Astrofisica delle alte energie

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2019-2020

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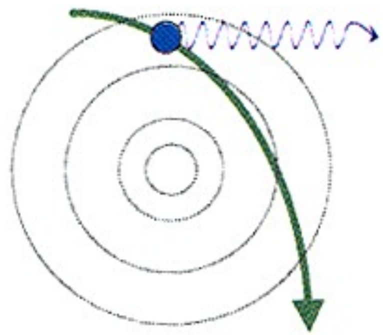
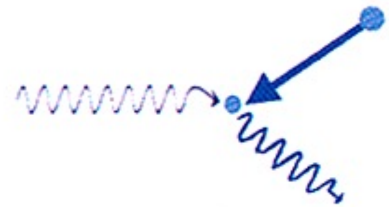
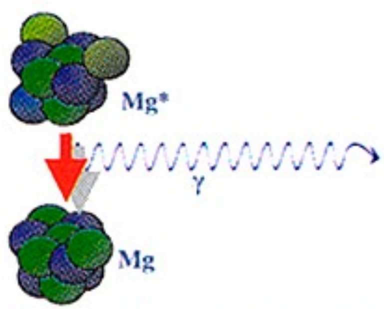
Basic radiation mechanisms for production of high-energy photons in the universe



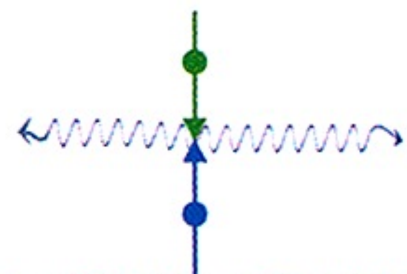
Accelerated Charged Particles



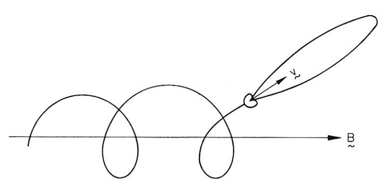
Inverse Compton Scattering



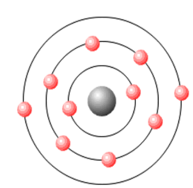
De-Excitation of Atomic Nuclei



Annihilation of Particle-Antiparticle Pairs



Synchrotron



Characteristic X-rays

Stellar explosions

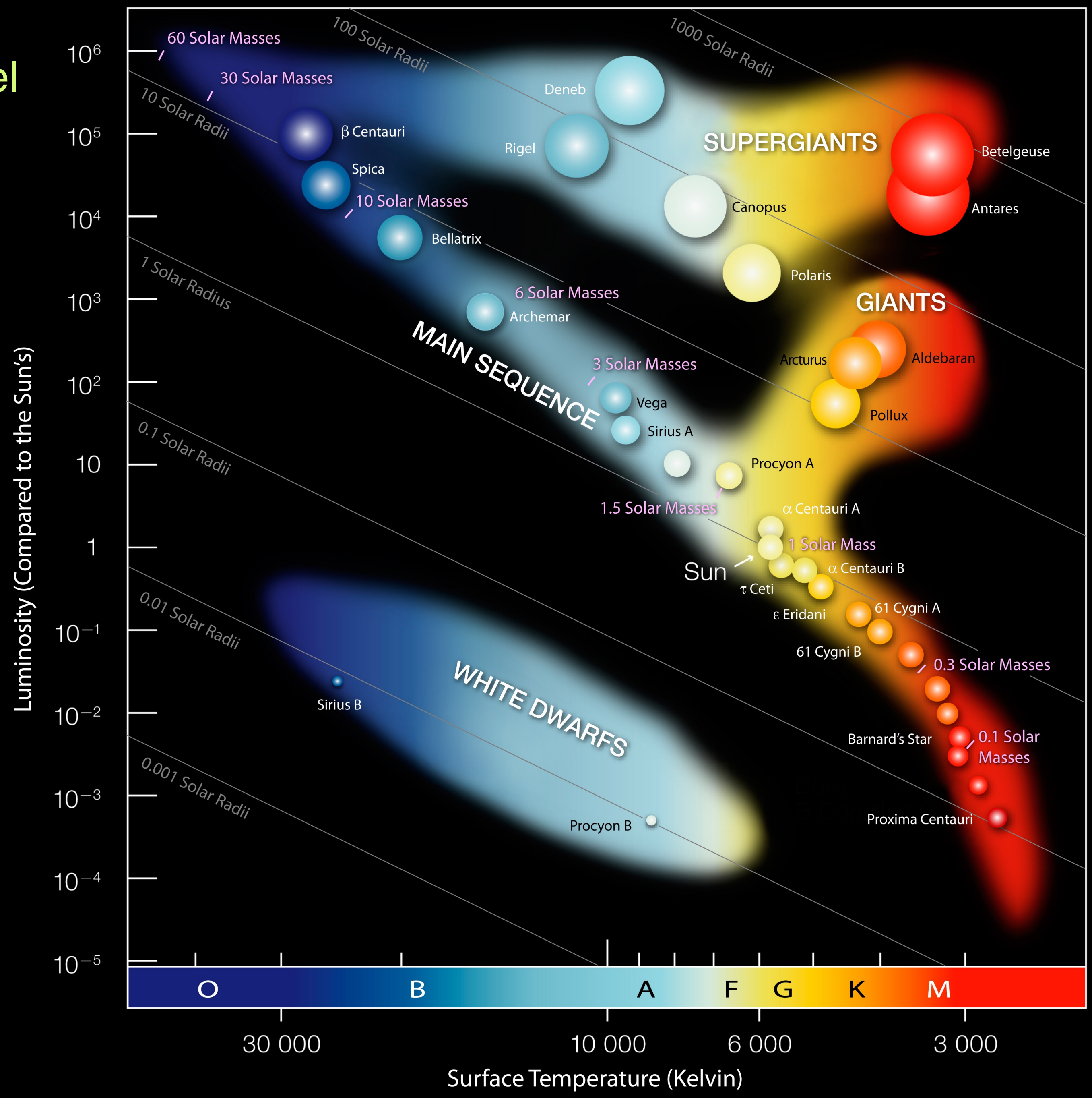
Explosions happen for:

- Massive stars with $M \gtrsim 8\ M_\odot$
  - ✦ But what matters is the mass of the core $M_{core} > 1.4\ M_\odot$
  - ✦ Important mass loss of external layer in pre-explosion phase
- Merging binary systems, where:
  - ✦1 is a compact stellar remnant
  - ✦1 is a donor

Hertzsprung-Russel diagram

Information on *L, T, R*

Solar luminosity:
$L_{\odot} = 3.846\times10^{26}$ W =
= 3.846×10^{33} erg/s



All stars with masses about $M \gtrsim 8\ M_\odot$ explode

(core-collapse supernova)

These include:

mass

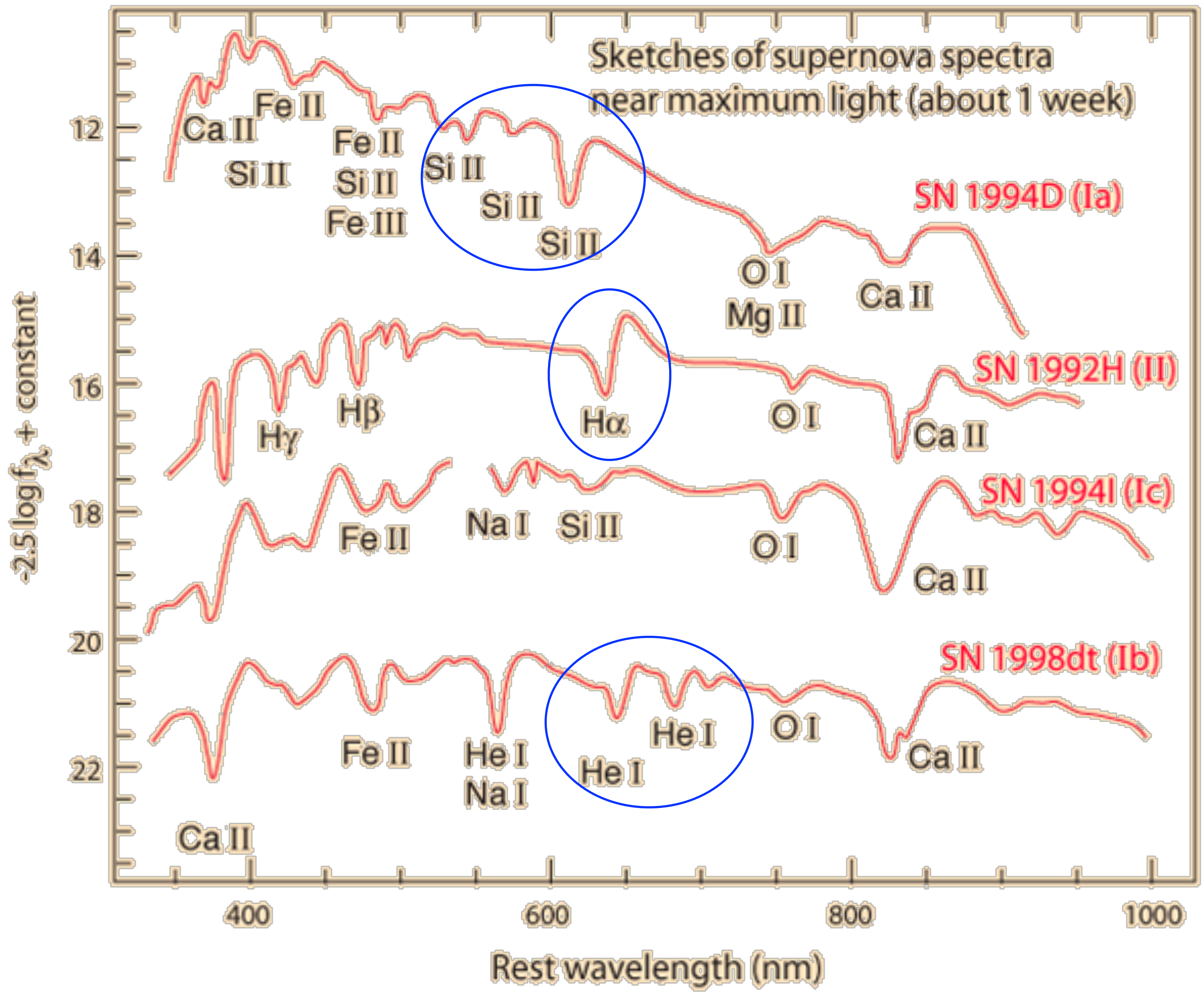
- supernova type II
- supernova type Ib
- supernova type Ic
- long-duration gamma-ray burst
- super-luminous supernova
- pair-instability supernova

Explosions in binary systems from:

- white dwarf & giant star $\Longrightarrow$ supernova type Ia
- NS-NS or NS-BH merger $\Longrightarrow$ short-duration gamma-ray burst & kilonova
- BH-BH merger $\Longrightarrow$ source of gravitational waves only

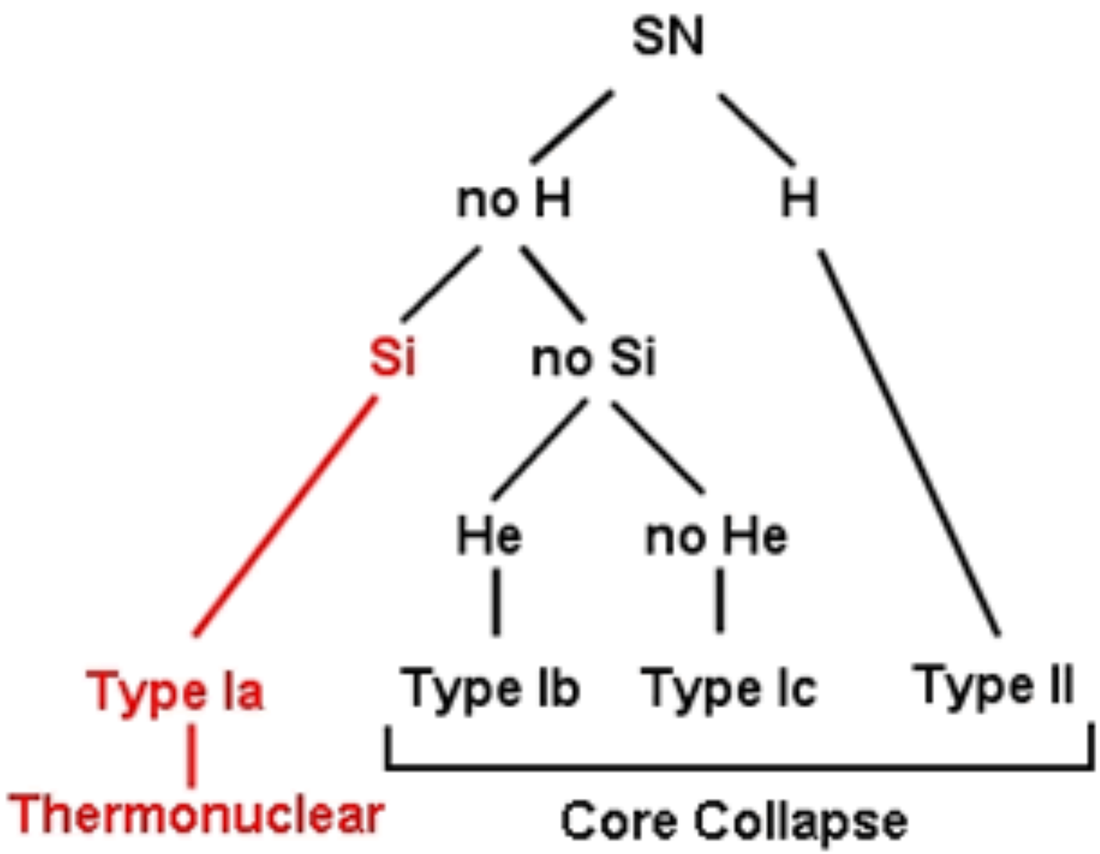
NS: neutron star
BH: black hole

Supernovae (SN) spectral classification

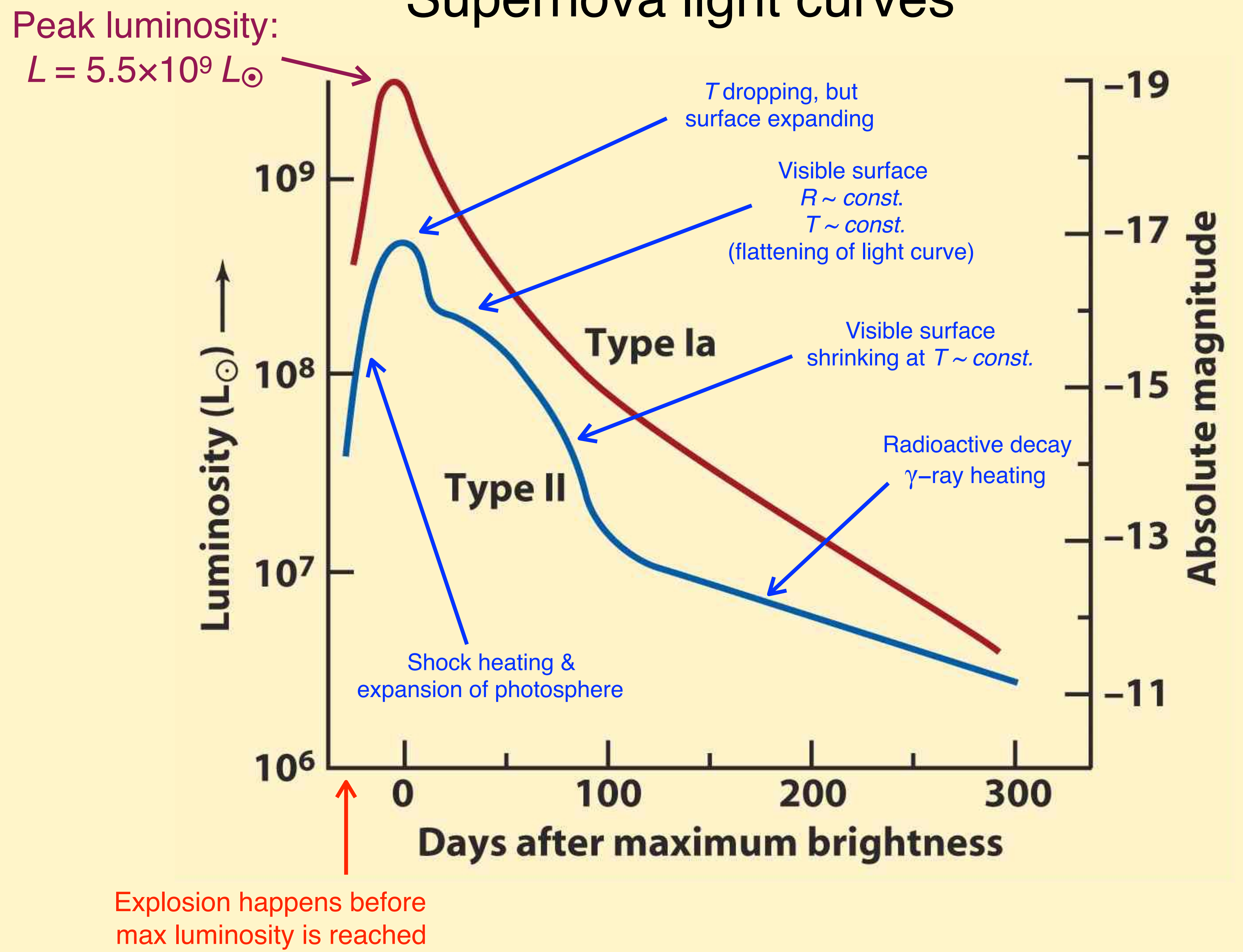


In SN Ic:
no H, Si, He

Supernovae (SN) spectral classification



Supernova light curves



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). For $M = 30 \div 40\ M_\odot$, P_{rad} large enough → envelope lost by stellar wind
Type Ia	no H spectral lines, Si lines. Binary system with white dwarf

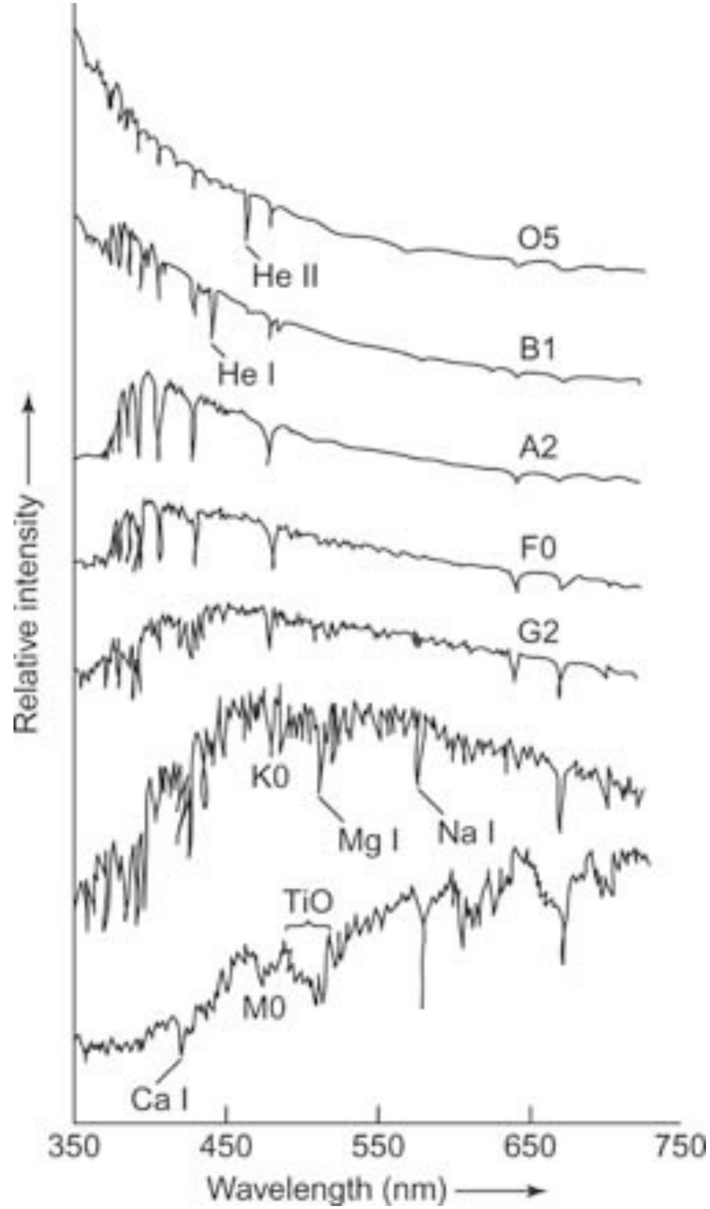
No core collapse
No massive star
(different kind of explosion)

Spectral classification of stars in *Main Sequence*

(main Sequence: when hydrogen is burned in core)

Time of hydrogen burning

Temperature & Luminosity



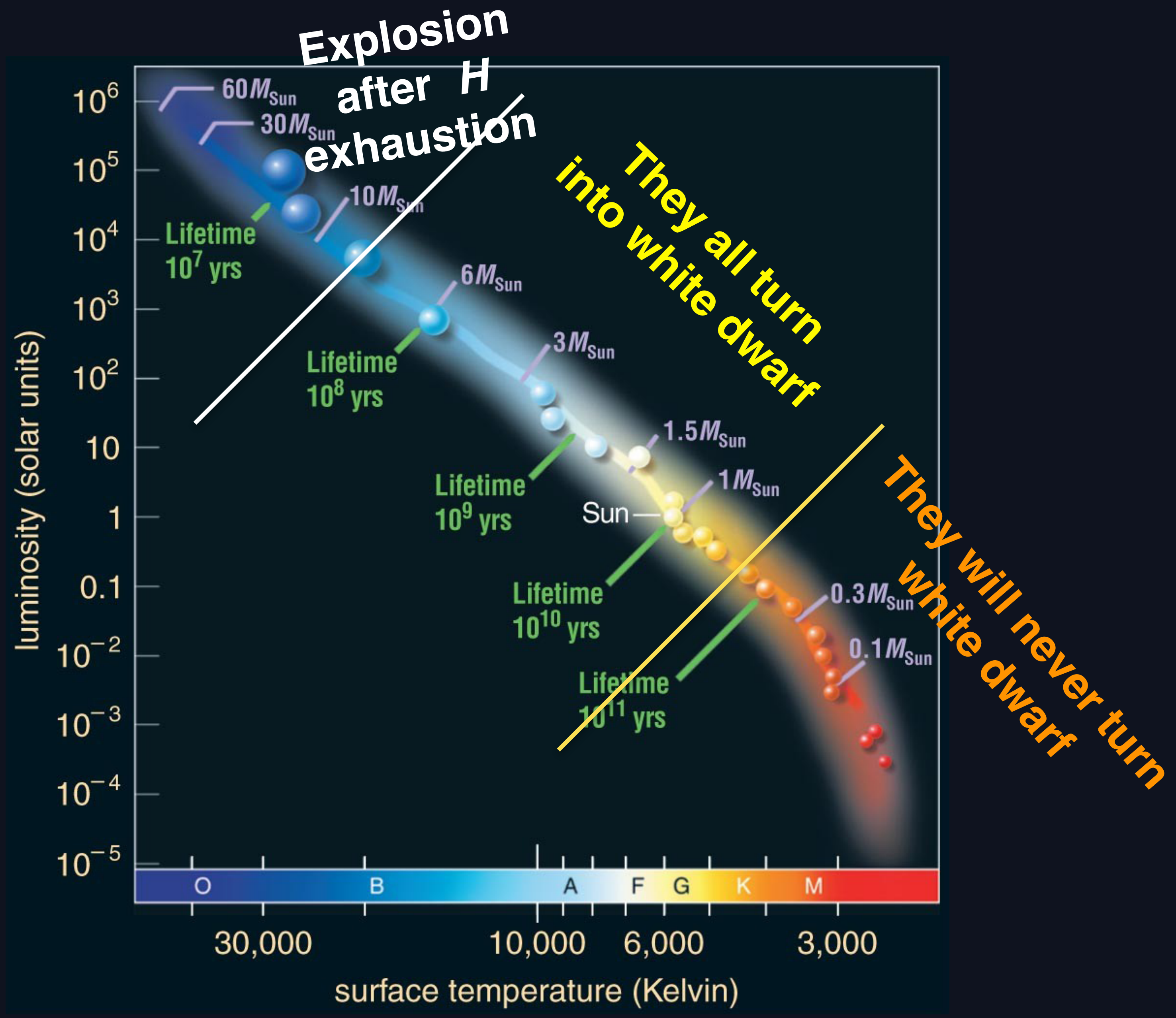
O5 star (T = 40,000 K)

B1 star (T = 25,000 K)

Explosive end

M0 star (3500 K).

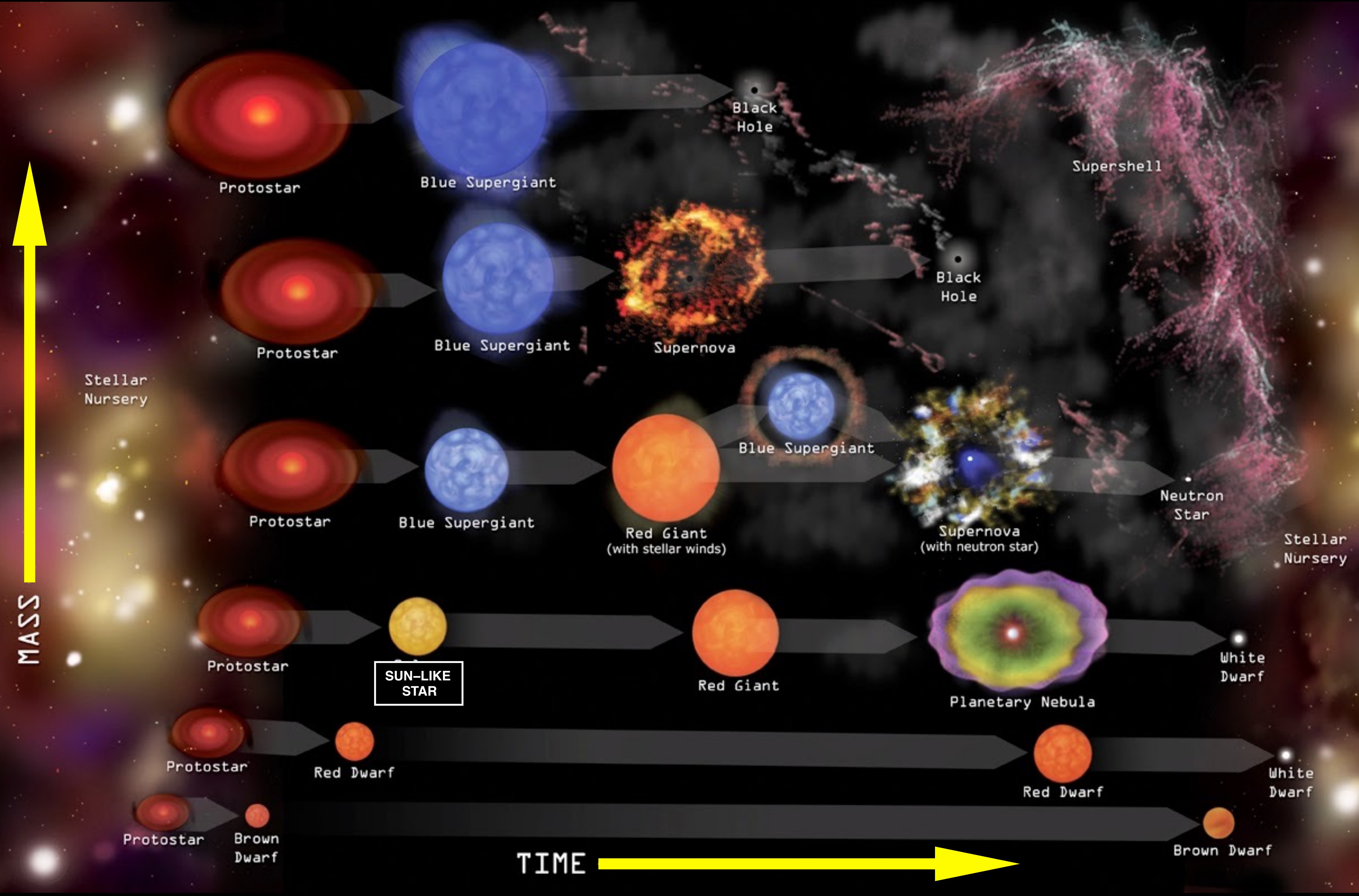
Lifetime of stars in Main Sequence with different mass



Life of a star with mass $M = 25\ M_\odot$

Hydrogen (main sequence) .... 6 million years
Helium .... 500,000 years
Carbon ……………………………………… 600 years
Neon ………………………………………….. 1 year
Oxygen ……………………………………… 6 months
Silicon ……………………………………… ~ 1 day

Evolution of stars with different mass



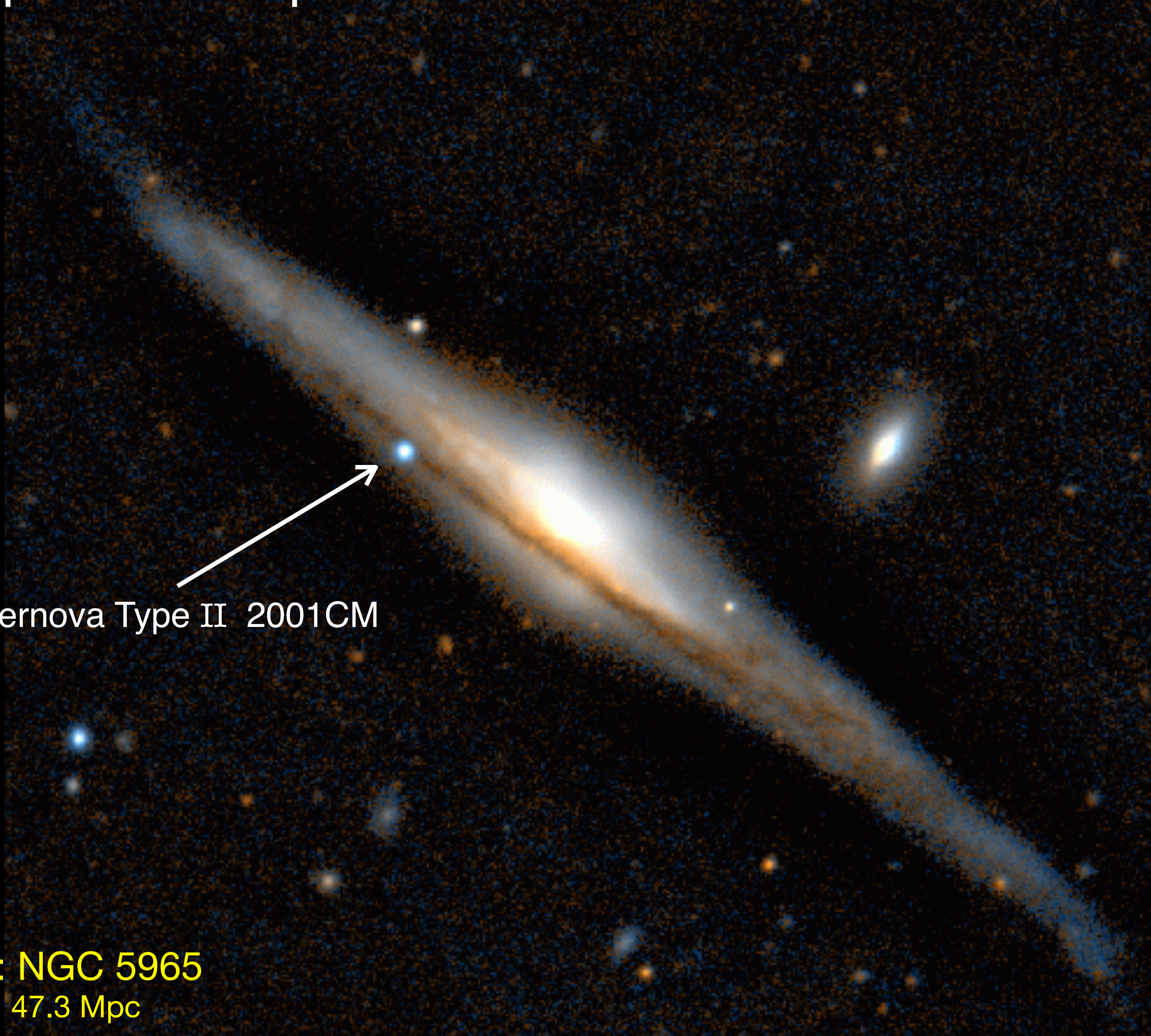
After core collapse, external envelope falling inwards at speed up to $v \sim 70{,}000$ km/s

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

Star destroyed by explosion

Stellar explosion = supernova (computer simulation)

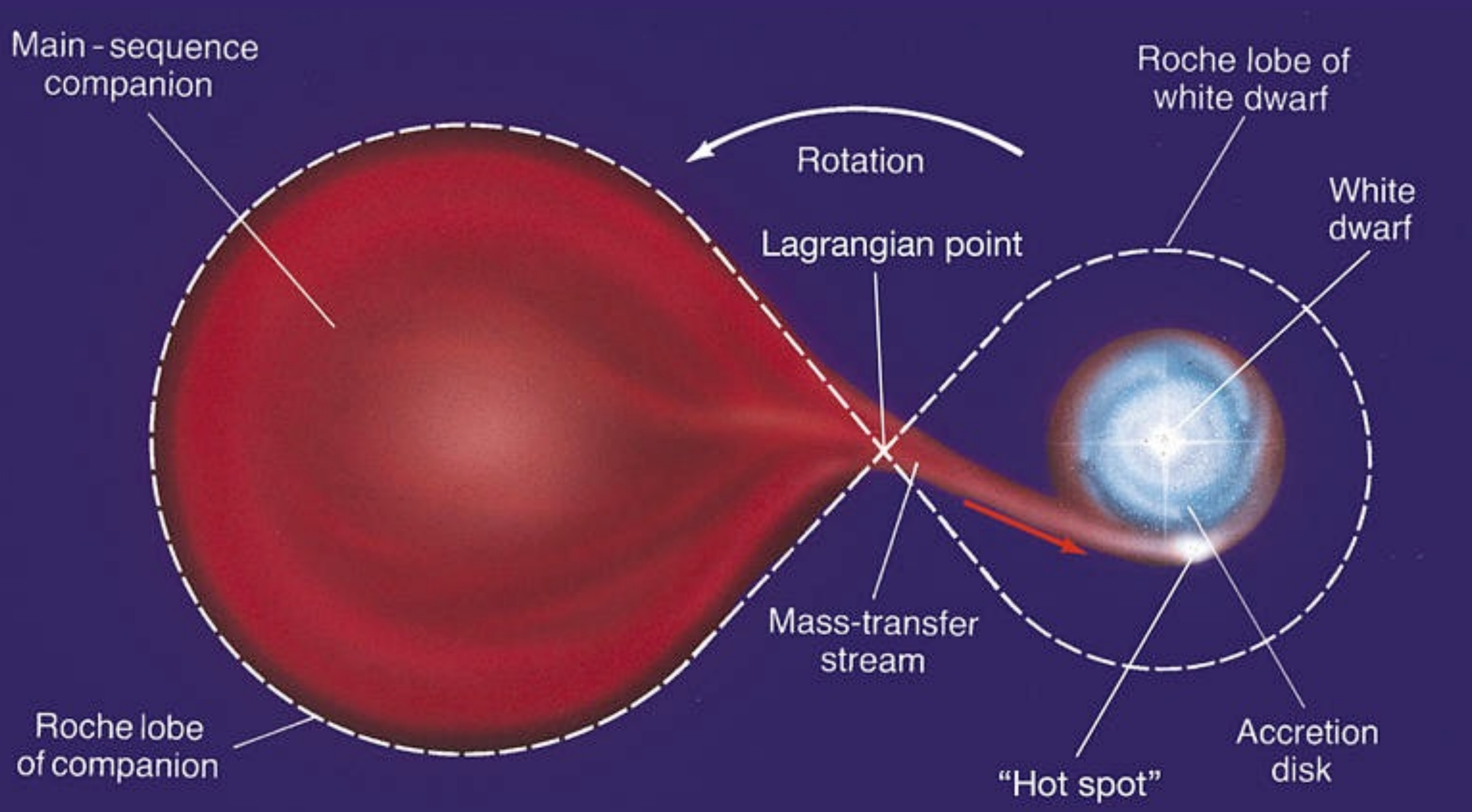
Supernova: explosion and destruction of a massive star

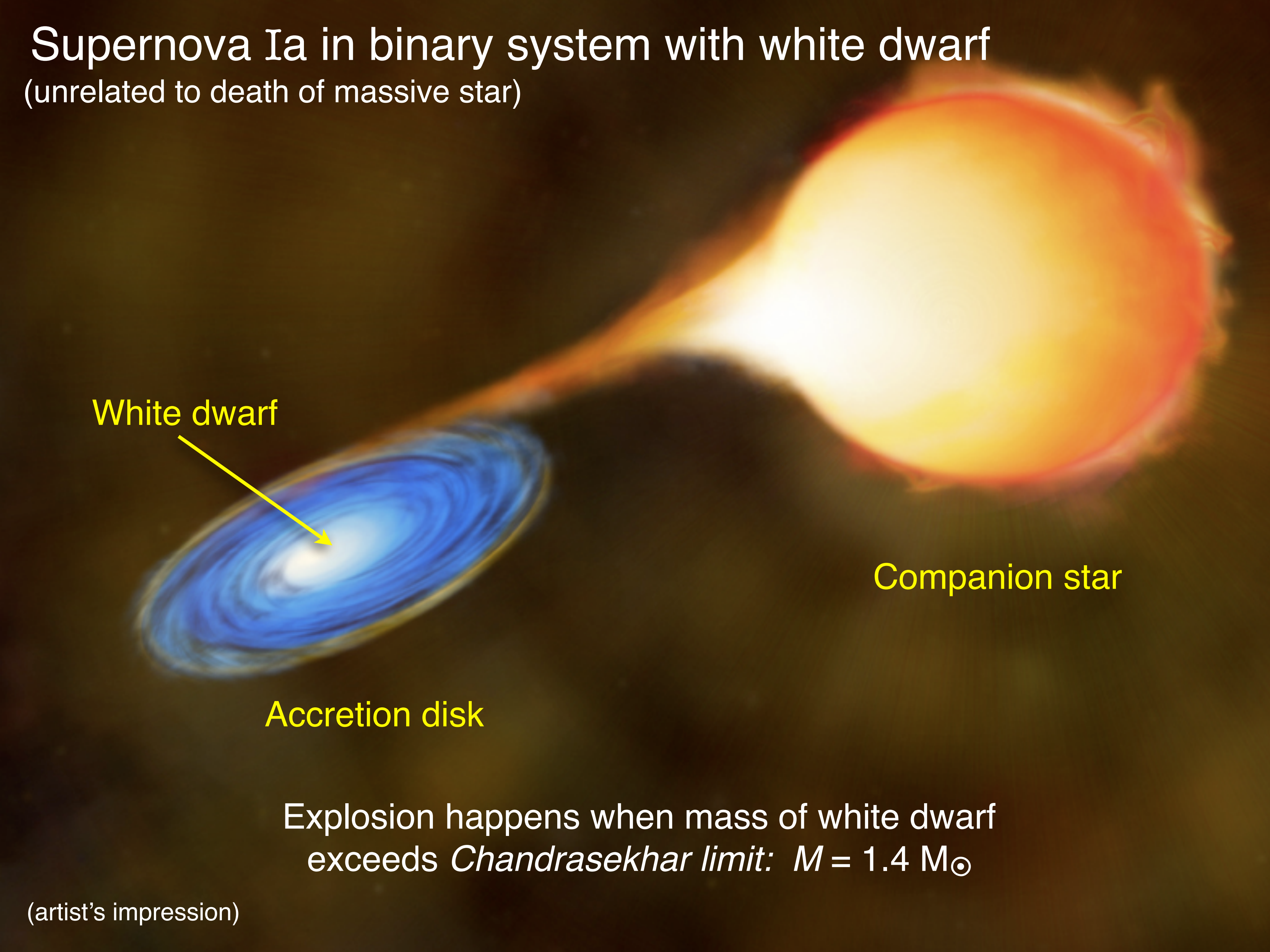


Galaxy: NGC 5965
Distance: 47.3 Mpc

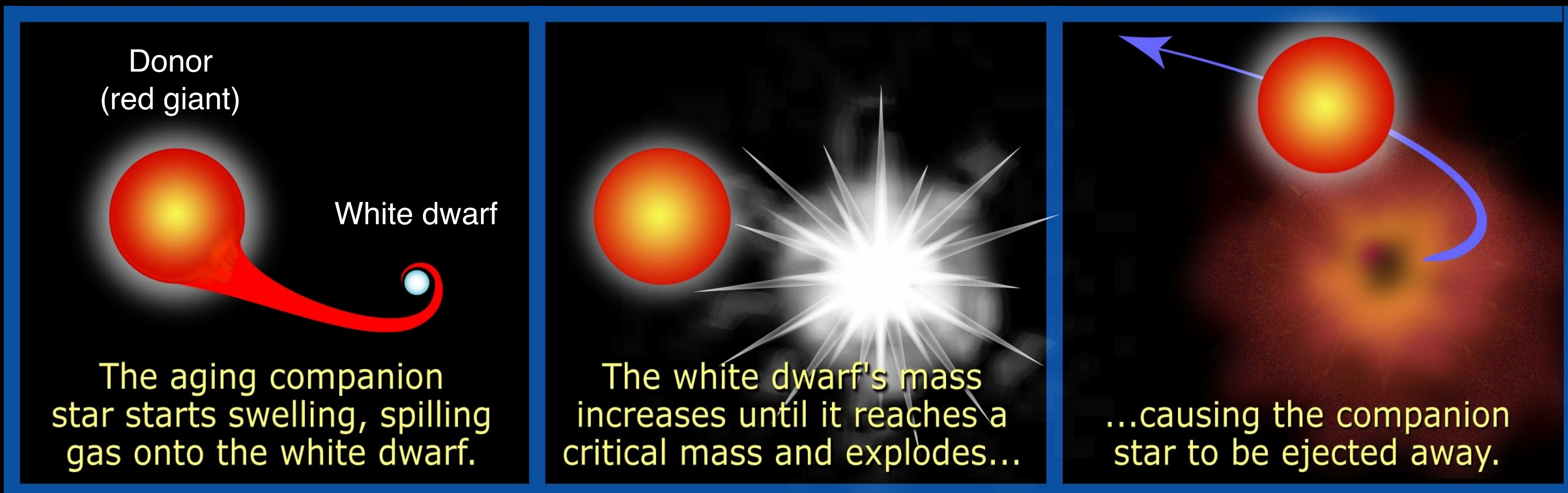
Stellar remnants in binary systems

Mass transfer in binary system




Supernova Ia in binary system with white dwarf
(unrelated to death of massive star)
White dwarf
Companion star
Accretion disk
Explosion happens when mass of white dwarf exceeds *Chandrasekhar limit:* $M = 1.4\ M_{\odot}$
(artist's impression)

Supernova Ia when critical mass $M \sim 1.4\ M_\odot$ reached (Chandrasekhar limit)



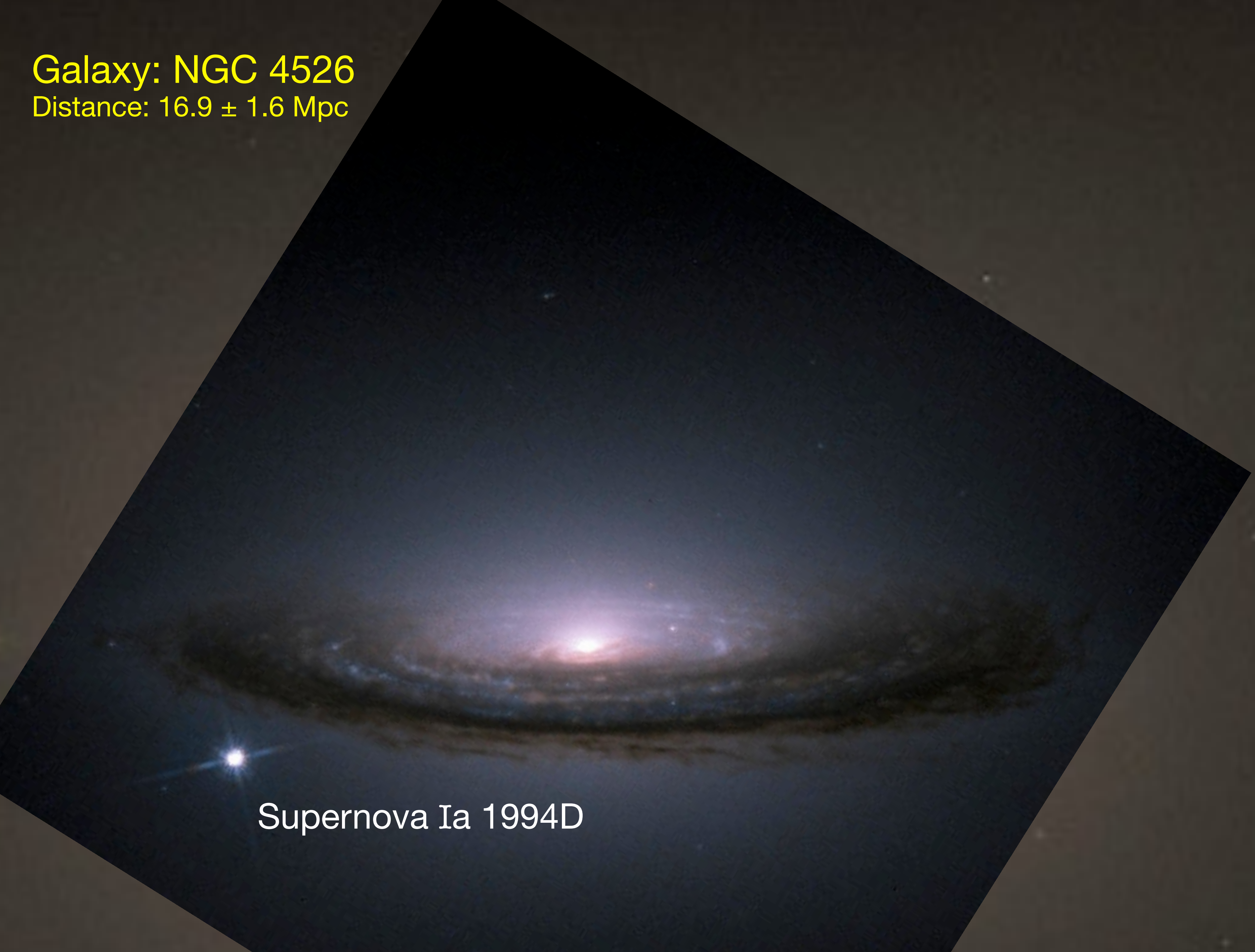
$T = 10^{10}$ K in core reached, nuclei converted into Fe, Co, Ni

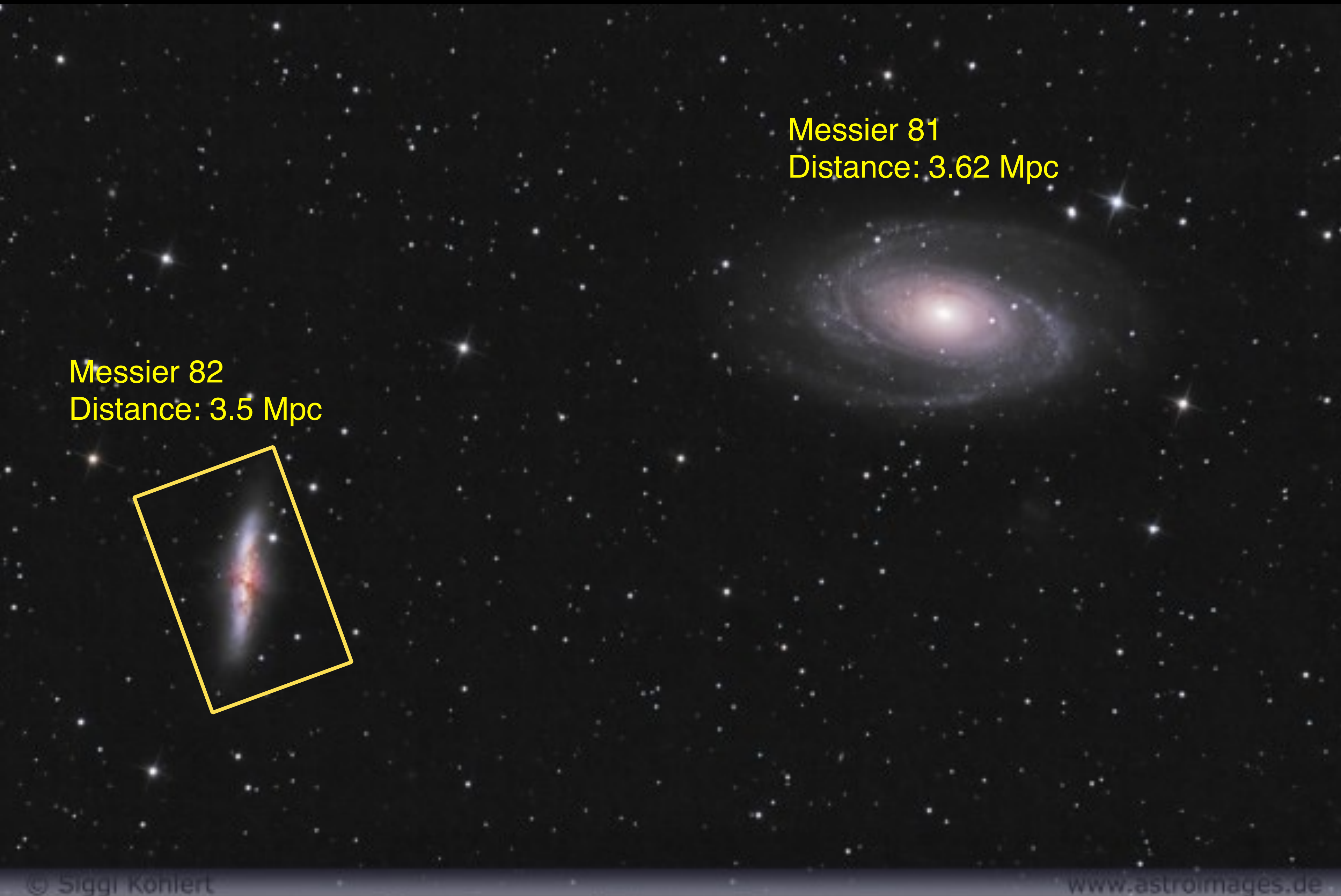
Lighter elements (Si or Ca) produced moving outwards


Galaxy: NGC 4526
Distance: 16.9 ± 1.6 Mpc

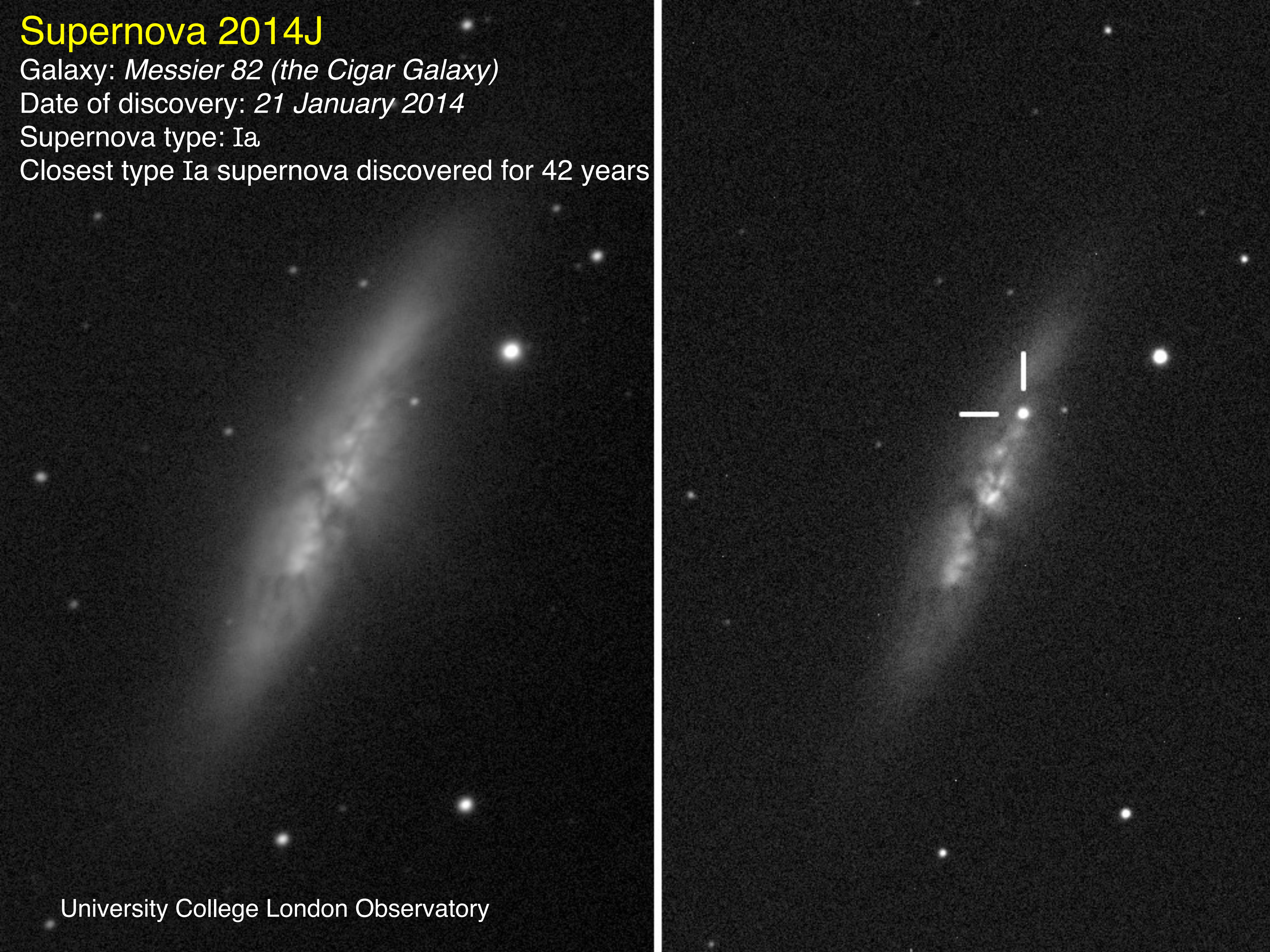
Galaxy: NGC 4526

Distance: 16.9 ± 1.6 Mpc




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

Observatory of University College (London)

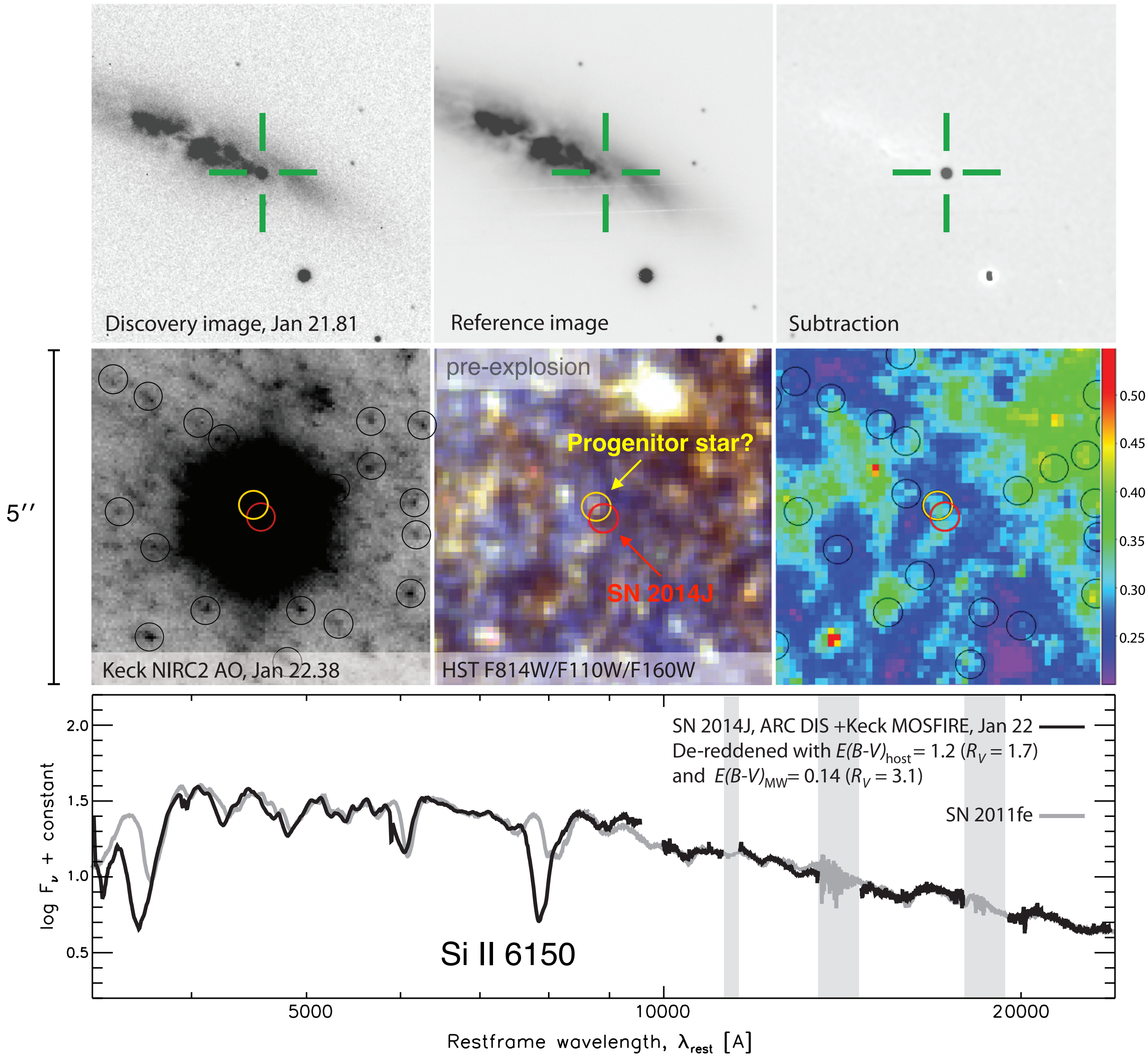

Supernova 2014J
Galaxy: *Messier 82 (the Cigar Galaxy)*
Date of discovery: *21 January 2014*
Supernova type: Ia
Closest type Ia supernova discovered for 42 years
University College London Observatory

Supernova 2014J in Galaxy M82

HST ▪ WFC3/UVIS ▪ ACS/WFC

NASA and ESA

STScI-PRC14-13a



Discovery image, Jan 21.81
Reference image
Subtraction
5′′
pre-explosion
Progenitor star?
SN 2014J
Keck NIRC2 AO, Jan 22.38
HST F814W/F110W/F160W
F110W - F160W [mag]
0.50
0.45
0.40
0.35
0.30
0.25
SN 2014J, ARC DIS +Keck MOSFIRE, Jan 22
De-reddened with $E(B-V)_{host}$= 1.2 (R_V = 1.7)
and $E(B-V)_{MW}$= 0.14 (R_V = 3.1)
SN 2011fe
Si II 6150
log F_ν + constant
2.0
1.5
1.0
0.5
5000
10000
20000
Restframe wavelength, λ_{rest} [A]

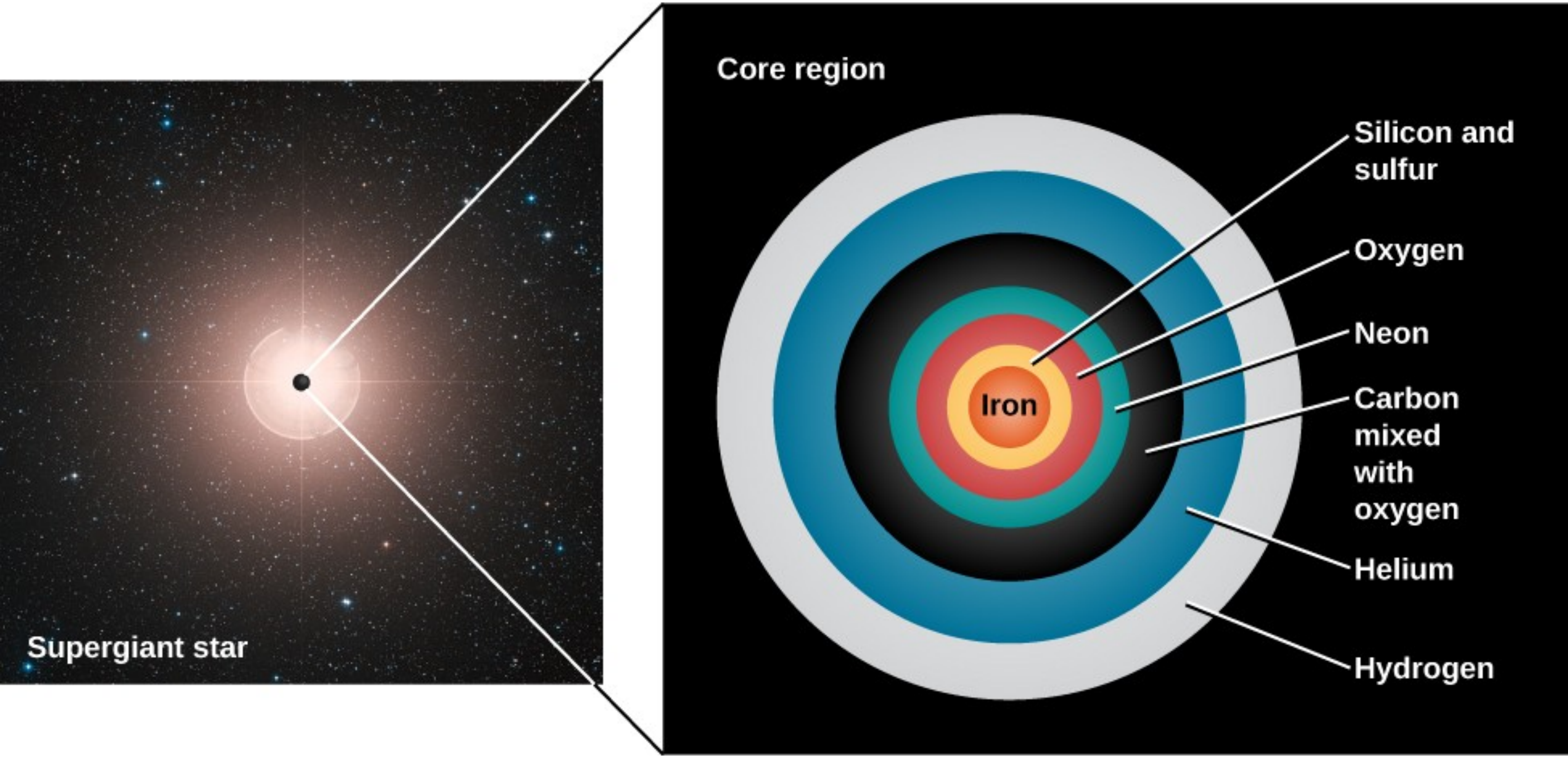
Before explosion of massive stars

Summary of element production in stars (before mass loss)

$M < 0.5\ M_\odot$	up to He
$0.5\ M_\odot < M < 8\ M_\odot$	up to about O
$8\ M_\odot < M < 10\ M_\odot$	up to about Mg + small amount of heavier elements
$M > 10\ M_\odot$	wide range of elements, including Fe peak & heavier

For massive stars, mass limits above which explosion occurs is not totally known!

Structure of evolved massive star
(core-collapse progenitor)



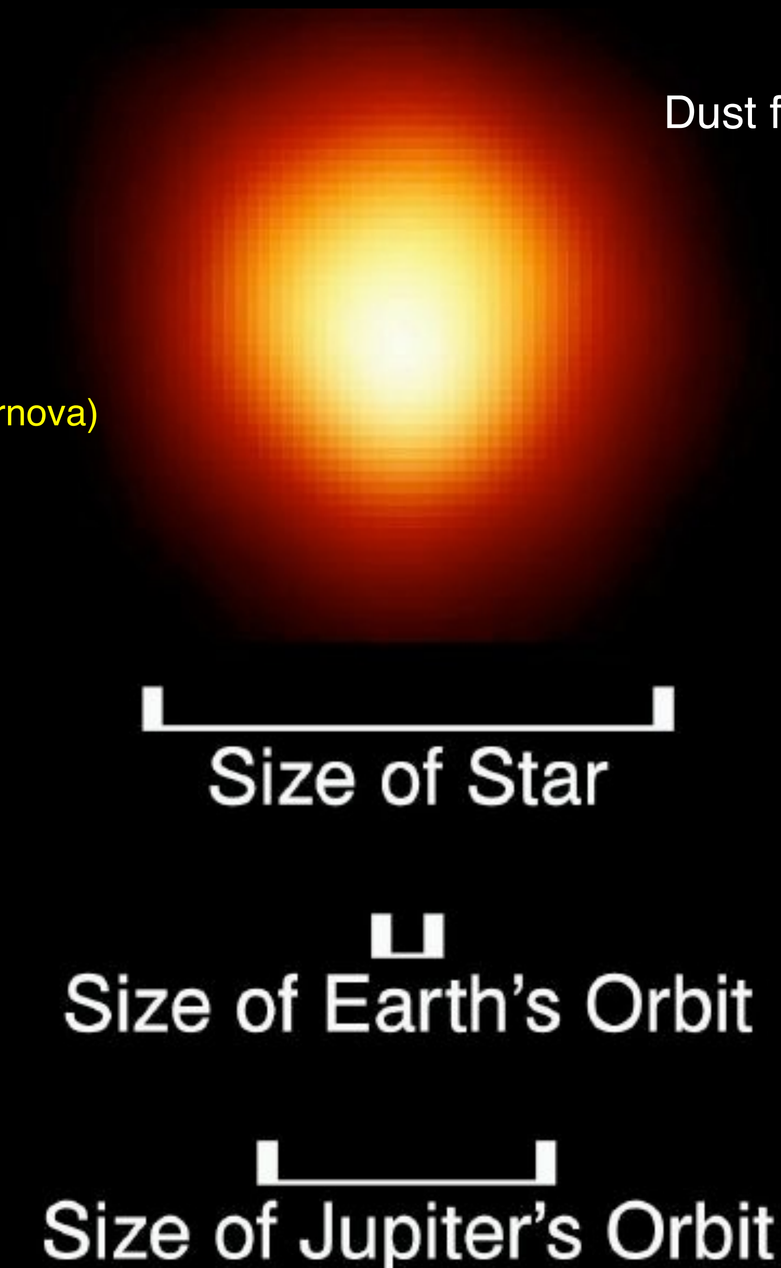
The iron core is surrounded by layers of different chemical elements (onion structure)

Before explosion: stellar wind with mass loss

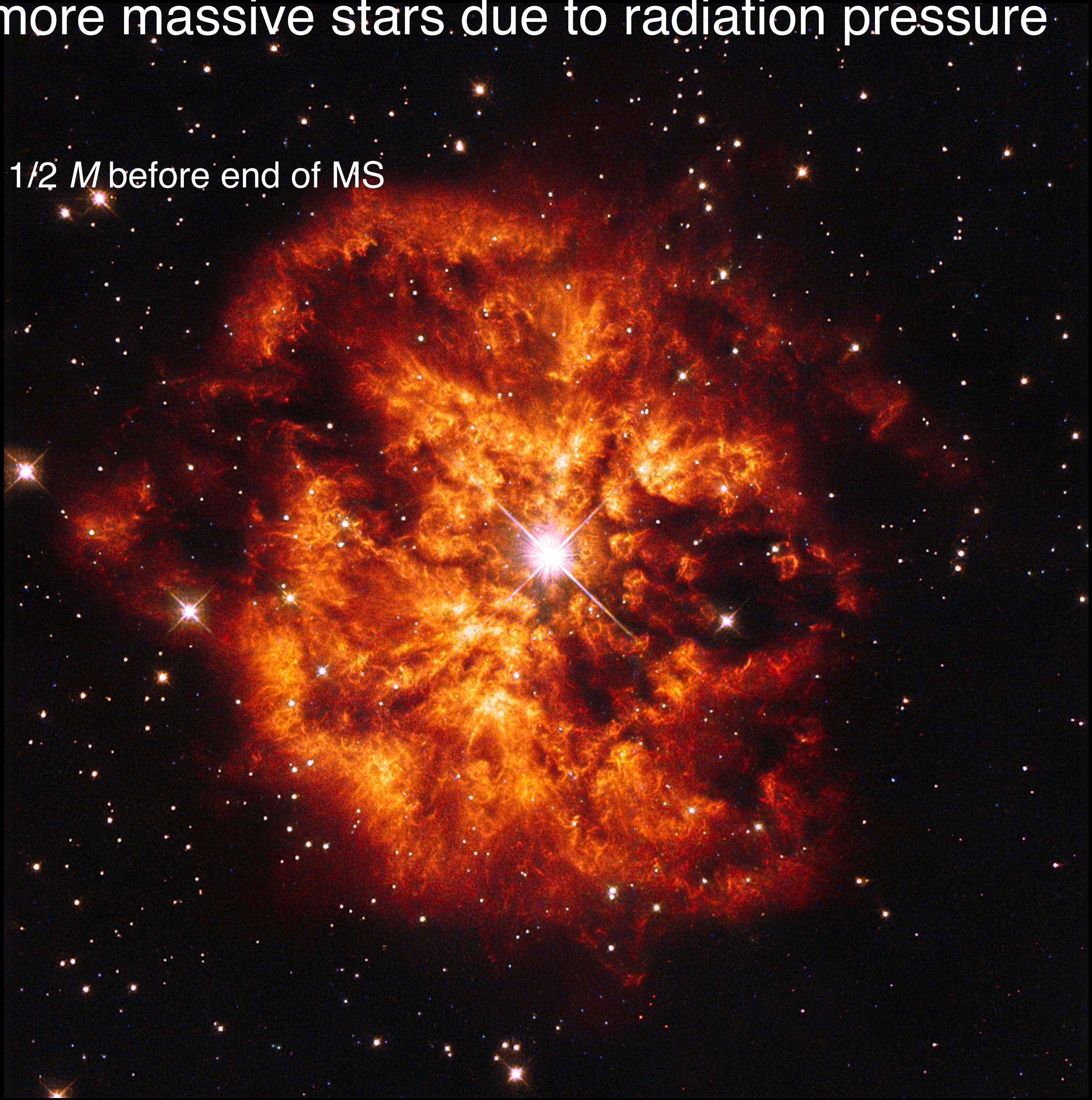
Betelgeuse

Mass: M = 15 – 20 $M_\odot$
Surface temperature: $T \sim$ 3600 K
Radius: $R \sim$ 1000 $R_\odot$
Stage before massive explosion (supernova)

Dust forms in atmosphere of red giant stars



Mass loss in more massive stars due to radiation pressure



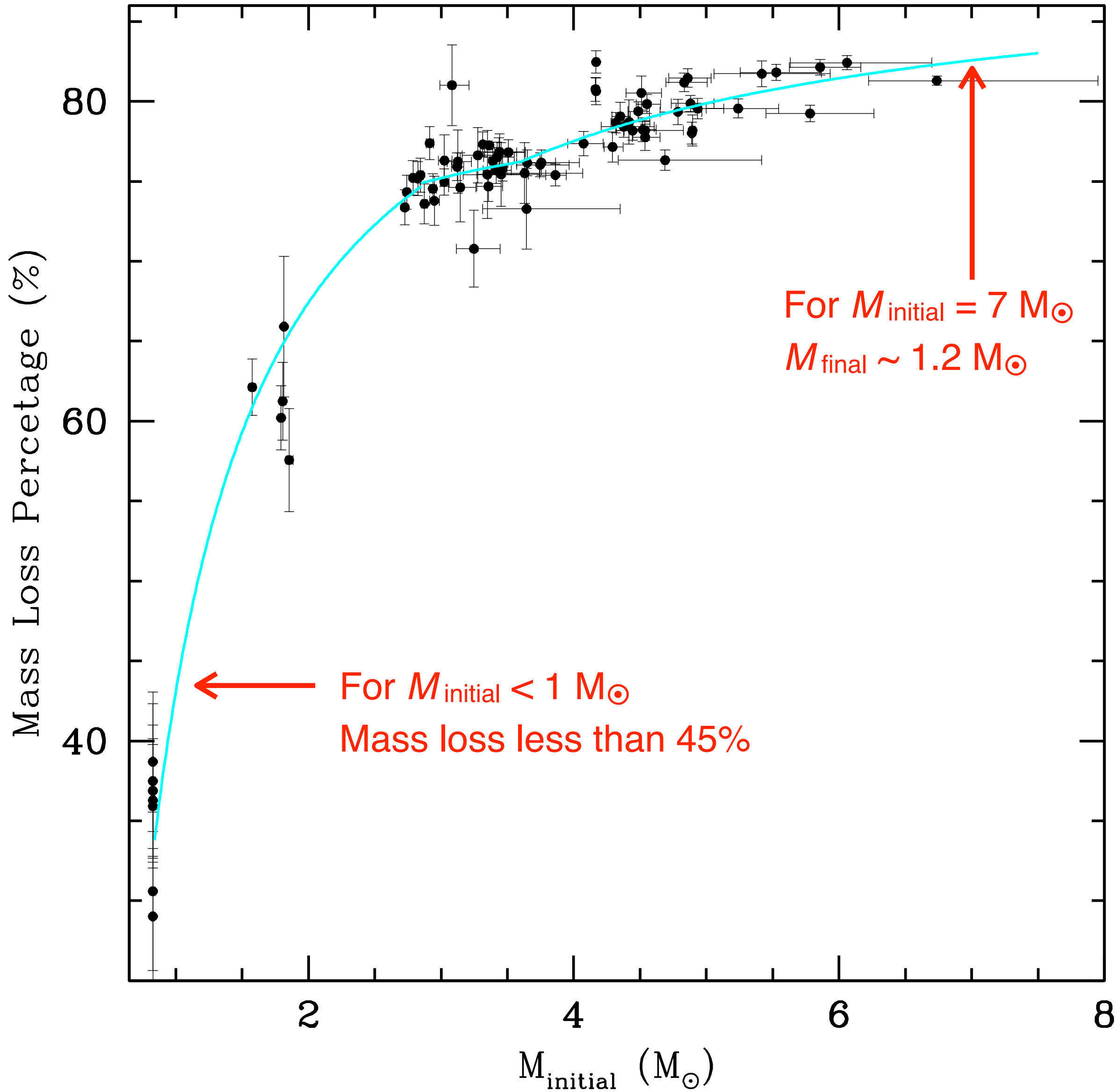
Mass loss rate:

$M = 100\ M_\odot$ star: up to 1/2 M before end of MS
O stars: $10^{-6}\ M_\odot$ / yr
The Sun: $10^{-14}\ M_\odot$ / yr

Wolf-Rayet star *WR124*
Distance: 3.35 kpc
Mass: $M = 9\ M_\odot$
Temperature: $T = 35{,}900$ K
Age: 8.6 Myr

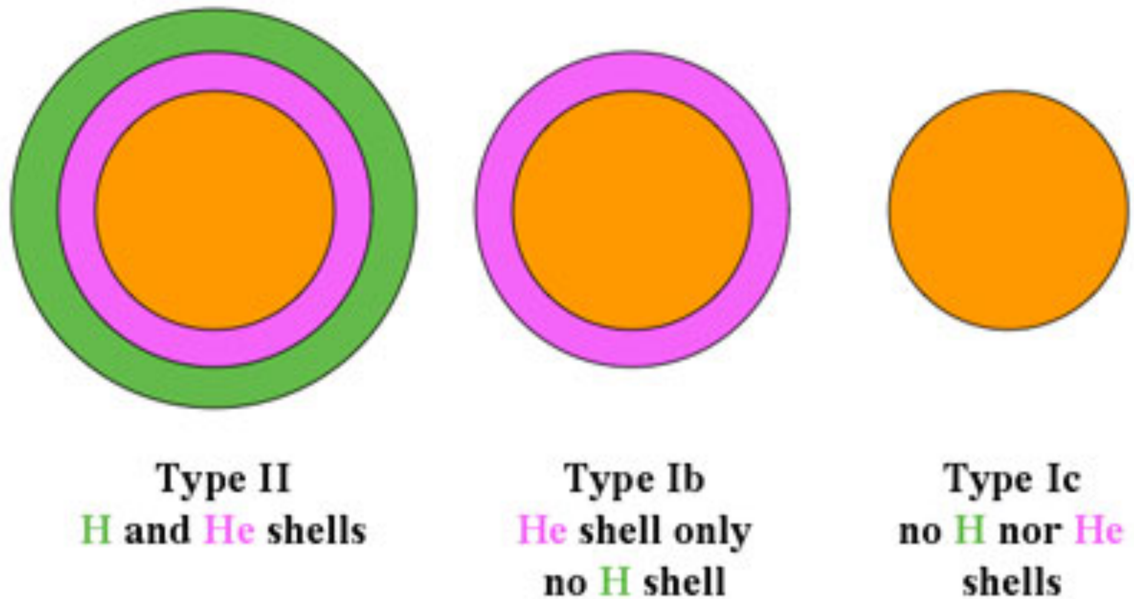
Mass loss is increasingly important

Total mass loss throughout a star's lifetime as a percentage of initial mass



Core-collapse supernova type depends on retained shells

Type II: hydrogen & helium retained
Type Ib: hydrogen lost
Type Ic: both hydrogen & helium lost



Progenitor mass →

A role also played by:

- Rotation
- Magnetic field
- Presence of companion star (removing gas from external shells)
- Chemical composition of external shells (radiation pressure is more efficient when gas contains more heavy elements)

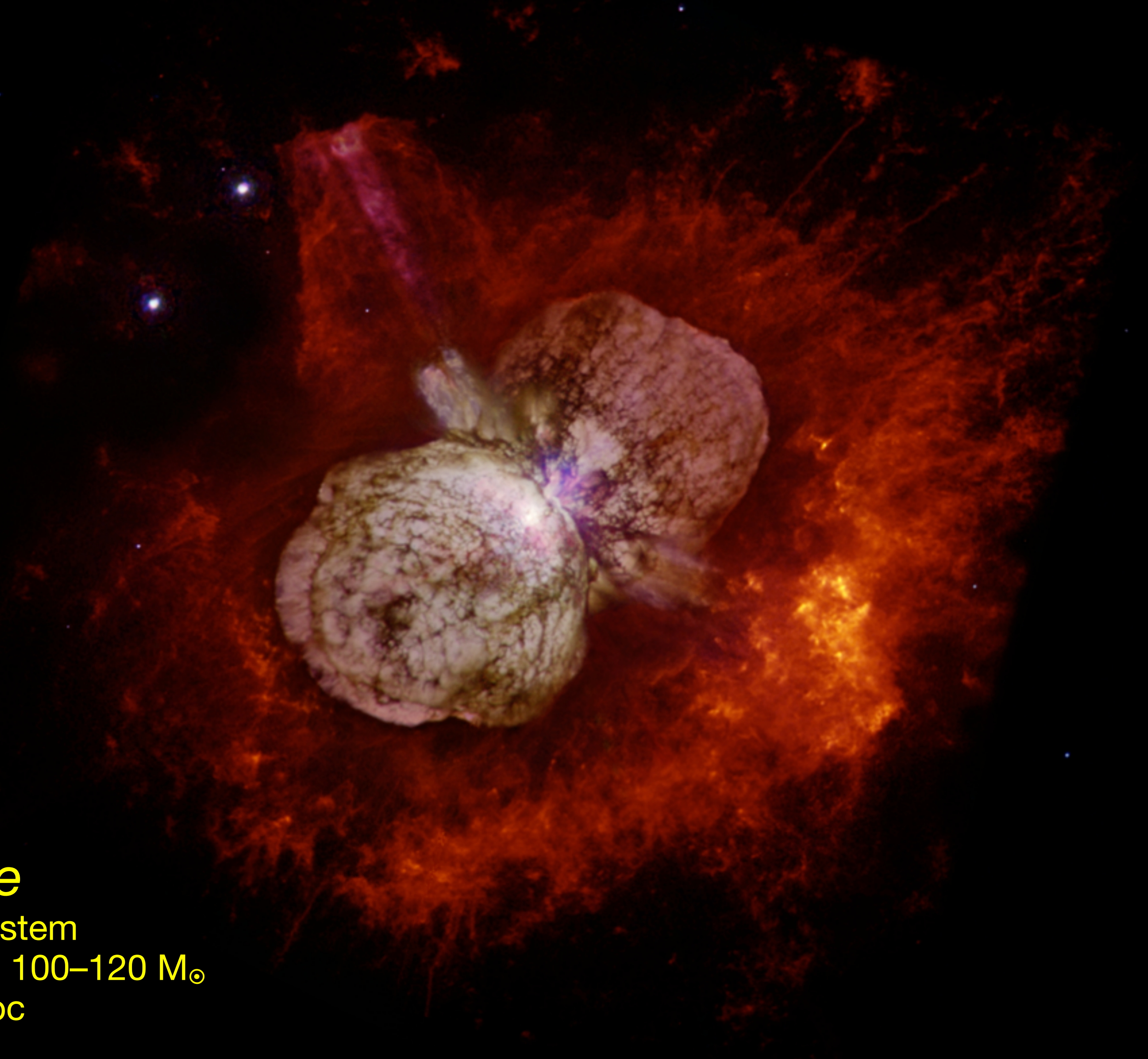
Most massive stars

- Mass loss most important property
- Upper limit for formation of massive star: $M = 300\text{-}500\ M_\odot$
- Radiation pressure prevents the formation for higher masses

AND

- Massive stars are all (at least initially) in binary systems

Most massive stars are often in binary systems



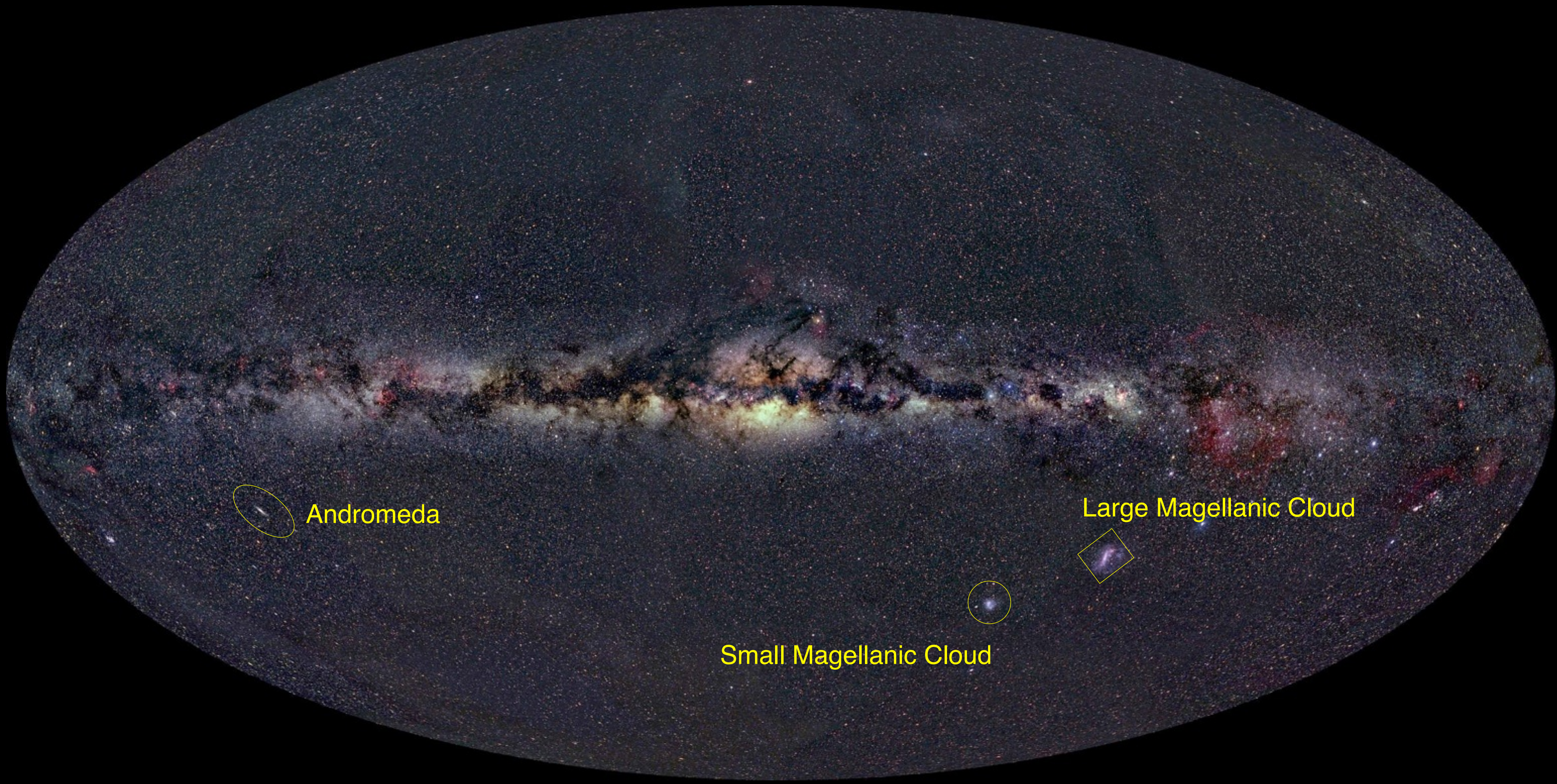
Eta Carinae

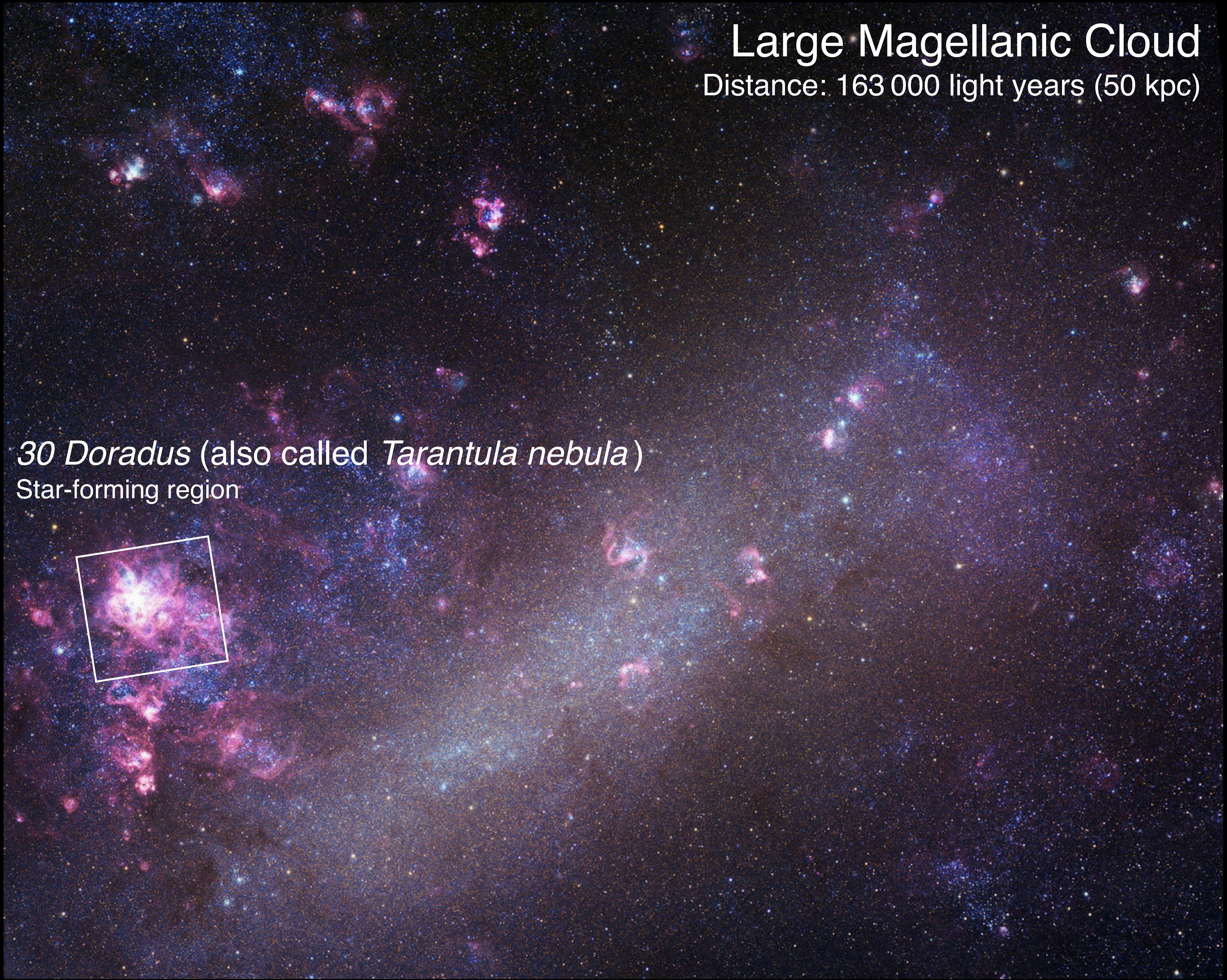
Binary stellar system

Total mass: M = 100–120 $M_\odot$

Distance: 2.3 kpc

Our Galaxy: the Milky Way

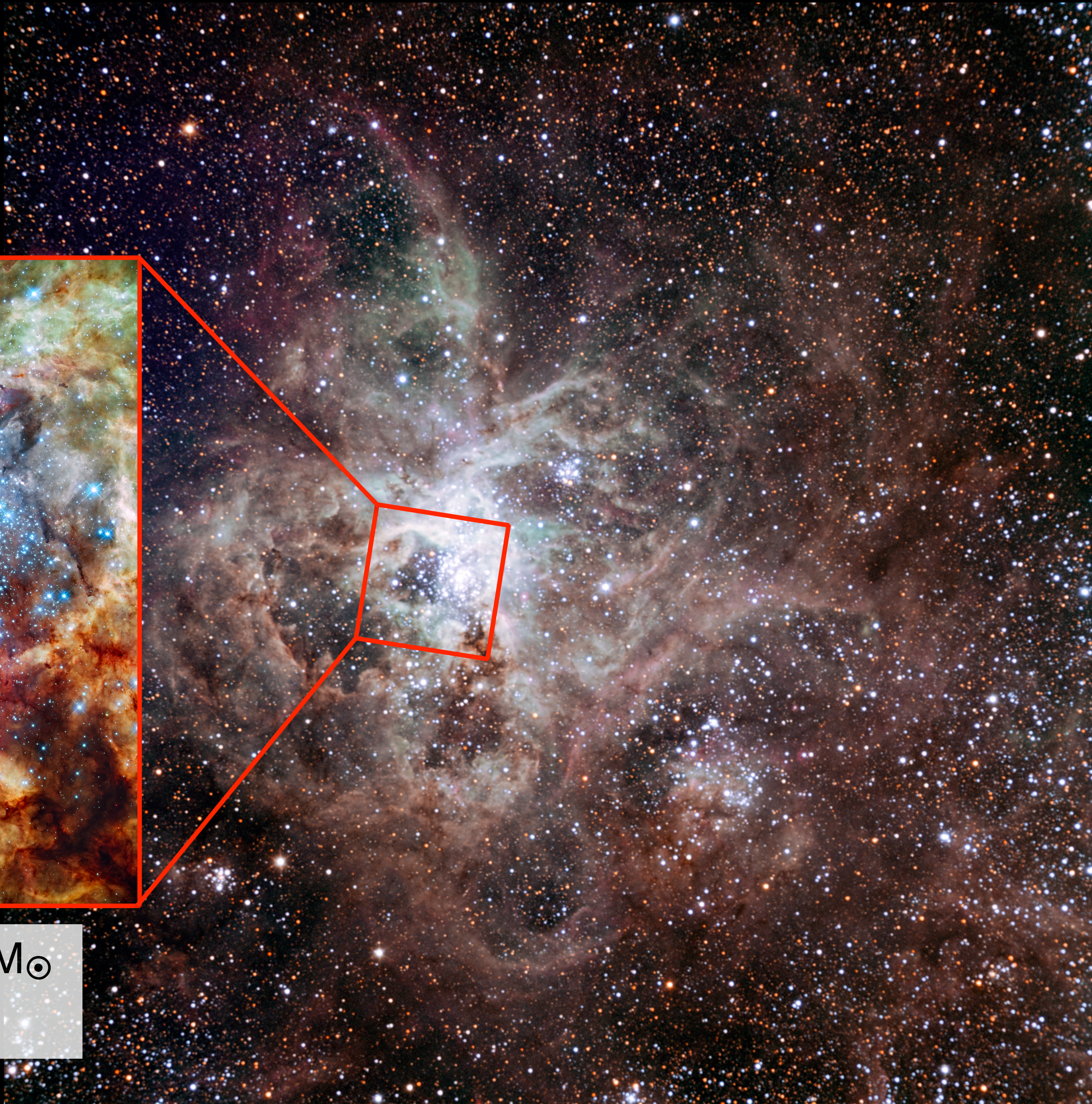



Large Magellanic Cloud
Distance: 163 000 light years (50 kpc)
30 Doradus (also called Tarantula nebula)
Star-forming region

Tarantula Nebula contains the open star cluster *R136*

In 185×146 pc^2 there are:

- 360 O stars
- 400 B stars

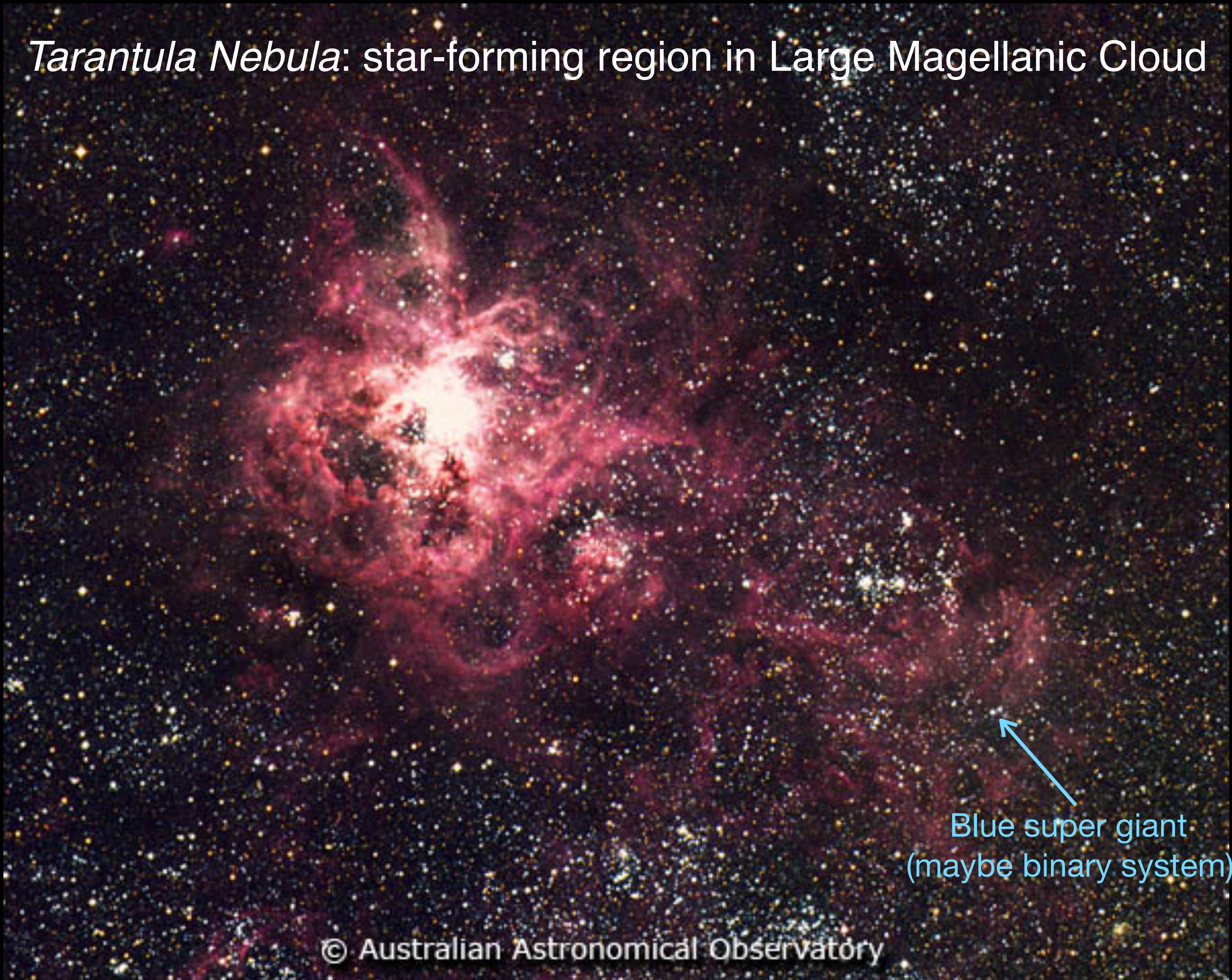


9 stars with $M > 100\ M_\odot$ in 1 pc size region

In open star clusters

- Many young 2-4 Myr-old stars
- 70% of these are massive binary stars
- Many are interacting
- 1/4 will merge

Tarantula Nebula: star-forming region in Large Magellanic Cloud



Tarantula Nebula: star-forming region in Large Magellanic Cloud

Neutrino detection from Supernova 1987A

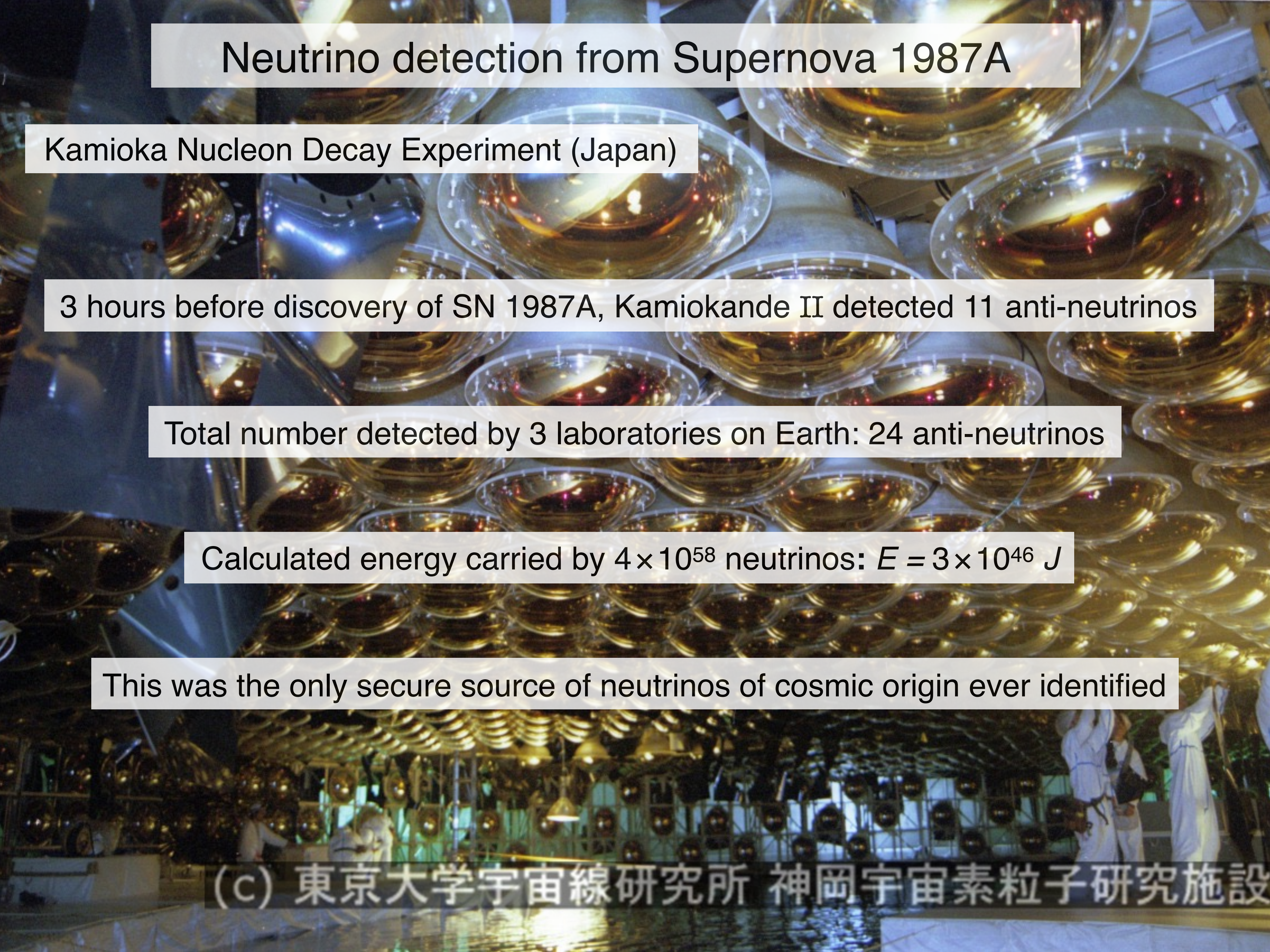
Kamioka Nucleon Decay Experiment (Japan)

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

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

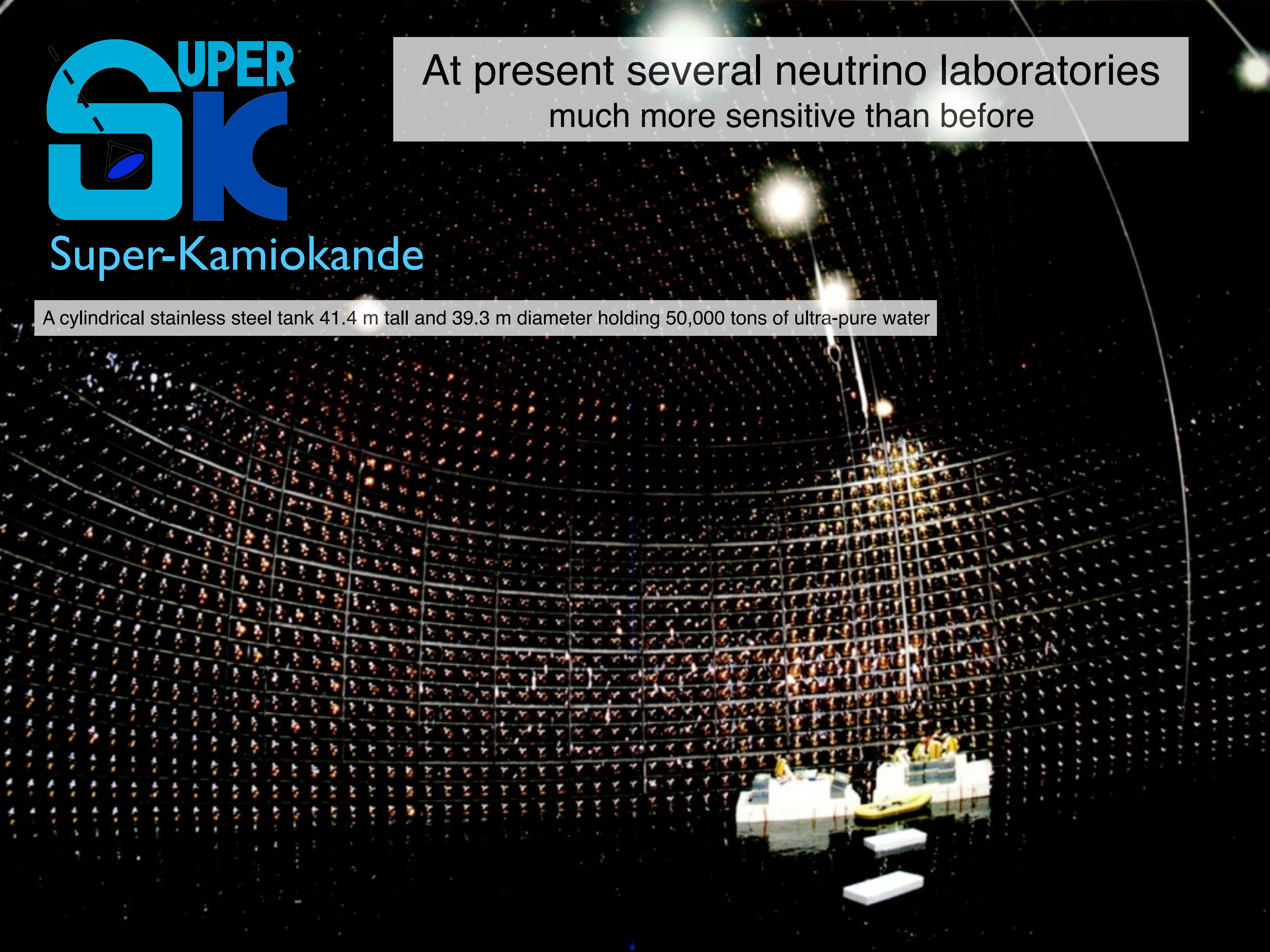
Calculated energy carried by 4×10^{58} neutrinos: $E = 3 \times 10^{46}$ J

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



At present several neutrino laboratories much more sensitive than before

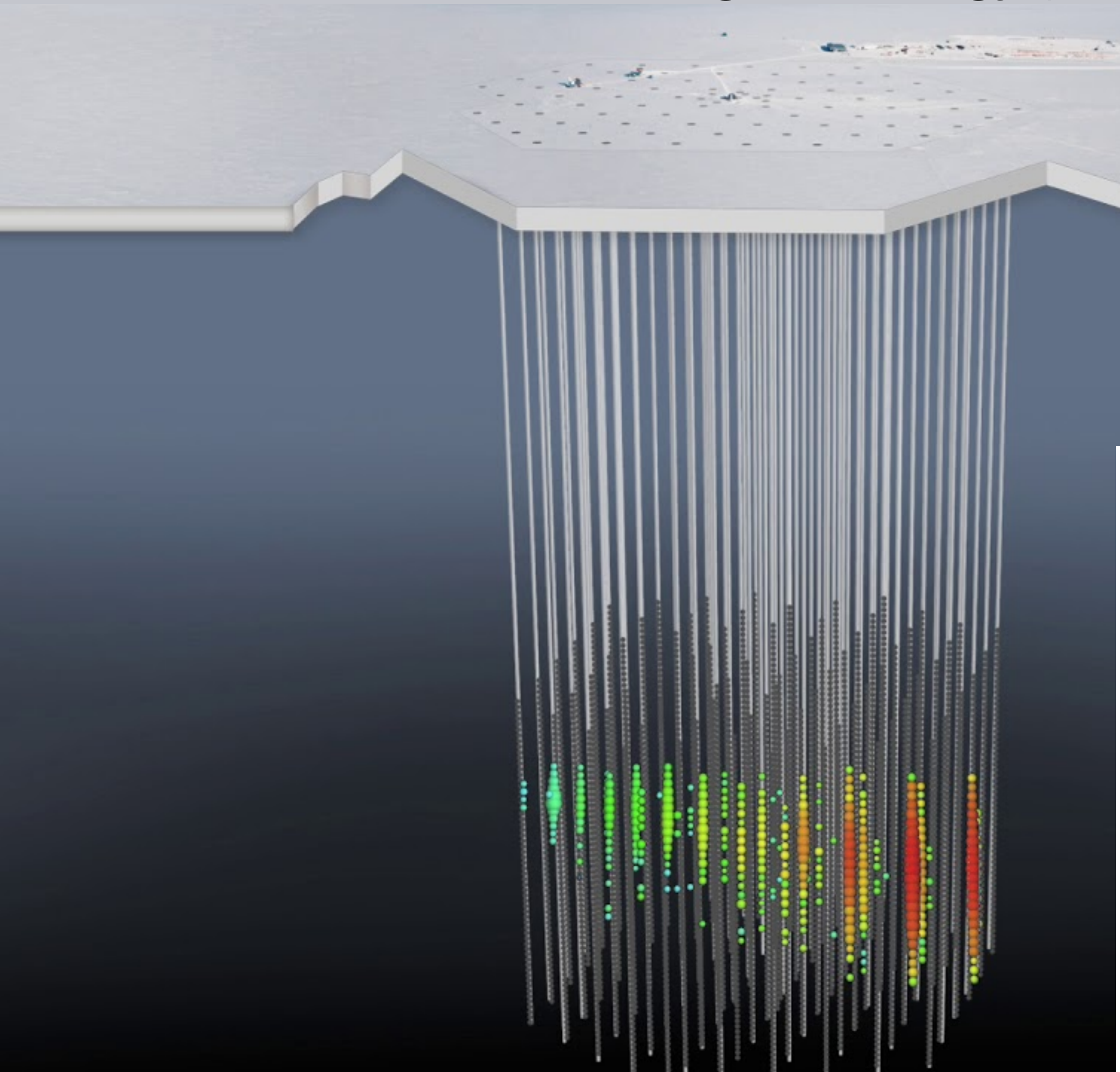
Super-Kamiokande

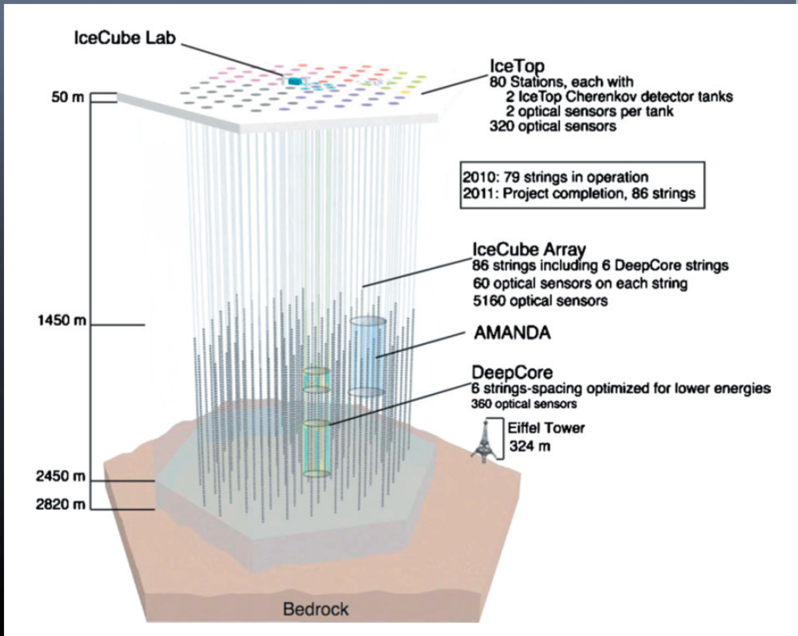


A cylindrical stainless steel tank 41.4 m tall and 39.3 m diameter holding 50,000 tons of ultra-pure water

IceCube Neutrino Observatory

Thousands of sensors (photomultiplier tubes) between 1450 to 2450 meters under the ice of the South Pole to detect highest-energy (TeV) neutrinos





Death of massive stars

$\boldsymbol{M > 8\ M_\odot}$ nuclear reactions stop at Fe $\Longrightarrow$ contraction continues to $\boldsymbol{T = 10^{10}\ K}$
(e^- degenerate gas can't support for core mass $\boldsymbol{M_{core} > 1.4\ M_\odot}$)

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

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

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

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

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

$\Longrightarrow$ collapse suddenly **stops**

$\Longrightarrow$ external matter falling inward at high speed

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

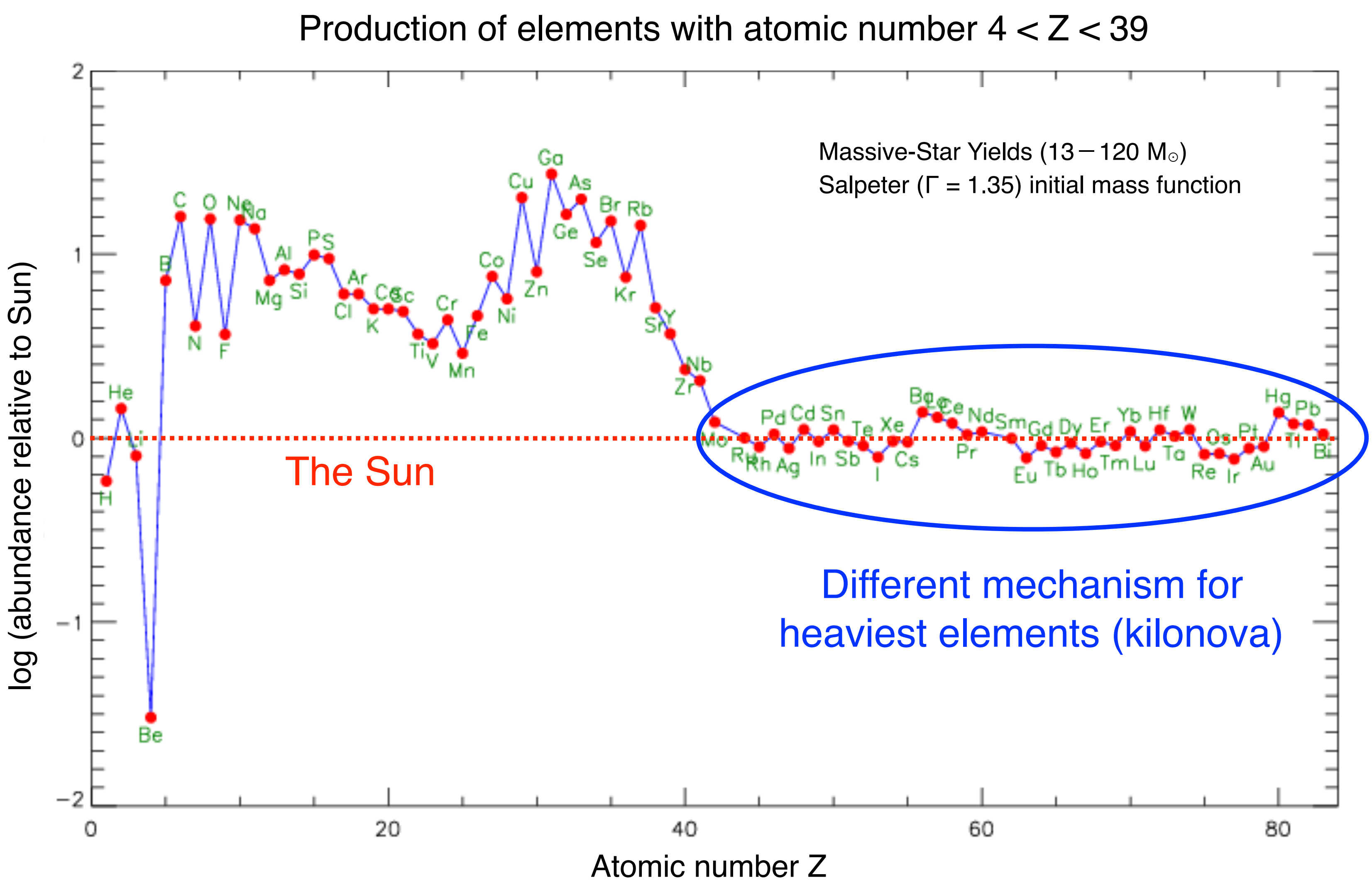
$\Longrightarrow$ **STAR EXPLODES (SUPERNOVA)**

$\Longrightarrow$ STAR EXPLOSION AS SUPERNOVA

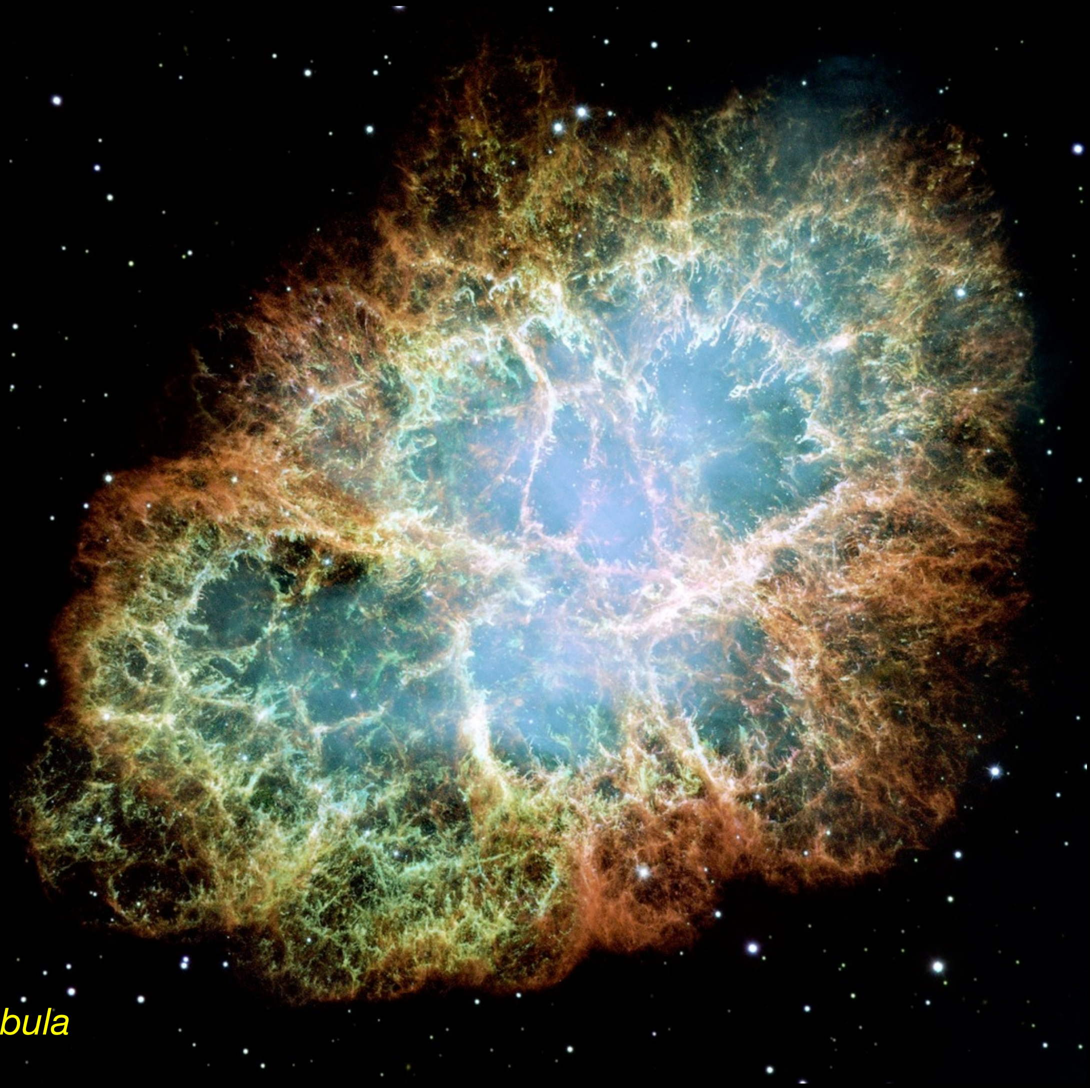
Not clear what happens, some or all of the following processes:

- 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

Nucleosynthesis in massive stars during explosion (models)

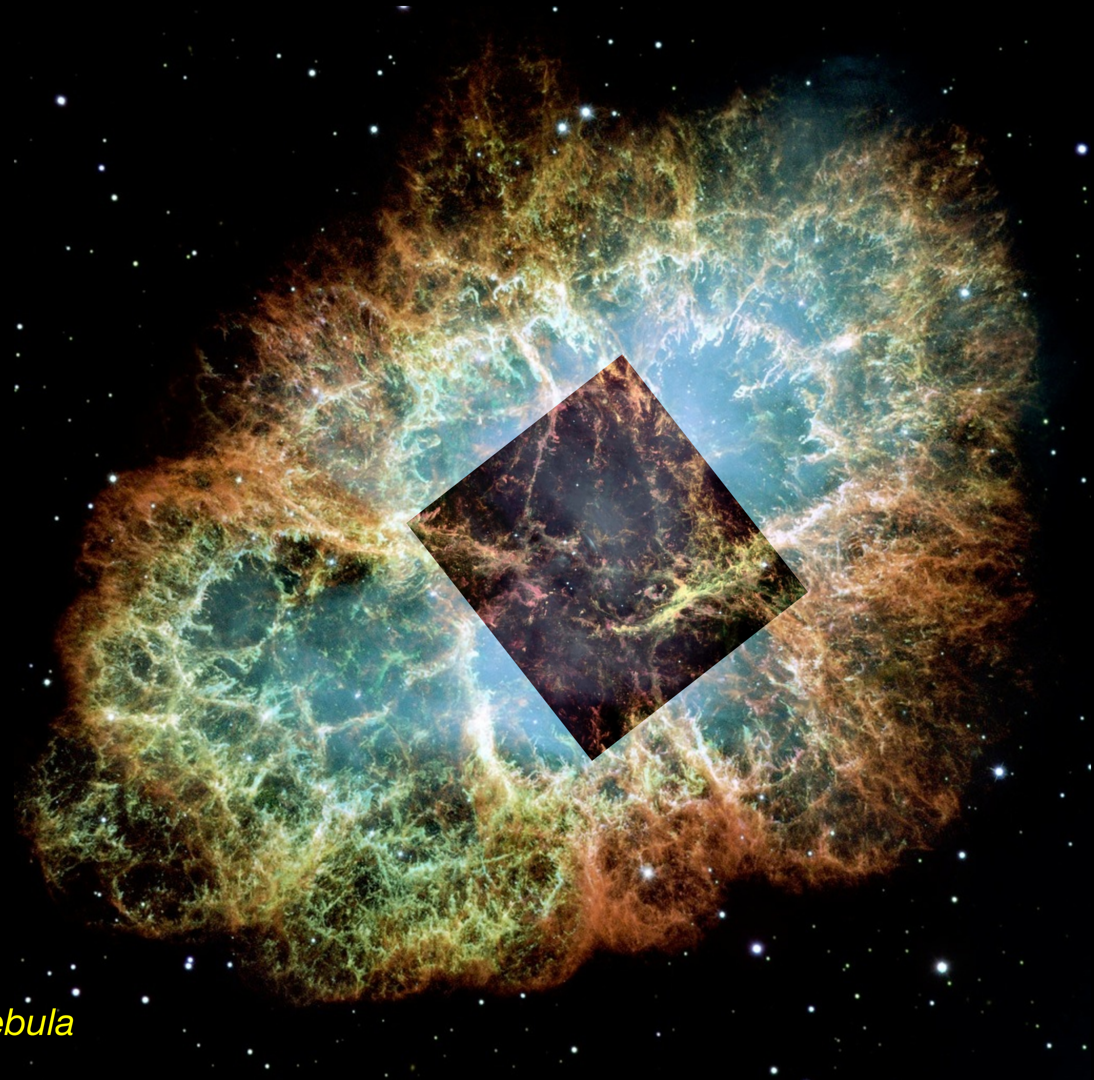


Final result of core collapse: neutron star



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



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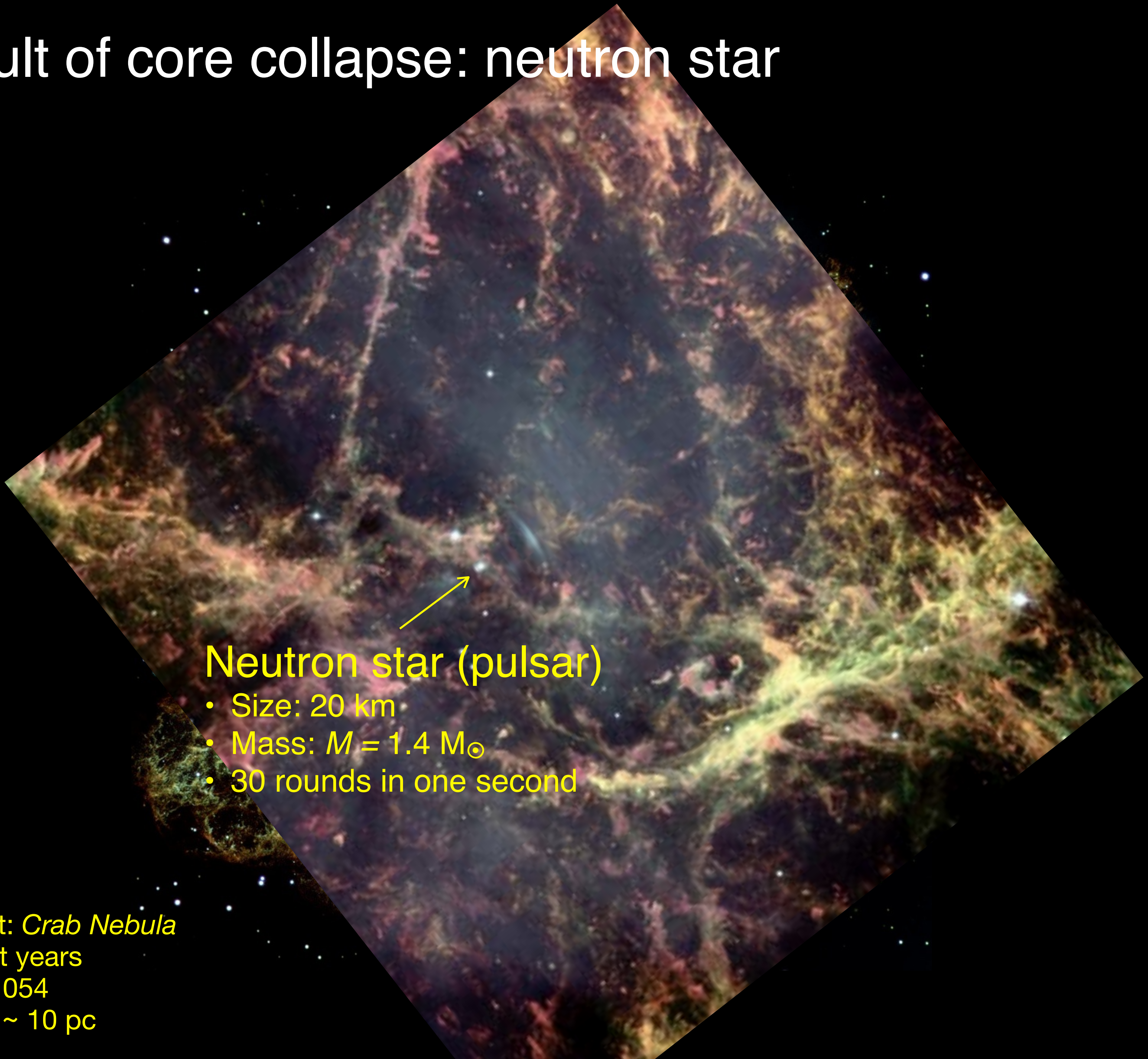

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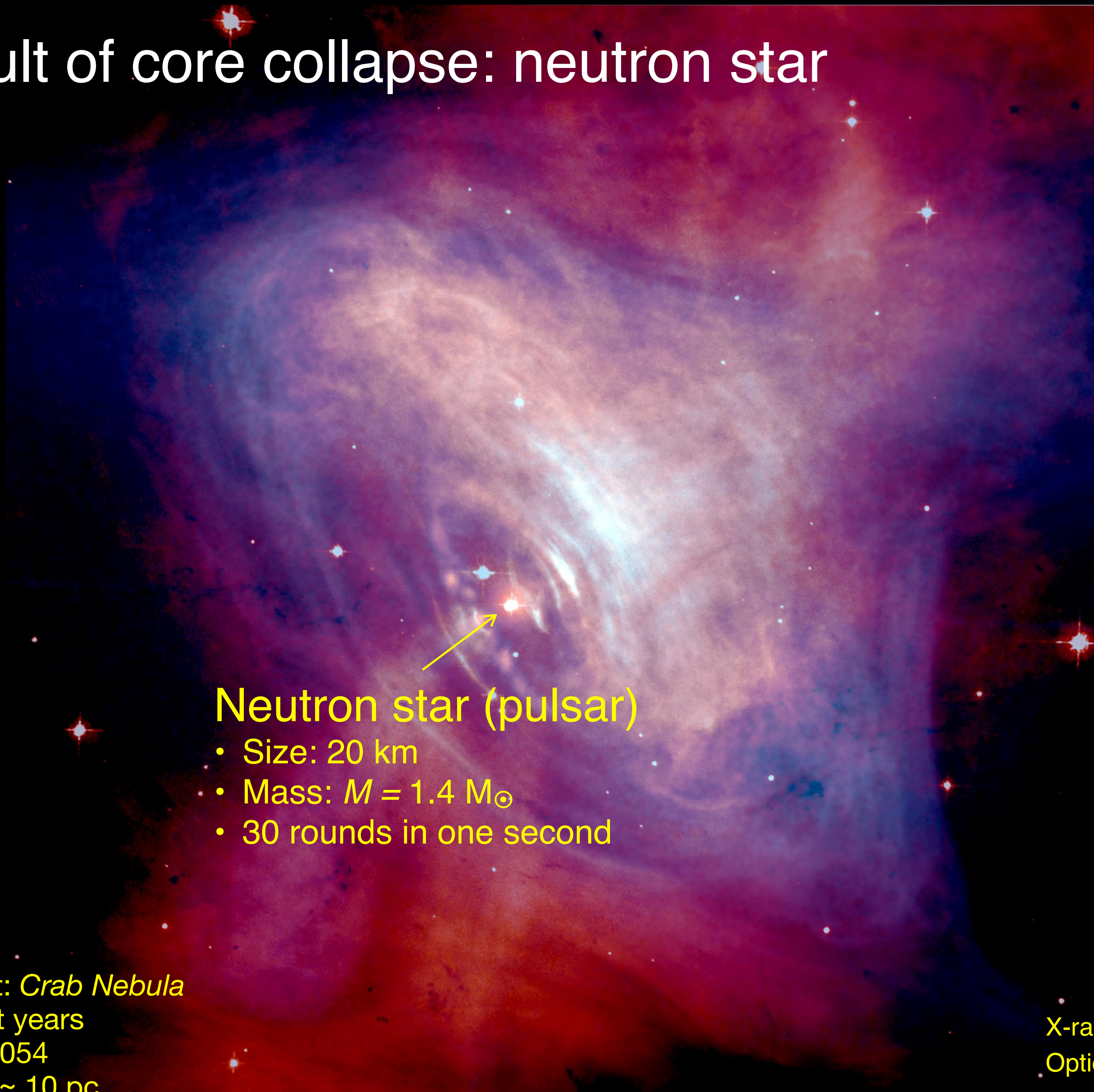


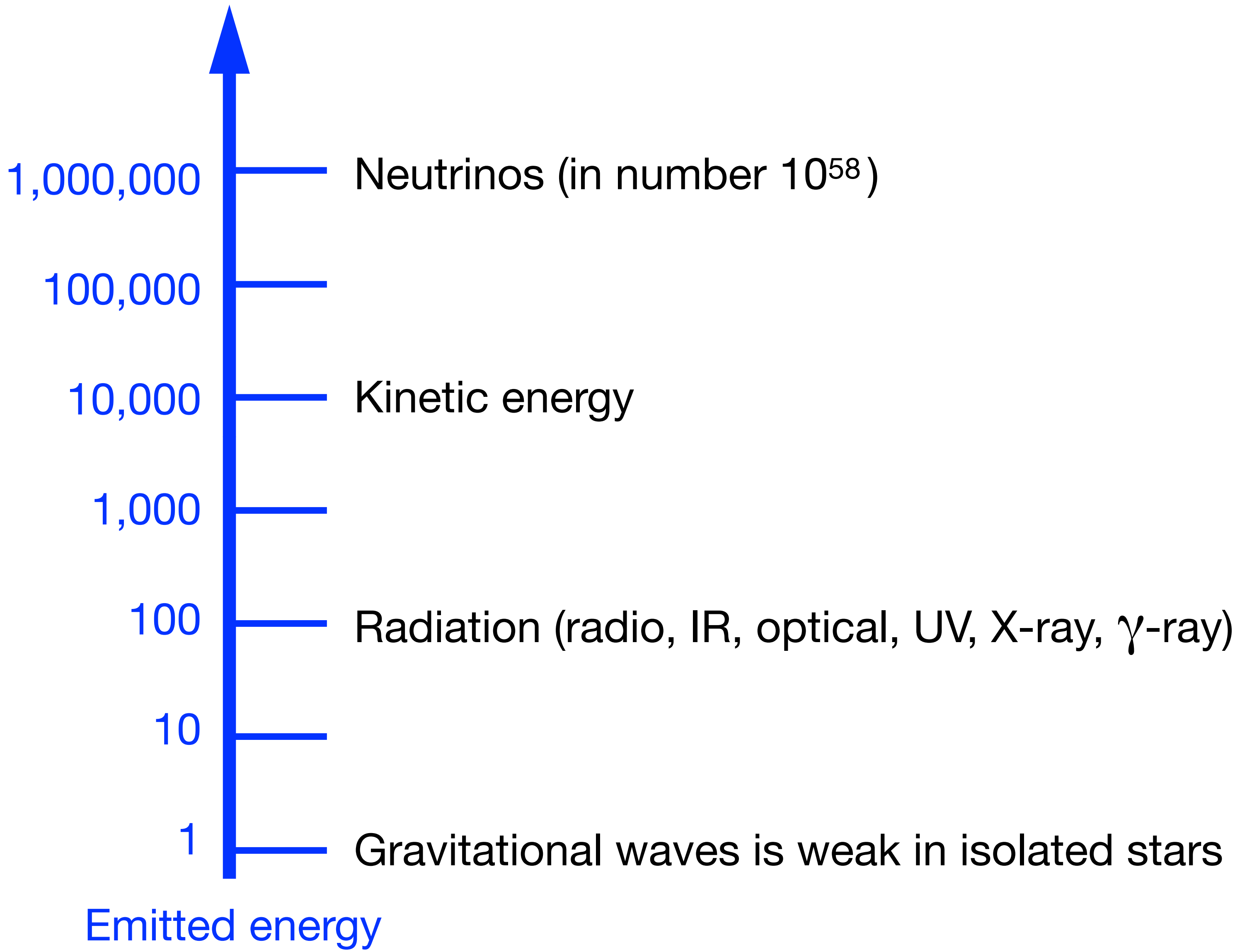
Neutron star (pulsar)

- 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

X-ray (blue)
Optical (red)

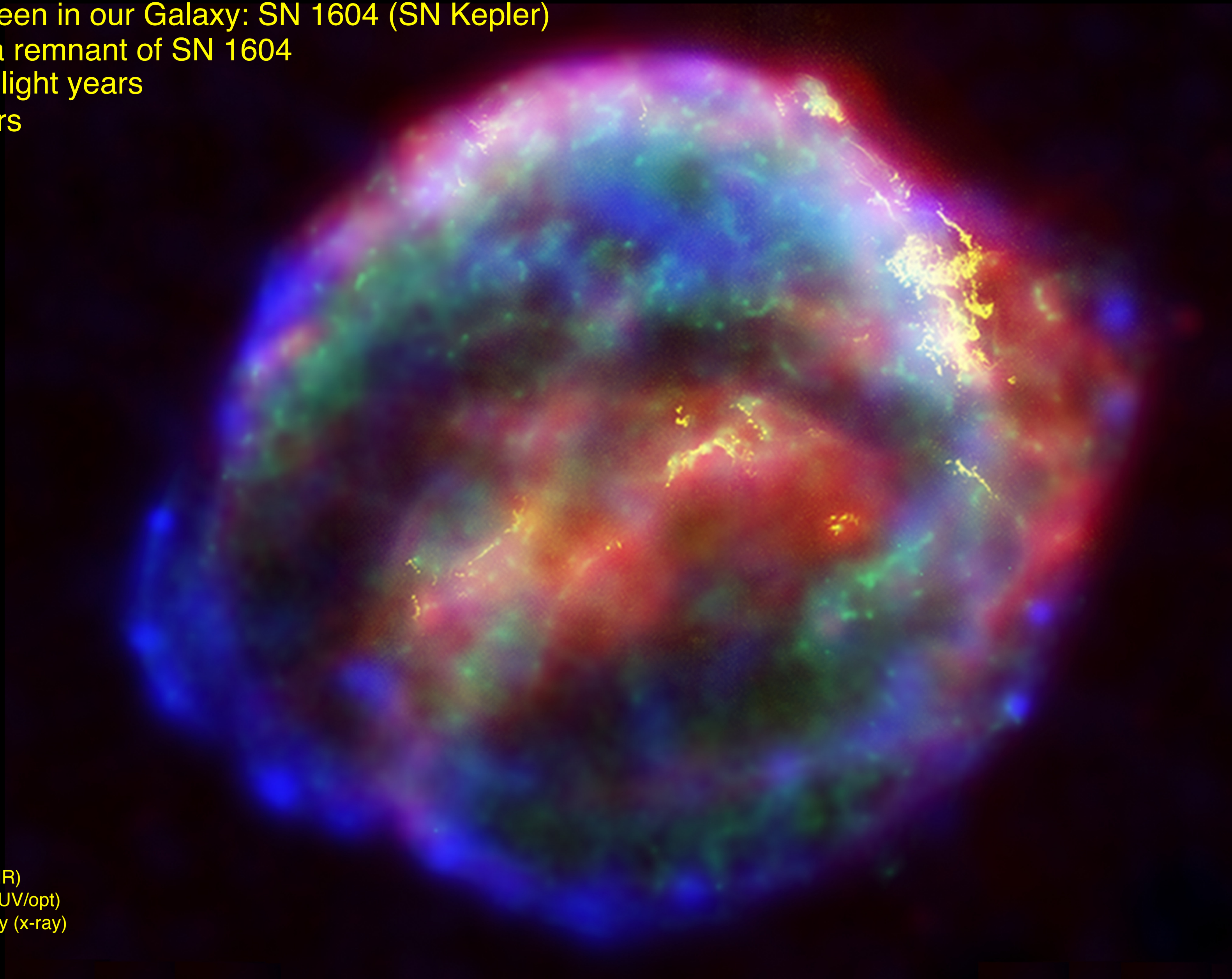
Supernova: energy production
(very indicative relative numbers)



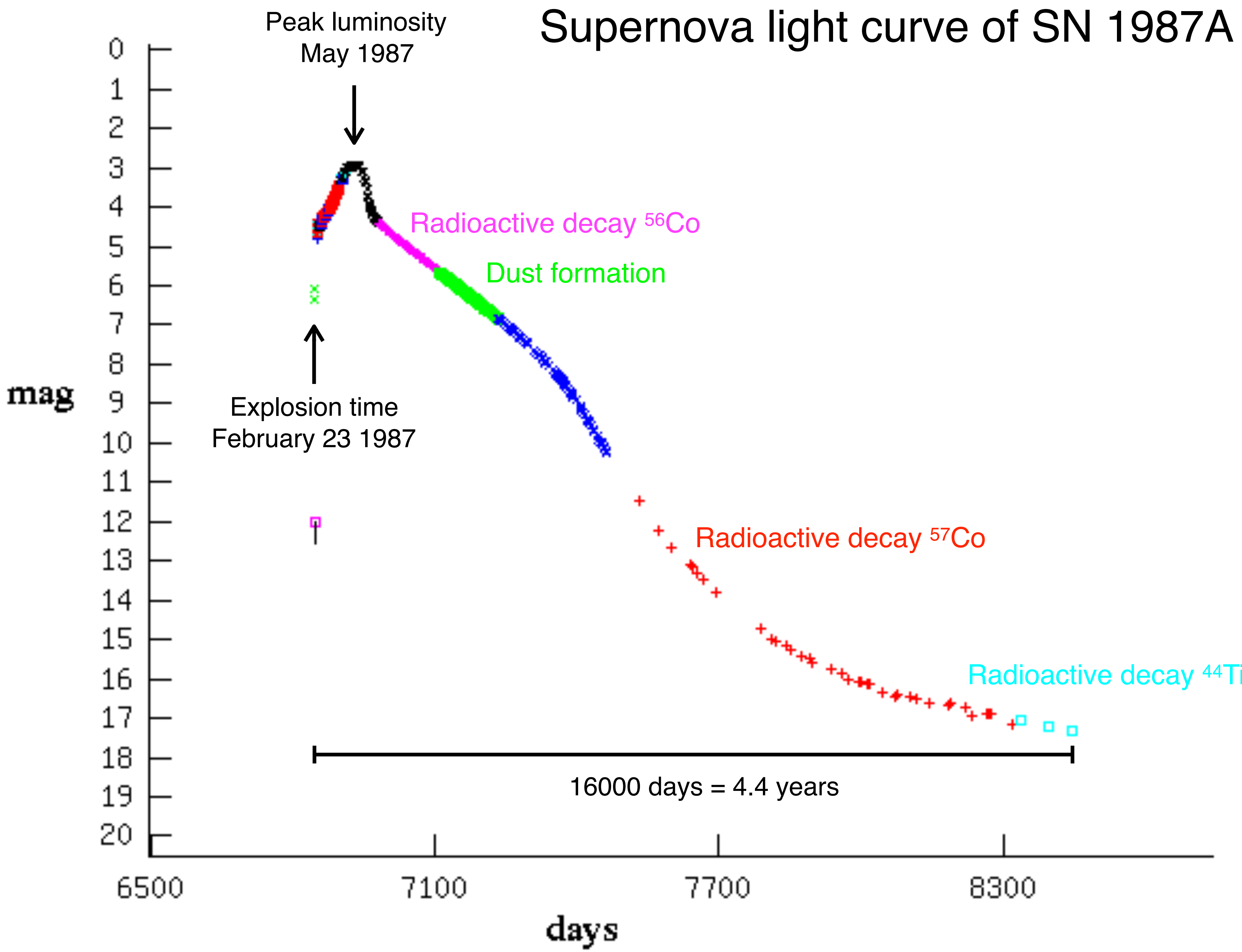
The remnant after the explosion

Supernova remnant

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 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
days
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

Supernova 1987A in recent times
(supernova remnant)

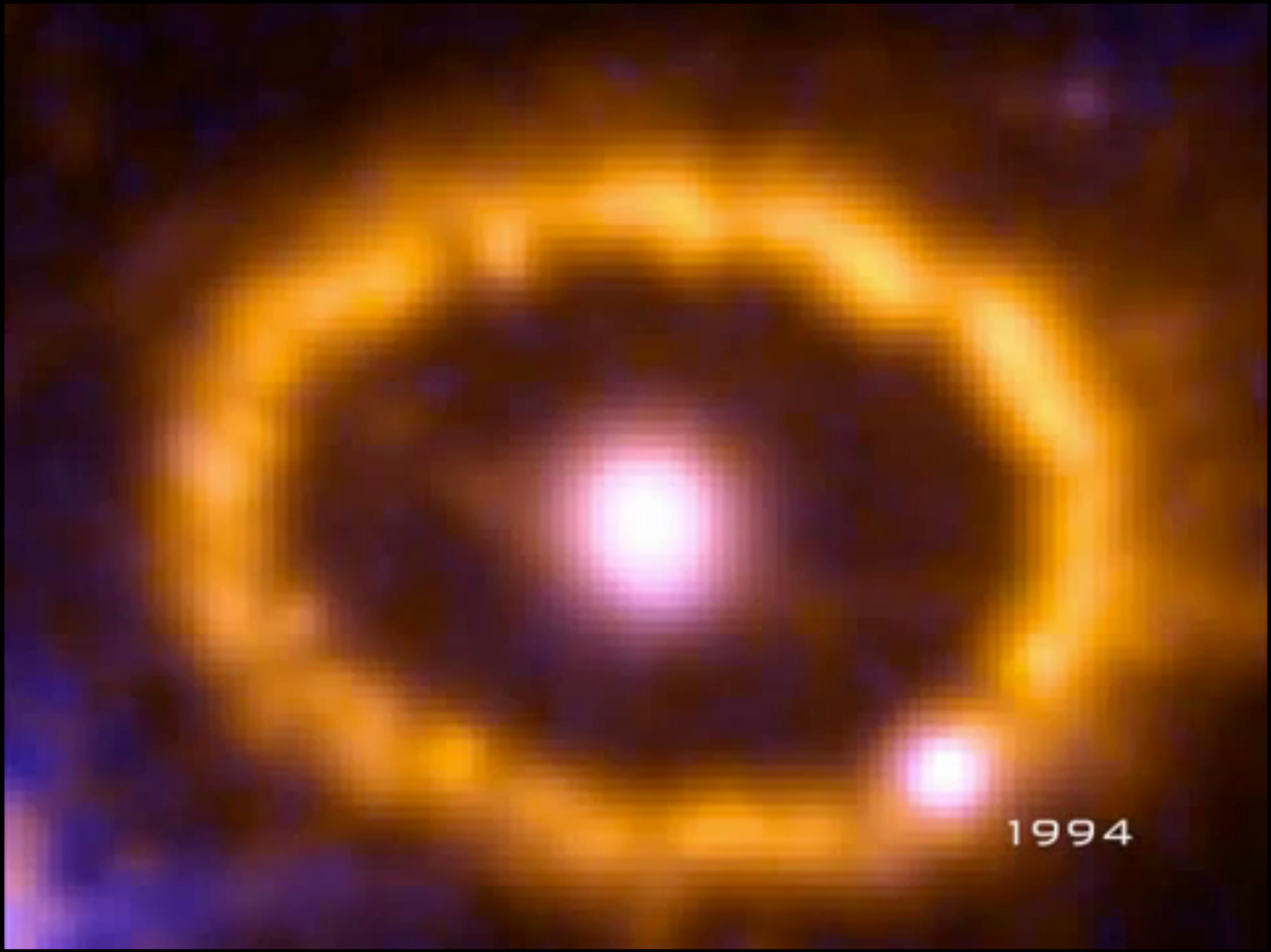
3 rings all created ~ 20,000 years before the supernova explosion
Shock waves from explosion heat them up causing bright glow

Supernova 1987A in recent times

(supernova remnant)

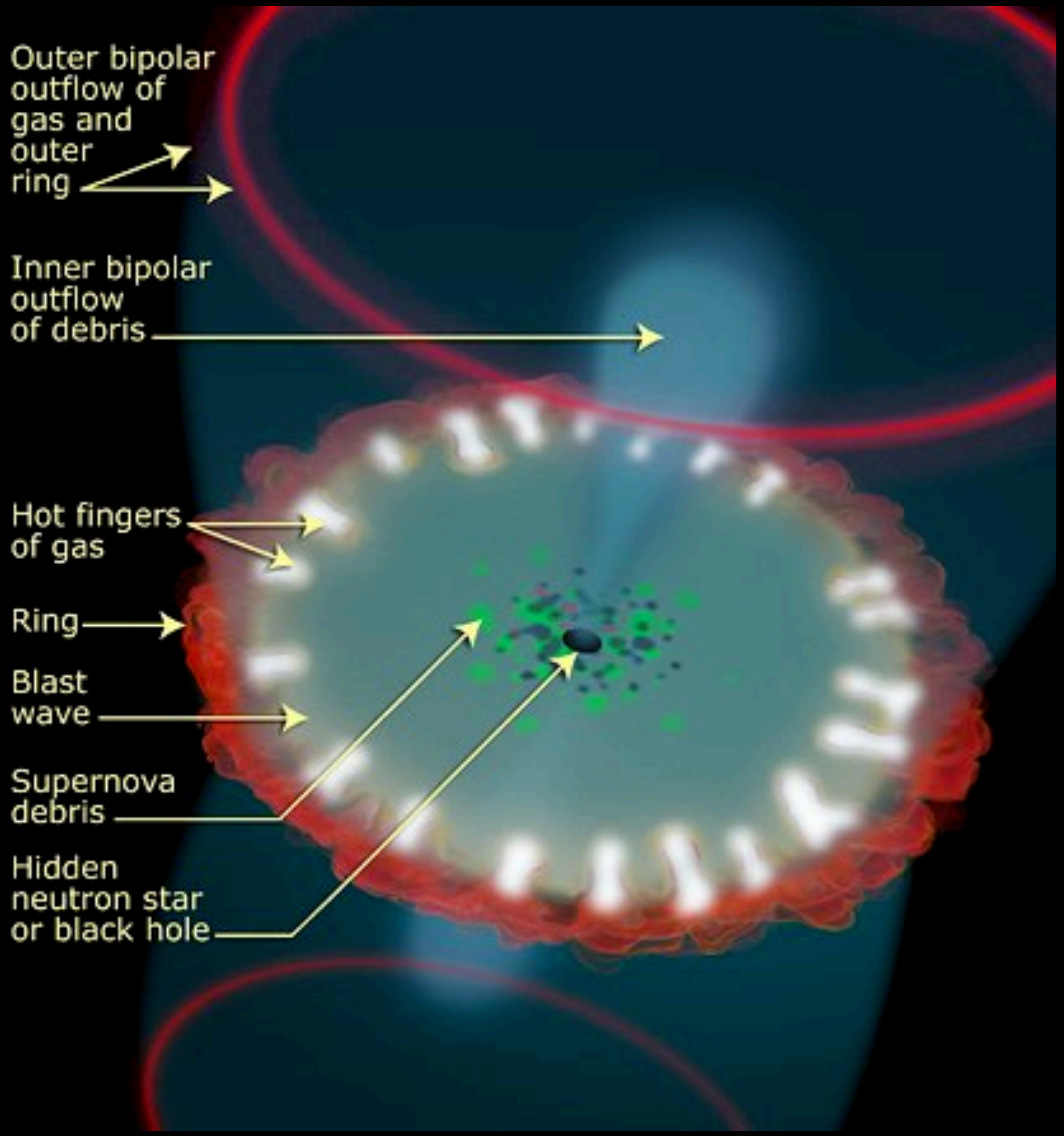
3D movie reconstructing movie

Supernova 1987A internal ring 1994 - 2006



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

Inner debris of the Supernova 1987A (SN 1987A) ring



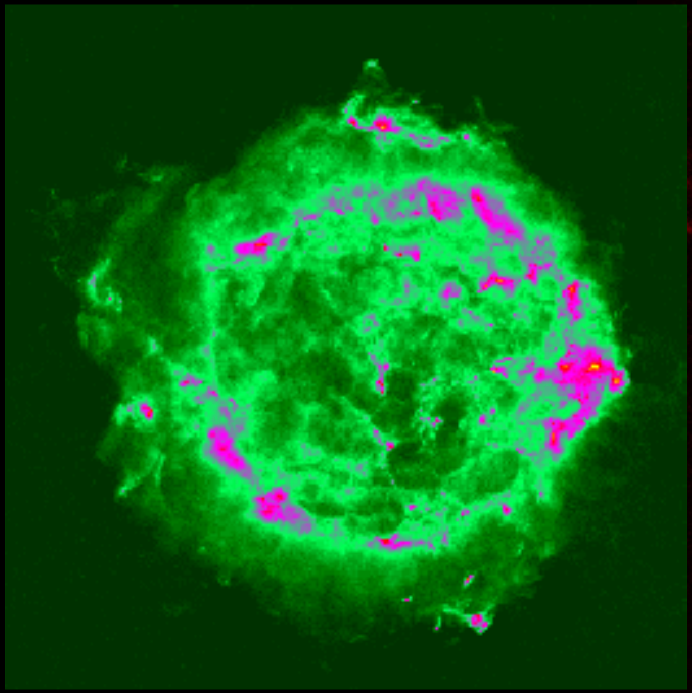
Supernova remnants

T = 10^5 - 10^7 K ⟹ X-ray thermal emission

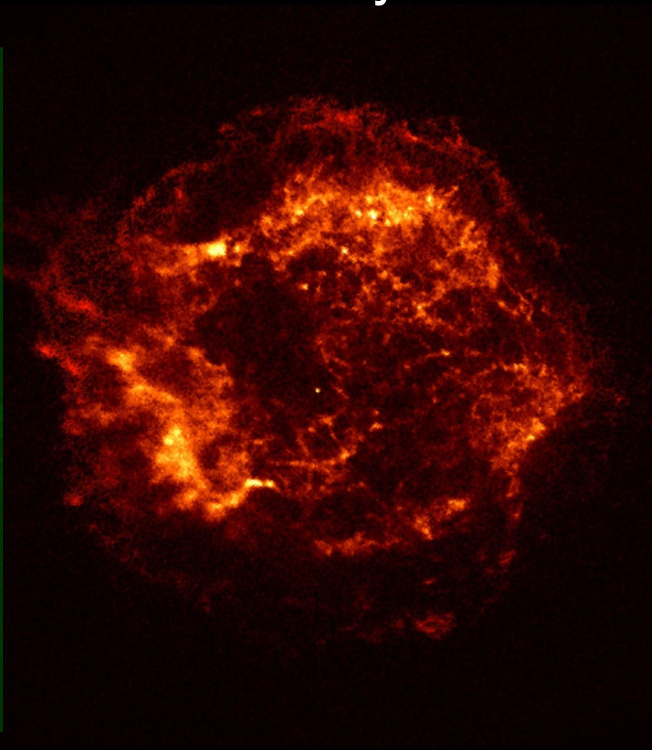
Accelerated charged particles ⟹ radio synchrotron emission

Visible

Radio



X–ray



Supernova remnant *Cassiopeia A*

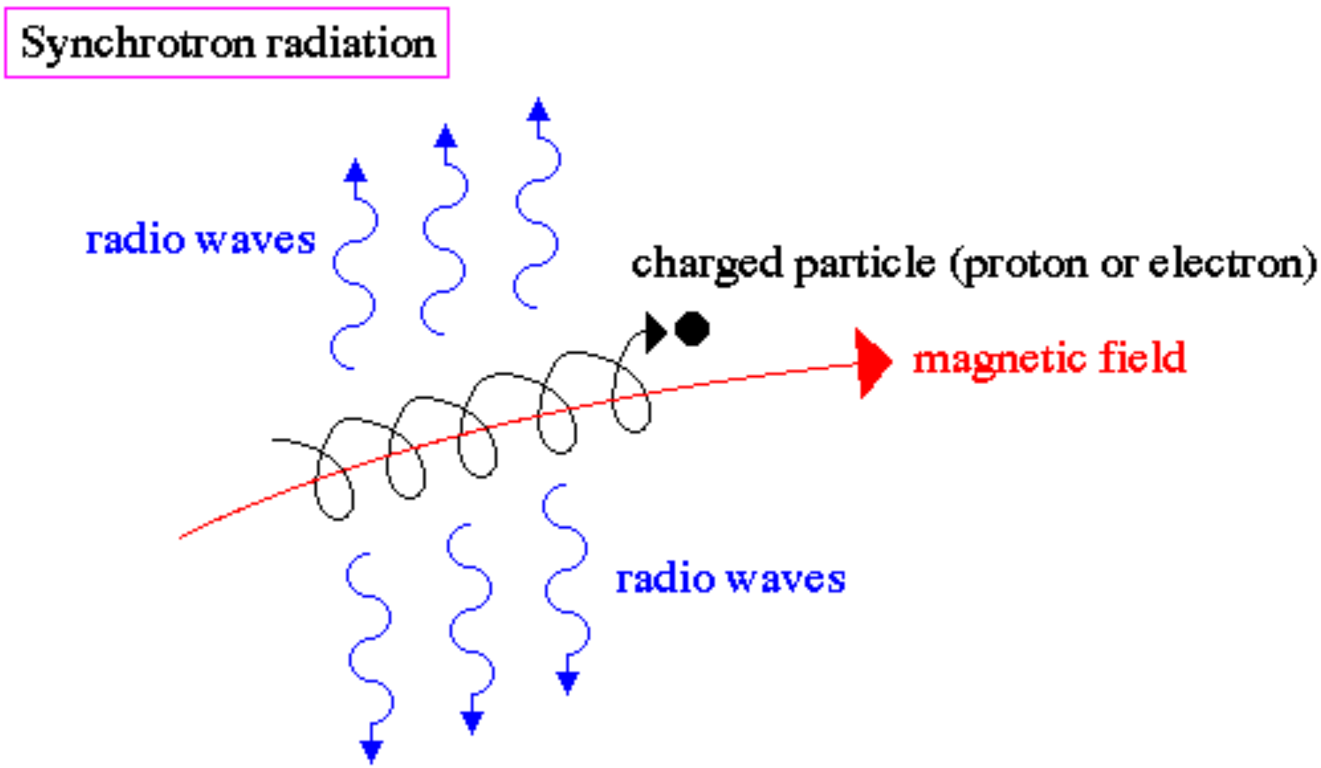
Size: 3 pc across

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

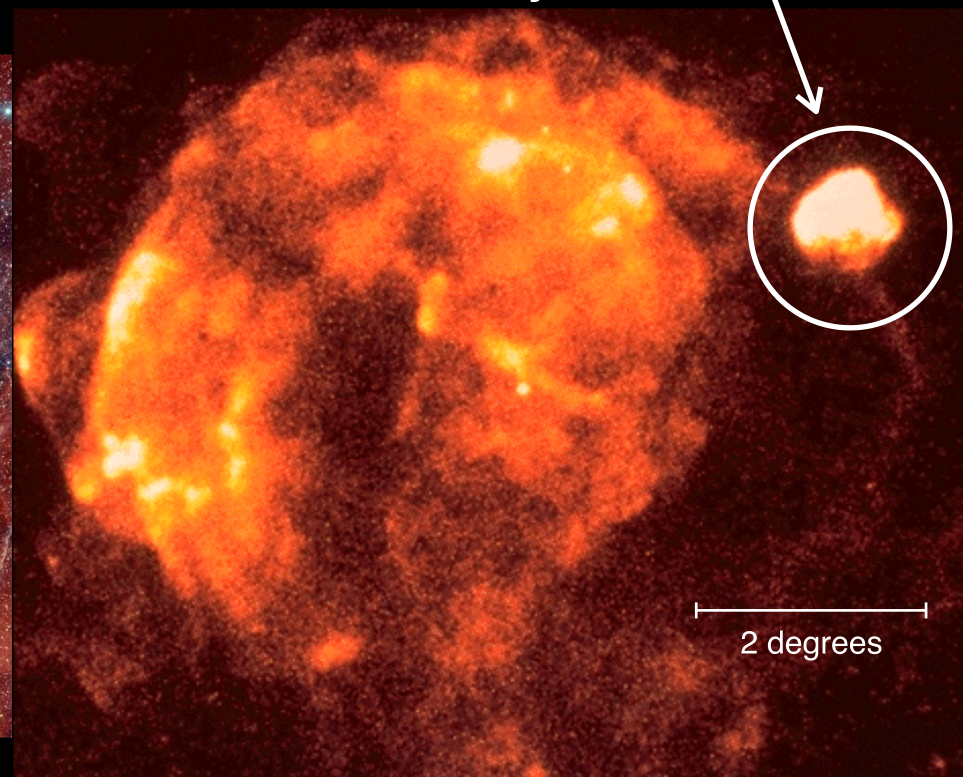
Supernova remnants

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

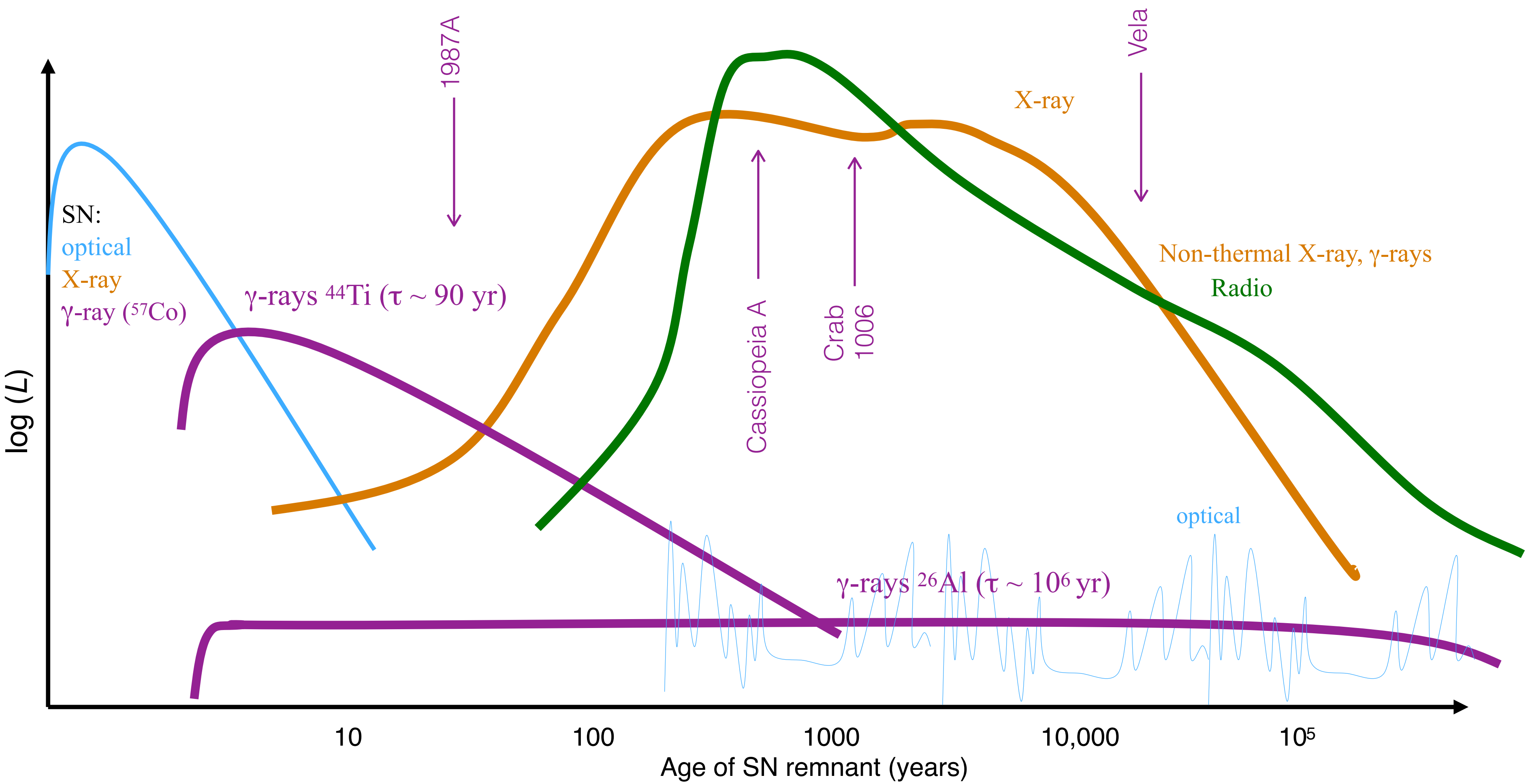
X–ray



~ 230 light years

Supernova remnants: time evolution

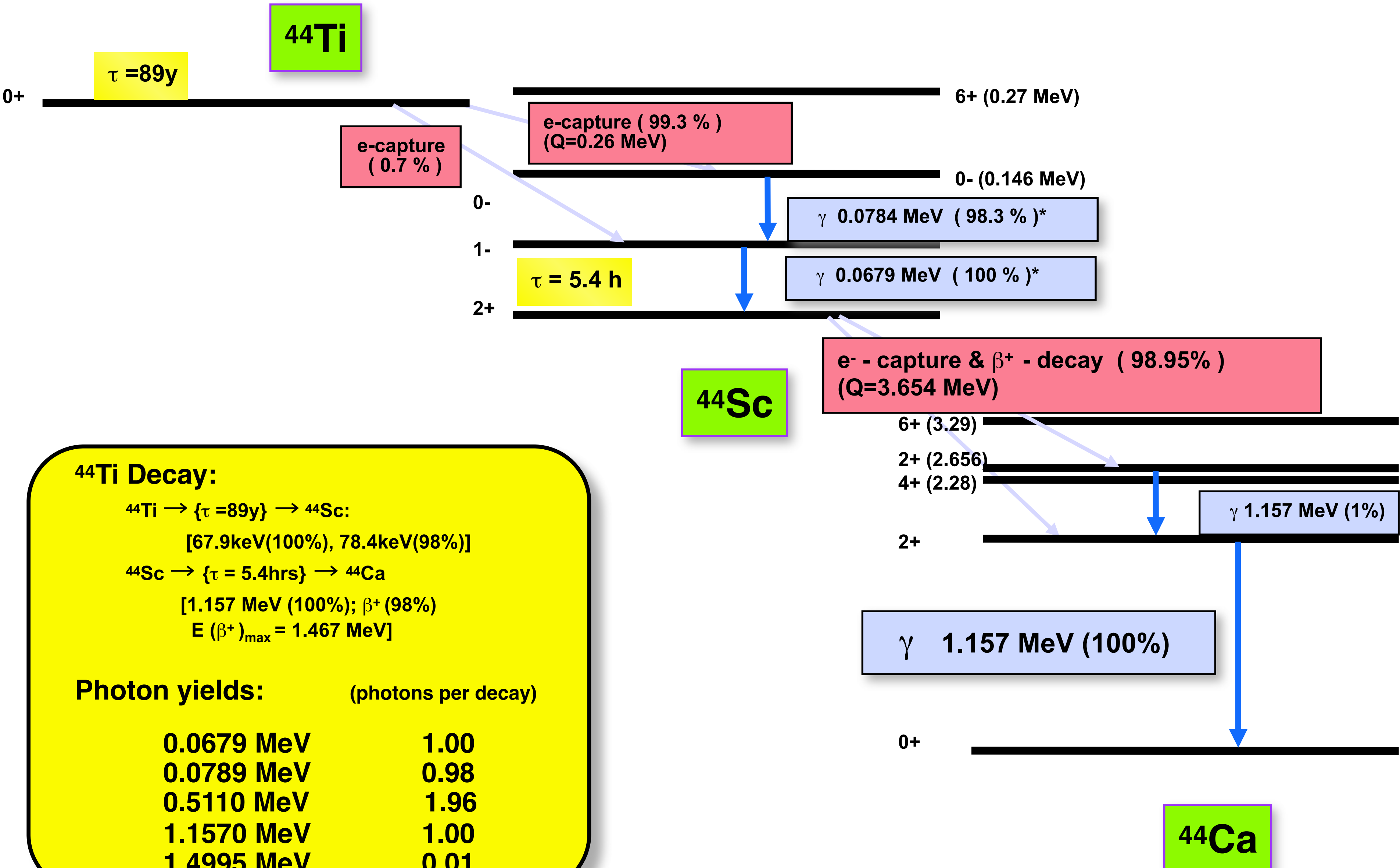
- Gamma-ray emission beyond X-ray/radio/optical regime
- Search for new supernova remnants



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

^{44}Ti decay



^{44}Ti Decay:

^{44}Ti $\rightarrow$ {τ =89y} $\rightarrow$ ^{44}Sc:

[67.9keV(100%), 78.4keV(98%)]

^{44}Sc $\rightarrow$ {τ = 5.4hrs} $\rightarrow$ ^{44}Ca

[1.157 MeV (100%); β^+ (98%)

E $(\beta^+)_{max}$ = 1.467 MeV]

Photon yields: (photons per decay)

0.0679 MeV	1.00
0.0789 MeV	0.98
0.5110 MeV	1.96
1.1570 MeV	1.00
1.4995 MeV	0.01

Nucleosynthesis study with gamma-ray lines

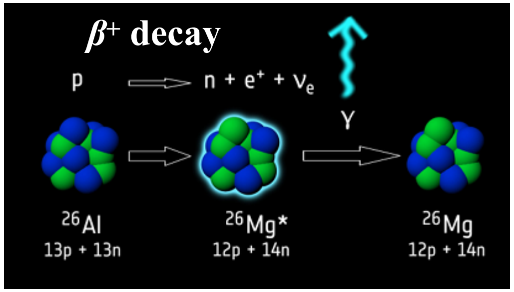
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^6$ y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$2.0\ 10^6$ y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... 10^5 y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

Gamma-rays produced by supernova remnants in the Milky Way

Nuclear energy level transitions in radioactive elements

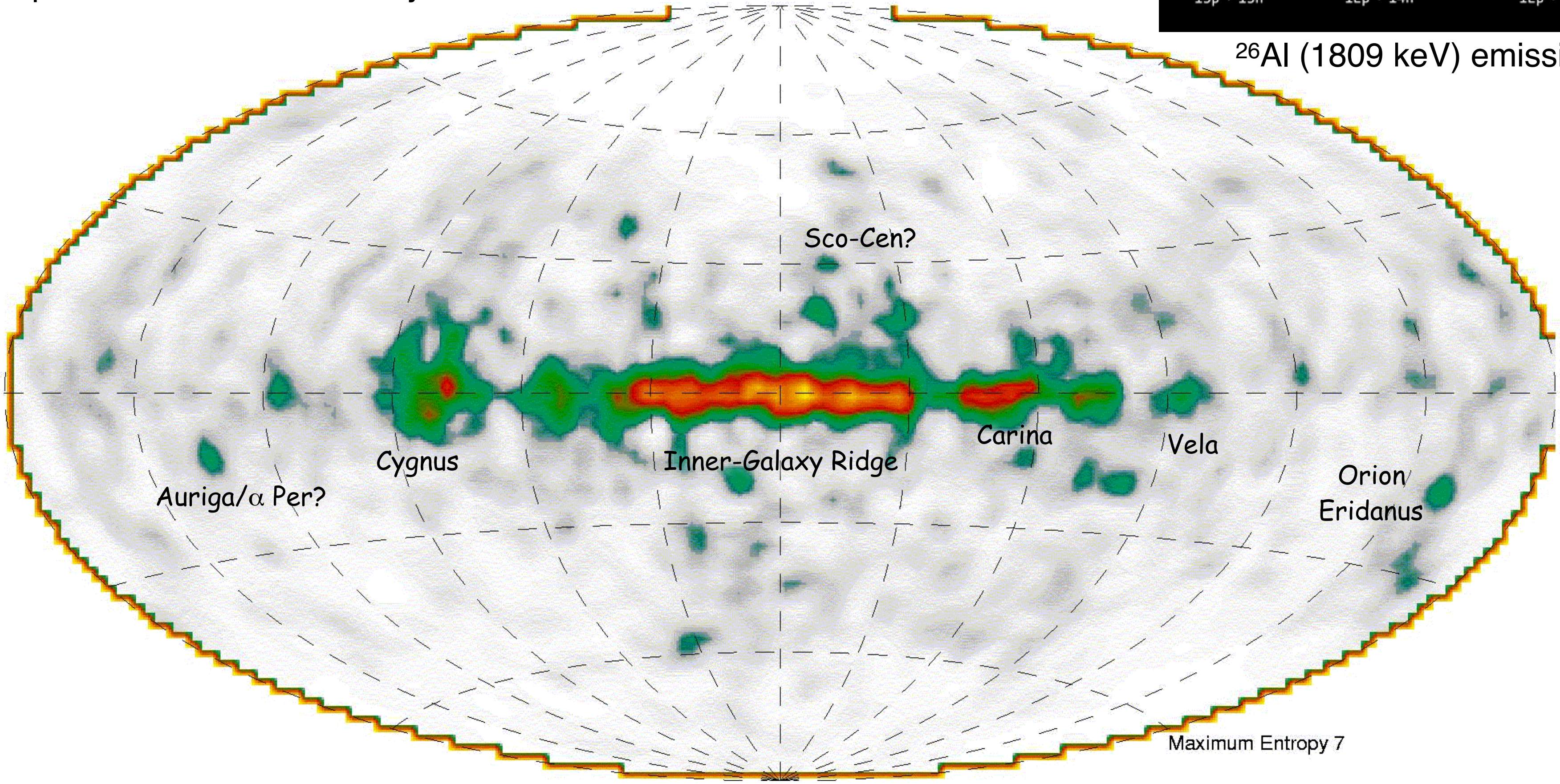
Decay of aluminum isotope ^{26}Al (1809 keV, $kT \sim 10^9$ K, mean lifetime 7.17×10^5 yr)

Estimated SN rate: 2 per century



^{26}Al (1809 keV) emission

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

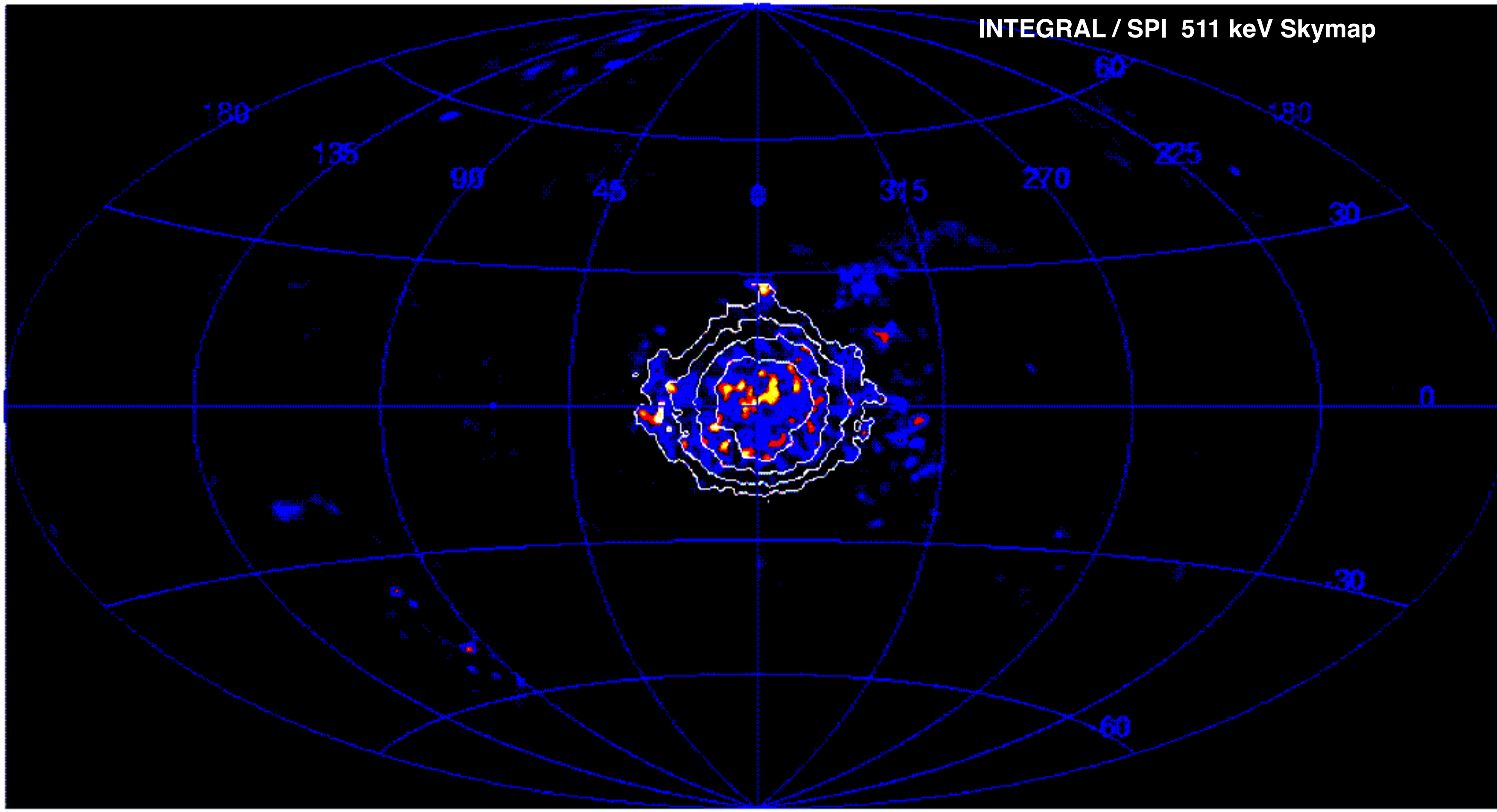


Gamma-rays in the central region of the Milky Way

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”

Gamma-rays in the central region of the Milky Way

Among suggested mechanisms of positron production:

- β^+ decay $p \rightarrow n + e^+ + \nu_e$ in radioactive elements in supernovae
- Pair production by micro quasars (black holes in binary systems of stellar origin)
- Accretion of stellar debris into massive black hole (spaghettification, tidal disruption event)
- Annihilation of non-baryonic matter-antimatter particles (dark matter)

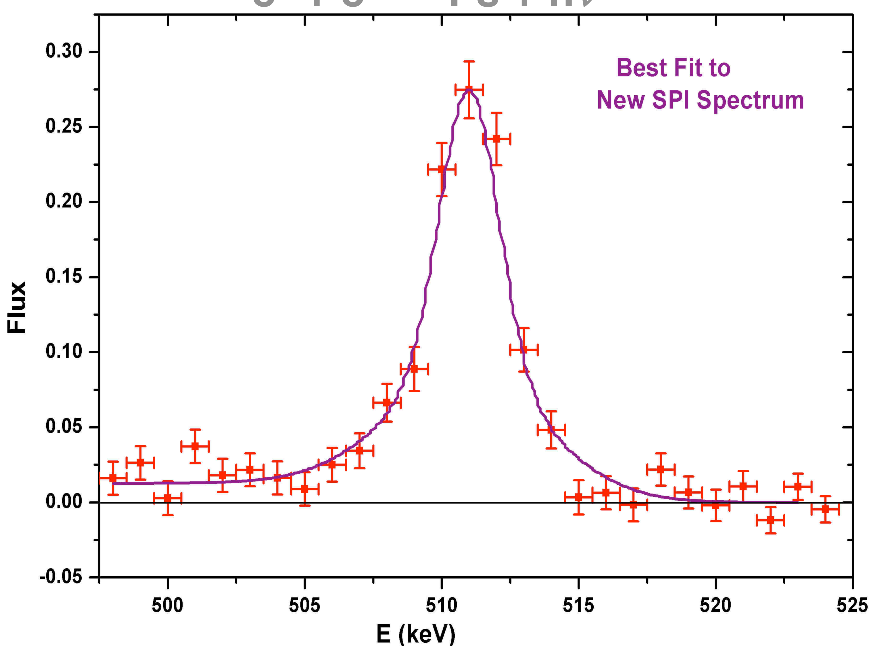
Diversity of annihilation processes:

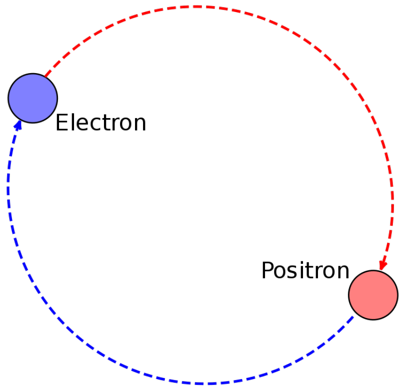
- **Direct Annihilation:**

  $e^- + e^+ \rightarrow 2h\nu$

- **Formation of a positronium atom:**

  $e^- + e^+ \rightarrow Ps + h\nu$





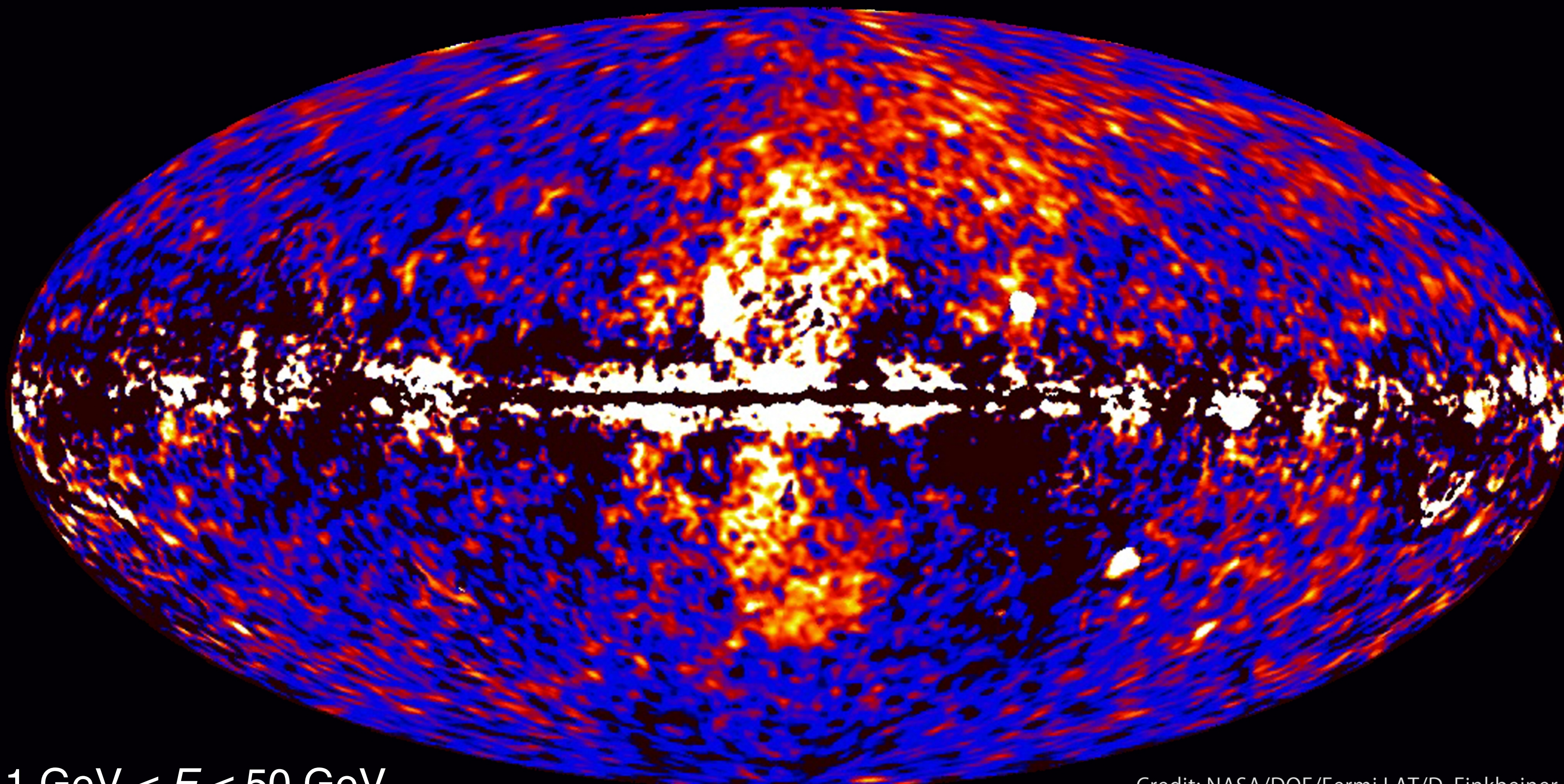
Positronium atom (Ps), unstable

From measured line luminosity, number of electron-positron pairs per second in our Galaxy is:

$$N = 5 \times 10^{43} \ s^{-1}$$

Giant diffuse gamma-ray glow revealed by satellite *Fermi*

Likely originating by energetic events in Center of Milky Way



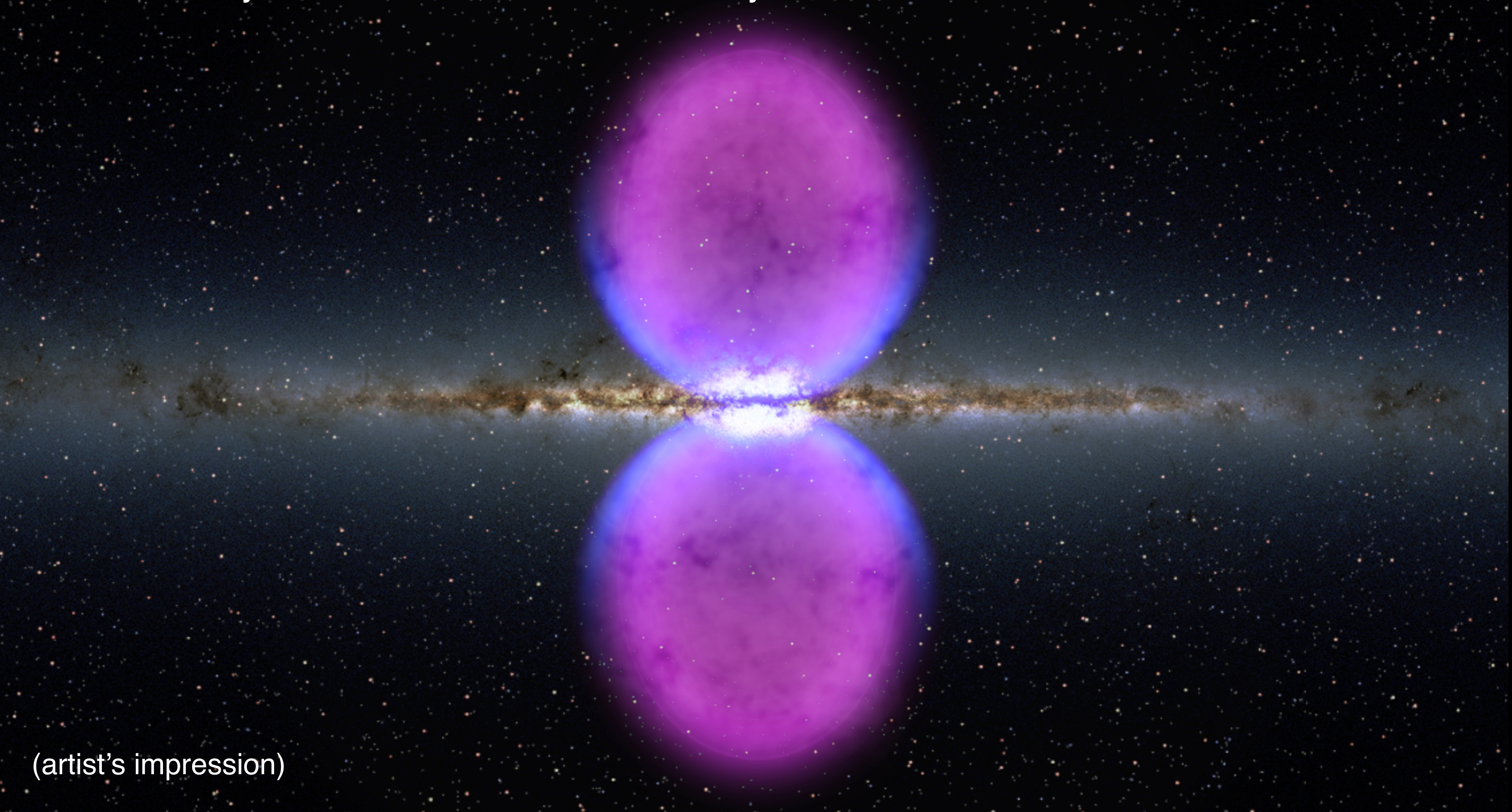
1 GeV < E < 50 GeV

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Likely originating by energetic events in Center of Milky Way

Among suggested mechanisms of emission:

- Millisecond pulsars (spectrum is very similar, but high number is necessary)
- Past accretion events onto central massive black hole
- Massive star formation in short time (starburst) in the last 10 Myr
- Likely unrelated to annahilation/decay of dark matter



(artist's impression)

Leftover of stellar explosion: **the core**

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

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

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

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

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

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

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):

$$L = I \times \omega$$

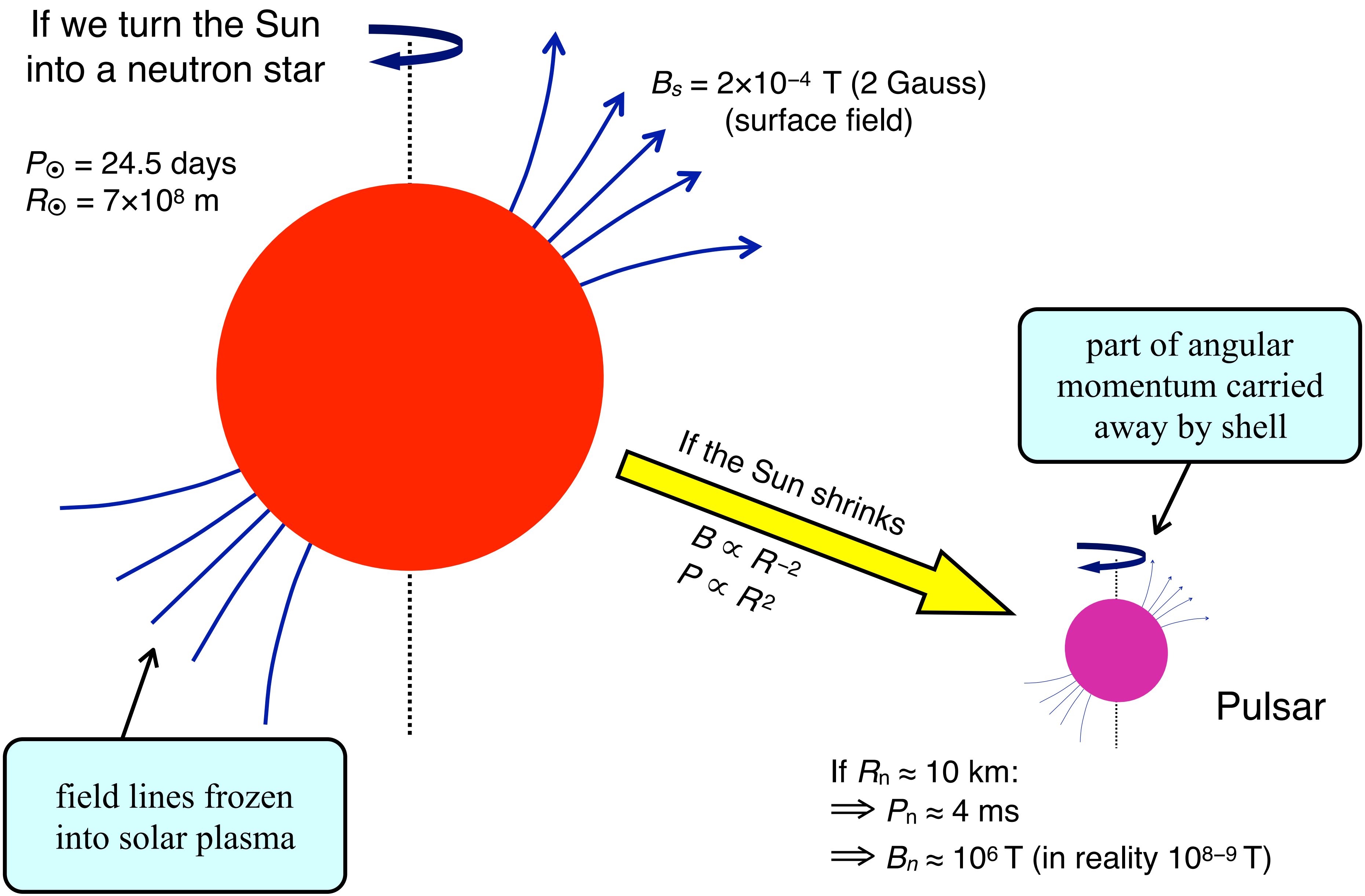
If rotation in star is initially like in **Sun** (24.5 days at equator), then in neutron star:

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

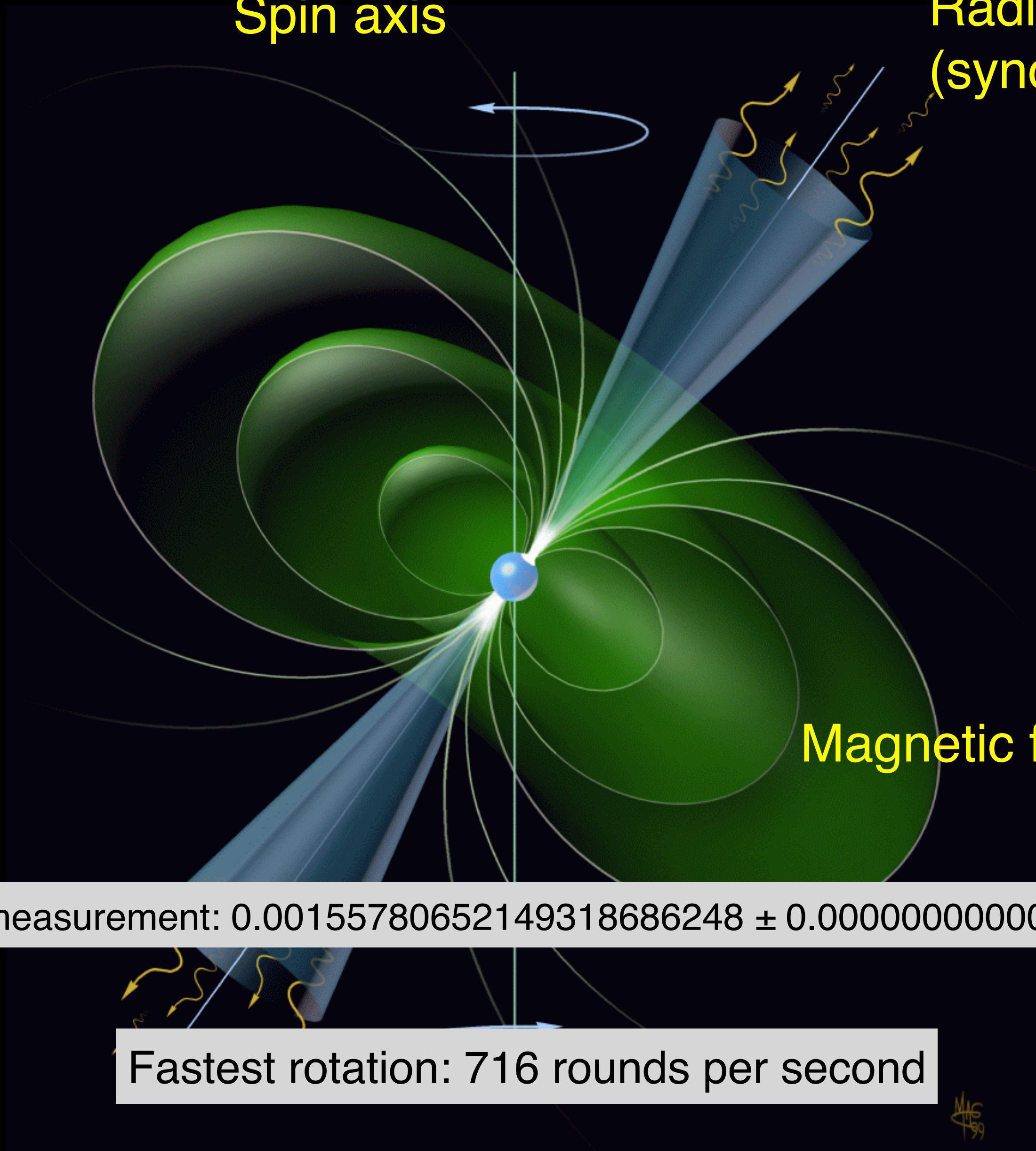
Rotation period in milliseconds: $P_n = 2\pi / \omega_n = 3.8 \times 10^{-3}$ s

Pulsar: fast rotating neutron star with strong magnetic field B

(the two axis are misaligned)



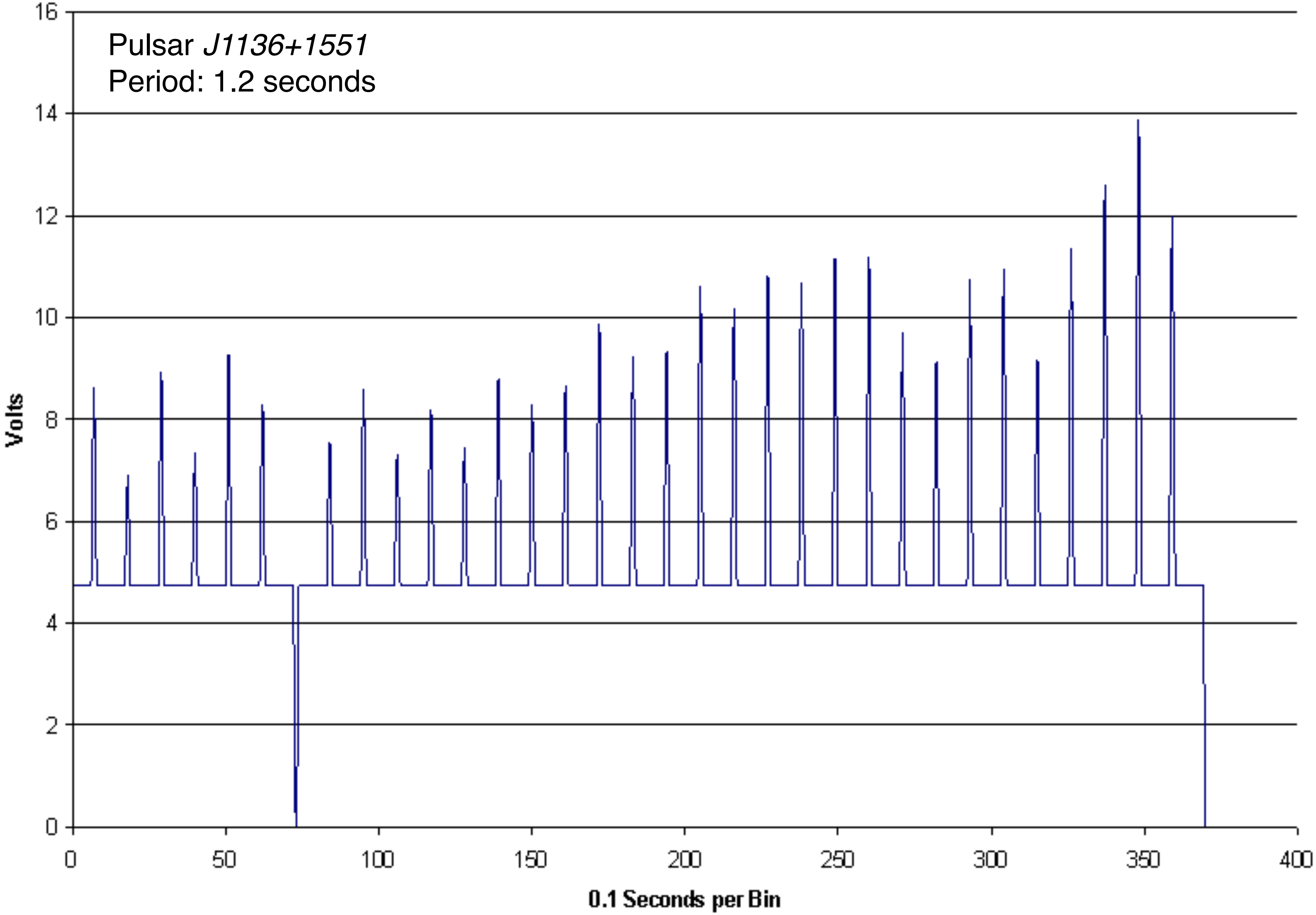
A pulsar is emitting a very regular radio pulsating signal



Most precise measurement: 0.0015578065214931868248 ± 0.0000000000000000000003 seconds

Fastest rotation: 716 rounds per second

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



Neutron star RX J1856.5-3754

Diamater: 14-17 km

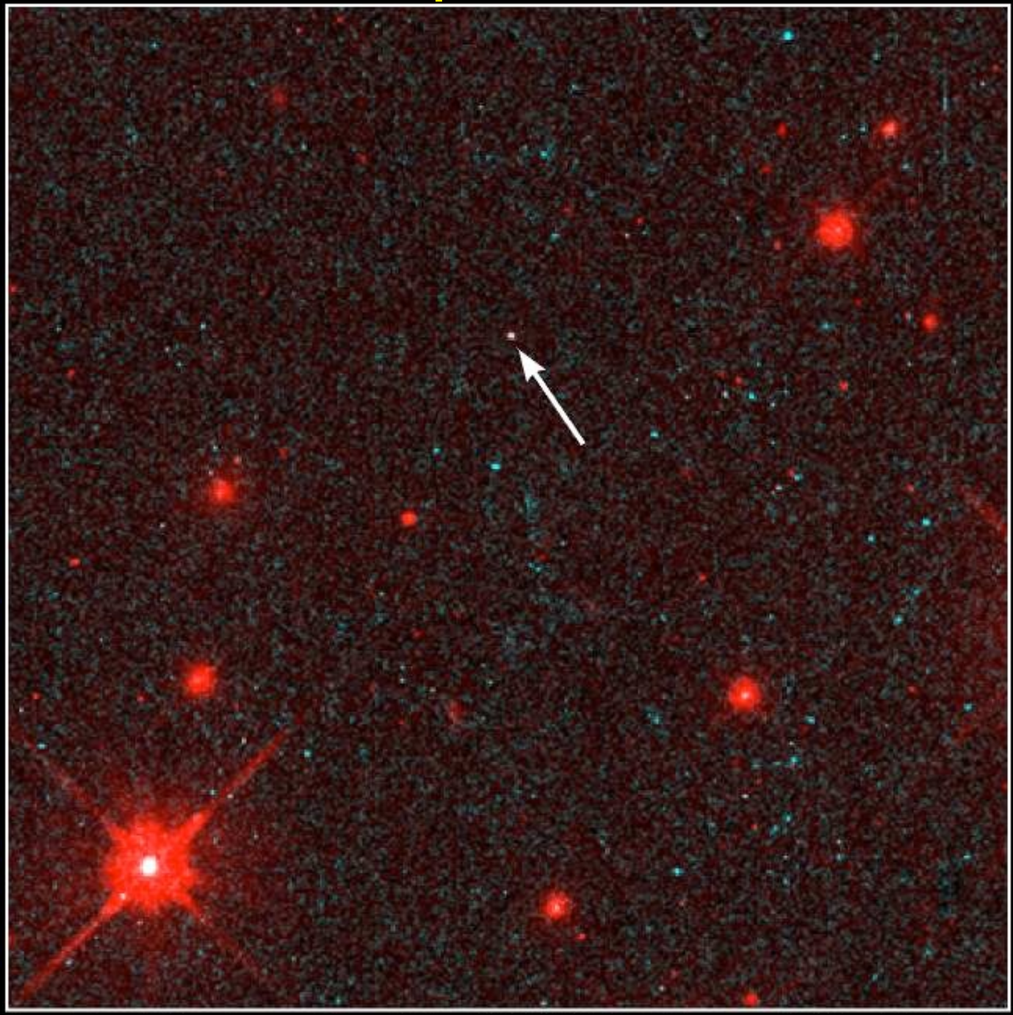
Surface temperature: T = 434,000 K

Distance: 140 pc (the closest to Earth yet discovered)

Explosion time: 1 million years ago

X-ray

Optical



Variation of pulsar period over period

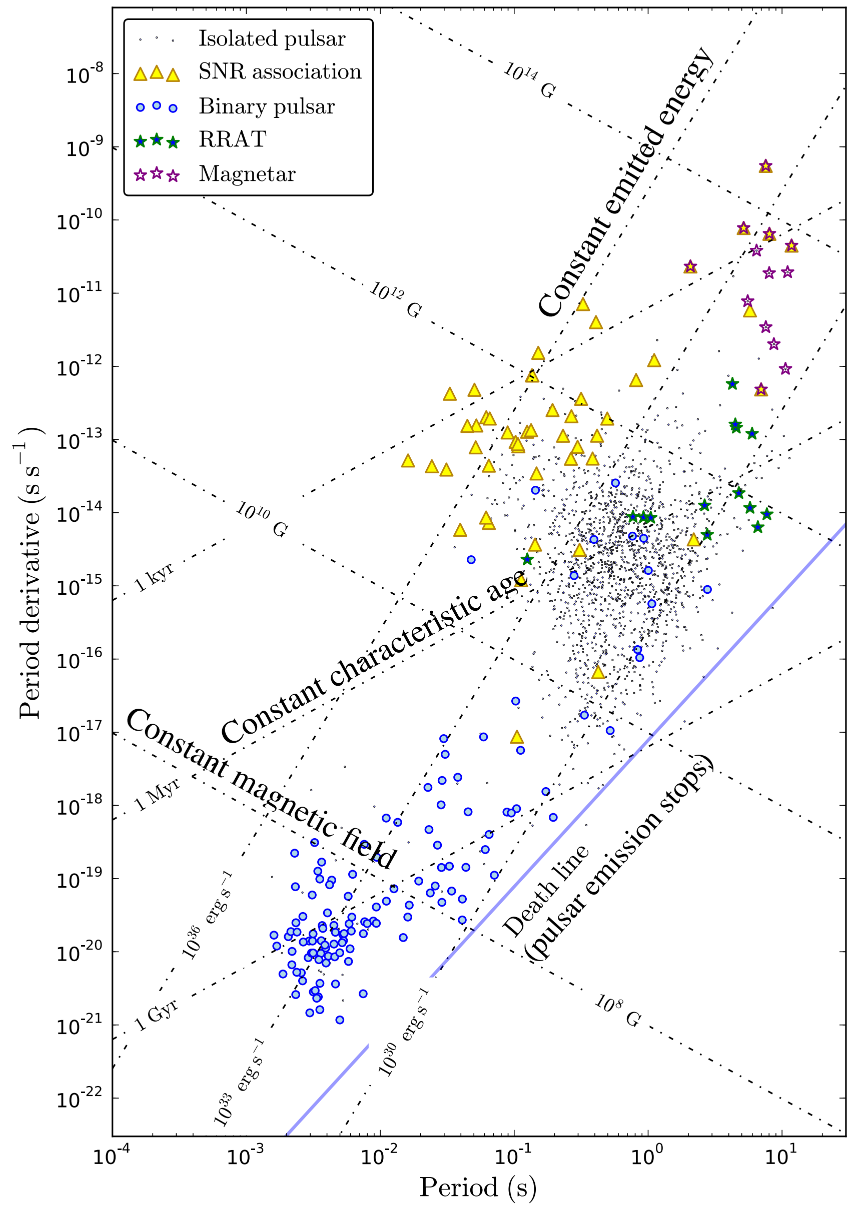
Old neutron stars stop pulsate

- 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)

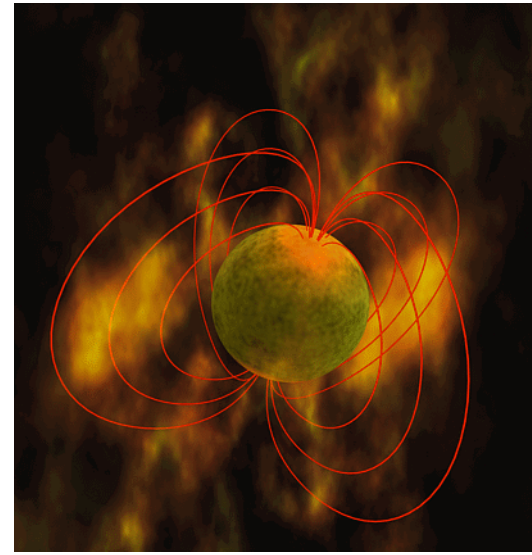
RRAT: rotating radio transient with higher pulse-to-pulse variability

Magnetar: pulsar with extremely high magnetic field

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



Magnetars



Neutron Stars with highest magnetic fields

- Size ~20 km
- $B \sim 10^{14\text{-}15}$ G powers large X-ray & gamma-ray emission
- Superfluid Core, Crust, Magnetosphere
- Slow rotation (1-10 sec)
- Short life (10 000 years)

Flares on magnetars: soft gamma-ray repeaters (SGR)

SGR 1806-20: giant flare 27 Dec 2004

- Distance: $d = 14.5$ kpc
- $E_{total} \sim 10^{46}$ erg! (100× other SGRs)
- Most energetic gamma-ray explosion ever measured from Earth
- $B \gtrsim 10^{15}$ G (the highest ever found)
- 7.56 sec pulsations (NS rotation?)
- Precursor at $t\text{-}t_0 = -143$ s