Lecture 17:

Supernovae and Neutron Stars

http://apod.nasa.gov/apod/

Outline of today's lecture

- Finish up lecture 16 (nucleosynthesis)

- Supernovae
  - 2 main classes: Type II and Type I
  - Their energetics and observable properties
  - Supernova remnants (pretty pictures!)

- Neutron Stars
  - Review of formation
  - Pulsars

REVIEWS OF MODERN PHYSICS, VOLUME 74, OCTOBER 2002

The evolution and explosion of massive stars

S. E. Woosley* and A. Heger†

Department of Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

T. A. Weaver

Lawrence Livermore National Laboratory, Livermore, California 94551

(Published 7 November 2002)

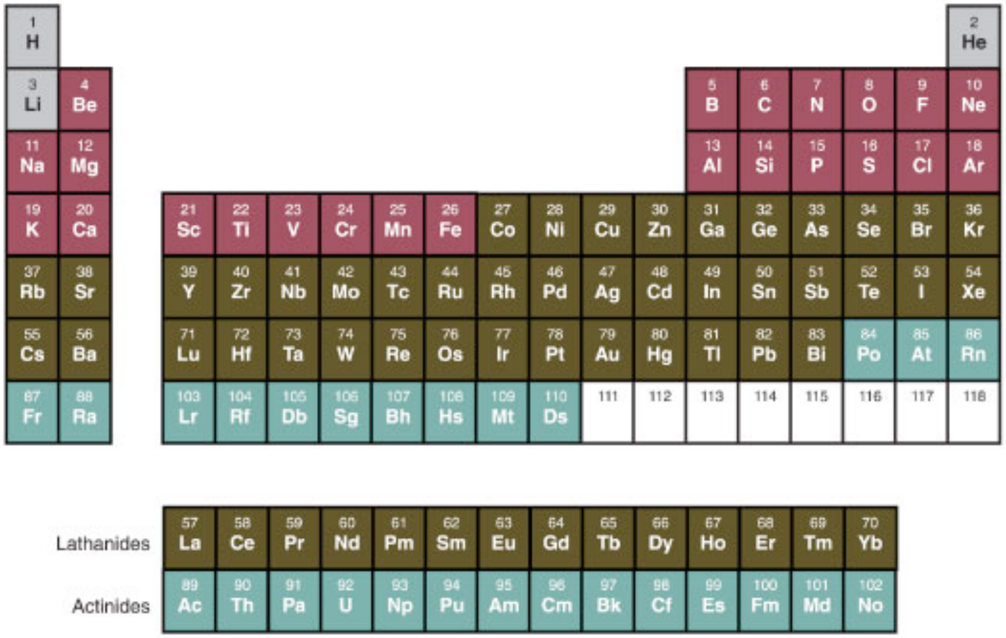
Like all true stars, massive stars are gravitationally confined thermonuclear reactors whose composition evolves as energy is lost to radiation and neutrinos. Unlike lower-mass stars ($M \lesssim 8 M_\odot$), however, no point is ever reached at which a massive star can be fully supported by electron degeneracy. Instead, the center evolves to ever higher temperatures, fusing ever heavier elements until a core of iron is produced. The collapse of this iron core to a neutron star releases an enormous amount of energy, a tiny fraction of which is sufficient to explode the star as a supernova. The authors examine our current understanding of the lives and deaths of massive stars, with special attention to the relevant nuclear and stellar physics. Emphasis is placed upon their post-helium-burning evolution. Current views regarding the supernova explosion mechanism are reviewed, and the hydrodynamics of supernova shock propagation and "fallback" is discussed. The calculated neutron star masses, supernova light curves, and spectra from these model stars are shown to be consistent with observations. During all phases, particular attention is paid to the nucleosynthesis of heavy elements. Such stars are capable of producing, with few exceptions, the isotopes between mass 16 and 88 as well as a large fraction of still heavier elements made by the r and p processes.

A 25 solar mass supernova ejects:

1.1 million	Earth	masses	of	oxygen *
160,000	"	"	"	carbon *
26,000	"	"	"	nitrogen *
6,200	"	"	"	sodium
76,000	"	"	"	magnesium
100,000	"	"	"	silicon
1,000	"	"	"	phosphorus *
35,000	"	"	"	sulfur
244	"	"	"	chlorine
107	"	"	"	potassium
3,500	"	"	"	calcium *
51,000	"	"	"	iron
0.01	"	"	"	silver
0.006	"	"	"	gold

plus about 70 other elements

All heavy elements are formed through fusion processes in stars.



gray = big bang, red = fusion, brown = *s*-process, teal = *r*-process

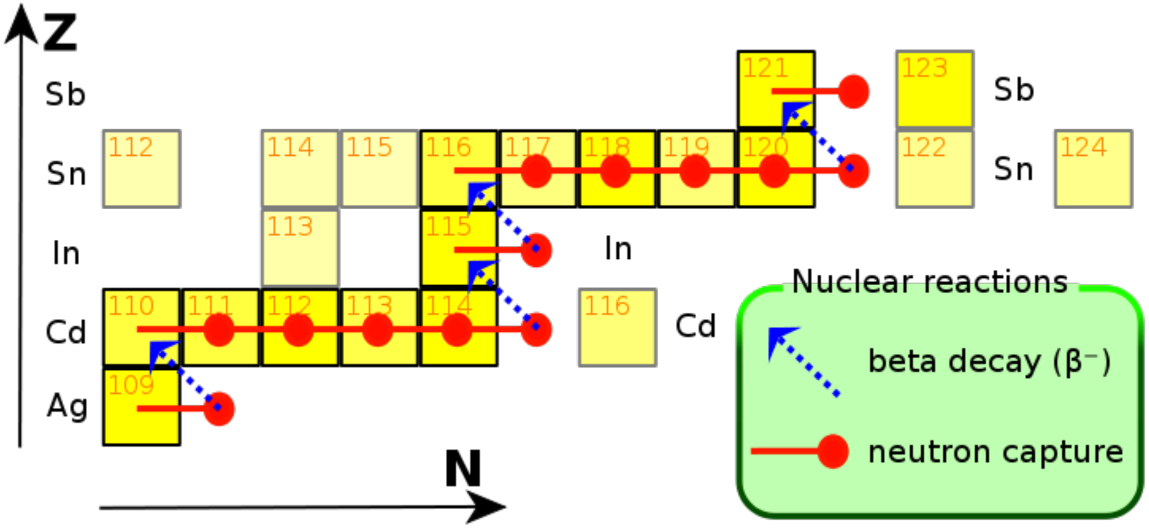
Nucleosynthesis

Process	Location	Products
Big bang nucleosynthesis	big bang	H, He, Li
Hydrogen burning	All MS stars	He
Helium burning	Post-MS stars $M > 0.5\,M_\odot$	C, O
C, O, Si burning	Post-MS stars $M > 8\,M_\odot$	Elements up to iron
s-process (*s* for "slow")	AGB stars $M < 8\,M_\odot$	Heavy elements up to bismuth
r-process (*r* for "rapid")	Type II supernovae	Remaining heavy elements

The “s-process”

The s-process occurs in AGB stars, during helium shell burning

Heavy elements are formed by the addition of neutrons, one at a time, followed by beta decay (neutron decays into proton)



Neutrons are produced in the following reactions

$^{22}\text{Ne} + {^4}\text{He} \longrightarrow {^{25}}\text{Mg} + n$

$^{13}\text{C} + {^4}\text{He} \longrightarrow {^{16}}\text{O} + n$

$^{56}\text{Fe} + n \longrightarrow {^{57}}\text{Fe} + \gamma$

$^{57}\text{Fe} + n \longrightarrow {^{58}}\text{Fe} + \gamma$

$^{58}\text{Fe} + n \longrightarrow {^{59}}\text{Fe} + \gamma$

$^{59}\text{Fe} \longrightarrow {^{59}}\text{Co} + e^- + \gamma$

$^{59}\text{Co} + n \longrightarrow {^{60}}\text{Co} + \gamma$

$^{60}\text{Co} \longrightarrow {^{60}}\text{Ni} + e^- + \gamma$

$^{60}\text{Ni} + n \longrightarrow {^{61}}\text{Ni} + \gamma$

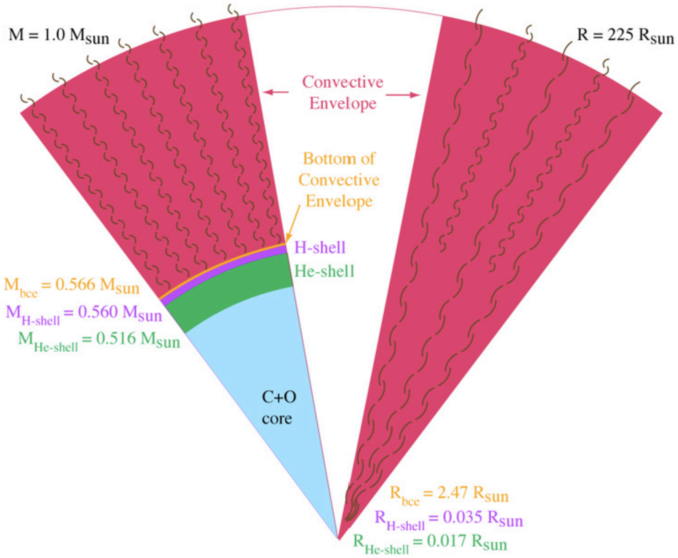
etc….. to lead & bismuth

The “s-process”

s stands for “slow”, because the time between neutron captures (~100 years) is long compared to the time for beta decay (~1 minute)

the s-process takes thousands of years to form the heavy elements

The s-process occurs at the base of the convective envelope, deep in the star’s interior



mass coordinates

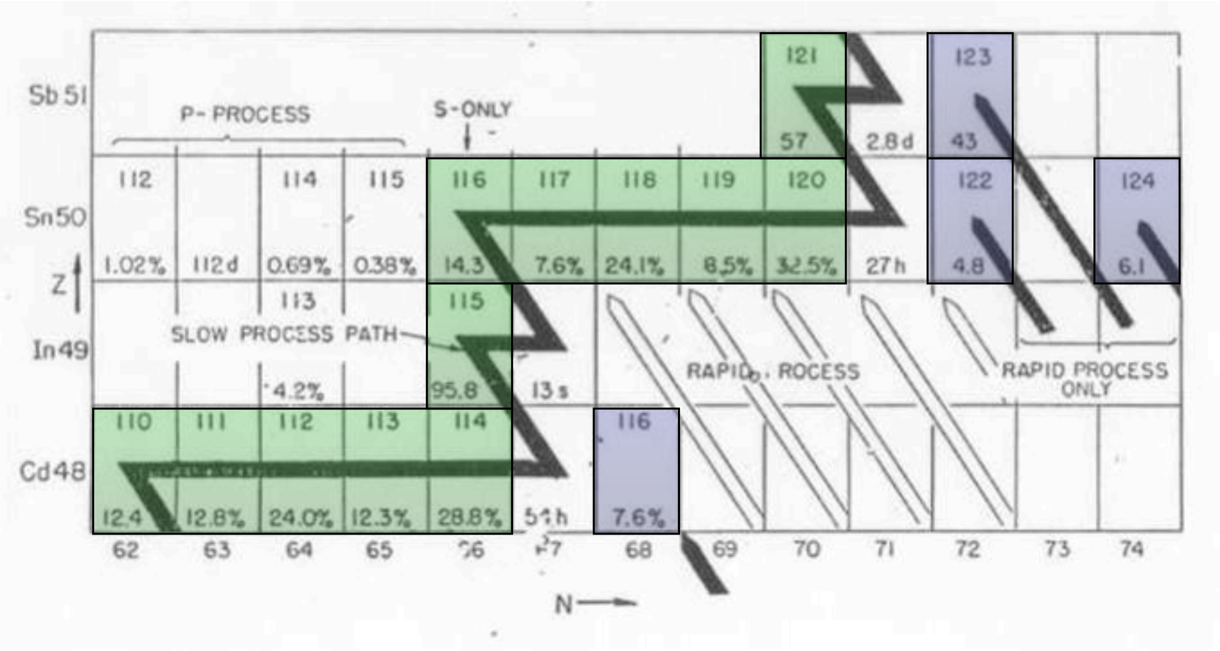
radius coordinates

The “r-process”

The r-process occurs during a Type II supernova explosion

Heavy elements are formed by the rapid addition of neutrons to nuclei (relative to the beta decay timescale)

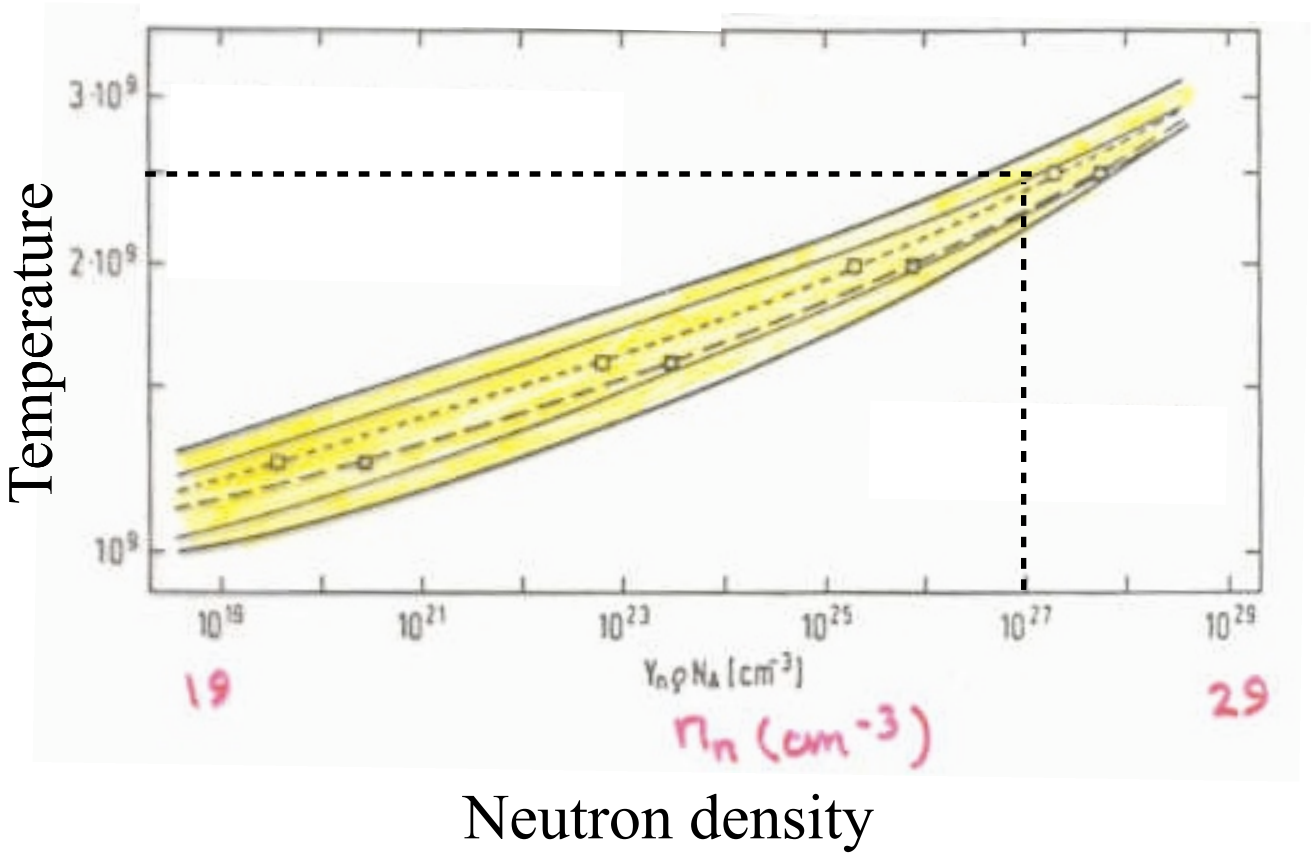
- A nucleus can gain lots of neutrons quickly before undergoing beta decay



Optimal conditions for the r-process

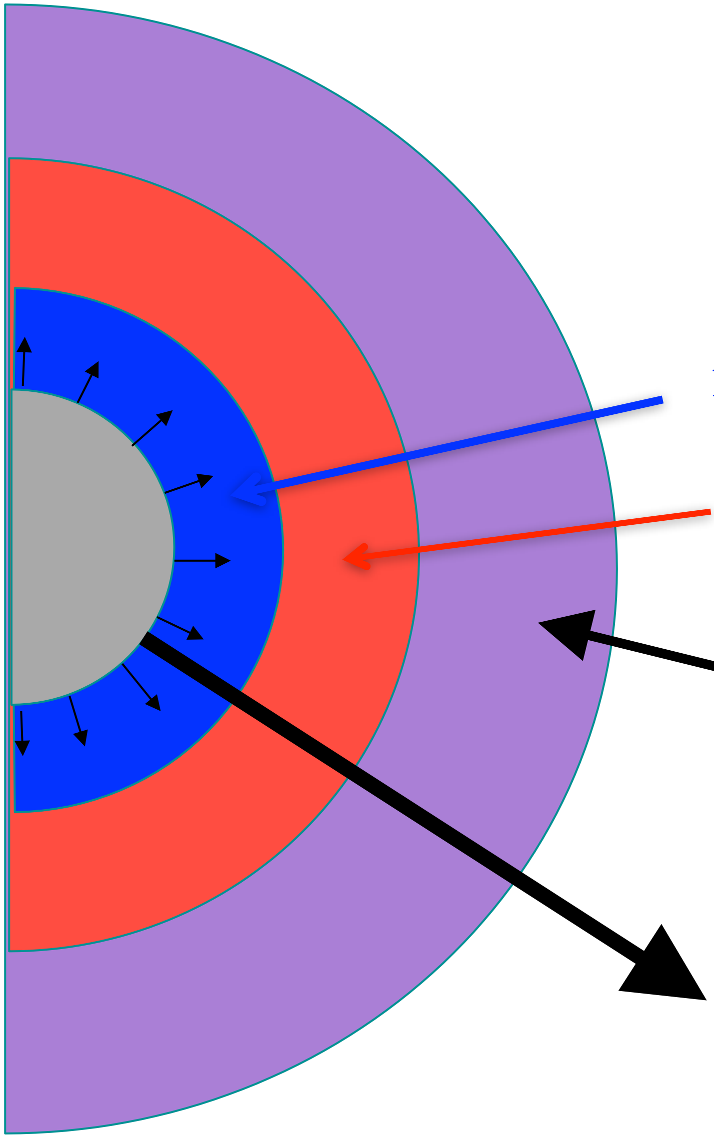
To build up heavy elements using the r-process, you need lots of neutrons bombarding the nuclei --> very high neutron densities are required

During the supernova explosion, temperatures and densities are sufficiently high for the r-process to proceed



For example, at $T = 2.5 \times 10^9$ K, $n_n \sim 10^{27}$ cm^{-3} or about a kilogram of neutrons per cubic cm.

r-Process Site #1: The Neutrino-powered Wind



n + p; $X_n > X_p$

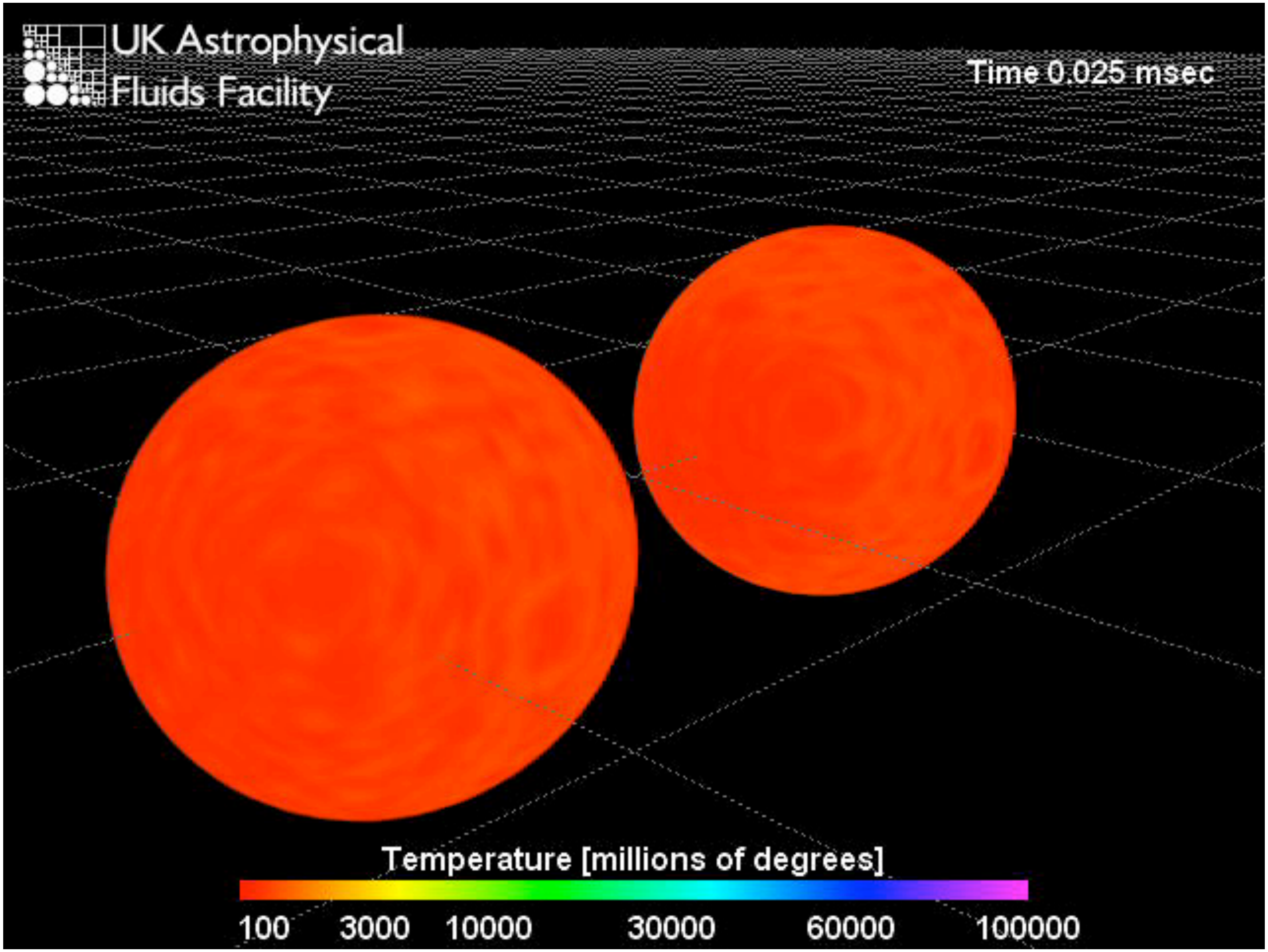
^{4}He + n

Iron plus neutrons

Wind, 1 - 10 seconds

Duncan, Shapiro, & Wasserman (1986), *ApJ*, **309**, 141
Woosley et al. (1994), *ApJ*, **433**, 229

r-Process Site #2: Merging neutron stars



Supernovae: Observations

SUPERNOVAE

- A supernova is the explosive death of a star. Unlike an ordinary nova, it does not repeat.

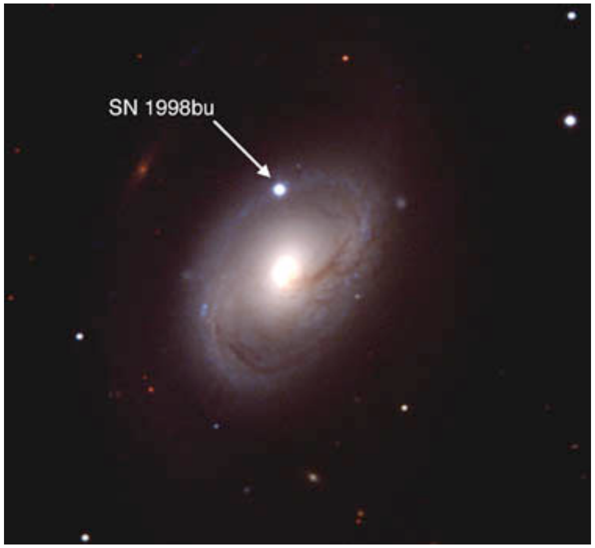
- Two types are easily distinguishable by their spectrum. Type II has hydrogen (H_α). Type I does not.

- Very luminous. Luminosities range from a few times 10^{42} erg s^{-1} (relatively faint Type II; about 300 million L_{sun}) to 2×10^{43} erg s^{-1} (Type Ia; 6 billion L_{sun}) - roughly as bright as a large galaxy.

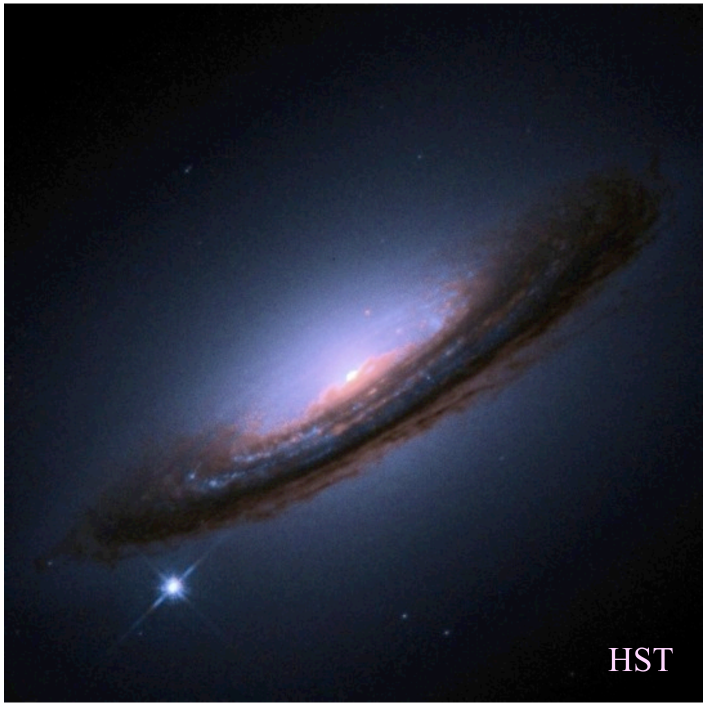
  (Recently some rare supernovae have been discovered to be even brighter)

SN 1998aq

SN 1998dh



SN 1998bu



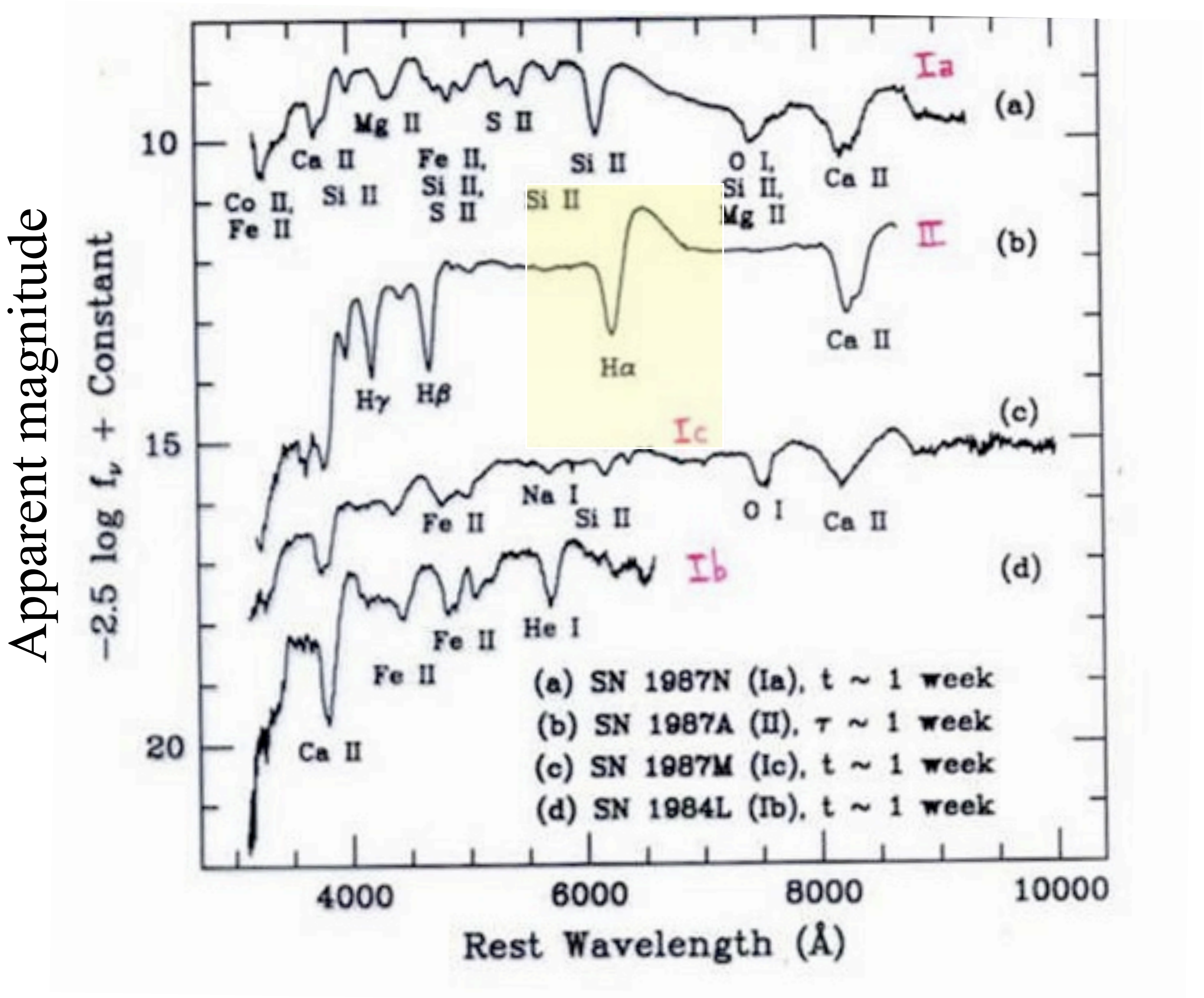
SN 1994D

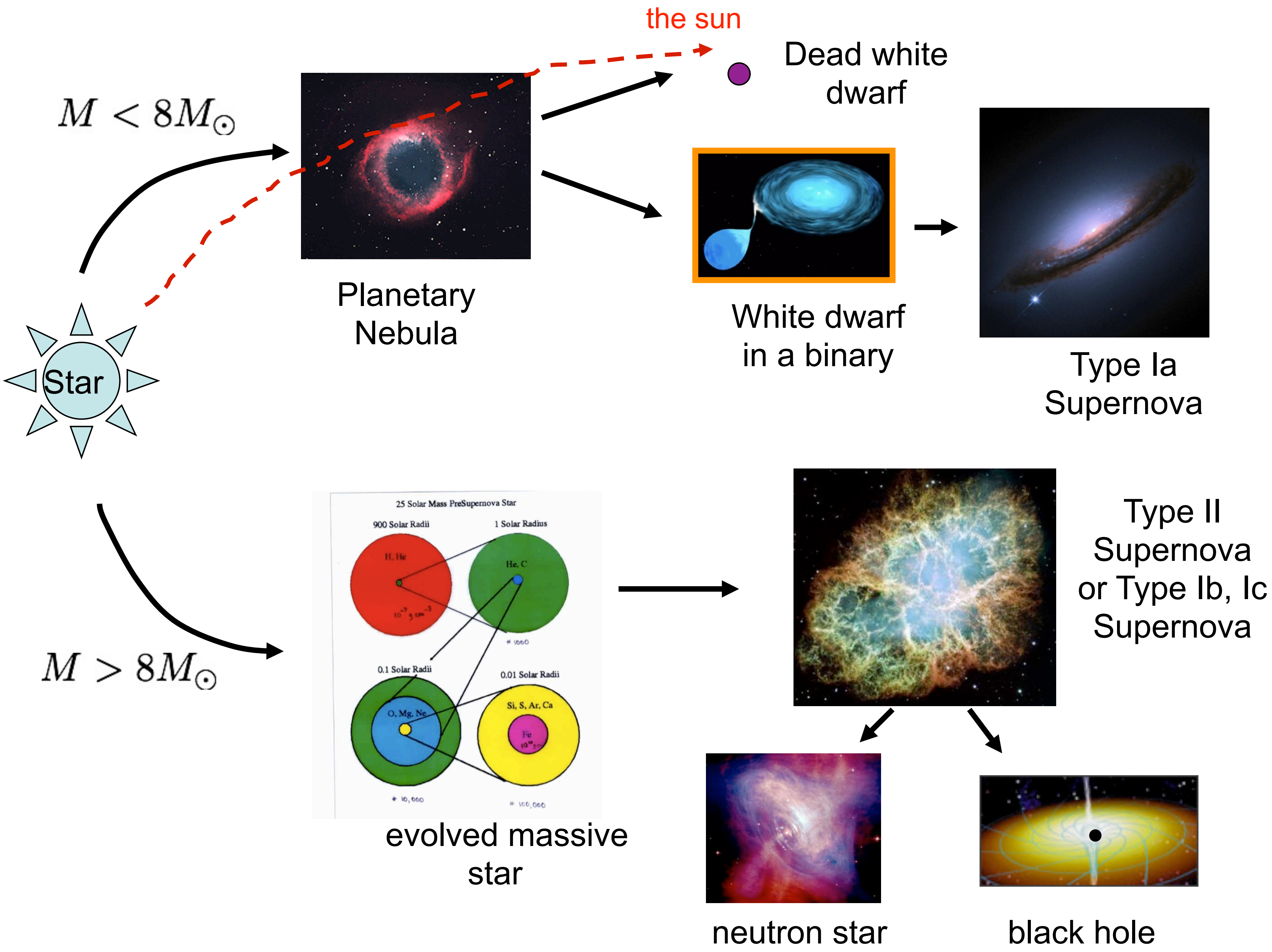
For several weeks a supernova's luminosity rivals that of a large galaxy.

Supernovae are named for the year in
which they occur + A .. Z, aa – az,
ba – bz, ca – cz, etc
Currently at SN 2014R

SPECTROSCOPICALLY

Type II SN has hydrogen (H_α). Type I does not.





Star

$M < 8M_\odot$

the sun

Planetary Nebula

Dead white dwarf

White dwarf in a binary

Type Ia Supernova

$M > 8M_\odot$

evolved massive star

Type II Supernova or Type Ib, Ic Supernova

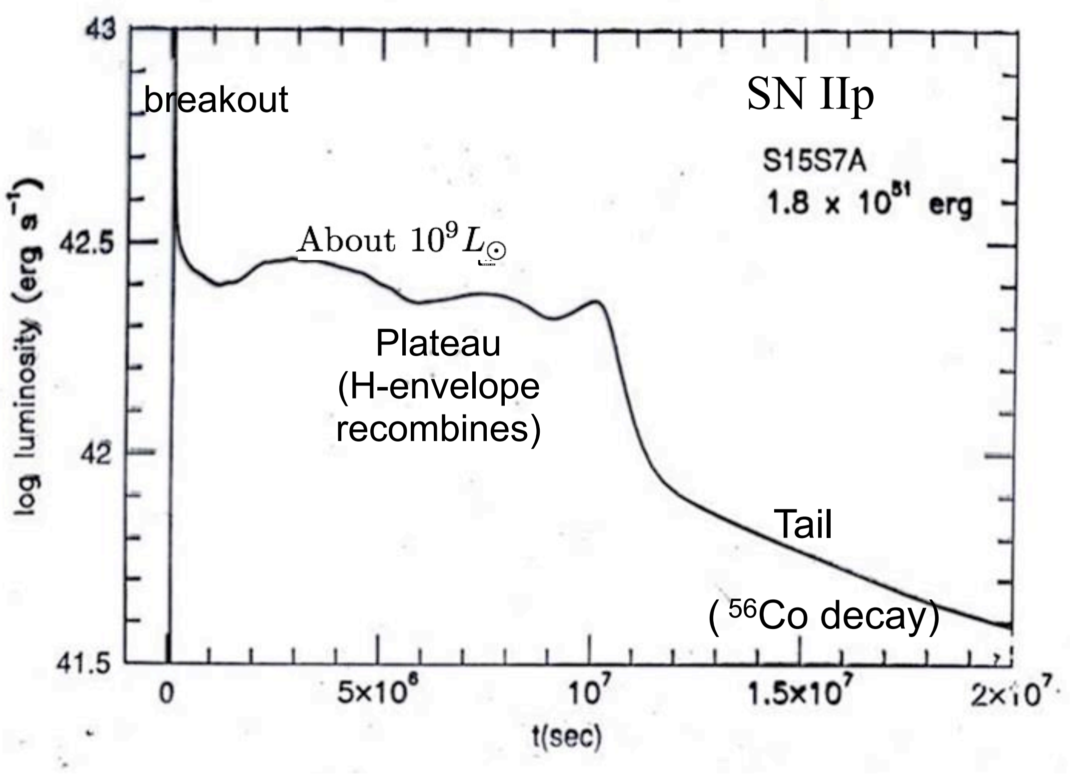
neutron star

black hole

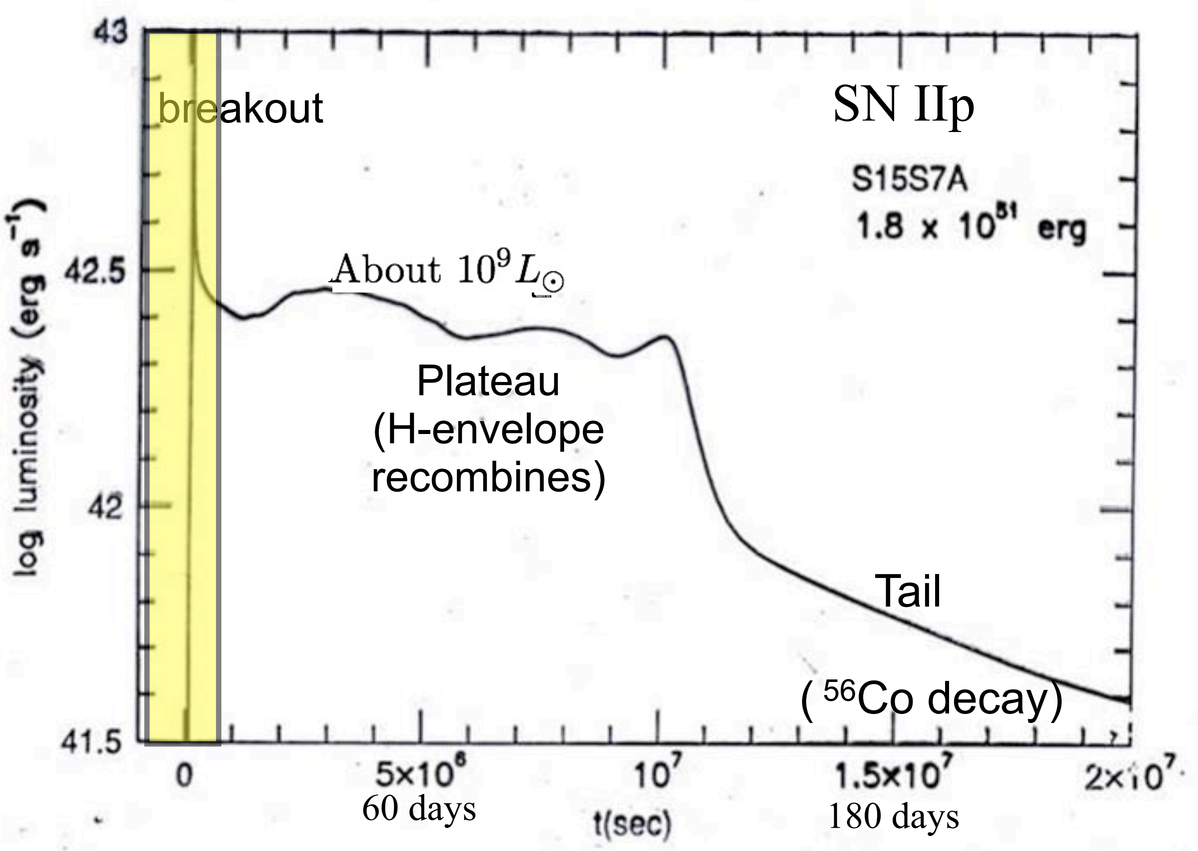
Light Curve of Type IIp Supernovae

- The most common kind of supernova. Death of a massive star that still has its hydrogen envelope. The star is a red (usually) or blue (rarely) supergiant when it dies.

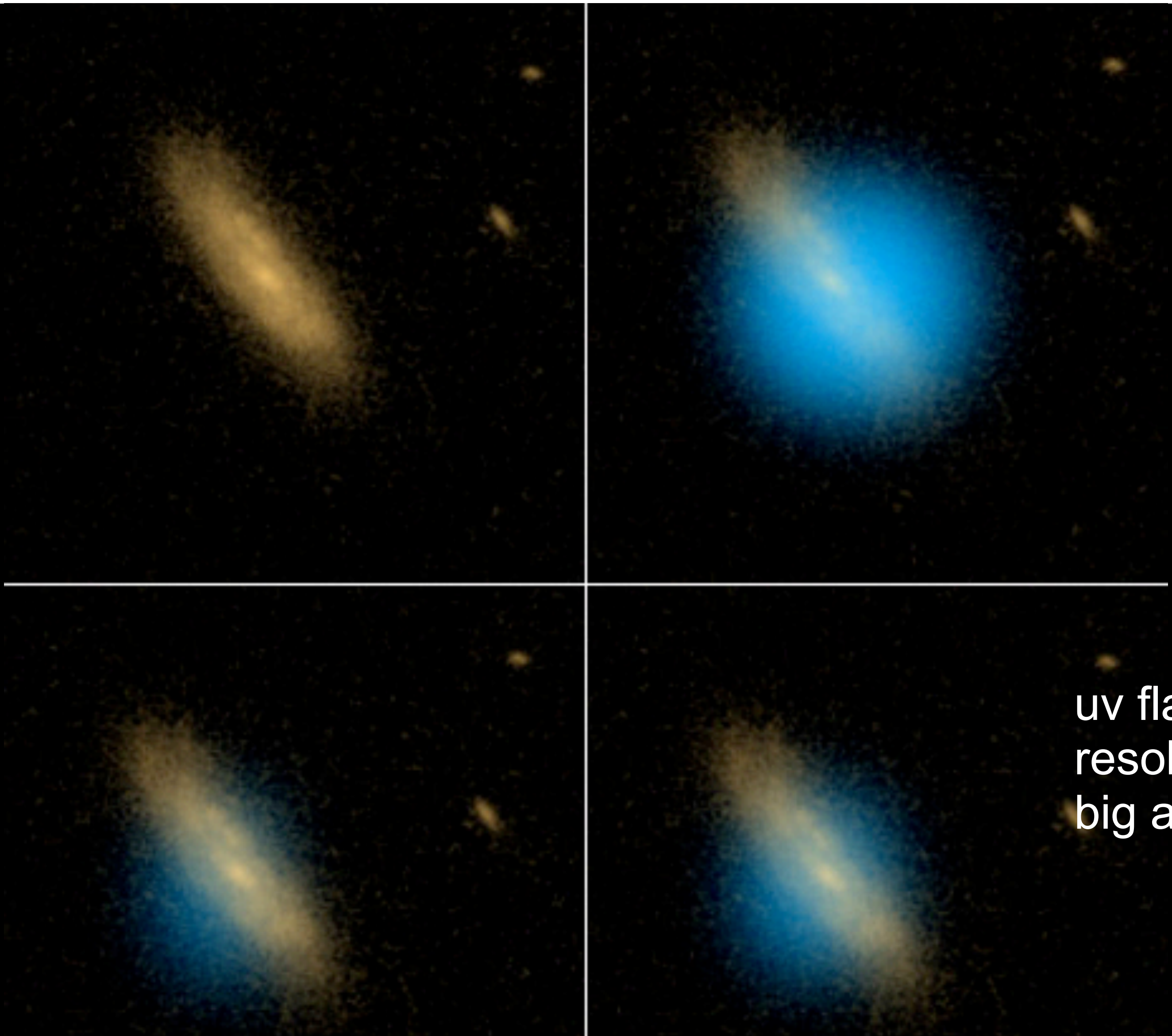
- There are three stages – shock breakout, the "plateau", and the decline (or tail).



Theoretical light curve of a Type IIp supernova



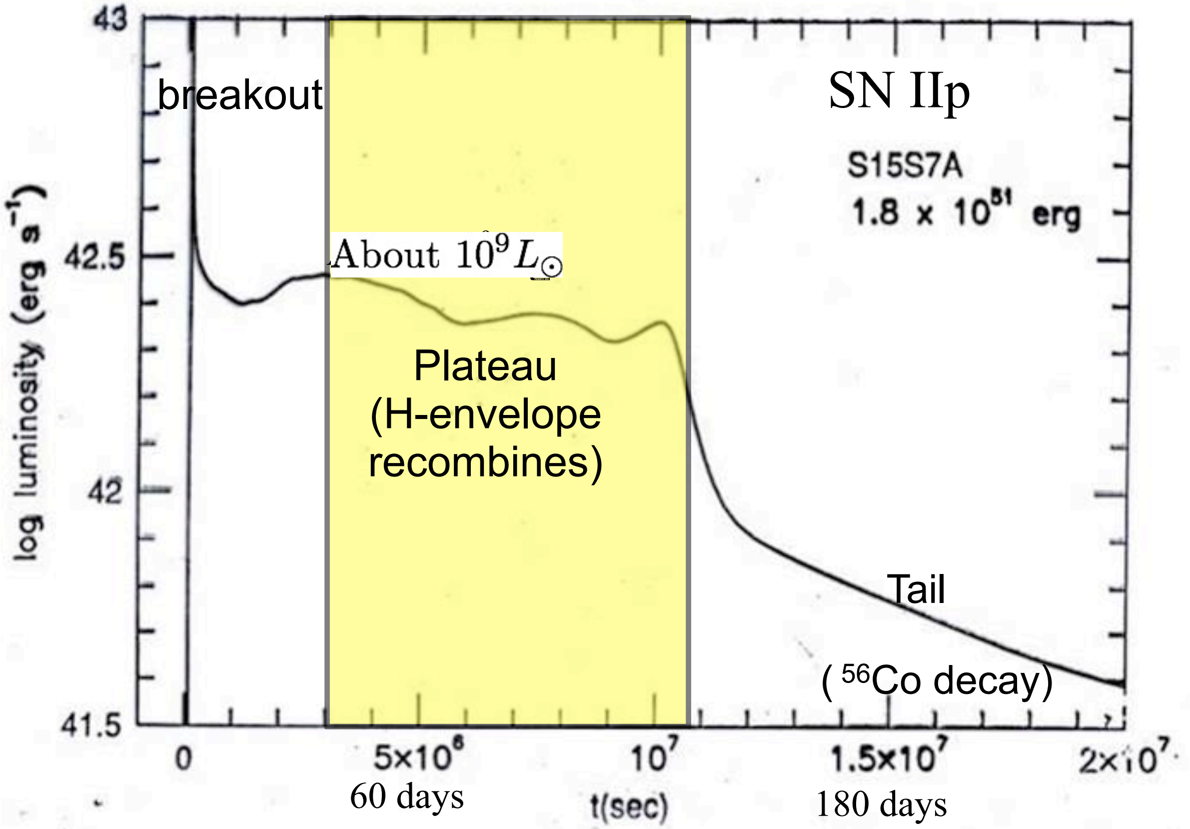
- Breakout is the first time the supernova brightens. The shock wave erupts from the surface heating it to about 200,000 K for about 2000 s. It declines to 30,000 K after one day. Meanwhile the luminosity declines from about 10^{11} solar luminosities to about 10^9 solar luminosities. This emission, in UV, has been seen in at least two supernovae less than one day after their explosion (Gezzari et al 2008)



uv flash poorly
resolved - not as
big as galaxy!

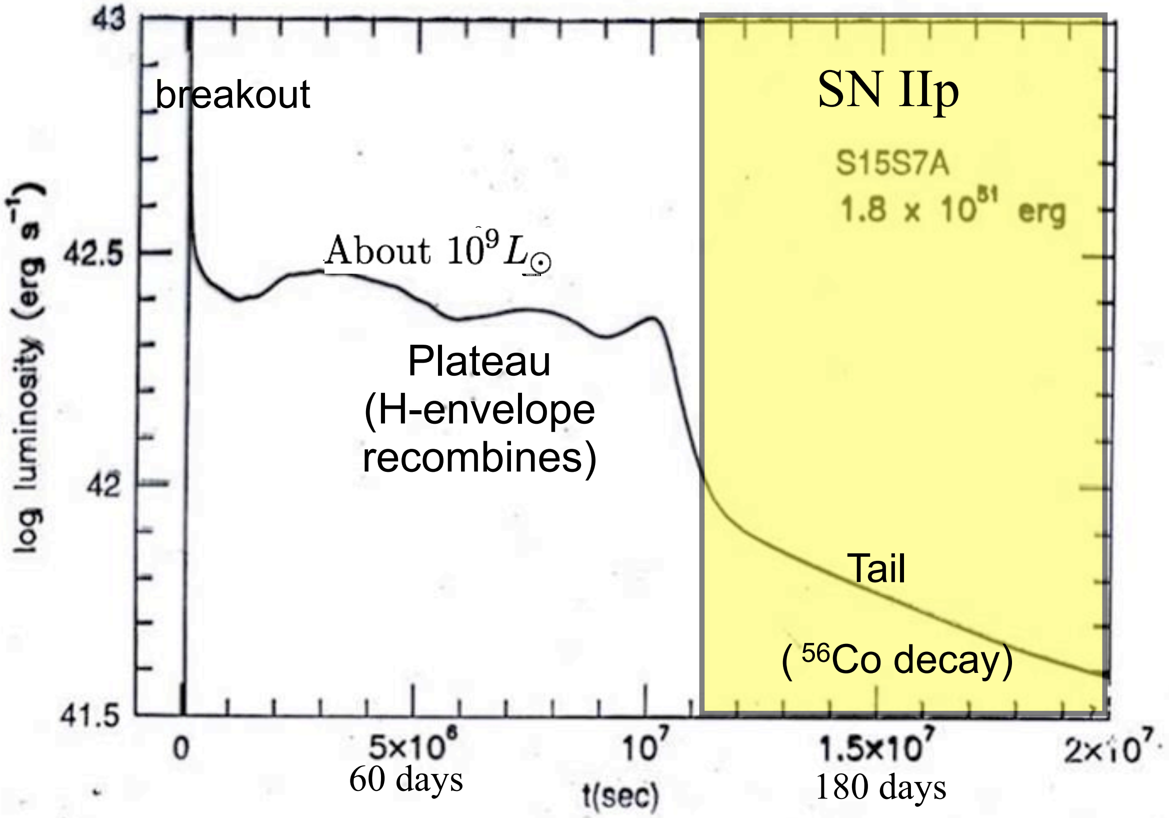
A sequence of ultraviolet images released in June 2008 shows shock break out. Just before the explosion, the host galaxy (top left) appears relatively quiet. Then a bright ultraviolet flash signals the onset of the supernova

Light Curve of Type IIp Supernovae (cont'd)



- As the hydrogen envelope expands and cools, it eventually reaches 5500 K where the hydrogen starts to recombine. This recombination moves into the expanding envelope as a wave over a period of about 3 months. The recombination reduces the opacity and lets out the energy deposited by the shock as it passed through the envelope. This is the plateau. The temperature stays pegged to 5500 K.

Light Curve of Type IIp Supernovae (cont'd)



- Still later the decay of radioactive nuclei produced in the supernova keeps it bright for years.

$$^{56}\mathrm{Ni} + e^- \rightarrow {}^{56}\mathrm{Co} + \nu_e + \gamma \quad (6.1\ \mathrm{days})$$

$$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe} + \nu_e + \gamma \quad (77\ \mathrm{days})$$

Together these reactions release 9.4 x 10^{16} erg g^{-1}. Thus 0.1 solar masses of ^{56}Ni releases 2 x 10^{49} erg.

Type IIp Supernovae (cont'd)

- The spectrum is dominated by the Balmer lines of hydrogen. On the plateau the spectrum is dominantly absorption lines, but at late time as the supernova becomes a nebula, one sees emission lines
- Radii inferred on the plateau are about 10^{15}cm (100 AU). The emission resembles a blackbody with T_{eff} approximately 5500 K
- Type II supernovae always leave behind either a neutron star or a black hole. In many instances the neutron star is a "pulsar".

Supernovae - General

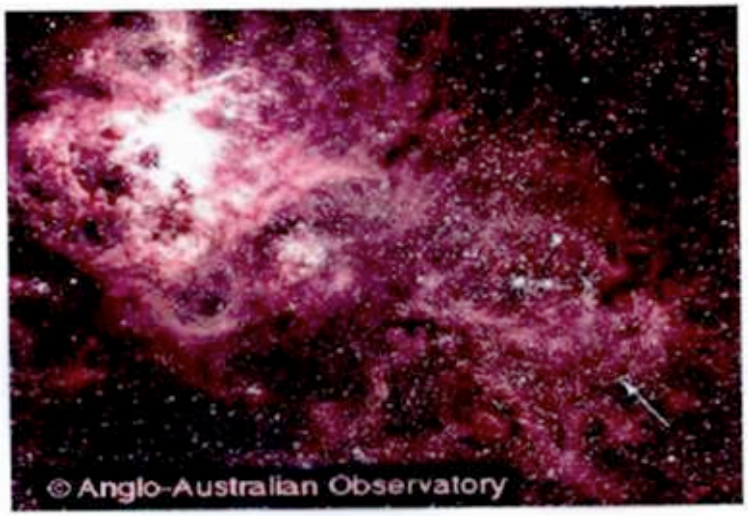
- In a Type II or Ibc supernova most of the energy comes out in the neutrino burst – 3 x 10^{53} erg. 300 times less is in the kinetic energy of the explosion – 10^{51} erg – and 100 times less than that, 10^{49} erg, is in the light. Bright as they are the electromagnetic radiation emitted by a supernova is a small part of its energy budget.

- The kinetic energy and total light output of SN II and SN I of all subtypes are comparable (though SN Ia are brighter), but a SN Ia emits no neutrino burst.

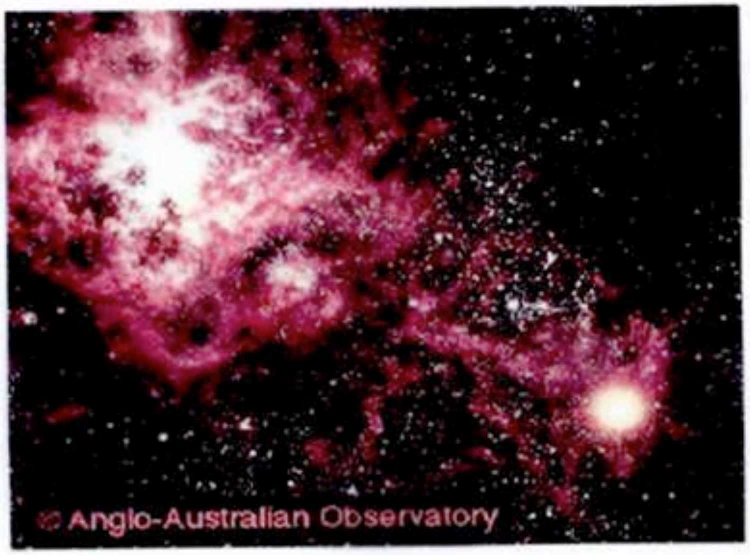
- The velocities of supernova ejecta typically range from 2000 to 20,000 km $s^{-1.}$ The highest velocities are seen early on. Type I supernovae expand faster than Type II.

Supernova 1987A A Type II supernova

before



after



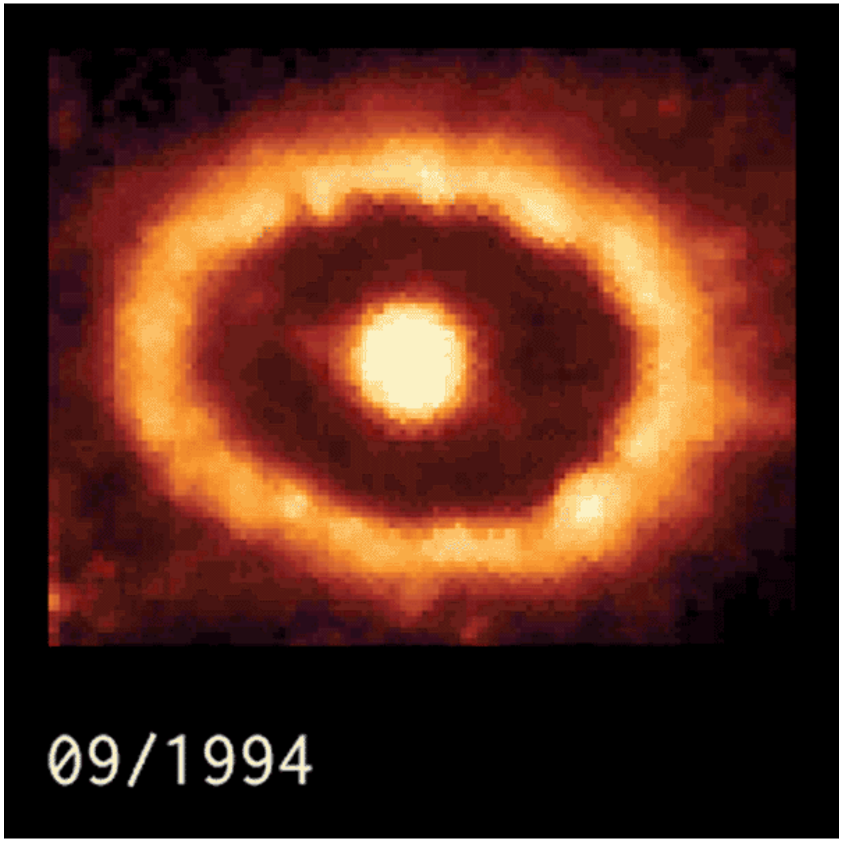
February 23, 1987
(+160,000 years)

Brightest supernova in over 400 years.

In the 30 Doradus H II region in the Large Magellanic Cloud.

Progenitor star was a previously catalogued blue supergiant Sk 202-69. Mass = 18 solar masses.

SN 1987A   Today


09/1994

A time sequence of Hubble Space Telescope images, showing the collision of the expanding supernova remnant with a ring of dense material ejected by the progenitor star 20,000 years before the supernova.

Type I Supernovae

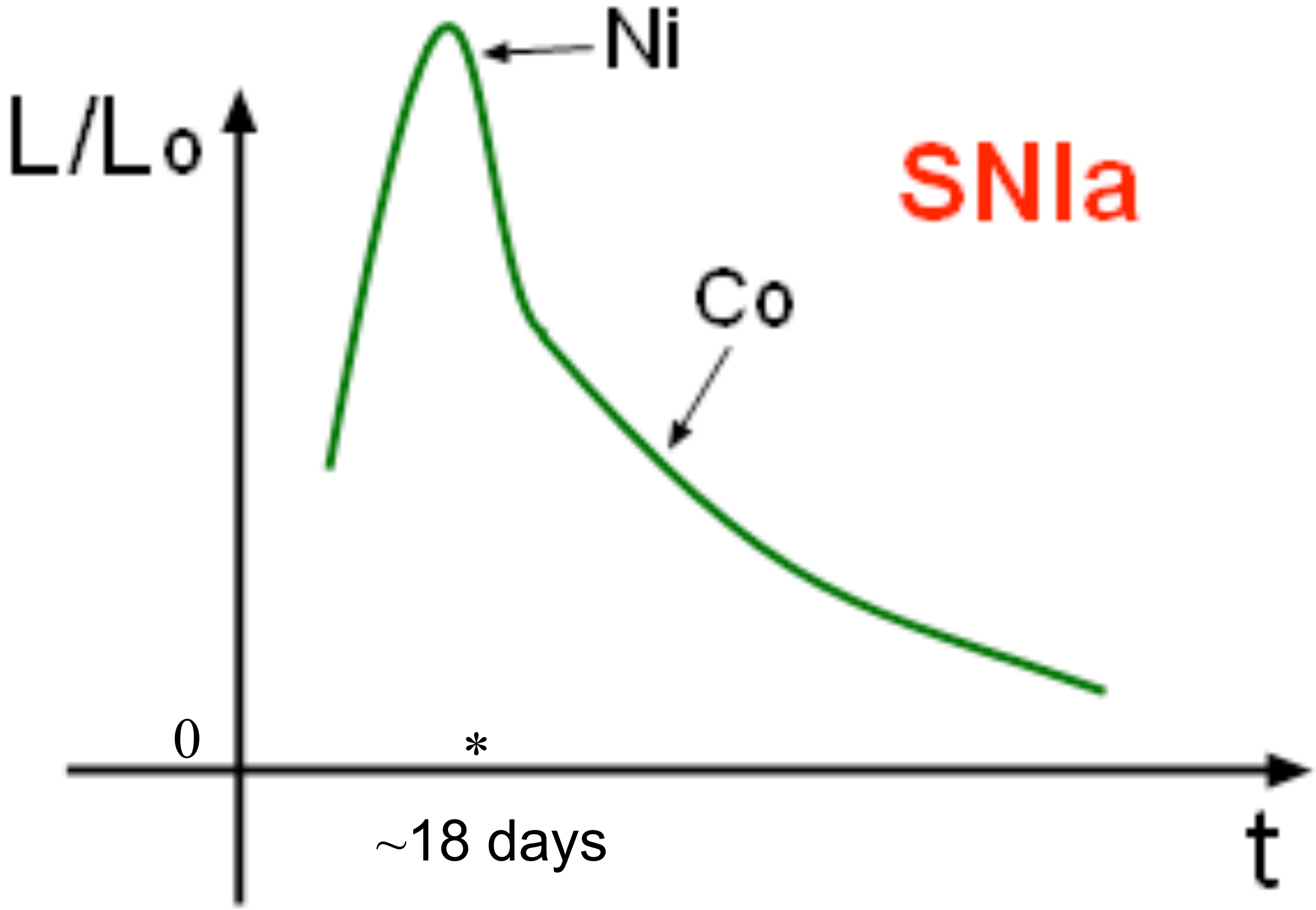
- Type I supernovae lack hydrogen and thus have no plateau stage. The shock break out is also considerably fainter and shorter in wavelength (x-rays)

- The Type I supernova light curve is thus powered at all times by the decay of radioactive ^{56}Ni and ^{56}Co.

- Type I supernovae are segregated into several classes: Type Ia, Ib, and Ic depending upon special features in their spectra (Si II, He I) and where they are found.

- Type Ib and Ic are caused by the death of a massive star, but one that has lost its envelope – most of the time to a binary companion. Type IIp and Ib/c are found in star-forming regions.

Type Ia Supernova Light Curve



Type I Supernovae (cont'd)

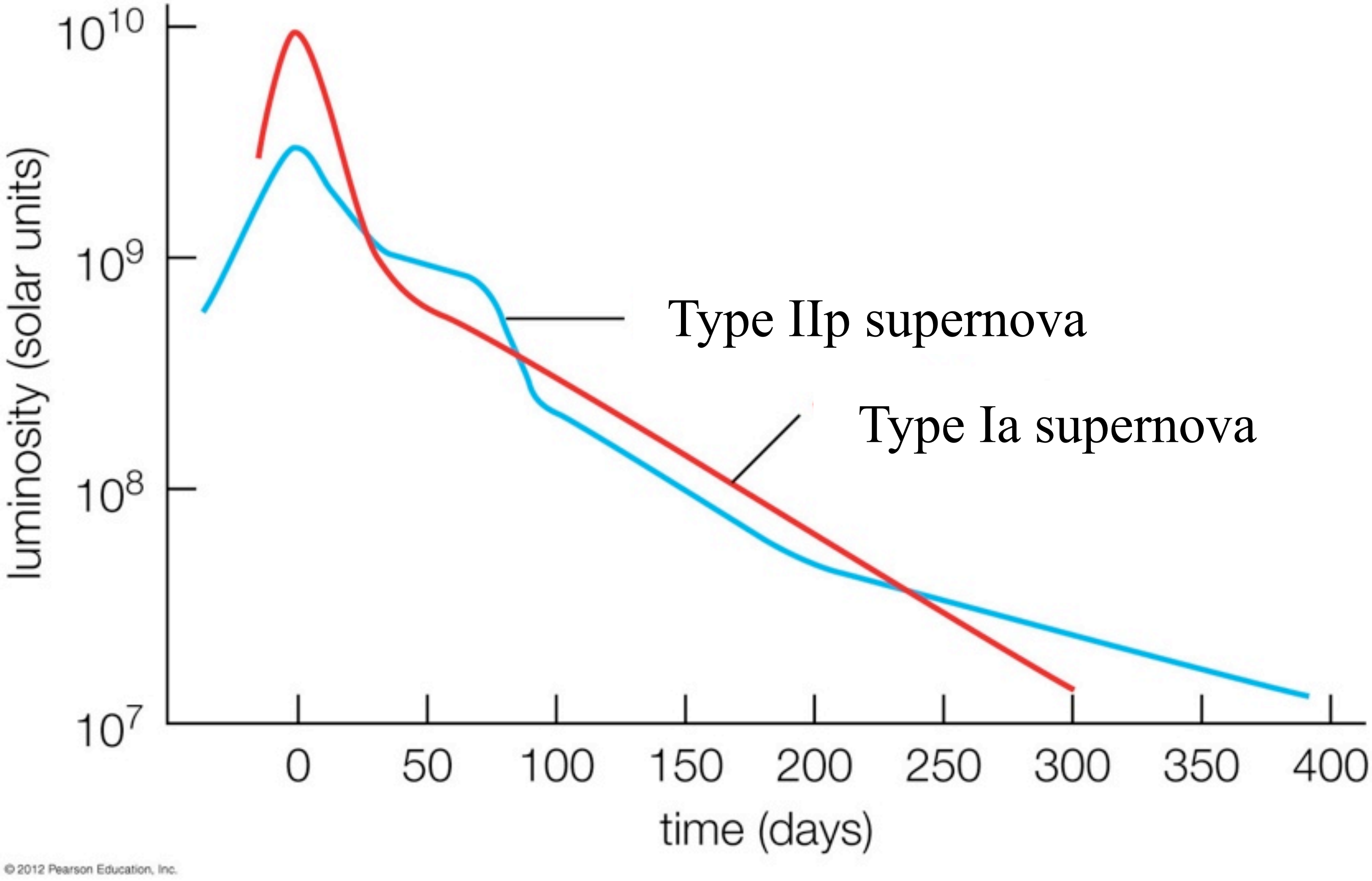
- Type Ia supernovae are **not** found in star forming regions. They show no preference for spiral arms and can occur in elliptical galaxies where the star formation rate is very low

- While the progenitor stars of about 10 Type II supernovae have been seen before they exploded (e.g. 1987A), no progenitor of a SN Ia has ever been identified. They must be faint

- Type Ia supernovae are brighter than any other class. Type I supernovae in general are bright a shorter time than SN IIp (weeks rather than months)

- Neutron stars and black holes may be produced by Type Ib and Ic supernovae, but never by Type Ia.

Comparison of light curves



Supernova

(Death of a star)

Type Ia

- No hydrogen
- Thermonuclear explosion of a white dwarf star
- No bound remnant
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 5{,}000 - 30{,}000$ km s^{-1}
- No neutrino burst
- $E_{optical} \sim 10^{49}$ erg
- $L_{peak} \sim 10^{43}$ erg s^{-1} for 2 weeks
- Radioactive peak and tail (^{56}Ni, ^{56}Co)
- 1 every 200 yr in our Galaxy
- Makes about 2/3 of the iron in the Galaxy

Type II

- Hydrogen in spectrum
- $M > 8$ solar masses
- Iron core collapses to a neutron star or black hole
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 2{,}000 - 30{,}000$ km s^{-1}
- Neutrino burst $\sim 3 \times 10^{53}$ erg
- $E_{optical} \sim 10^{49}$ erg
- $L_{peak} \sim 3 \times 10^{42}$ erg s^{-1} for about 3 months (varies from event to event)
- Radioactive tail (^{56}Co)
- 2 every 100 yr in our Galaxy
- Makes about 1/3 iron and all the oxygen plus many other elements

There are also Type Ib and Ic supernovae that share many of the properties of Type II but have no hydrogen in their spectra

Supernovae - General

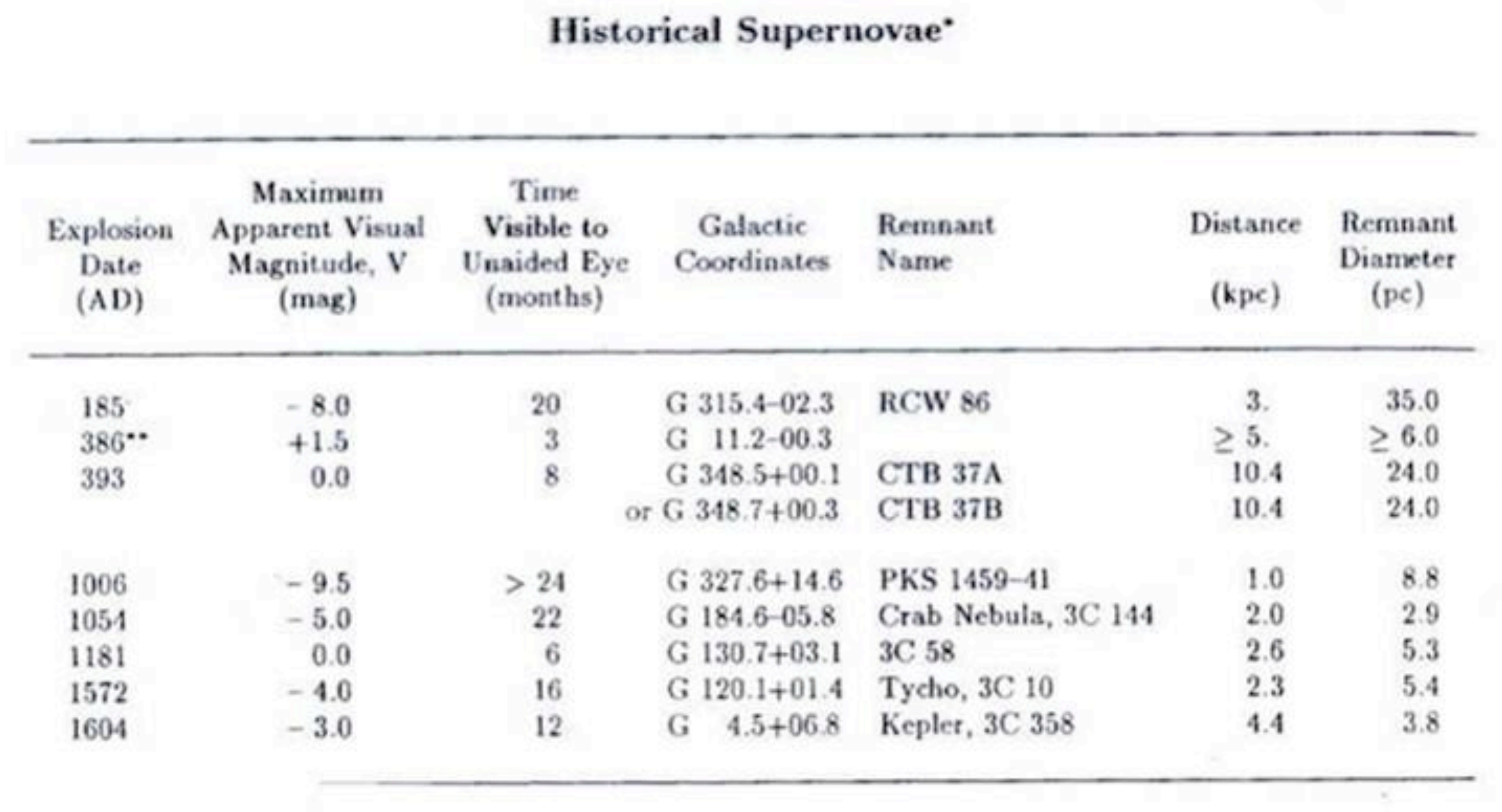
- There have been 6 supernovae visible to the unaided eye in the last 1000 years. The last one before SN 1987A was Kepler’s supernova in 1604. This was about 2.5 kpc away and reached a magnitude of -2.5. The brightest supernova in history was SN 1006 which reached magnitude -8 to -10, as bright as a quarter moon.

- About two Type II supernovae are thought to occur in our galaxy every century and about one Type Ia every other century. Most have gone undetected.

- We see many more supernovae – hundreds each year – in other galaxies

- Supernovae have produced most of the elements heavier than nitrogen

Year	Report	Status
185 A.D.	Chinese	Identification in doubt (Chin and Huang 1994)
386	Chinese	unknown
393	Chinese	unknown
1006	China, Japan, Korea, Arab lands, Europe	Identified with radio SNR
1054	China, Japan	Crab Nebula
1181	China, Japan	Possible identification with radio SNR 3C58
1572	Europe (Tycho Brahe), China, Japan	Tycho's remnant
1604	Europe (Kepler), China, Japan, Korea	Kepler's remnant



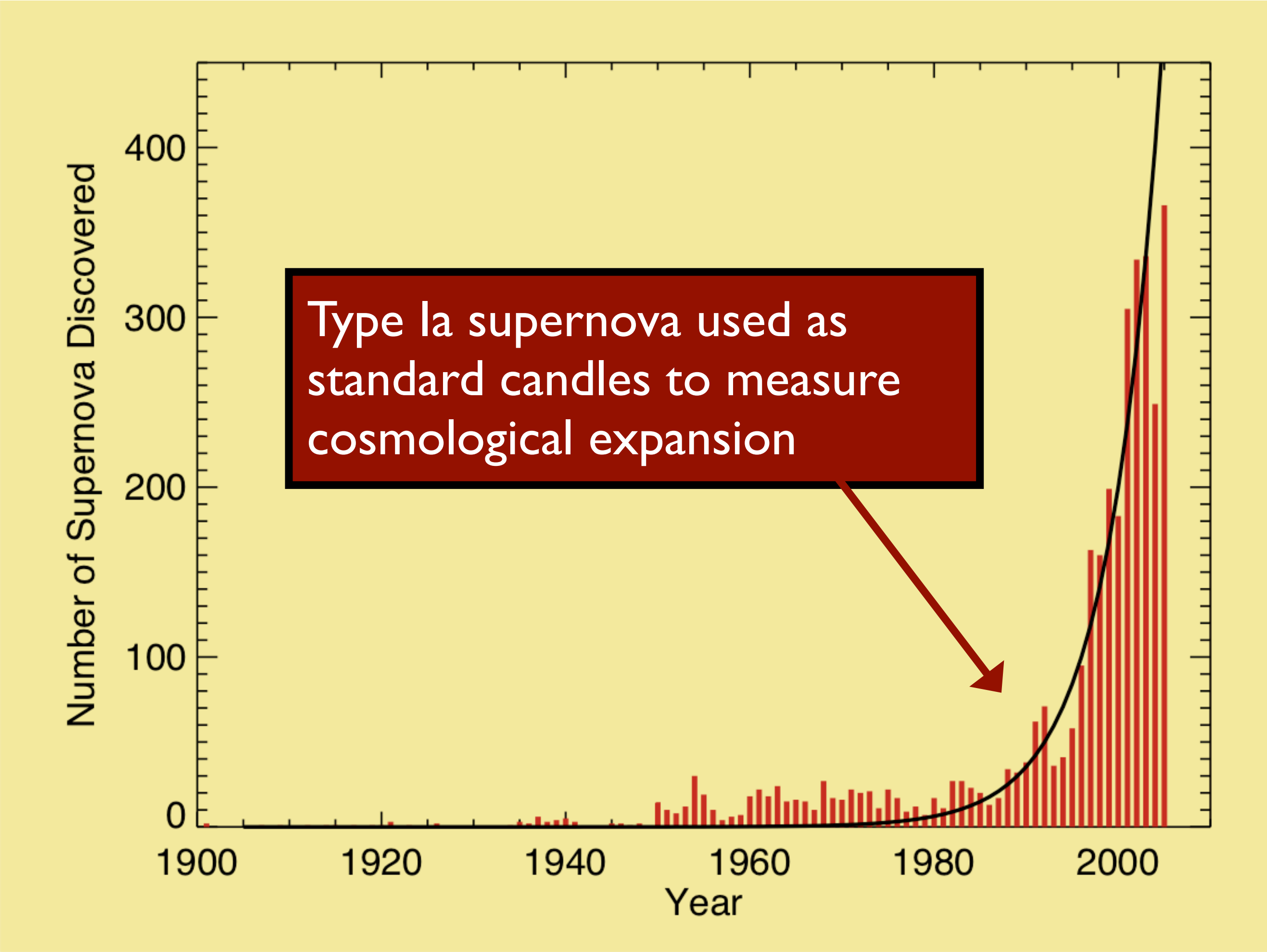
Historical Supernovae*

Explosion Date (AD)	Maximum Apparent Visual Magnitude, V (mag)	Time Visible to Unaided Eye (months)	Galactic Coordinates	Remnant Name	Distance (kpc)	Remnant Diameter (pc)
185	− 8.0	20	G 315.4−02.3	RCW 86	3.	35.0
386**	+1.5	3	G 11.2−00.3		≥ 5.	≥ 6.0
393	0.0	8	G 348.5+00.1	CTB 37A	10.4	24.0
			or G 348.7+00.3	CTB 37B	10.4	24.0
1006	− 9.5	> 24	G 327.6+14.6	PKS 1459−41	1.0	8.8
1054	− 5.0	22	G 184.6−05.8	Crab Nebula, 3C 144	2.0	2.9
1181	0.0	6	G 130.7+03.1	3C 58	2.6	5.3
1572	− 4.0	16	G 120.1+01.4	Tycho, 3C 10	2.3	5.4
1604	− 3.0	12	G 4.5+06.8	Kepler, 3C 358	4.4	3.8

1680 Cassiopeia-A

Supernova Discovery History

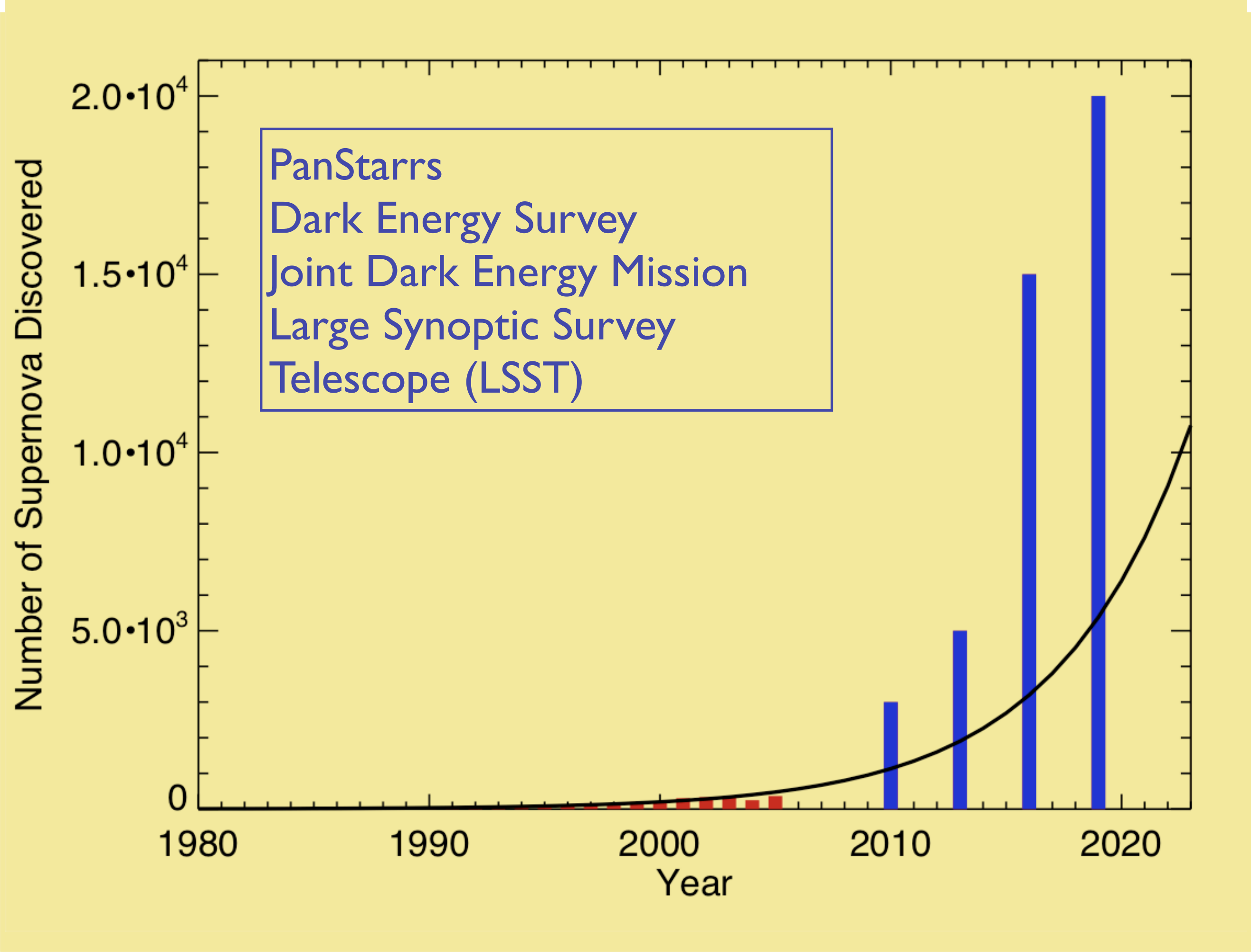
Asiago Catalog (all supernova types)



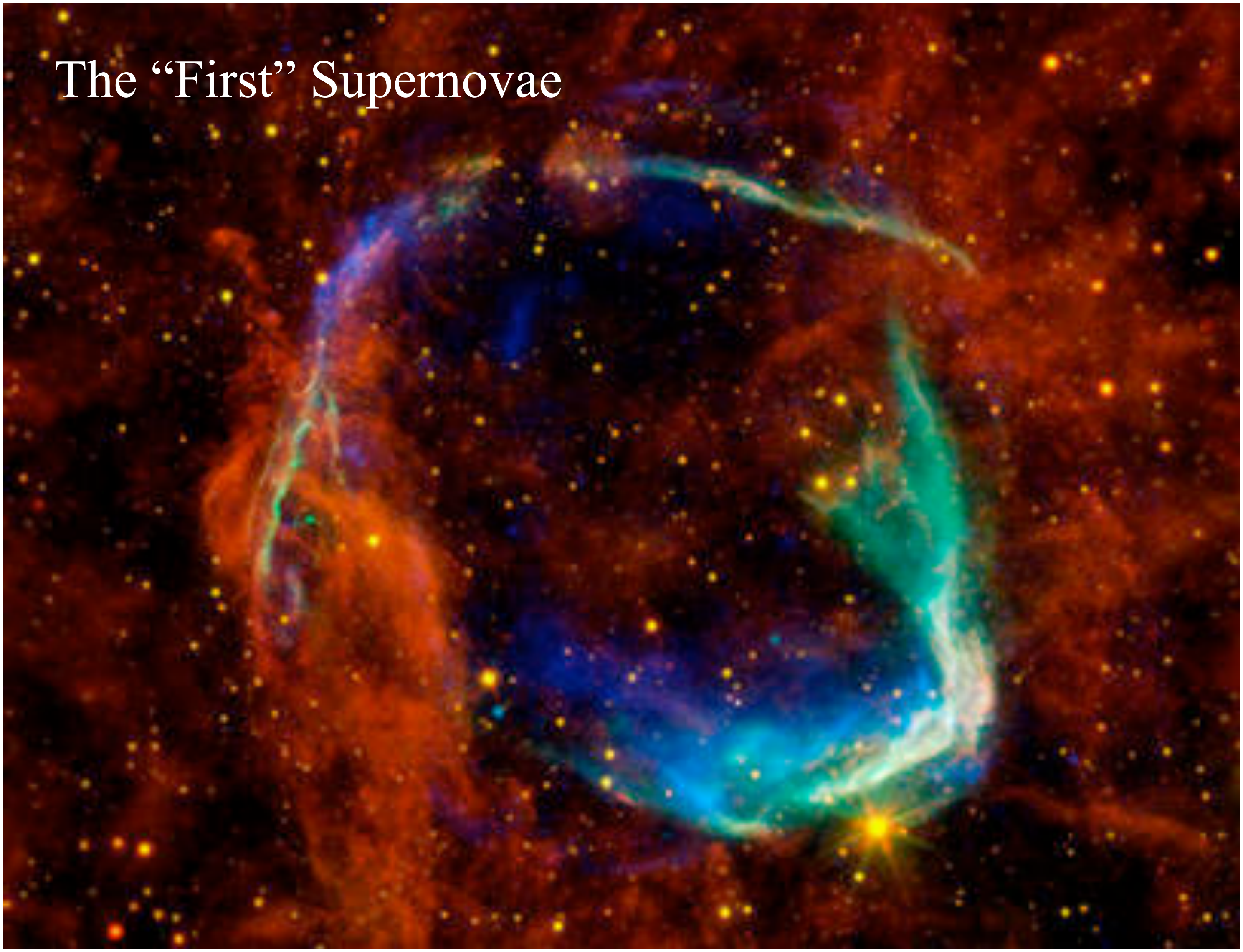
Type Ia supernova used as standard candles to measure cosmological expansion

Supernova Discovery Future

Rough predictions and promises…

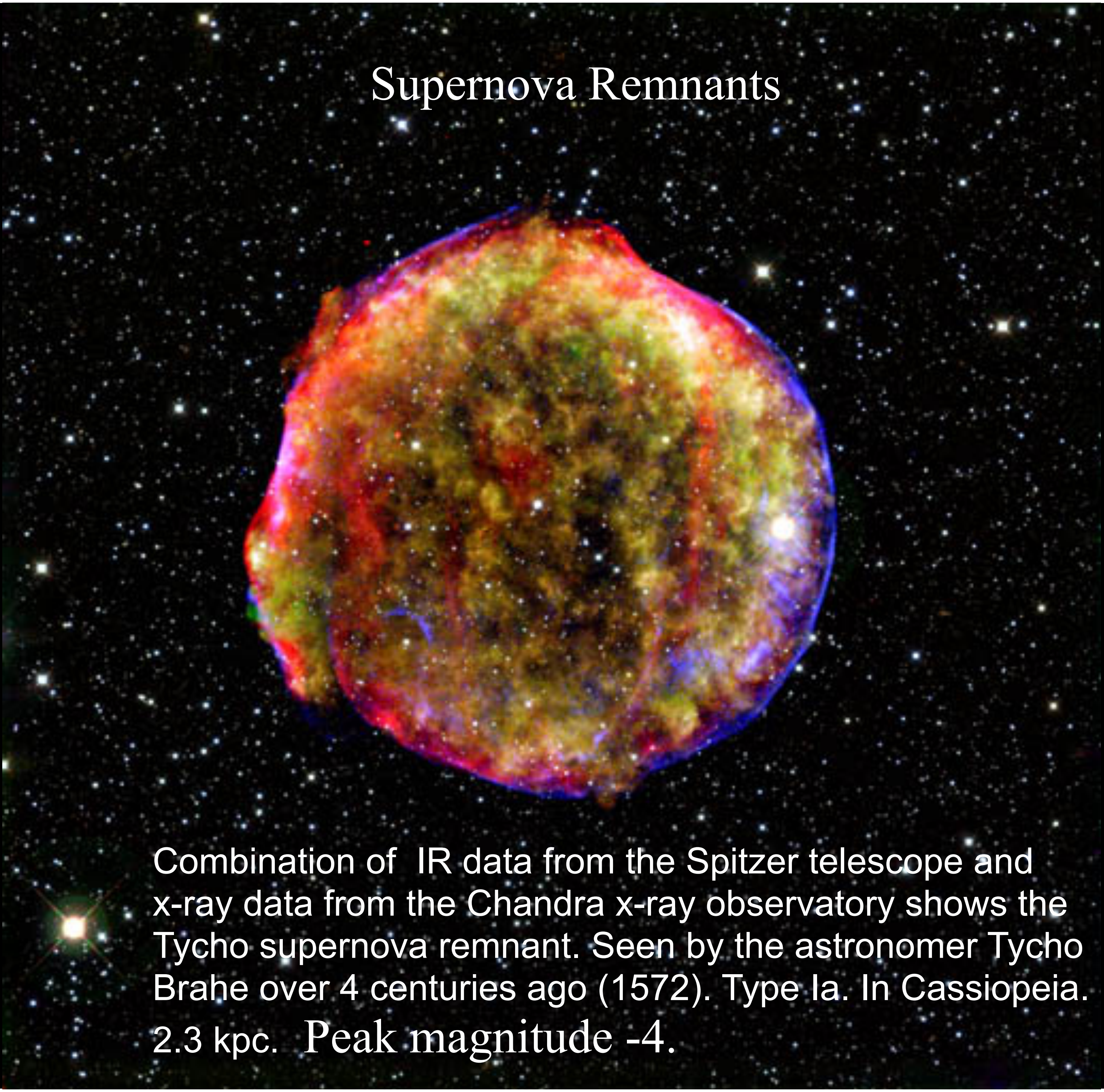


The “First” Supernovae

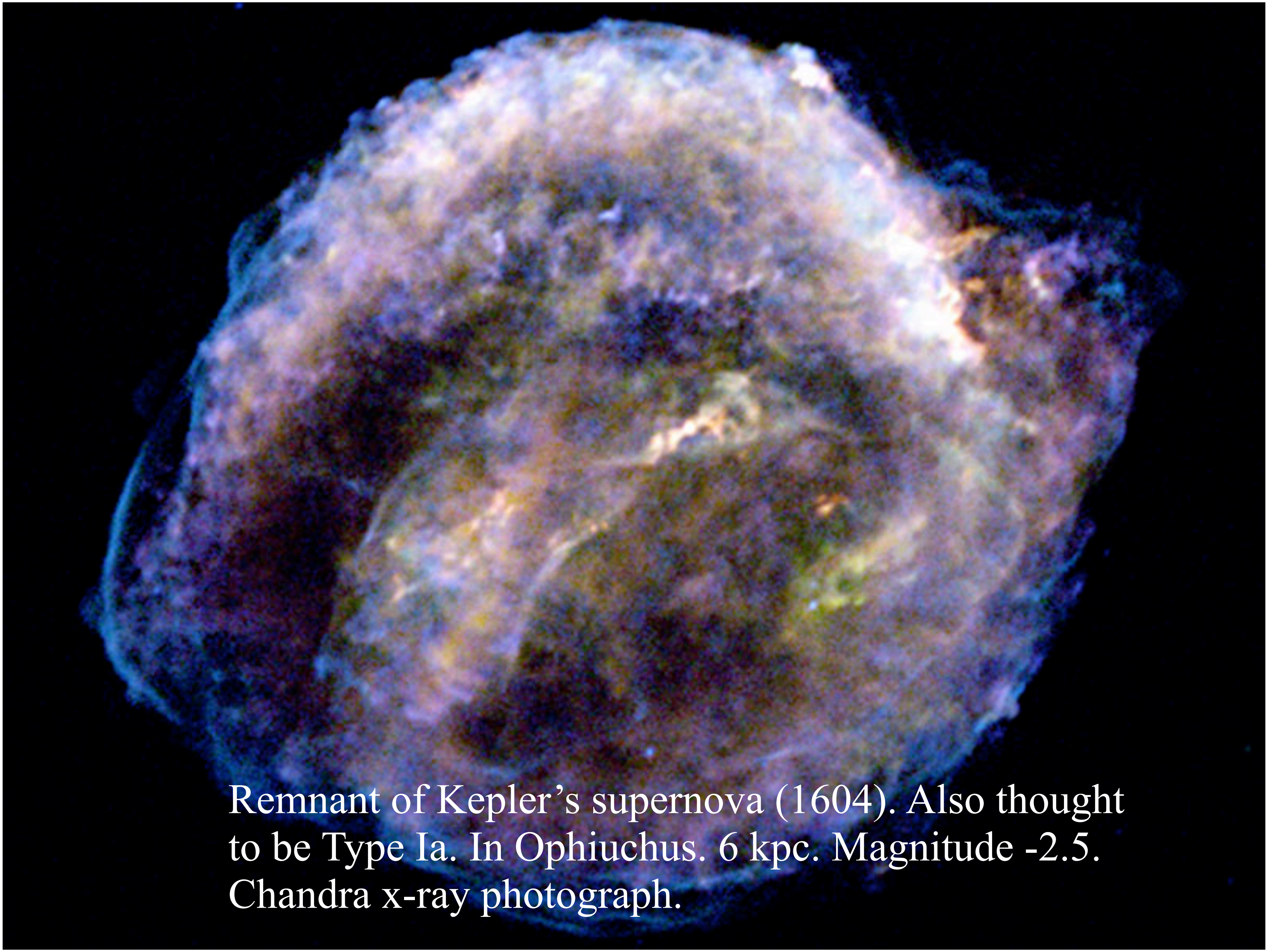


Oldest recorded supernova, RCW 86, first documented by the Chinese in December, 185 A.D. (WISE telescope – infrared)

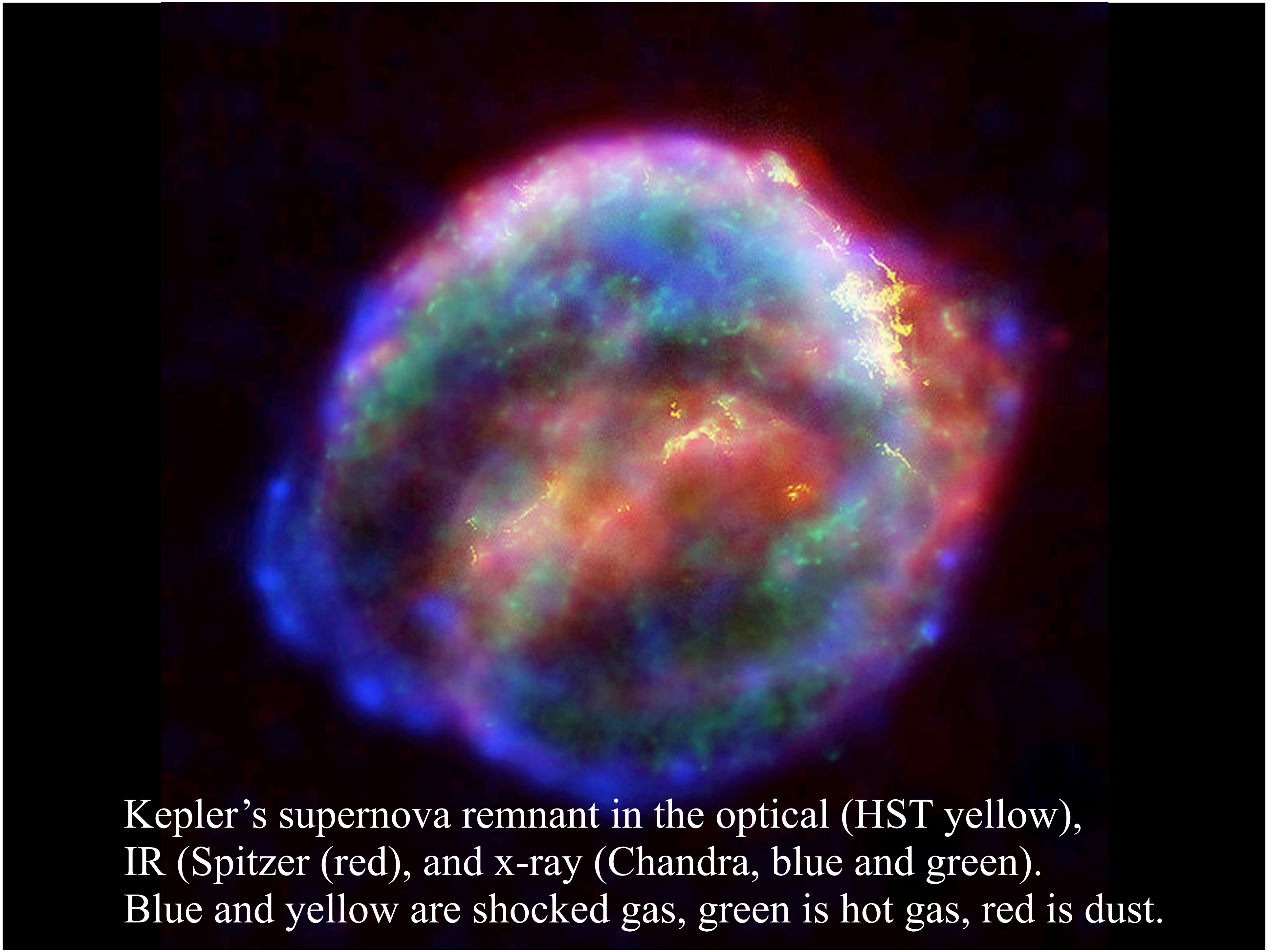
Supernova Remnants



Combination of IR data from the Spitzer telescope and x-ray data from the Chandra x-ray observatory shows the Tycho supernova remnant. Seen by the astronomer Tycho Brahe over 4 centuries ago (1572). Type Ia. In Cassiopeia. 2.3 kpc. Peak magnitude -4.

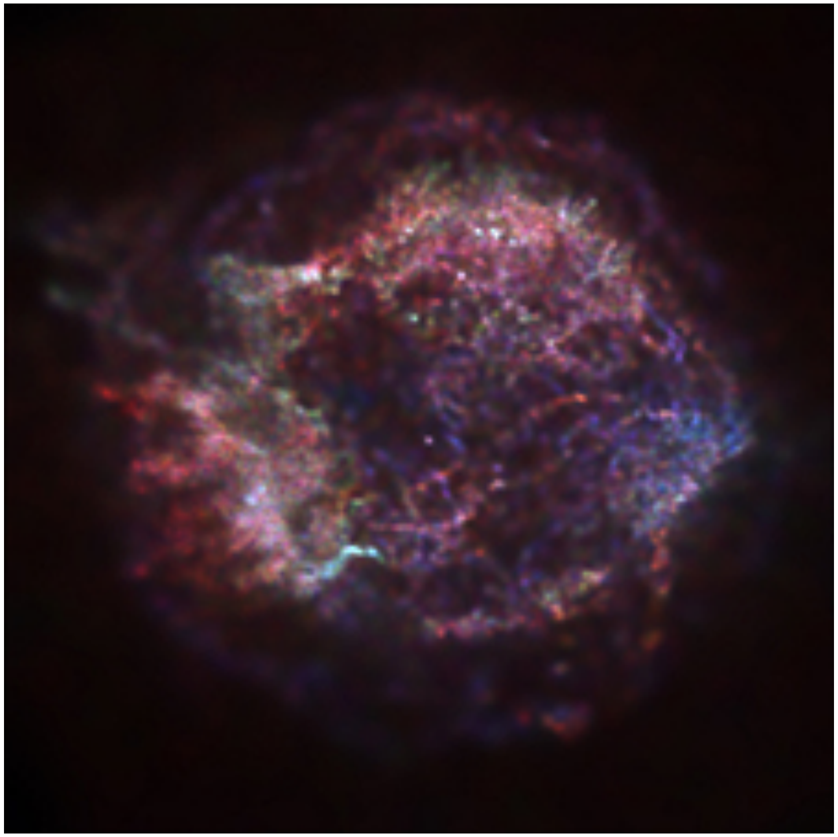


Remnant of Kepler’s supernova (1604). Also thought to be Type Ia. In Ophiuchus. 6 kpc. Magnitude -2.5. Chandra x-ray photograph.



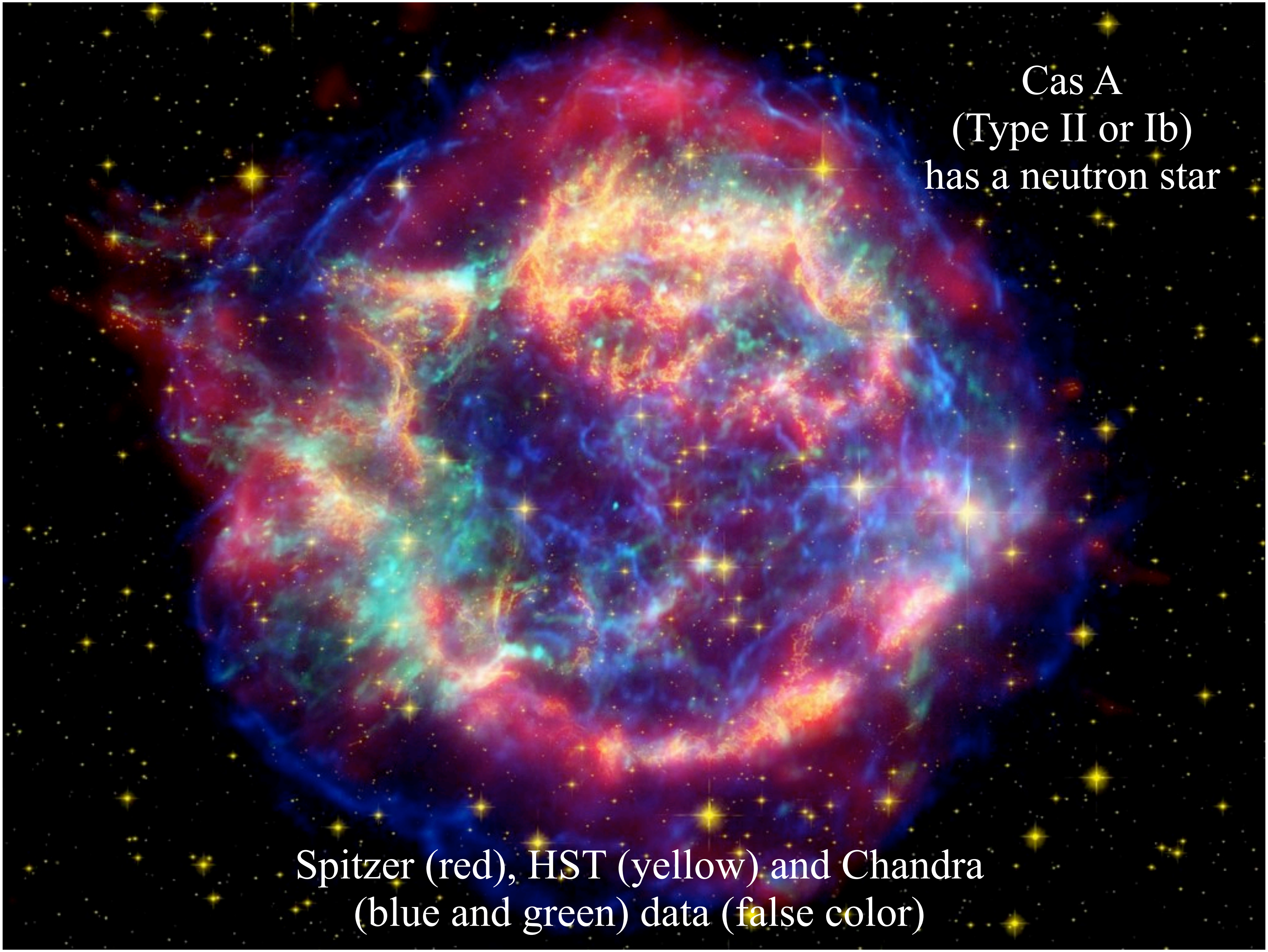
Kepler’s supernova remnant in the optical (HST yellow),
IR (Spitzer (red), and x-ray (Chandra, blue and green).
Blue and yellow are shocked gas, green is hot gas, red is dust.

http://chandra.harvard.edu/photo/



Last SN seen(?)
in our galaxy

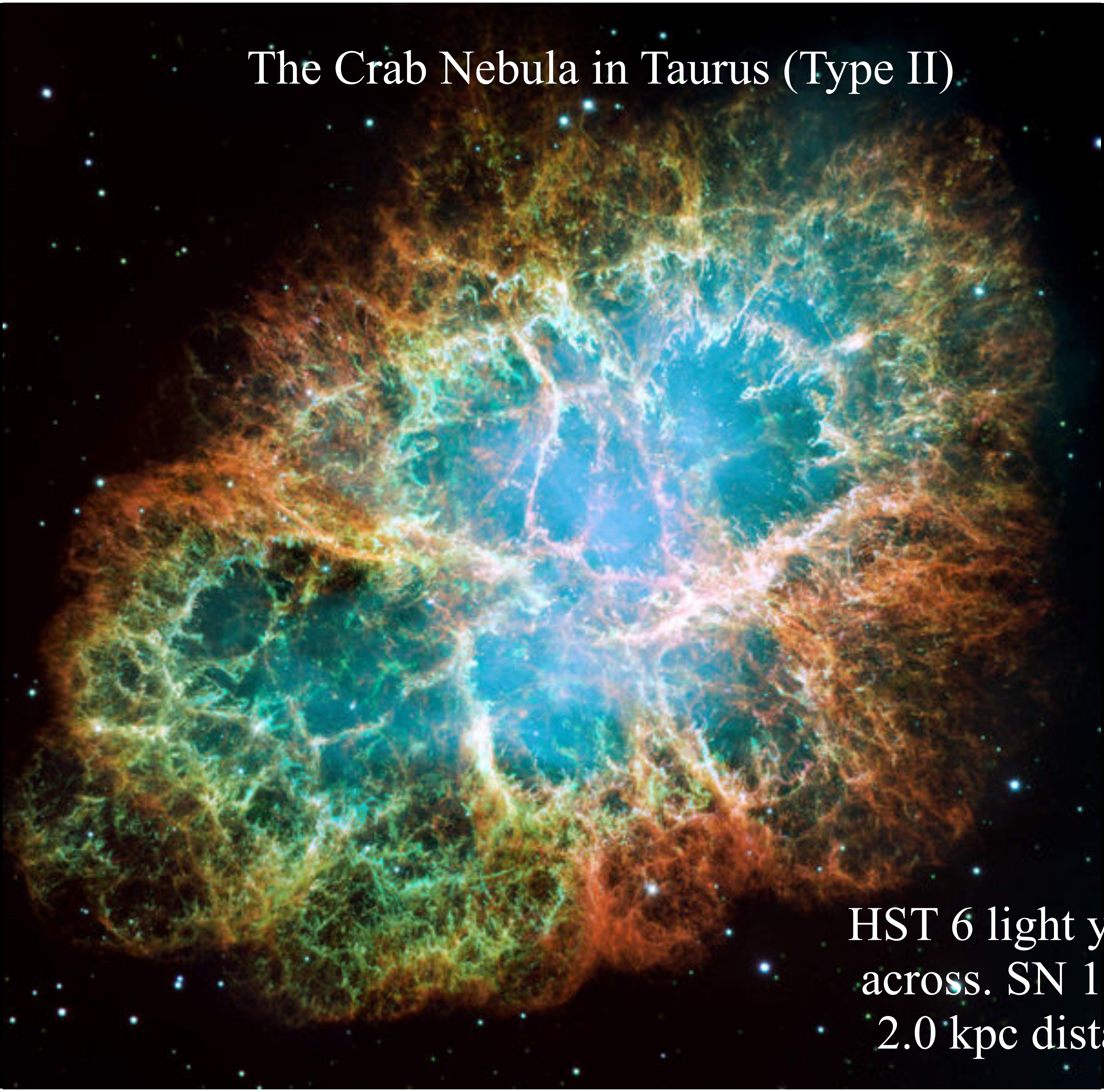
Cassiopeia A (*aka* Cas A) is the remnant of an optically faint supernova (about m = 6) perhaps observed by John Flamsteed in 1680. It is 3.4 kpc away and 10 ly in diameter. This is a color coded x-ray photo by the Chandra X-Ray Astronomy Observatory taken in 1999. Red is about 20 million K; blue about 30 million K. Spectroscopy shows prominent lines of Fe, Si, O, S. Fe knots are found near the left outer boundary despite having been synthesized near the center. Brightest knots are Si, S.



Cas A
(Type II or Ib)
has a neutron star

Spitzer (red), HST (yellow) and Chandra (blue and green) data (false color)

The Crab Nebula in Taurus (Type II)



HST 6 light years
across. SN 1054
2.0 kpc distant

SN 1054 (The Crab)

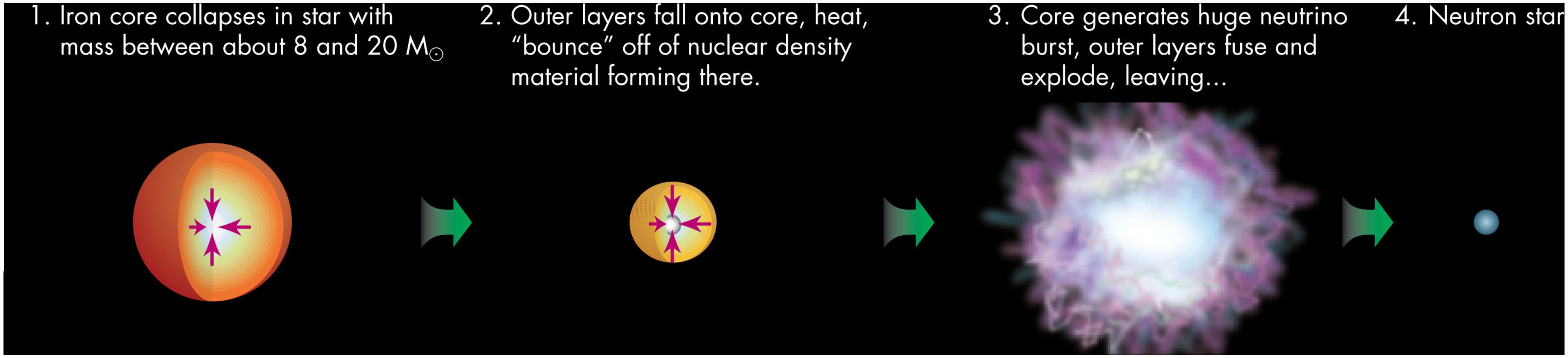
- Well observed by Chinese astronomers
- Bright enough to be seen in daylight for 23 days.
  Bright enough to cast a shadow.
- Visible in the night sky for 653 days
- 6300 ly distant
- May also have been seen by Anasazi and Irish.
  No conclusive European sightings (“Dark Ages”).
  Maybe records were lost.

Pulsars and Neutron Stars

A neutron star is the remnant core of a high-mass star.

Recall that a NS is formed from the collapsed core of a high-mass star.

A NS is essentially a giant ball of neutrons supported by <u>neutron degeneracy pressure</u>.



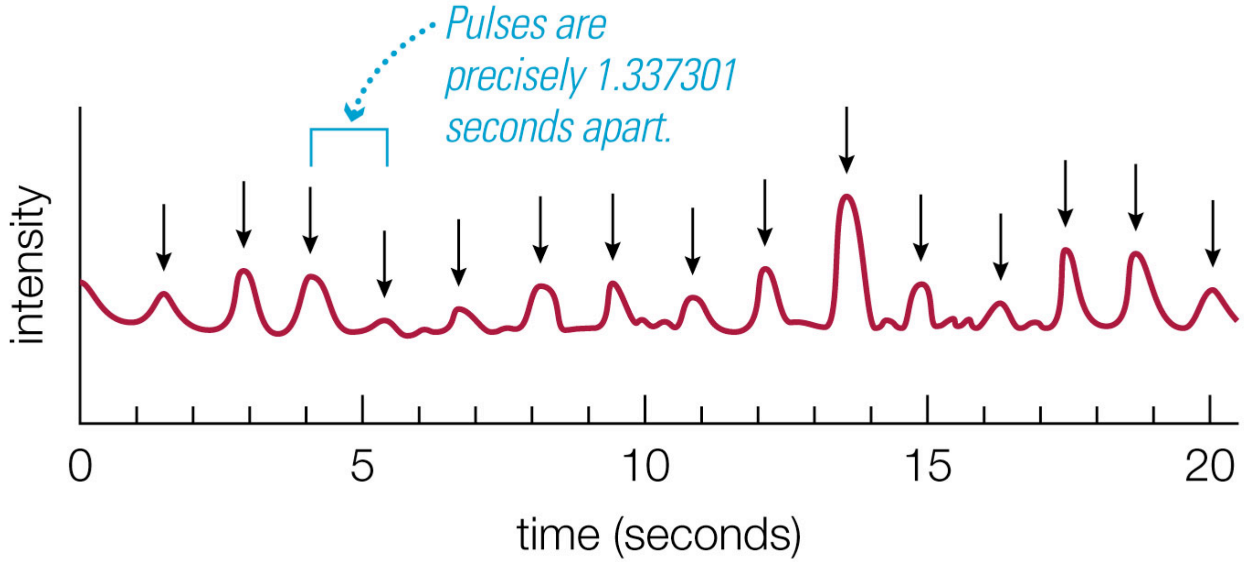
1. Iron core collapses in star with mass between about 8 and 20 $M_\odot$
2. Outer layers fall onto core, heat, "bounce" off of nuclear density material forming there.
3. Core generates huge neutrino burst, outer layers fuse and explode, leaving...
4. Neutron star

Neutron stars were discovered by their radio emission.

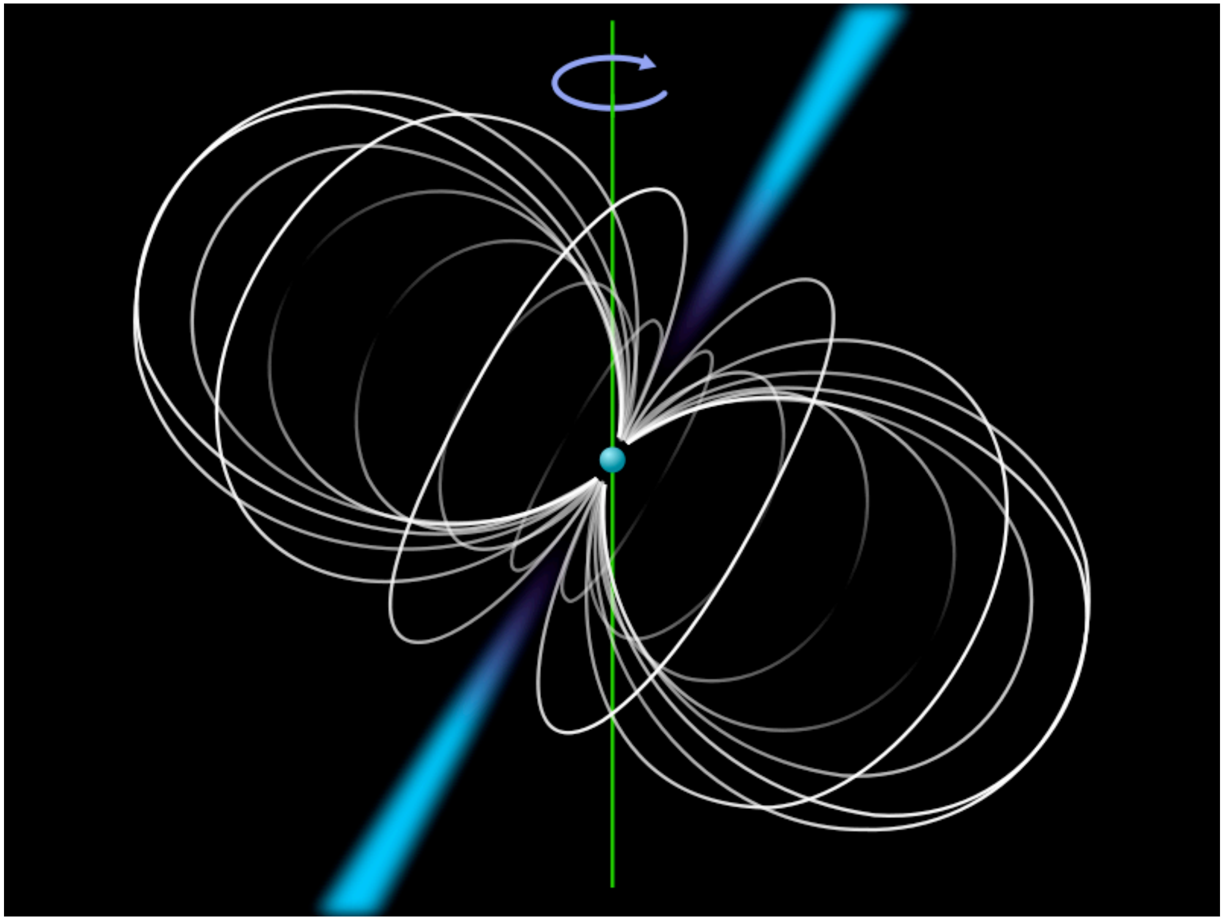
1967: Jocelyn Bell discovered radio pulses having a precise period (graph below), but she didn't know where they came from.

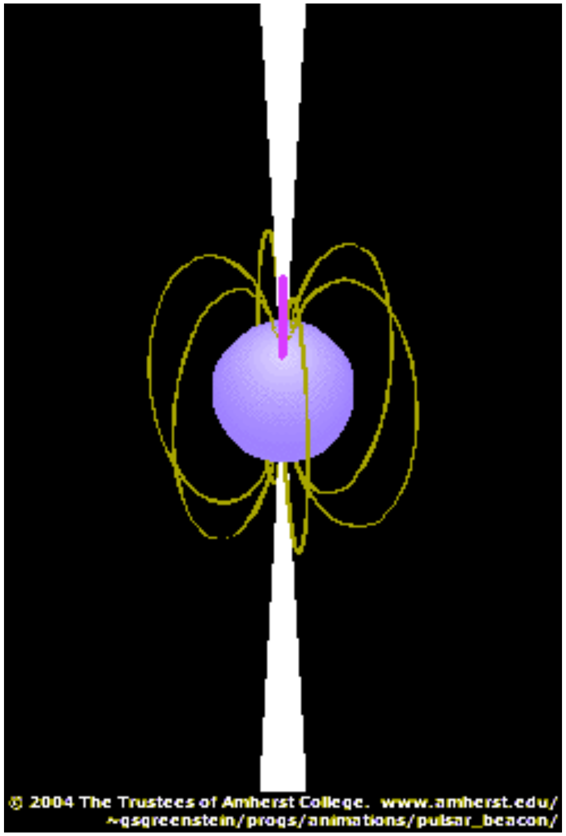
By 1968, these mysterious sources were found in the middle of two supernova remnants, suggesting a link to neutron stars.

These objects are called <u>pulsars</u>.



PULSAR





© 2004 The Trustees of Amherst College. www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/

PULSARS

- Are rotating magnetic neutron stars with their rotational and magnetic axes not aligned. B ~ 10^{12} Gauss (average sun ~ 100 Gauss; sunspot ~ 1000 Gauss; Earth ~1 Gauss)

- Over 1000 now known. Periods range from about 1 ms to over 5 seconds. Accurate clocks (16 decimal places). Gradually slowing down. Concentrated towards Galactic disk.

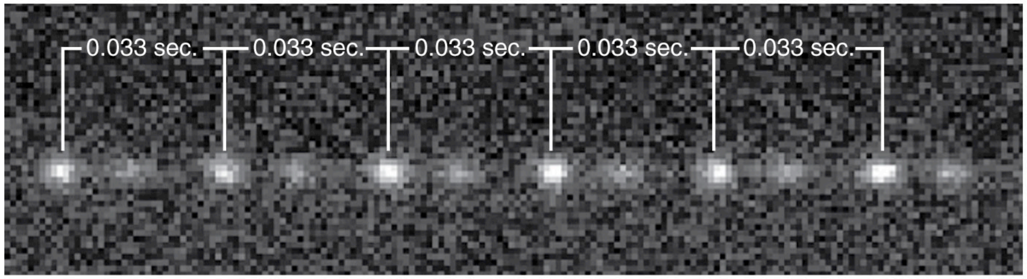
- Evidence for high "peculiar" velocities of typically several hundred km s^{-1}. May get "kicked" in the explosion. Many leave the galaxy.

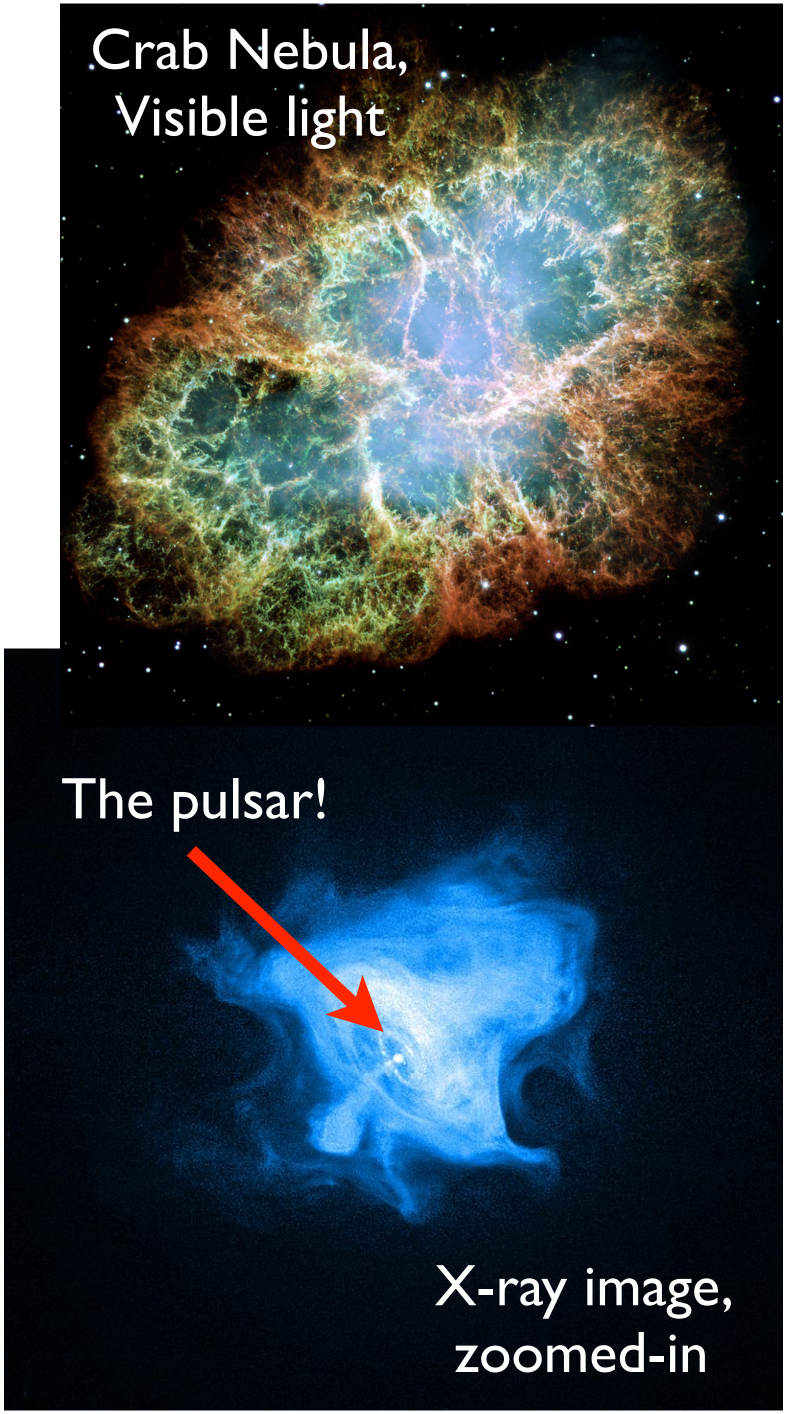
- Some evidence they turn off after ~ 10^7 years due to magnetic field decay and spin down.

The Crab Nebula contains a pulsar.

A pulsar is found at the center of the Crab Nebula, which is a supernova remnant.

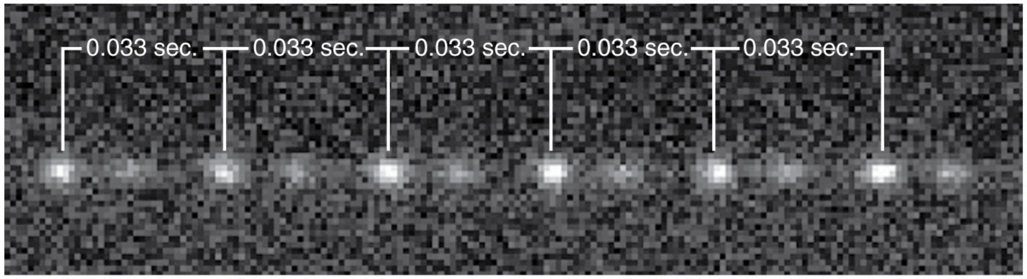
Emission from the pulsar has been observed at regular intervals (0.033 sec apart).





Pulsars are extremely precise clocks.

The interval between pulses of the Crab pulsar is actually 0.0335028583 sec.




Voyager Golden Record

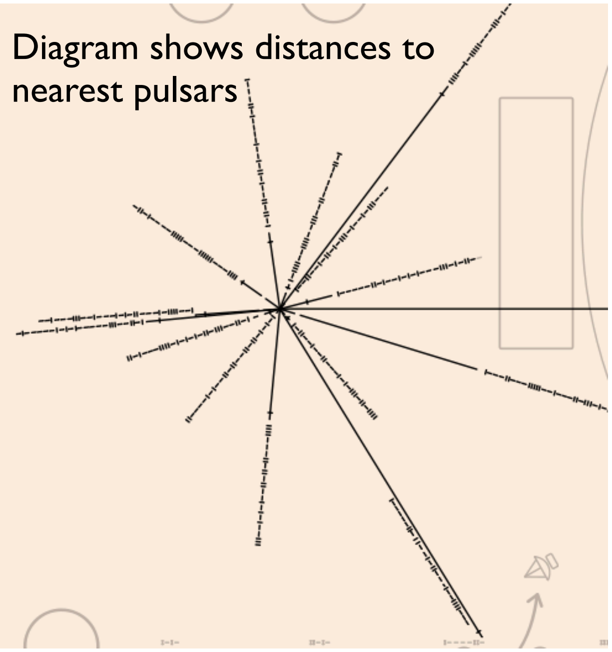
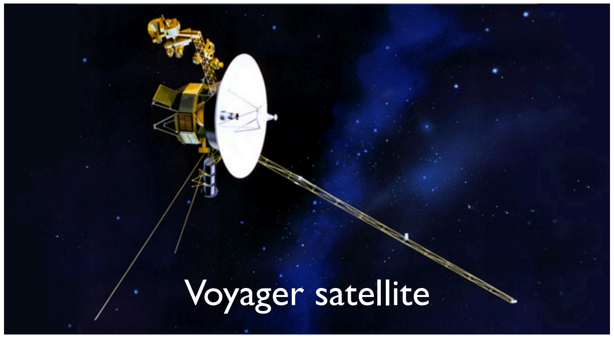
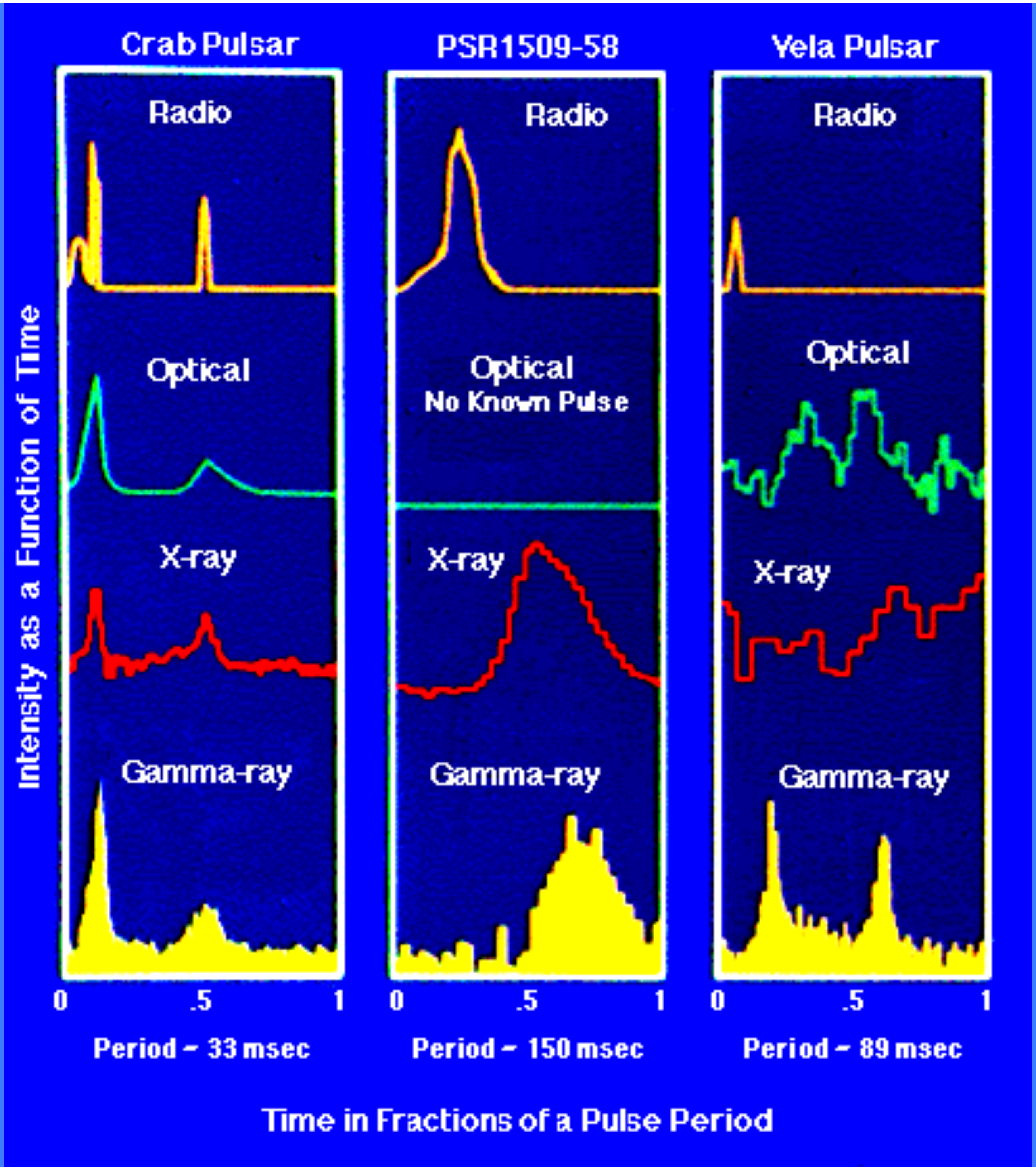
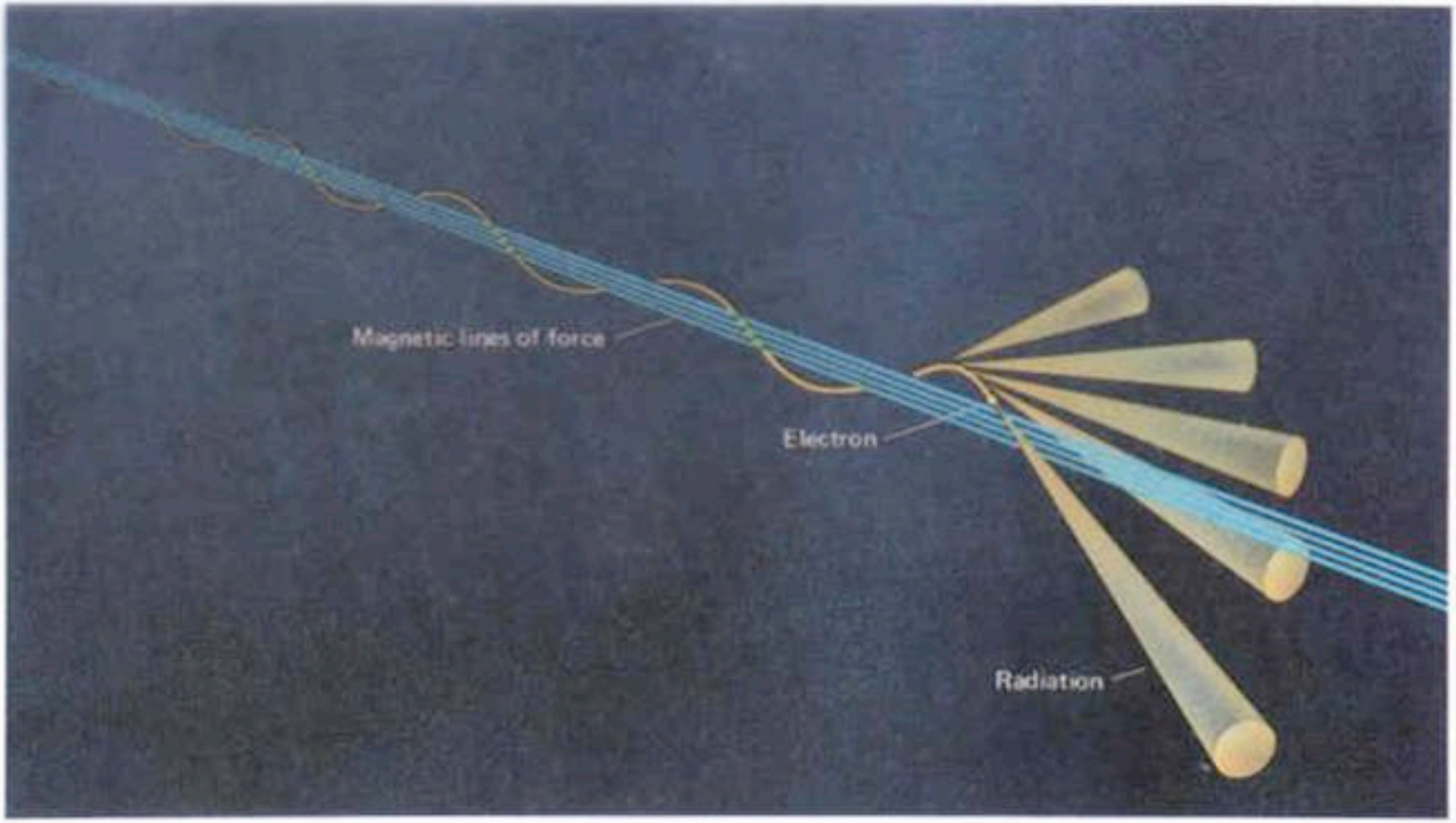


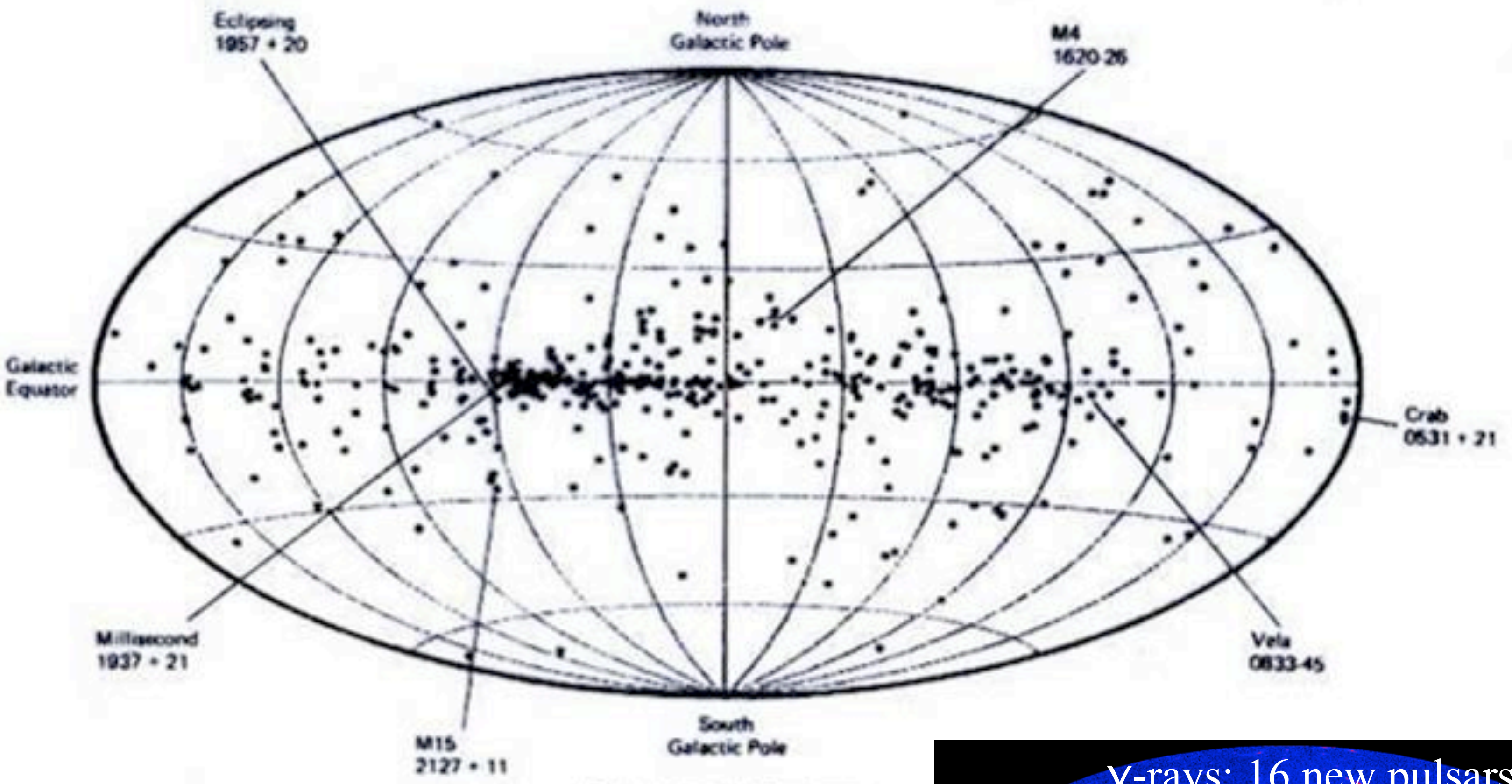
Diagram shows distances to nearest pulsars


Voyager satellite

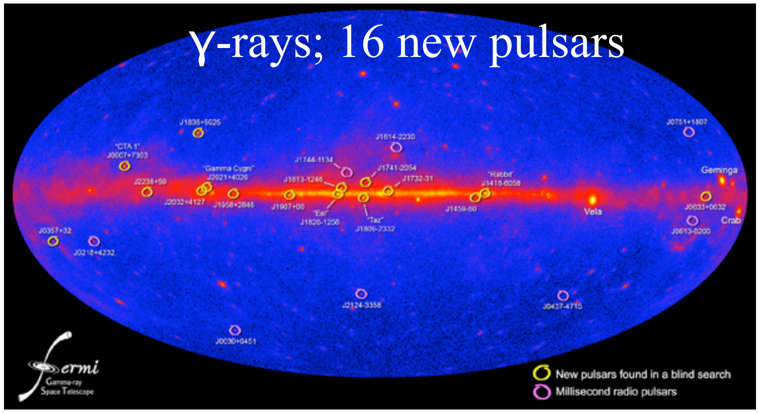

Crab Pulsar
PSR1509-58
Vela Pulsar
Radio
Radio
Radio
Optical
Optical
No Known Pulse
Optical
X-ray
X-ray
X-ray
Gamma-ray
Gamma-ray
Gamma-ray
Intensity as a Function of Time
0
.5
1
0
.5
1
0
.5
1
Period – 33 msec
Period – 150 msec
Period – 89 msec
Time in Fractions of a Pulse Period

SYNCHROTRON RADIATION





Pulsars in Galactic Coordinates



γ-rays; 16 new pulsars

Listen to pulsars:

http://csep10.phys.utk.edu/astr162/lect/pulsars/pulsars.html

PULSARS (continued)

- Occasionally experience abrupt changes in period due to "starquakes"
- Emit pulsed radiation at all wavelengths. Not blackbody emitters.
- Spin down times for solitary neutron stars in supernova remnants are thousands of years consistent with the ages of the remnants in which they are found
- Most rapid rotators are in mass-exchanging binaries – probably spun up.
- Sometimes in binaries with other pulsars, white dwarfs or black holes - and even a planet

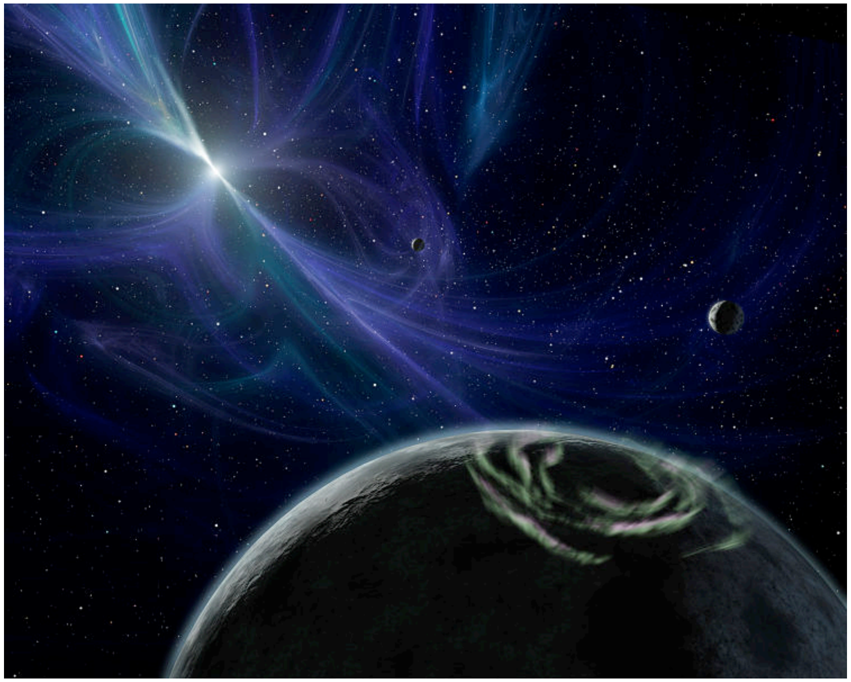
http://www.astro.psu.edu/users/alex/pulsar_planets_text.html

Planets around pulsars?!

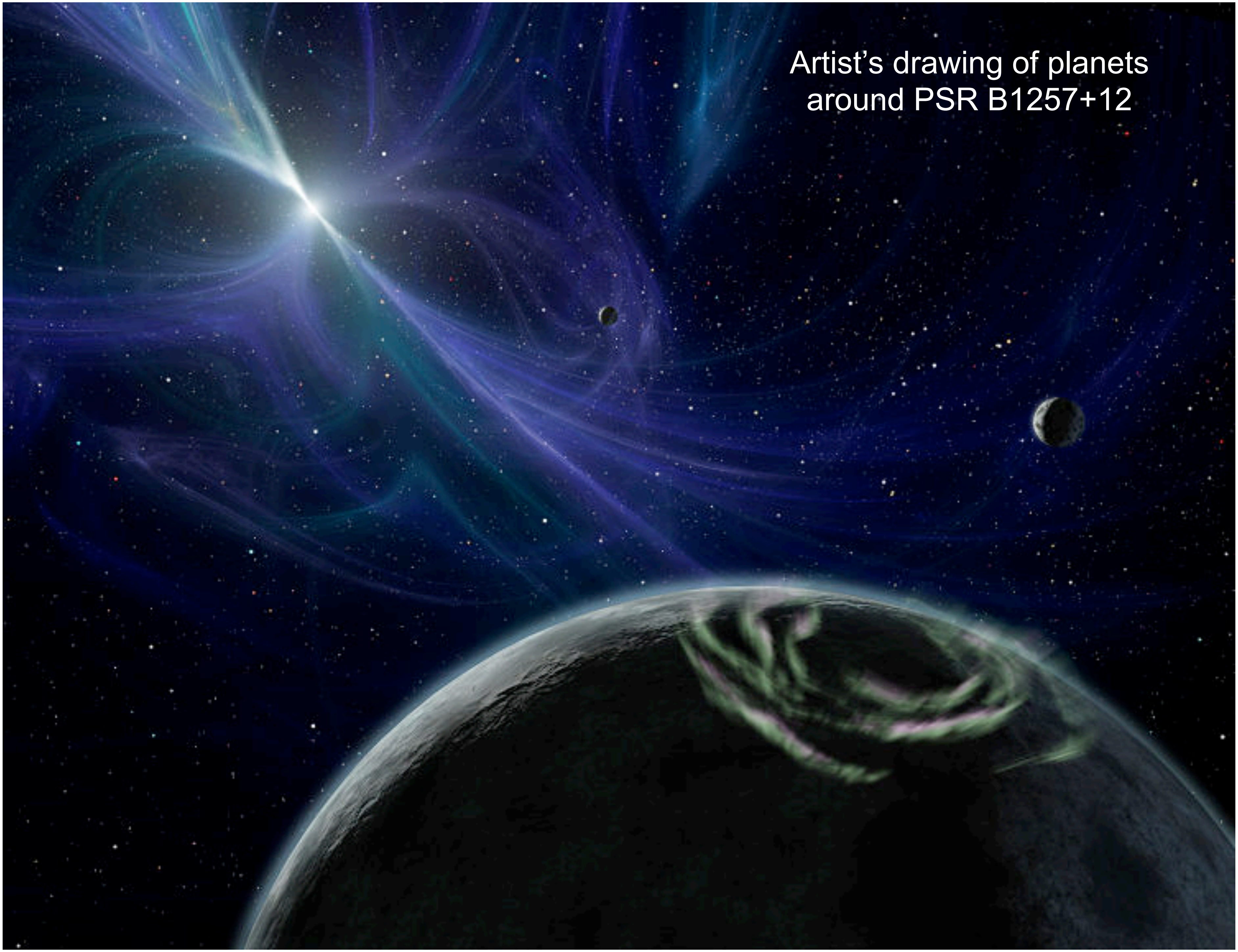
1992: Two planets were detected orbiting a pulsar by measuring tiny variations in the pulse period.

Four pulsar planets have been confirmed so far.

How could they have formed?



3 planets orbiting a pulsar



Artist's drawing of planets
around PSR B1257+12

The Pulsar B 1257+12 planetary system

Companion	Mass (Earths)	semimajor axis (AU)	Orbital period (d)	Eccentricity	Radius
A	.02+-.002	.19	25	0	-
B	4.3 +- .2	.36	66	0.0186	-
C	3.9+-.2	.46	98	0.0252	-
D	.0004	2.6	1250		-

Vertical line is at $1.35 \pm 0.04 M_\odot$

Note that the iron core that collapsed had ~20% more mass

Ransom et al., *Science*, **307**, 892, (2005) find compelling evidence for a 1.68 solar mass neutron star in Terzian 5

More recently (Oct 28, 2010 Nature) Demorest et al find a 1.97 solar mass neutron star in a binary system where the mass could be accurately determined.

Thorsett and Chakrabarty, (1999)