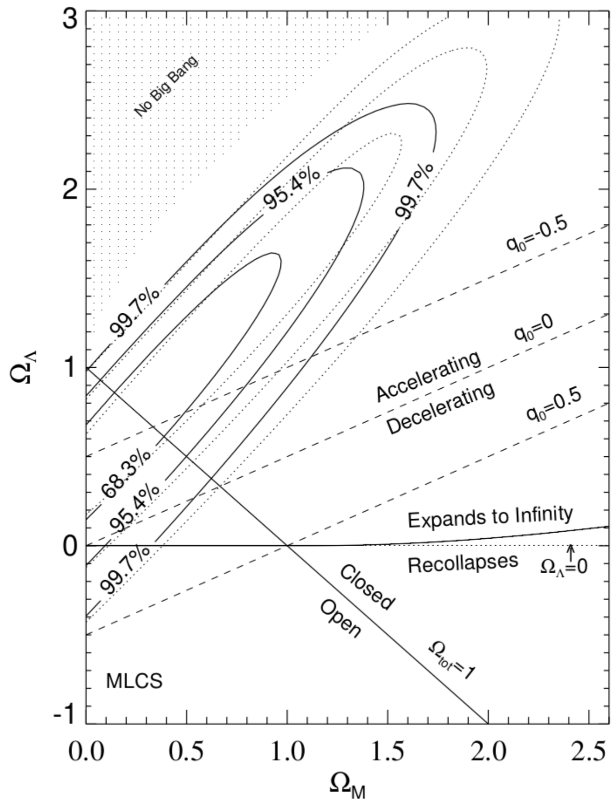
Phillips et al. (1993)

SN as Standard Candles

- SNIa exhibit brightnesses at maximum that range from about +1.5 to -1.5 mag around a typical SNIa.
- The over or under luminosity is correlated to how quickly the Type Ia light curve decays in the 15 days after maximum light in the B band. This is known as the luminosity – decline rate relation
- The term ‘standarizable” is now used, and employs lightcurve fitting techniques
- Type Ia supernovae have become one of the primary distance indicators in astronomy, helping to tie down the Hubble constant and revealing that the Universe expansion is accelerating.

Cosmological application





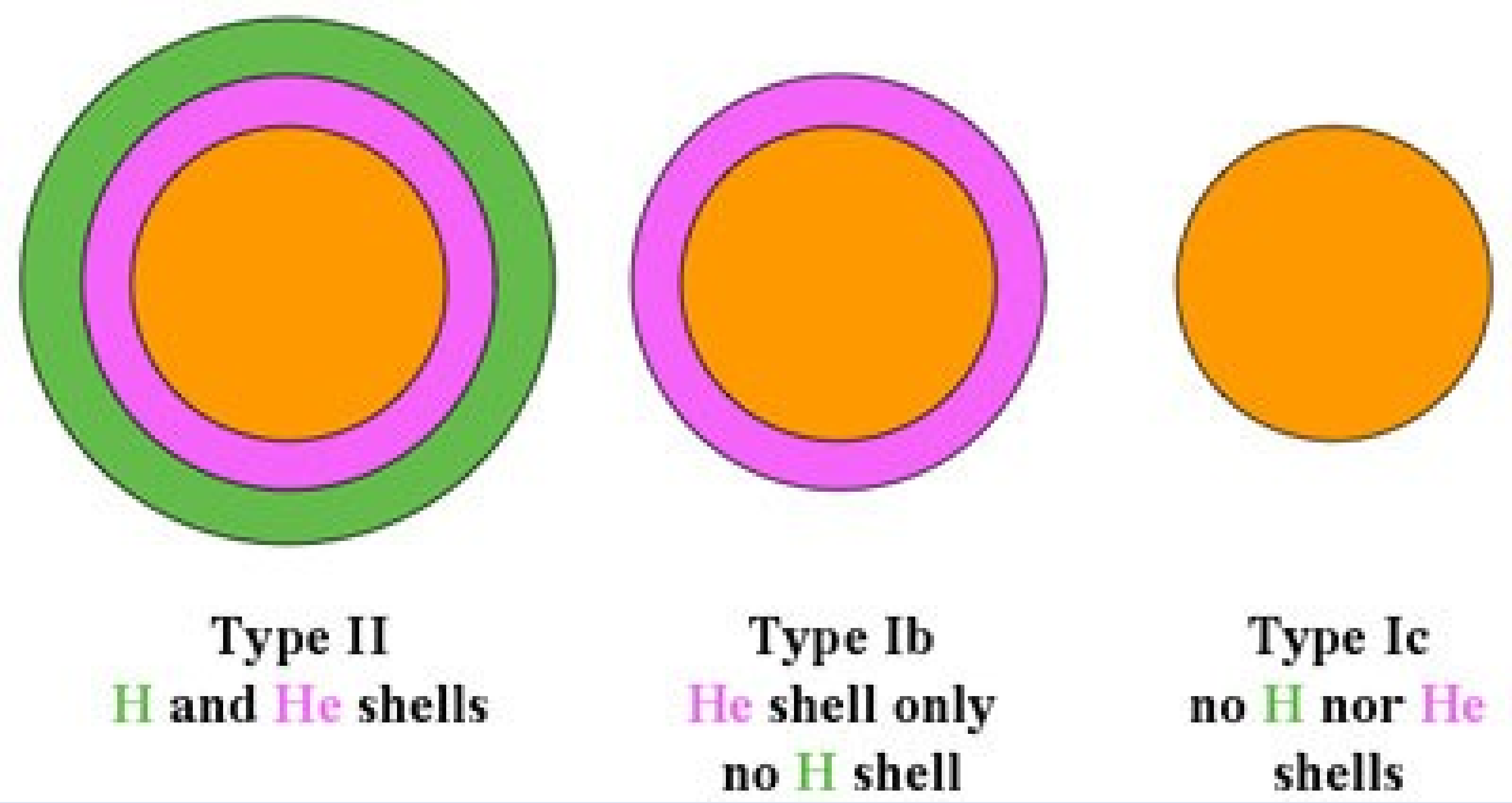
Type Ia SN sample and cosmology (Riess et al. 1998)

Break

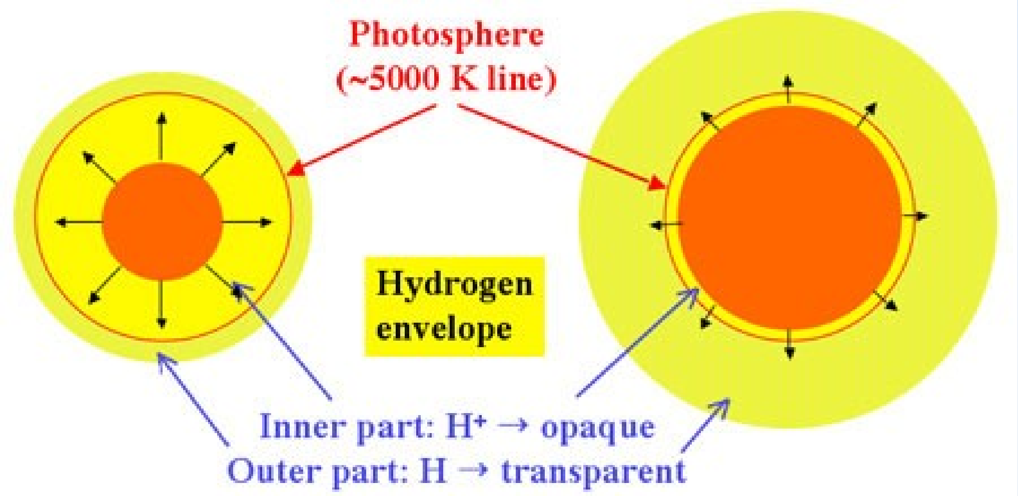
Type I b/c

- Today there remains some controversy about whether SNIb and SNIc are indeed different objects, with some astronomers labelling supernovae of both types, SNIb/c.
- The uncertainty arises since both SNIb and SNIc have similar light curves, spectral evolution and radio properties.
- The only real observable difference between them is the apparent lack of Helium in the spectra of SNIc.

Core collapse SN



Type II SN



Type II supernovae are modeled as implosion-explosion events of a massive star. They show a characteristic plateau in their light curves a few months after initiation.

This plateau is reproduced by models which assume that the energy comes from the expansion and cooling of the star's outer envelope as it is blown away into space.

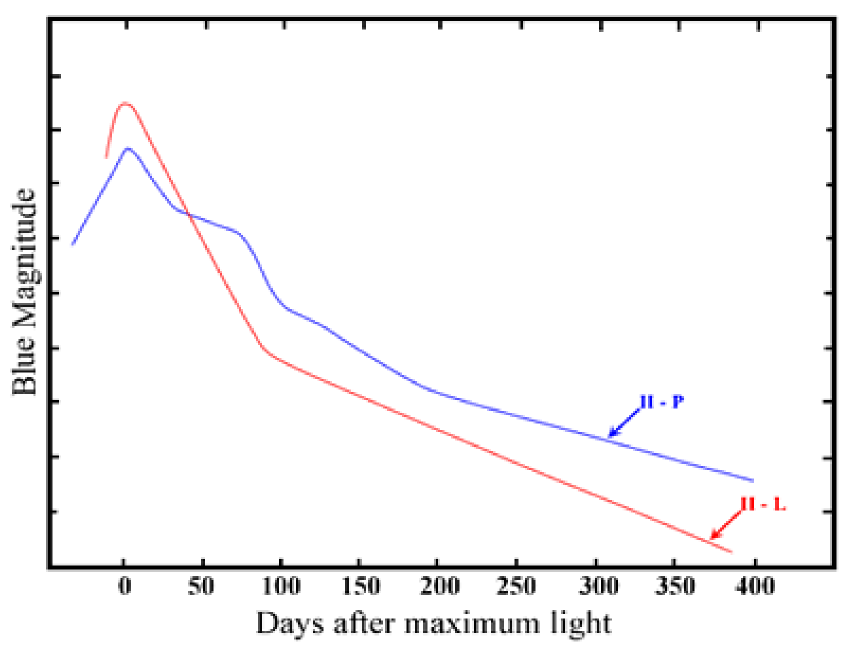
This model is corroborated by the observation of strong hydrogen and helium spectra for the Type II supernovae.

Type II SN

- In a Type II supernova, the position of the photosphere corresponds to where hydrogen recombination is taking place.
- Since the temperature of recombination is constant, as the supernova expands and cools, the photosphere receeds into the star and a plateau (the length of which is dependent on the depth of the hydrogen envelope) is created in the light curve.

Lightcurves of Type II SN

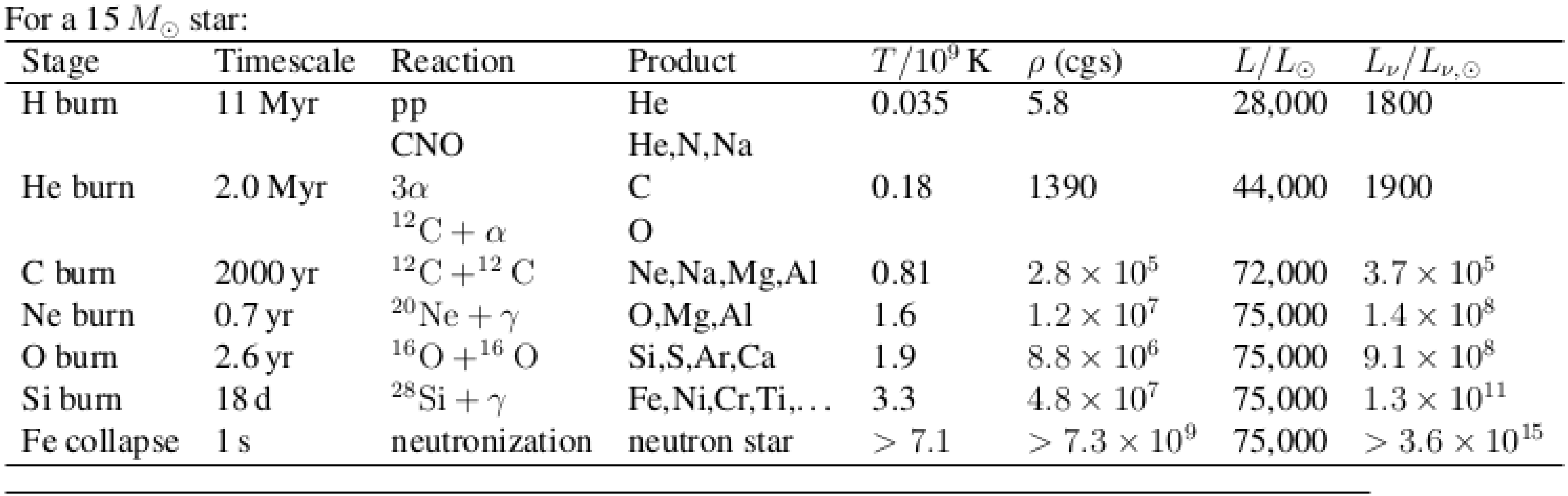
- Type II SN are sub-divided into two classes based on the shape of their light curves.
- Type II-Linear (SNII-L) supernovae have a fairly rapid, linear decay after maximum light.
- Type II-Plateau (SNII-P) supernovae remain bright (on a plateau) for an extended period of time after maximum.
- The peak brightness of SNII-L are nearly uniform at ~2.5 magnitudes fainter than a Type Ia supernova.
- The peak brightness of SNII-P show a large dispersion, which is almost certainly due to differences in the radii of the progenitors.



Core formation

- Main Sequence star fuses Hydrogen to Helium, via pp and CNO cycles.
- In advanced stage, Helium is fused with Carbon and Oxygen, to produce Neon. Magnesium, Oxygen fuses to Silicon.
- Photodissociacion may break Sillicon to Magnesium, at high temperatures.
- Silicon burning makes Iron, at $T=3x10^9$ K. Iron core is formed, surrounded by shells of lighter elements.

Example of stellar evolution stages for 15 M$_{\text{Sun}}$

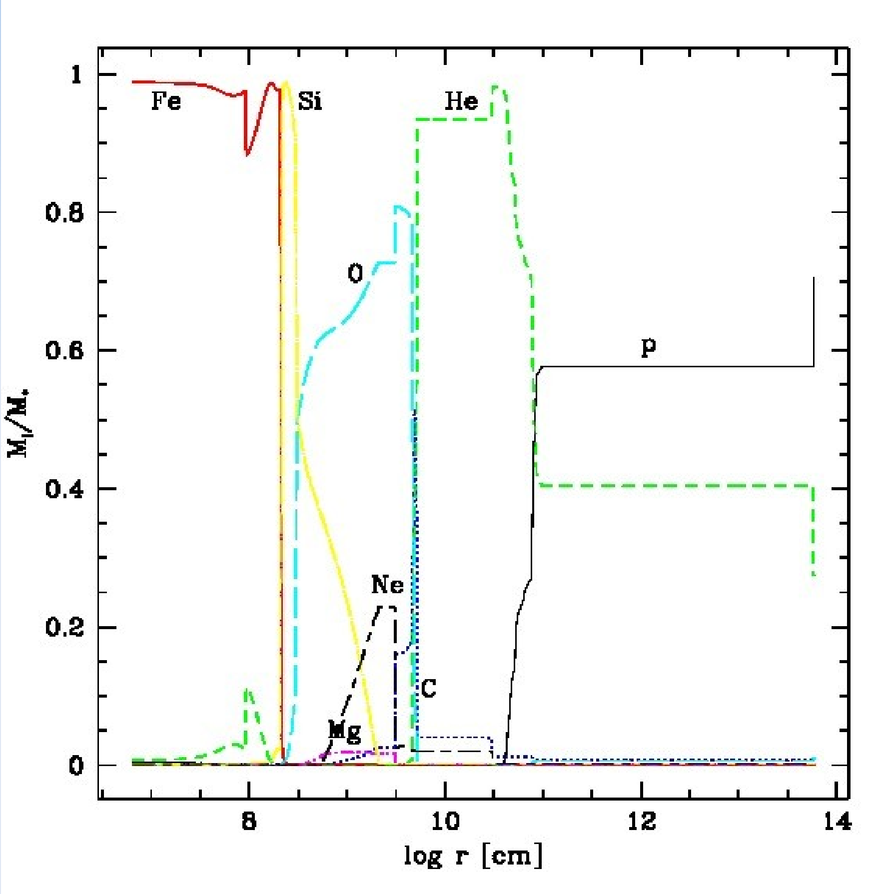


For a 15 $M_\odot$ star:

Stage	Timescale	Reaction	Product	$T/10^9$ K	ρ (cgs)	$L/L_\odot$	$L_\nu/L_{\nu,\odot}$
H burn	11 Myr	pp	He	0.035	5.8	28,000	1800
		CNO	He,N,Na				
He burn	2.0 Myr	3α	C	0.18	1390	44,000	1900
		$^{12}\mathrm{C} + \alpha$	O				
C burn	2000 yr	$^{12}\mathrm{C} +^{12}\mathrm{C}$	Ne,Na,Mg,Al	0.81	2.8×10^5	72,000	3.7×10^5
Ne burn	0.7 yr	$^{20}\mathrm{Ne} + \gamma$	O,Mg,Al	1.6	1.2×10^7	75,000	1.4×10^8
O burn	2.6 yr	$^{16}\mathrm{O} +^{16}\mathrm{O}$	Si,S,Ar,Ca	1.9	8.8×10^6	75,000	9.1×10^8
Si burn	18 d	$^{28}\mathrm{Si} + \gamma$	Fe,Ni,Cr,Ti,...	3.3	4.8×10^7	75,000	1.3×10^{11}
Fe collapse	1 s	neutronization	neutron star	> 7.1	$> 7.3 \times 10^9$	75,000	$> 3.6 \times 10^{15}$

Structure of pre-SN star

- Spherically symmetric pre-SN model (Woosley & Weaver 1995).
- Calculation with „Kepler” code.
- Mass of the star is 25 MSun



Onset of collapse

- Iron-56 is one of the most tightly bound nuclei. Exoenergetic reactions are no longer possible after iron core has formed.
- In this case, the core contraction reduces pressure and collapse starts.
- Photodisintegration uses energy of photons to unbind nuclei. Also, neutrinos are produced via inverse beta-decay, and take away energy.
- Collapse proceeds on free-fall timescale (~ 1 ms).

Neutronisation

- When $T=10^{10}$ K and rho>10^9 g/cm^3, 75% of Iron is photodissociated.
- Degenerate electrons have Fermi energies $E_F >$ 1.3 MeV. This leads to neutronisation, because neutron decay is stopped.
- Protons insiode nuclei also turn into neutrons: elements like Mn-56 and Cr-56 are formed, when density is >10^{10} g/cm^3.
- Energy is lost in neutrinos, and pressure support is lost.

Neutrino burst

- When core reaches density of 2×10^{14} g/cm^3, and size of R~30 km, the collapse stops as nuclear forces produce ‘bounce’.
- Core forms a protoneutron star.
- Neutrinos diffuse out in about $t_{diff} \sim 10$ s. Their mean free path is $\lambda \sim 50$ cm

Energy of the collapse is

$E = GM^2/R \sim 10^{53}$ erg

Luminosity in neutrinos

$L \sim E/t_{diff} = 10^{52}$ erg/s

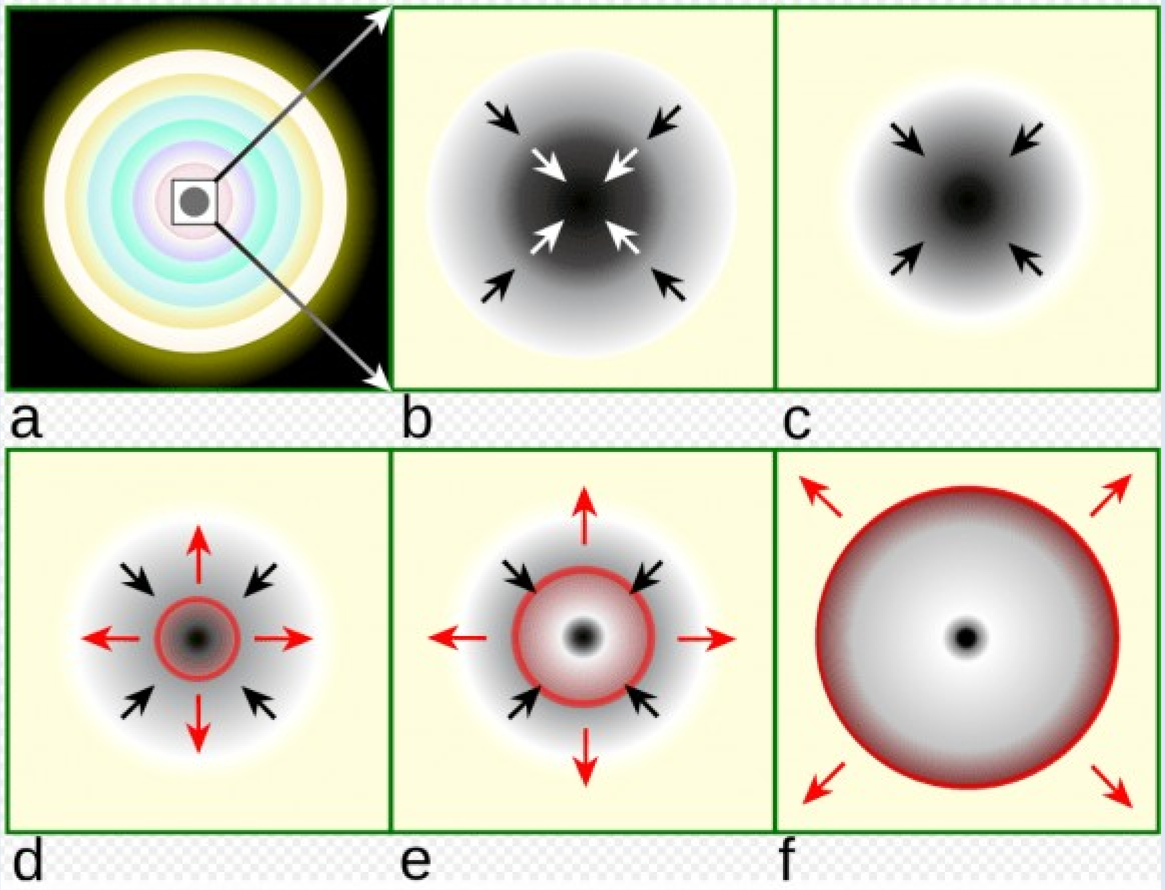
Supernova energetics

- In the collaspse of Iron Core of a massive star, total of 10^{53} erg is released.
- 1% of this goes into kinetic energy of explosion (10^{51} erg = 1 foe)
- 0.01% goes into photons (Optical energy of 10^{49} erg, over the first year)
- 99% goes into neutrinos

Bounce and shock

Energy per nucleon is $E=GMm_p/R\sim 62$ MeV.

Shock wave moves out and stalls at ~ 300 km.

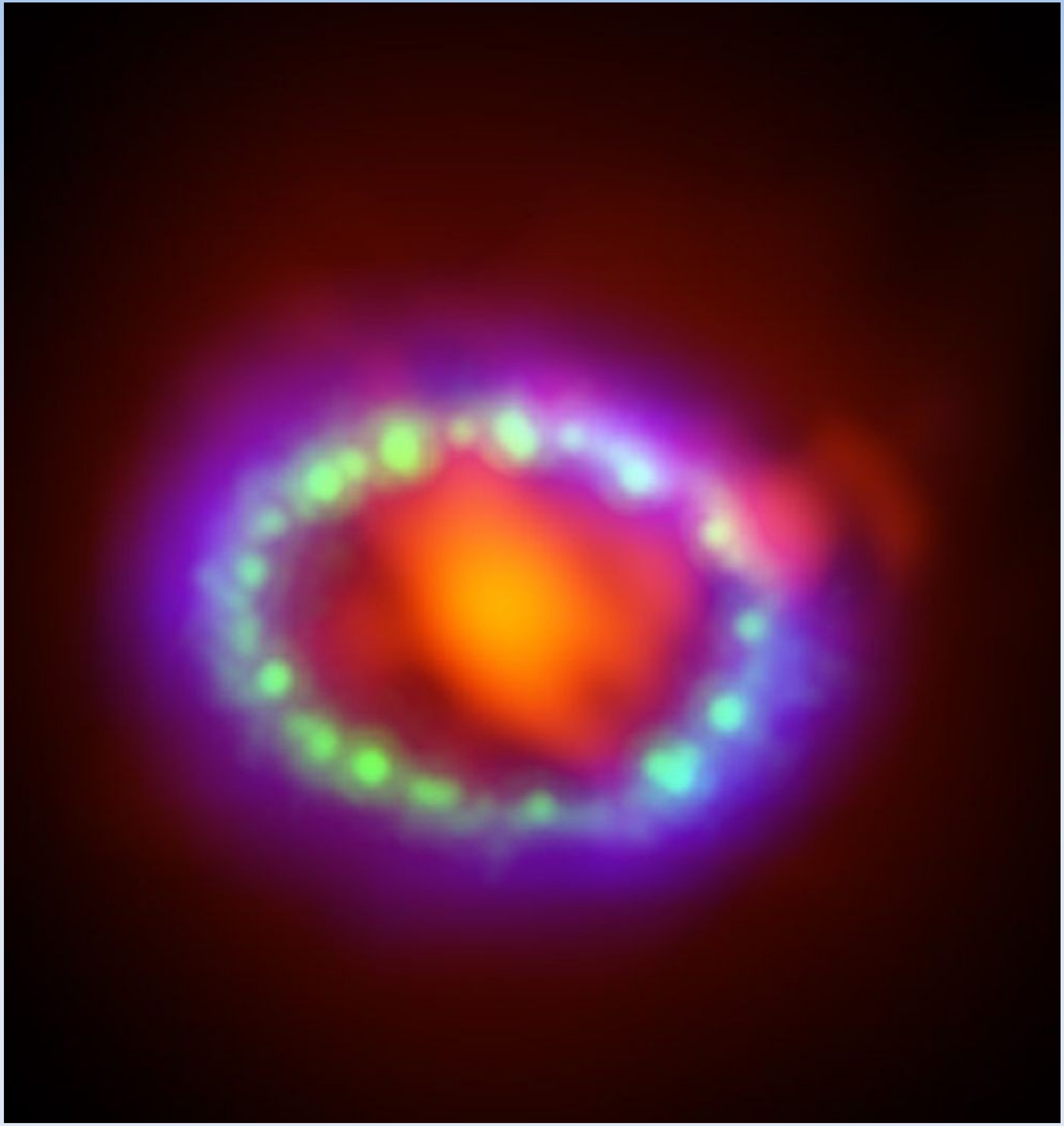


The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red).

The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction.

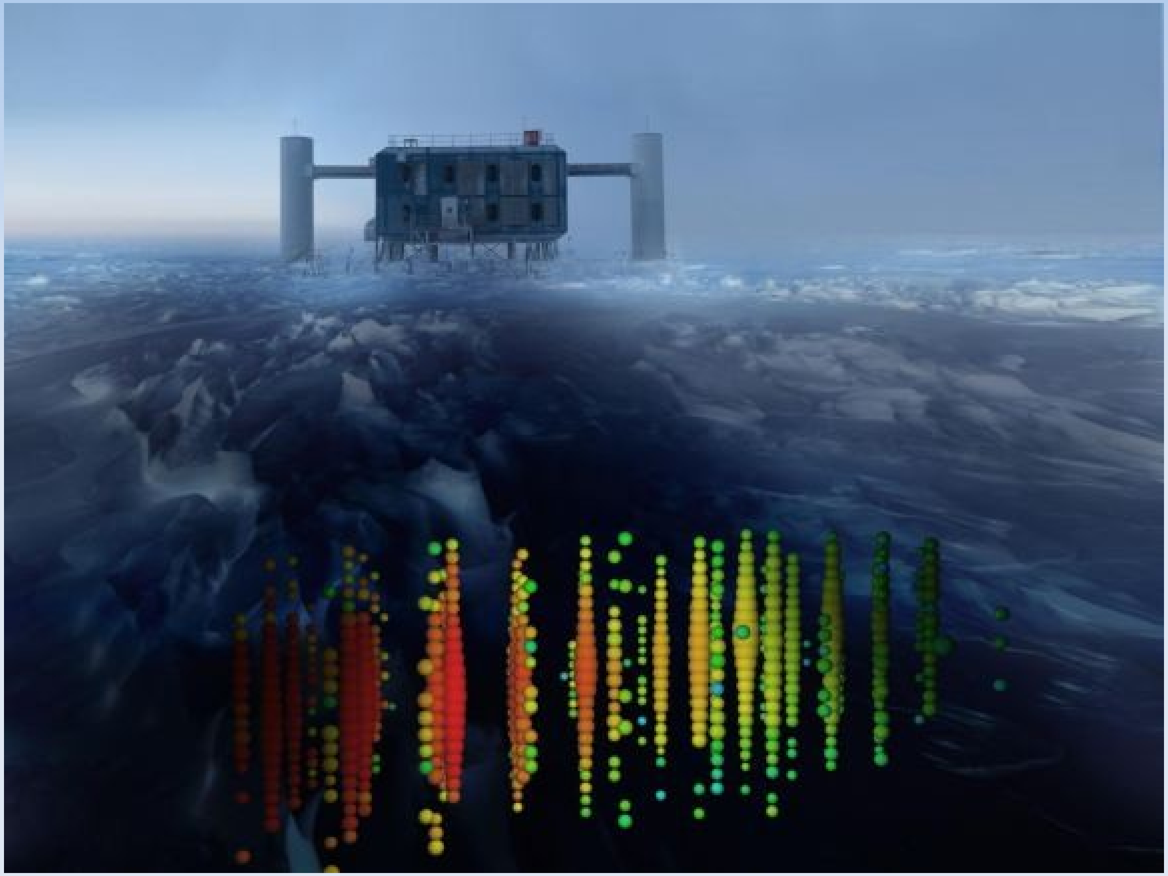
The surrounding material is blasted away (f), leaving only a degenerate remnant

SN 1987A



A composite image of SN 1987A from Hubble, Chandra, and ALMA.

IceCube detection



The IceCube Neutrino Observatory, for instance, tries to detect neutrinos with strings of detectors buried down to a depth of 2450 meters in the dark Antarctic ice.

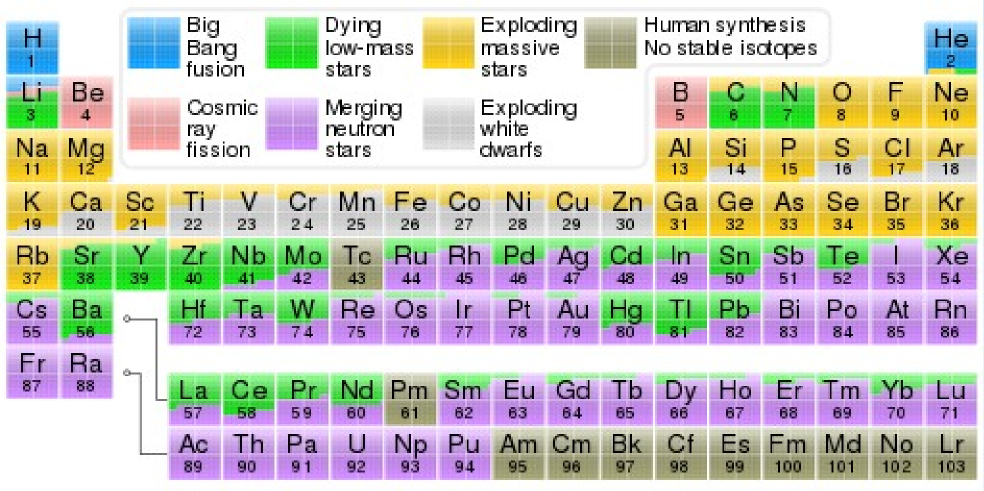
with SN1987A, a supernova exploded in the Large Magellanic Cloud in 1987.

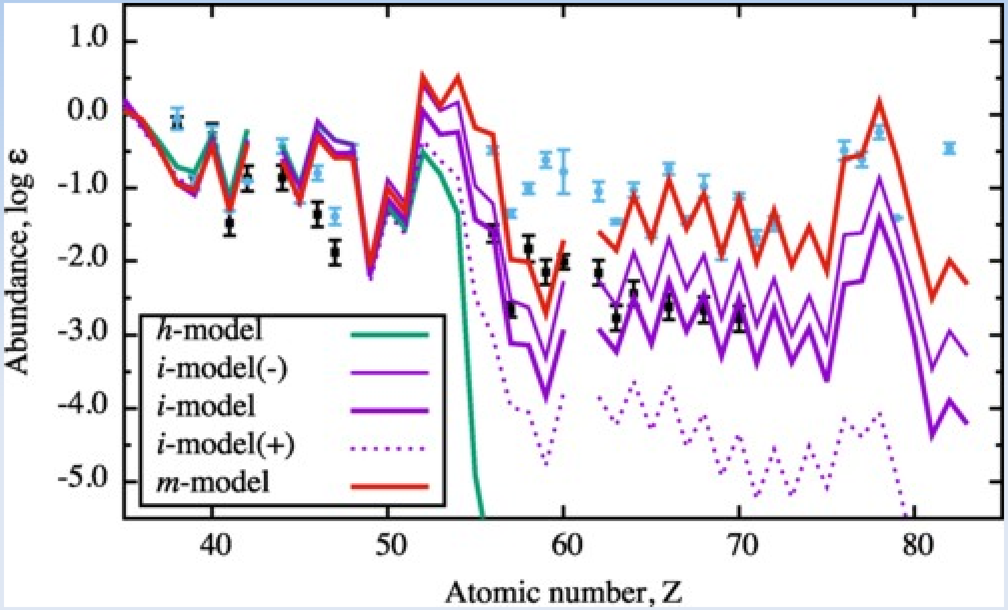
About two or three hours before the light from that supernova reached us, three separate neutrino observatories detected a burst of neutrinos.

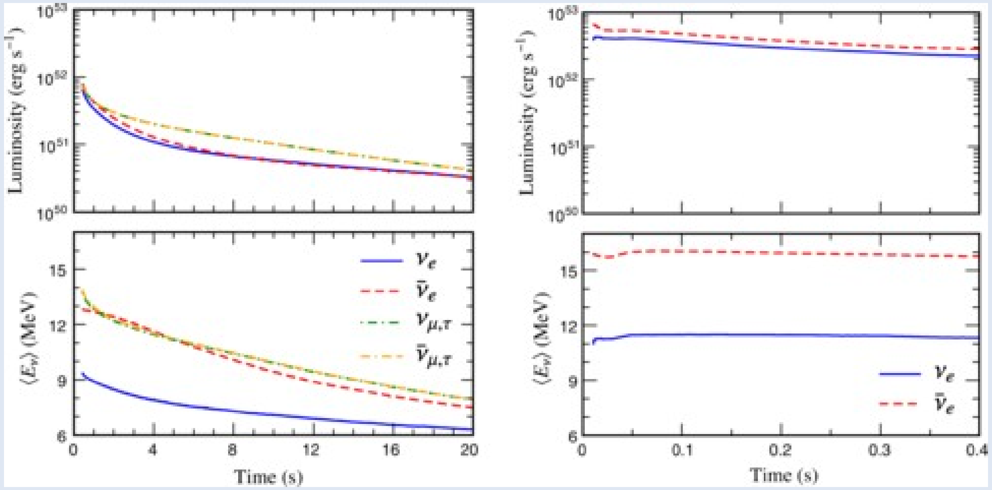
Though the supernova released an enormous number of neutrinos, the three observatories only detected a total of 25 of them, emphasizing how difficult studying neutrinos is.

Today’s neutrino detectors are better, and scientists think that if a similar supernova were to explode today, we’d detect many more neutrinos. Rather than the 25 detected in 1987, we would detect a whopping 50,000.

R-process elements from SNe



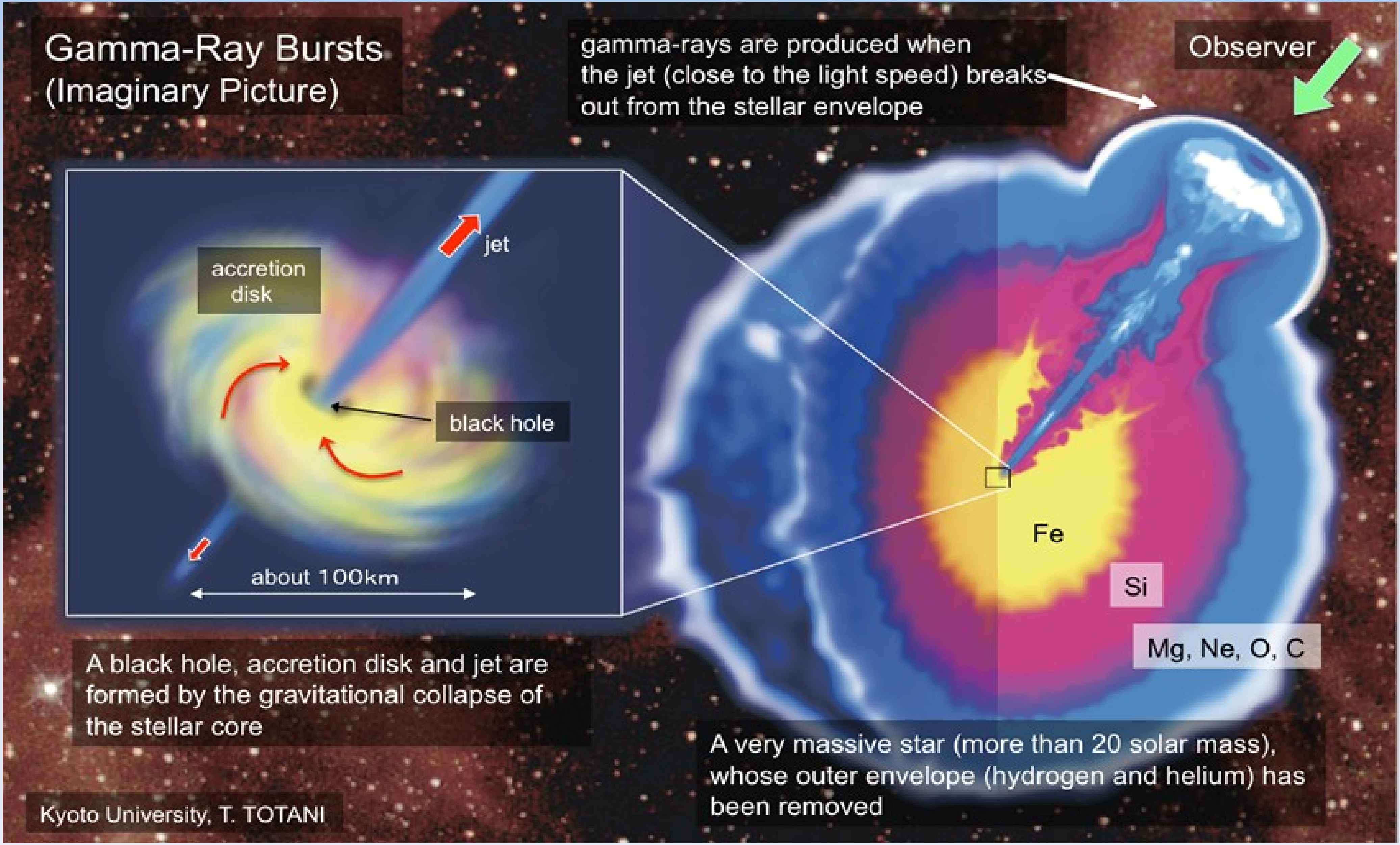




Neutrino energies and luminosities emitted during PNS cooling phase and core-collapse SN (left) compared iwth the case of NS-NS merger (right).

The r-rpocess elements are formed in CC SNe, and their abundance pattern is sensitive to ratio of magnetic field strength to neutrino heating (top)

GRB from CC SNe



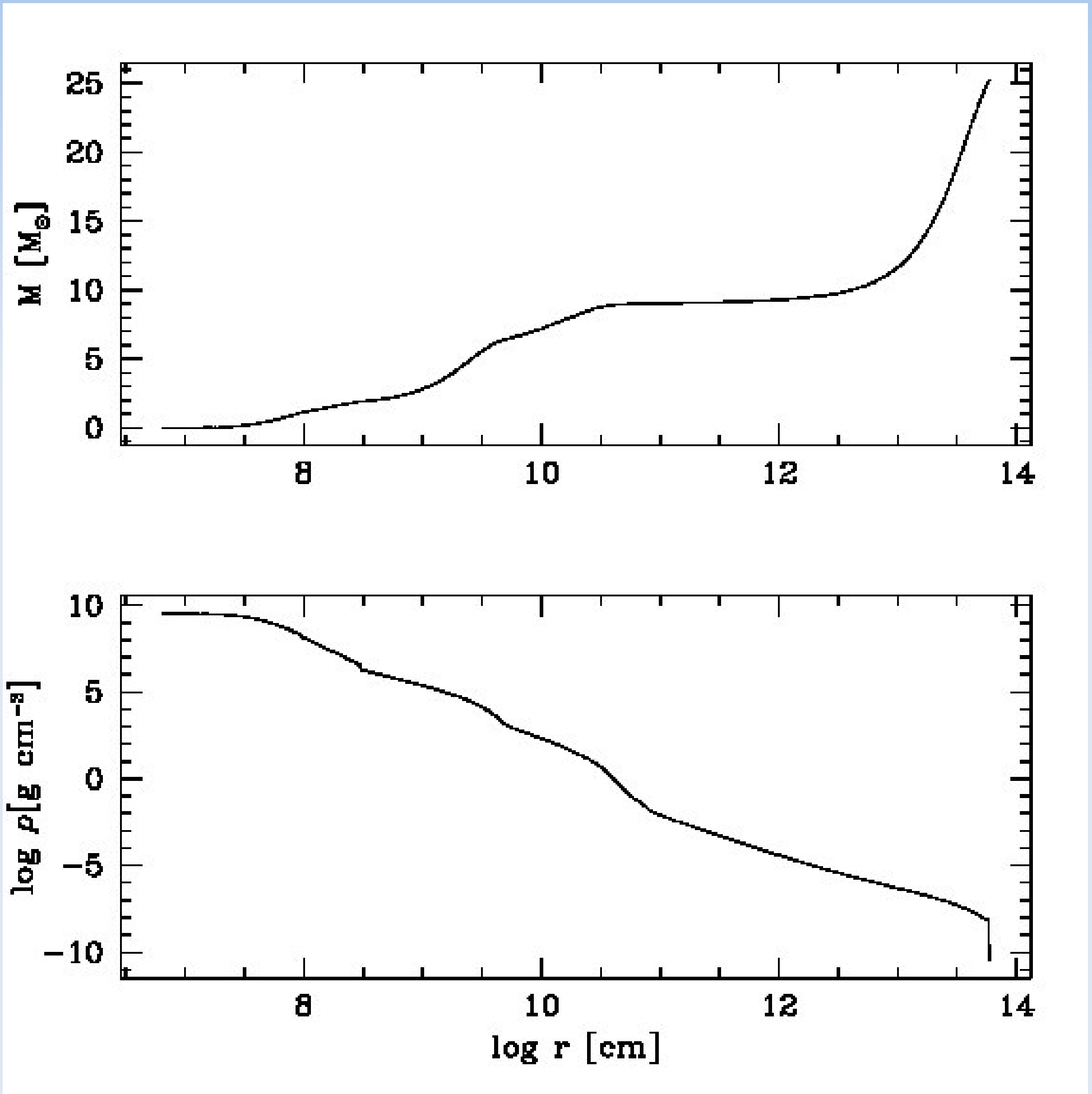
Model of pre-supernova star

Pre-supernova star (Woosley & Weaver 1995)

Enclosed mass is 25 M_{Sun}

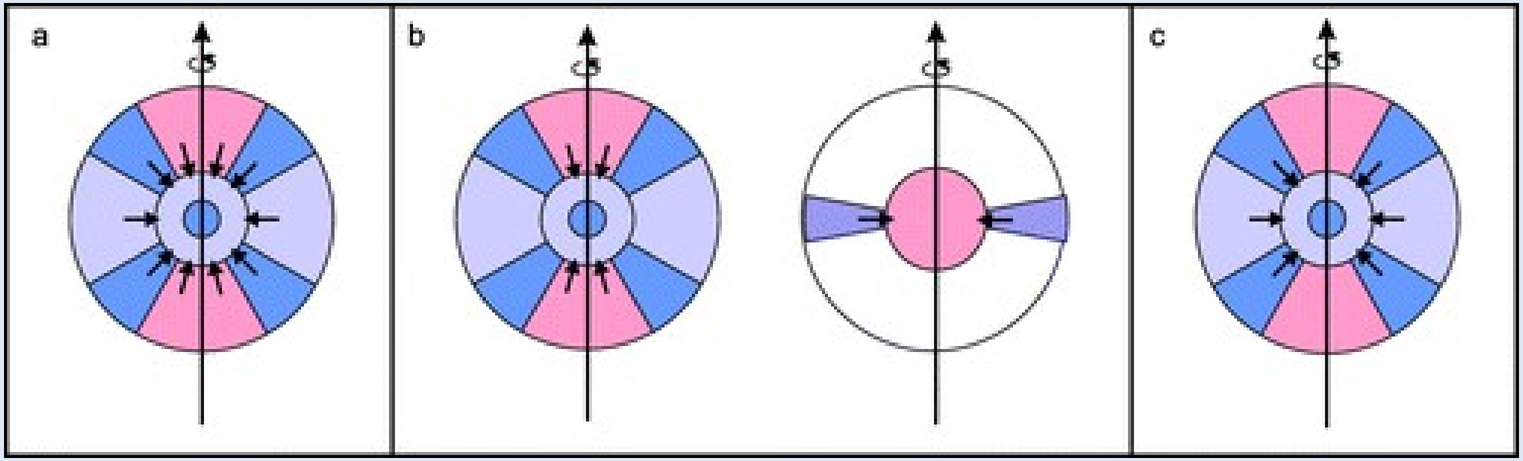
Density distribution: chemical composition of an evolved star (Fe, Si, C, O, He, H)

Iron core of mass 1.4 M_{Sun}



How long can be a long GRB?

- The rotating torus and BH spin drive GRB engine. Accretion of fallback matter from the SN explosion triggers this process and regulates its duration.
- Angular momentum is transported to the black hole via accretion. If specific momentum in the envelope exceedds critical one, the black hole spins up (Janiuk, Moderski & Proga 2008)



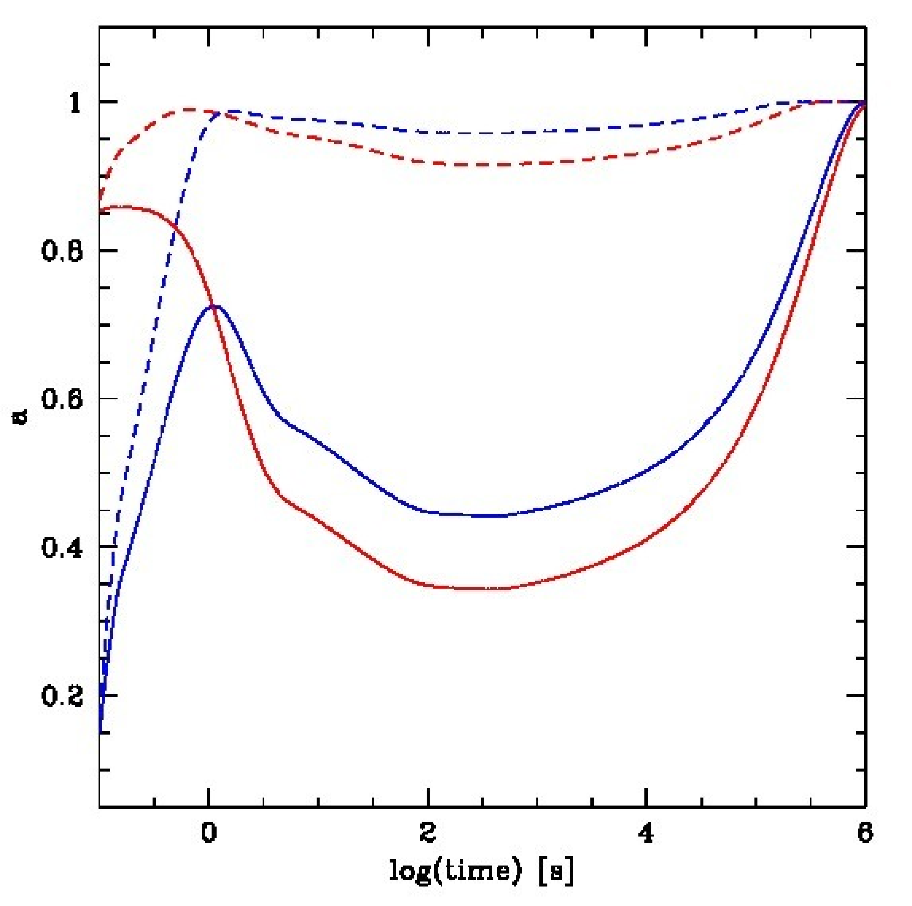
Spinning up the black hole from accretion

We adopt specific angular momentu distribution in the star (differential rotation)

$$l_{spec}(r,\theta)=l_0(1-|\cos(\theta)|)$$

The infalling envelope matter adds mass and spins the black hole. The rotationally supported torus must ob (Bardeen et al. 1972):

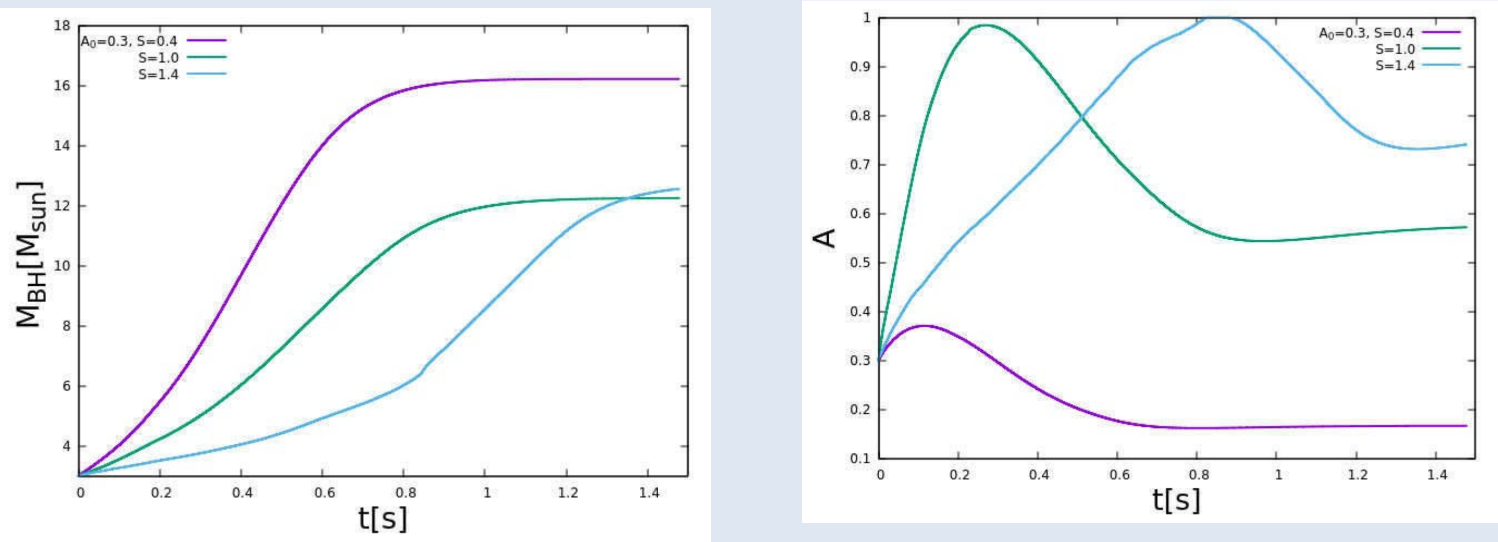
$$l_{spec}>l_{crit}=\frac{2GM_{BH}}{c}\sqrt{2-a+2\sqrt{1-a}}$$



Semi-analytical homologous model result

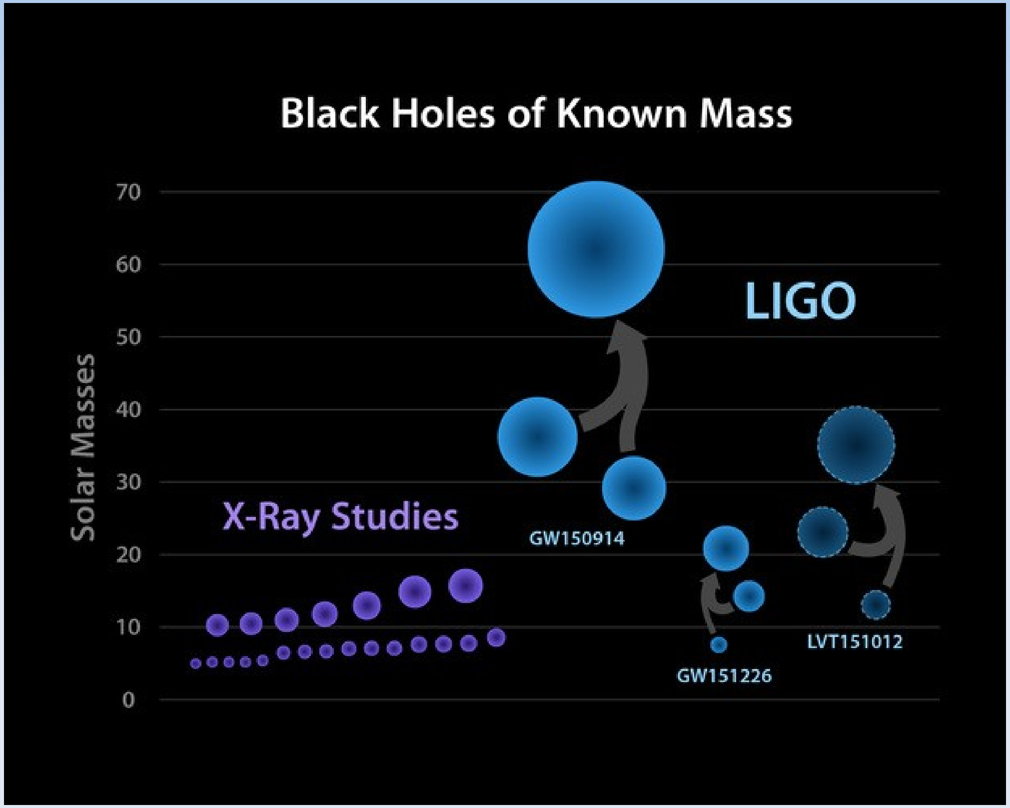
Black hole mass and spin growth during the collapse

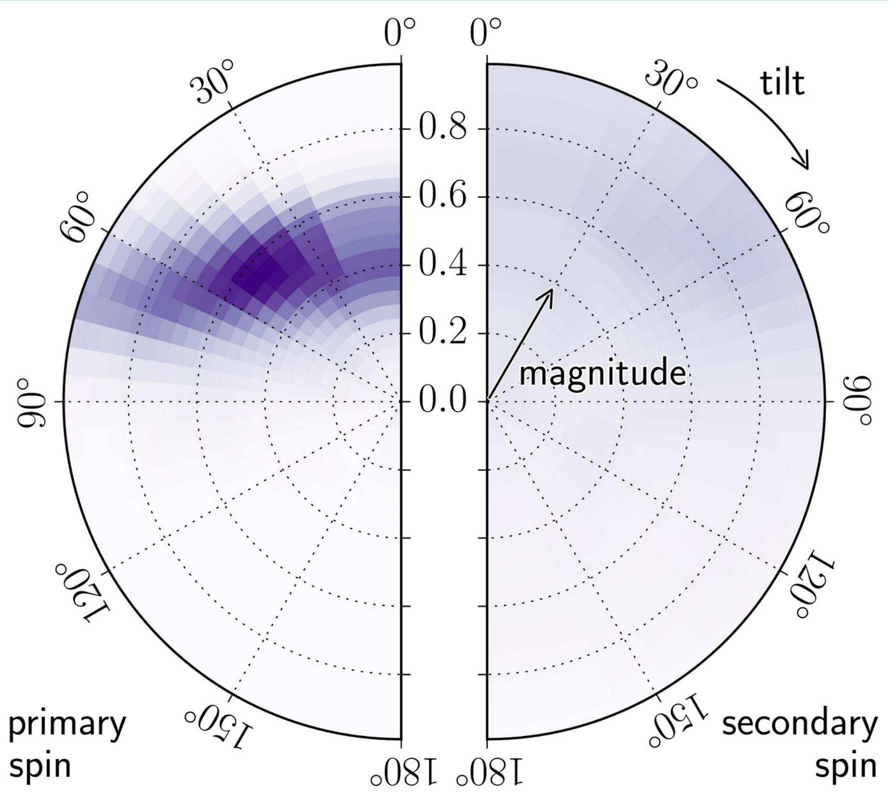
- Accretion rate profile depends on envelope rotation
- BH mass and spin parameter is changing accordingly
- For higher initial spins, also net spin-down is possible



Hydrodynamical simulation results. Lines correspond to 3 values of star’s angular momentum normalisations, S = 0.4, S = 1.0, and S = 1.4. (from D. Krol & A.Janiuk, 2021, ApJ)

Application to LIGO black holes

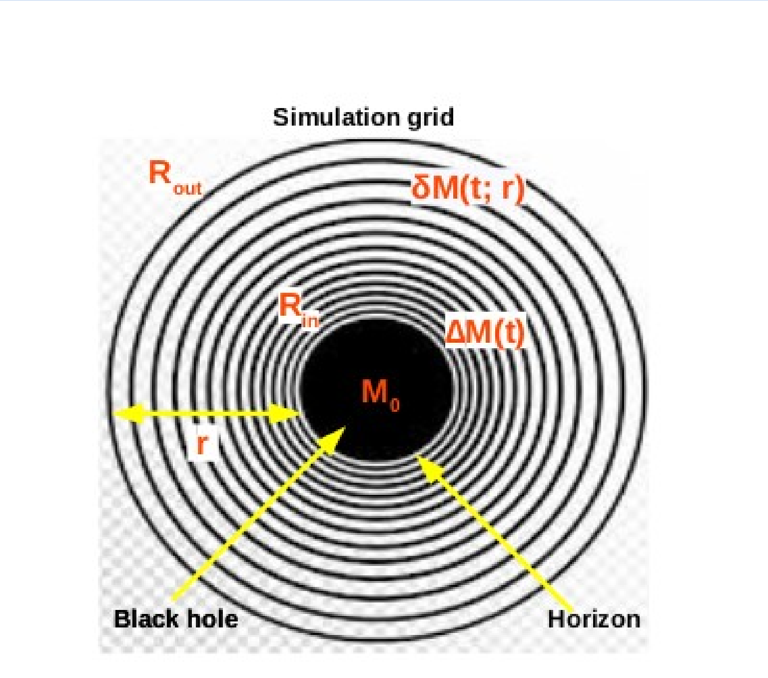


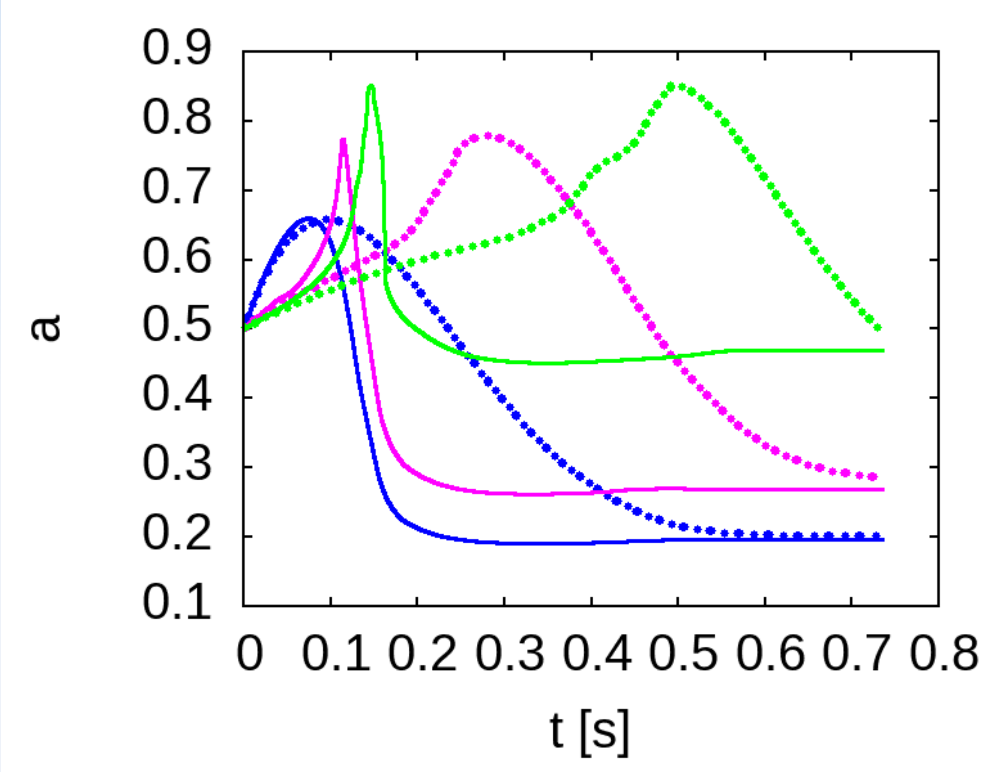


In LIGO data, a negative correlation between mass and the mean effective spin is found (Safarzadeh et al. 2020).

Data disfavour large spins. Typical spins are constrained to a ~ 0.4.
For aligned spins the constraints are tighter, spins required a ~ 0.1 (Rouet & Zaldarriaga, 2019)

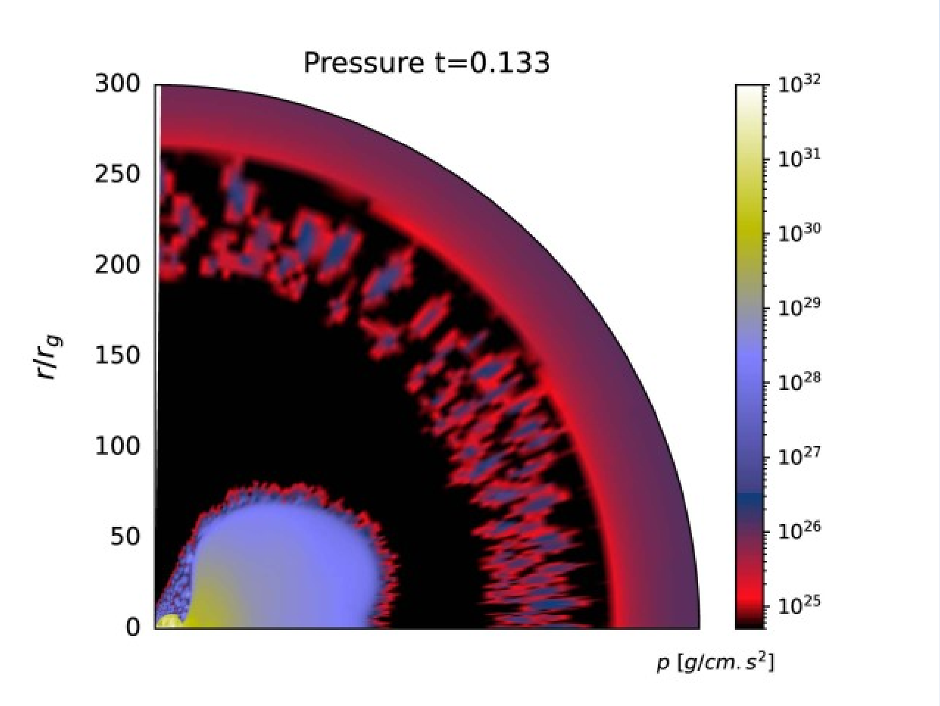
Self-gravity of the star during collapse

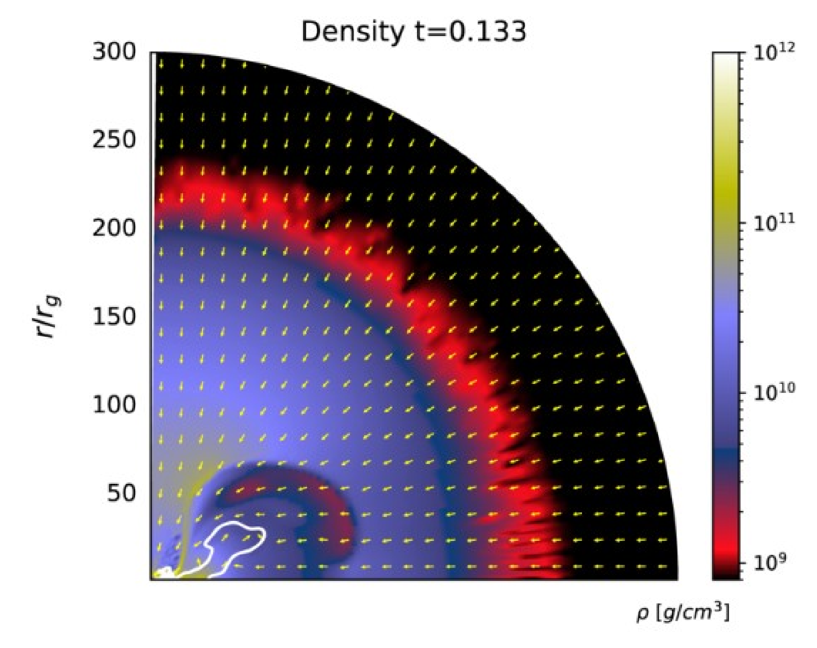




We developed numerical model of the collapsing stellar core where we account for the dynamical evolution of central black hole mass and its spin. The related coefficients of the Kerr space-time metric are evolved accordingly. In addition, we calculate the self-gravity of the stellar envelope and we add the relevant perturbative terms to the dynamical evolution of the black hole spin parameter (Janiuk et al. 2023, A&A).

SGI instability





- The dynamical spacetime is shown to have an impact on the global evolution of the collapsing star, and produces dramatic fluctuations in the accretion rate at the initial phase of collapse.
- More importantly, it also plays crucial role in development of the self-gravity interfacial instability in its specific regions.

Next week

- Primordial black holes
- Stellar black holes: mass gap, intermediate mass range, observational evidence for IMBHs
- Supermassive black holes and cosmology: Soltan argument, mass-velocity dispersion relation

Further reading

- J. Cowan, K.-F. Thielemann, „”R-process nucleosynthesis in supernovae”, 2004, Physics Today