Explosive end of a star

(masses $M > 8\ M_\odot$)

Death of massive stars

M > 8 M$_\odot$ nuclear reactions stop at Fe $\Longrightarrow$ contraction continues to ***T*** **= 10^{10} K**

(e^- degenerate gas cannot support the star for core mass ***M*****$_{core}$ > 1.4 M$_\odot$**)

$\Longrightarrow$ **Fe photo-disintegration** (production of α particles, neutrons, protons)

$\Longrightarrow$ energy absorbed, contraction goes faster, density grows to point when:

$e^- + p \rightarrow n + \nu_e$ $\Longrightarrow$ ***e*****$^-$ are removed**

support of e^- degenerate gas drops $\Longrightarrow$ collapse continues

$T = 10^{12}$ K, core **density 3×10^{17} kg/m^3** $\Longrightarrow$ neutron degeneracy pressure

$\Longrightarrow$ collapse suddenly **stops**

$\Longrightarrow$ **matter falling inward** at high high speed

matter bounces when core reached $\Longrightarrow$ **shock front outwards**

$\Longrightarrow$ **STAR EXPLODES (SUPERNOVA)**

$\Longrightarrow$ **STAR EXPLODES (SUPERNOVA)**

Not clear what happens, some or all of the following processes:

- Shock wave blows apart outer layer, mainly light elements
- Shock wave heats gas to $T = 10^{10}$ K $\Longrightarrow$ explosive nuclear reactions $\Longrightarrow$ fusion produce Fe-peak elements $\Longrightarrow$ outer layer blown apart
- Enormous amount of neutrinos formed. Most escape without interaction, some lift off mass in outer layer

External envelope falling inwards at speed up to **$v \sim$ 70,000 km/s**

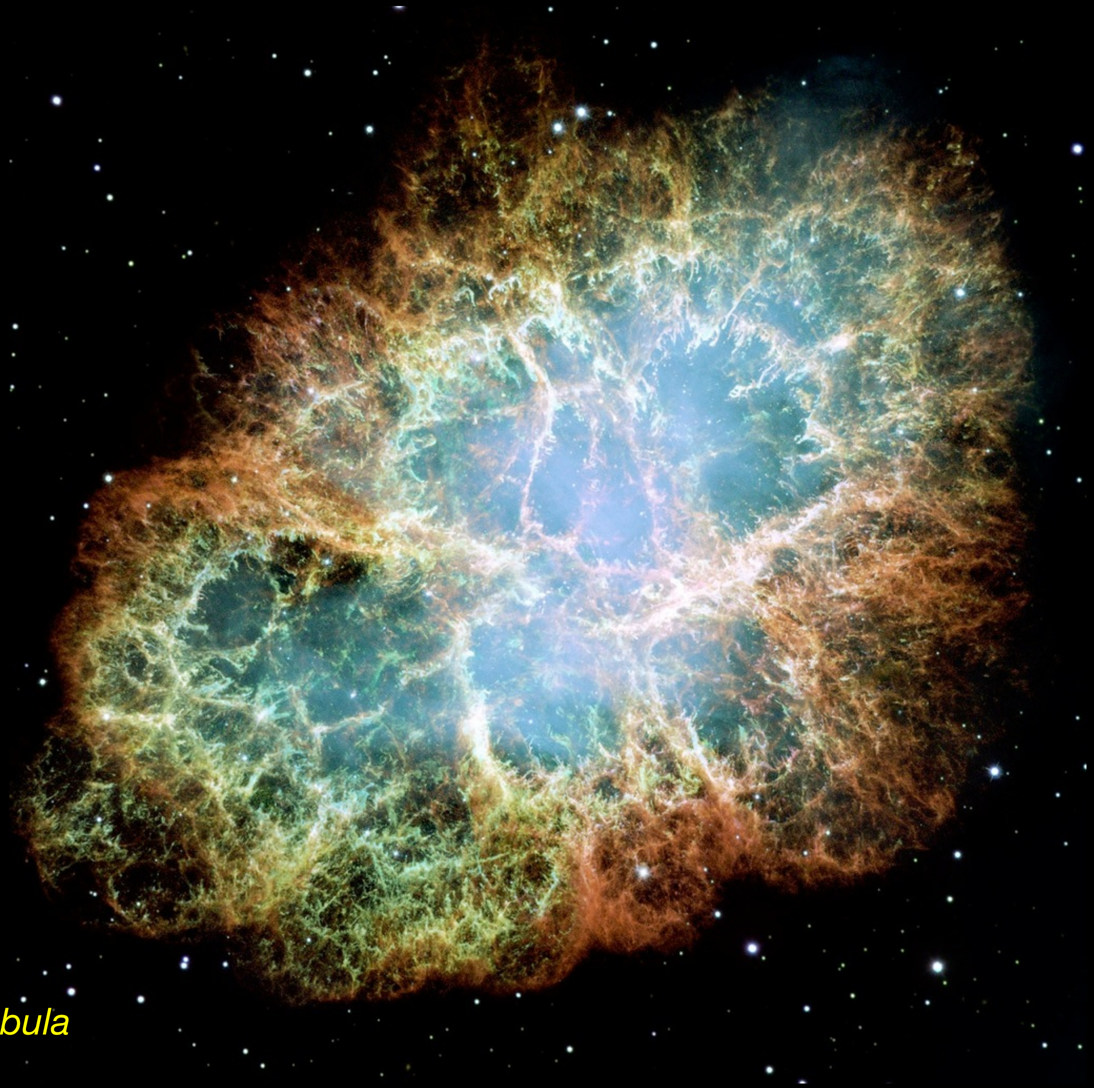
Bounce backward when core reached $\rightarrow$ Shock front outward

Star destroyed by explosion

Stellar explosion = supernova (computer simulation)

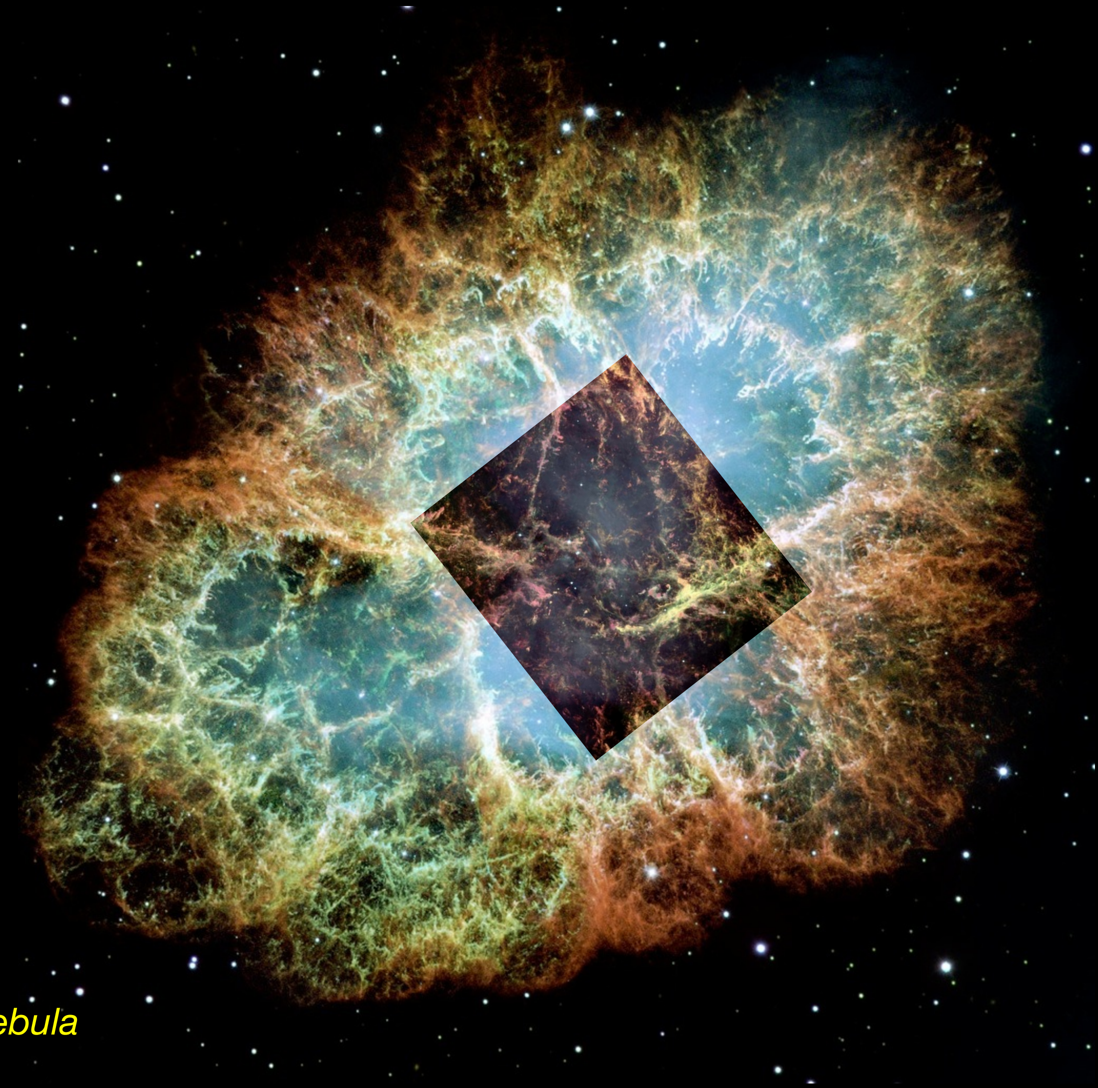
Video: https://www.youtube.com/watch?v=xVk48Nyd4zY

Final result of core collapse: **neutron star**



Supernova remnant: *Crab Nebula*
Distance: 6500 light years
Explosion seen in 1054
Size of the bubble: ~ 10 pc

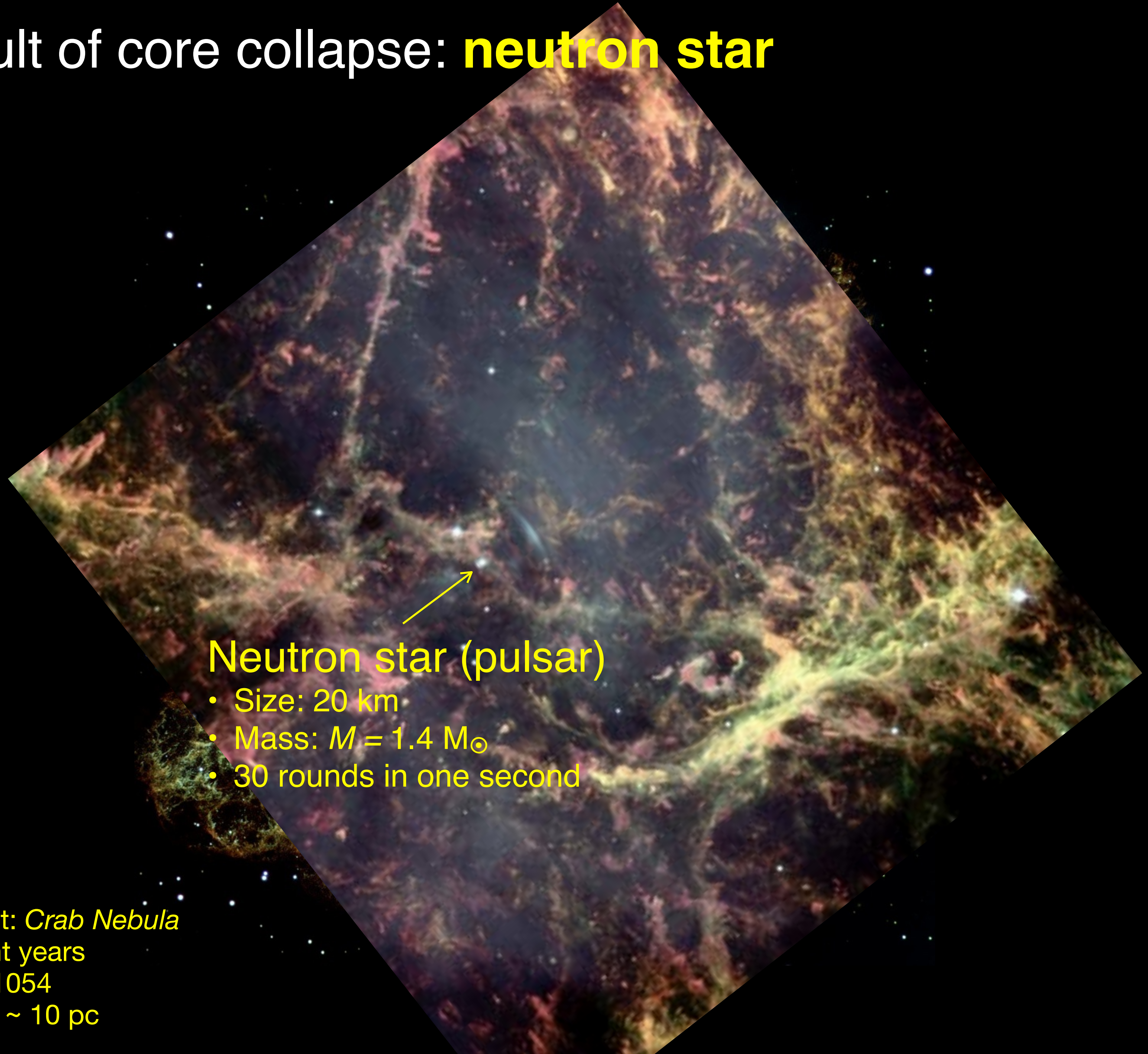
Final result of core collapse: **neutron star**



Supernova remnant: *Crab Nebula*
Distance: 6500 light years
Explosion seen in 1054
Size of the bubble: ~ 10 pc

X-ray (blue)
Optical (red)

Final result of core collapse: **neutron star**



Neutron star (pulsar)

- Size: 20 km
- Mass: $M = 1.4\ M_\odot$
- 30 rounds in one second

Supernova remnant: *Crab Nebula*
Distance: 6500 light years
Explosion seen in 1054
Size of the bubble: ~ 10 pc

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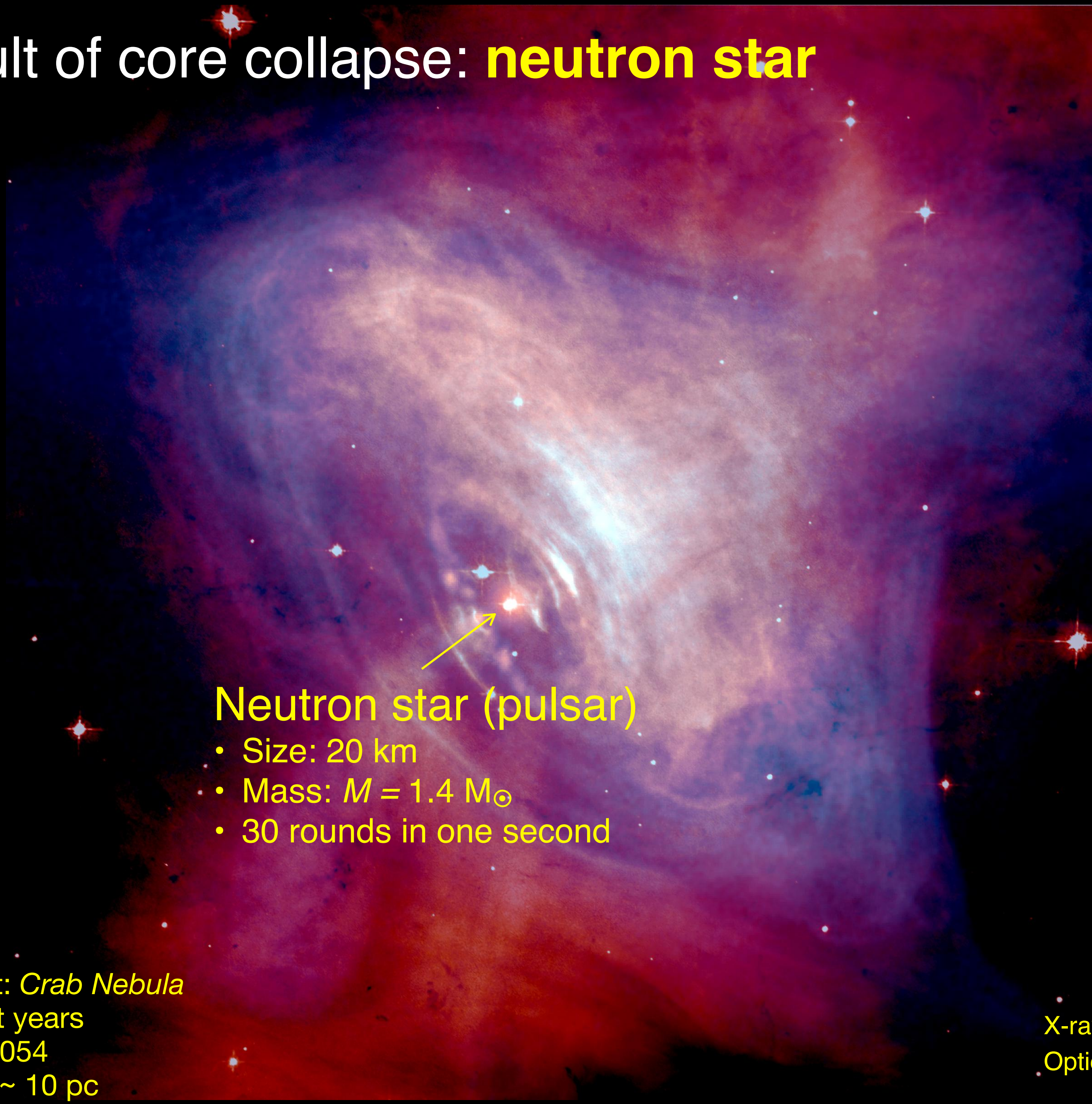

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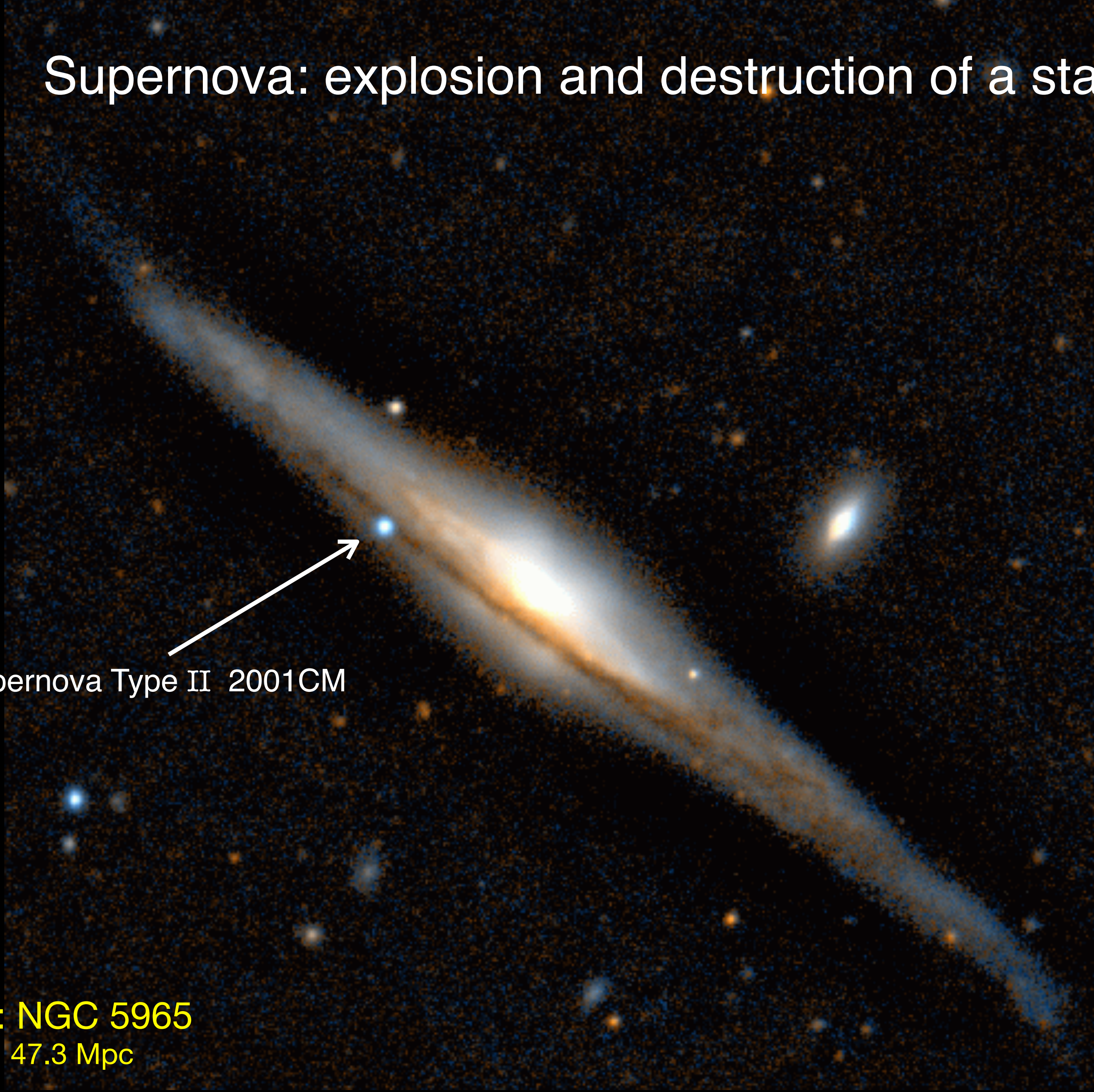
Supernova remnant: *Crab Nebula*
Distance: 6500 light years
Explosion seen in 1054
Size of the bubble: ~ 10 pc

X-ray (blue)
Optical (red)

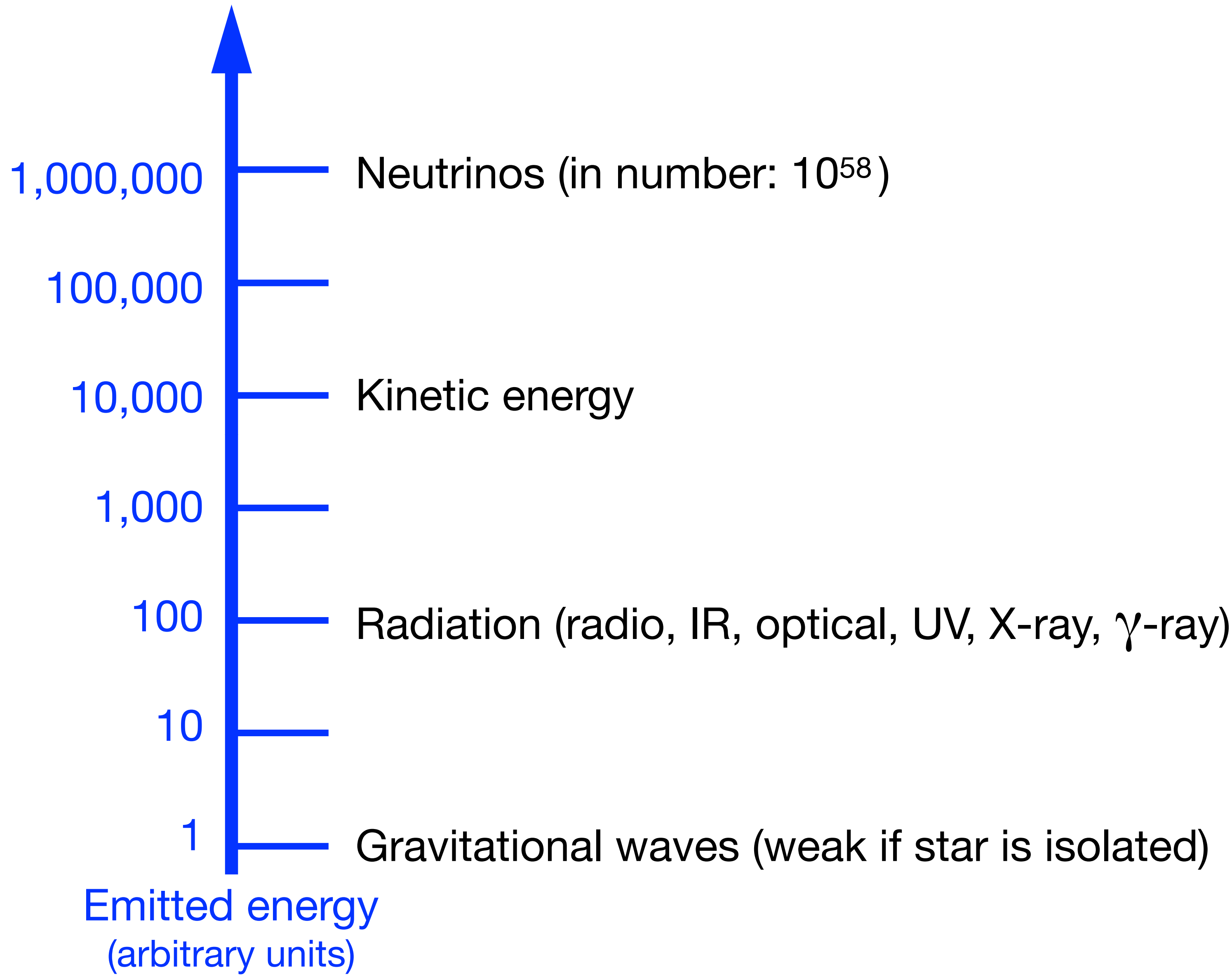
Supernova: explosion and destruction of a star



Galaxy: NGC 5965
Distance: 47.3 Mpc

Supernova: **energy production**

(very indicative relative numbers)



Supernovae: **energy emission**

Core collapse and supernova in seconds:

E (core collapse) ~ 10^{46} J (at least 99% in neutrinos)
E (kinetic energy of expanding ejected gas) ~ 10^{44} J
E (electromagnetic radiation) ~ 10^{42} J
Some *E* in *cosmic rays* (mostly protons, α particles, electrons)

Star brightens typically by 10^8 (20 mag)

Classification of supernovae:

Collapse of core of **massive star**:

Type II — H spectral lines. Supergiant core collapse

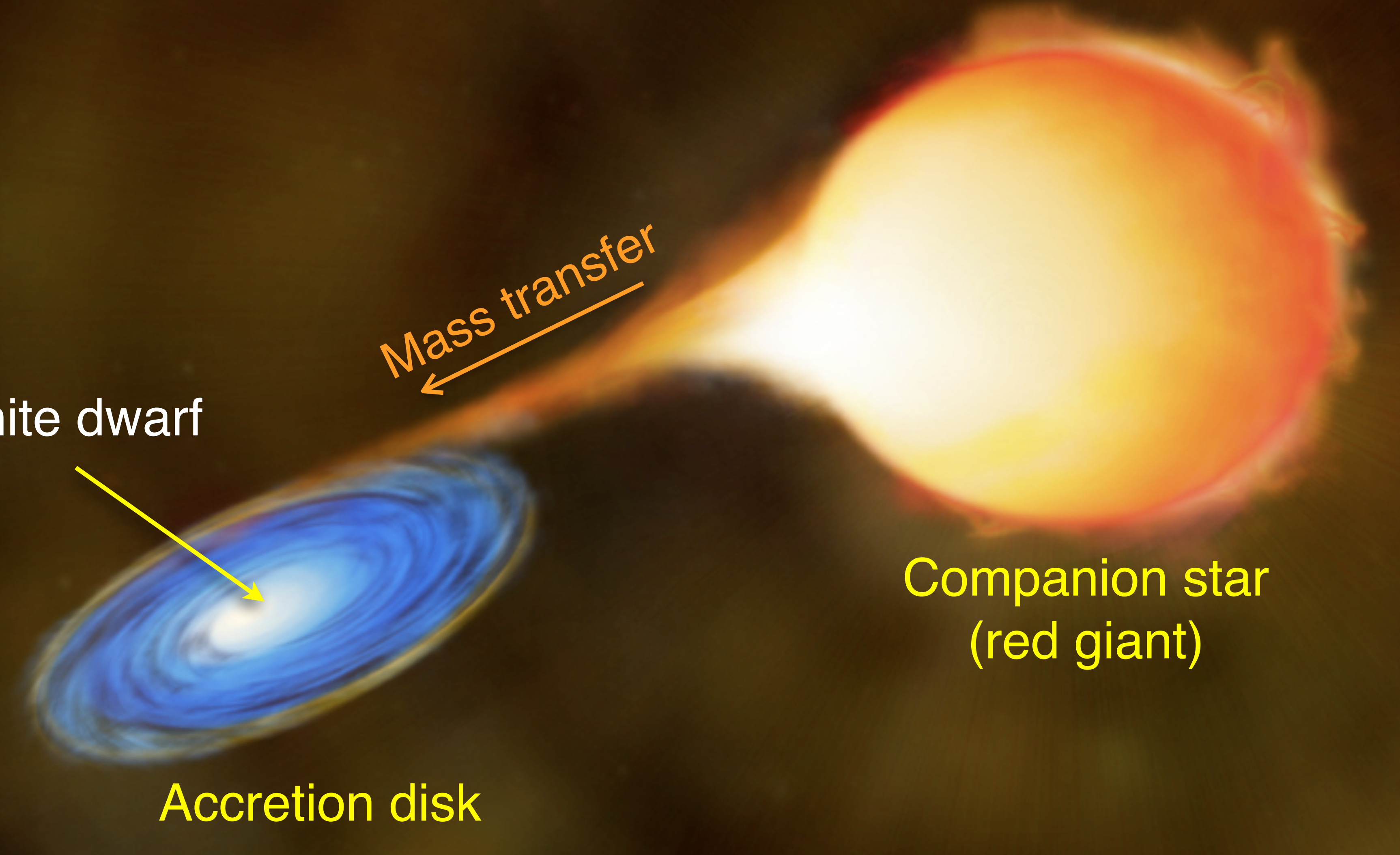
Type Ib, Ic — no H nor Si spectral lines (**no He for Ic**). Mass: $M = 30 \div 40\ M_\odot$, P_{rad} large enough $\Longrightarrow$ envelope lost by stellar wind

Type Ia — no H spectral lines, Si lines. **Binary system with white dwarf**

No core collapse
No massive star
(different kind of explosion)

Supernova type Ia: in binary system with white dwarf accreting mass

(different from explosion of massive star)

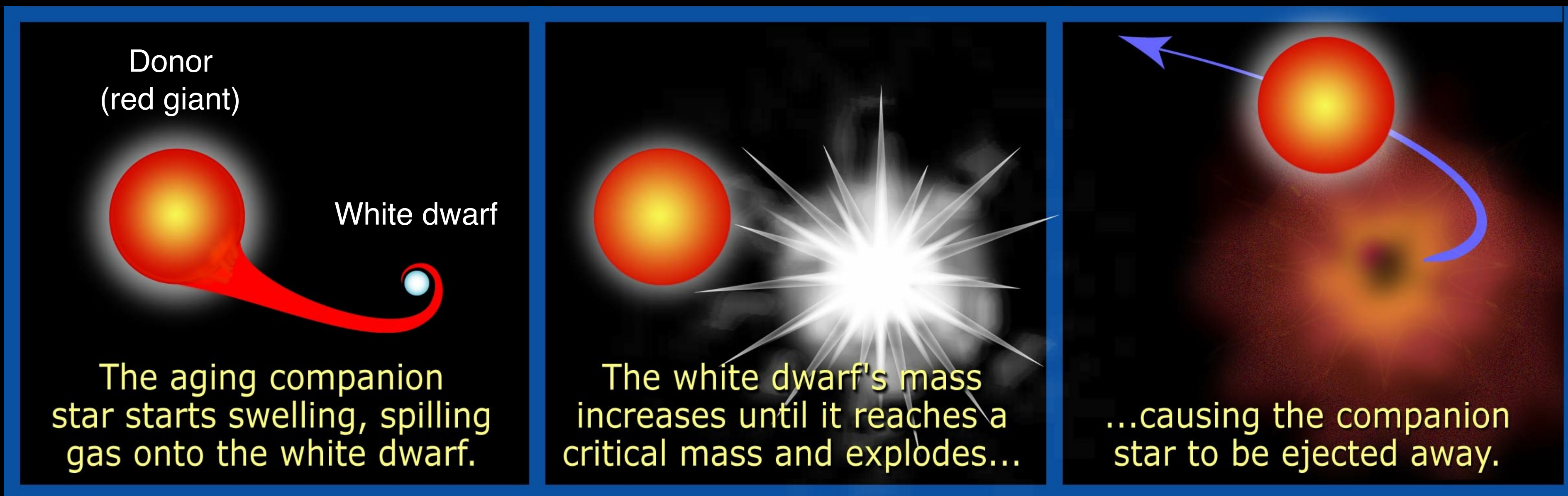


Explosion happens when mass of white dwarf exceeds ***Chandrasekhar limit:*** $\boldsymbol{M = 1.4\ M_{\odot}}$

(artist's impression)

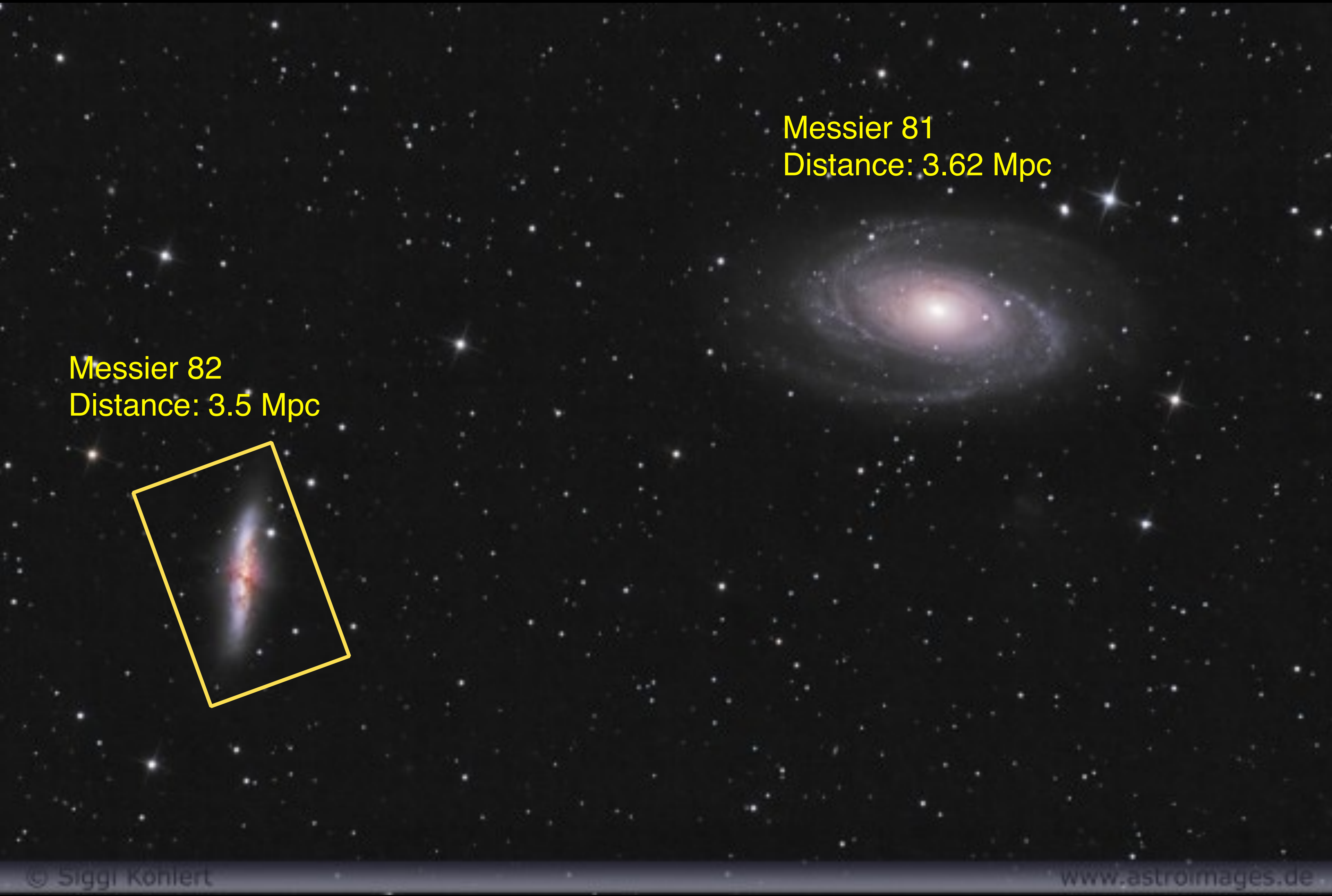
Explosion happens when mass of white dwarf exceeds

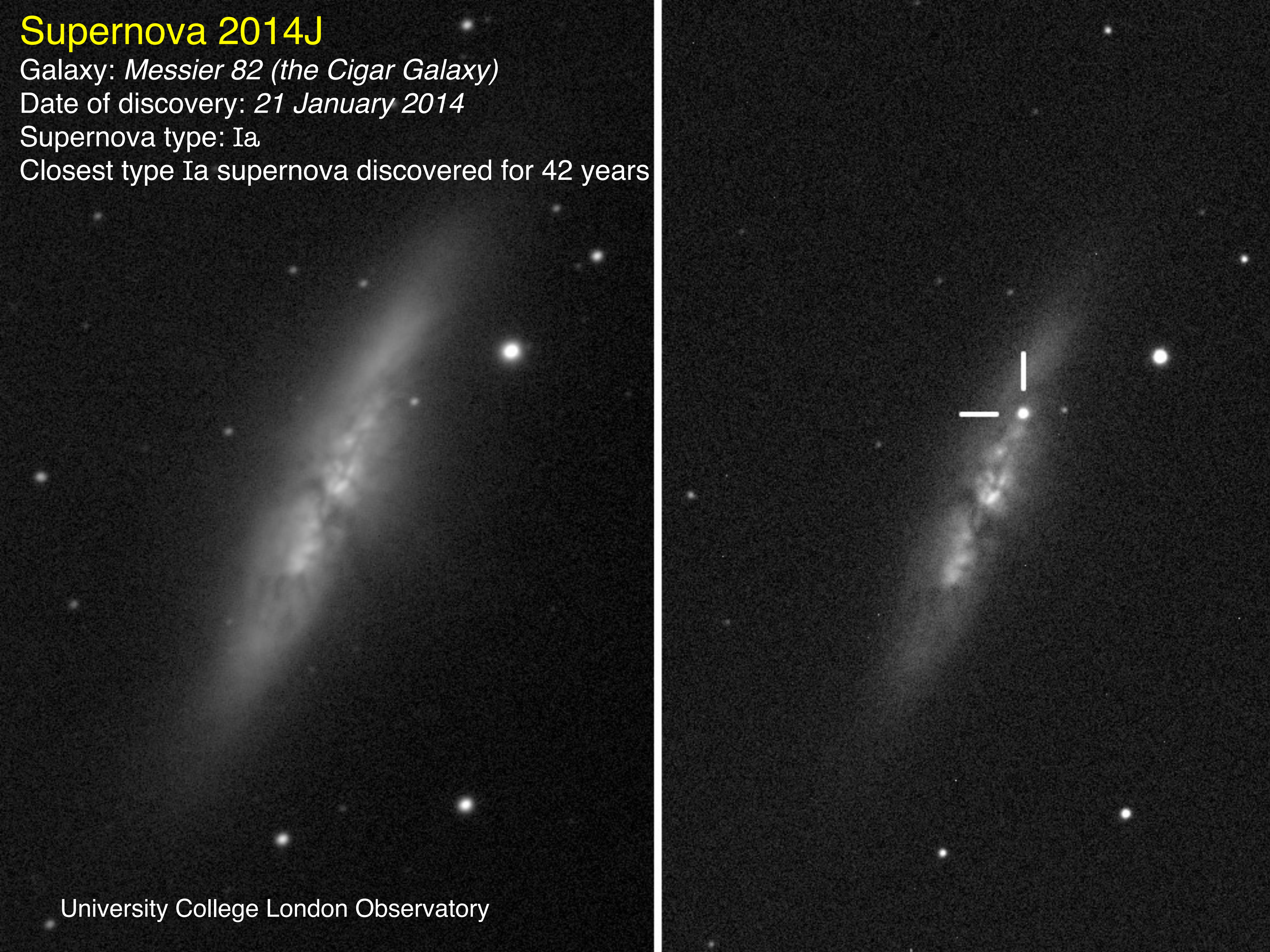
Chandrasekhar limit: $M = 1.4\ M_{\odot}$



$T = 10^{10}$ K in core reached, nuclei converted into Fe, Co, Ni

Lighter elements (Si or Ca) produced moving outwards


Messier 81
Distance: 3.62 Mpc
Messier 82
Distance: 3.5 Mpc
© Siggi Kohlert
www.astroimages.de


Supernova 2014J
Galaxy: *Messier 82 (the Cigar Galaxy)*
Date of discovery: *21 January 2014*
Supernova type: Ia
Closest type Ia supernova discovered for 42 years
University College London Observatory

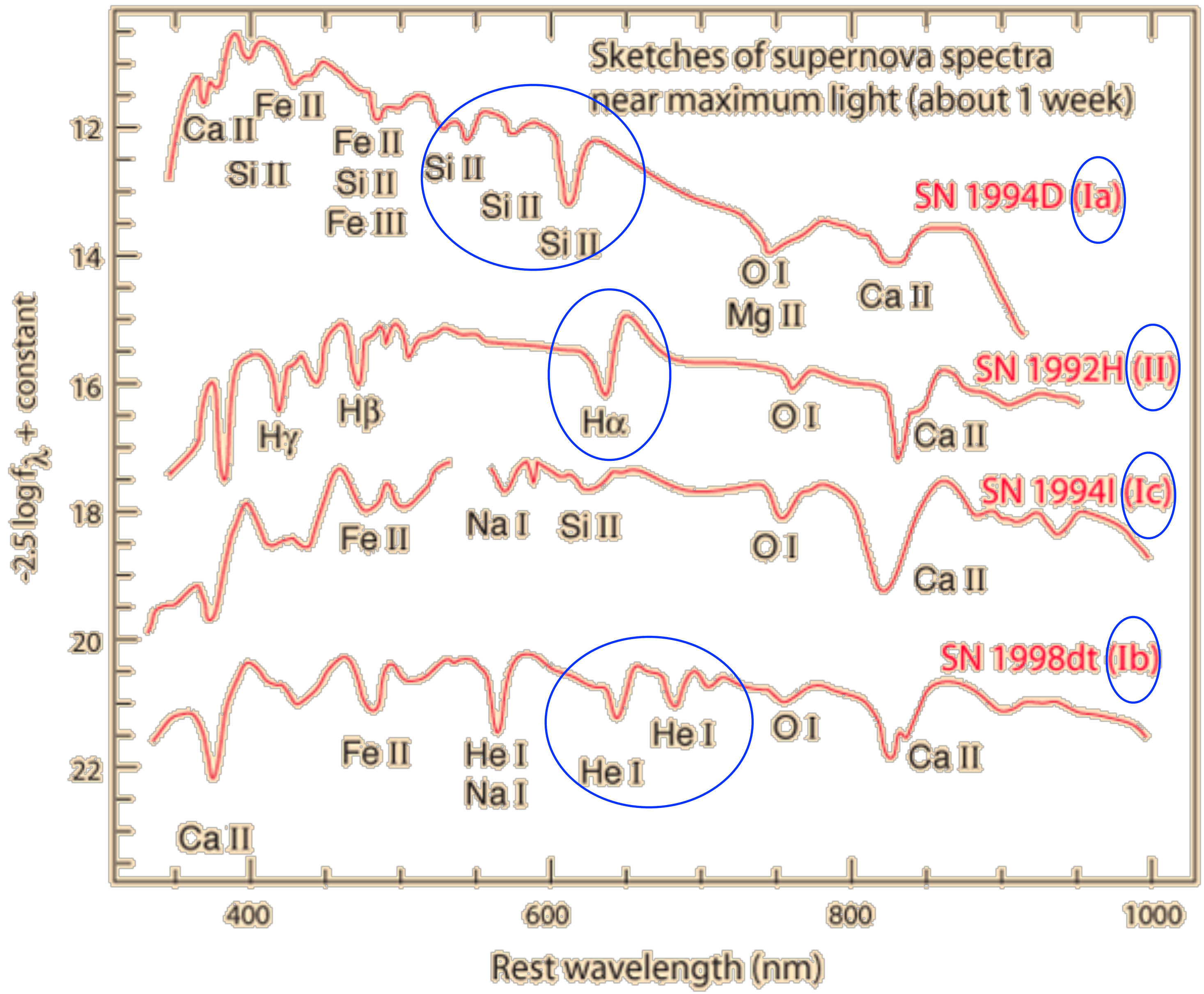
Images obtained with the Hubble Space Telescope

Supernova 2014J in Galaxy M82

NASA and ESA

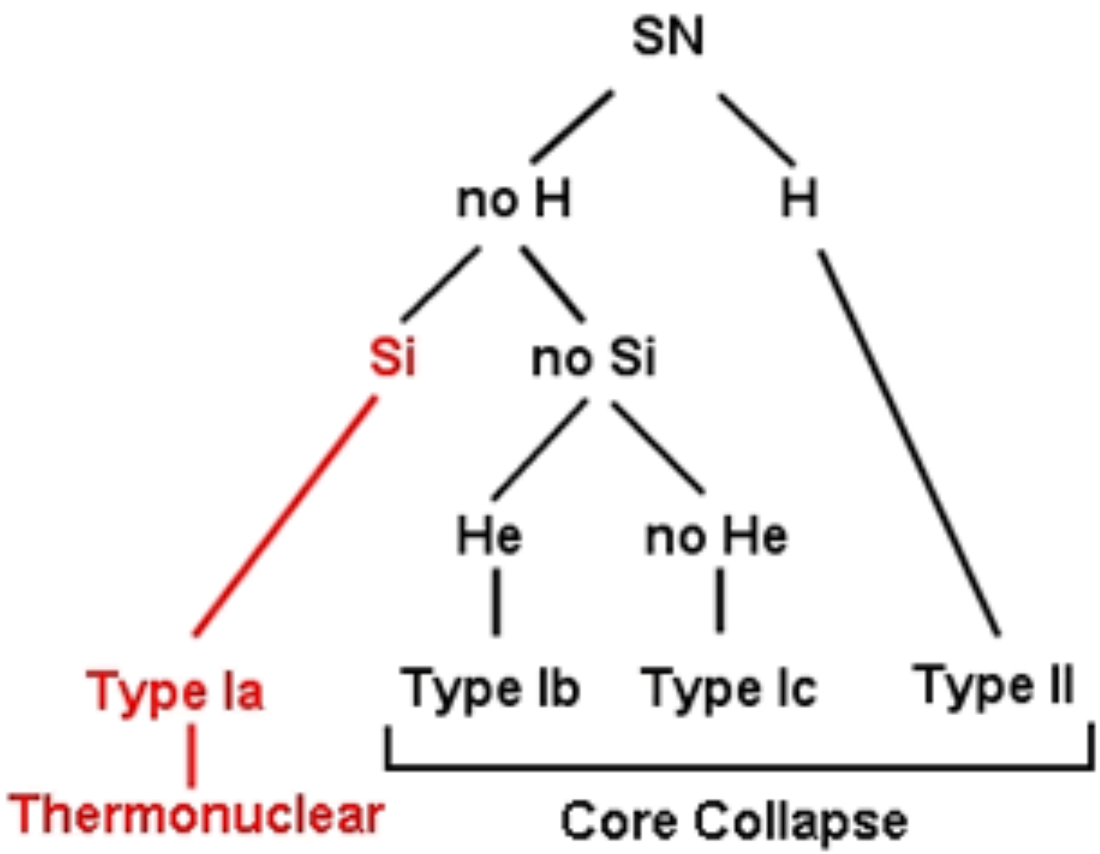
Images obtained with the Hubble Space Telescope

Supernovae (SN) spectral classification

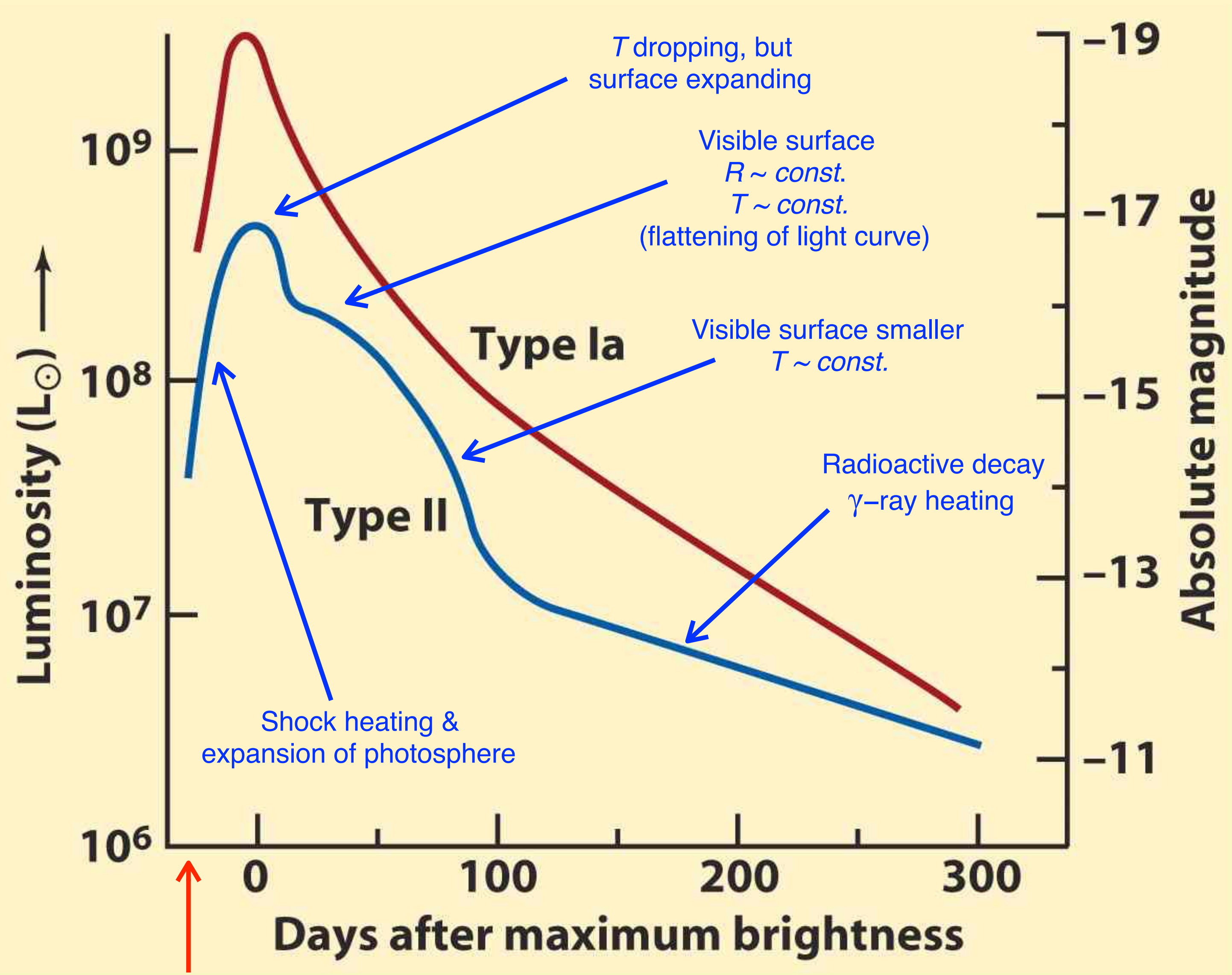


In SN Ic:
no H, Si, He

Supernovae (SN) spectral classification



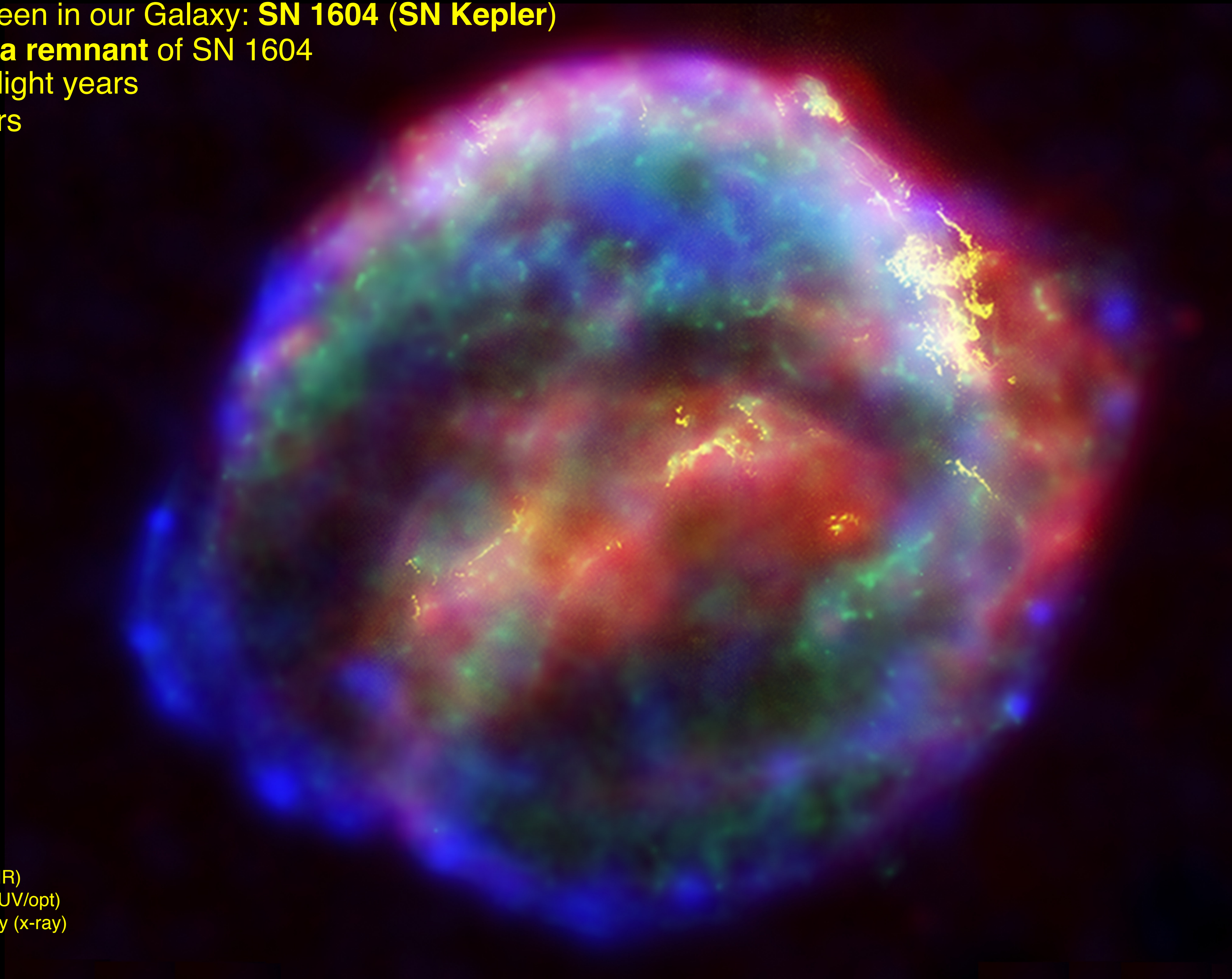
Supernova **light curves**



Explosion happens before
max luminosity is reached

Supernova rate in our Galaxy

Last supernova seen in our Galaxy: **SN 1604** (**SN Kepler**)
Today: **supernova remnant** of SN 1604
Distance: 20 000 light years
Size: 14 light years



Spitzer Space Telescope (IR)
Hubble Space Telescope (UV/opt)
Chandra X-ray Observatory (x-ray)

Supernova rate in our Galaxy

The number of supernovae discovered in the Milky Way in the **last one thousand years is 6**

Name	Year of explosion	Distance (light years)	Type
Lupus (SN1006)	1006	4600	Ia
Crab	1054	6500	II
3C58 (SN1181)	1181 ?	8500	II
Tycho	1572	8200	Ib
Kepler (SN1604)	1604	20000	Ib/II
Cassiopea A	1658 ?	11000	Ib?/IIb

Supernova rate in our Galaxy

Not all supernovae have been seen

- Conversion to supernova rate:
  - Assumes 6 SNe/1000 years (alternatively: 7/2000)
  - Assumes 85% sky coverage (region behind *Galaxy Center* not accessible)
  - Model $\Longrightarrow$ 11% of SNe are Brighter than $m_V = 0$ (seen by naked eye)

$\Longrightarrow$ SN Rate = (6/0.11/0.85)/1000 = 6.42 SNe/100 years

(7/0.11/0.85)/2000 = 3.74 SNe/100 years

- Alternative SN rate studies:
  - Other Spiral Galaxies

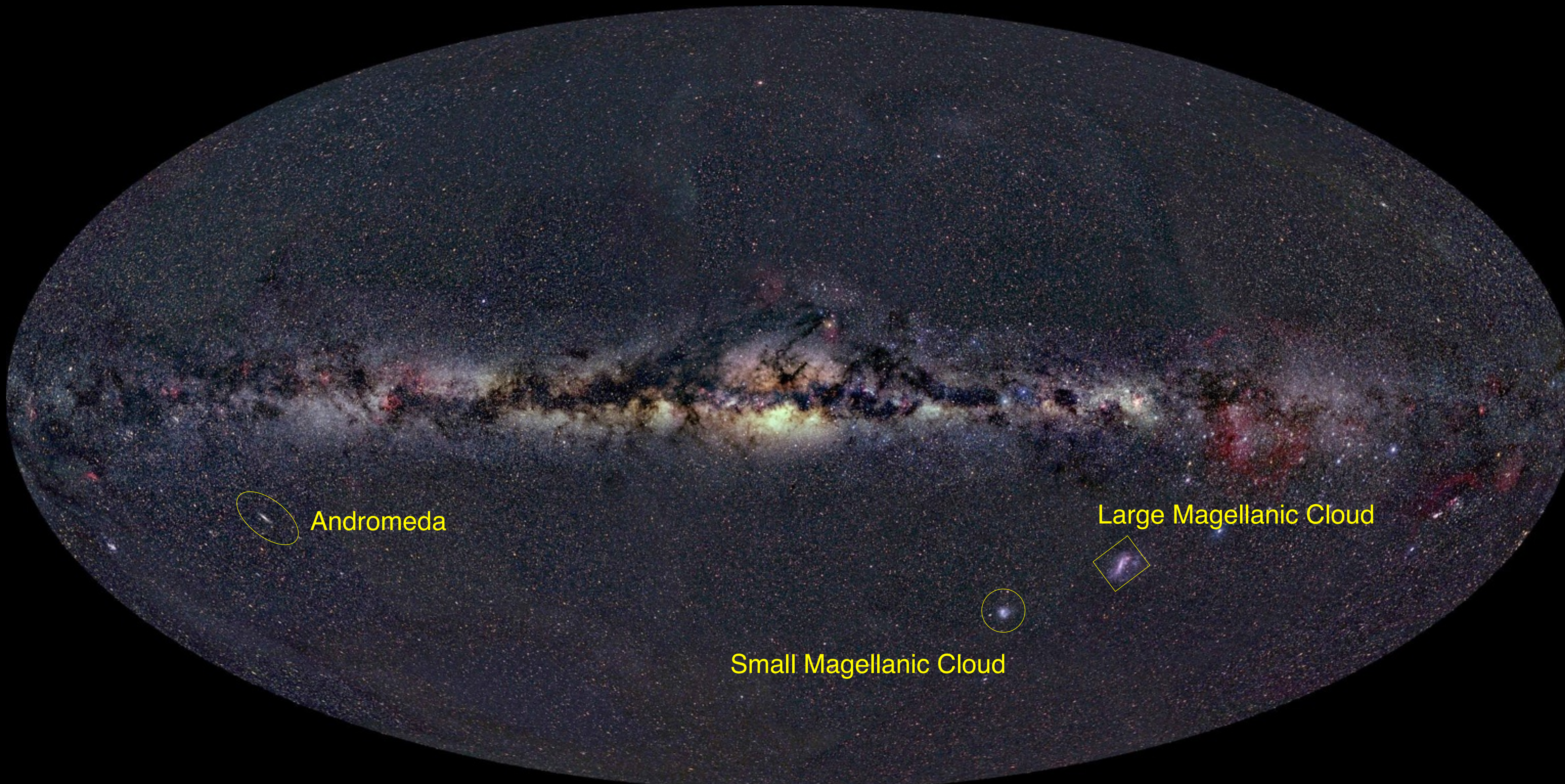
$\Longrightarrow$ SN Frequency ~ 1/30 years on average

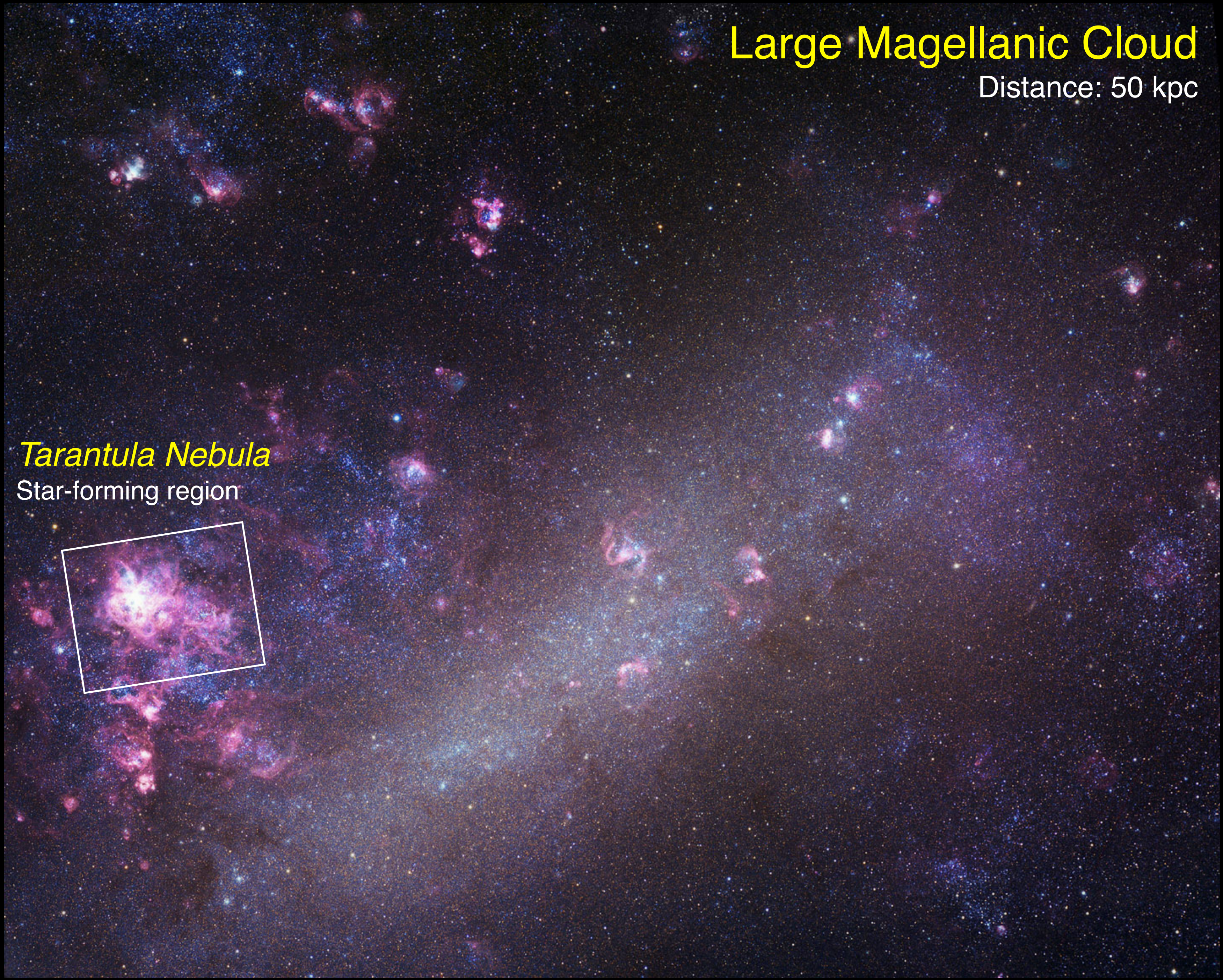
We are waiting for the next supernova in our Galaxy!

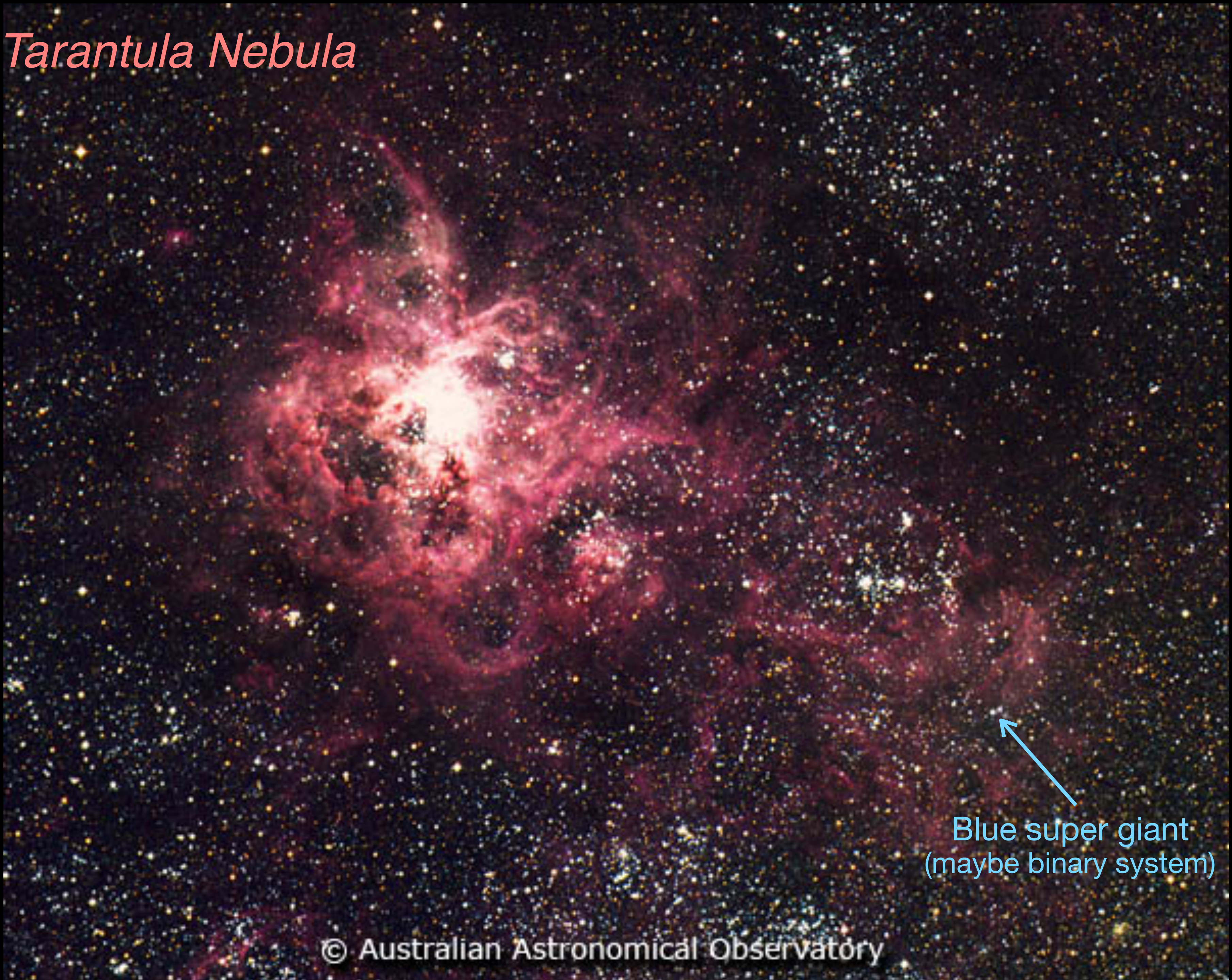
Supernova 1987A: the most recent & closest supernova

(Type II, core-collapse)

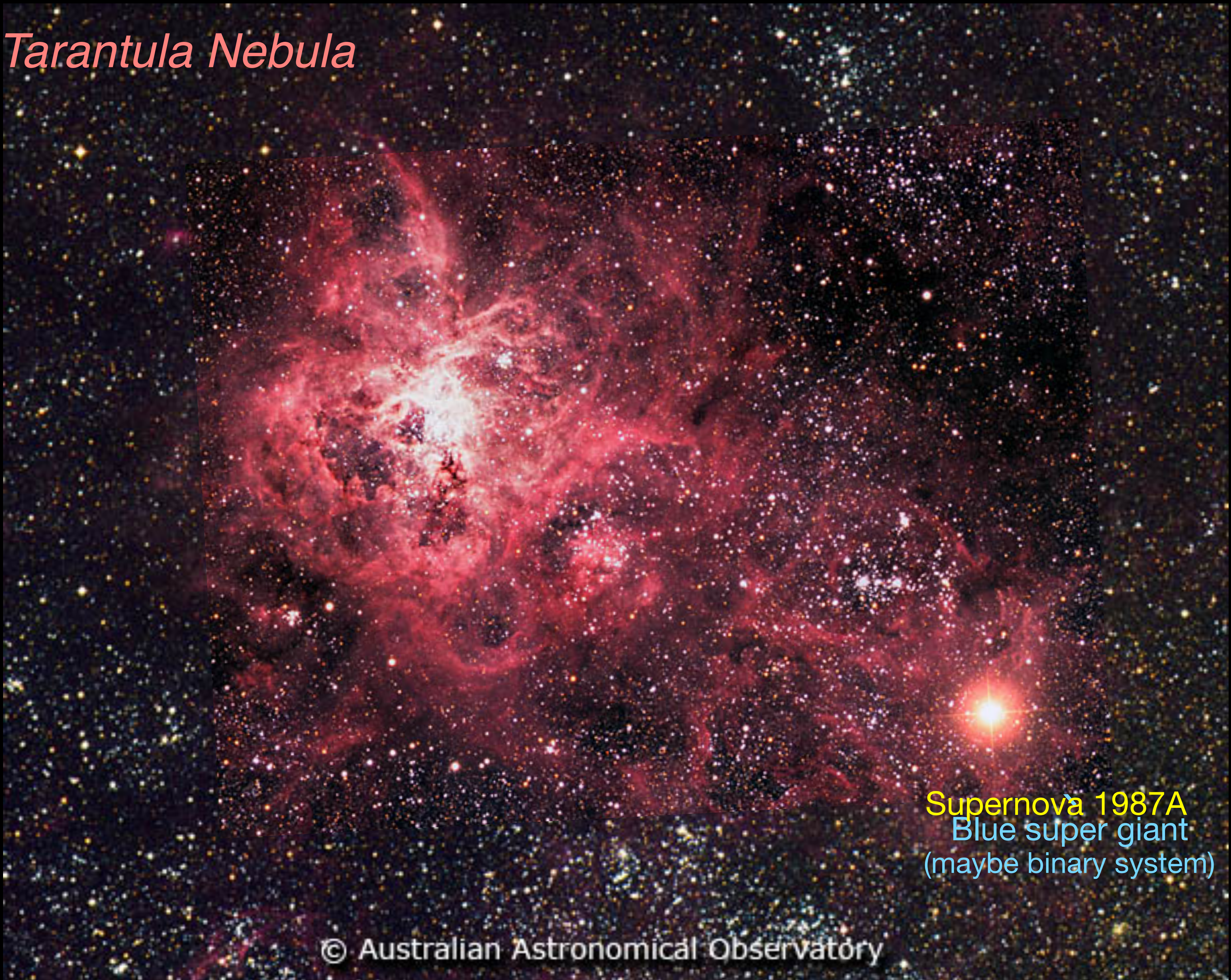
Our Galaxy: the Milky Way




Large Magellanic Cloud
Distance: 50 kpc
Tarantula Nebula
Star-forming region


Tarantula Nebula
Blue super giant
(maybe binary system)
© Australian Astronomical Observatory

Tarantula Nebula



Neutrino detection from Supernova 1987A

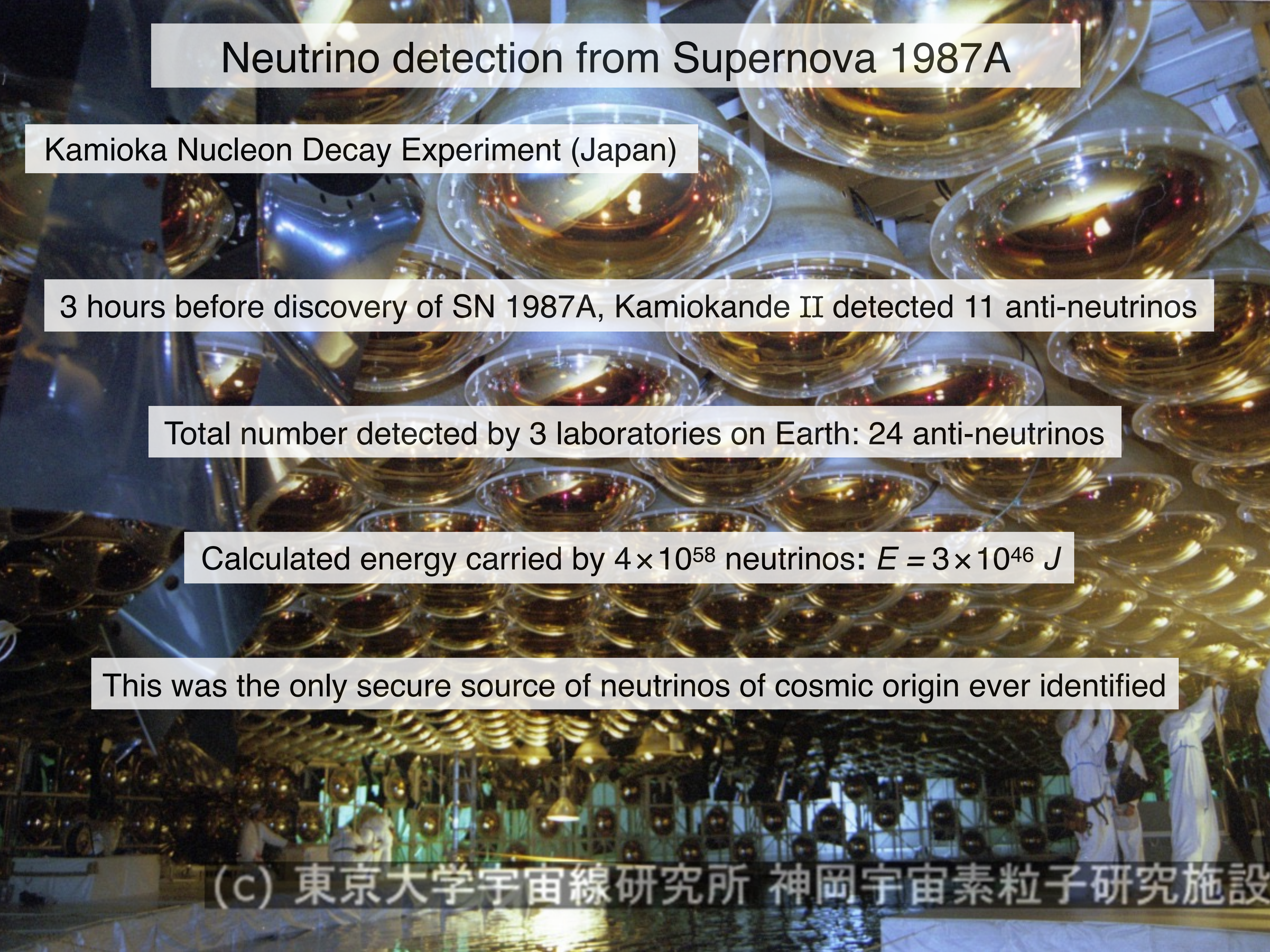
Kamioka Nucleon Decay Experiment (Japan)

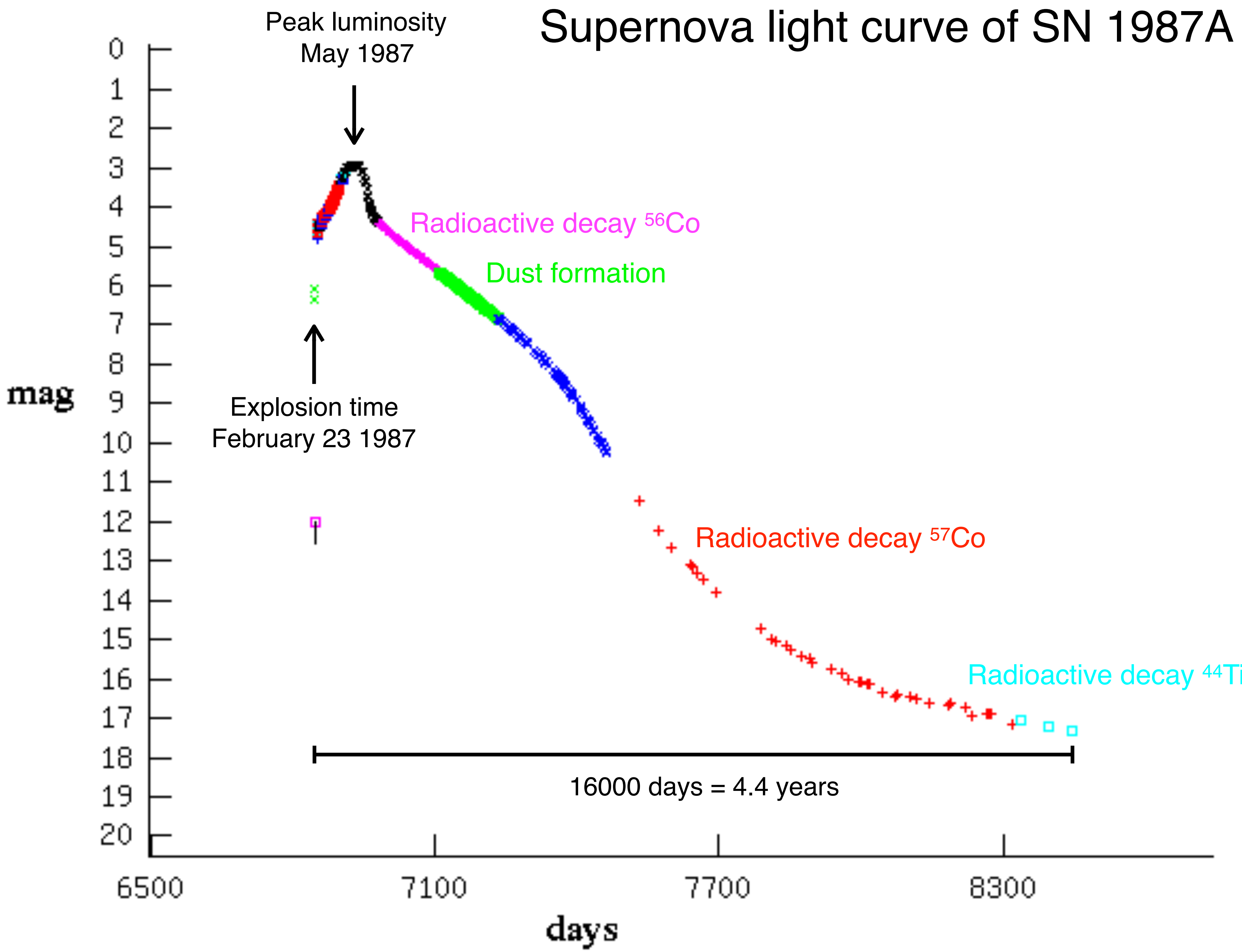
3 hours before discovery of SN 1987A, Kamiokande II detected 11 anti-neutrinos

Total number detected by 3 laboratories on Earth: 24 anti-neutrinos

Calculated energy carried by 4×10^{58} neutrinos: $E = 3\times10^{46}\ J$

This was the only secure source of neutrinos of cosmic origin ever identified




Supernova light curve of SN 1987A
Peak luminosity
May 1987
Radioactive decay 56Co
Dust formation
Explosion time
February 23 1987
Radioactive decay 57Co
Radioactive decay 44Ti
16000 days = 4.4 years
mag
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
6500
7100
7700
8300
days


Supernova 1987A in recent times
(supernova remnant)
All 3 rings were created ~ 20 000 years before supernova explosion
Shock waves from explosion heat them up causing bright glow

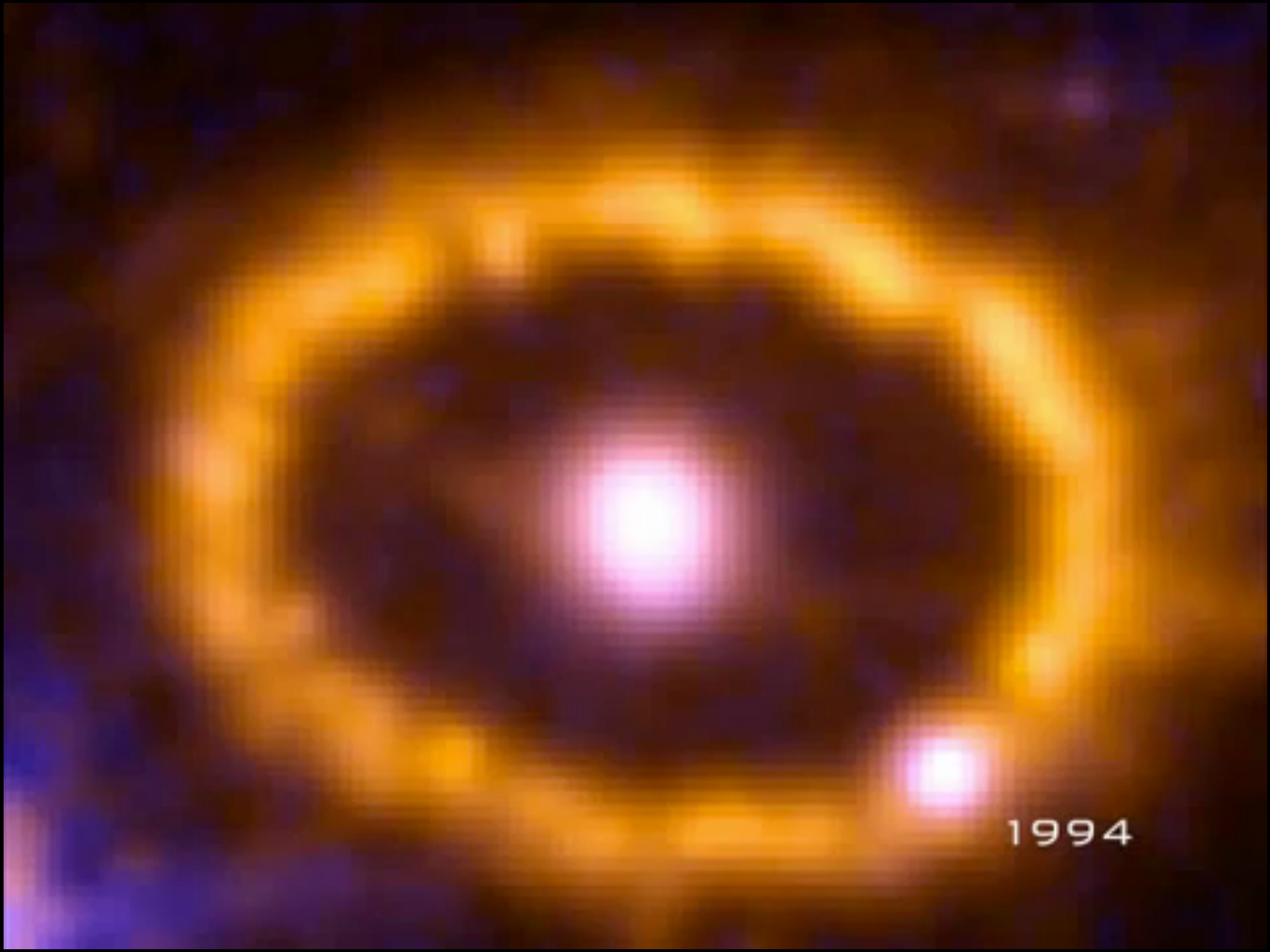
Supernova 1987A in recent times

(supernova remnant)

3D movie reconstructing movie

video: https://www.eso.org/public/hungary/videos/eso1032a/?lang

Supernova 1987A internal ring 1994 - 2006



Video: https://www.youtube.com/watch?v=P1zH146iyiM

Production of chemical elements in galaxies

Chemical composition after primordial nucleosynthesis (20 minutes after Big Bang)

Element	Mass(X) / Mass(total)
H	0.78
He	0.22
Z	$< 10^{-9}$

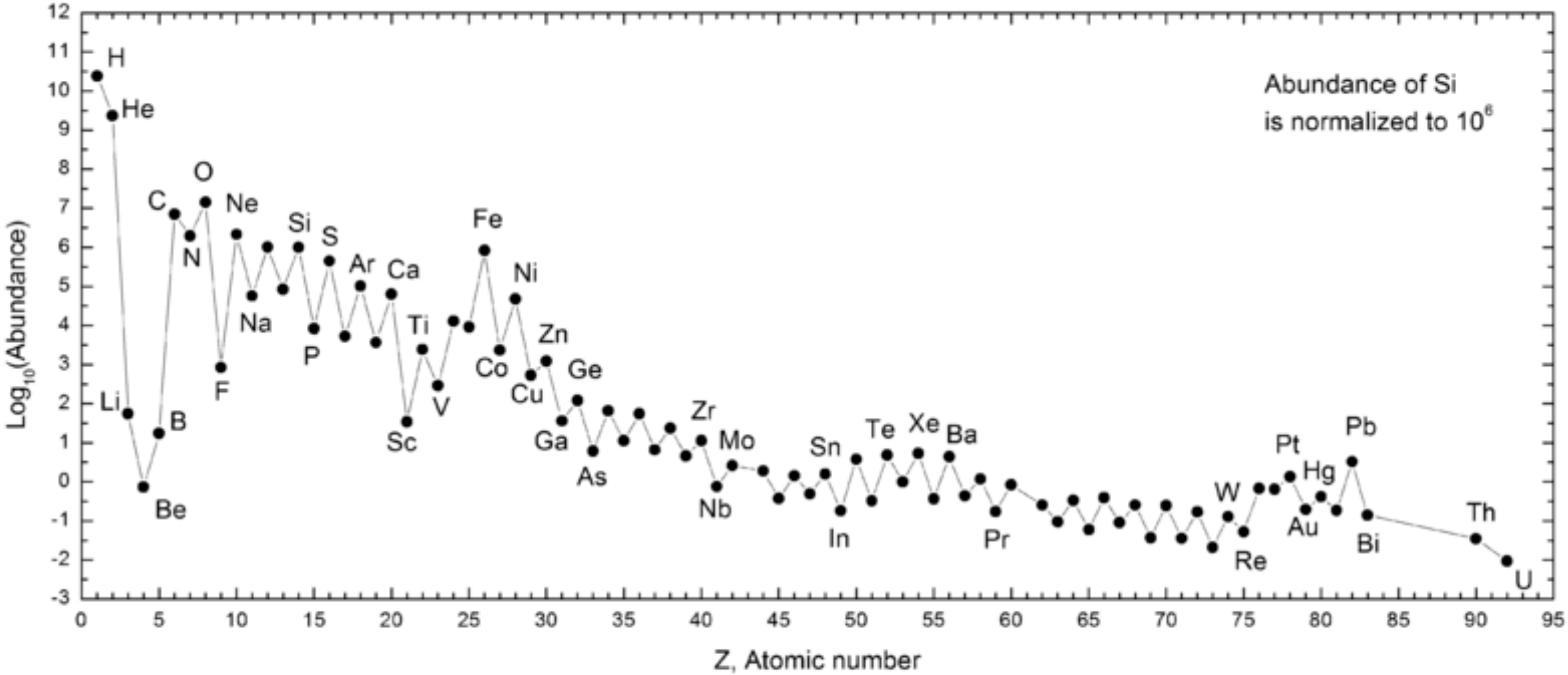
Z: all elements heavier than helium (called metals)

Cosmic cycling of matter (and chemical enrichment) happened
3 times in the history of the universe (Population III, II I)
The Sun is last and 3rd generation star (**Population I**)

Abundances of chemical elements in the Solar system (13.7 Gyr later)

Element	Mass(X) / Mass(total)
H	0.74
He	0.25
Z	0.014

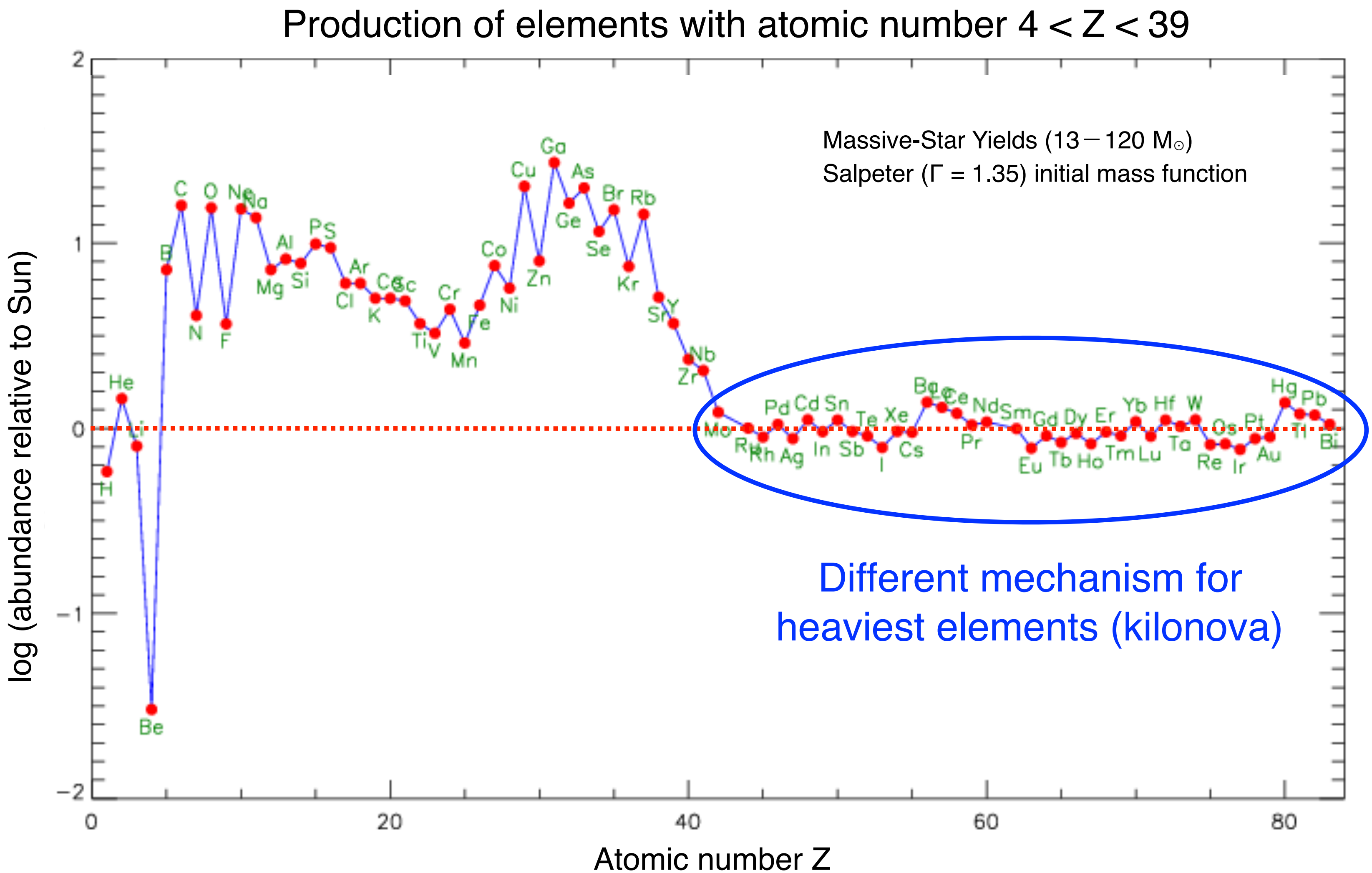
Abundances of chemical elements in the Sun
(they are from proto-stellar system)



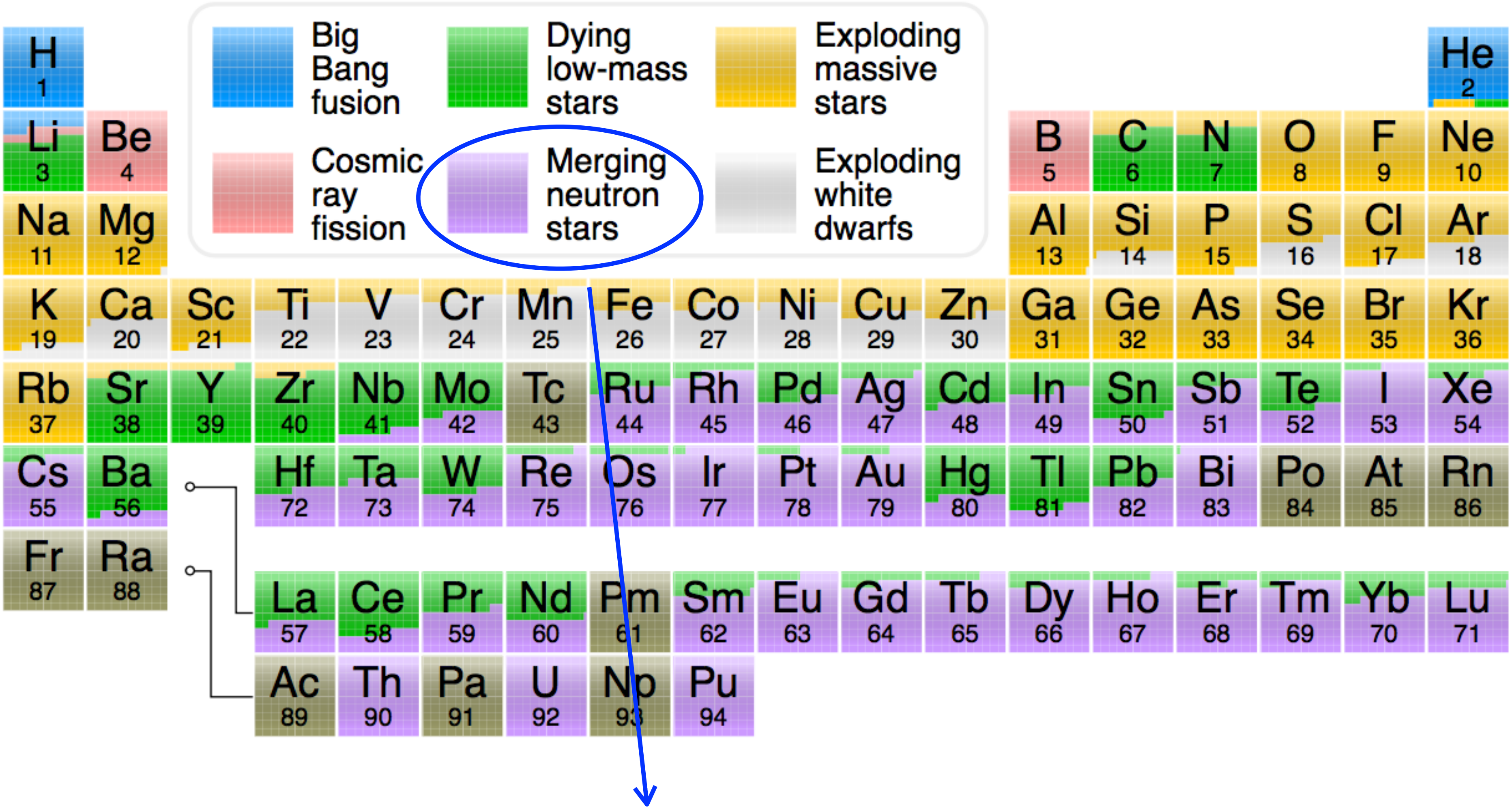
Abundances of chemical elements in the Solar system (13.7 Gyr later)

Element	**#particles.**	**Mass(X) / Mass(total)**
H	92.1%	0.74
He	7.8%.	0.25
Z	0.1%.	0.014

Nucleosynthesis & production of chemical elements in massive stars (models)

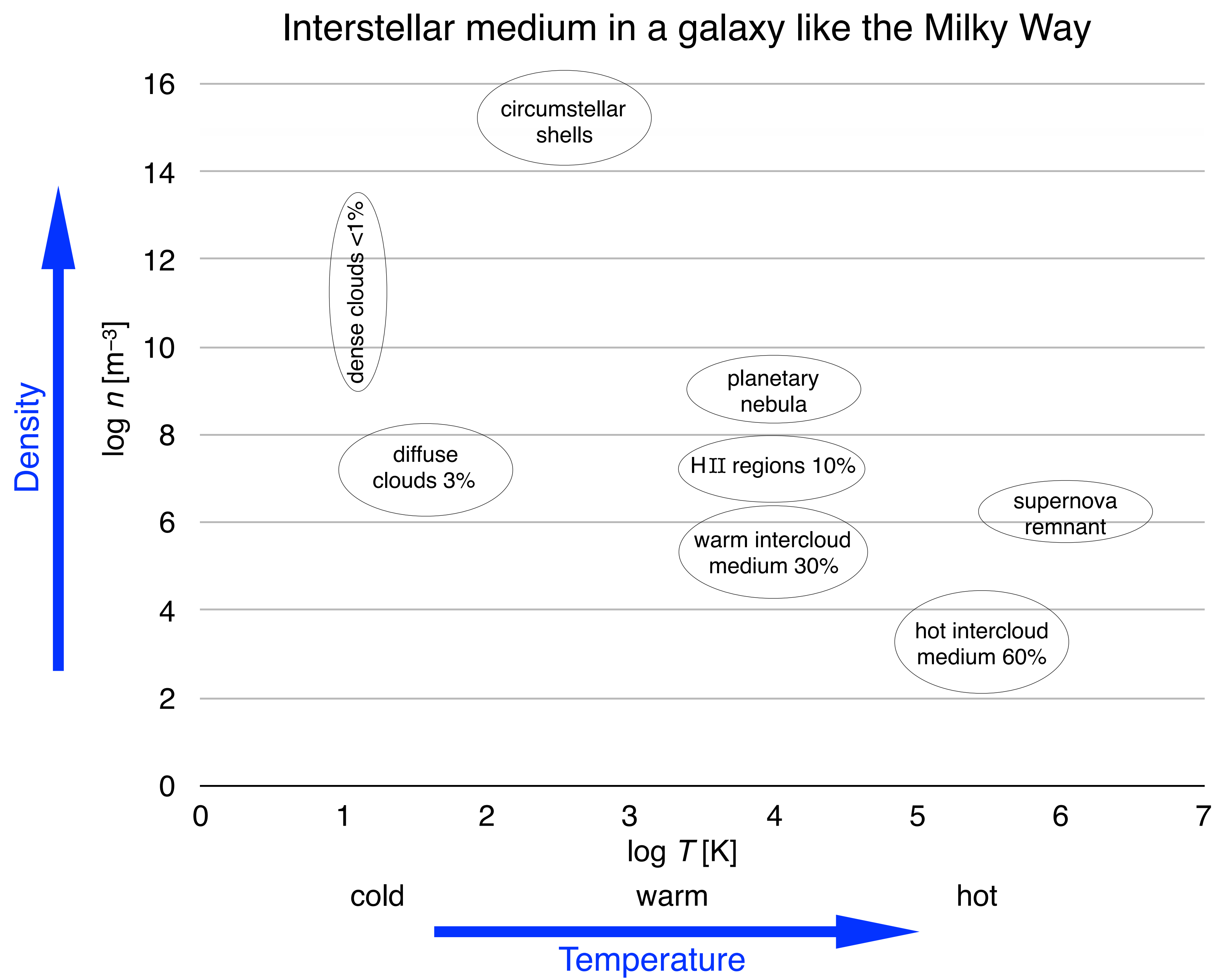


Production of chemical elements in the Universe (new!)

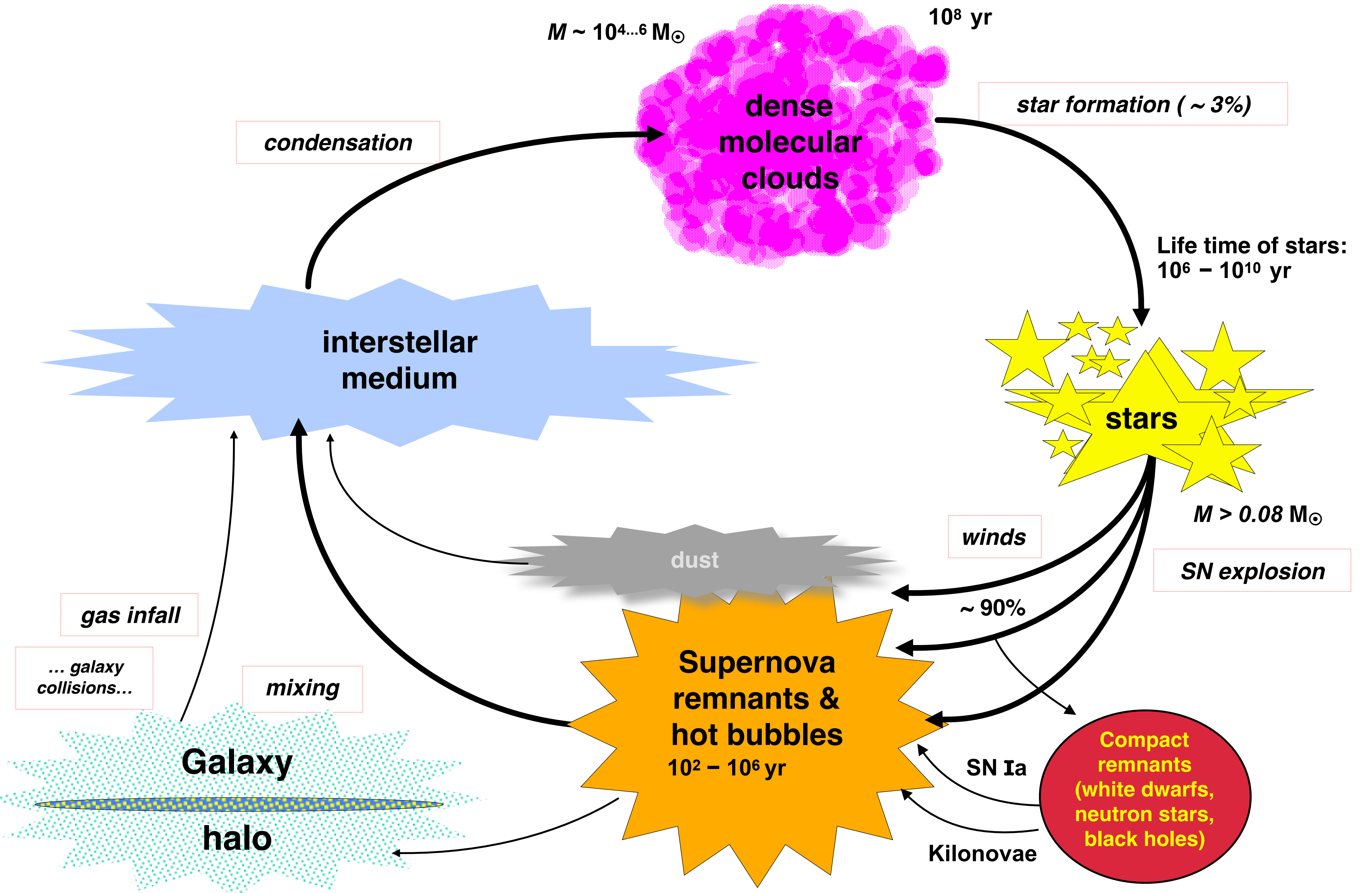


Explosion called ***Kilonova***, discovered in August 2017

thanks to simultaneous detection of gravitational waves and electromagnetic radiation for same event


Interstellar medium in a galaxy like the Milky Way
16
14
12
10
8
6
4
2
0
log n [m⁻³]
Density
circumstellar shells
dense clouds <1%
planetary nebula
diffuse clouds 3%
H II regions 10%
supernova remnant
warm intercloud medium 30%
hot intercloud medium 60%
0
1
2
3
4
5
6
7
log T [K]
cold
warm
hot
Temperature

The cosmic cycling of matter



The remnant of stars

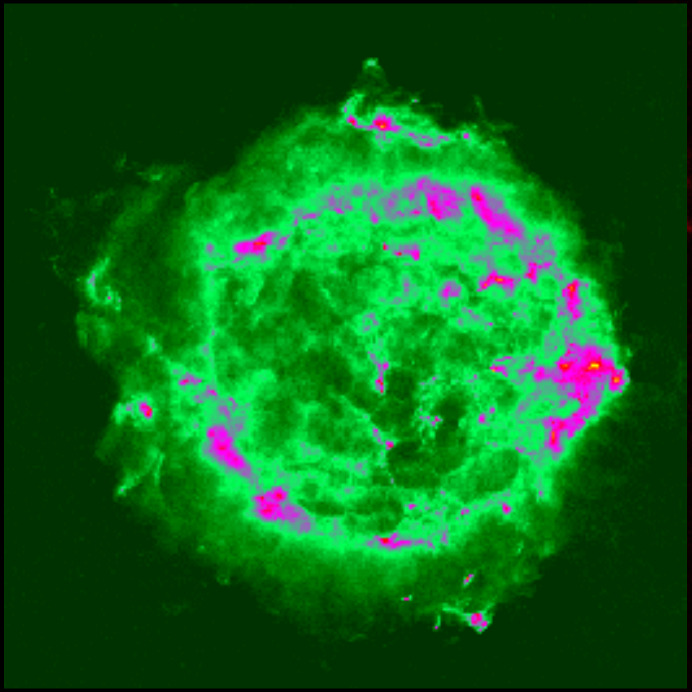
Supernova remnants

T = 10^5 - 10^7 K $\Longrightarrow$ X-ray thermal emission

Accelerated charged particles $\Longrightarrow$ radio synchrotron emission

Visible

Radio



X–ray

Supernova remnant *Cassiopeia A*

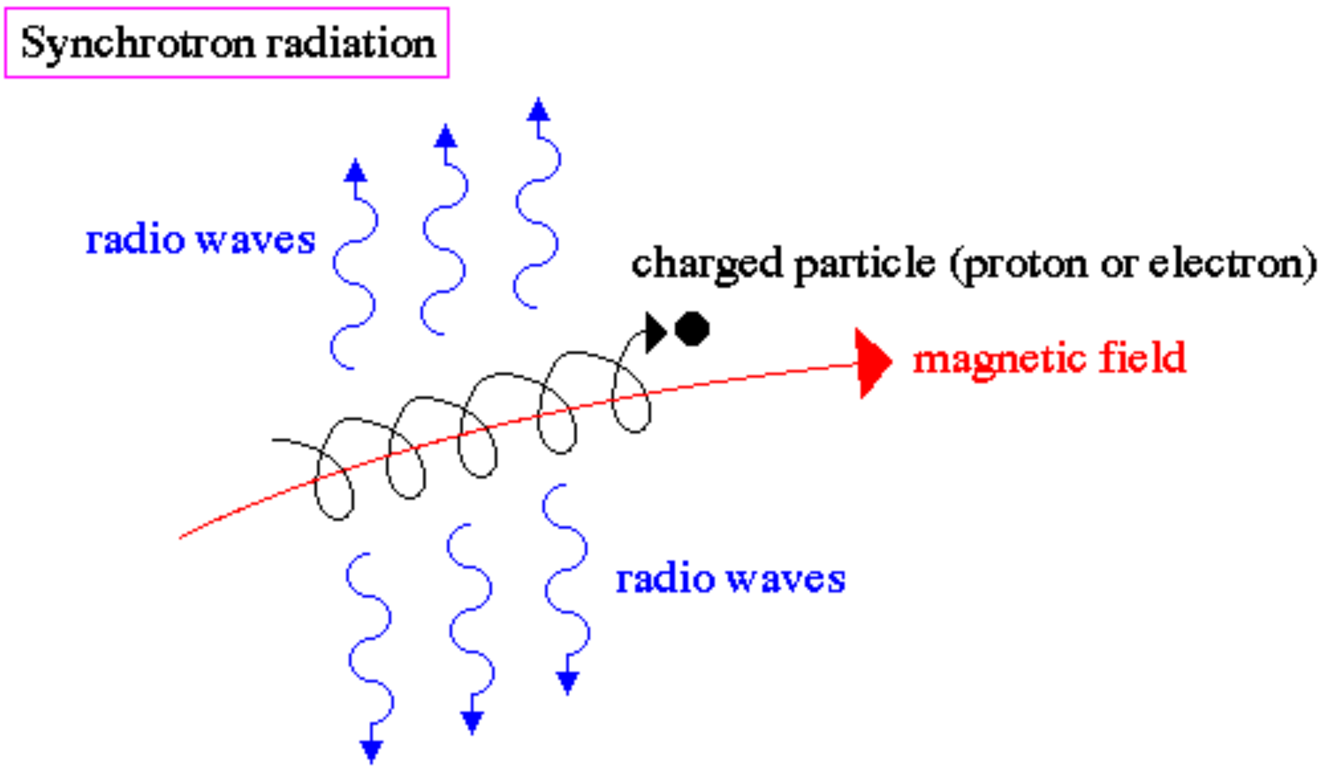
Size: 3 pc across

Distance: 3.4 kpc

Explosion: 1658?

Radio emission from supernova remnants

Synchrotron radiation of sub-relativistic electrons in strong magnetic field



synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

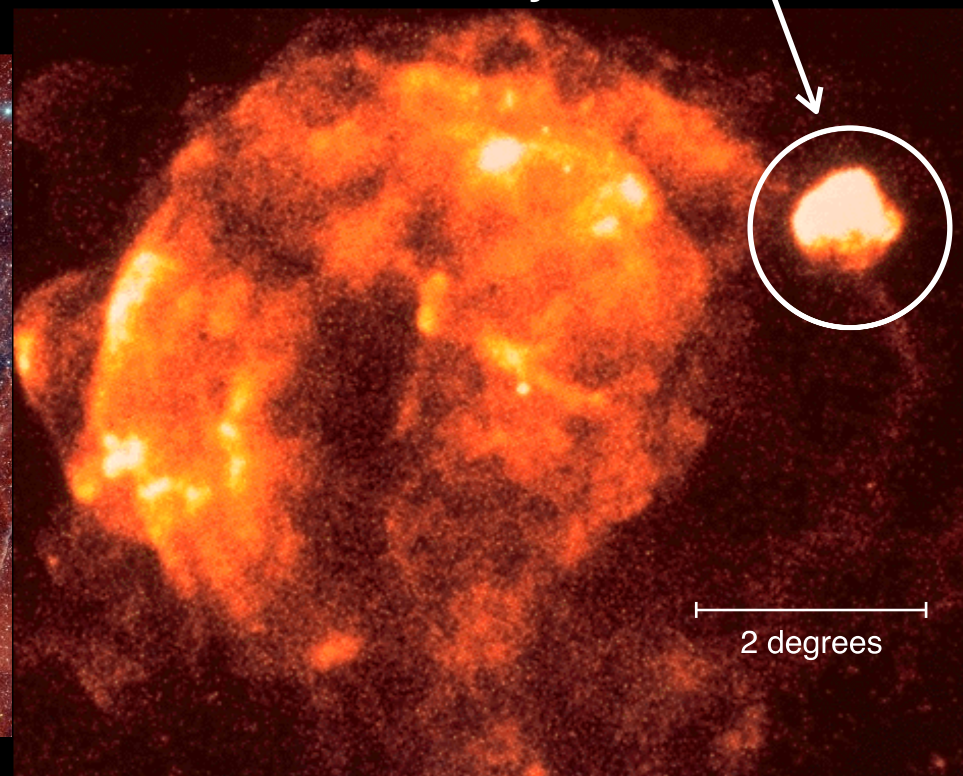
Supernova remnants

Puppis supernova *remnant*
(unrelated to *Vela*)
Distance: ~ 2 kpc

Vela supernova remnant
Explosion: 11,000–12,300 years ago
Size: 70 pc across
Distance: 250±30 pc

Visible

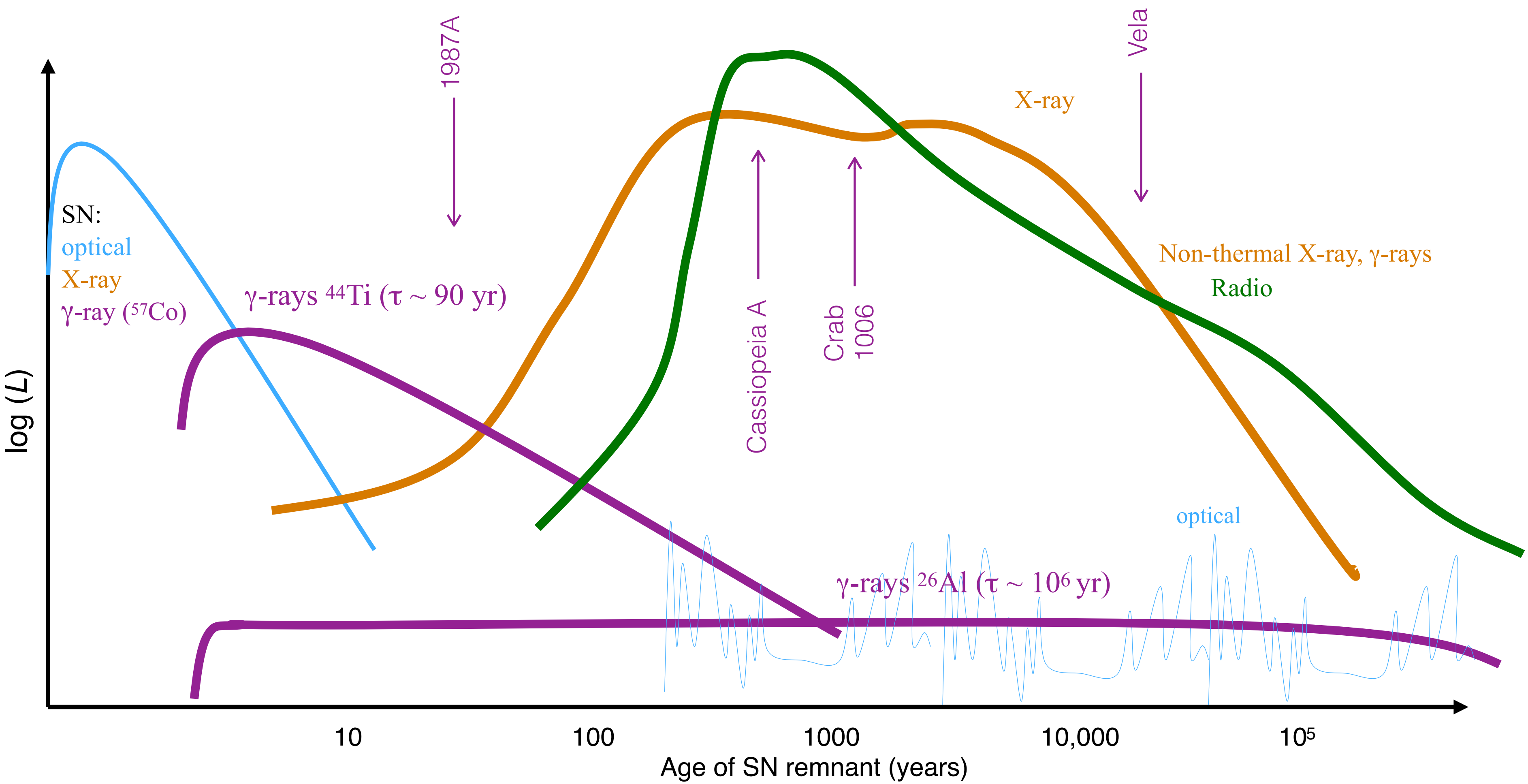
X–ray



~ 230 light years

Supernova remnants: time evolution

- Gamma-ray emission beyond x-ray/radio/optical regime
- Search for new supernova remnants



Supernova remnants: **numbers** in the Milky Way

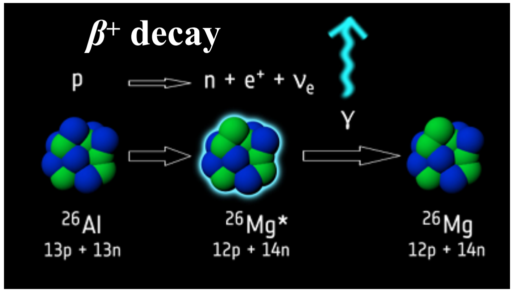
- In the past, more easily detected in the radio, today also in X-ray
- Given that:
  - 1–3 SNe per century are expected
  - SN remnants dissipate after 50–100 thousand years
  - 2000 are expected today
- Discovery time sequence:
  - October 2013: …………….. 274
  - September 2014: …………. 294
  - February 2018: ……………. 350
  - Many still missing

Gamma-rays produced by supernova remnants in the Milky Way

Nuclear energy level transitions in radioactive elements

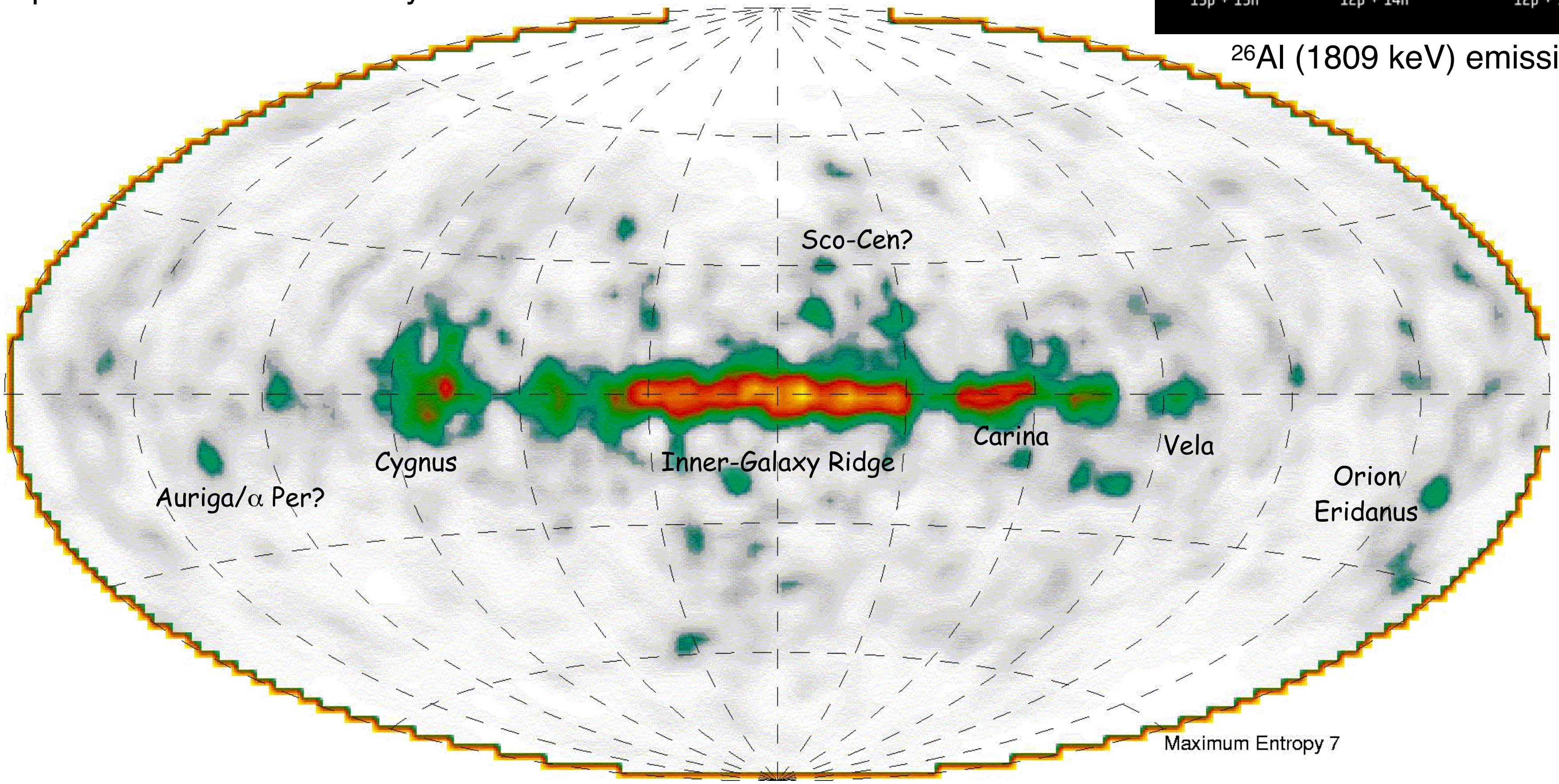
Decay of aluminum isotope ^{26}Al (1809 keV, $kT \sim 10^9$ K, mean lifetime 7.17×10^5 yr)

Estimated SN rate: 2 per century



- Gamma-ray signal is detection of “current” (last 1 Myr) nuclear transitions
- Cumulative contributions from formation of massive stars
- Supernova rate in our Galaxy

^{26}Al (1809 keV) emission

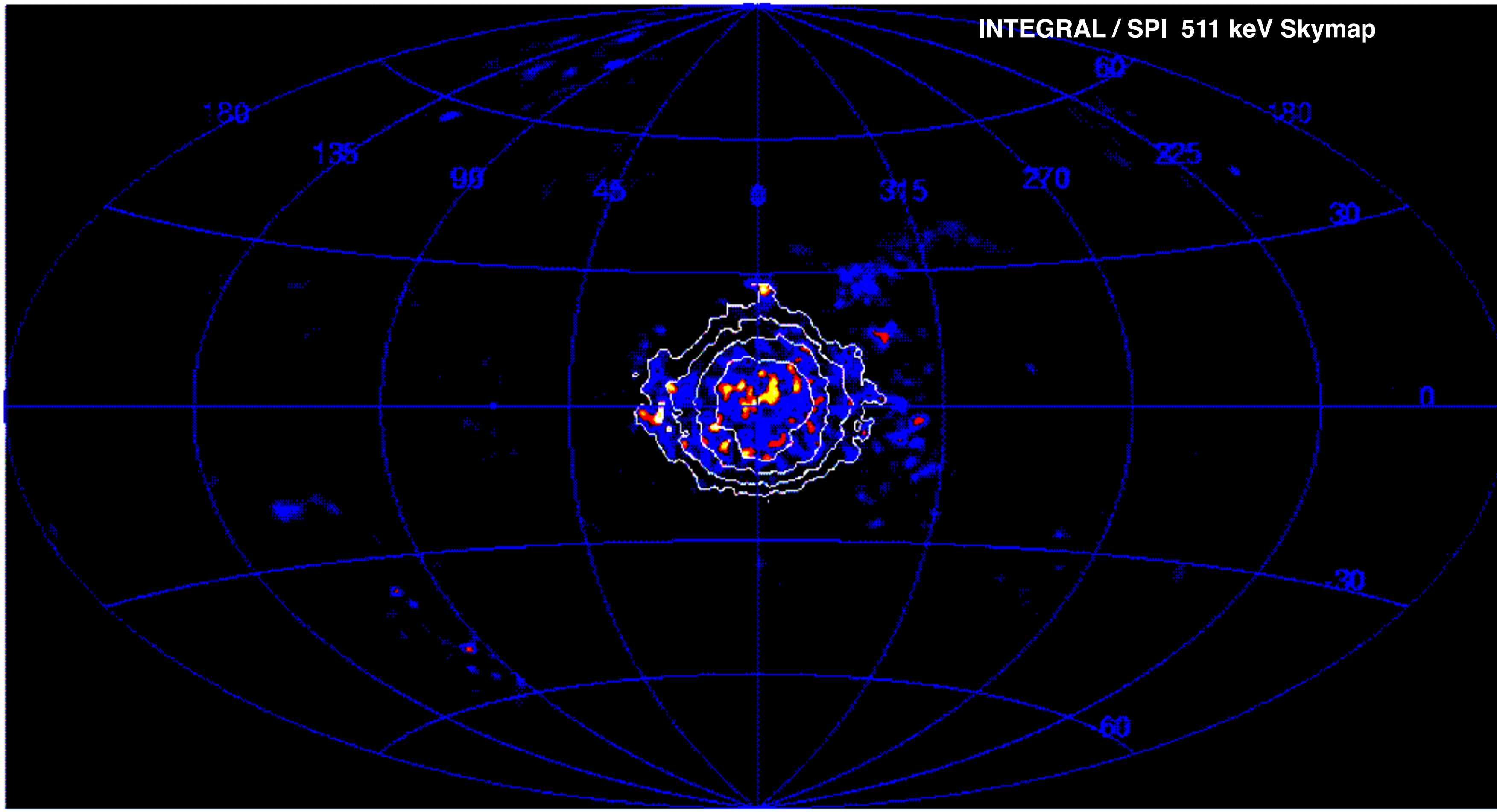


Gamma-rays in the central region of the Milky Way

Annihilation of electron-positron of unknown origin

- Produced by supernovae?
- Or decay of dark-matter particles?

511 keV line emission (corresponding to electron rest mass)



- Extended, bulge-like Emission (apparent size: ~ 8^o)
- Weak disk emission, no “fountain”

After explosion of star with $M > 8\ M_\odot$ & formation of neutron star

Fe photo-disintegration (α particles, neutrons, protons)

$e^- + p \rightarrow n + \nu_e \implies$ collapse continues

$\boldsymbol{T = 10^{12}}$ **K**, core density $3 \times 10^{17}\ \mathrm{kg\,m^{-3}} \implies$ neutron degeneracy pressure

Gravity of neutron star with $M = 1.5\ M_\odot$ and $R = 10$ km:

$$g = GM/R^2 = 2.00 \times 10^{12}\ \mathrm{m\ s^{-2}}$$

In $t = 10^{-5}$ s, velocity of falling object: $\boldsymbol{v = g\,t = 2 \times 10^7}$ **m s^{-1}**

Moment of inertia:

$$I = mR^2$$

Conservation of angular momentum (ω is angular speed):

$$L = I \times \omega$$

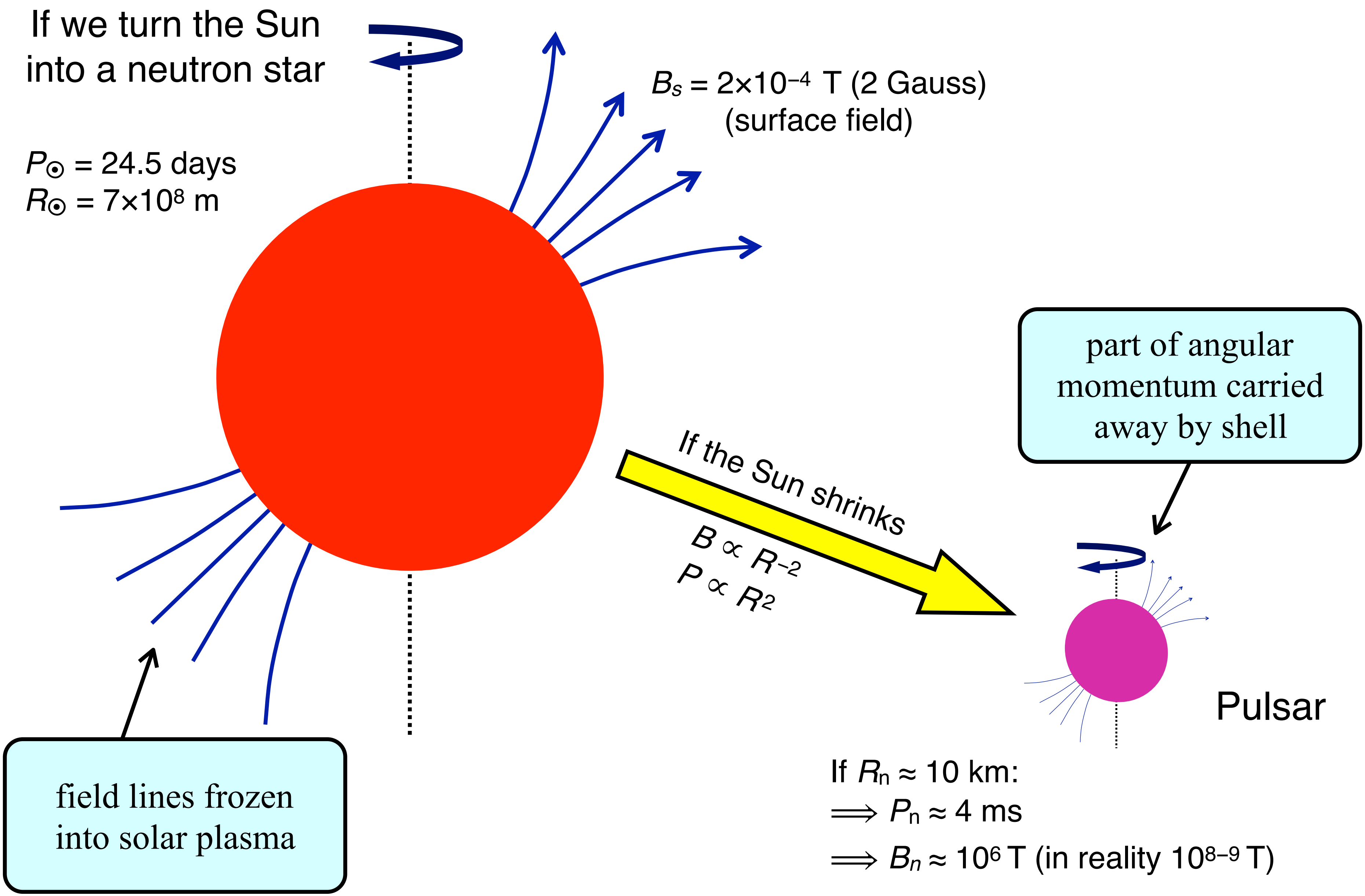
If rotation in star is initially like in Sun (24.5 days at equator), then in neutron star:

$$I_\odot \times \omega_\odot = I_n \times \omega_n$$

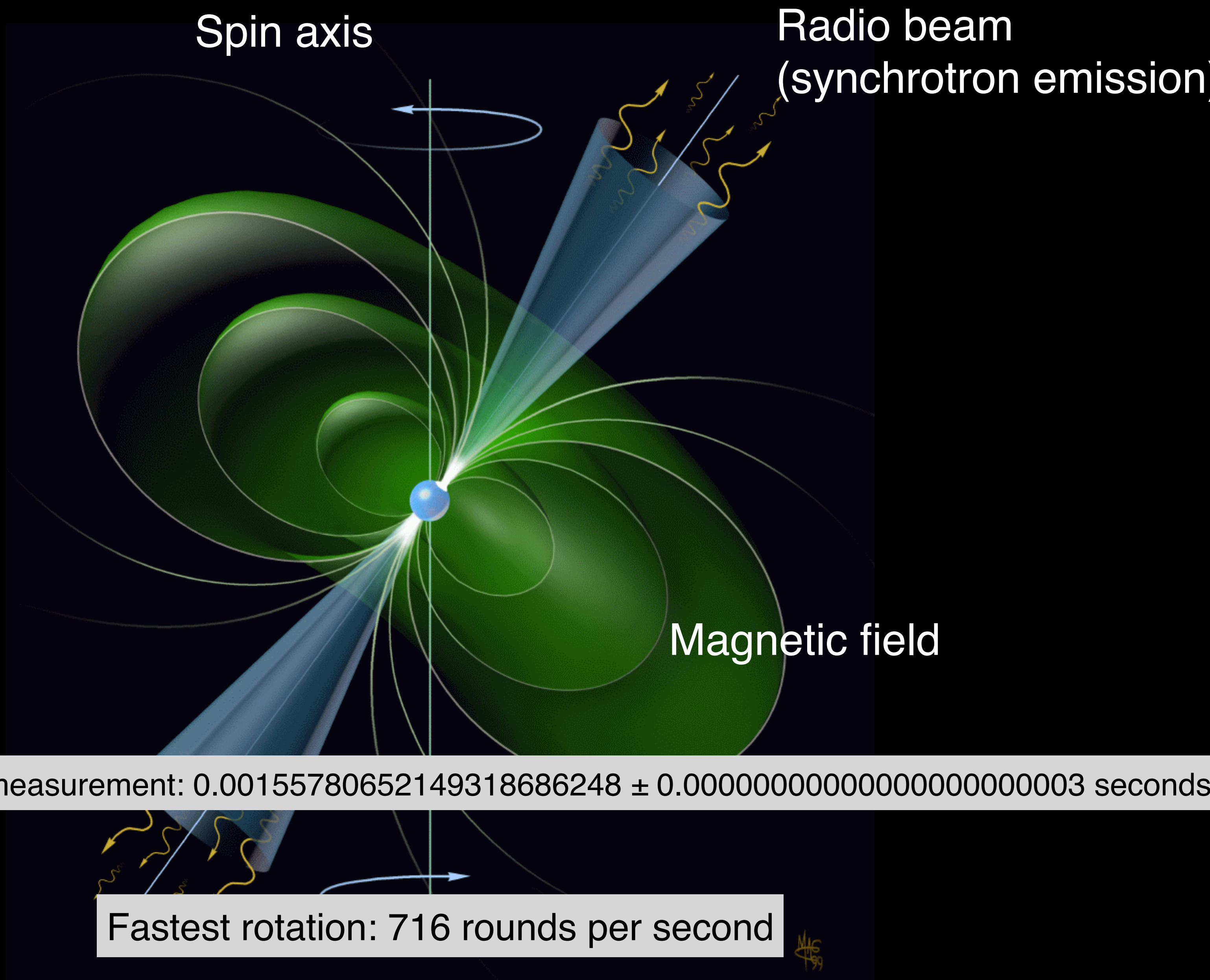
Rotation period in milliseconds: $P_n = 2\pi / \omega_n = 3.8 \times 10^{-3}$ s

Pulsar: fast rotating neutron star with **strong magnetic field *B***

(the two **axis** are **misaligned**)



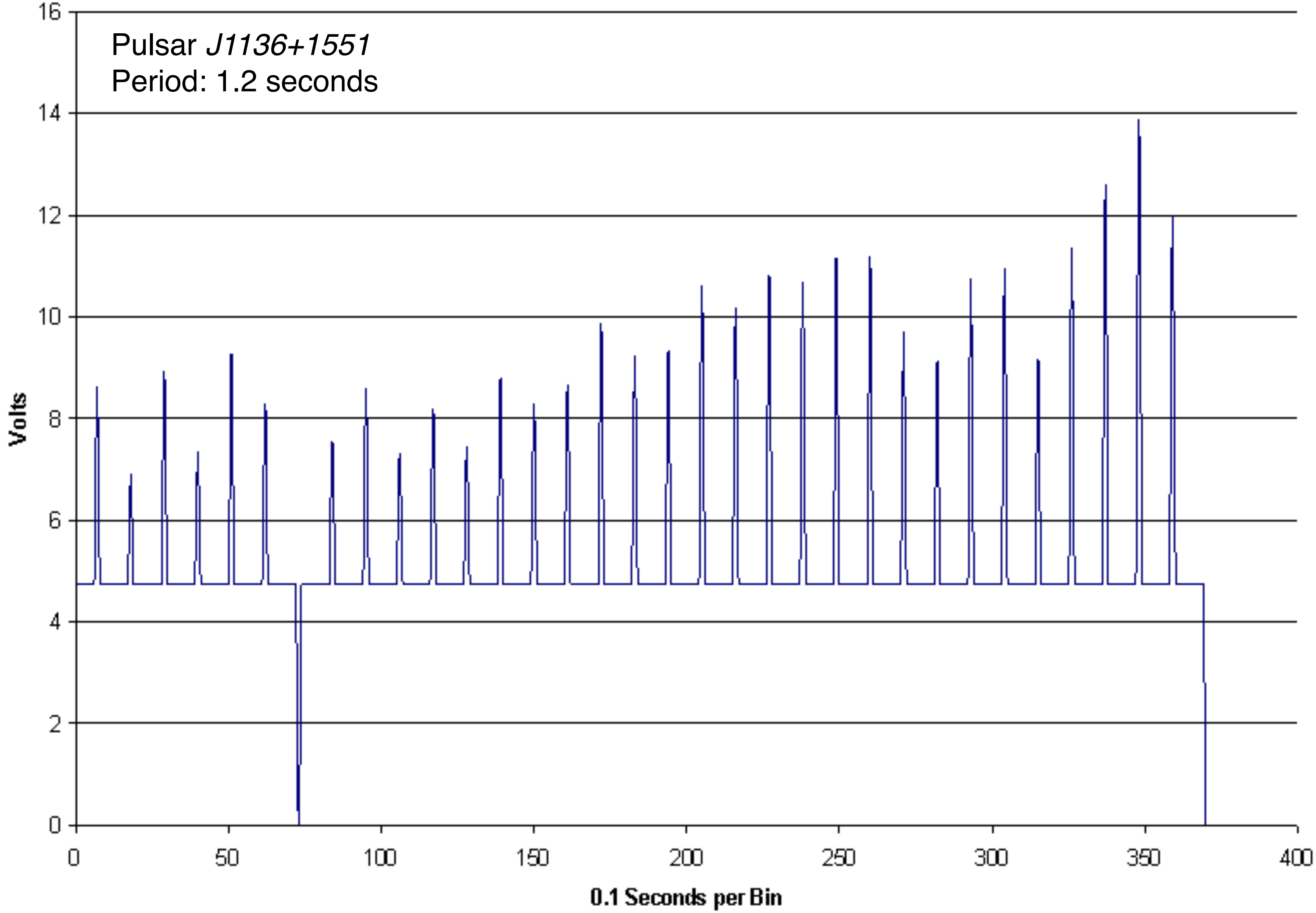
A pulsar is emitting a **very regular** radio pulsating signal



Most precise measurement: 0.00155780652149318686248 ± 0.00000000000000000000003 seconds

Fastest rotation: 716 rounds per second

A pulsar is emitting a **very regular** radio pulsating signal



Variation of pulsar period over period

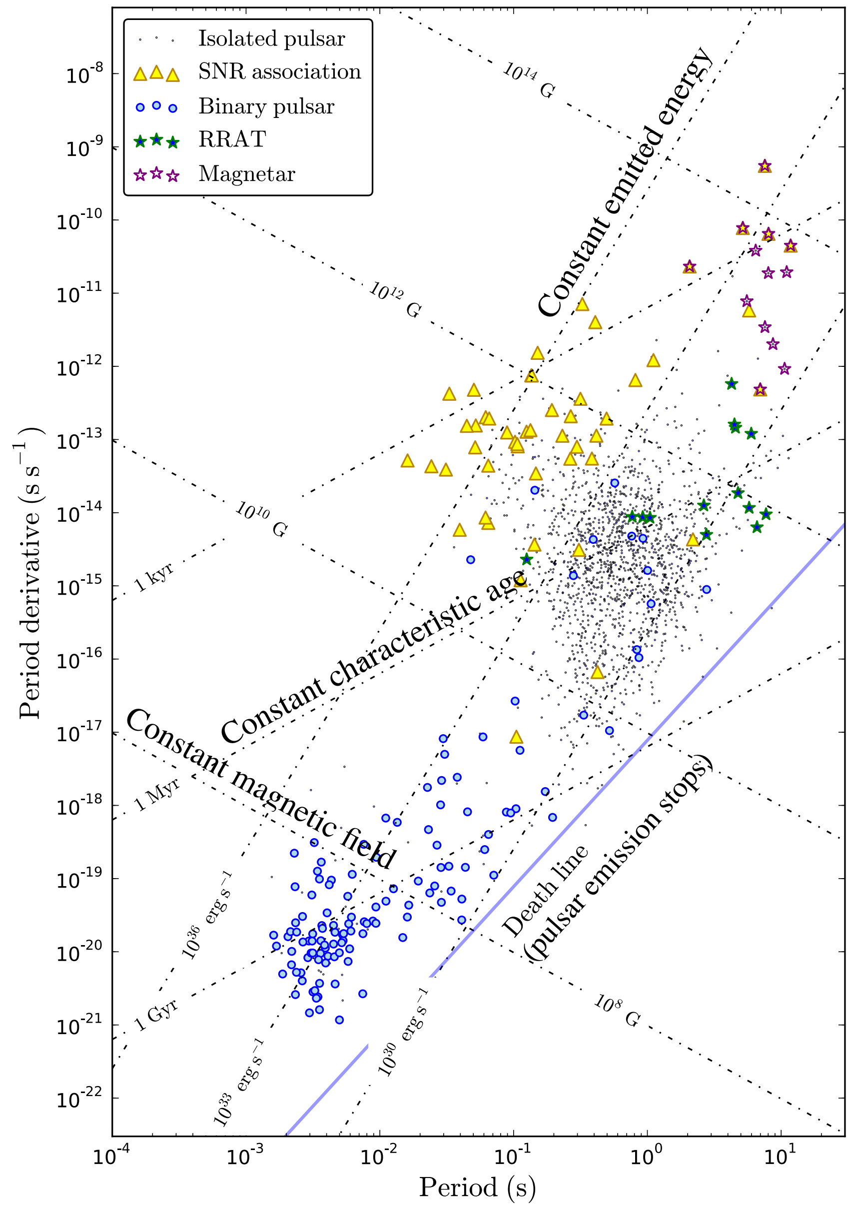
Old neutron stars stop pulsate

- Neutron stars: huge magnetic fields & (initially) fast rotation
- Stable period: $1/10^{14}$ precision, 32 μs error per century
- Typical rate of spin down ~ 3 μs per century
- P ~ 0.5 s after ~ 10^6 yr
- Pulsar invisible when P a few seconds (age 10^{7-8} yr after SN)
- Pulsars in binary systems are millisecond pulsars (mass and angular momentum transfer)

RRAT: rotating radio transient with higher pulse-to-pulse variability

Magnetar: pulsar with extremely high magnetic field

Period P and spin down $\dot{P}$ for 1805 pulsars in Galactic disk



Stellar remnants are:

- White dwarfs
- Neutron stars
- Black holes

They have in common:

- Small radius
- High density

$\Longrightarrow$ high gravitational field

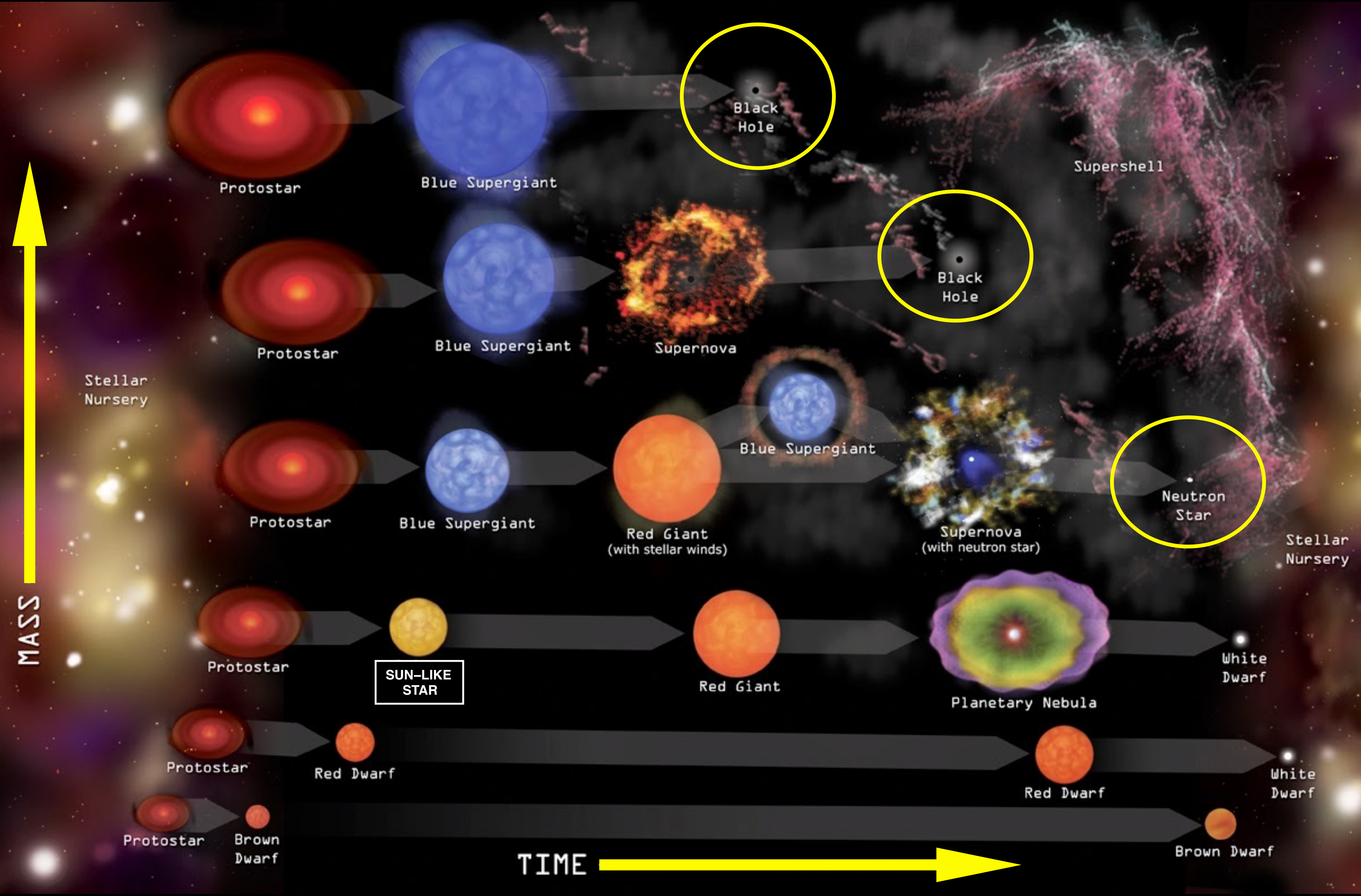
$\Longrightarrow$ low luminosity

Hard to detect (black holes don't emit radiation)

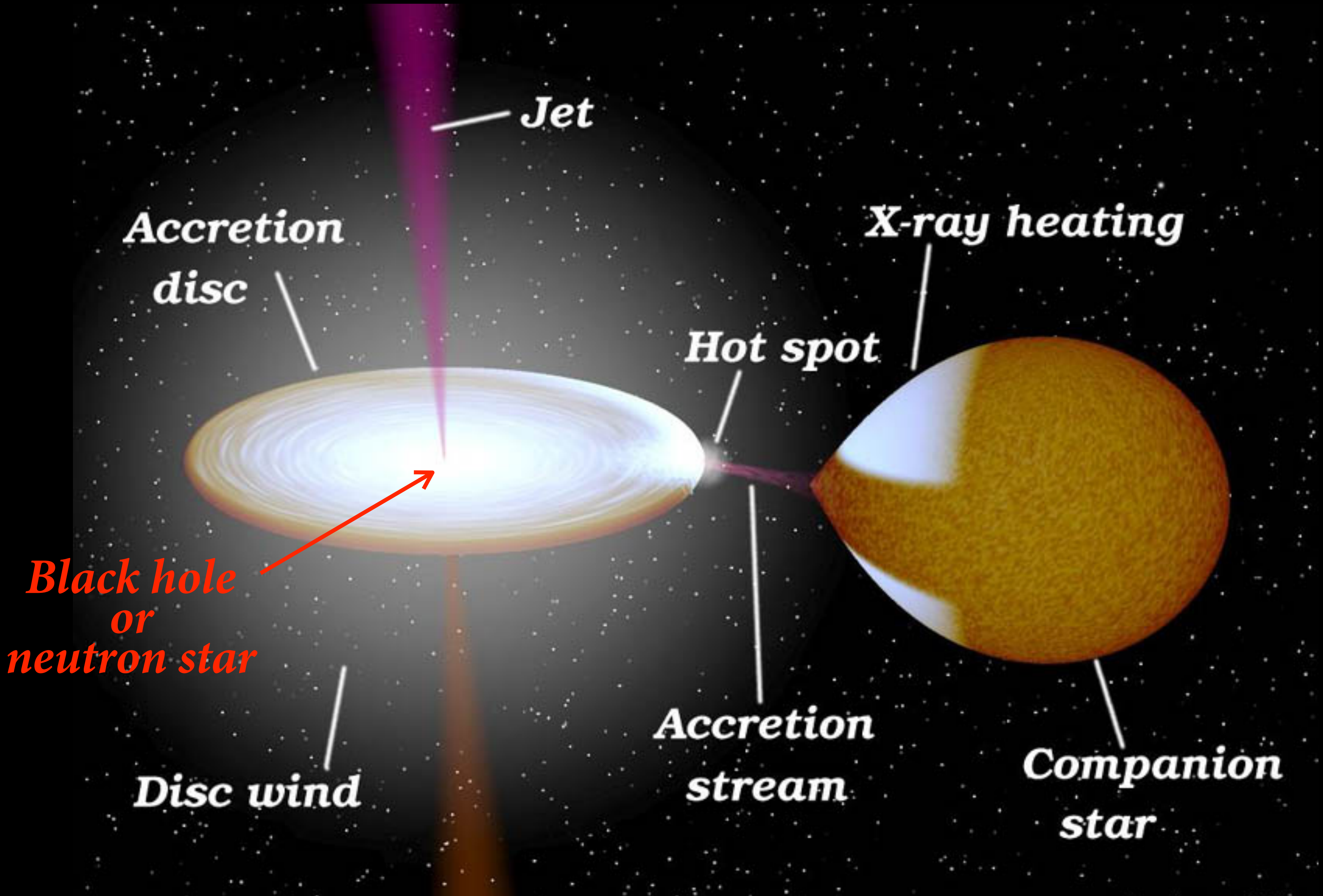
Solution: much easier if in binary systems

Black hole of stellar origin: $M_{core} > 3 - 5\ M_\odot$

Evolution of stars and back holes of stellar origin

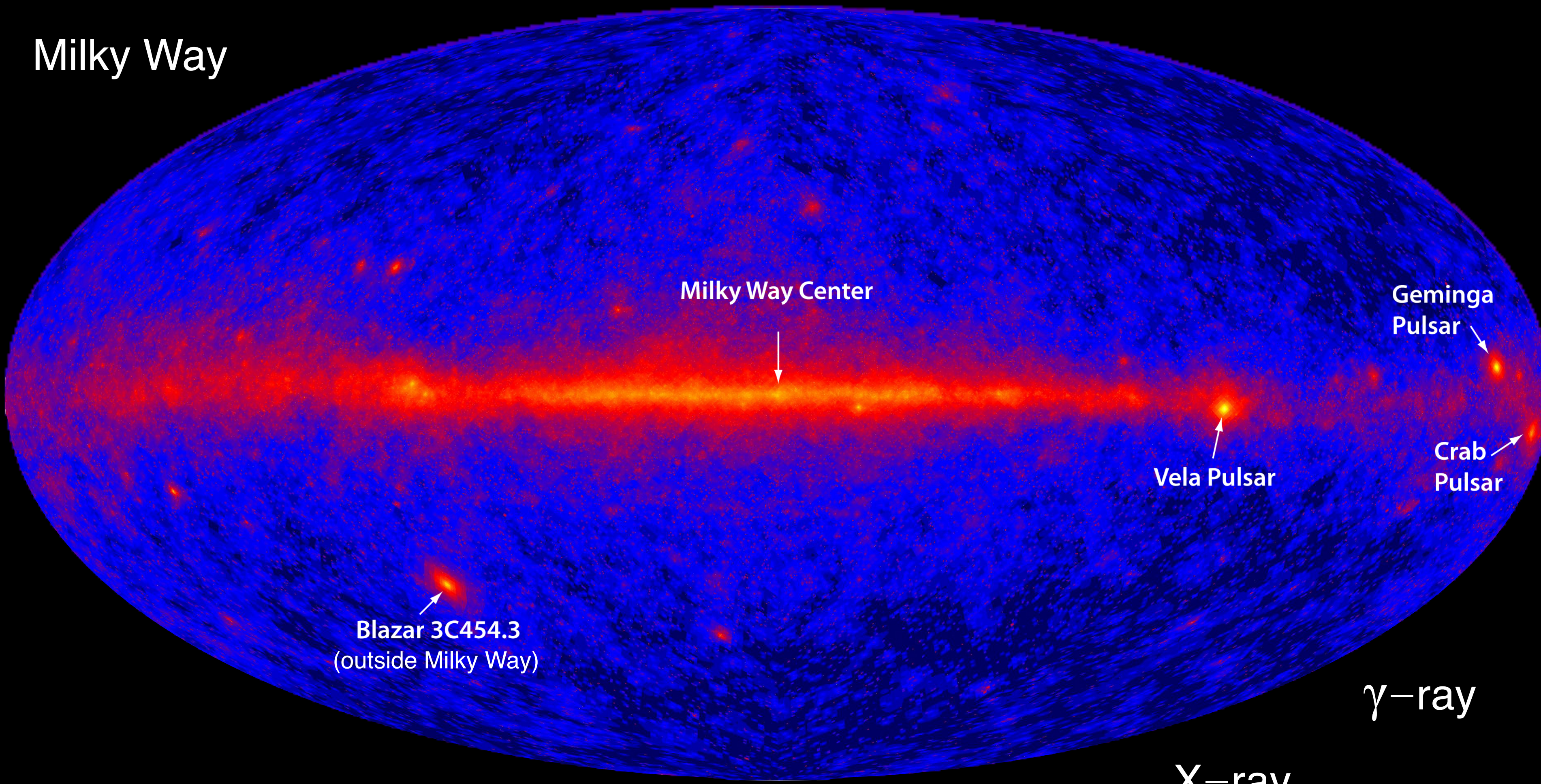


Neutron star or stellar black hole can be seen in binary systems
Strong X-ray emitters



Neutron star or black hole in binary systems strong X-ray emitters

Milky Way

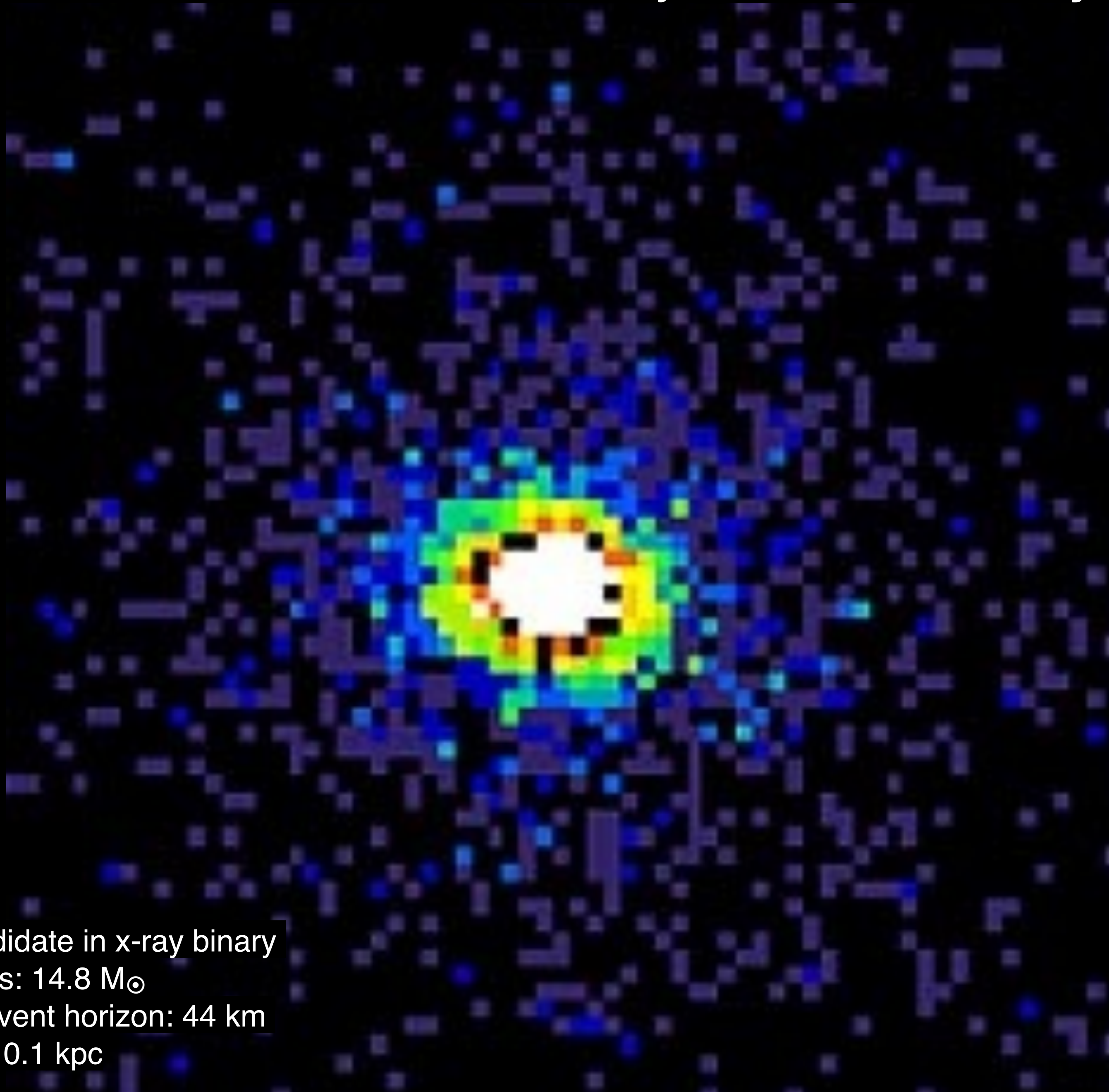


γ−ray

X−ray

X-ray binaries dominate X-ray sky

Stellar black holes detected from x-ray emission in **binary systems**



Cygnus X-1

X-ray image

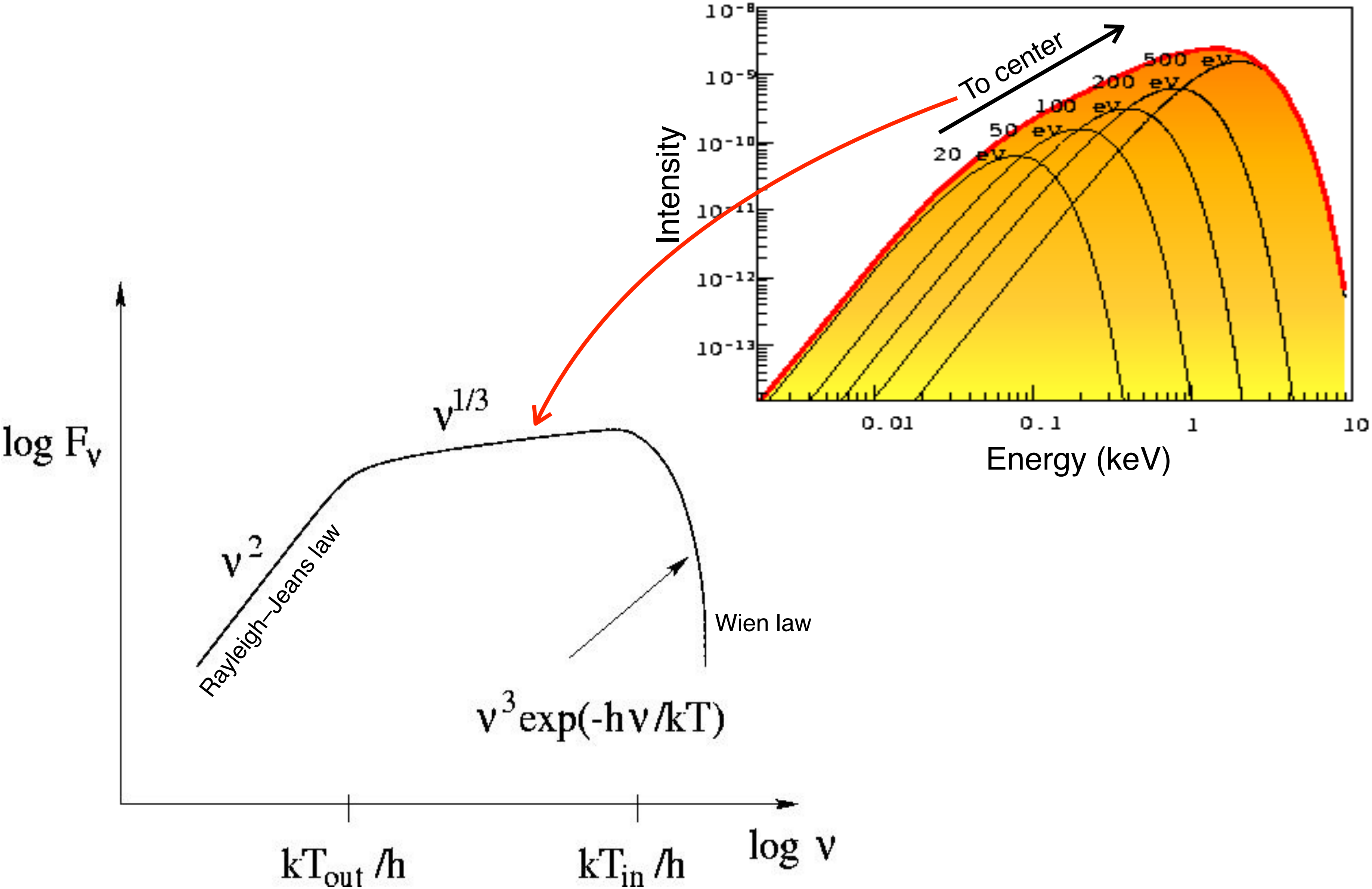
Black hole candidate in x-ray binary

Black hole mass: 14.8 $M_\odot$

Radius of the event horizon: 44 km

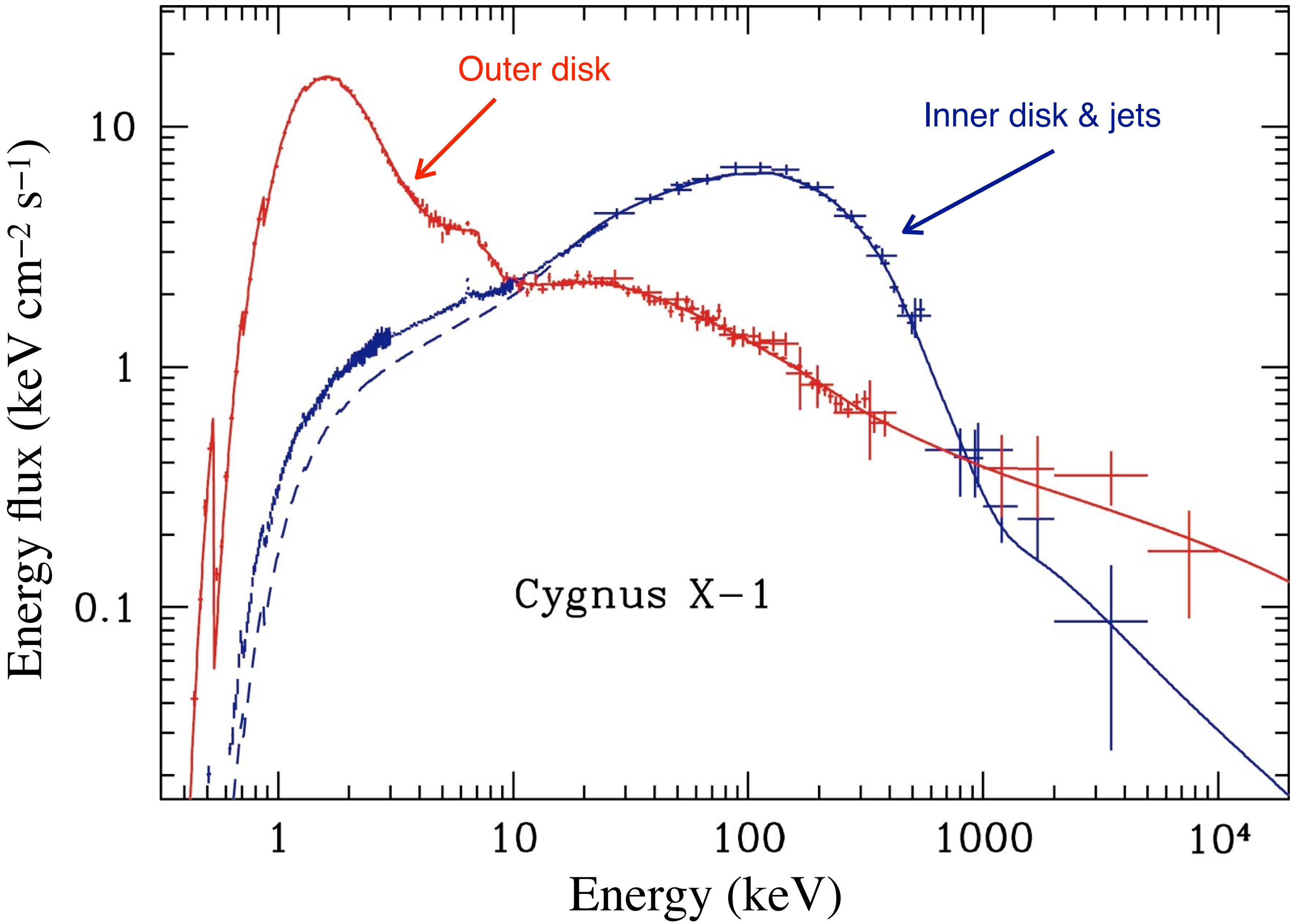
Distance: 1.8 ± 0.1 kpc

Several **black-body** spectra in accretion disk

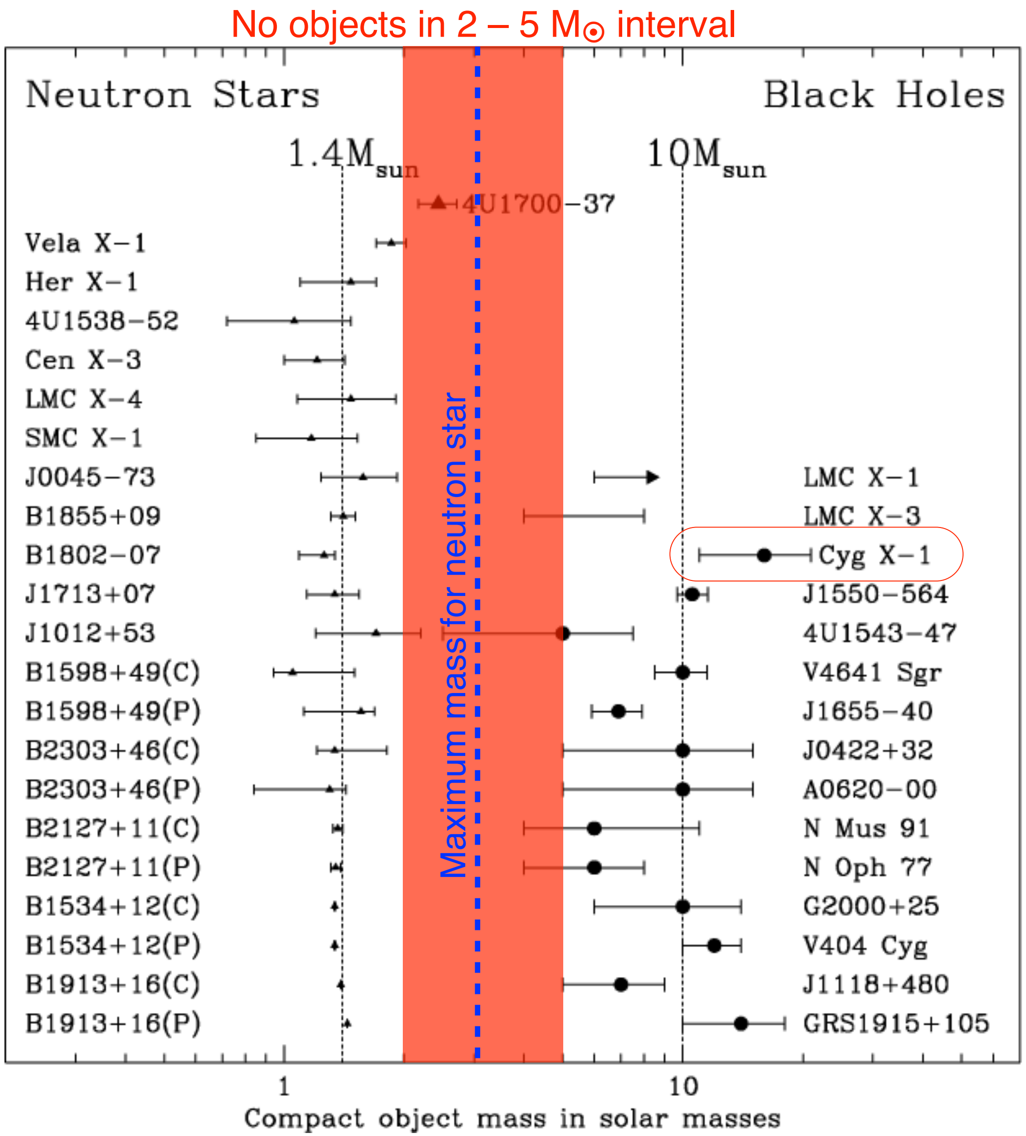


Accreting black hole

Cygnus X-1: first source widely accepted to be a black hole



Neutron stars and stellar black hole candidates



60 stellar black hole candidates in X-ray binaries in the Milky Way (as of October 2016)
(black-hole in X-ray binaries are vast majority of black-hole population)