Lecture 18: exploding stars

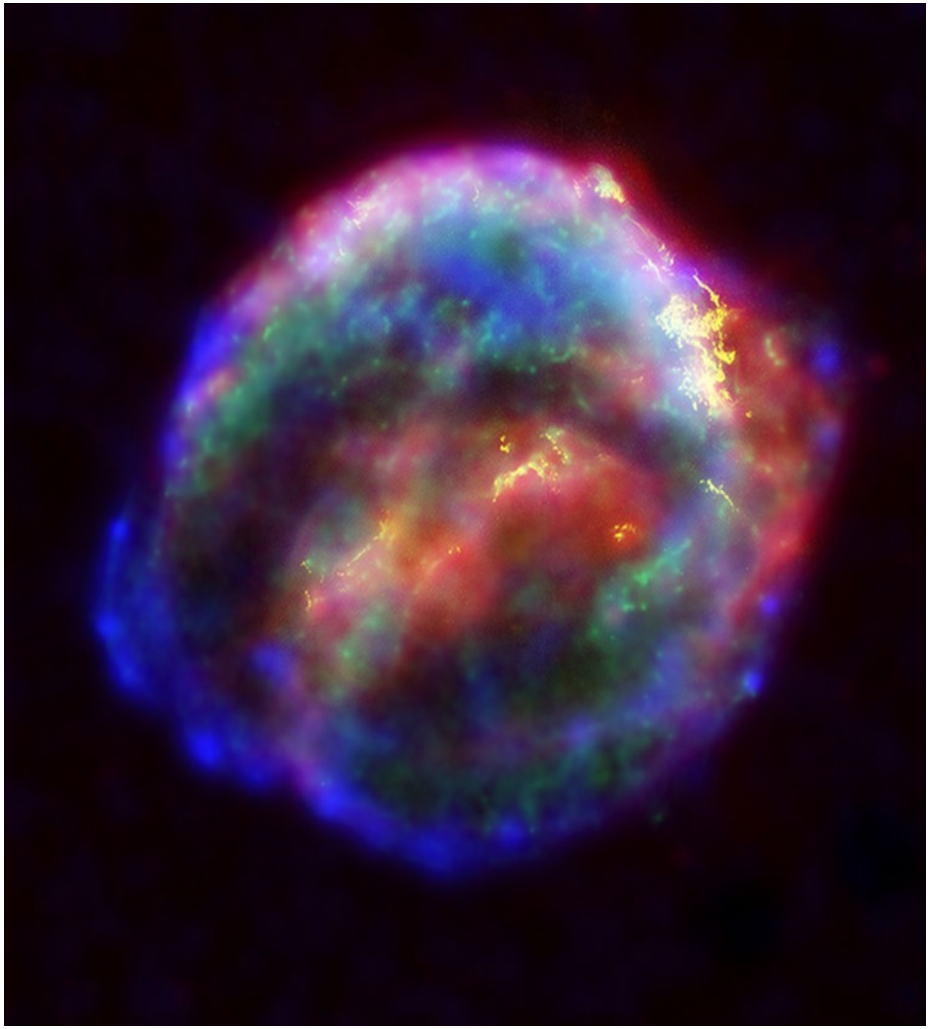
Kepler's super-nova
distance: 26000 LY, in the milky way

original observation:
Oct. 9, 1604 (naked eye)

a false-color composite (CXO/HST/Spitzer Space Telescope) image of the supernova remnant nebula from SN 1604

the nebula is composed of the ejecta from the explosion, about a few solar masses, and is bounded by the shock wave from the explosion

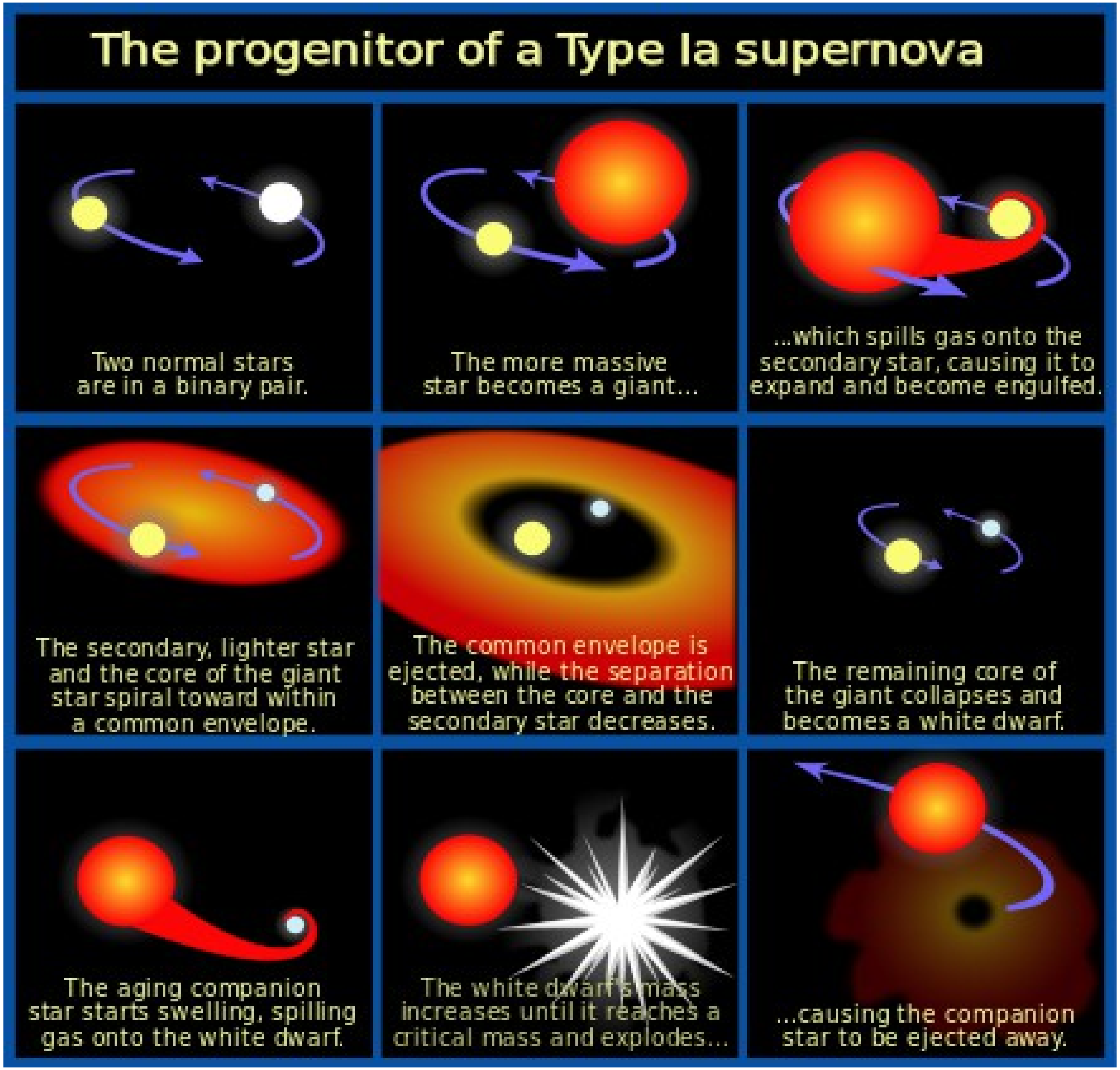
it was visible to the naked eye for about 18 months



size of image: about 25 LY across, shock wave moves at about 5% c

Image credit:
http://www.nasa.gov/multimedia/imagegallery/image_feature_219.html

supernovae classification part 1



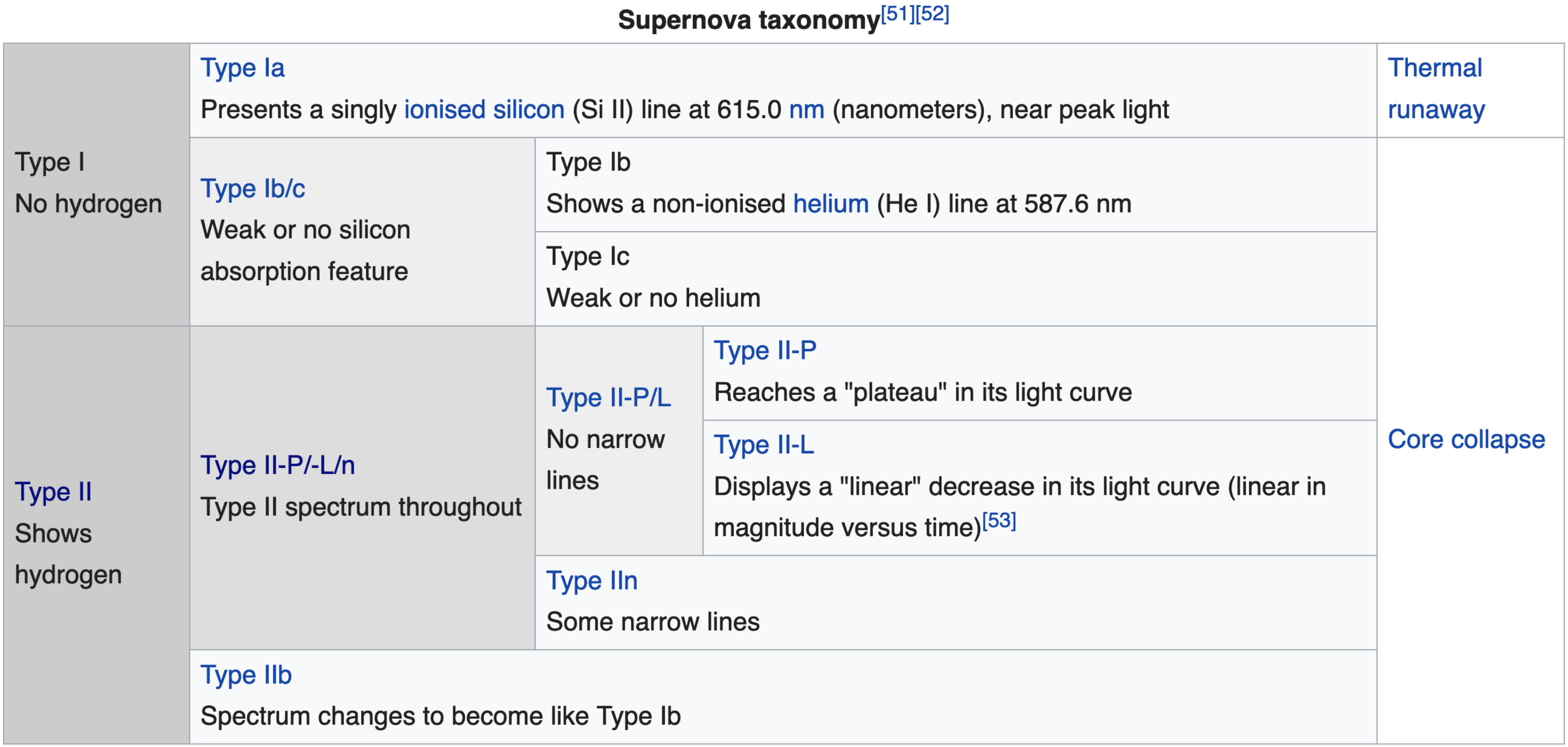
type Ia supernovae can be used as 'standard candles' because the have all essentially the same absolute luminosity. this can be used to measure the distance to their host galaxy

energy release
$(1–2)\times10^{44}$ J

up to 5 billion times brighter than the Sun

source: wikipedia

critical (Chandasekhar) mass ≈ 1.44 solar masses



Supernova taxonomy[51][52]

Type I No hydrogen	Type Ia Presents a singly ionised silicon (Si II) line at 615.0 nm (nanometers), near peak light			Thermal runaway
	Type Ib/c Weak or no silicon absorption feature	Type Ib Shows a non-ionised helium (He I) line at 587.6 nm		Core collapse
		Type Ic Weak or no helium		
Type II Shows hydrogen	Type II-P/-L/n Type II spectrum throughout	Type II-P/L No narrow lines	Type II-P Reaches a "plateau" in its light curve	
			Type II-L Displays a "linear" decrease in its light curve (linear in magnitude versus time)[53]	
		Type IIn Some narrow lines		
	Type IIb Spectrum changes to become like Type Ib			

source: Wikipedia

note: all supernovae but type Ia are core-collapse supernovae

the rise and fall of supernova SN 2012fr was discovered by French astronomer Alain Klotz on the 27 October 2012 in the galaxy NGC 1365

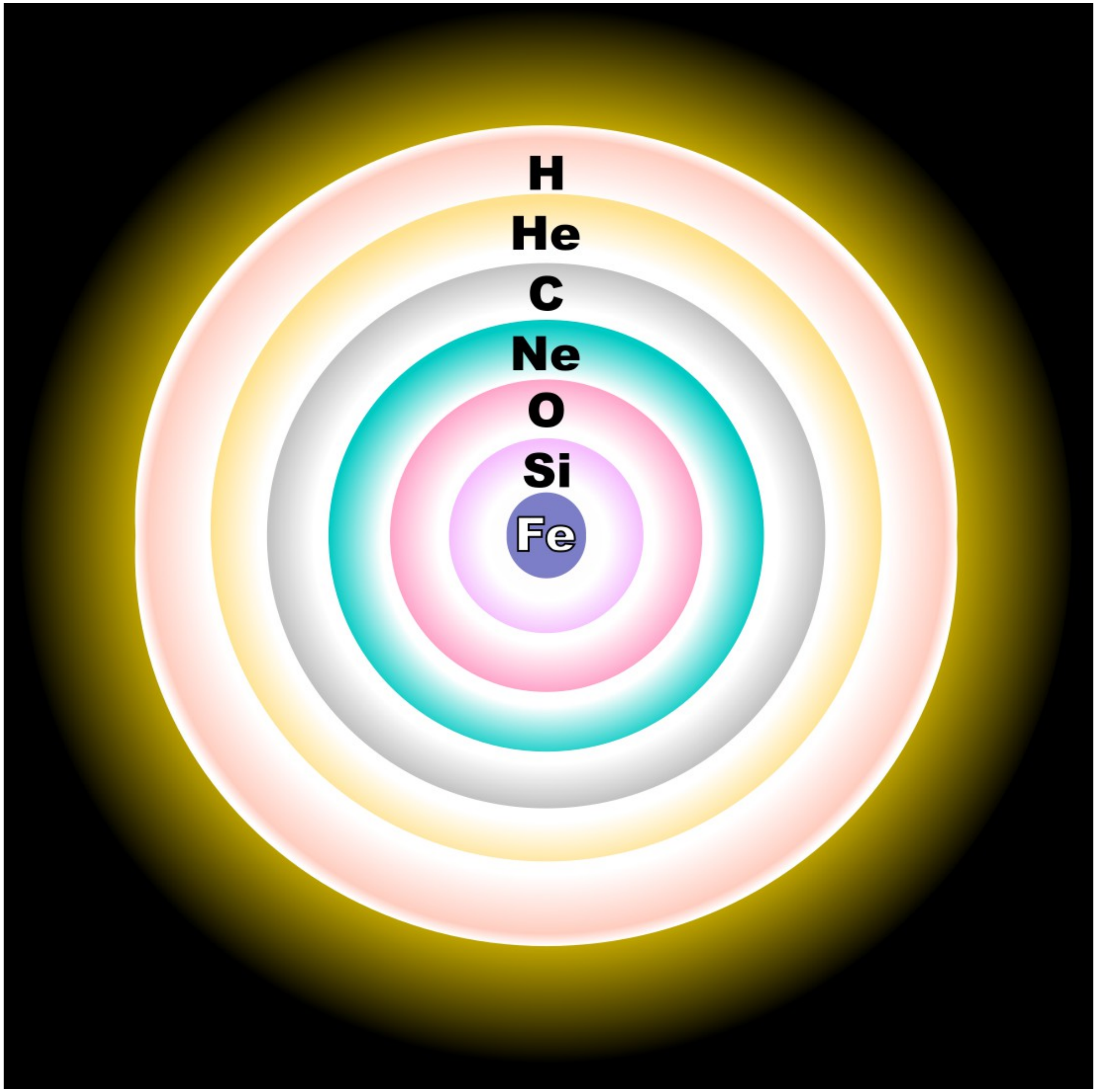
SN 2012fr is of Type Ia

source:

http://www.eso.org/public/images/potw1323a/

supernovae classification part 2

core collapse supernovae



fusion burning inside a large (> 10 solar masses) star

when the Fe core in the center reaches the Chandrasekhar limit, the star collapses and an explosion may result

the collapse usually forms a neutron star (for very massive stars a black hole)

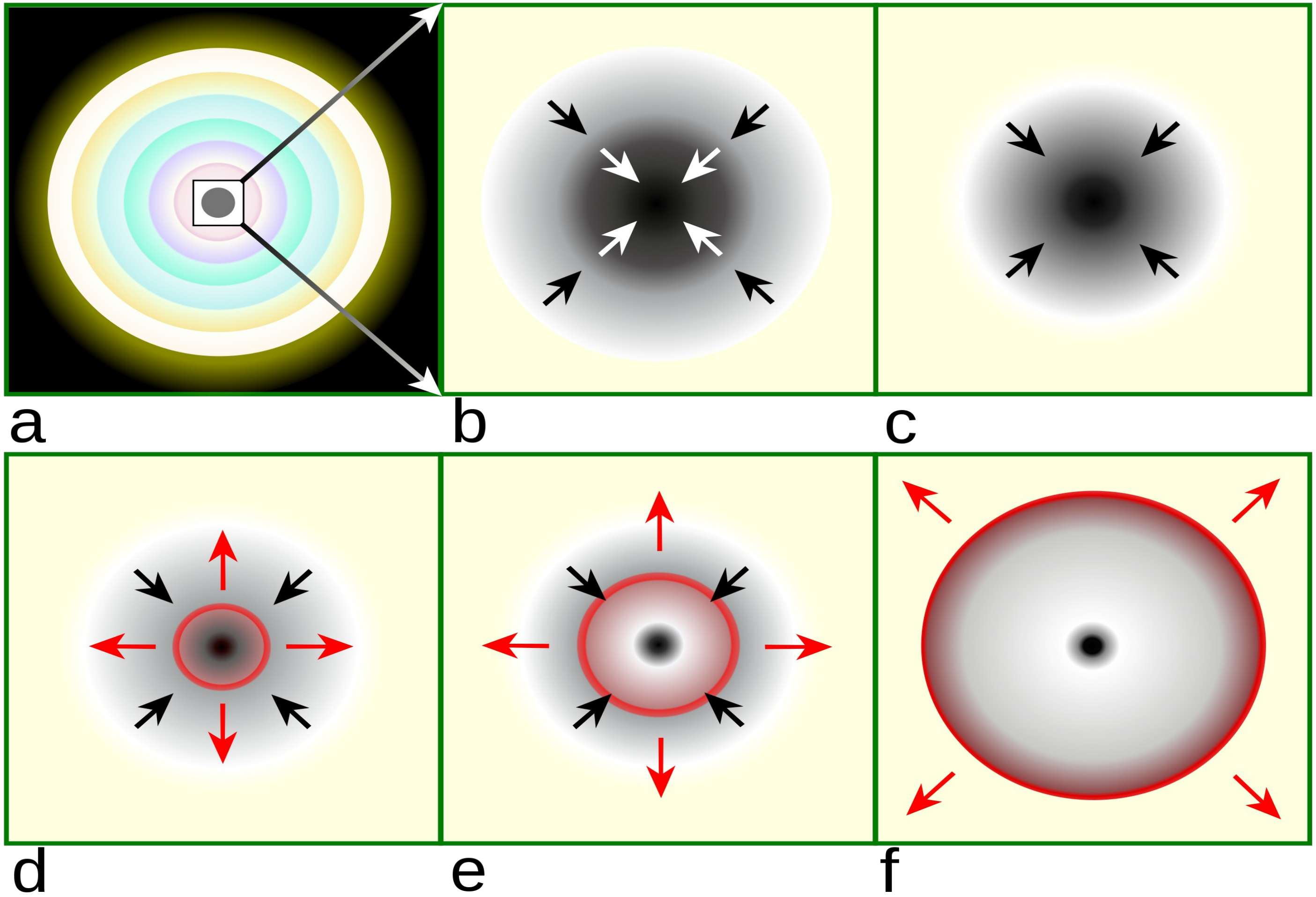
the neutron star at the center of the core stops the collapse
the core can reach temperatures of > 10 MeV and powers a roughly 10 s long neutrino burst

energy release in the collapse is about 10^{43} - 10^{46} J, mostly in thermal neutrinos,
can reach 10% of the star's rest mass

fig: source: wikipedia CC BY 2.5

explosion scenario in core collapse supernovae

simplified core collapse scenario: (a) A massive, evolved star has onion-layered shells of elements undergoing fusion. An inert iron core is formed from the fusion of Silicon in the inner-most shell. (b) This iron core reaches Chandrasekhar-mass and starts to collapse, with the outer core (black arrows) moving at supersonic velocity (shocked) while the denser inner core (white arrows) travels sub-sonically; (c) The inner core compresses into neutrons and the gravitational energy is converted into neutrinos. (d) The infalling material bounces off the neutron star and forms an outward-propagating shock wave (red). (e) The shock begins to stall as nuclear processes drain energy away, but it is re-invigorated by interaction with neutrinos. (f) The material outside the inner core is ejected, leaving behind only a degenerate remnant.



source: wikipedia,
CC BY-SA 3.0

further plan of the lecture

- hydrostatic equilibrium, collapse and bounce in large mass stars
- equation of state
- prompt and delayed shocks – the pause that refreshes
- the light curve
- from 1d to 3d simulations
- a case in point: SN1987A
- outlook

this lecture is based on:

Hans Bethe, Rev. Mod. Phys. 62 (1990) 801 and refs. here, historical review
Adam Burrows, Rev.Mod.Phys. 85 (2013) 245 and refs. there
Hans-Thomas Janka, Tobias Melson, Alexander Summa, Ann. Rev. Nucl. Part. Sci. 66 (2016) 1 and refs. there
Dany Page et al., arXiv:2004.06078 [astro-ph.HE] the newest results on a possible neutron star remnant of SN1987A

core collapse supernovae – summary sheet, facts and questions

1. energy released in explosion: 1 foe = 1 Bethe = 10^{51} ergs = 10^{44} J,
   distribution 0.1 – 10 Bethe, mostly in a few solar masses of ejecta with $v \approx$ a few % c.

2. mass and radius of proto-neutron star before explosion: 1.5 solar masses,
   radius $R \approx 10$ km, if mass exceeds the Chandrasekhar limit of typically 1.46 solar masses,
   collapse and explosion →

3. nucleosynthesis yields as function of progenitor?

4. asymmetry of the explosion?

5. total energy and time distribution of neutrinos emitted: ≈ 100 foe =10^{46} J
   this number is calculated from the temperature of the temperature of the
   proto-neutron star (10- 30 MeV)
   note: rest mass energy of the sun: 1.7 10^{47} J
   neutrinos observed on earth $n_{\nu} \approx 15$ (SN1987A)
   over time period of about 10 s
   need more measurements

6. optical spectrum (light yield) contains strong H2 lines

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Gravitation binding energy of a neutron star

we assume $m_{ns} = 1.5 \cdot m_{\odot} = 3 \cdot 10^{30}\,kg$

$r_{ns} = 10\,km$

the gravitational energy of such a uniform sphere

$$V_{ns} = \frac{3}{5} G \cdot \frac{M^2}{r_{ns}} = \frac{3}{5} G \cdot \frac{m_{NS}^2}{r_{nS}}$$

(see also the Coulomb energy of a uniformly charged sphere)

$\Rightarrow V_{ns} = 3.6 \cdot 10^{46}\,J$ $\Rightarrow$ dividing by the number of nucleons in ns

$V_{ns}/\text{nucleon} \approx 125\,MeV$ compared to $\approx 8\,MeV$ in a nucleus

hydrostatic equilibrium, collapse and bounce in stars

we first start with a small cell a distance r from the star's center. In hydrostatic equilibrium, the gravitational and pressure-indued forces on the cell balance (assuming rotational symmetry):

$$\frac{dP}{dr} = - \frac{G \cdot M(r)\, \rho(r)}{r^2}$$

P = pressure

G: grav. constant

ρ: mass density

here $M(r) = 4\pi \cdot \int_0^r dr'\, r'^2 \rho(r')$ is the enclosed mass at radius r. Fusion burning in a star leads to the onion-like structure sketched above.

the hydrostatic equilibrium eq. above is valid for low densities $\rho(r) << \rho_{nucl}(r) \equiv \frac{0.16}{fm^3} \cdot 1\,GeV$

in astrophys. units, $\rho_{nucl} = 2{,}6 \cdot 10^{14}\ g/cm^3$

if we deal with higher densities, such as in a neutron star, we need to take relativistic effects into account. This was first done by Oppenheimer and Volkoff, Phys. Rev. 55 (1939) 374 with important contributions by Tolman, Phys. Rev. 55 (1939) 364

this yields (note that the Newtonian result is obtained for $c \to \infty$)

$$\frac{dP}{dr} = - \frac{GM(r)\rho(r)}{r^2}\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi r^3 P}{Mc^2}\right)\left(1 - \frac{2GM}{rc^2}\right)^{-1}$$

if we go away from equilibrium solutions to describe a possible collapse, the (Newtonian) eq. of motion is

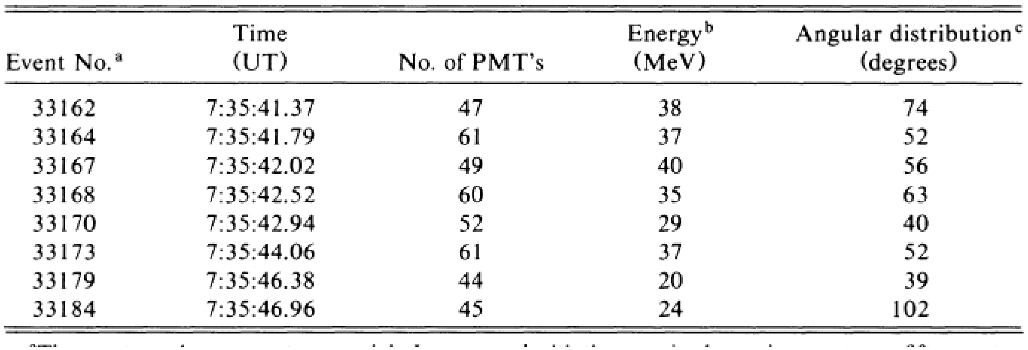
$$\frac{d^2r}{dt^2} = -\frac{GM_r}{r^2} - \frac{1}{\rho}\frac{\partial P}{\partial r}$$

here, the pressure $P = P(\rho, T, Y_e)$ depends on density, temperature T, and $Y_e = \frac{\#\text{ of electrons}}{\#\text{ of protons}}$

The relation between P and ρ, T, Y_e is called the equation of state and needs to be specified for a solution of the dynamical eq. In relevant cases, only numerical solutions are available. Typically, the Fe core and the region above it are divided into zones, a few hundreds of them

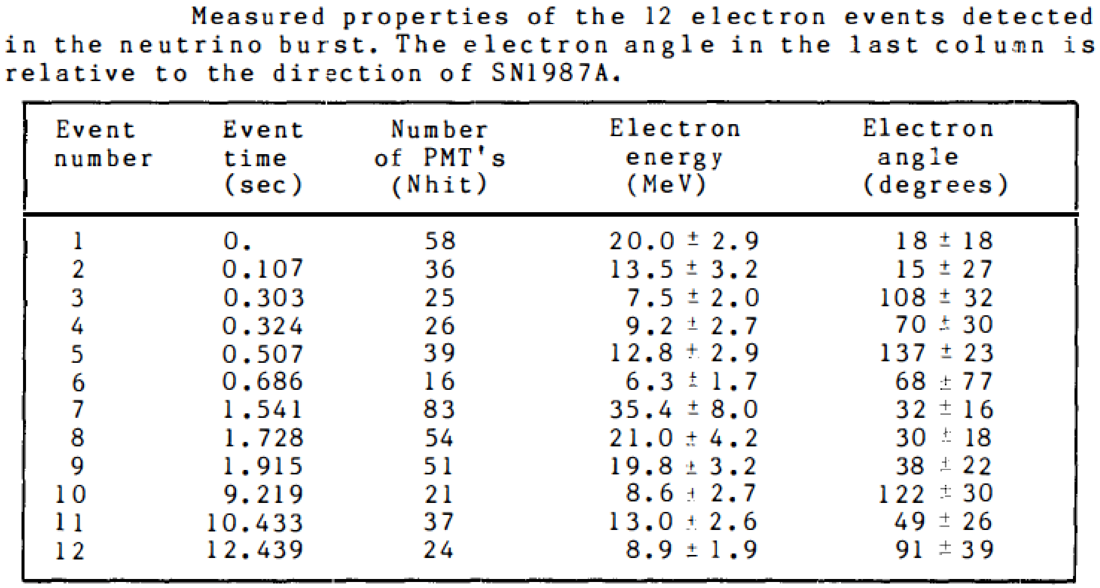
the critical period of the collapse lasts typically a few ms, so $10^4 - 10^5$ time steps of order 1 μs are required for a good solution

an aside: measurement of neutrinos from SN1987A



Event No.[a]	Time (UT)	No. of PMT's	Energy[b] (MeV)	Angular distribution[c] (degrees)
33162	7:35:41.37	47	38	74
33164	7:35:41.79	61	37	52
33167	7:35:42.02	49	40	56
33168	7:35:42.52	60	35	63
33170	7:35:42.94	52	29	40
33173	7:35:44.06	61	37	52
33179	7:35:46.38	44	20	39
33184	7:35:46.96	45	24	102

IMB events



Measured properties of the 12 electron events detected in the neutrino burst. The electron angle in the last column is relative to the direction of SN1987A.

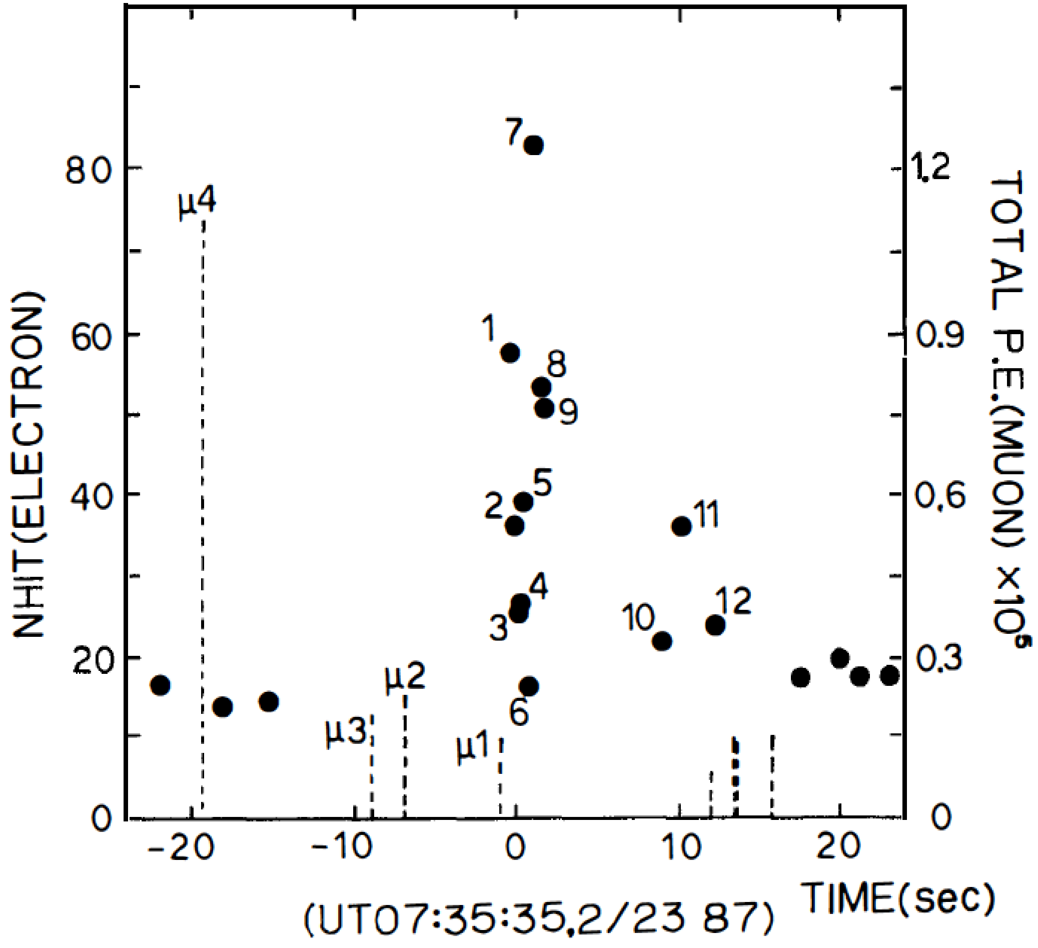
Event number	Event time (sec)	Number of PMT's (Nhit)	Electron energy (MeV)	Electron angle (degrees)
1	0.	58	20.0 ± 2.9	18 ± 18
2	0.107	36	13.5 ± 3.2	15 ± 27
3	0.303	25	7.5 ± 2.0	108 ± 32
4	0.324	26	9.2 ± 2.7	70 ± 30
5	0.507	39	12.8 ± 2.9	137 ± 23
6	0.686	16	6.3 ± 1.7	68 ± 77
7	1.541	83	35.4 ± 8.0	32 ± 16
8	1.728	54	21.0 ± 4.2	30 ± 18
9	1.915	51	19.8 ± 3.2	38 ± 22
10	9.219	21	8.6 ± 2.7	122 ± 30
11	10.433	37	13.0 ± 2.6	49 ± 26
12	12.439	24	8.9 ± 1.9	91 ± 39

Kamiokande II events

Phys.Rev.Lett. 58 (1987) 1494, IMB

Phys. Rev. Lett. 58 (1987) 1490, Kamiokande II

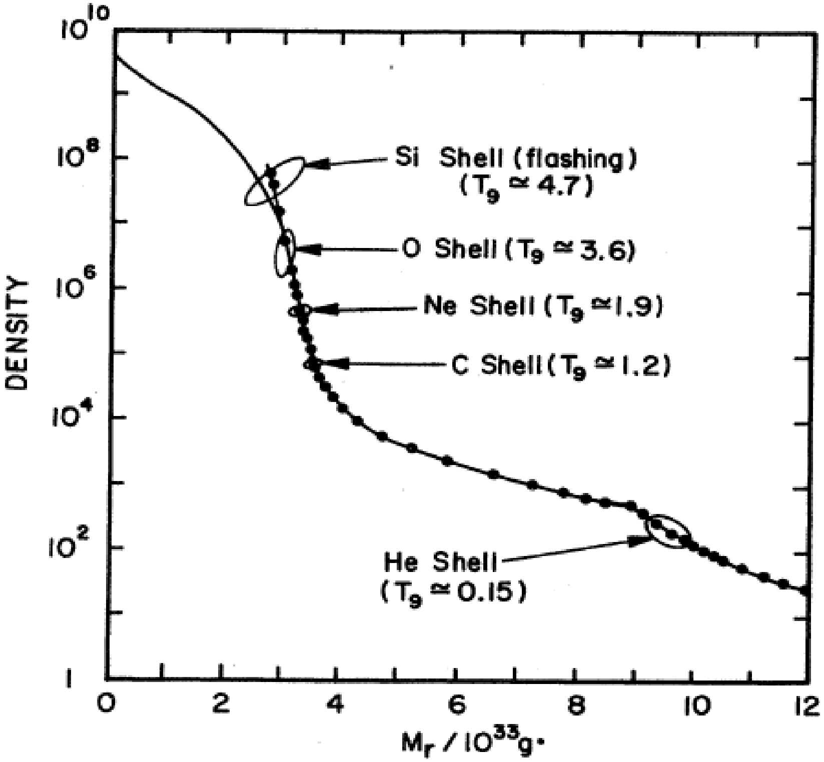
arrival time distribution of Kamiokande II events



the progenitor object

the material inside the Si shell is mostly Fe with a mass of
2.8 10^{33} g, about 1.4 solar masses,
the density is in (g/cm^3)

the density at the sun's center is about 160 g/cm^3



Density distribution of a star before supernova collapse, according to Arnett (1977a). The enclosed mass is given in units of 10^{33} grams; the Sun's mass is 2×10^{33} g. The location of shells is indicated in which various nuclear reactions take place, together with the temperature in units of 10^9 K.

fig. taken from the 1990 Bethe review

the equation of state (EoS) of the dense matter – nuclear physics input

dominant contribution from the degenerate, relativistic electrons prior to collapse, nuclei and nucleons play an important role at the end of the collapse

the EoS should be usable to describe the regions of:

- the progenitor star before collapse
- the development of the collapse before formation of the proto-neutron star at electron fractions $0 < Y_e < 0.6$
- the proto-neutron star where temperatures up to 100 MeV and densities $> 5\ \rho_{nucl}$ are expected
- the remaining cold neutron star after the collapse with similar densities at $T = 0$

for a very recent survey see Oertel et al., Rev.Mod.Phys. 89 (2017) 1, 015007 and arXiv:1703.03772 and refs. there

the density and temperature regime to be covered by the EoS

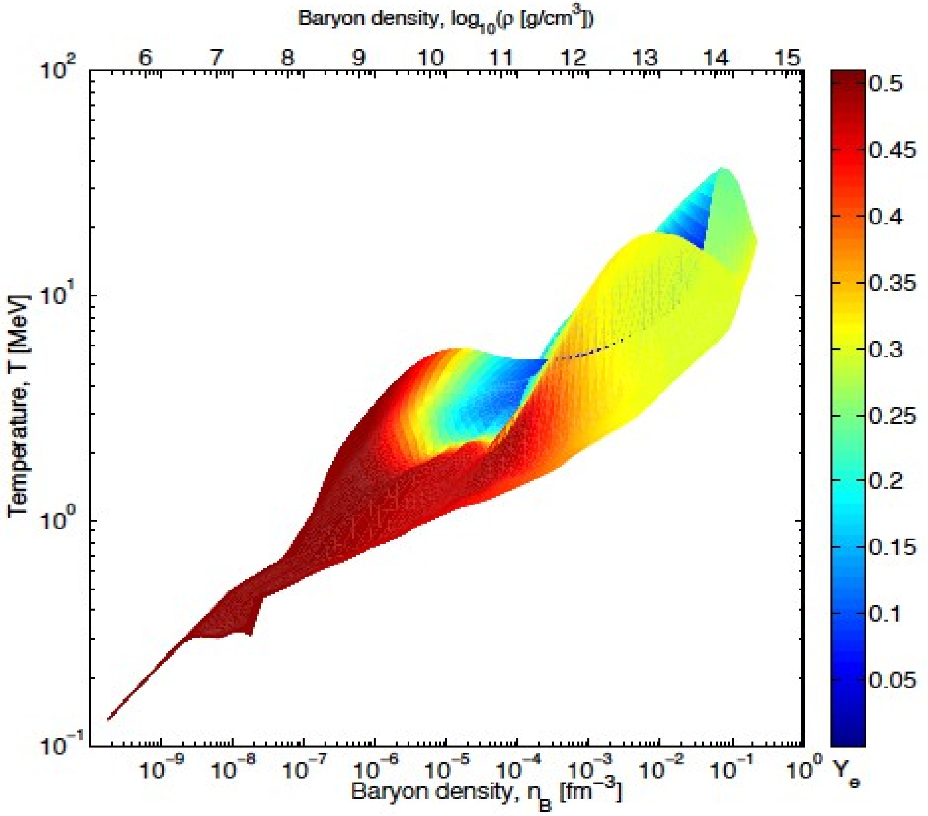
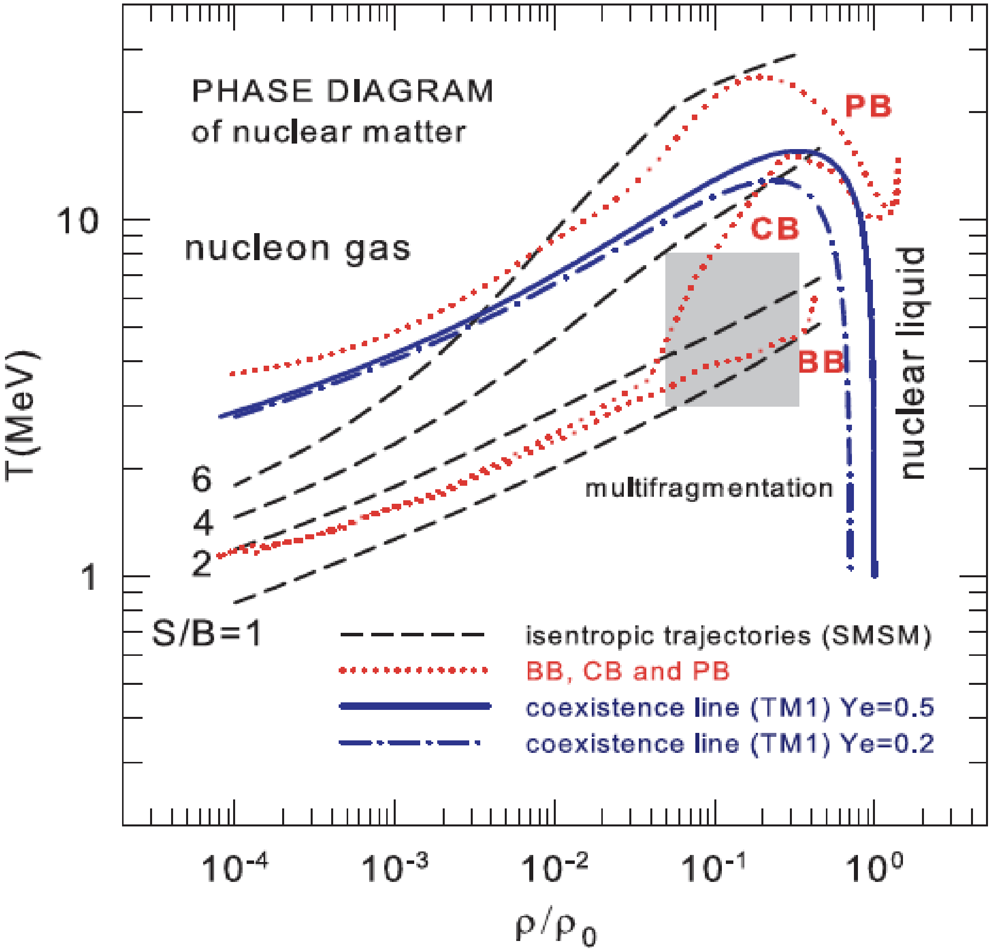


FIG. 1 (color online) Temperatures and densities (lower scale shows the baryon number density and the upper scale shows the mass density) reached during a CCSN simulation at 1 s post bounce. The color-coding shows the electron fraction Y_e.

Fischer, C. S., J. Luecker, and J. A. Mueller, 2011, Phys.Lett. **B702**, 438.

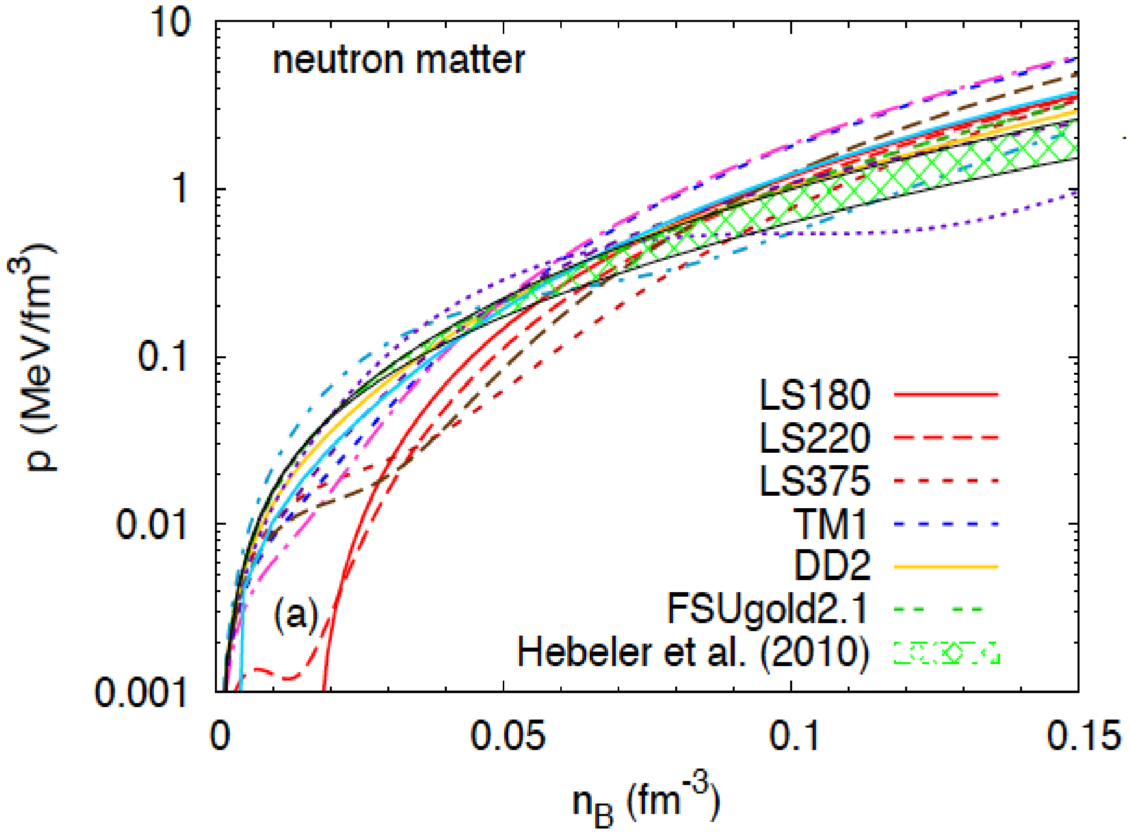
the phase diagram of nuclear matter



from Oertel et al, Rev. Mod. Phys. 89 (2017) 1, 015007

BB: before bounce, CB: core bounce, PB: past bounce

different EoS compared to nuclear matter calculations (Hebeler et al.)



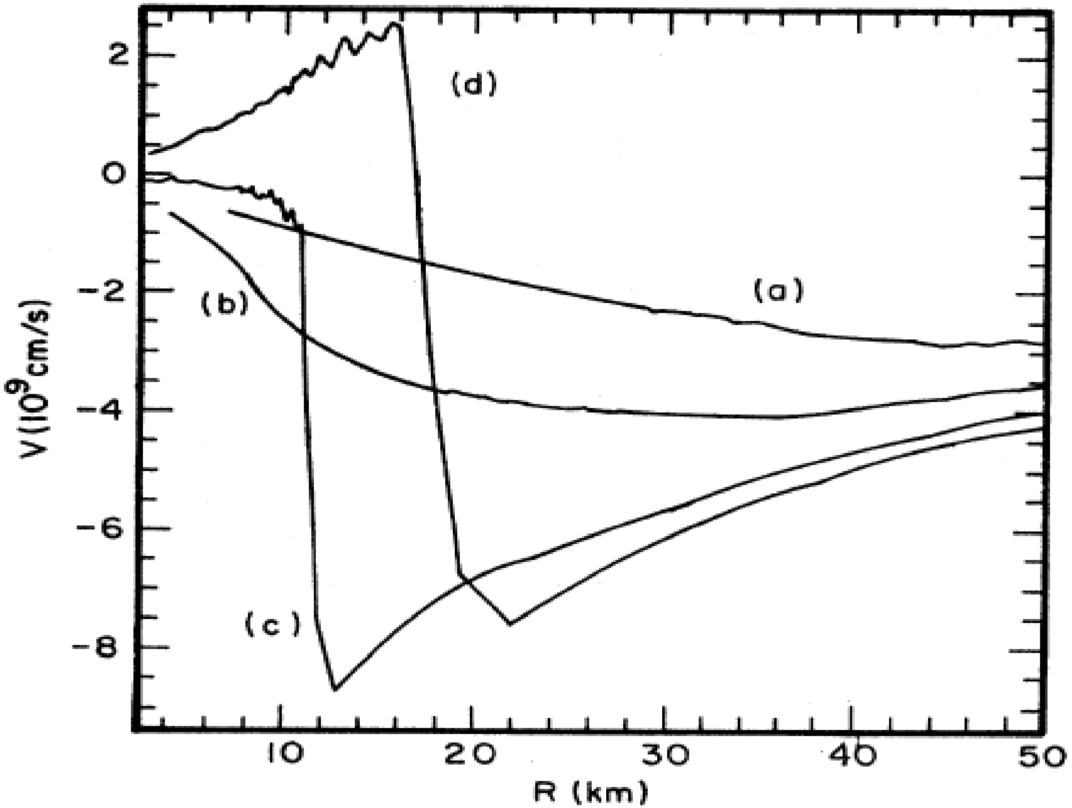
from Oertel et al, Rev. Mod. Phys. 89 (2017) 1, 015007

prompt and delayed shocks and the role of thermal neutrino emission

The collapse is stopped at the boundary to the highly compressed proto-neutron star. This inner core subsequently rebounds and sends a shock wave back into the surrounding star material. Unfortunately, this material consists mostly of nuclei, not nucleons as initially thought, because the nuclei when heated do not disintegrate but rather get excited into their many available quantum states (Bethe, Brown, Applegate and Lattimer, see Bethe 1990 review). Most of the shock's energy is dissipated into disassembly of the nuclei and the shock wave stalls.

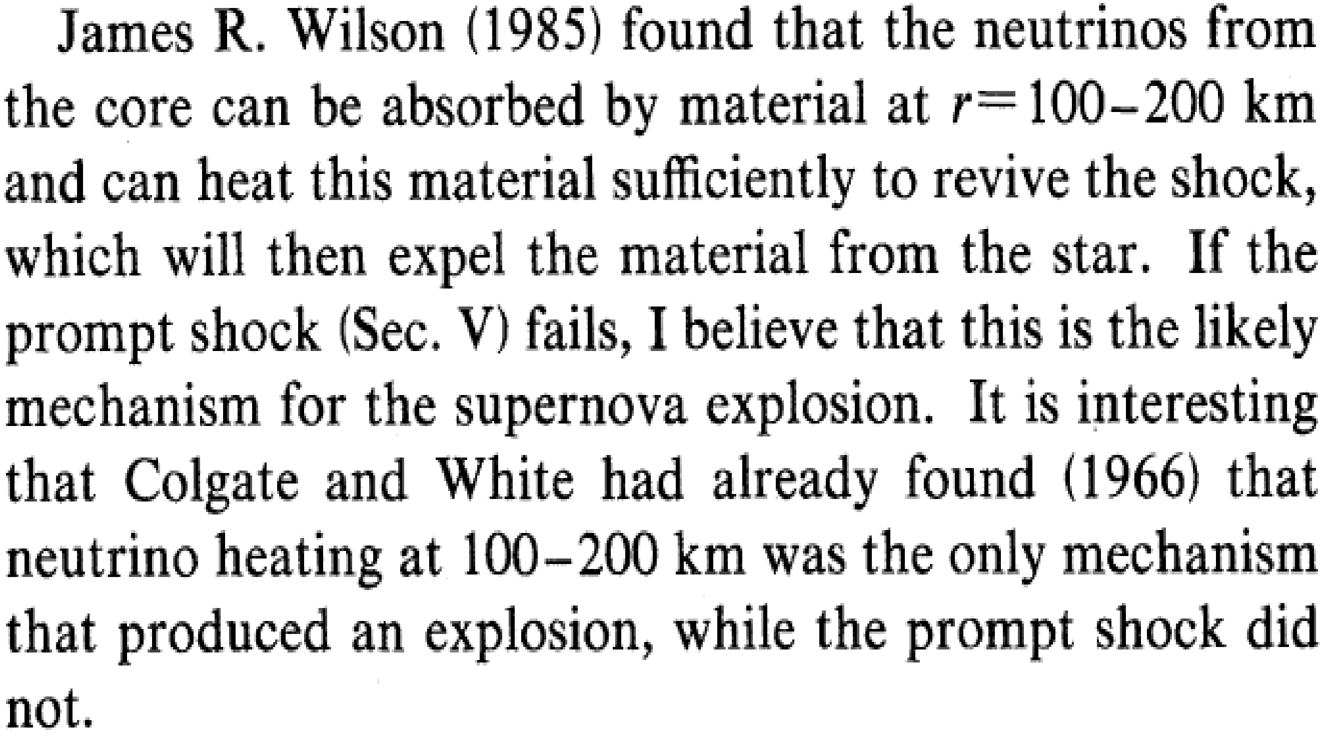
However, the proto-neutron star is heated to temperatures of several tens of MeV. This leads to a huge amount of thermal neutrinos whose total energy can reach 100 foe, see above). If only a percent of this energy is re-absorbed in the surrounding star material, this can lead to a powerful, delayed shock.

development of prompt shock, see Bethe 1990



. Start of the shock, according to Cooperstein and Baron (1990). (a) Last time when velocity of infall is roughly proportional to radius; (b) nuclear density has been reached at center; (c) inner 10 km have been brought to rest; (d) shock has started.

the Wilson mechanism



James R. Wilson (1985) found that the neutrinos from the core can be absorbed by material at $r = 100-200$ km and can heat this material sufficiently to revive the shock, which will then expel the material from the star. If the prompt shock (Sec. V) fails, I believe that this is the likely mechanism for the supernova explosion. It is interesting that Colgate and White had already found (1966) that neutrino heating at 100–200 km was the only mechanism that produced an explosion, while the prompt shock did not.

from the Bethe 1990 review

... but life is more complicated than even Hans Bethe could foresee

before we describe this we have a look at SN1987a including its light curve

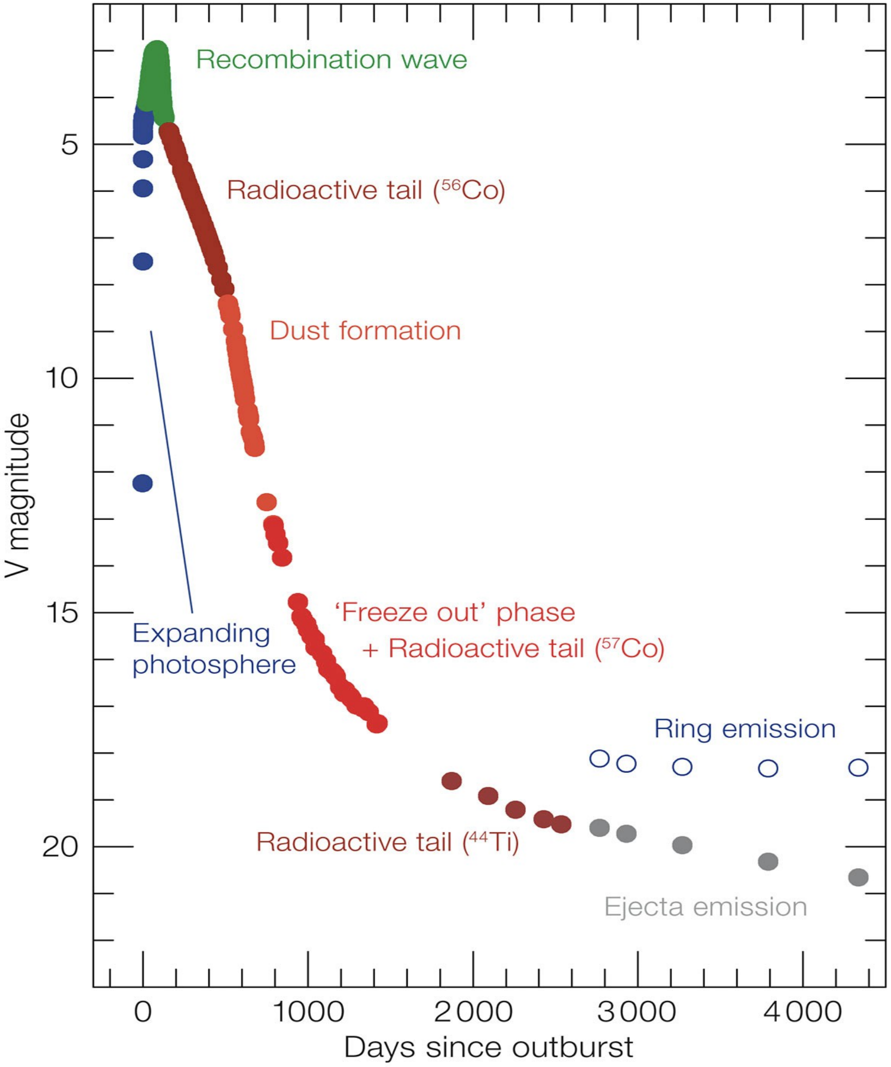
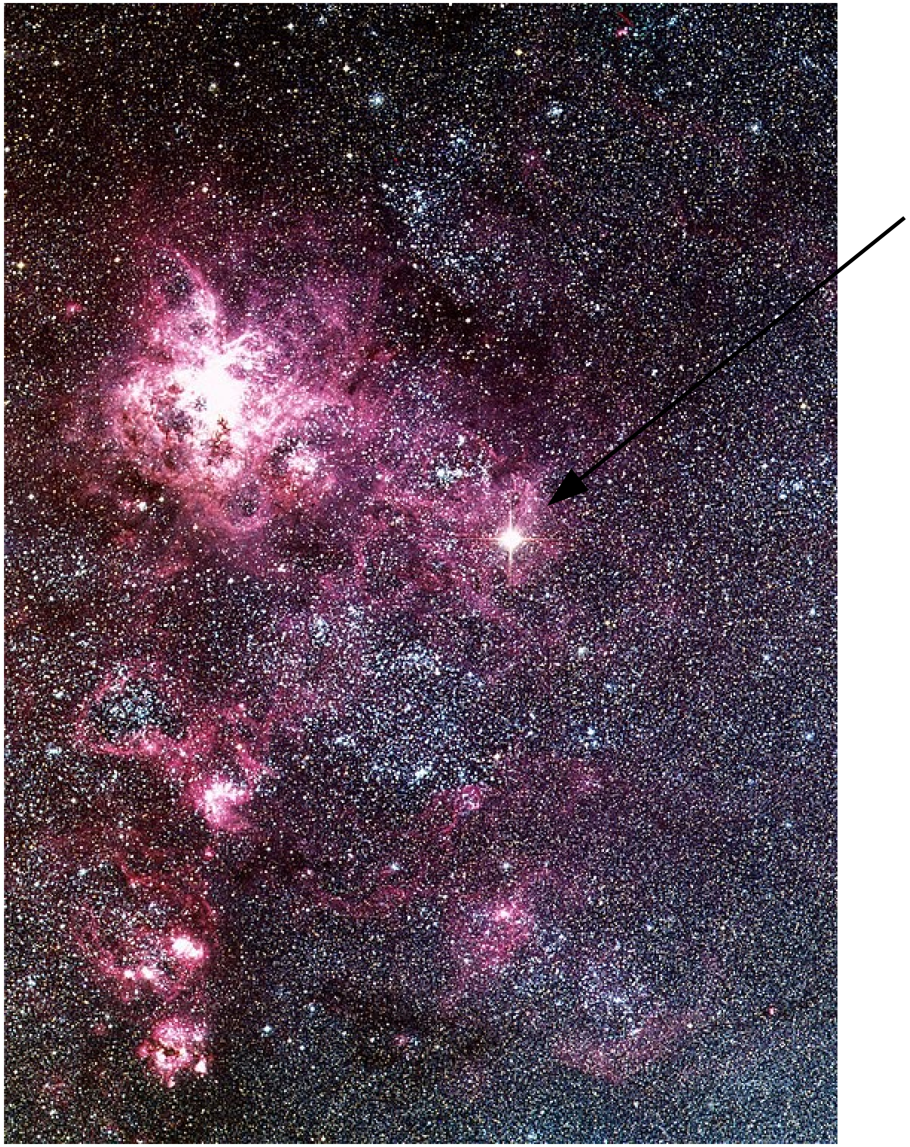


image: ESO

SN1987a – a supernova in the Large Magellanic Cloud



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

Spectral class Type II (peculiar)
Date: February 24, 1987 (23:00 UTC)
Las Campanas Observatory

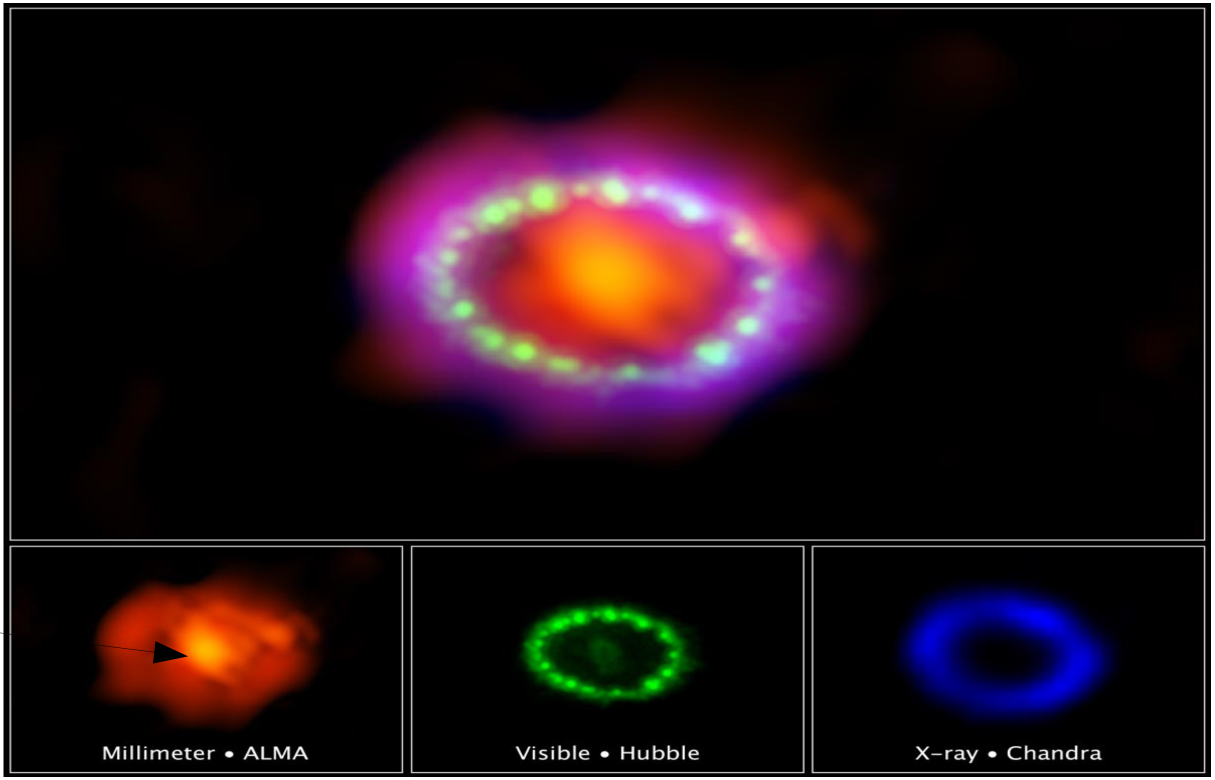
figure from Wikipedia, Eso0708a

newest results from SN1987A
distance: 168000 LY in the Large Magellanic Cloud
progenitor star: Sanduleak −69 202, a blue supergiant

see Dany Page et al., arXiv:2004.06078

maybe there is a neutron star in the hot remains of SN1987a

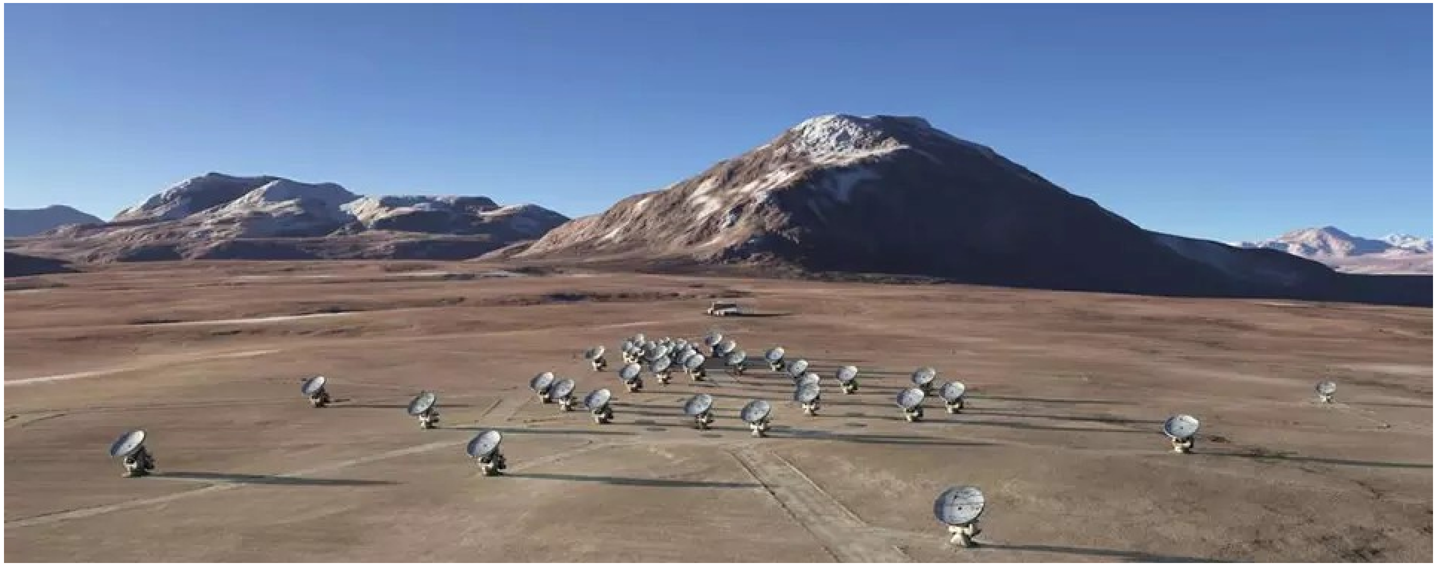
33 years after the explosion, a first indication



pictures of the 1987A
ring region by ALMA,
Hubble, Chandra

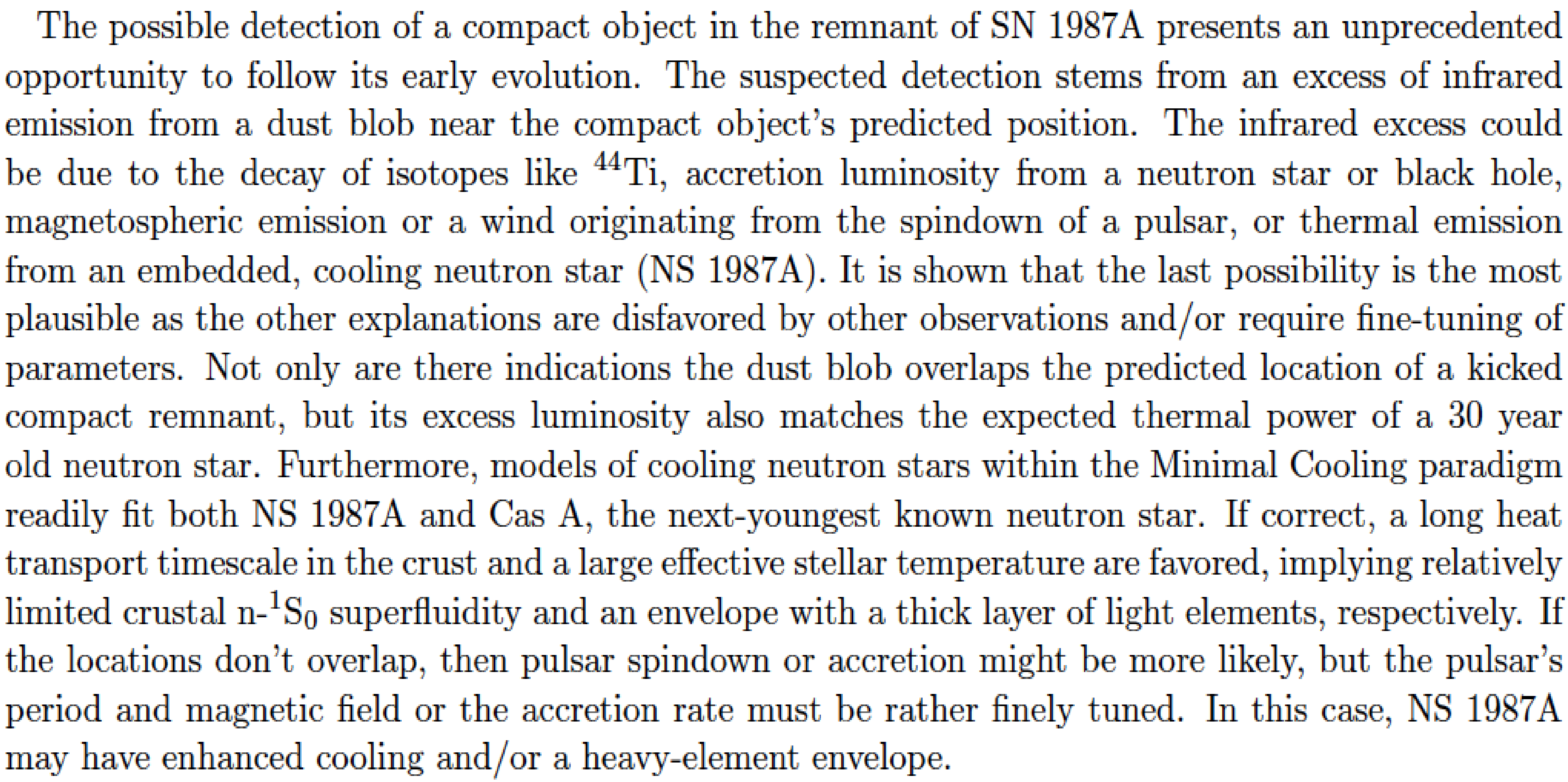
image: ALMA collaboration

hot blob maybe
consistent with neutron
star



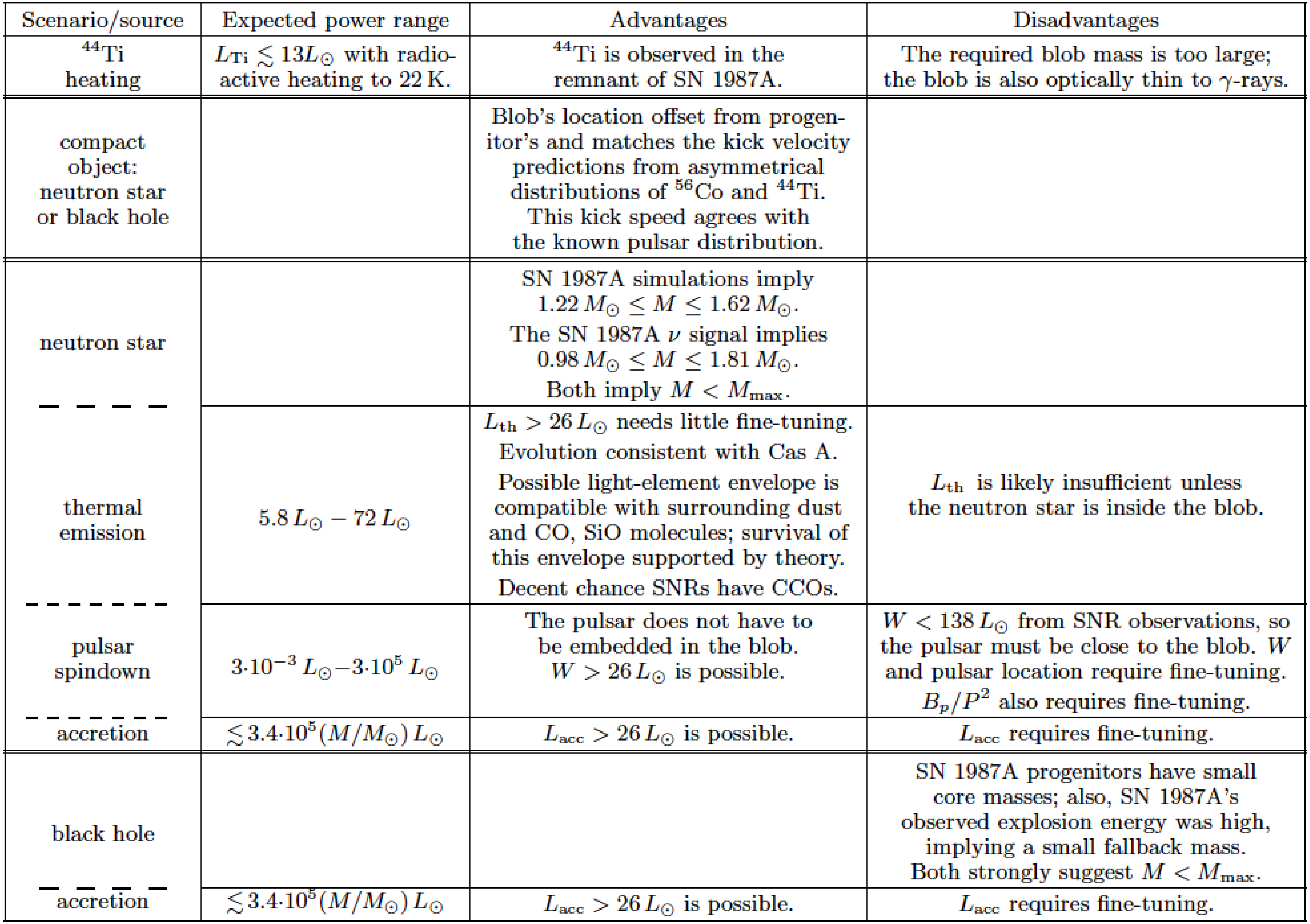
Artist rendering of the ALMA Array, in an extended configuration. © ALMA (ESO/NAOJ/NRAO)

from arXiv:2004.06078



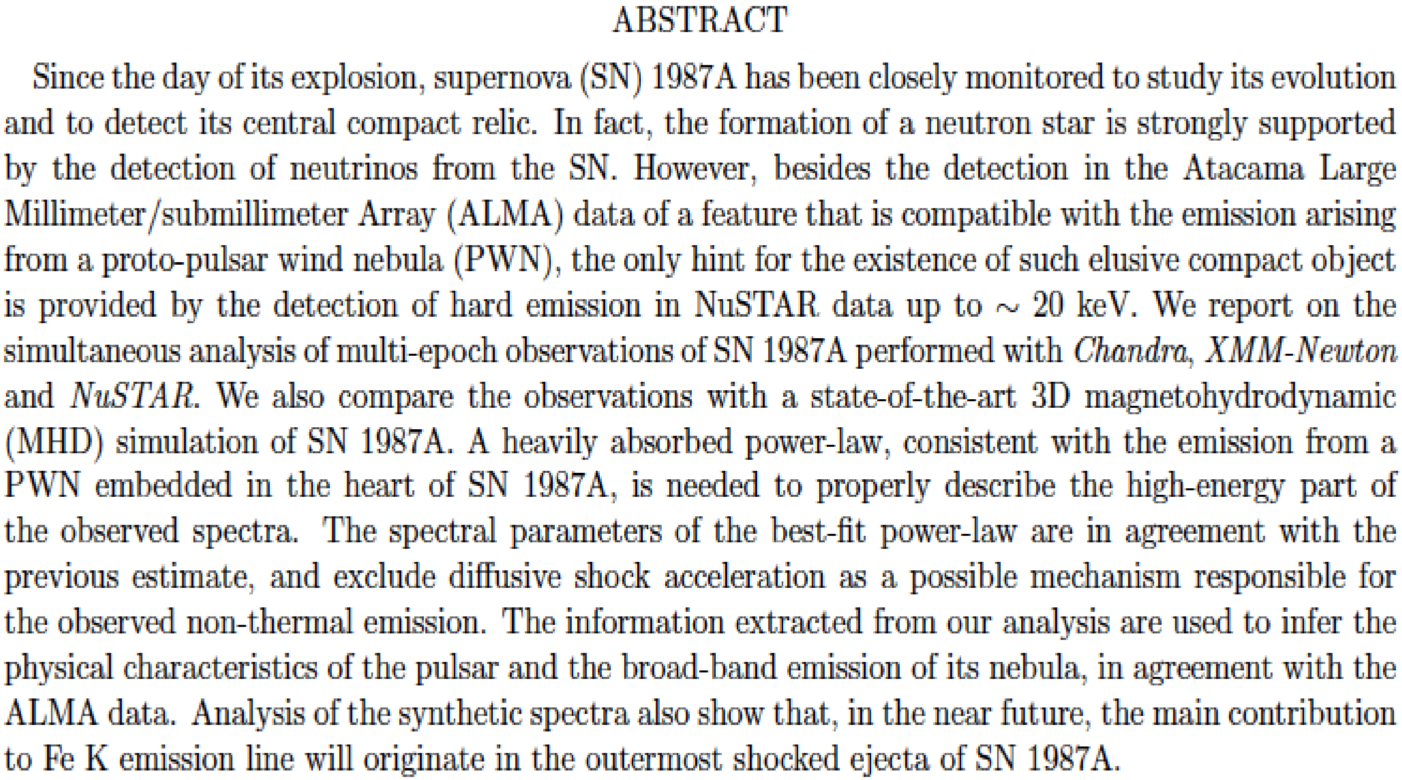
The possible detection of a compact object in the remnant of SN 1987A presents an unprecedented opportunity to follow its early evolution. The suspected detection stems from an excess of infrared emission from a dust blob near the compact object's predicted position. The infrared excess could be due to the decay of isotopes like ^{44}Ti, accretion luminosity from a neutron star or black hole, magnetospheric emission or a wind originating from the spindown of a pulsar, or thermal emission from an embedded, cooling neutron star (NS 1987A). It is shown that the last possibility is the most plausible as the other explanations are disfavored by other observations and/or require fine-tuning of parameters. Not only are there indications the dust blob overlaps the predicted location of a kicked compact remnant, but its excess luminosity also matches the expected thermal power of a 30 year old neutron star. Furthermore, models of cooling neutron stars within the Minimal Cooling paradigm readily fit both NS 1987A and Cas A, the next-youngest known neutron star. If correct, a long heat transport timescale in the crust and a large effective stellar temperature are favored, implying relatively limited crustal n-$^1S_0$ superfluidity and an envelope with a thick layer of light elements, respectively. If the locations don't overlap, then pulsar spindown or accretion might be more likely, but the pulsar's period and magnetic field or the accretion rate must be rather finely tuned. In this case, NS 1987A may have enhanced cooling and/or a heavy-element envelope.

summary from arXiv:2004.06078



Scenario/source	Expected power range	Advantages	Disadvantages
^{44}Ti heating	$L_{\rm Ti} \lesssim 13 L_\odot$ with radioactive heating to 22 K.	^{44}Ti is observed in the remnant of SN 1987A.	The required blob mass is too large; the blob is also optically thin to γ-rays.
compact object: neutron star or black hole		Blob's location offset from progenitor's and matches the kick velocity predictions from asymmetrical distributions of ^{56}Co and ^{44}Ti. This kick speed agrees with the known pulsar distribution.	
neutron star		SN 1987A simulations imply $1.22\, M_\odot \leq M \leq 1.62\, M_\odot$. The SN 1987A ν signal implies $0.98\, M_\odot \leq M \leq 1.81\, M_\odot$. Both imply $M < M_{\rm max}$.	
thermal emission	$5.8\, L_\odot - 72\, L_\odot$	$L_{\rm th} > 26\, L_\odot$ needs little fine-tuning. Evolution consistent with Cas A. Possible light-element envelope is compatible with surrounding dust and CO, SiO molecules; survival of this envelope supported by theory. Decent chance SNRs have CCOs.	$L_{\rm th}$ is likely insufficient unless the neutron star is inside the blob.
pulsar spindown	$3{\cdot}10^{-3}\, L_\odot – 3{\cdot}10^{5}\, L_\odot$	The pulsar does not have to be embedded in the blob. $W > 26\, L_\odot$ is possible.	$W < 138\, L_\odot$ from SNR observations, so the pulsar must be close to the blob. W and pulsar location require fine-tuning. B_p/P^2 also requires fine-tuning.
accretion	$\lesssim 3.4{\cdot}10^5 (M/M_\odot)\, L_\odot$	$L_{\rm acc} > 26\, L_\odot$ is possible.	$L_{\rm acc}$ requires fine-tuning.
black hole			SN 1987A progenitors have small core masses; also, SN 1987A's observed explosion energy was high, implying a small fallback mass. Both strongly suggest $M < M_{\rm max}$.
accretion	$\lesssim 3.4{\cdot}10^5 (M/M_\odot)\, L_\odot$	$L_{\rm acc} > 26\, L_\odot$ is possible.	$L_{\rm acc}$ requires fine-tuning.

newest information:
Additional Evidence for a Pulsar Wind Nebula in the Heart of SN 1987A from Multiepoch X-Ray Data and MHD Modeling,
Astrophys.J. 931 (2022) 2, 132
arXiv:2204.06804 [astro-ph.HE]



ABSTRACT

Since the day of its explosion, supernova (SN) 1987A has been closely monitored to study its evolution and to detect its central compact relic. In fact, the formation of a neutron star is strongly supported by the detection of neutrinos from the SN. However, besides the detection in the Atacama Large Millimeter/submillimeter Array (ALMA) data of a feature that is compatible with the emission arising from a proto-pulsar wind nebula (PWN), the only hint for the existence of such elusive compact object is provided by the detection of hard emission in NuSTAR data up to ~ 20 keV. We report on the simultaneous analysis of multi-epoch observations of SN 1987A performed with *Chandra*, *XMM-Newton* and *NuSTAR*. We also compare the observations with a state-of-the-art 3D magnetohydrodynamic (MHD) simulation of SN 1987A. A heavily absorbed power-law, consistent with the emission from a PWN embedded in the heart of SN 1987A, is needed to properly describe the high-energy part of the observed spectra. The spectral parameters of the best-fit power-law are in agreement with the previous estimate, and exclude diffusive shock acceleration as a possible mechanism responsible for the observed non-thermal emission. The information extracted from our analysis are used to infer the physical characteristics of the pulsar and the broad-band emission of its nebula, in agreement with the ALMA data. Analysis of the synthetic spectra also show that, in the near future, the main contribution to Fe K emission line will originate in the outermost shocked ejecta of SN 1987A.

PWN:

A pulsar wind nebula (PWN, plural PWNe), sometimes called a plerion (derived from the Greek "πλήρης", pleres, meaning "full"),[1] is a type of nebula sometimes found inside the shell of a supernova remnant (SNR), powered by winds generated by a central pulsar. These nebulae were proposed as a class in 1976 as enhancements at radio wavelengths inside supernova remnants.[1] They have since been found to be infrared, optical, millimetre, X-ray [2] and gamma ray sources.[3][4]

source: Wikipedia

fast forward to the present

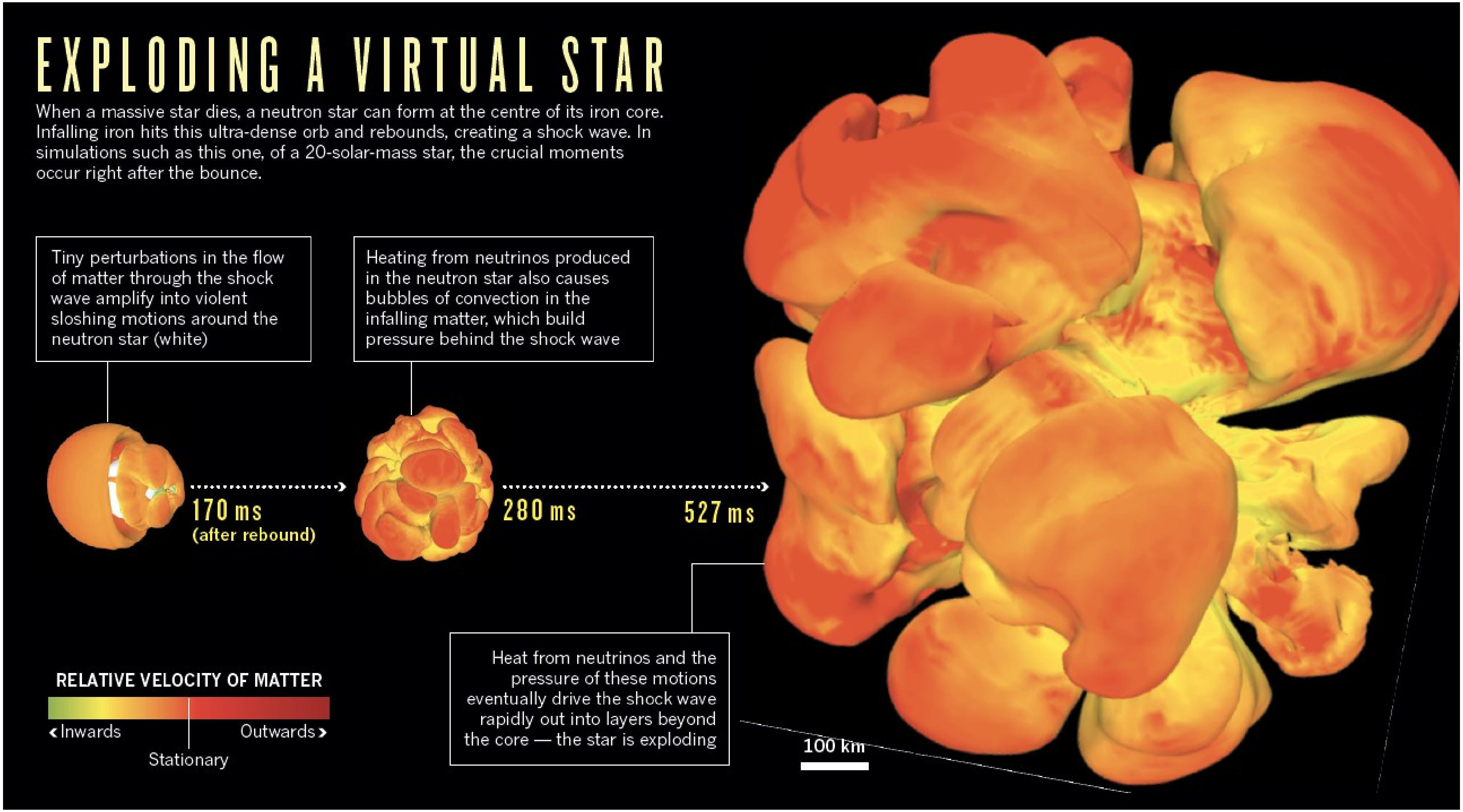
Nature 559 (2019) 287


FEATURE NEWS

LAST SECONDS OF STARDOM

BY ELIZABETH GIBNEY

Three-dimensional simulations are closing in on a 50-year-old problem: what makes massive stars explode when they die?



EXPLODING A VIRTUAL STAR

When a massive star dies, a neutron star can form at the centre of its iron core. Infalling iron hits this ultra-dense orb and rebounds, creating a shock wave. In simulations such as this one, of a 20-solar-mass star, the crucial moments occur right after the bounce.

Tiny perturbations in the flow of matter through the shock wave amplify into violent sloshing motions around the neutron star (white)

Heating from neutrinos produced in the neutron star also causes bubbles of convection in the infalling matter, which build pressure behind the shock wave

Heat from neutrinos and the pressure of these motions eventually drive the shock wave rapidly out into layers beyond the core — the star is exploding

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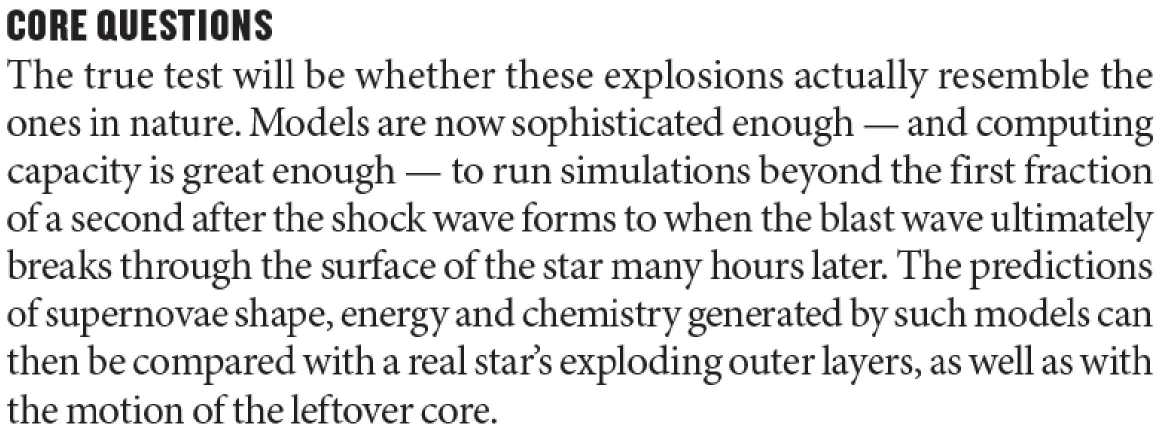

CORE QUESTIONS

The true test will be whether these explosions actually resemble the ones in nature. Models are now sophisticated enough — and computing capacity is great enough — to run simulations beyond the first fraction of a second after the shock wave forms to when the blast wave ultimately breaks through the surface of the star many hours later. The predictions of supernovae shape, energy and chemistry generated by such models can then be compared with a real star's exploding outer layers, as well as with the motion of the leftover core.

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the shock wave and instabilities

when a star explodes, the first part is the implosion when stellar matter is accelerated towards the forming proto-neutron star. This implosion is stopped when the innermost density reaches values beyond that of normal nuclear matter and leads to an outwardmoving shock front.

This first shock resulting from the bounce of matter at super-nuclear densities is significantly weakened due to the energy lost in excitation and dis-assembly of the matter further out, i.e. it stalls roughly at a radius of 200 km. A few hundred ms before the explosion, an instability develops leading to violent oscillations of the matter with period of tens of ms, and with strong departure from spherical symmetry, the SASI instability (standing accretion shock instability)

Meanwhile the thermal neutrino emisson from the compressed proto-neutron star reaches this radius about 1.5 ms later.
If only 1% of the neutrinos are absorbed, the shocked matter is strongly accelerated and likely to be ejected --> explosion.

For references see:
Hans-Thomas Janka, Tobias Melson, Alexander Summa, Ann. Rev. Nucl. Part. Sci. 66 (2016) 1

figure from Janka review 2016

explicitely showing the departure from spherical symmetry

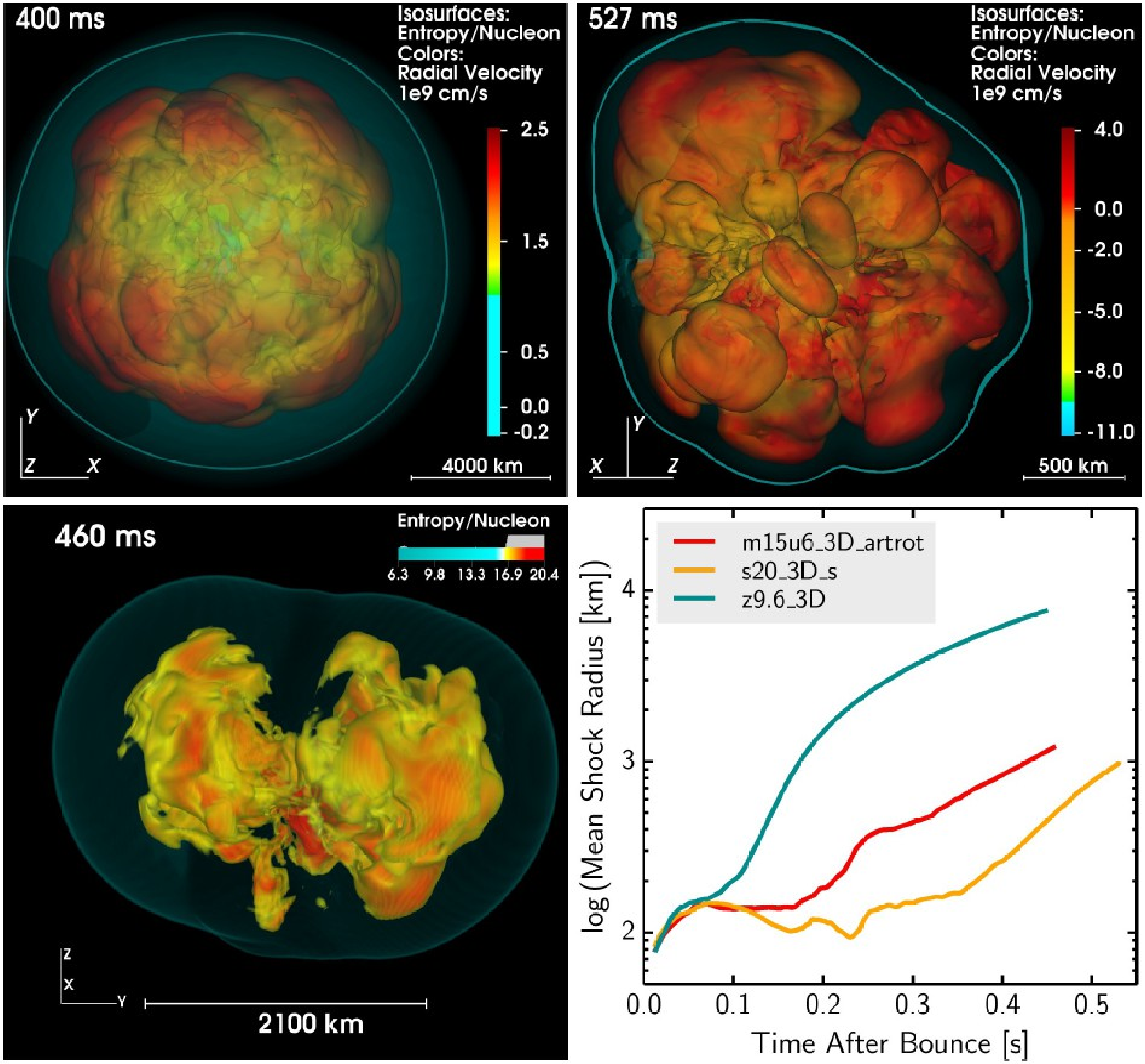


Figure 2

Successful 3D explosion models of the Garching group obtained in self-consistent neutrino-hydrodynamics simulations with the PROMETHEUS-VERTEX code. The panels show isoentropy surfaces of neutrino-heated, buoyant matter for a 9.6 $M_\odot$ star (top left; 97), a 20 $M_\odot$ progenitor (top right; 98), and a rotating 15 $M_\odot$ model (bottom left; 122). The supernova shock is visible as a blue, enveloping surface. The average shock radii as functions of time are displayed in the lower right panel.

many of the previous arguments of a neutrino-driven shock revival are collected in the recent preprint by H.Th. Janka, arXiv:1702.08825

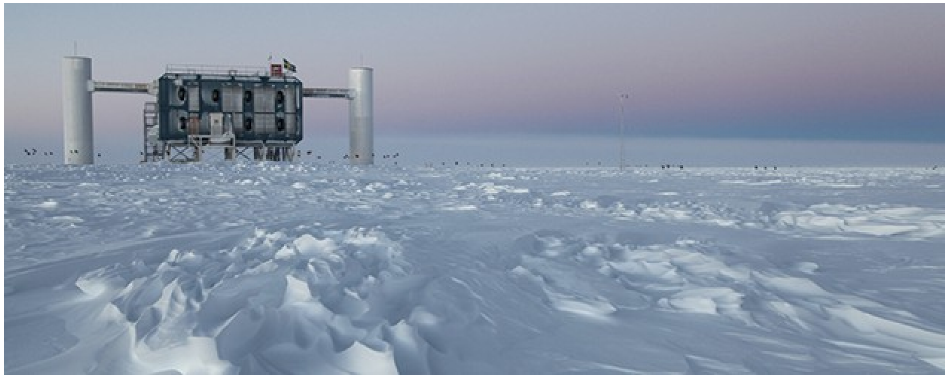
how can this all be tested experimentally?

the large amplitude motion of material in the stalled-shock matter induces large fluctuations in the accretion rate of material onto the neutron star. Increased accretion leads to increased heating of the neutron star, and in turn, to increased number of emitted neutrinos along with increased neutrino mean energies. Typical time scales are tens of ms corresponding to frequencies of order 100 Hz.

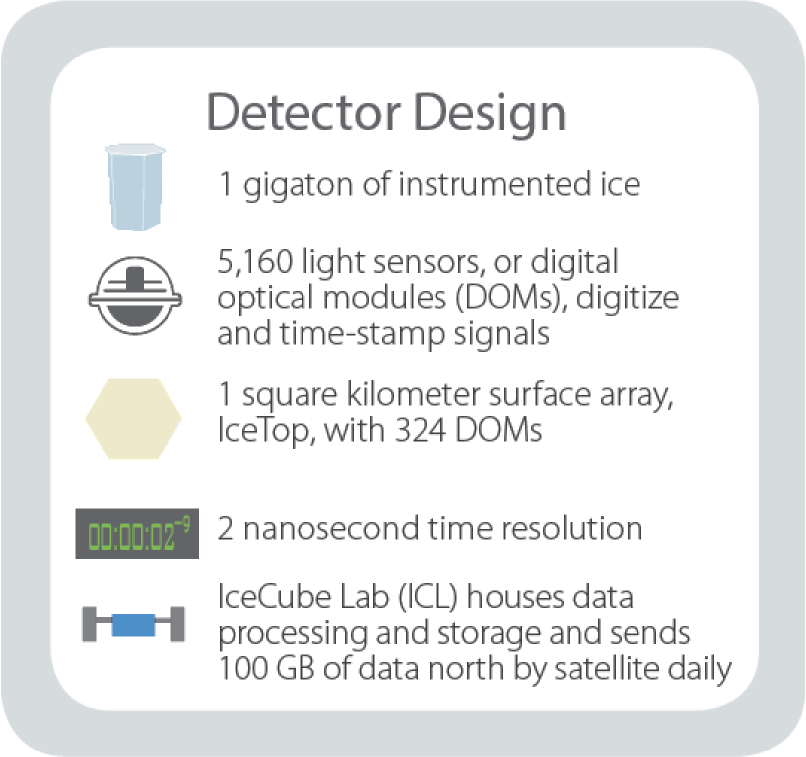
Such variations should be detectable via neutrino measurements in the ICECUBE and HYPER-Kamiokande experiments for a supernova explosion anywhere in our galaxy. This would provide strong evidence for the neutrino-driven explosion mechanism. Unfortunately, as discussed above, the mean number of supernovae is about 2/100years, the last one having taken place in 1604.

The ICECUBE neutrino detector

detecting neutrinos by their Cerenkov light emitted when they pass through > 1 km^3 of highly transparent south-polar ice at depths from 1,450 meters to 2,450 meters

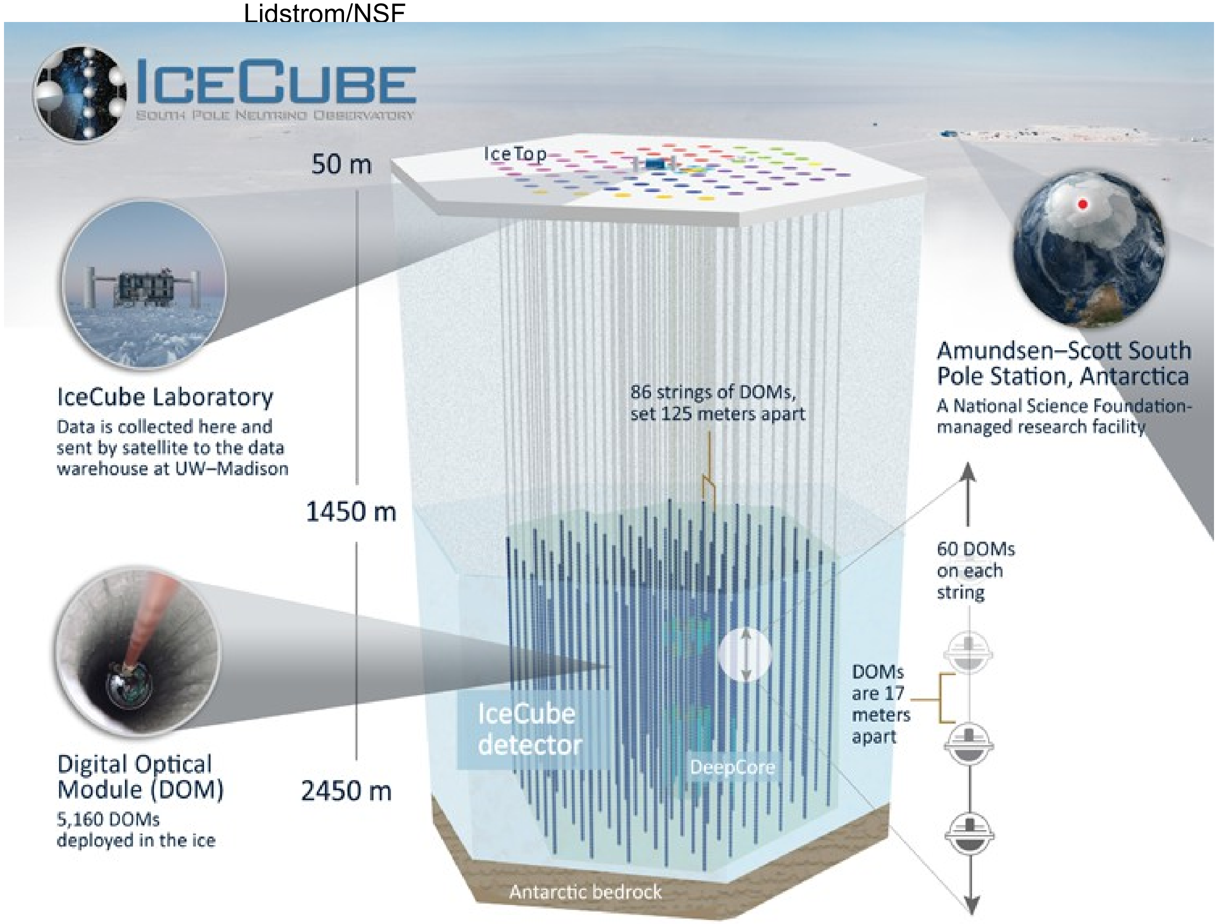


The IceCube Lab at the South Pole in Antarctica. Image: S. Lidstrom/NSF



Detector Design

- 1 gigaton of instrumented ice
- 5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
- 1 square kilometer surface array, IceTop, with 324 DOMs
- 2 nanosecond time resolution
- IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily



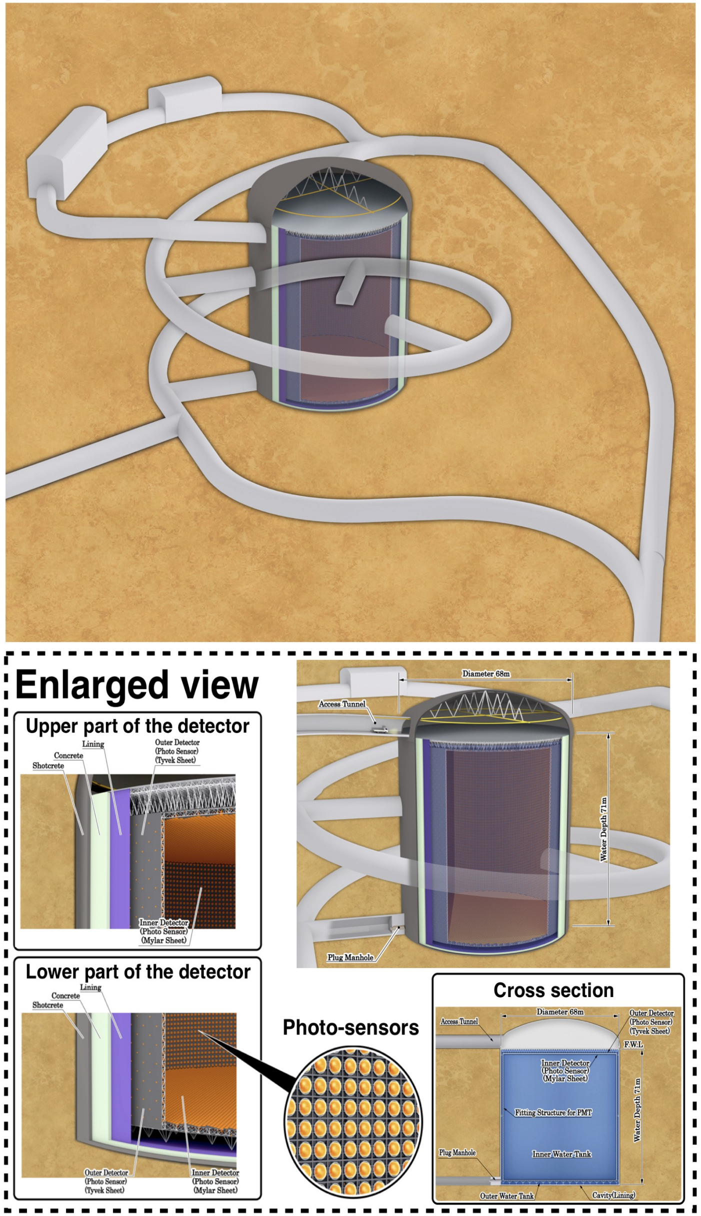
low energy neutrino detection in ICECUBE

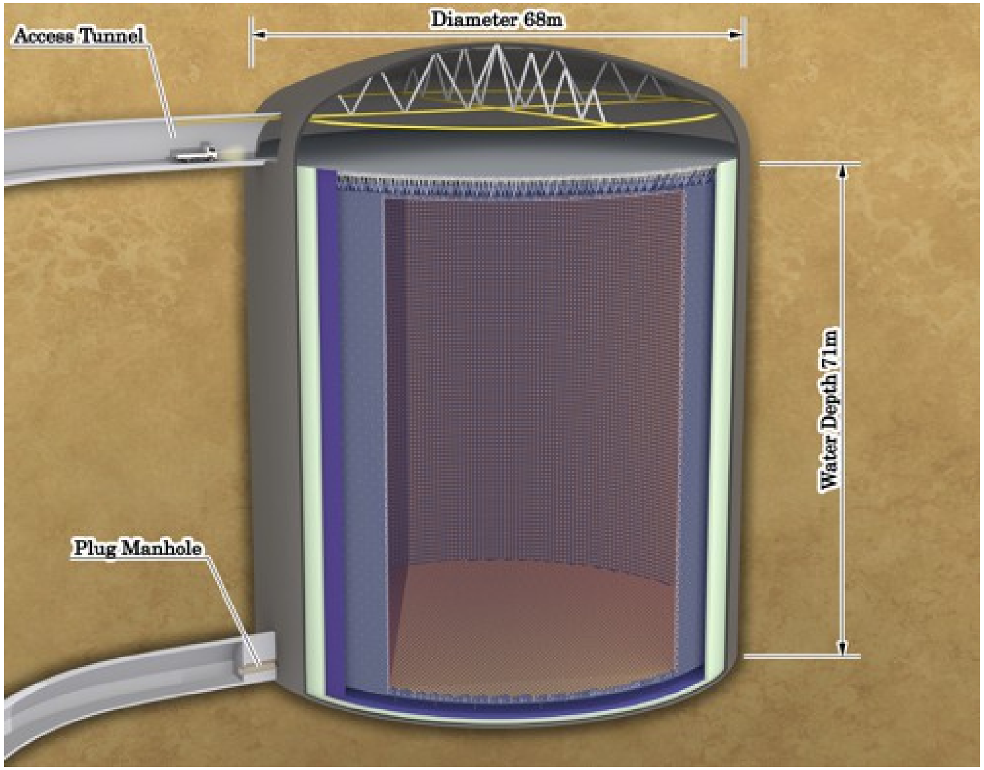
IceCube can (also) detect large numbers of MeV neutrinos by observing a collective rise in all photomultiplier rates on top of the dark noise. With 2 ms timing resolution, IceCube can track subtle features in the temporal development of the supernova neutrino burst. For a supernova at the galactic center, its sensitivity matches that of a background-free megaton-scale supernova search experiment. The sensitivity decreases to 20 standard deviations at the galactic edge (30 kpc) and 6 standard deviations at the Large Magellanic Cloud (50 kpc). IceCube is sending triggers from potential supernovae to the Supernova Early Warning System.

Lutz Koepke, ICECUBE coll., arXiv:1106.6225

the hyper-kamiokande experiment and neutrinos from supernova explosions

Schematic view of Hyper-Kamiokande detector





graphics from Hyper-Kamiokande homepage

Developing ultrasensitive photodetectors for Hyper-Kamiokande. The top left image shows a new large-aperture high-sensitivity "hybrid" photodetector, which uses a semiconductor called an "avalanche diode" for signal amplification. In the top right image a high-sensitivity photomultiplier tube is shown. The signal amplification stages of each photosensor appear in the bottom panel.

picture and text from Hyper-Kamiokande Homepage

supernova neutrino detection in hyper-kamiokande

Hyper-Kamiokande is a next-generation neutrino detector that will be able to observe the neutrino flux from the next galactic supernova in unprecedented detail. In this thesis, I investigate how well such an observation would allow us to reconstruct the explosion mechanism. I develop a high-precision supernova event generator and use a detailed detector simulation and event reconstruction to explore Hyper-Kamiokande's response to five supernova models simulated by different groups around the world. I show that 300 neutrino events in Hyper-Kamiokande---corresponding to a supernova at a distance of at least 60 kpc---are sufficient to distinguish between these models with high accuracy.

Jost Migenda, Hyper-K coll., arXiv:2002.01649