

Lecture 17:

Supernovae and Neutron Stars

<http://apod.nasa.gov/apod/>

SUPERNOVAE

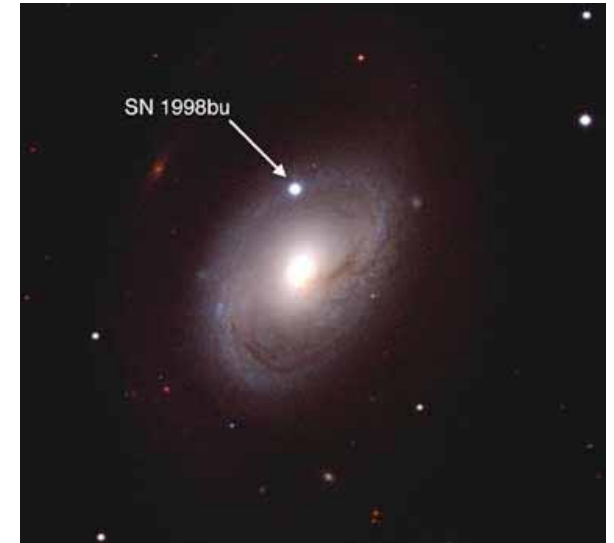
- A supernova is the explosive death of a star. Unlike an ordinary nova, it does not repeat.
- Two types are easily distinguishable by their spectrum. Type II has hydrogen (H_{α}). Type I does not.
- Very luminous. Luminosities range from a few times 10^{42} erg s^{-1} (relatively faint Type II; about 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

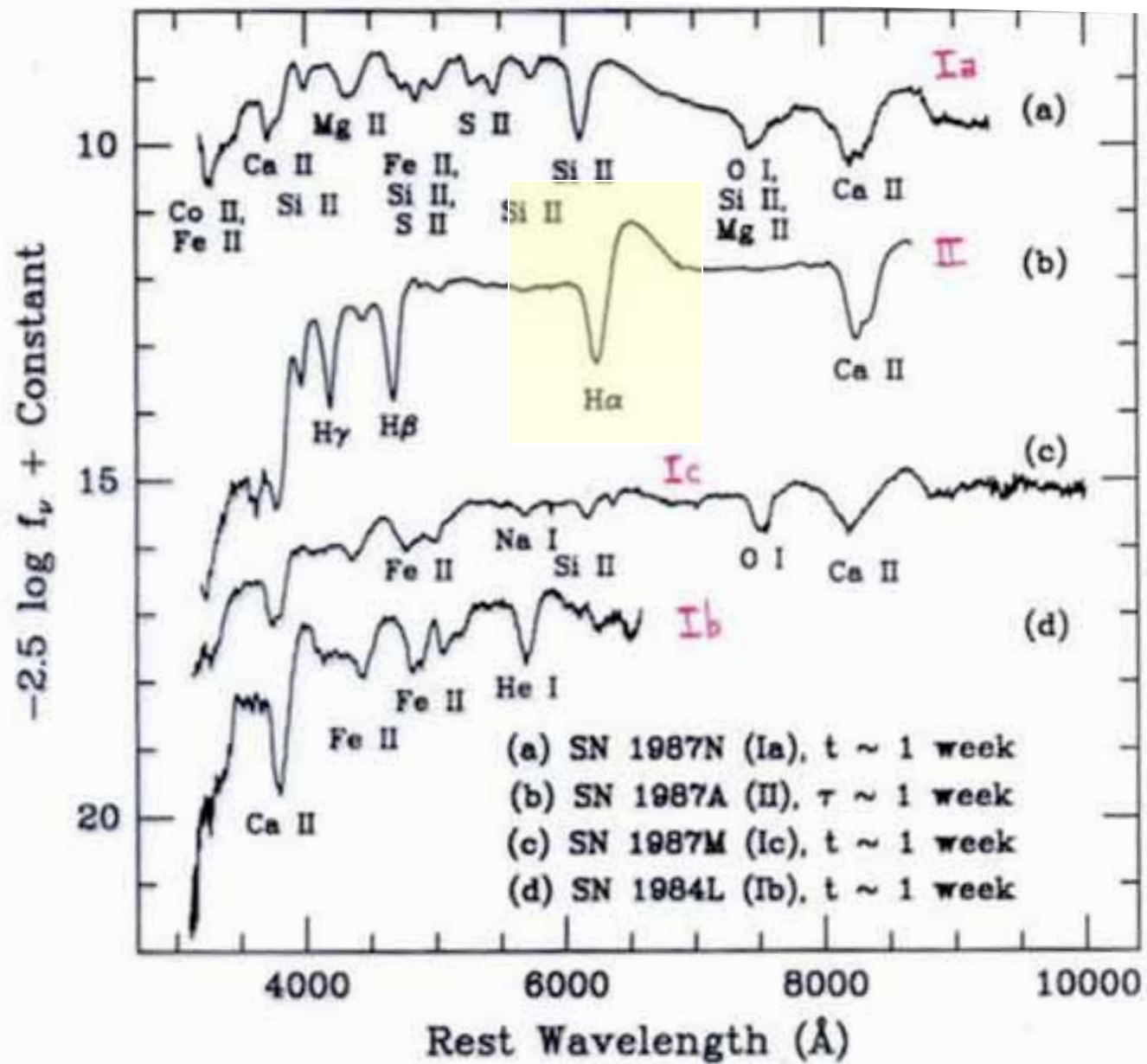


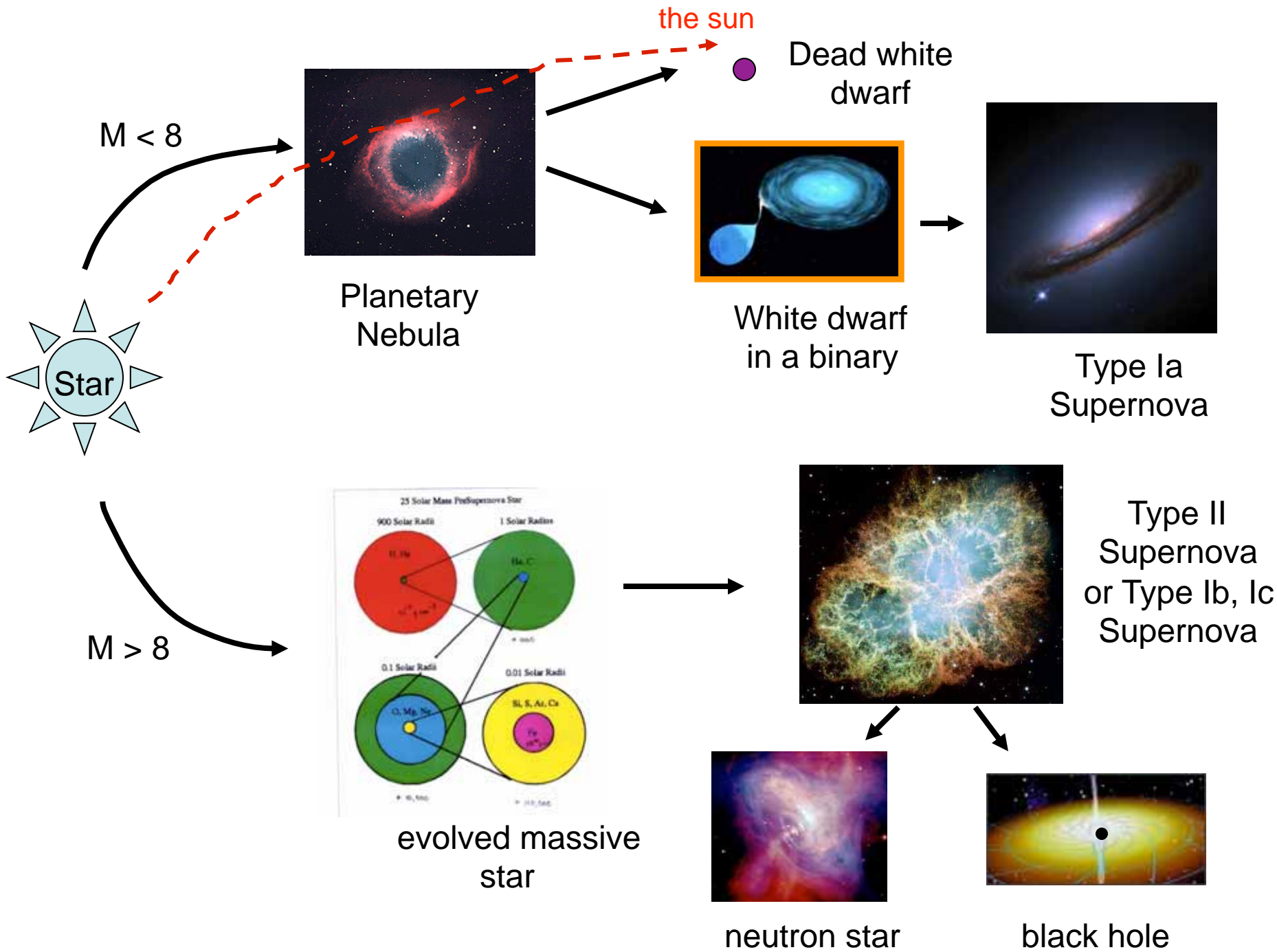
SN 1994D

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 2012gx*

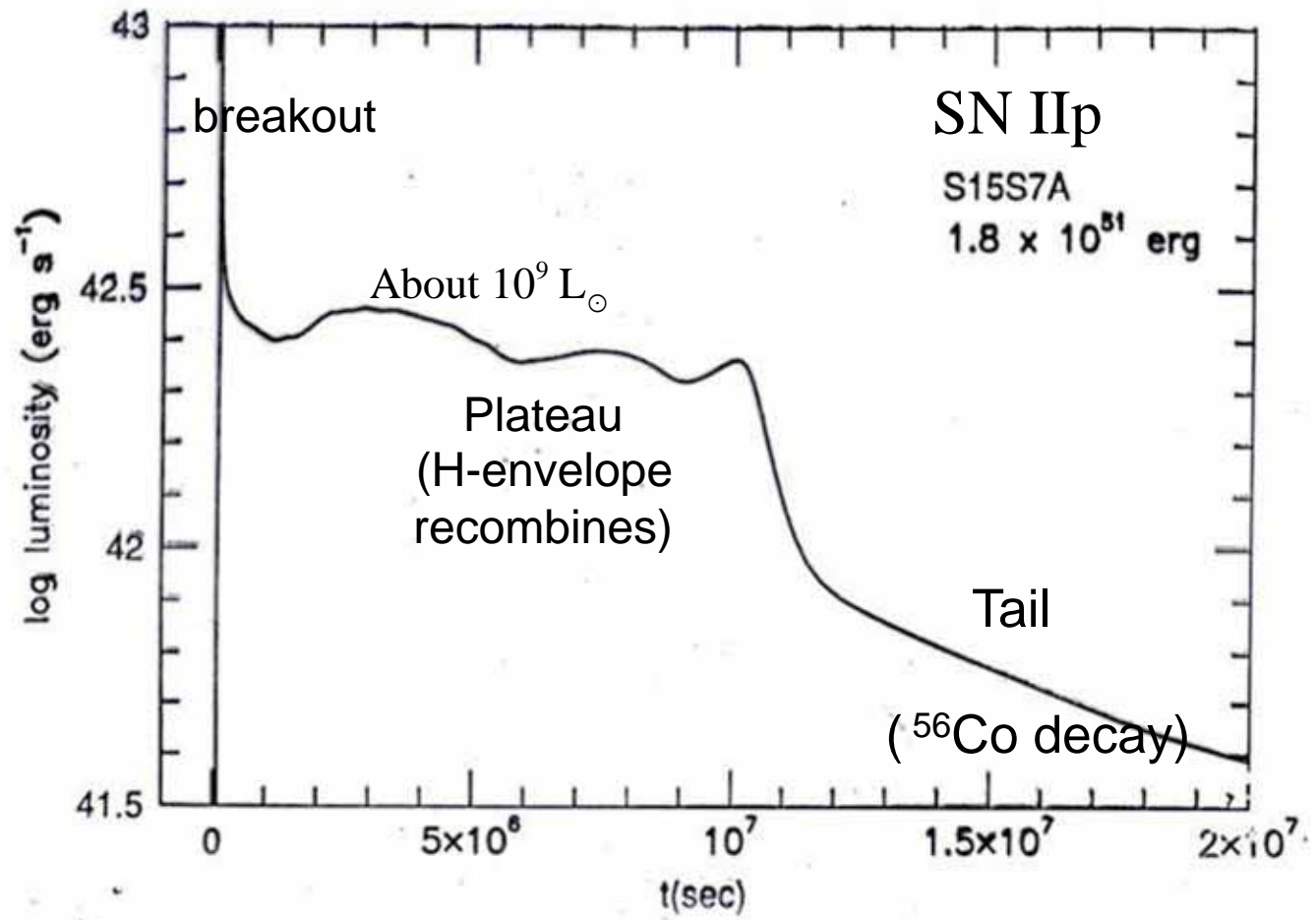
SPECTROSCOPICALLY

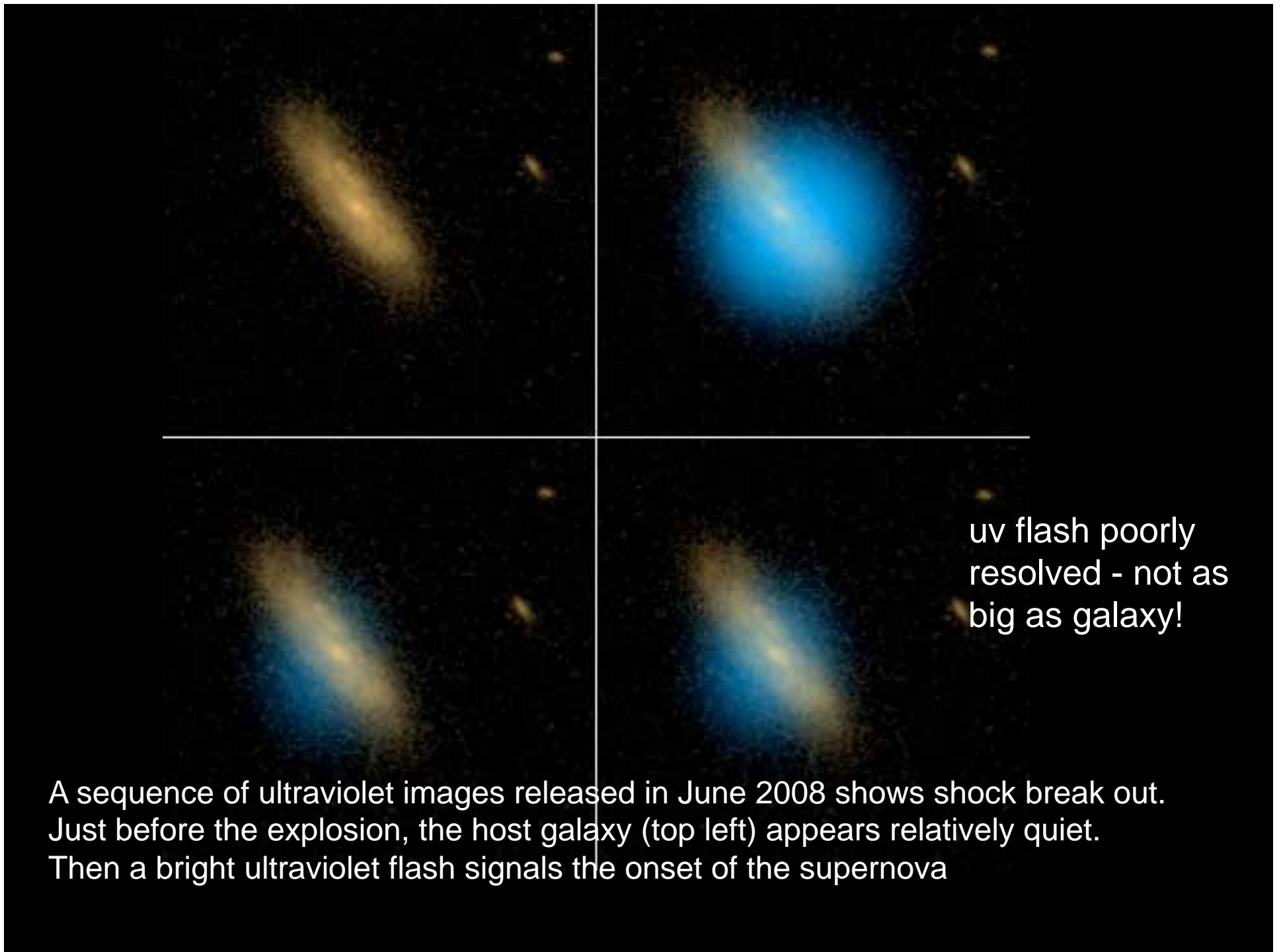




Light Curve of Type IIp Supernovae

- 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.
- 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)



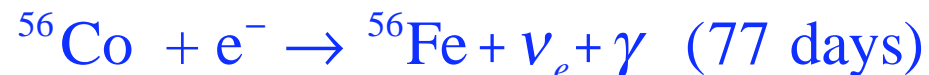
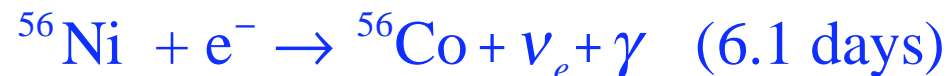


uv flash poorly
resolved - not as
big as galaxy!

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

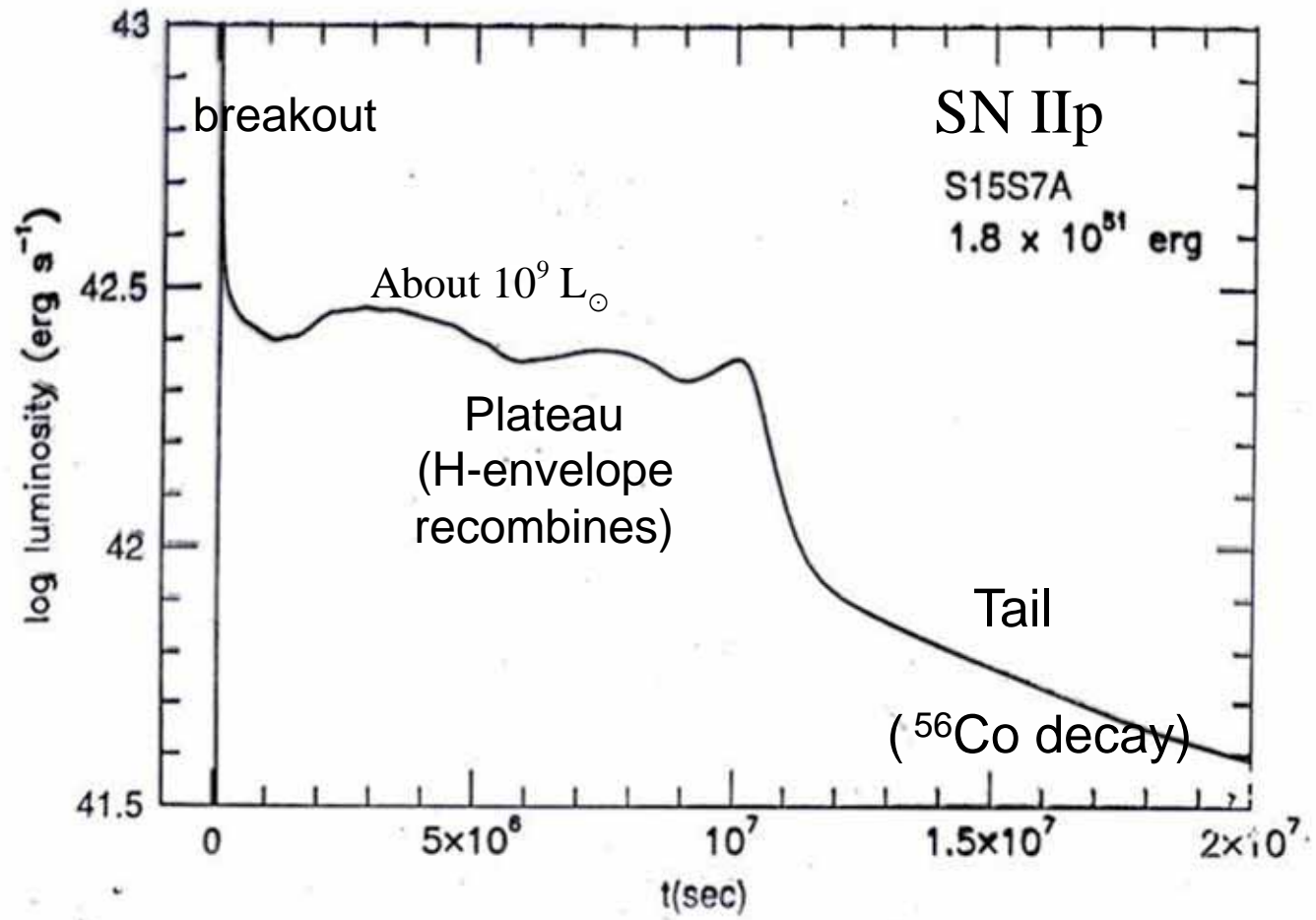
Light Curve of Type IIp Supernovae (cont'd)

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



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

Theoretical light curve of a Type IIp supernova

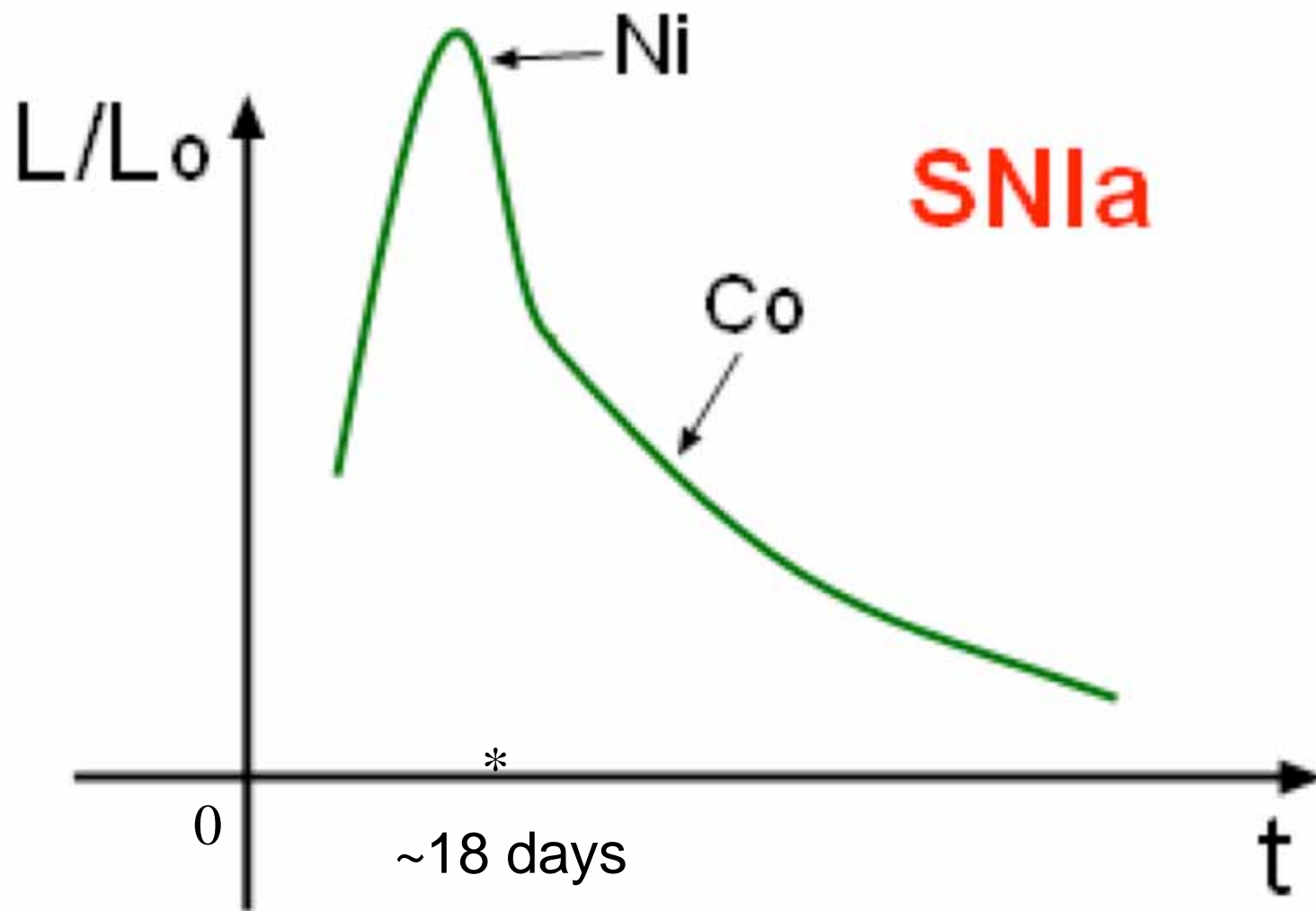


Type IIp Supernovae (cont'd)

- 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”

Type I Supernovae

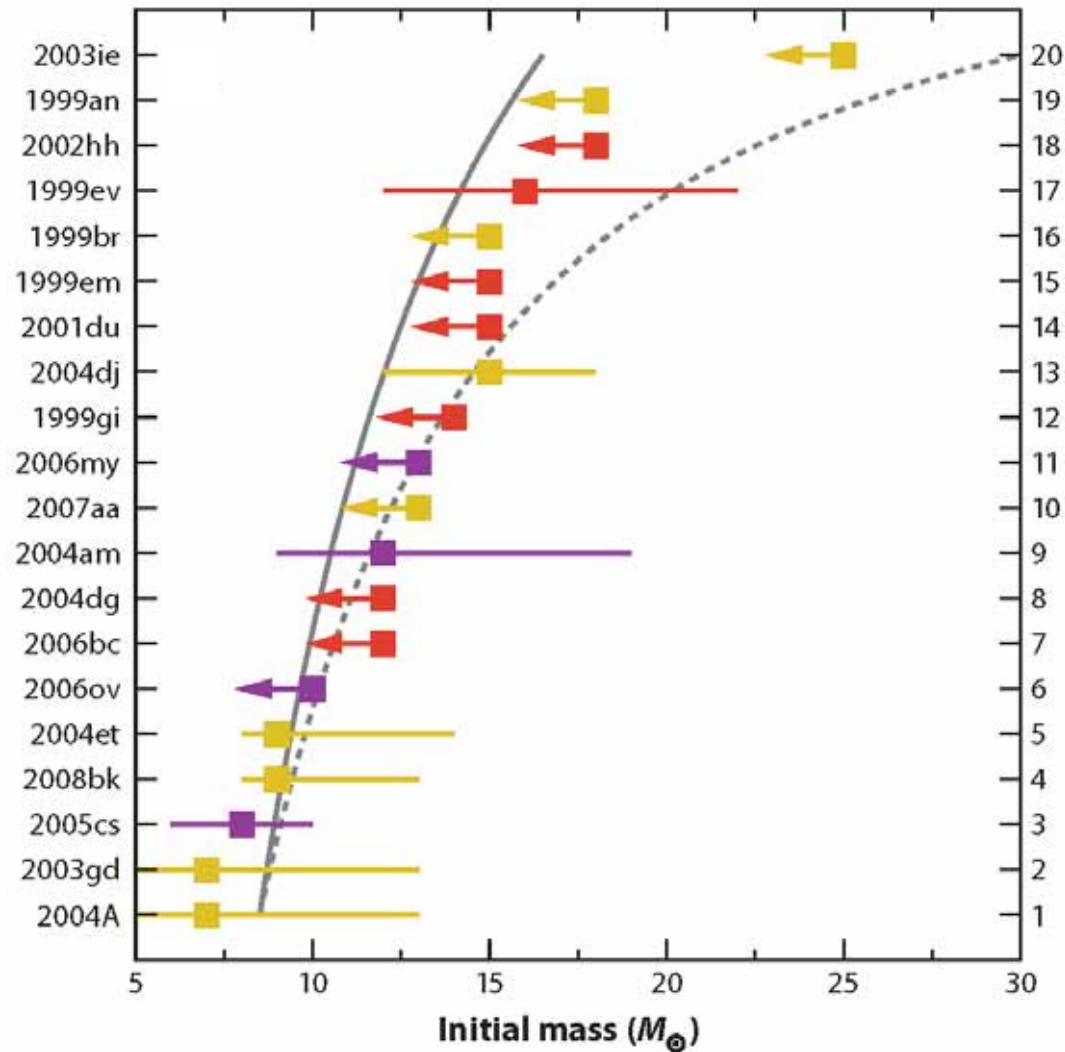
- Type I supernovae lack hydrogen and thus have no plateau stage. The shock break out is also considerably fainter and shorter in wavelength (x-rays)
- The Type I supernova light curve is thus powered at all times by the decay of radioactive ^{56}Ni and ^{56}Co .
- Type I supernovae are segregated into 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 also 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 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.

Presupernova stars – Type IIp and II-L

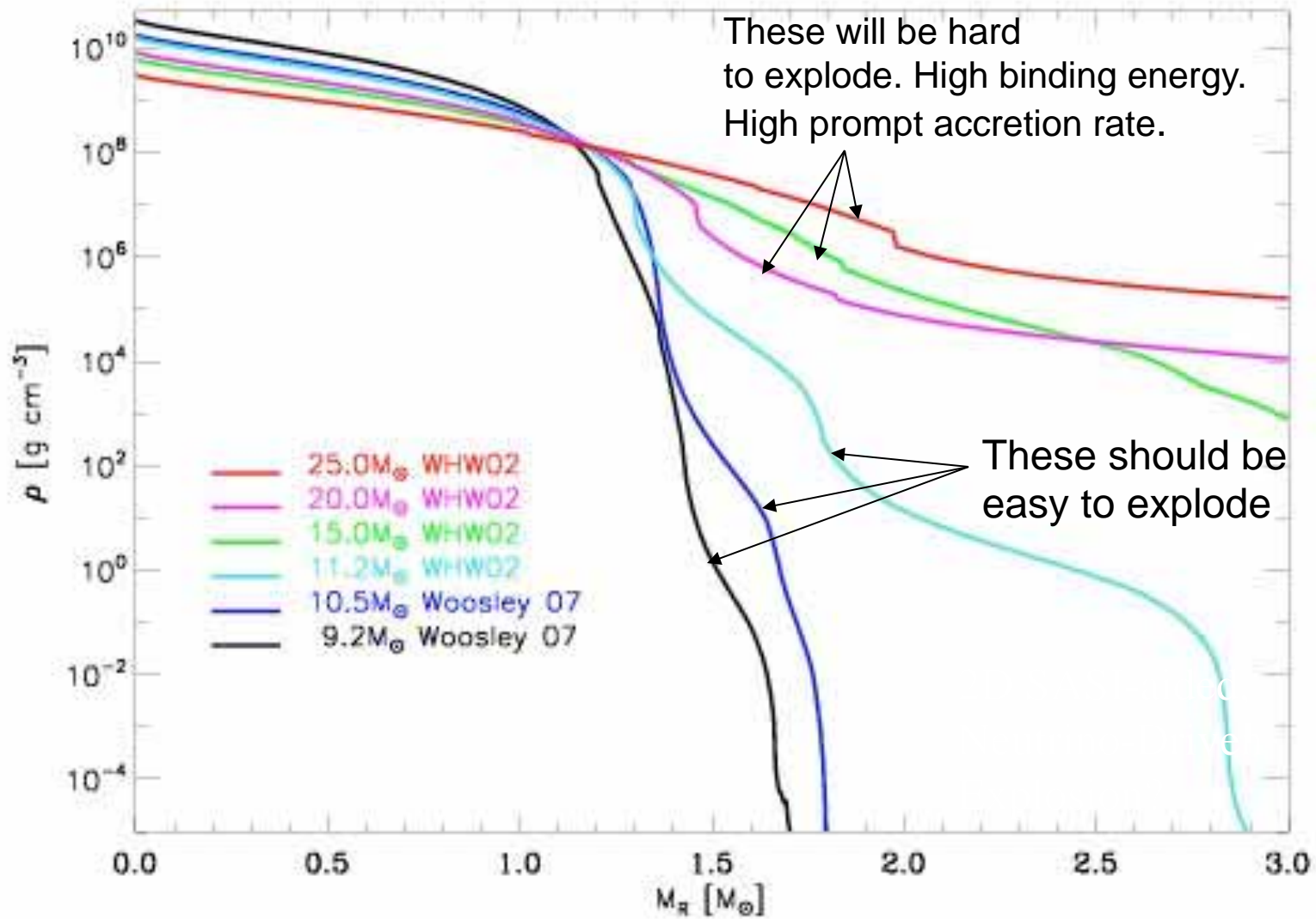


Smartt, 2009
ARAA

*Progenitors
heavier than 20
solar masses
excluded at the
95% confidence
level.*

The solid line is for a Salpeter IMF with a maximum mass of 16.5 solar masses. The dashed line is a Salpeter IMF with a maximum of 35 solar masses

Density Profiles of Supernova Progenitor Cores



Supernovae - General

- In a Type II or Ibc supernova most of the energy comes out in the neutrino burst – 3×10^{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 supernovae 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

February 23, 1987
(+160,000 years)

before



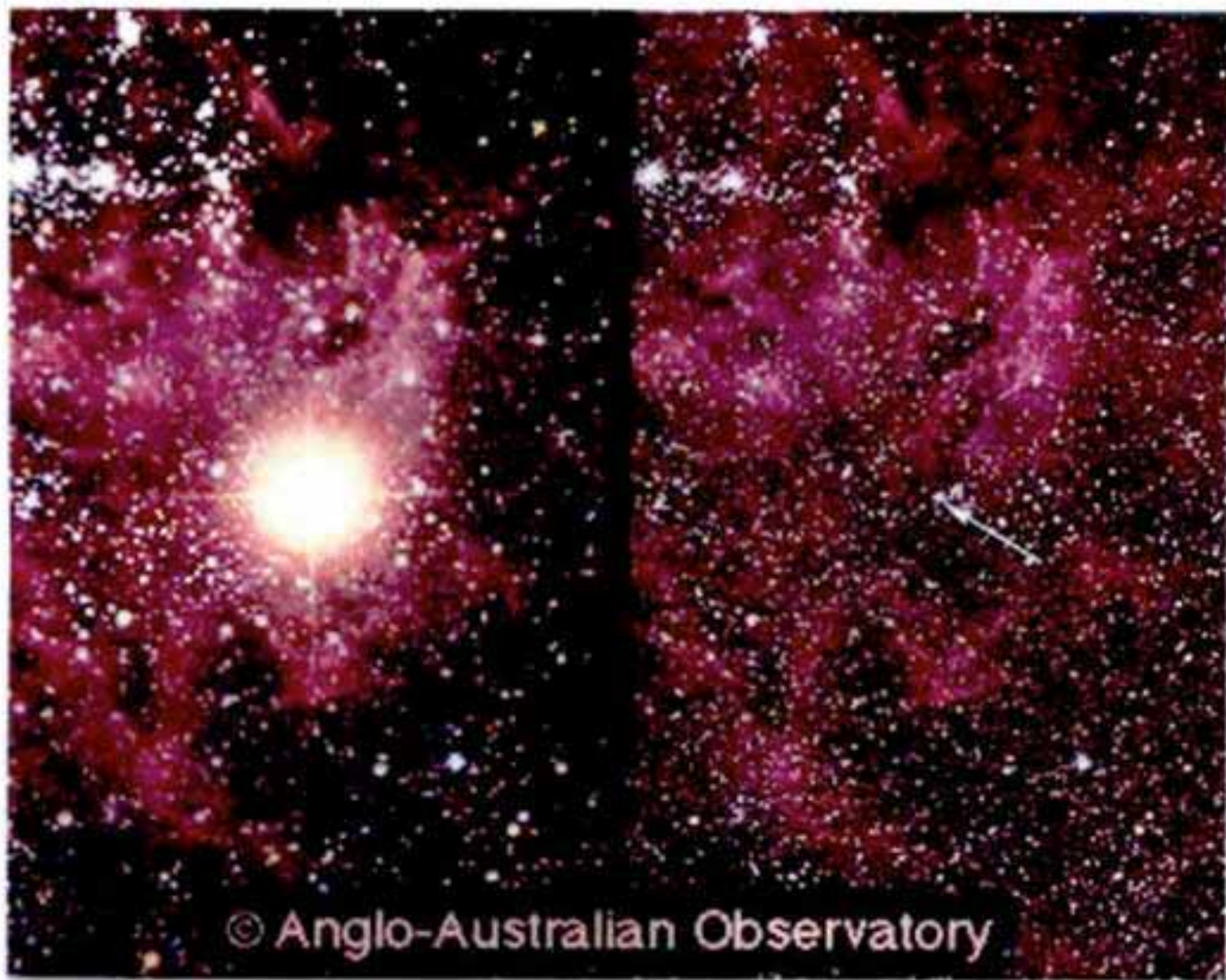
Brightest supernova in
over 400 years.

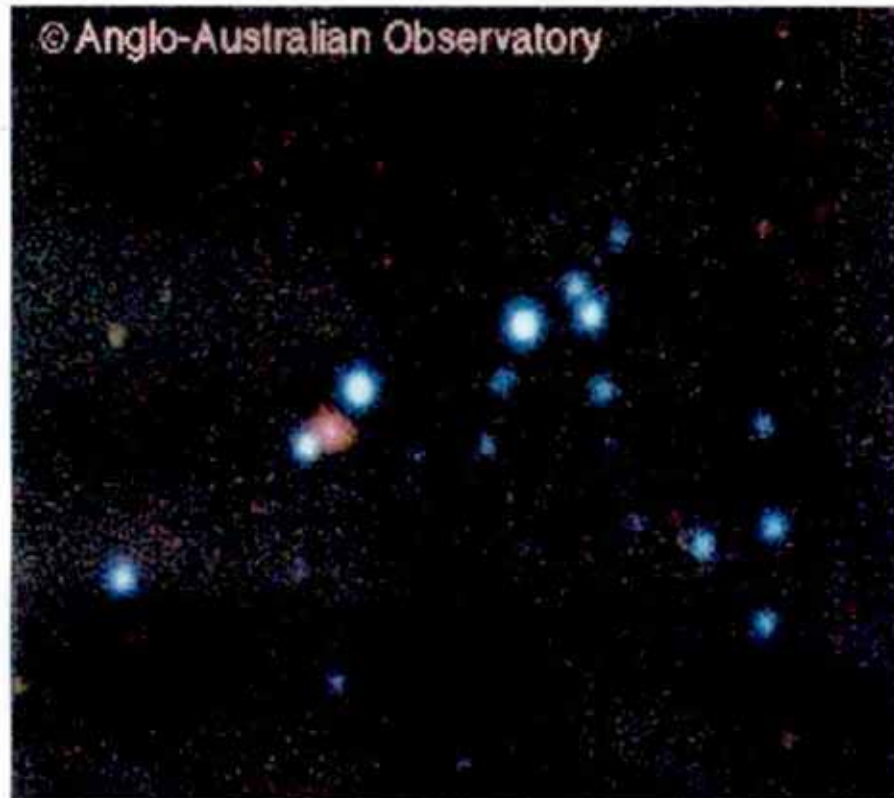
In the 30 Doradus H II
region in the Large
Magellanic Cloud.

after



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





SN 1987A four years after its explosion. The reddish spot between the two bright stars is the supernova. The two stars are also in the LMC.

SN 1987A Today



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.

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

Supernova

(Death of a star)

Type Ia (TBD)

- No hydrogen
- Thermonuclear explosion of a white dwarf star
- No bound remnant
- $\sim 10^{51}$ erg kinetic energy
- $v \sim 5,000 - 30,000 \text{ km s}^{-1}$
- No neutrino burst
- $E_{\text{optical}} \sim 10^{49}$ erg
- $L_{\text{peak}} \sim 10^{43} \text{ erg s}^{-1}$ for 2 weeks
- Radioactive peak and tail (^{56}Ni , ^{56}Co)
- 1/200 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
- $v \sim 2,000 - 30,000 \text{ km s}^{-1}$
- Neutrino burst $\sim 3 \times 10^{53}$ erg
- $E_{\text{optical}} \sim 10^{49}$ erg
- $L_{\text{peak}} \sim 3 \times 10^{42} \text{ erg s}^{-1}$ for about 3 months (varies from event to event)
- Radioactive tail (^{56}Co)
- 2/100 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

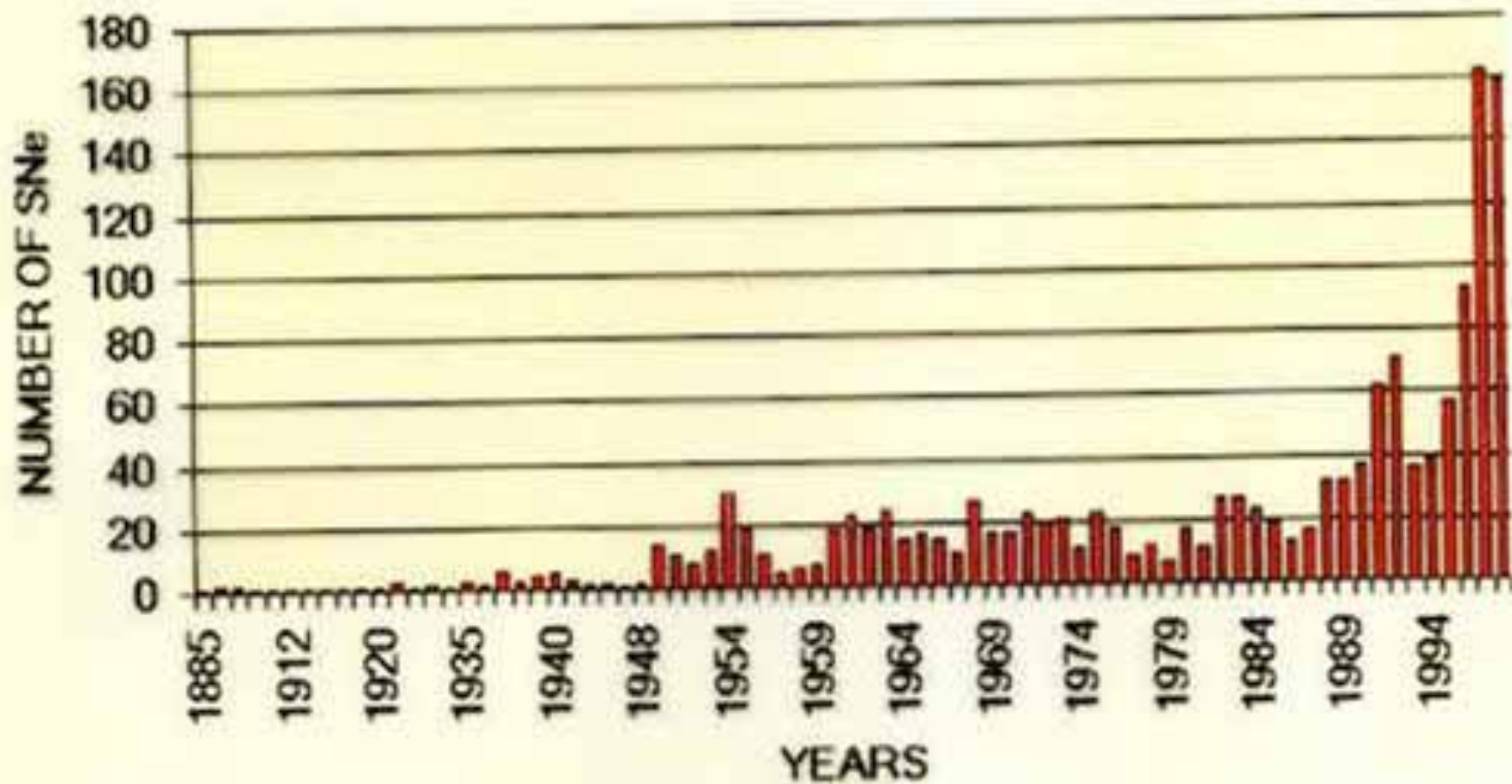
Year	Report	Status
185 A.D.	Chinese	Identification in doubt (Chin and Huang 1994)
386	Chinese	unknown
393	Chinese	unknown
1006	China, Japan, Korea, Arab lands, Europe	Identified with radio <u>SNR</u>
1054	China, Japan	<u>Crab Nebula</u>
1181	China, Japan	Possible identification with radio <u>SNR 3C58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

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

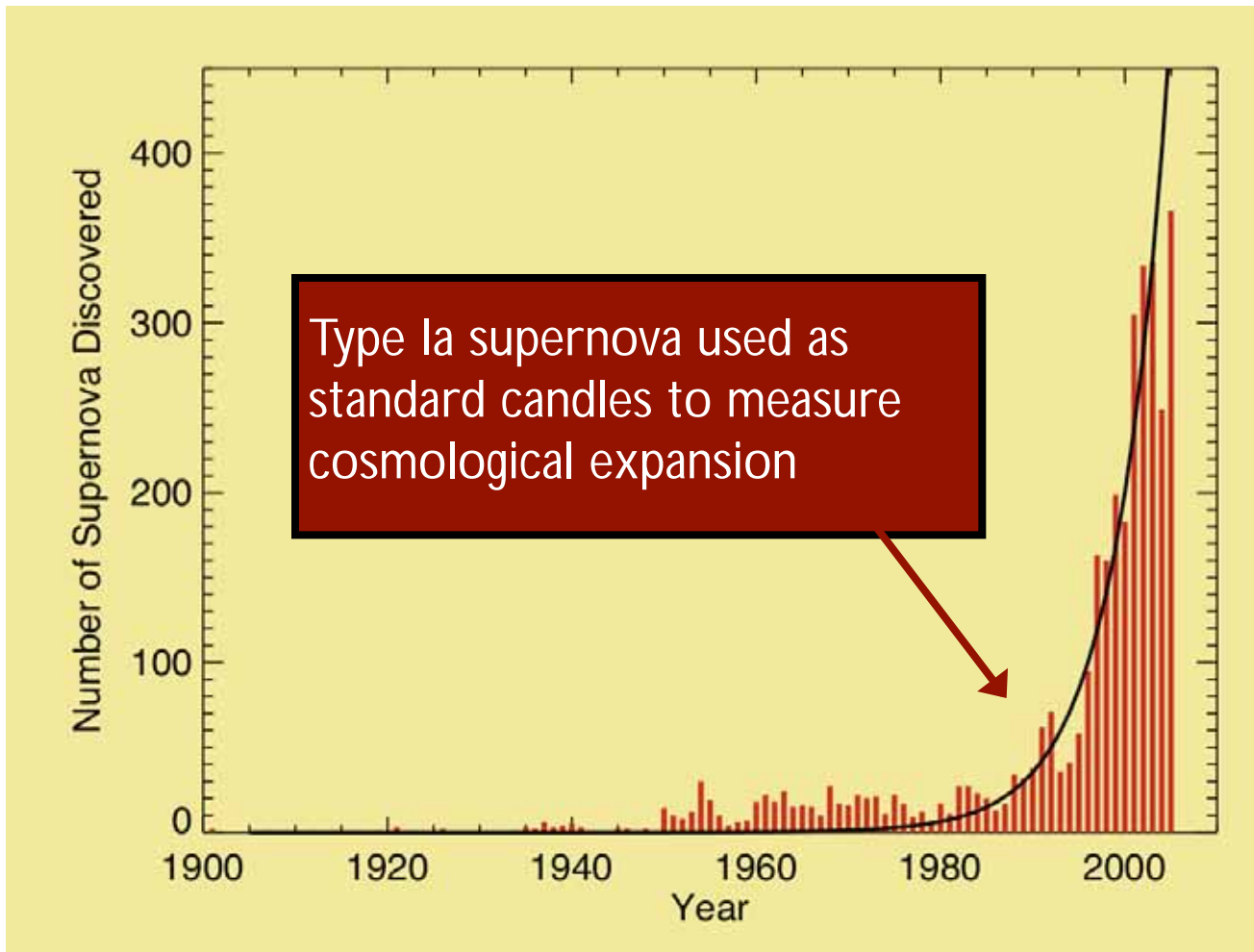
1680 Cassiopeia-A

EXTRAGALACTIC SNe_I DISCOVERED SINCE 1885



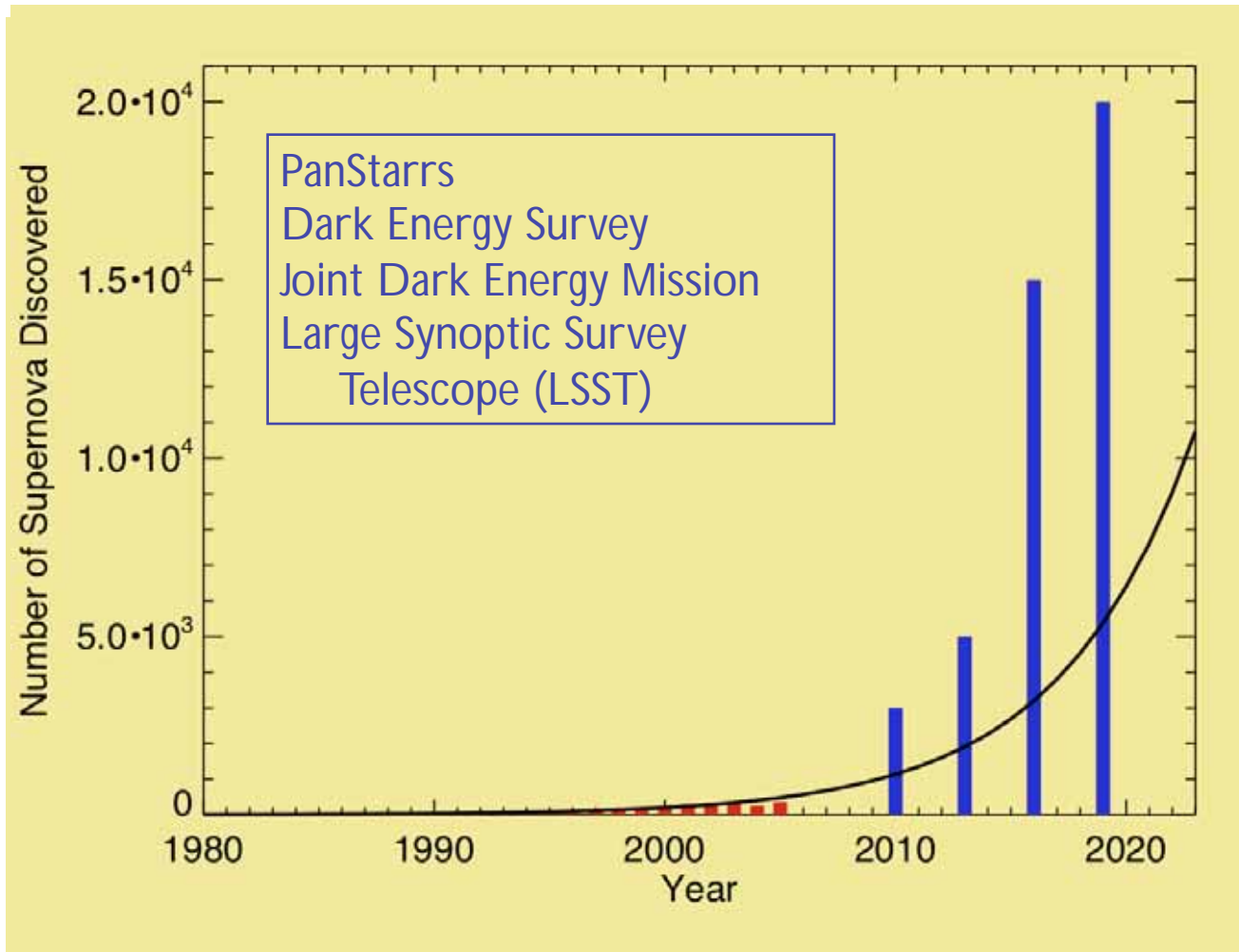
Supernova Discovery History

Asiago Catalog (all supernova types)



Supernova Discovery Future

Rough predictions and promises...

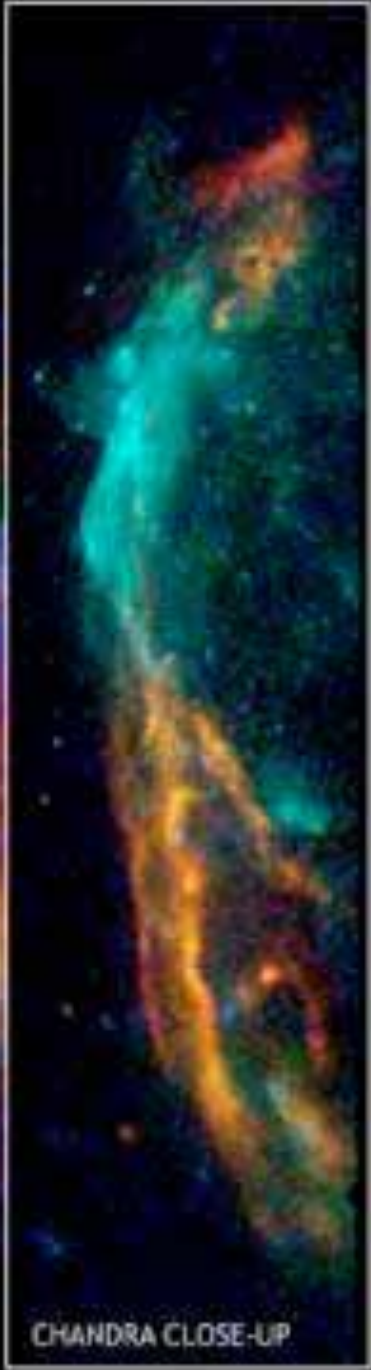


The “First” Supernovae



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

RCW 86 – X-rays
Probably Type Ia
No neutron star
2.8 kpc
Circinus-Centaurus



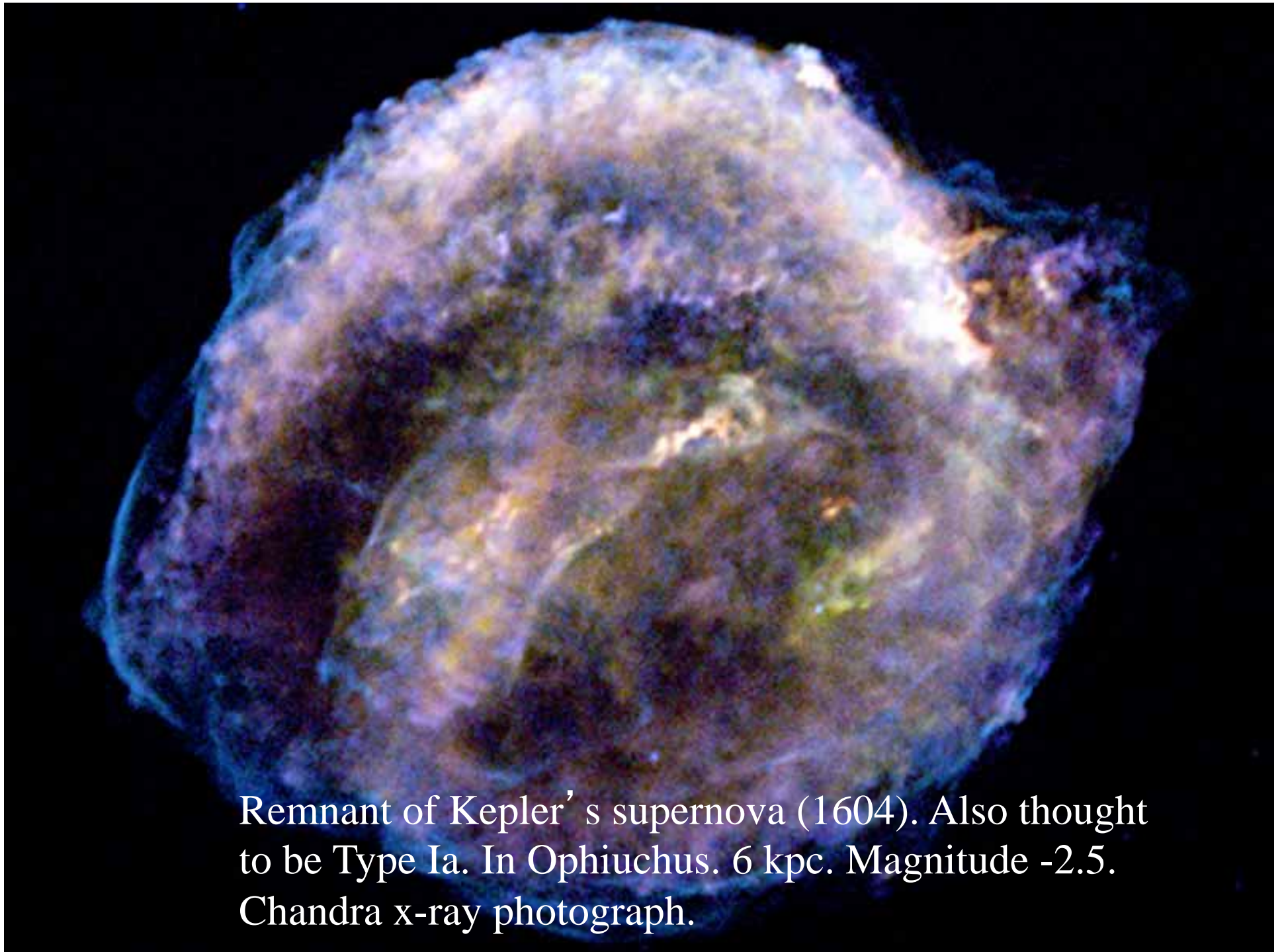
XMM FULL-FIELD

CHANDRA CLOSE-UP

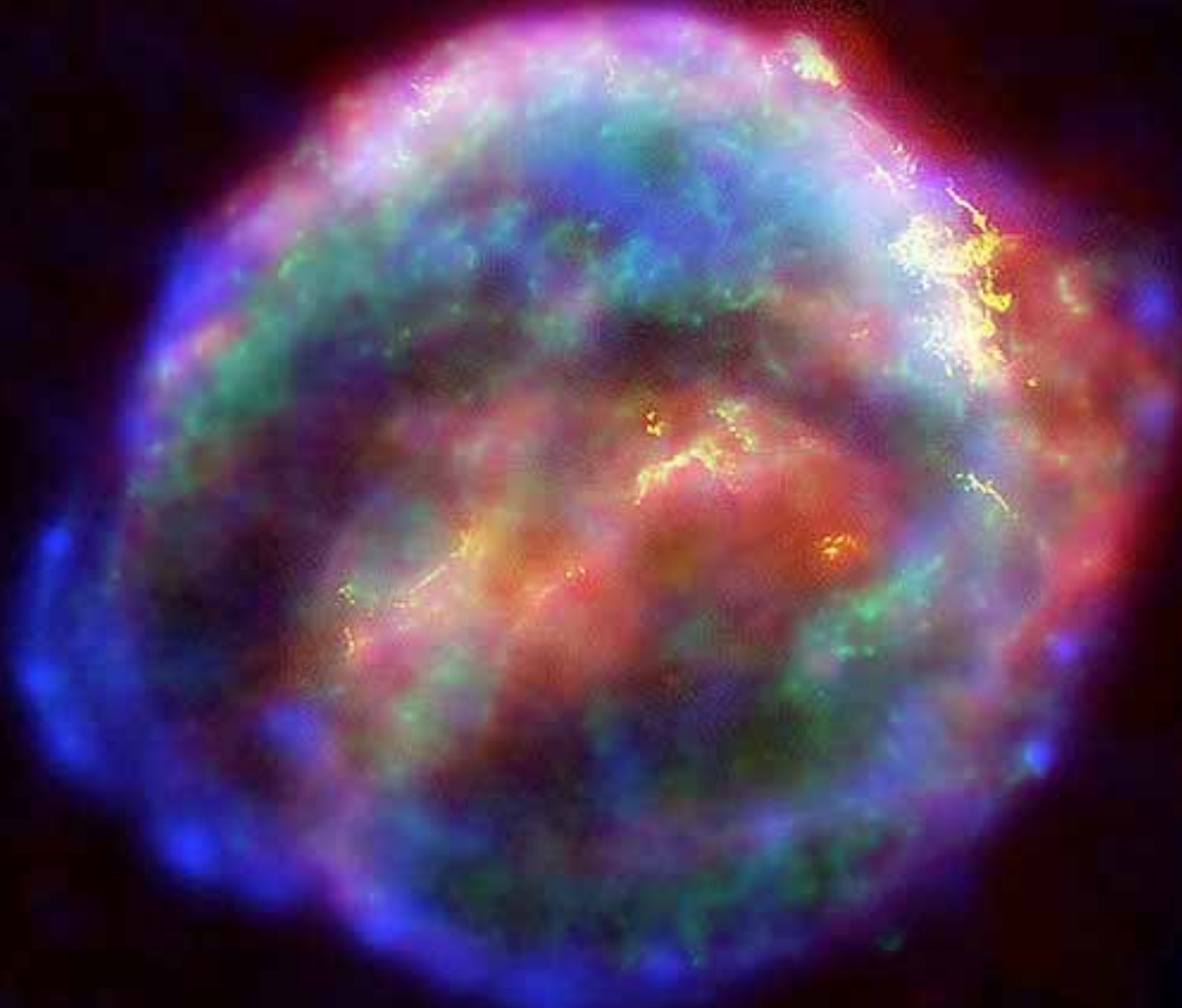
Supernova Remnants



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.

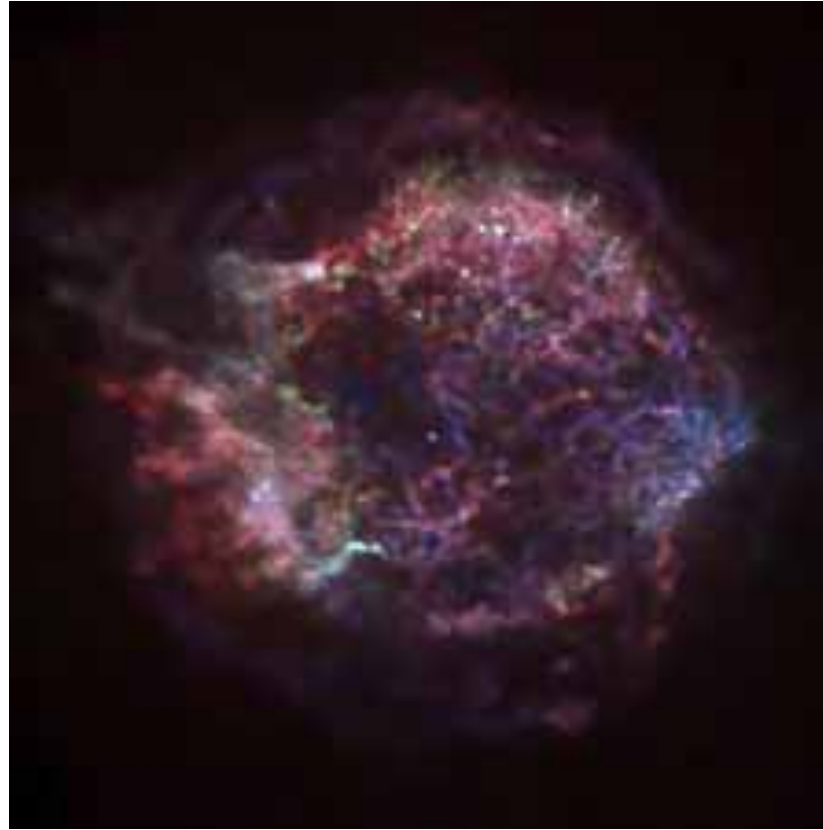


Remnant of Kepler's supernova (1604). Also thought to be Type Ia. In Ophiuchus. 6 kpc. Magnitude -2.5. Chandra x-ray photograph.



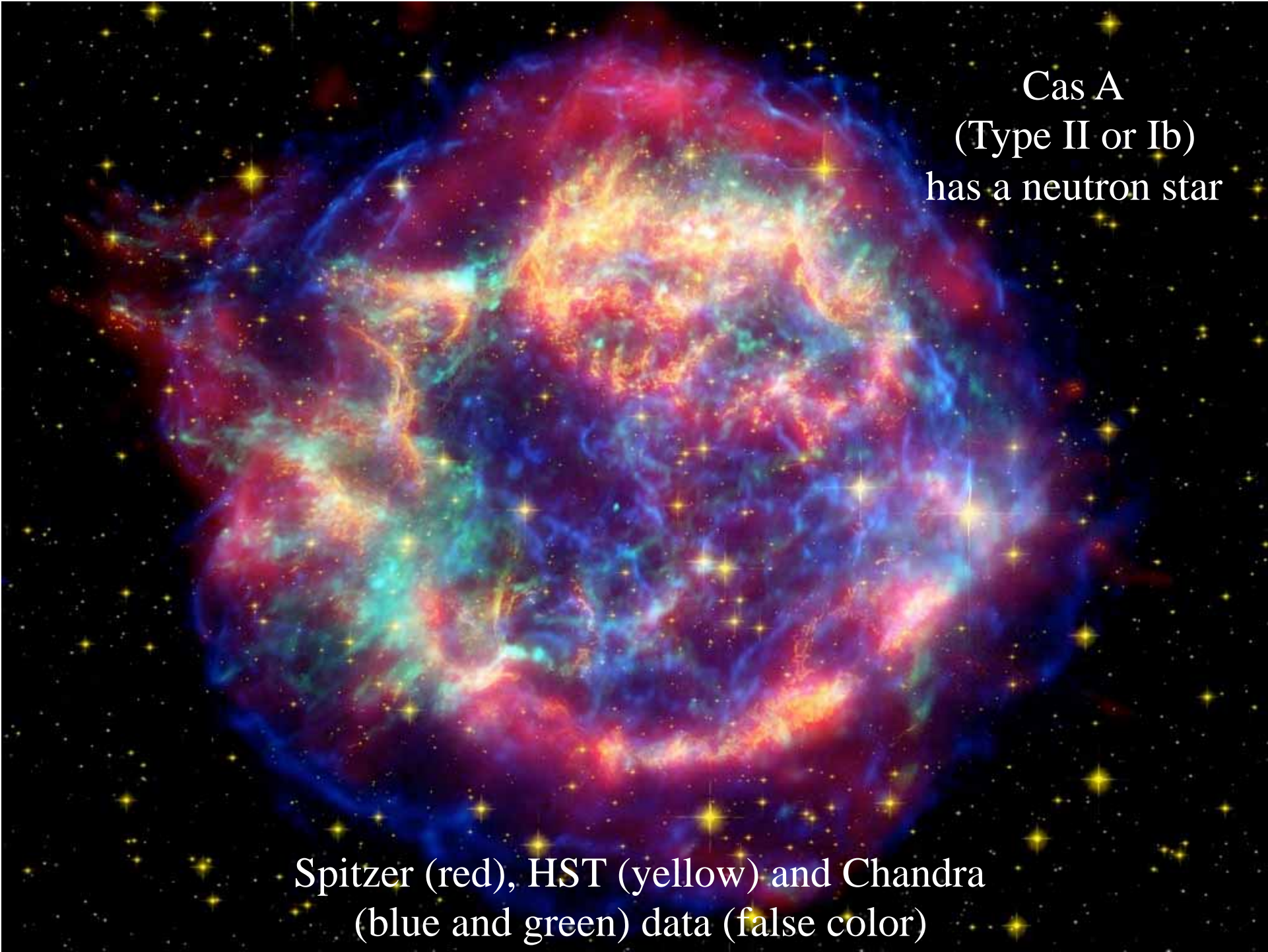
Kepler's supernova remnant in the optical (HST yellow), IR (Spitzer (red)), and x-ray (Chandra, blue and green). Blue and yellow are shocked gas, green is hot gas, red is dust.

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



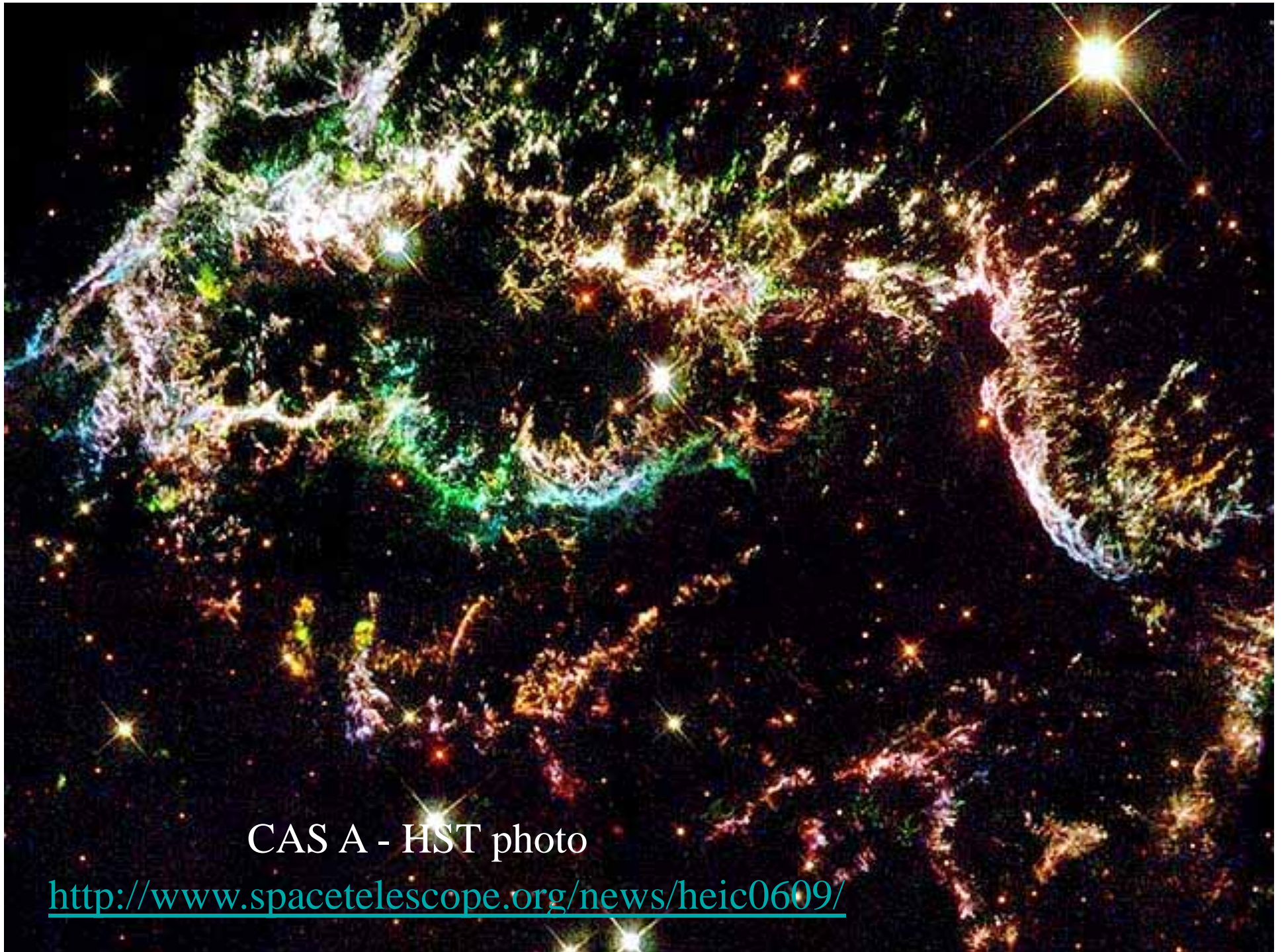
Last SN seen(?)
in our galaxy

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.



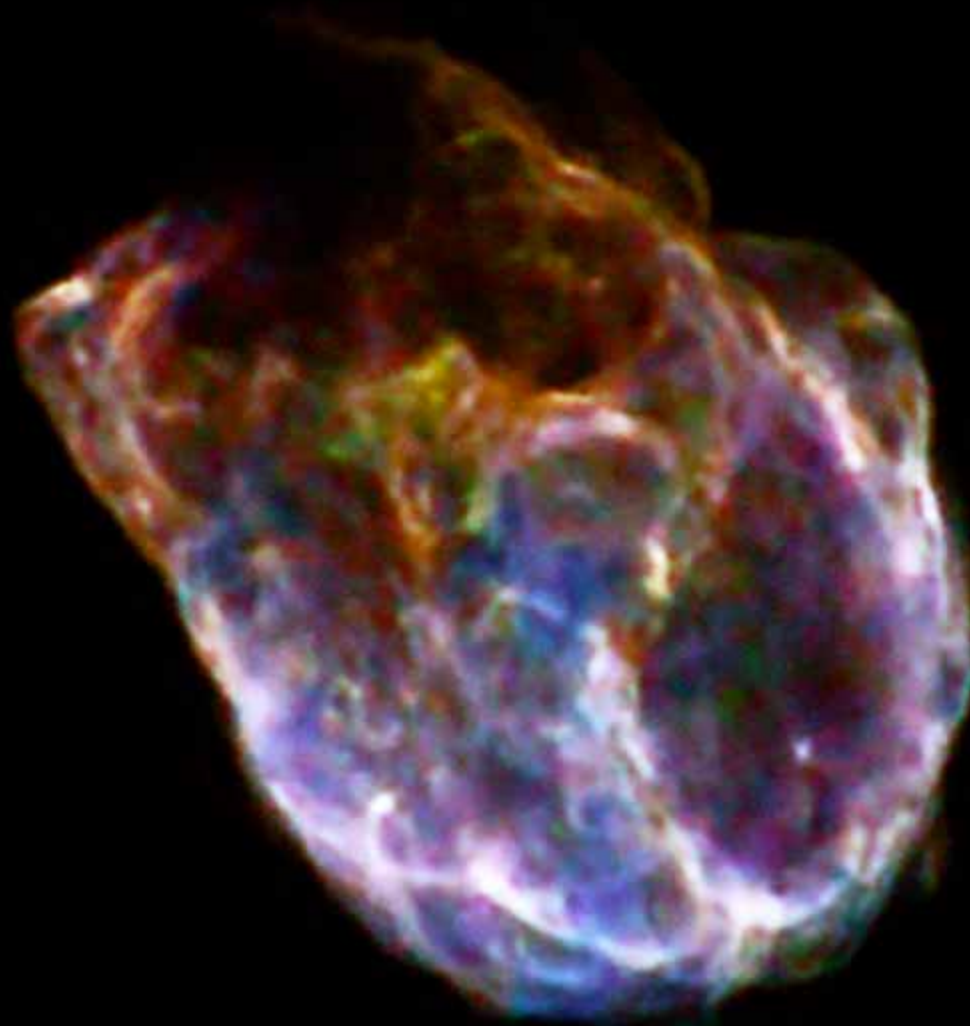
Cas A
(Type II or Ib)
has a neutron star

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



CAS A - HST photo

<http://www.spacetelescope.org/news/heic0609/>



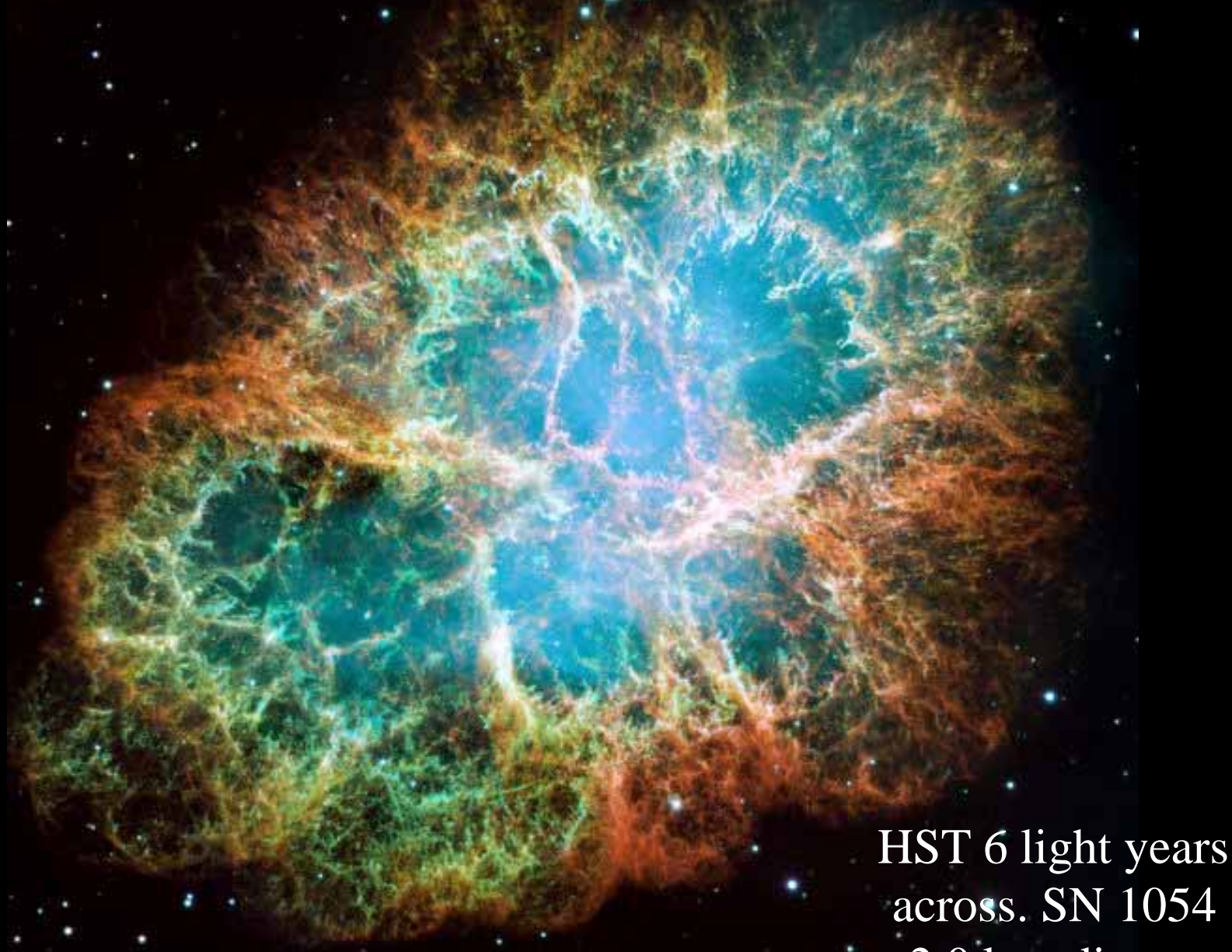
Supernova remnant N132D in the Large Magellanic Cloud
Chandra x-ray image. Gas temperature is millions of K.
Image is 100 arc sec on an edge. $d = 180,000$ ly

x-ray photograph - Chandra - G292.0+1.8



Young oxygen-rich SNR with a pulsar in its center (lower left of center) surrounded by outflowing material 36 light years across. Estimated age 1600 years. In our galaxy. O, Mg, Ne, Si, S clearly present. Type II or Ib.

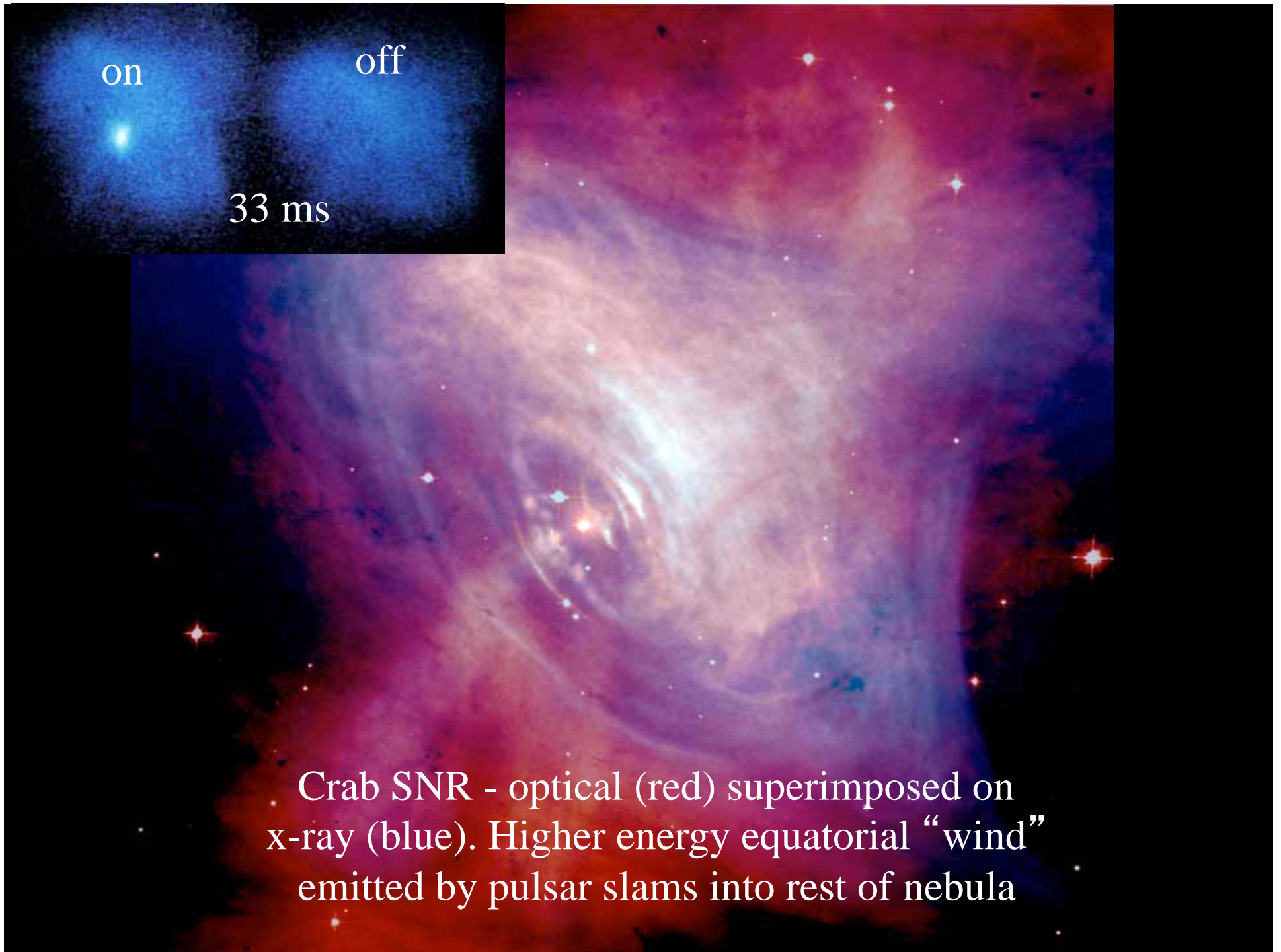
The Crab Nebula in Taurus (Type II)



HST 6 light years
across. SN 1054
2.0 kpc distant

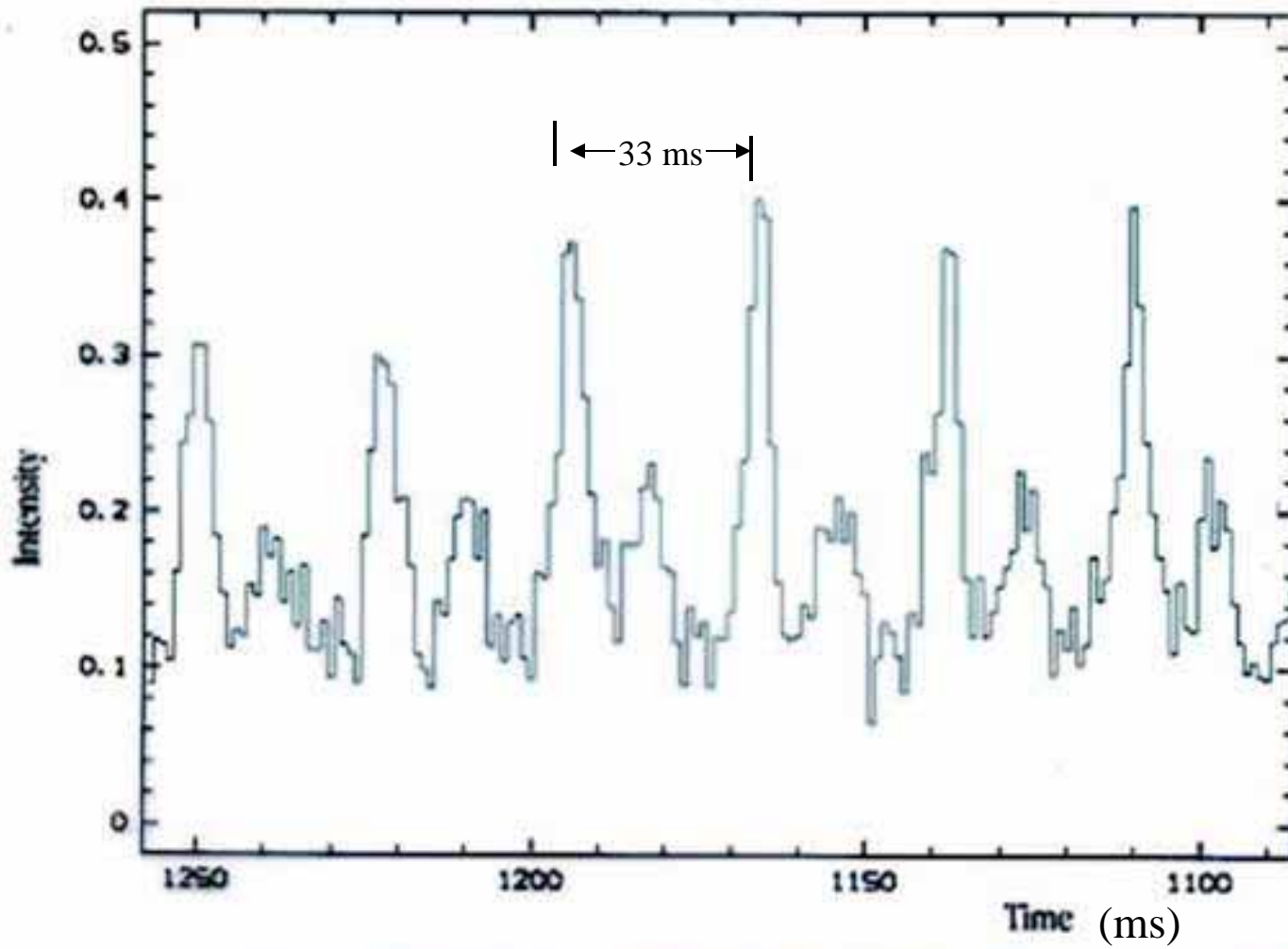
SN 1054 (The Crab)

- 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.



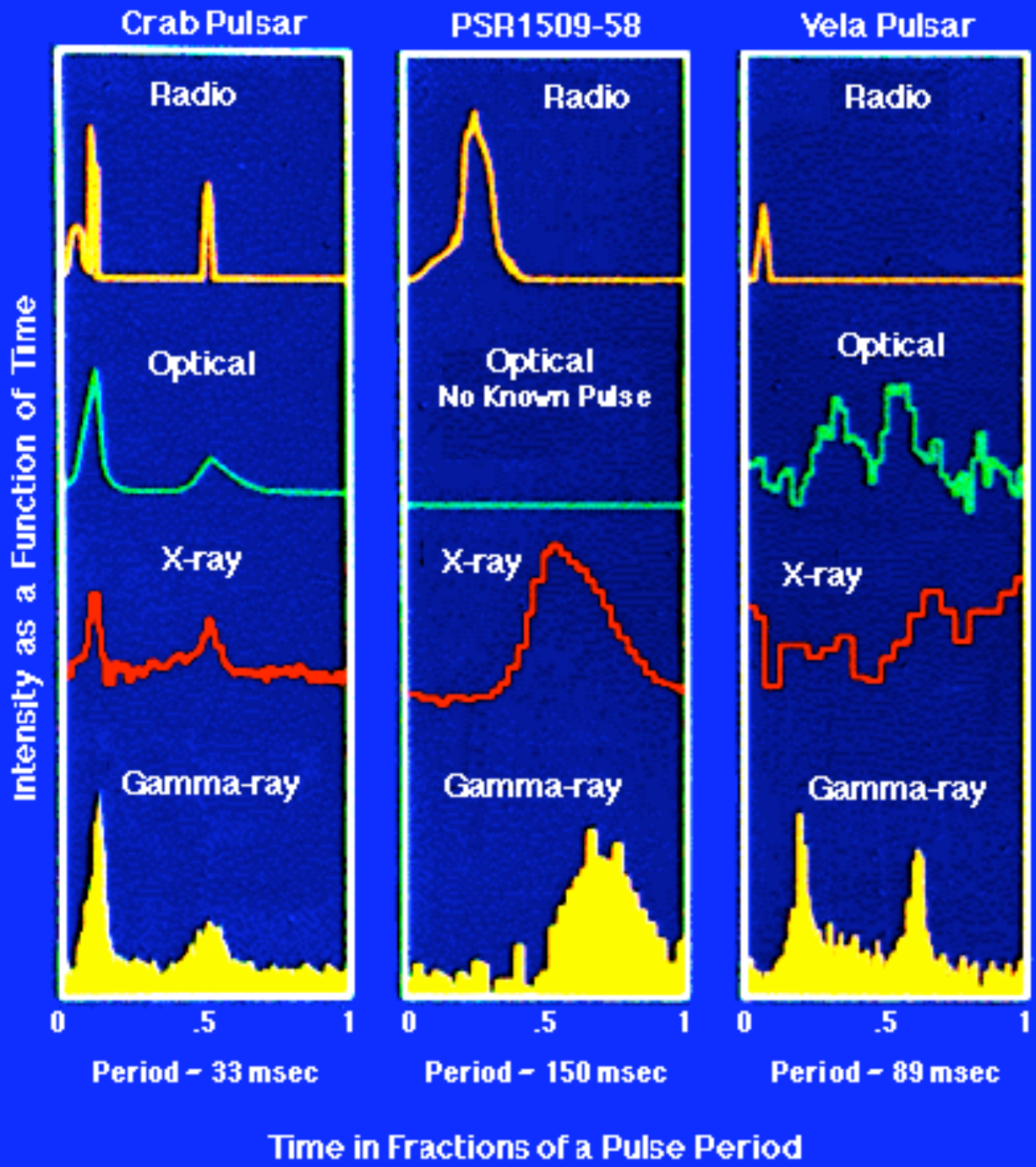
Crab SNR - optical (red) superimposed on x-ray (blue). Higher energy equatorial “wind” emitted by pulsar slams into rest of nebula

*Pulsars and
Neutron Stars*



Lightcurve of Crab Pulsar (VLT KUEYEN + FORS2 + FIERA)

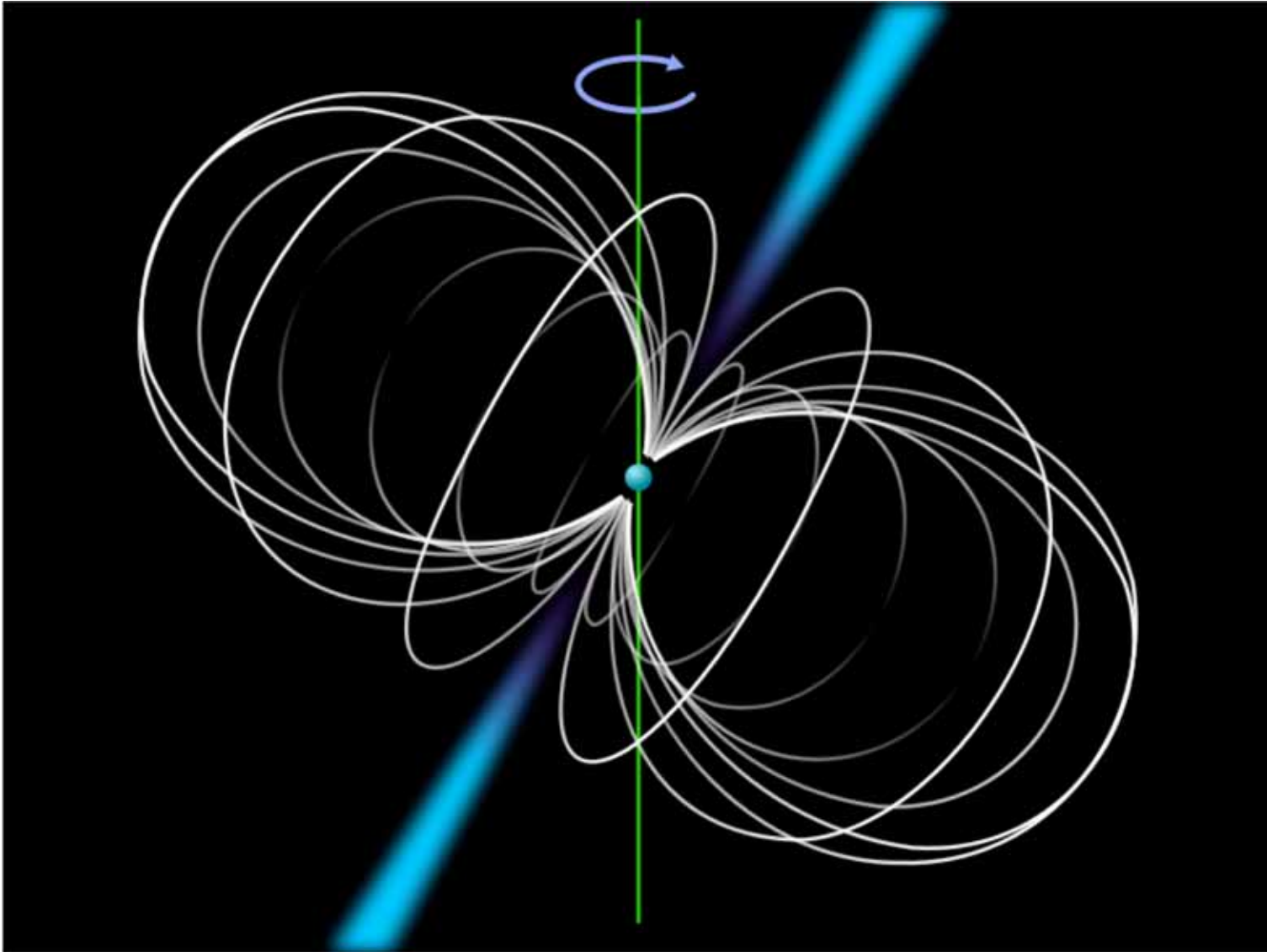


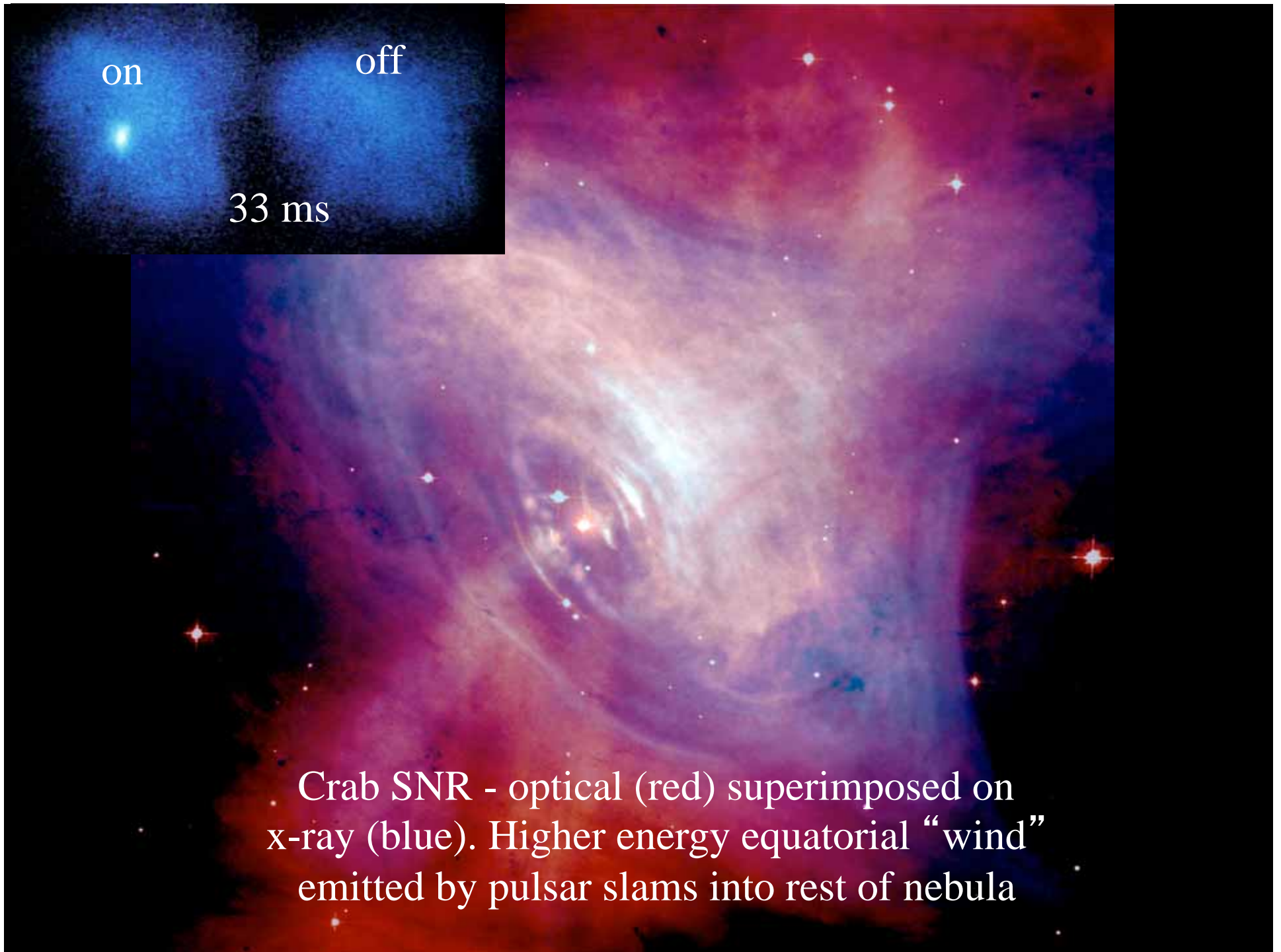


PULSARS

- Are rotating magnetic neutron stars with their rotational and magnetic axes not aligned. $B \sim 10^{12}$ 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). Concentrated towards Galactic disk. Gradually slowing.
- 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 $\sim 10^7$ years due to magnetic field decay and spin down.

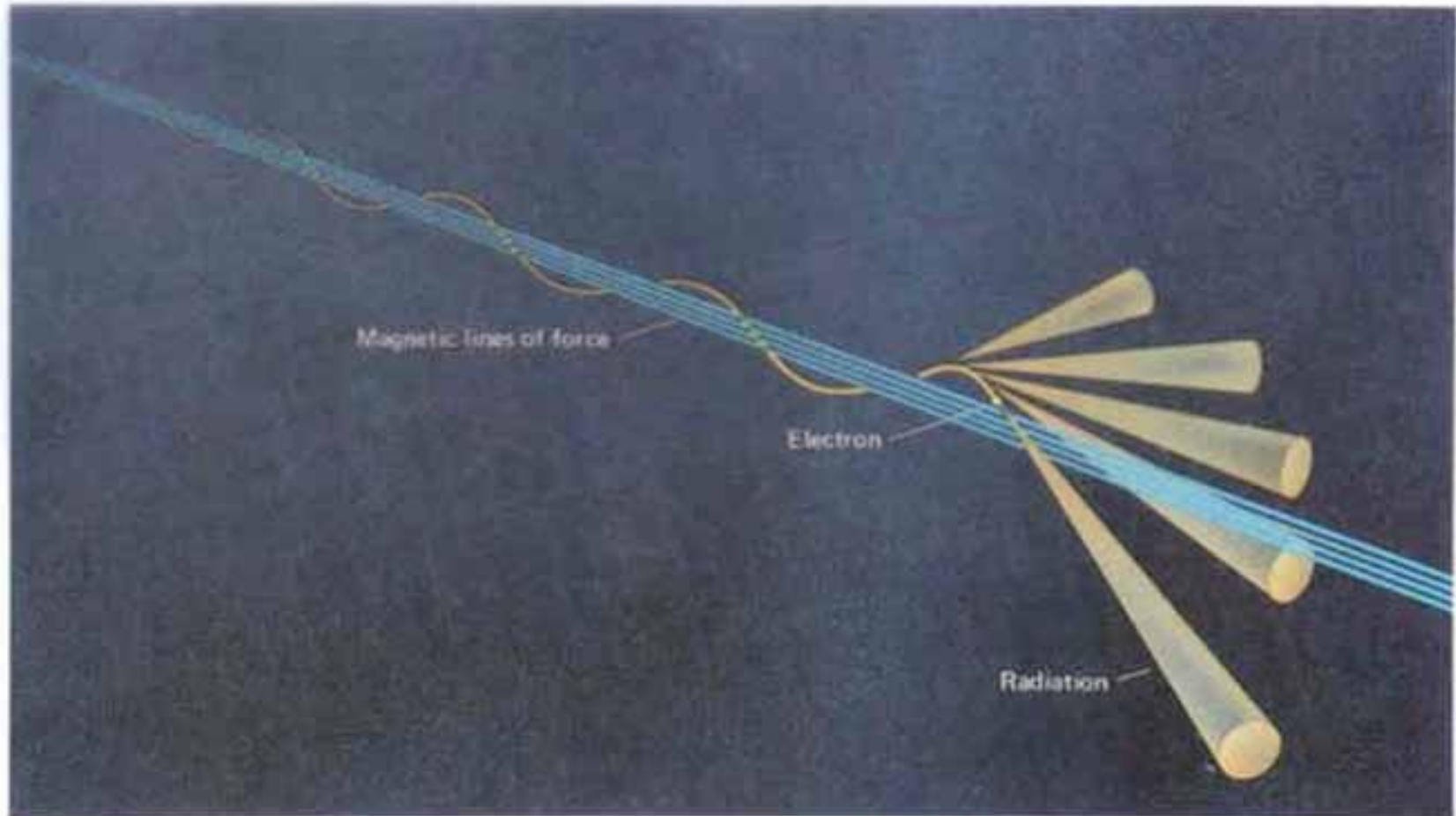
PULSAR

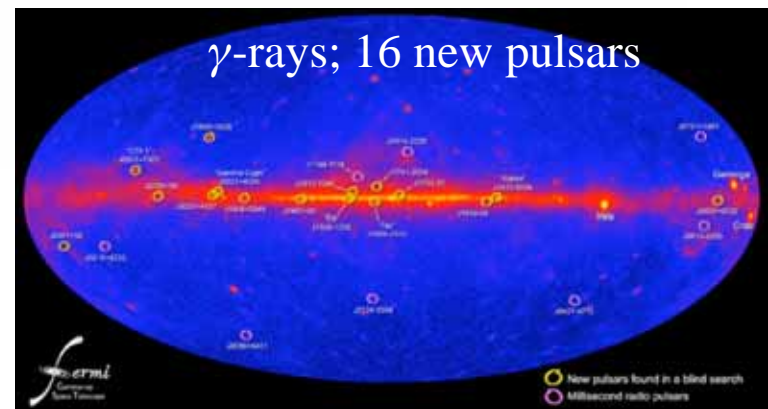
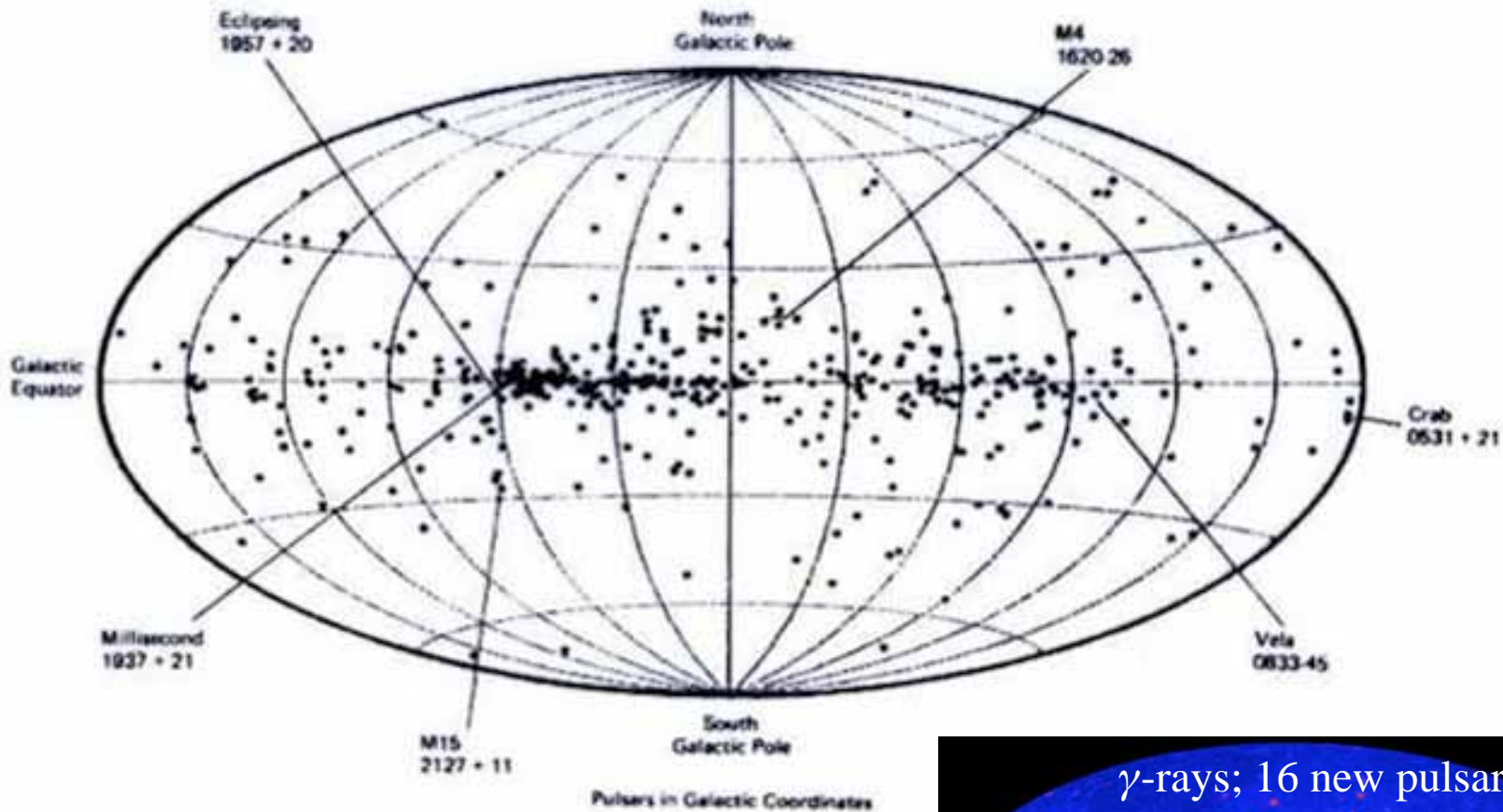




Crab SNR - optical (red) superimposed on x-ray (blue). Higher energy equatorial "wind" emitted by pulsar slams into rest of nebula

SYNCHROTRON RADIATION





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 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

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+-0.002	.19	25	0	-
B	4.3 +- .2	.36	66	0.0186	-
C	3.9+-0.2	.46	98	0.0252	-
D	.0004	2.6	1250		-

Thorsett and Chakrabarty, (1999)

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.

