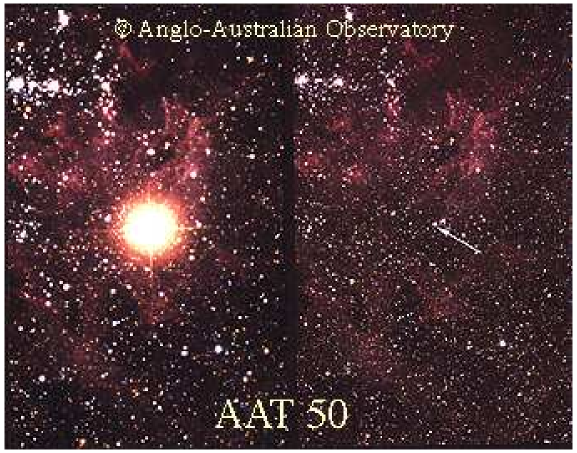
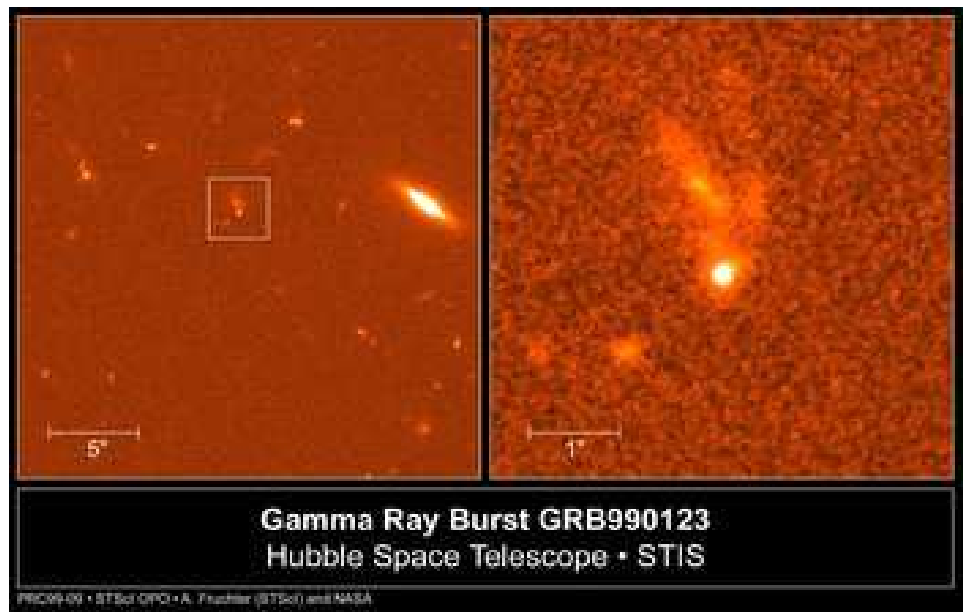
Supernova Explosions and their Role in the Universe

Philipp Podsiadlowski (Oxford)

• explosions of stars are some of the most dramatic events in the Universe





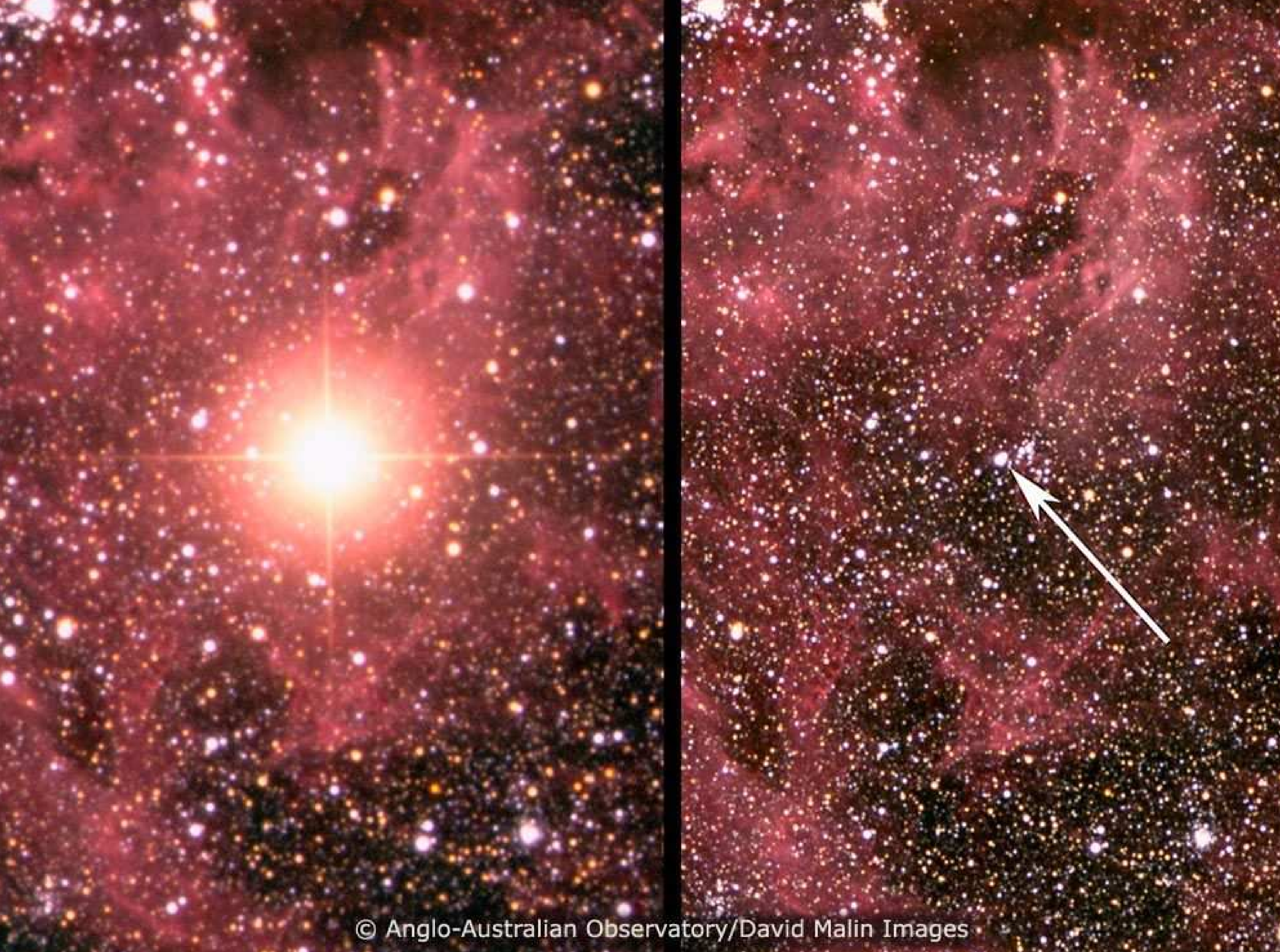
I. Supernova Light

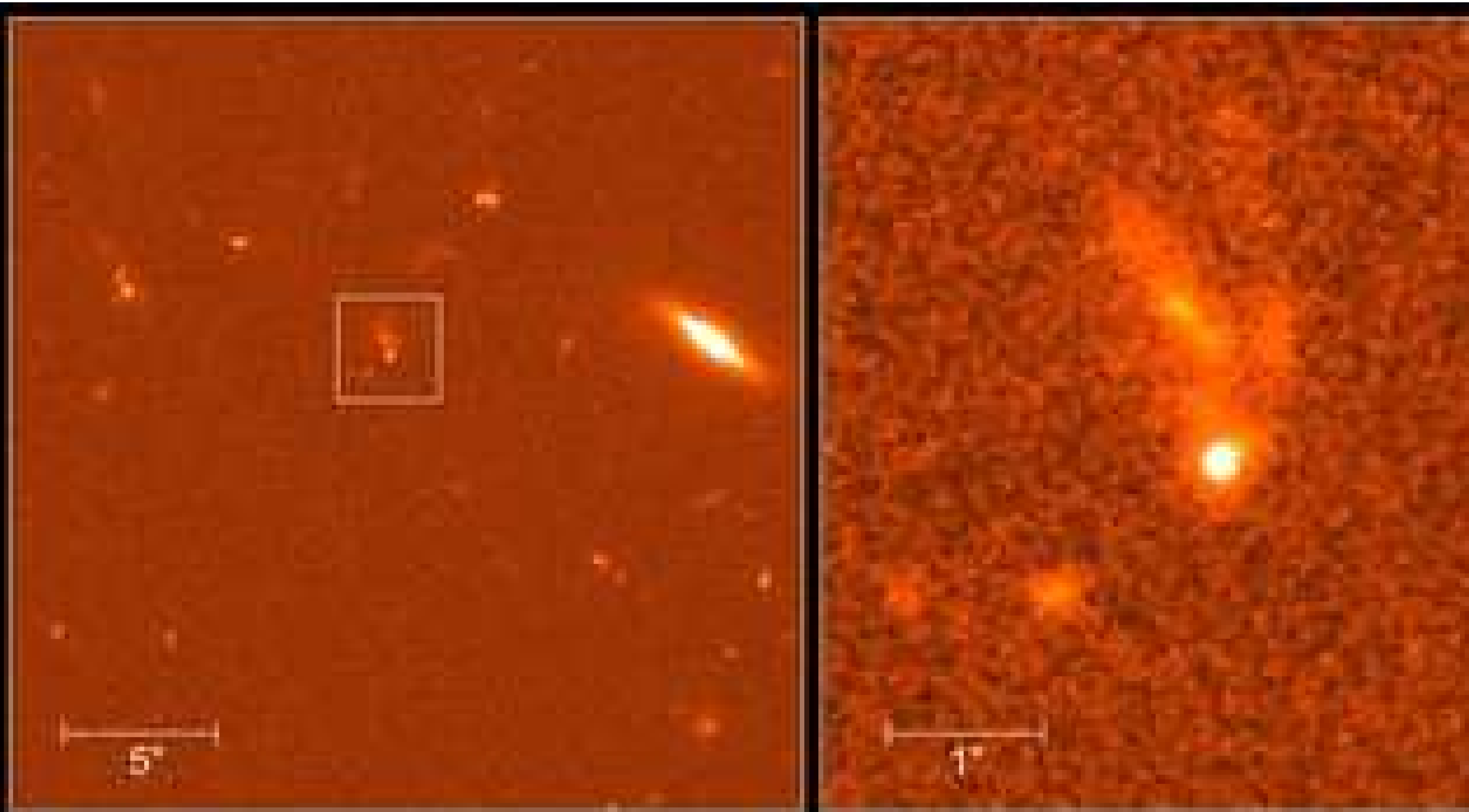
II. Diversity of Supernovae

III. SN 1987A

IV. Gamma-Ray Bursts

V. The Importance of Supernovae





Gamma Ray Burst GRB990123
Hubble Space Telescope • STIS

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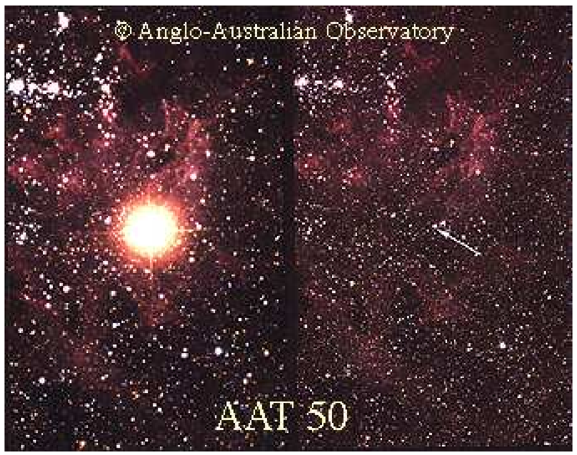

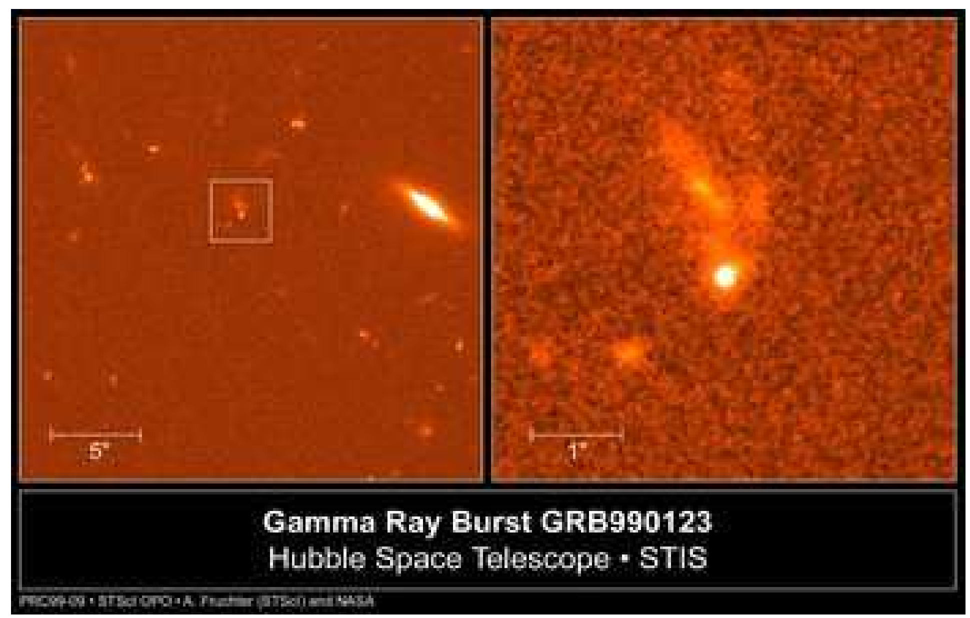

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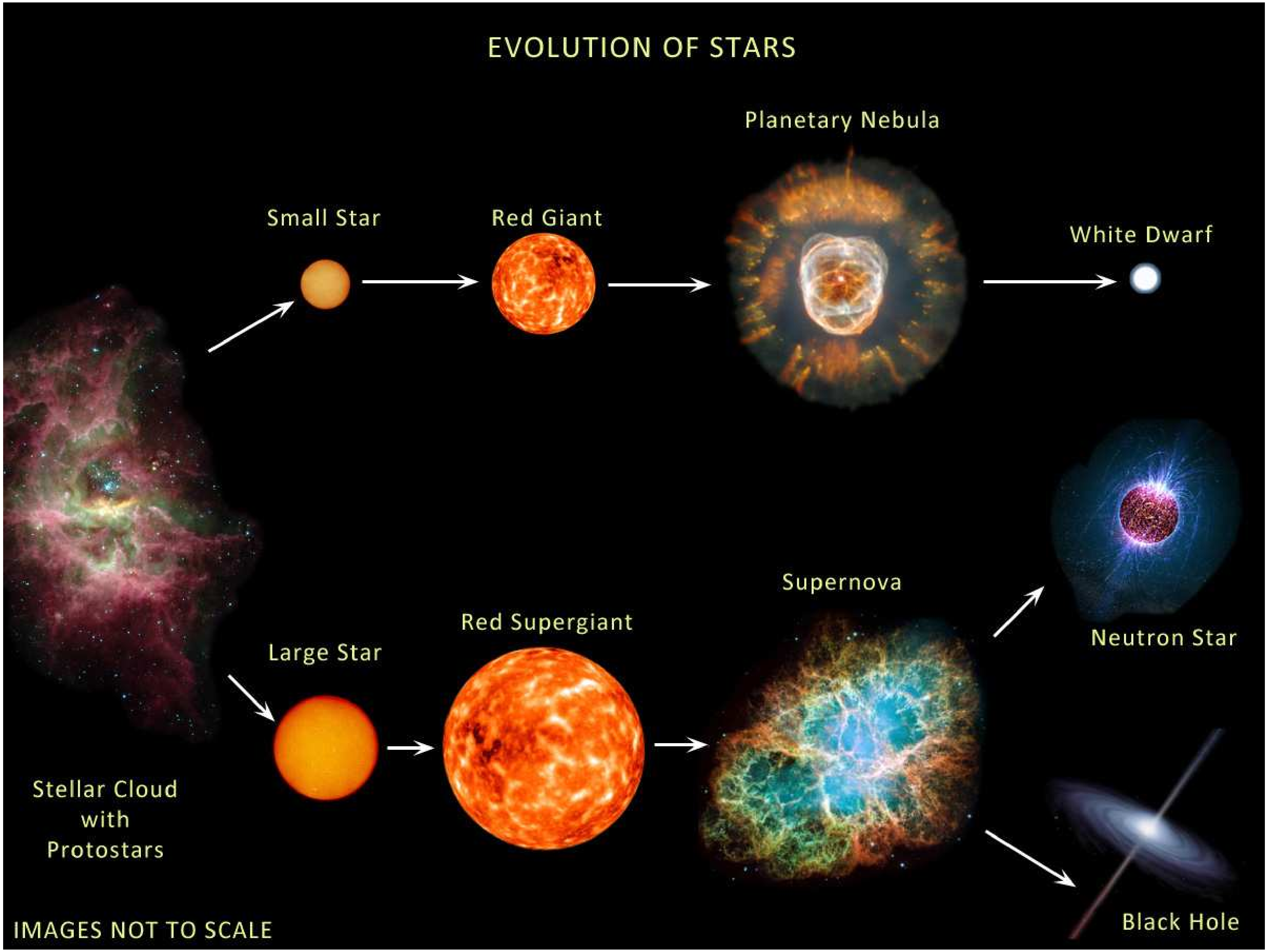
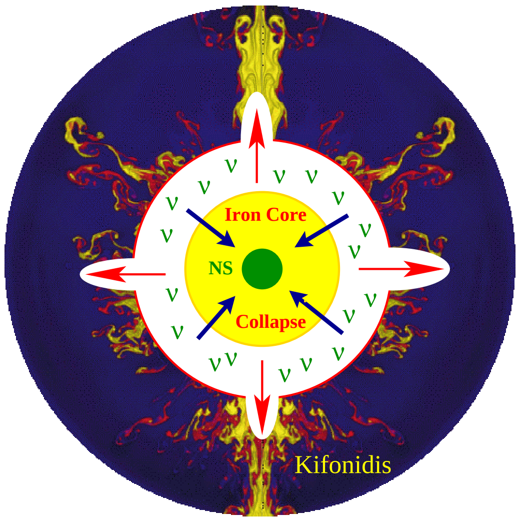
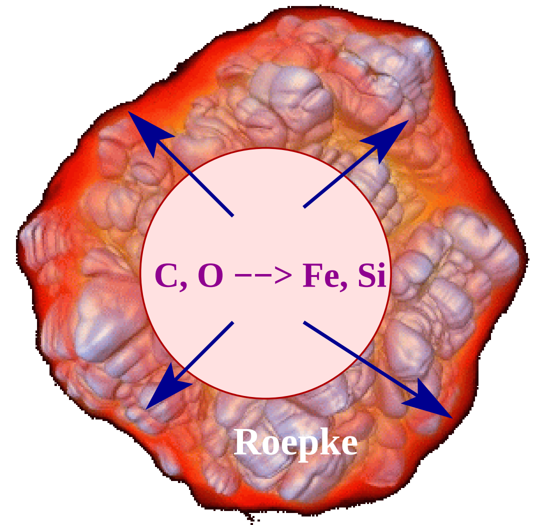

EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Cloud with Protostars
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
IMAGES NOT TO SCALE

Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}$ J)
- most of the energy comes out in neutrinos (SN 1987A!)
- energy in supernova: $\sim 10^{44}$ J

Thermonuclear Explosions



- occurs in accreting carbon/oxygen white dwarf

$\rightarrow$ carbon ignited under degenerate conditions

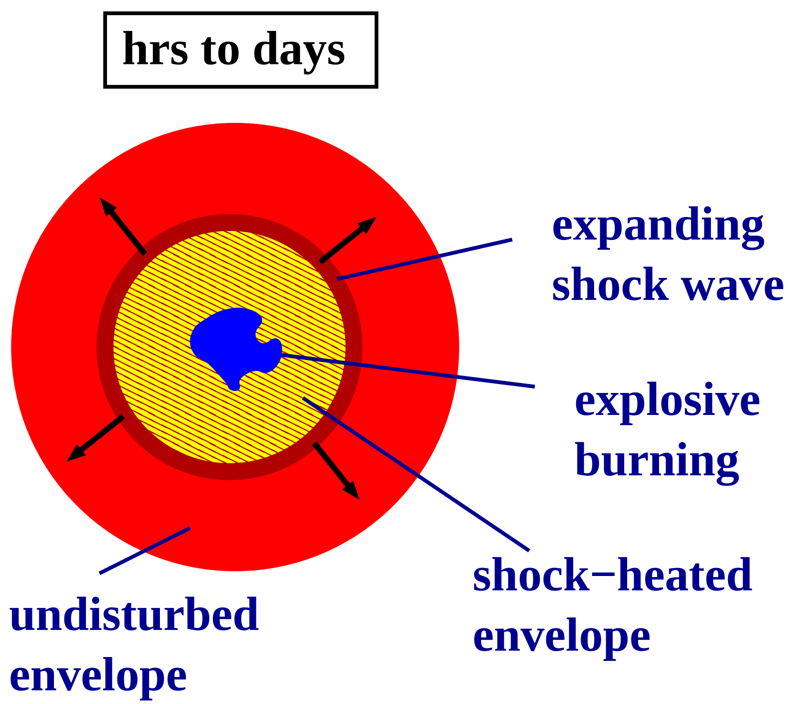
$\rightarrow$ thermonuclear runaway

$\rightarrow$ incineration and complete destruction of the star $\rightarrow$ no compact remnant

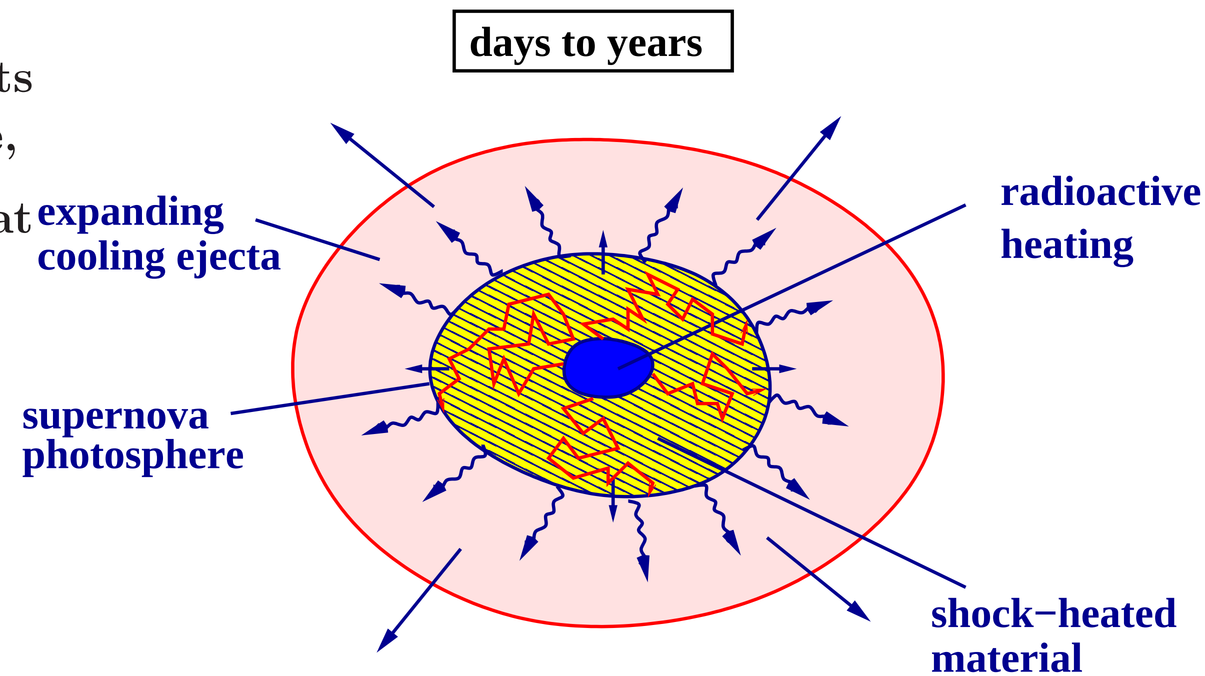
- energy source is nuclear energy (10^{44} J)
- main producer of iron
- used as standardizable candle (see Subir Sarkar's talk)

Supernova Light

- supernova "explosion" phase lasts ~ 1s, depositing 10^{44} J in the centre,
- "central engine" generates shock that ejects envelope/star.



- energy sources
  - ▷ cooling of shock-heated ejecta
  - ▷ radioactive heating from ^{56}Ni produced in explosion

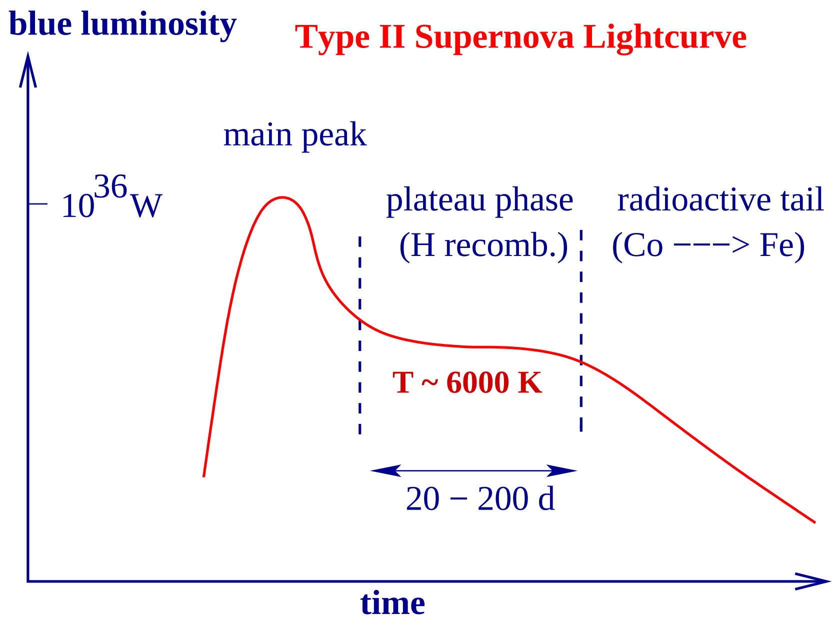


- after shock breakout (first light), ejecta become increasingly transparent (cooling)

→ photons "diffuse" (random-walk) out → determines duration of main supernova phase

- after few 100 days (yrs), ejecta are mostly transparent → supernova remnant (up to 10^5 yrs)

Supernova Lightcurves



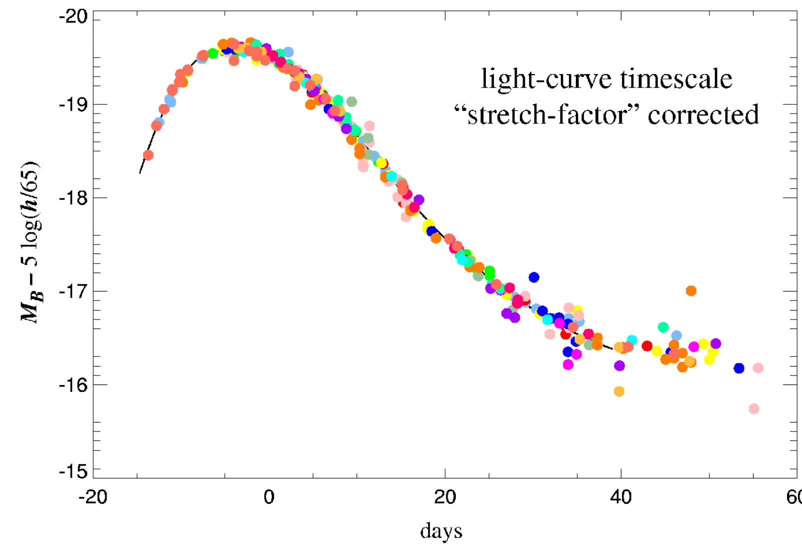
- Explosion energy: $E \sim 10^{44}\,J$ ($\sim$ binding energy of Fe core $\sim GM_{Fe}^2/R_{Fe}$ with $M_{Fe} \sim 1\,M_\odot$, $R_{Fe} \sim 2 \times 10^6\,m$)
- much larger than the binding energy of the envelope (for $R \sim 10^3\,R_\odot$)

$\rightarrow$ most of the energy $\rightarrow$ kinetic energy $E \sim M_{eject} v^2/2$

$$< v > \simeq \left(\frac{2E}{M_{eject}}\right)^{1/2} \sim 3000\,\mathrm{km\,s^{-1}}$$

- the rest $\rightarrow$ thermal energy (photons) that diffuse out of the expanding ejecta
- diffusion time: $t_{diff} \simeq R^2/(lc)$,

Type Ia supernova (standardized)



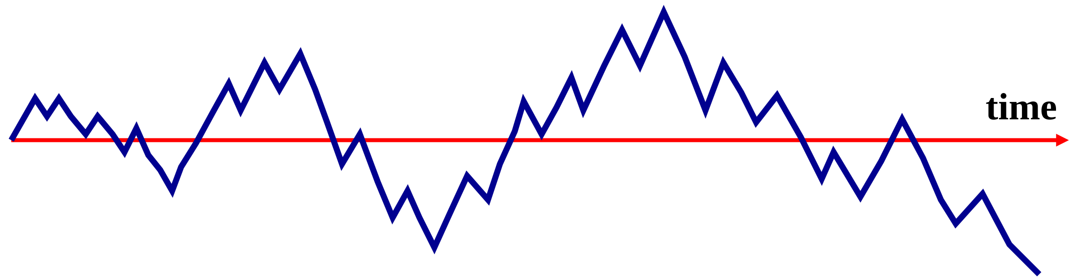
- Explosion energy: $E \sim 10^{44}\,J$ ($\sim$ binding energy of CO white dwarf)
- lightcurve width is determined by the diffusion time
- late-time light curve is powered by radioactive decay of Ni and Co

$$^{56}Ni \xrightarrow{t_{1/2}=6.1\,d} {}^{56}Co \xrightarrow{t_{1/2}=77.3\,d} {}^{56}Fe,$$

- releasing $5.9 \times 10^{41}\,J$ and $1.3 \times 10^{42}\,J$ for each $0.1\,M_\odot$ of Ni
- radioactive luminosity:

$$L_{radioact} \simeq 1.3 \times 10^{35}\,W \left(\frac{M_{Ni}}{0.1\,M_\odot}\right) \exp\left(\frac{-t}{112\,d}\right)$$

The Diffusion Time



Diffusion is a random-walk process

- consider a random-walk: after N steps of length l, distance R:

  $< R_N >= 0,$

  $< R_N^2 >= Nl^2,$

  $R_{rms} =< R_N^2 >^{1/2} = \sqrt{N}l \simeq R_{photo},$

$\rightarrow$ $N = (R_{photo}/l)^2,$

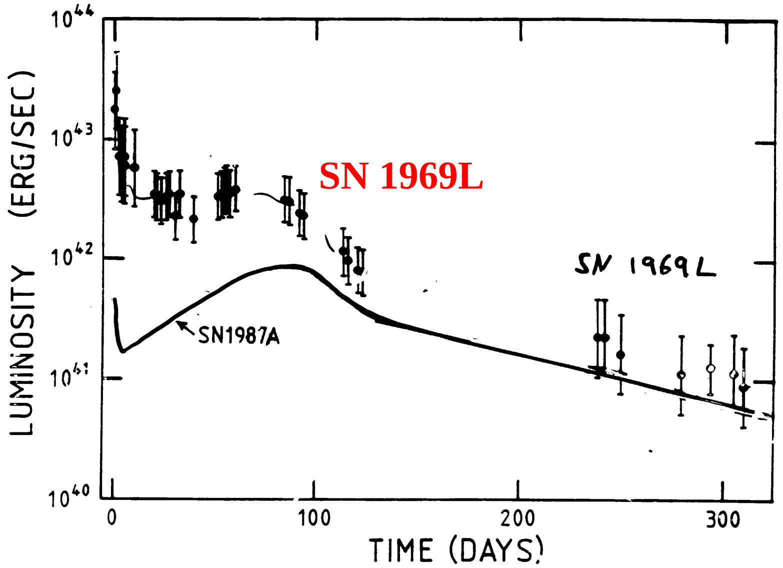
$\rightarrow$ $t_{diff} = N(l/c) = R^2_{photo}/lc,$

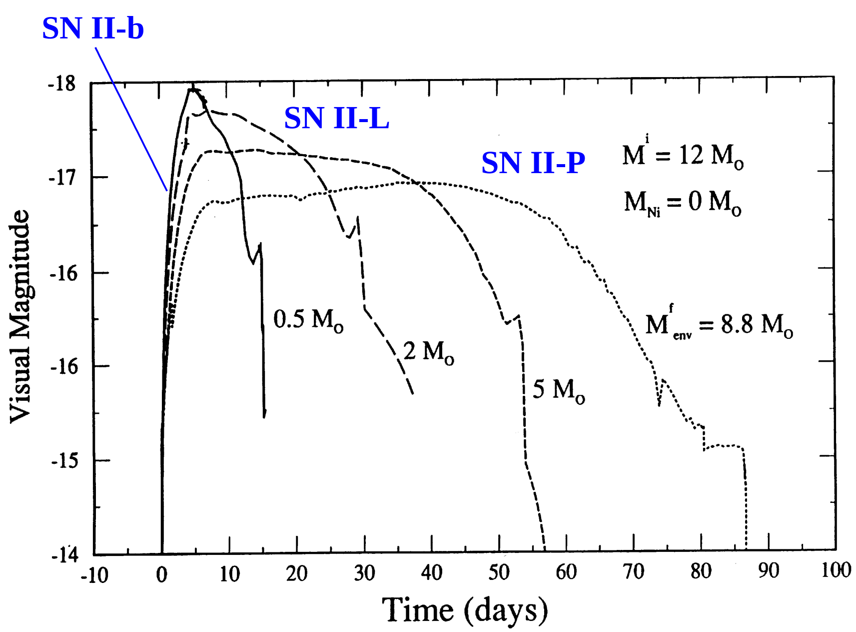
- mean free path: $l = 1/\kappa\rho,$
- ejecta expansion: $R(t) = vt,\ v = \sqrt{2E/M_{eject}},$

$$t_{diff} \simeq \frac{M_{eject}^{3/4}\kappa^{1/2}}{2(2E)^{1/4}c^{1/2}} \simeq 150\,d$$

$(\text{for } E = 10^{44}\,J,\ M_{env} = 10\,M_\odot,\ \kappa = 0.034 m^2/kg)$

Supernova lightcurves (core collapse)





Hsu, Ross, Joss, P.

LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

- central explosion may be very similar in all cases (with $E \sim 10^{44}$ J)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - ▷ envelope mass: determines thermal diffusion time and length/existence of plateau
  - ▷ envelope radius: more compact progenitor → more expansion work required → dimmer supernova
- binary interactions mainly affect stellar envelopes

→ binary interactions are, at least in part, responsible for the large variety of supernova (sub-)types

SN II-P → SN II-L → SN IIb → SN Ib → SN Ic

SUPERNOVA CLASSIFICATION

observational:

- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:

- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole

relation no longer 1 to 1 → confusion
→ use spectral lines to resolve ambiguities

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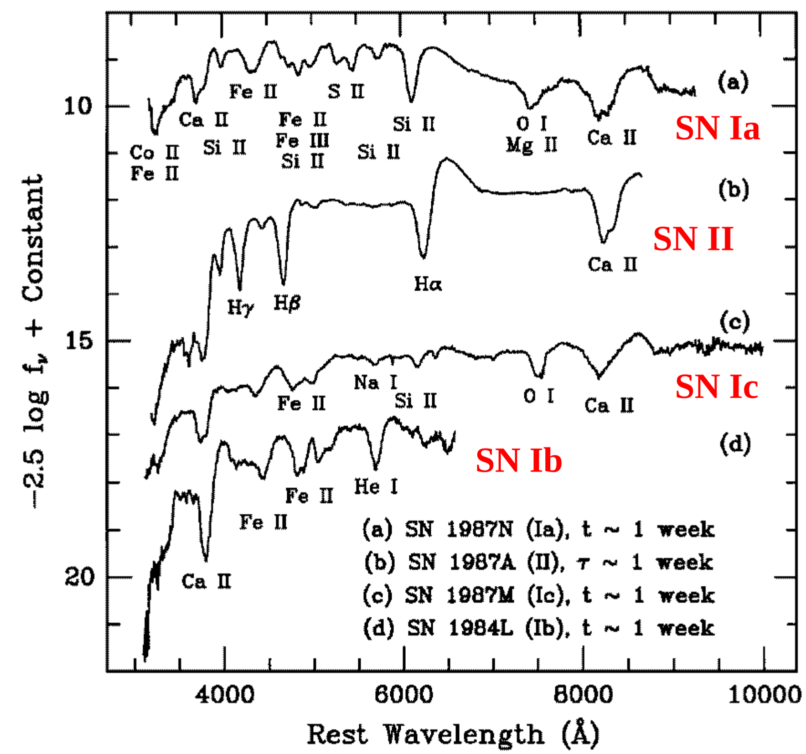
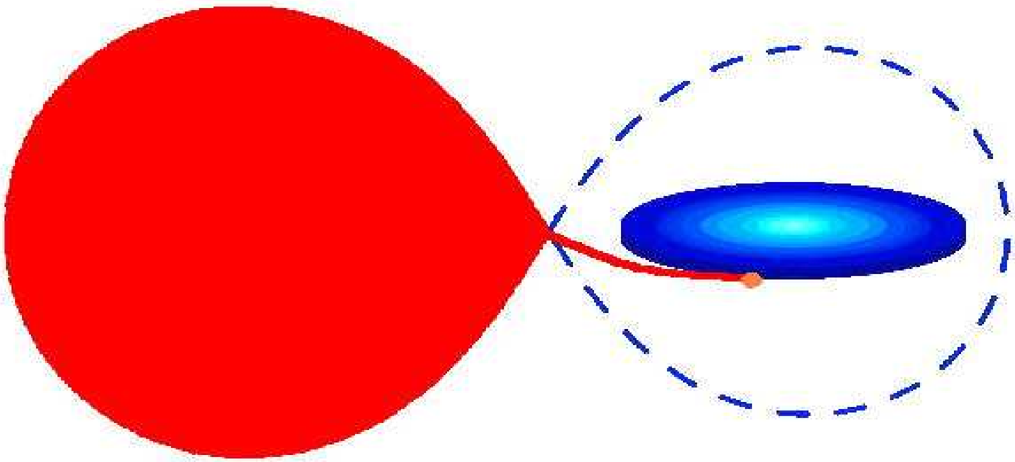
Supernova Classification



- **Si lines:** signature of thermonuclear explosion of a white dwarf → **Type Ia**
- **no Si; He or no He:** core collapse of a He/CO star (massive star that has lost its H and/or He envelope) → **Type Ib/c**
- **strong H lines, extended lightcurve:** "classical" core collapse of a massive star with hydrogen envelope → **Type II-P**

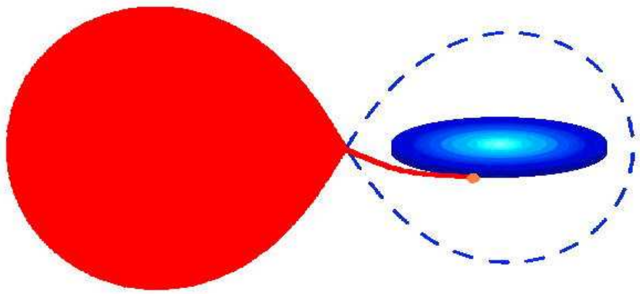
The Importance of Binary Interactions



- most massive stars are in binary systems
- up to 70 % of binaries interact

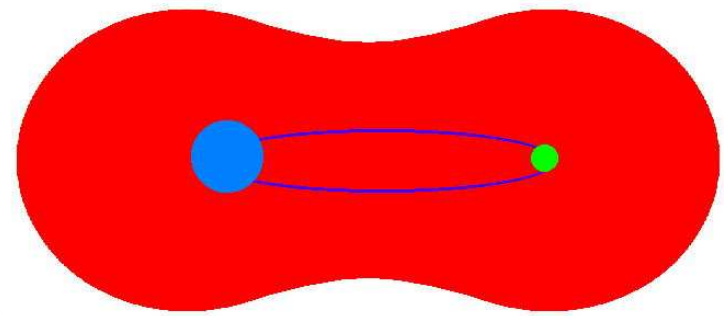
→ mass transfer → change structure (and further evolution) of the star

Stable Mass Transfer



- mass transfer is 'largely' conservative, except at very mass-transfer rates
- mass loss + mass accretion
- the mass loser tends to lose most of its envelope → formation of helium stars
- the accretor tends to be rejuvenated (i.e. behaves like a more massive star with the evolutionary clock reset)
- orbit generally widens

Unstable Mass Transfer



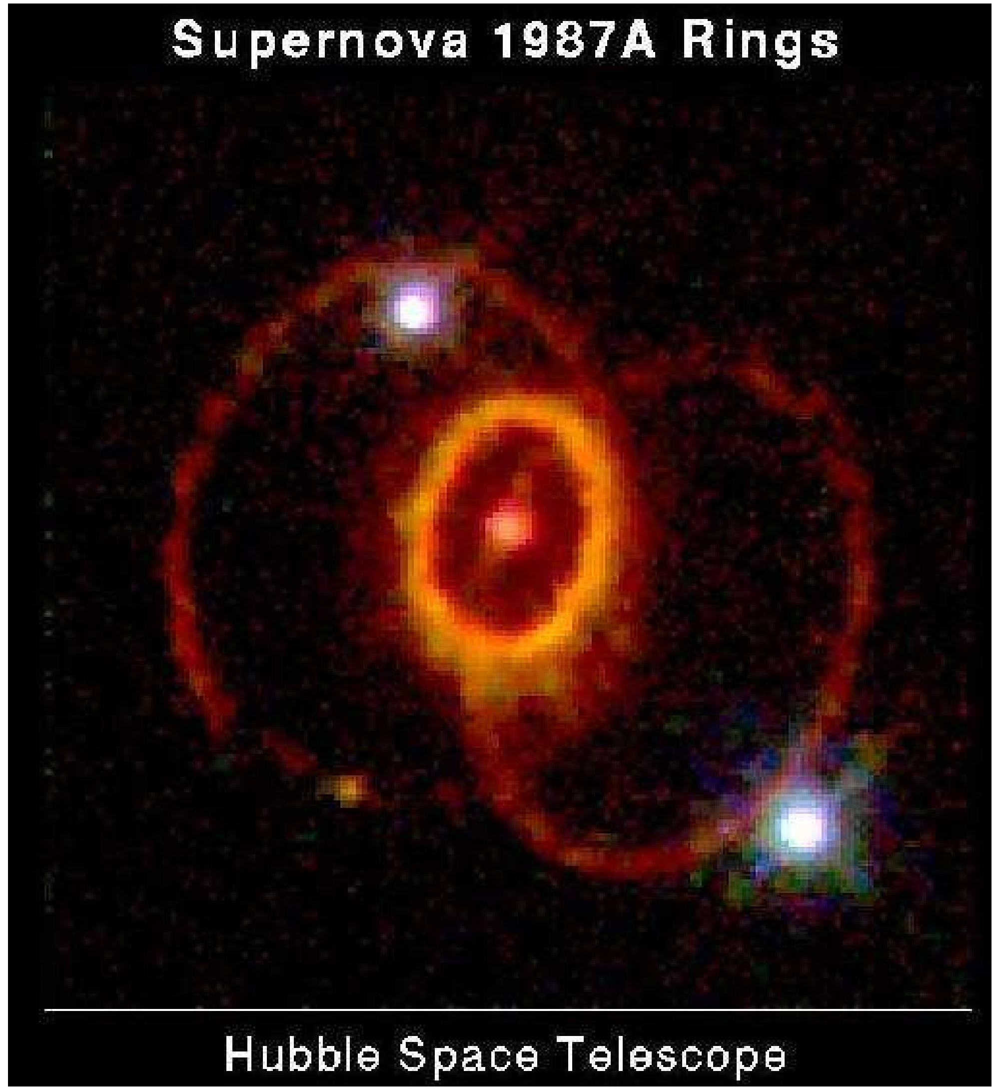
- dynamical mass transfer → common-envelope and spiral-in phase (mass loser is usually a red giant)
  - ▷ mass donor (primary) engulfs secondary
  - ▷ spiral-in of the core of the primary and the secondary immersed in a common envelope
- if envelope ejected → very close binary (compact core + secondary)
- otherwise: complete merger of the binary components → formation of a single, rapidly rotating star

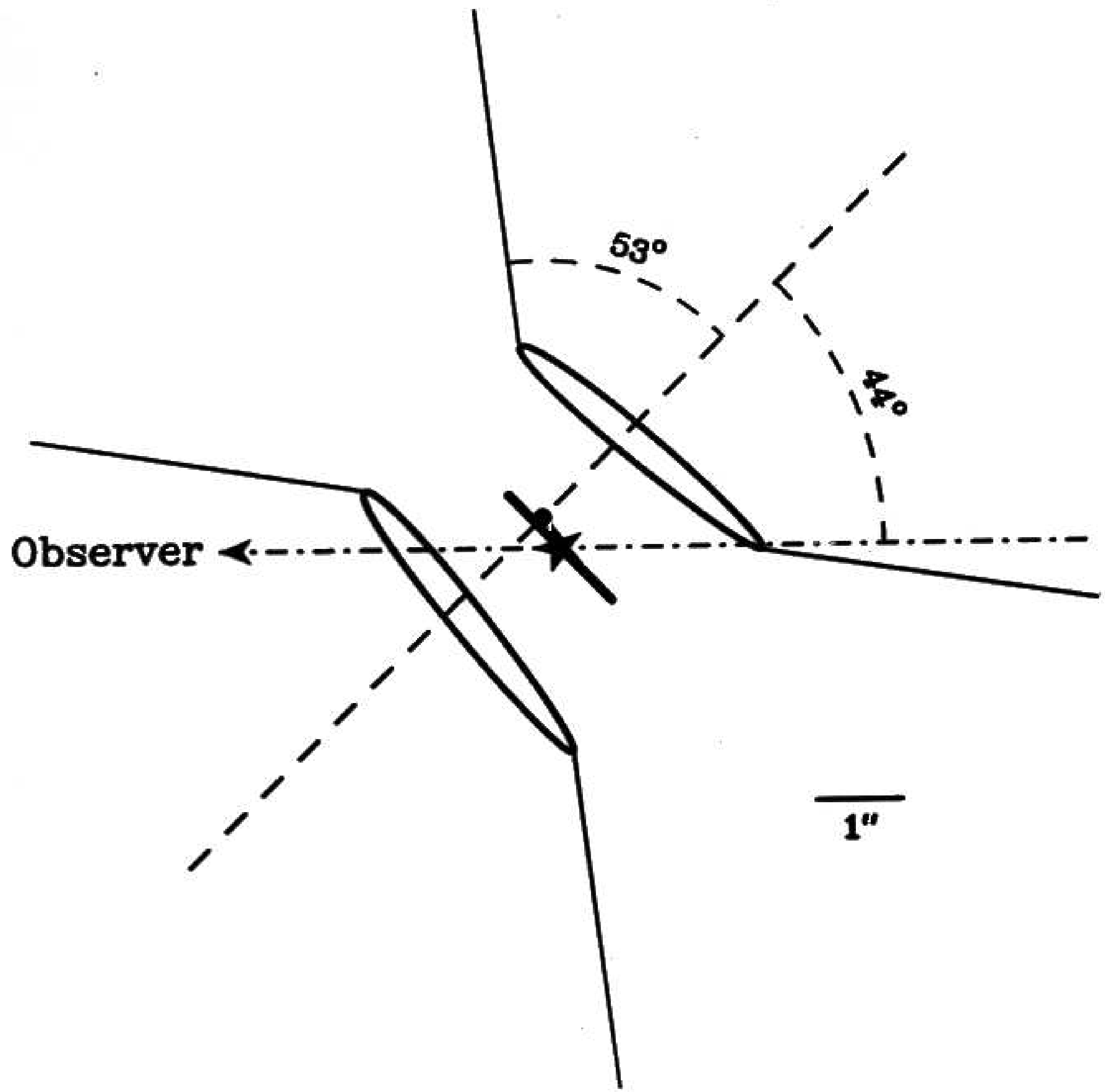
The Progenitor of SN 1987A

Thomas Morris (Oxford/MPA), Ph.P.

SN 1987A: an anomalous supernova

- the detection of 18 neutrinos confirmed the basic model of core collapse
- progenitor (SK $-69^{\circ}202$) completely unexpected: blue supergiant with recent red-supergiant phase (10^4 yr)
- the triple-ring nebula
  - → axi-symmetric, but highly non-spherical
  - → signature of rapid rotation

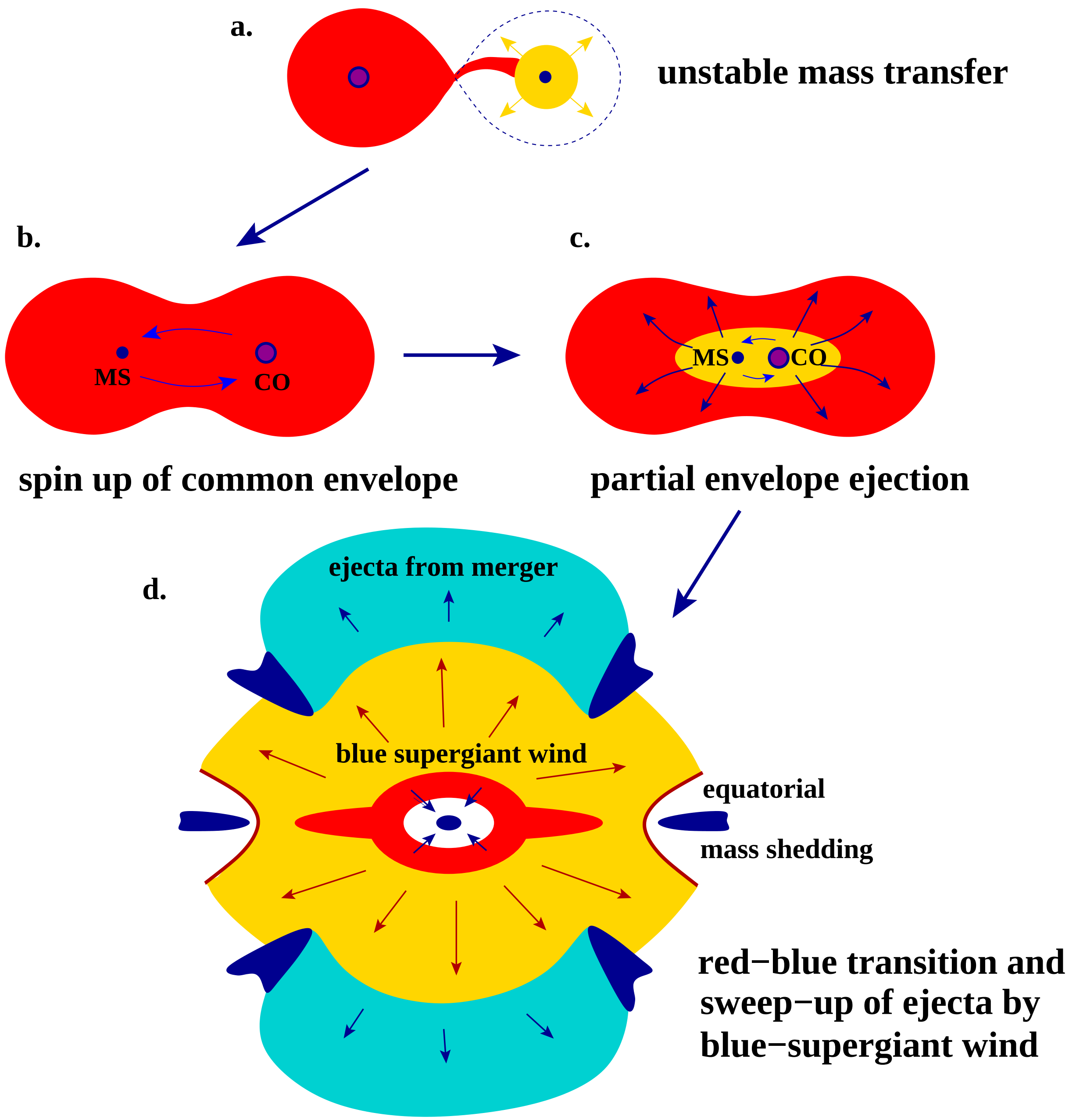


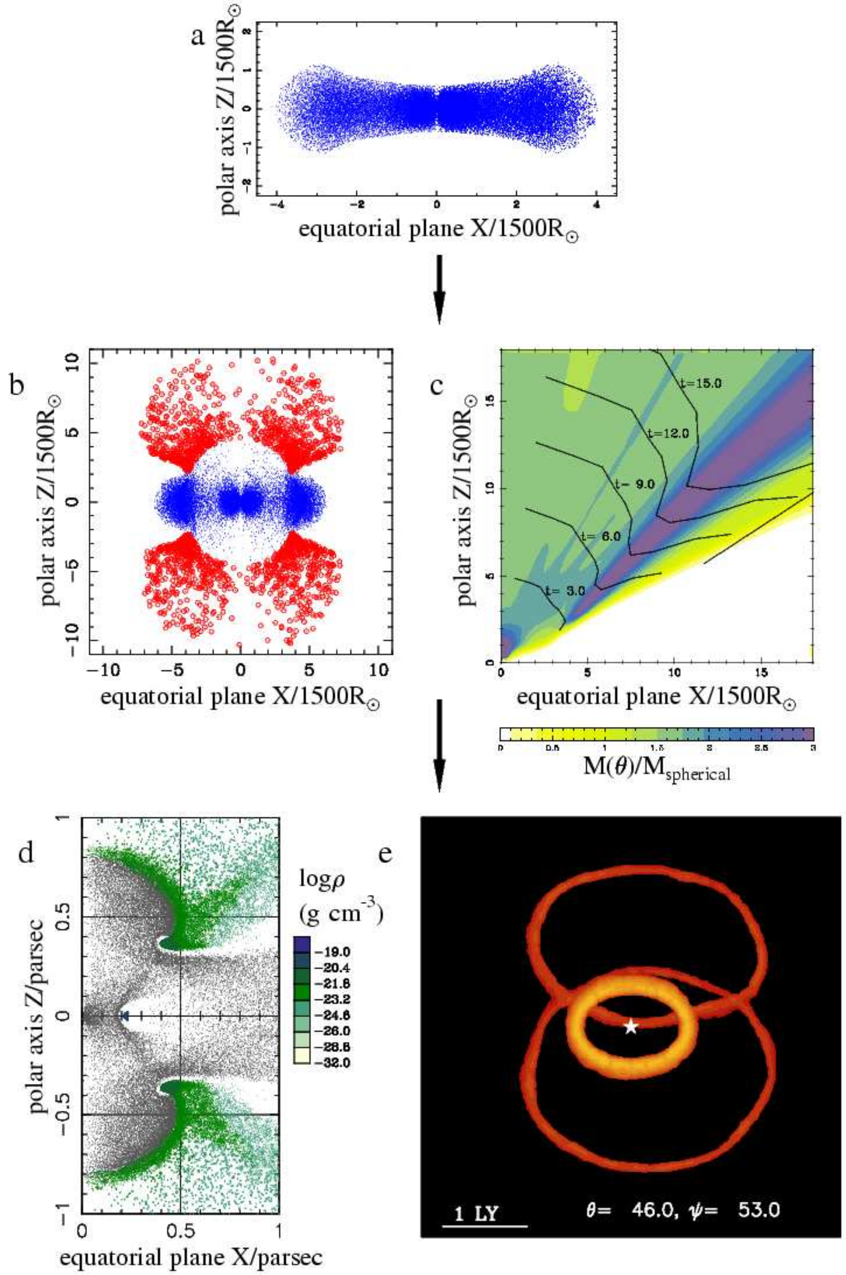


53°
44°
Observer
1"

Formation of the Triple-Ring Nebula

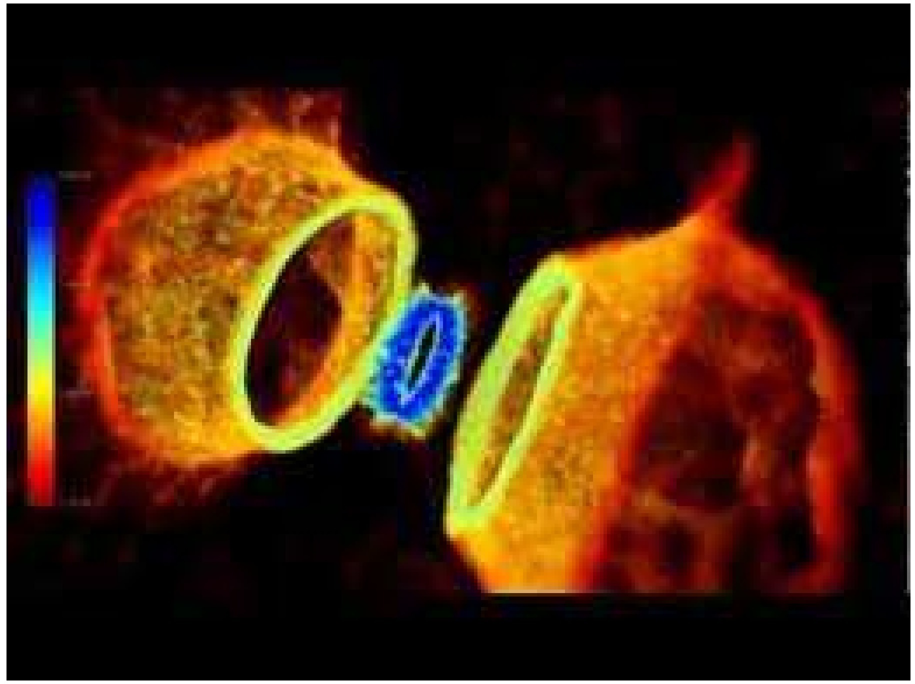
(Podsiadlowski, Morris, Ivanova)



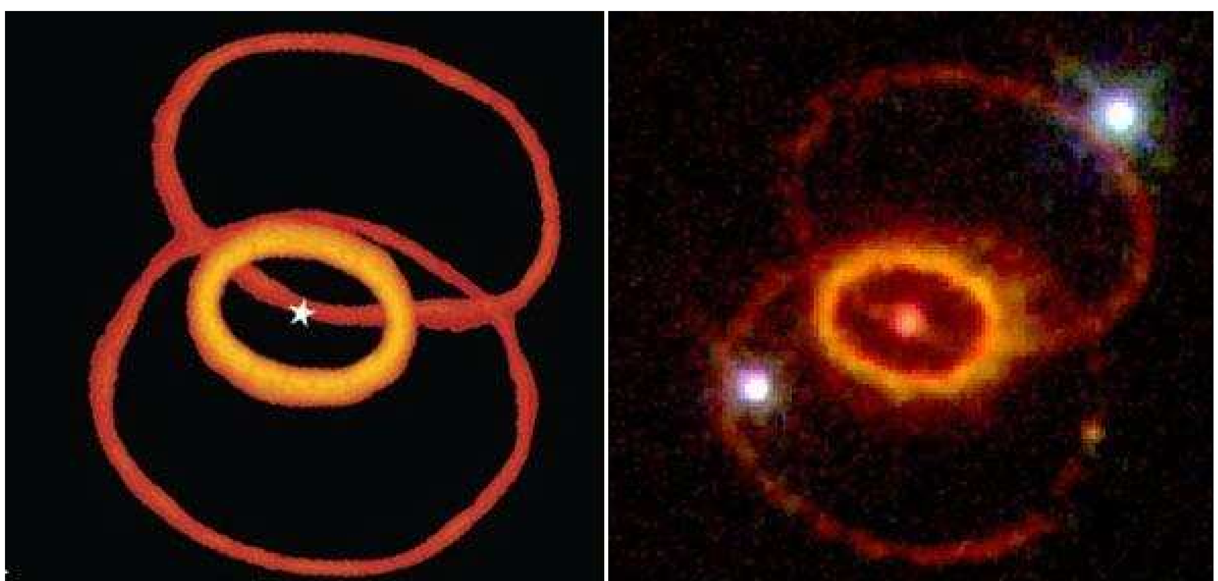


a
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
b
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
c
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
t=15.0
t=12.0
t= 9.0
t= 6.0
t= 3.0
M(θ)/M$_{spherical}$
d
polar axis Z/parsec
equatorial plane X/parsec
logρ
(g cm^{-3})
-19.0
-20.4
-21.8
-23.2
-24.6
-26.0
-28.8
-32.0
e
1 LY
θ= 46.0, ψ= 53.0

Final Structure

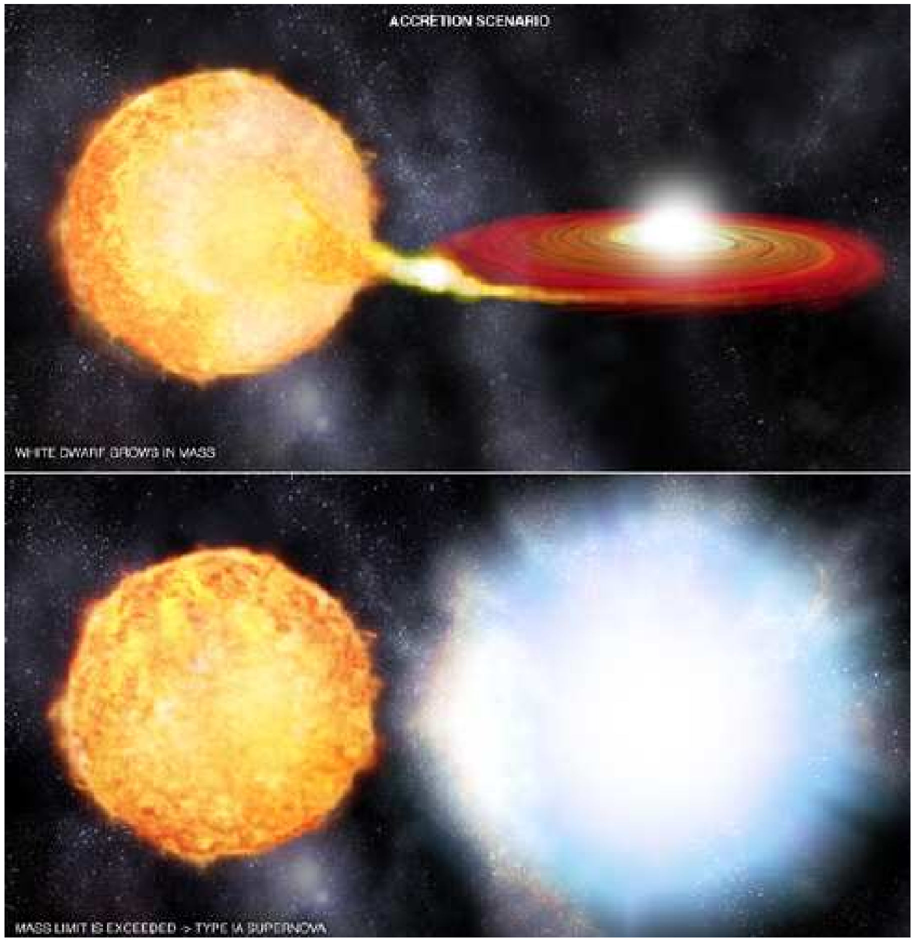


Rings: Theory vs. Observations

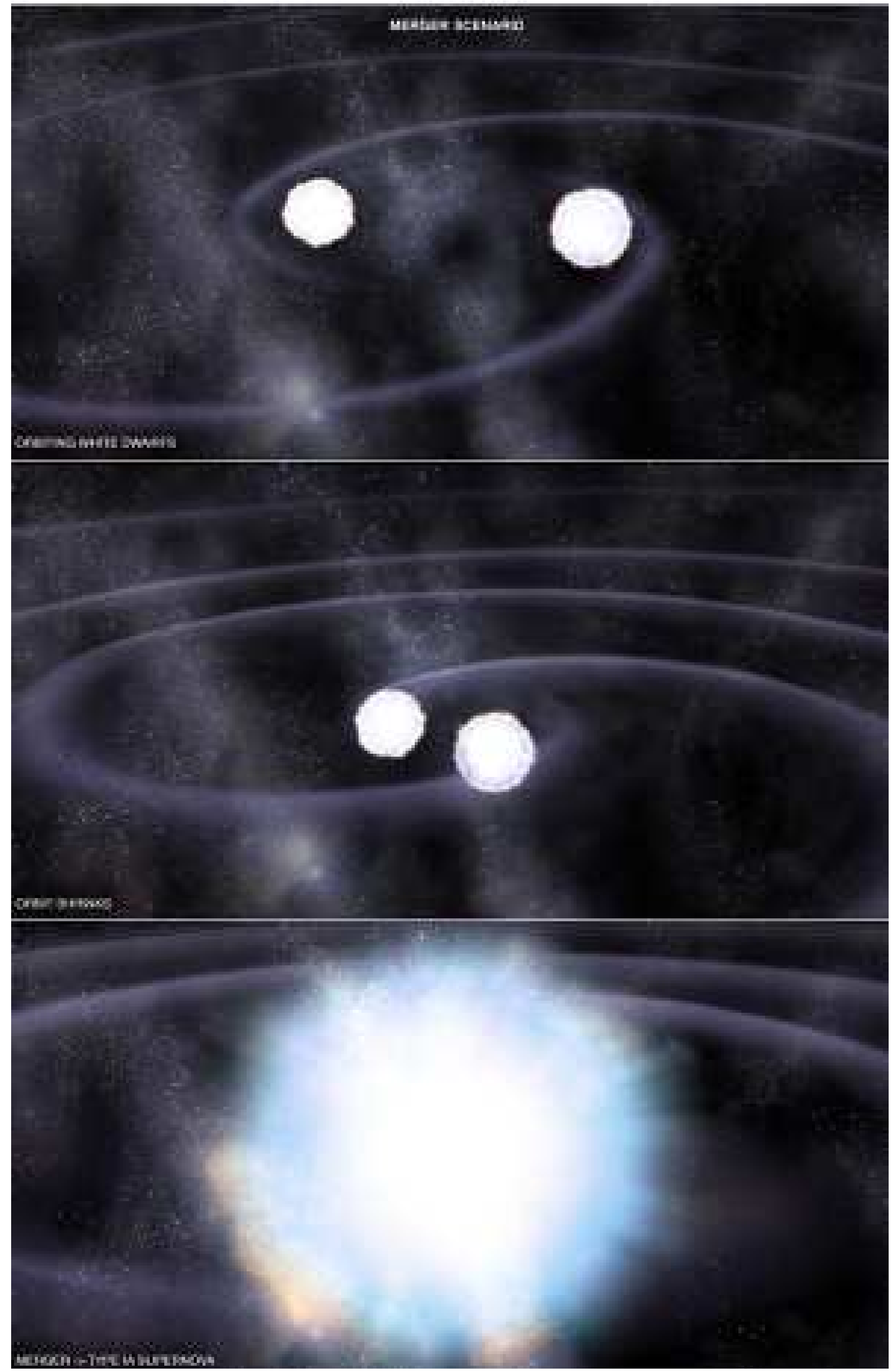


Binary Models for Thermonuclear Explosions

Accretion Model

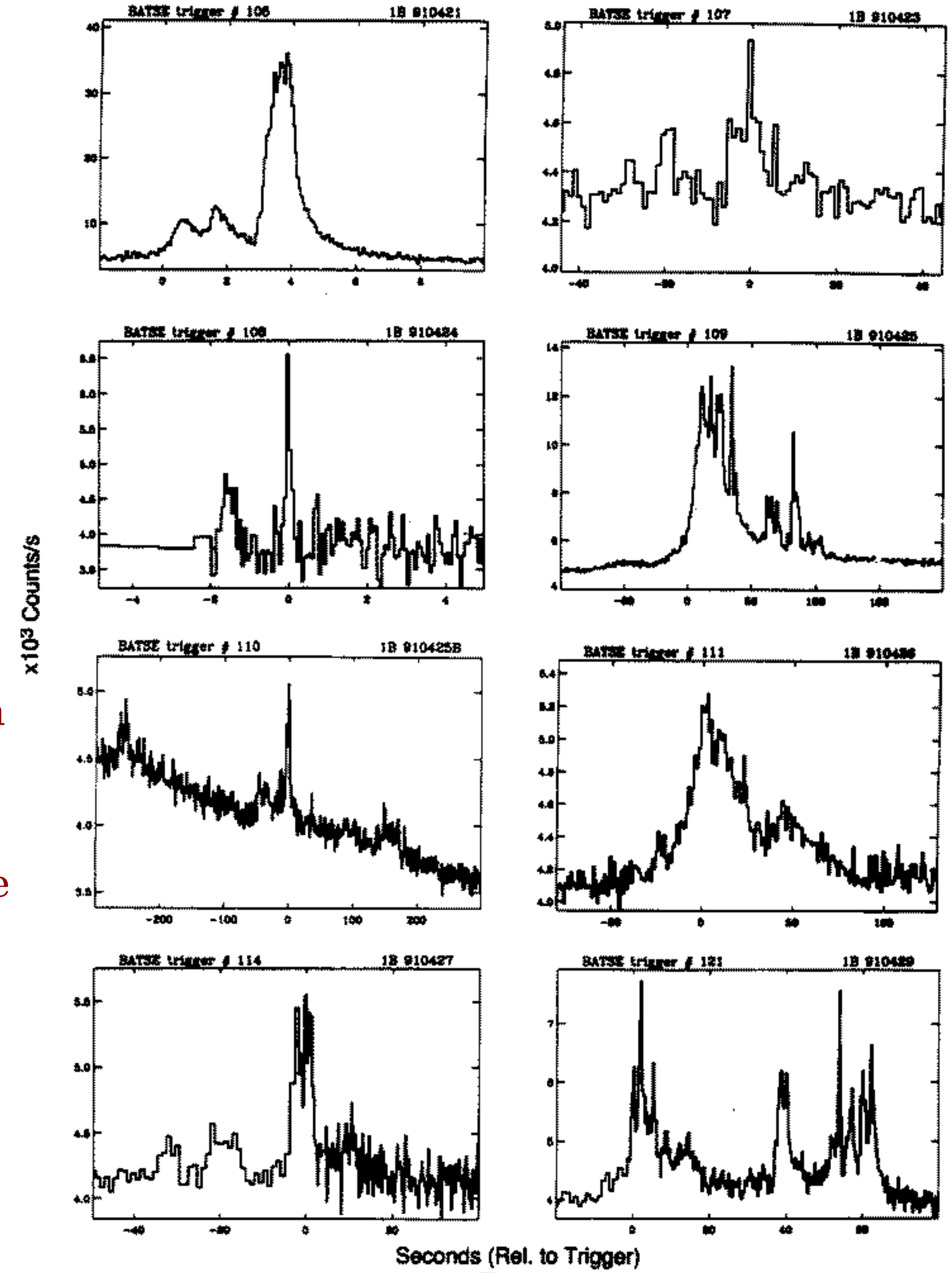


Merger Model

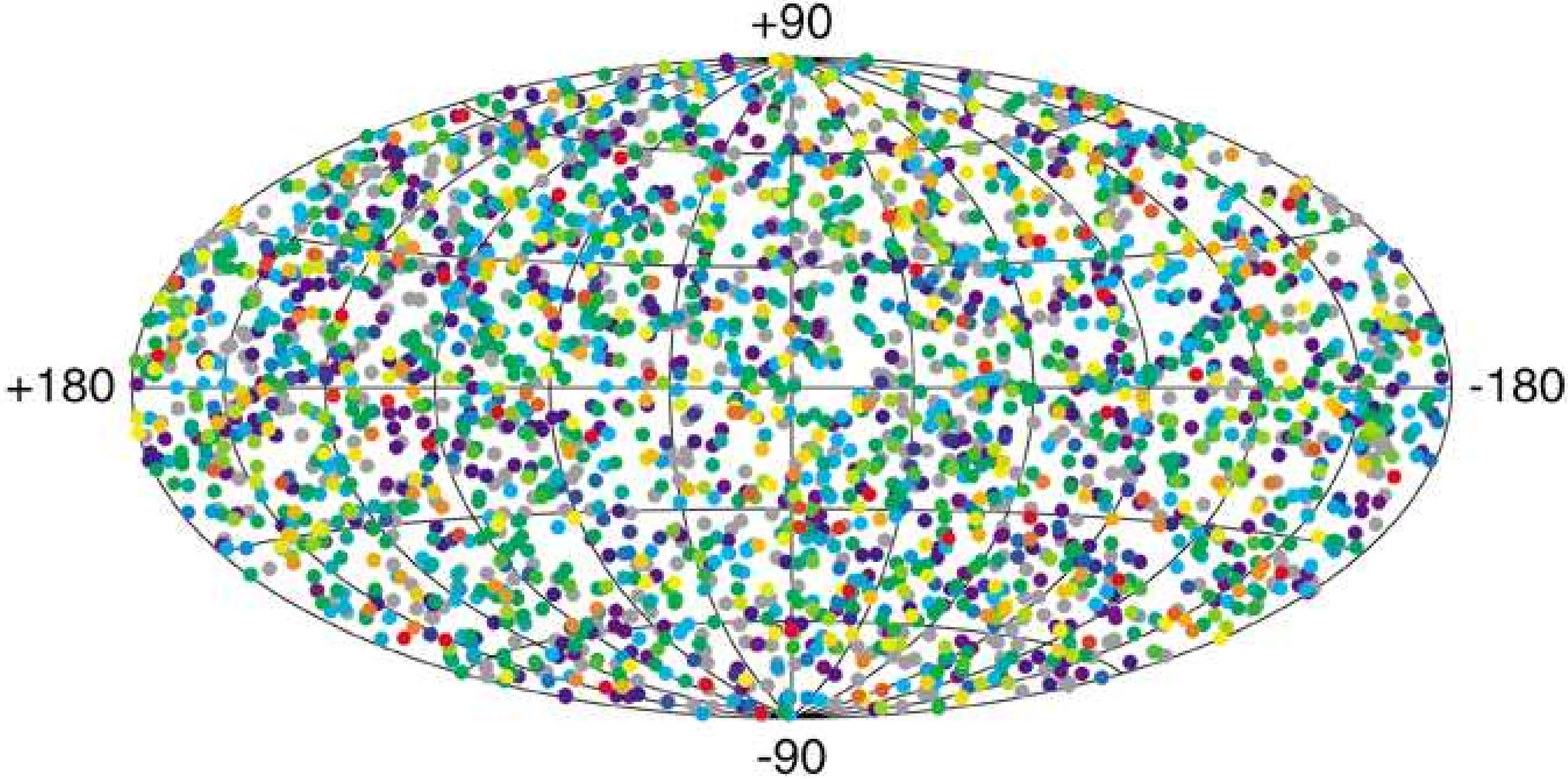


Gamma-Ray Bursts (GRBs)

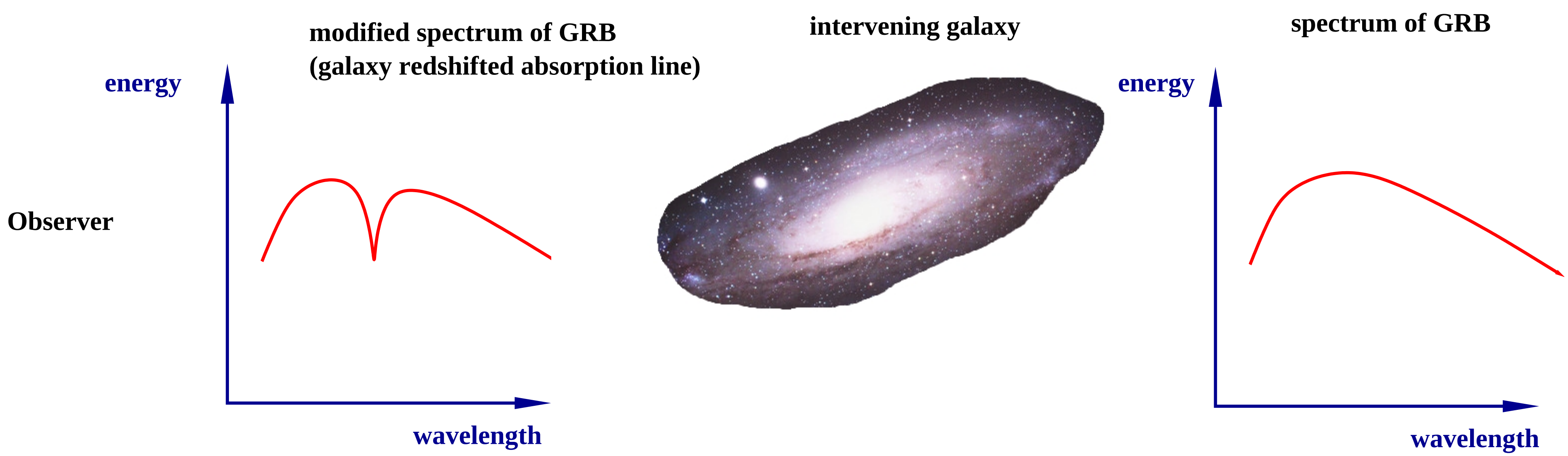
- discovered by a U.S. spy satellite (1967; secret till 1973)
- have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, Universe?)
- discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs → GRBs are the some of the most energetic events in the Universe
- duration: 10^{-3} to 10^{3} s (large variety of burst shapes)



2704 BATSE Gamma-Ray Bursts

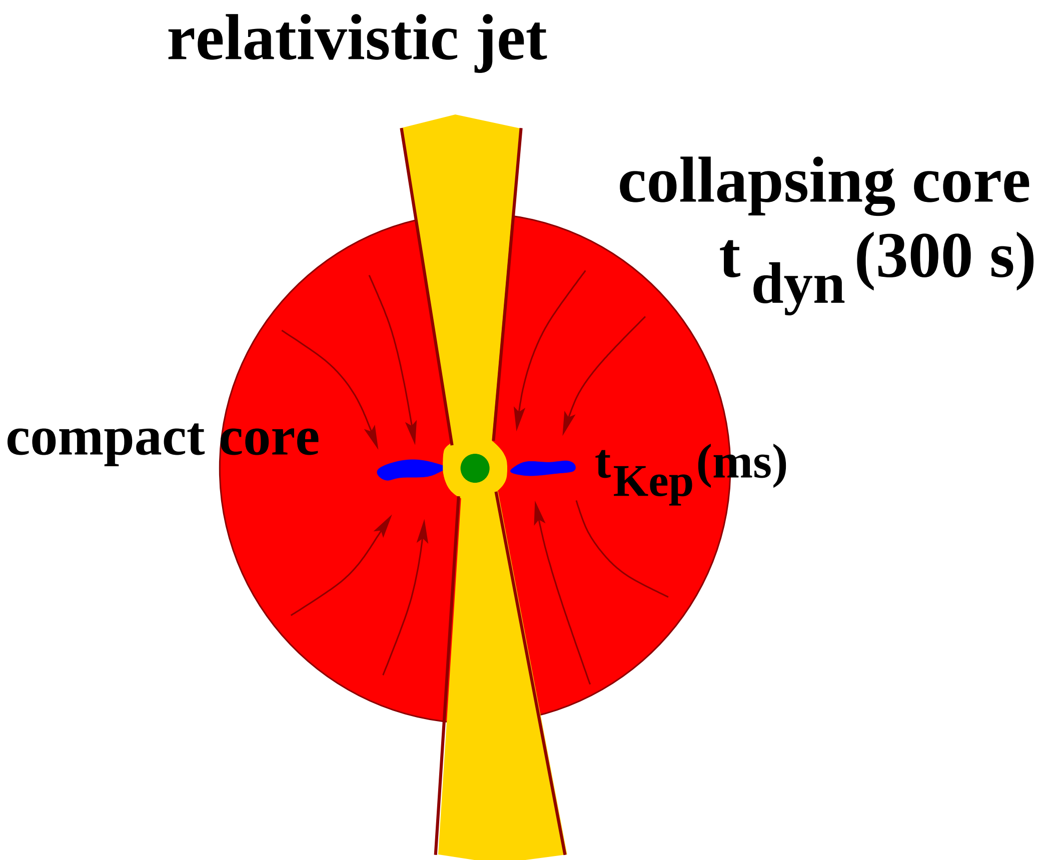


The distance scale of gamma−ray bursts (GRBs)



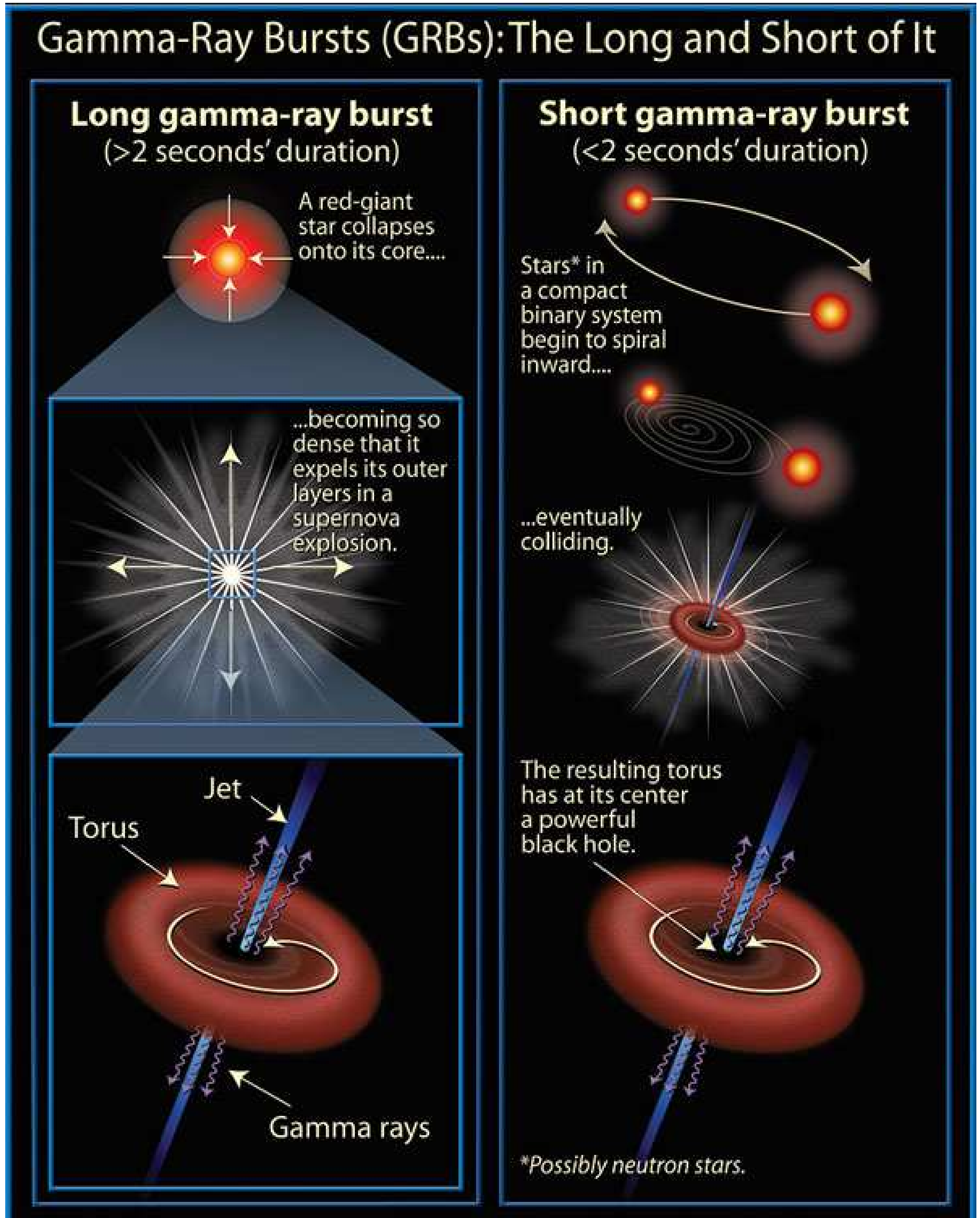
proof: GRBs are explosions at cosmological distances

The collapsar model



- GRBs are associated with energetic supernovae (hypernovae) with $E \sim 10^{45}$ J
- two-step black-hole formation: neutron star, accretion from massive disk $\rightarrow$ black hole $\rightarrow$ relativistic jet $\rightarrow$ drills hole through remaining stellar envelope $\rightarrow$ escaping jet $\rightarrow$ GRB
- extracts rotational energy: $\sim 10^{45}$ J
- requires rapidly rotating He/CO star
- HNe/GRBs are rare! (1 in 1000 core-collapse SNe)
- GRBs can be seen in the very distant Universe
  - ▷ most distant object seen so far in 2011 ($z \simeq 9.4$ [$\sim 4 \times 10^8$ yr])
- progenitors?

•

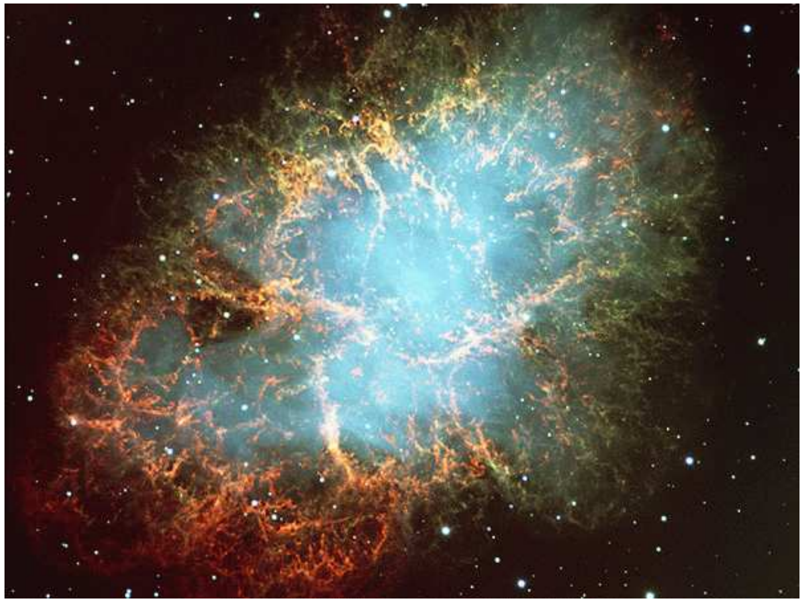


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

SUPERNOVA REMNANTS

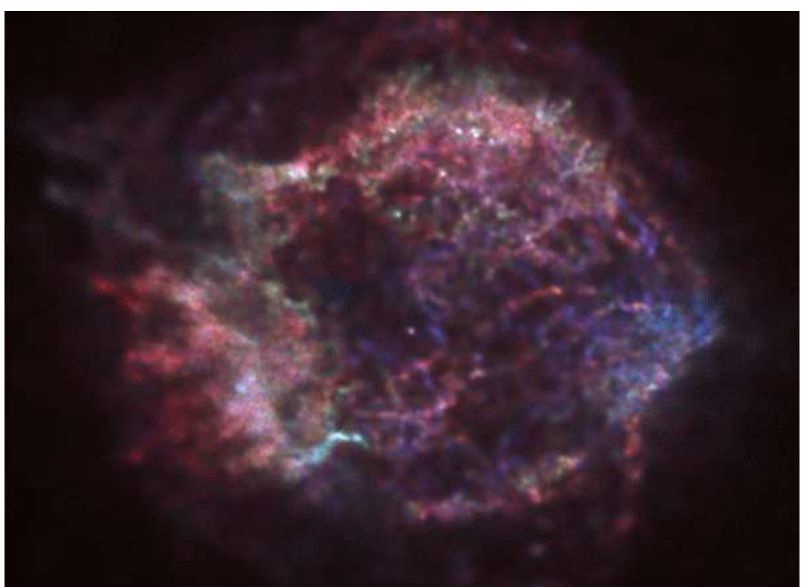
The Crab Nebula (plerionic/filled)

VLT



Chandra
(X-rays)

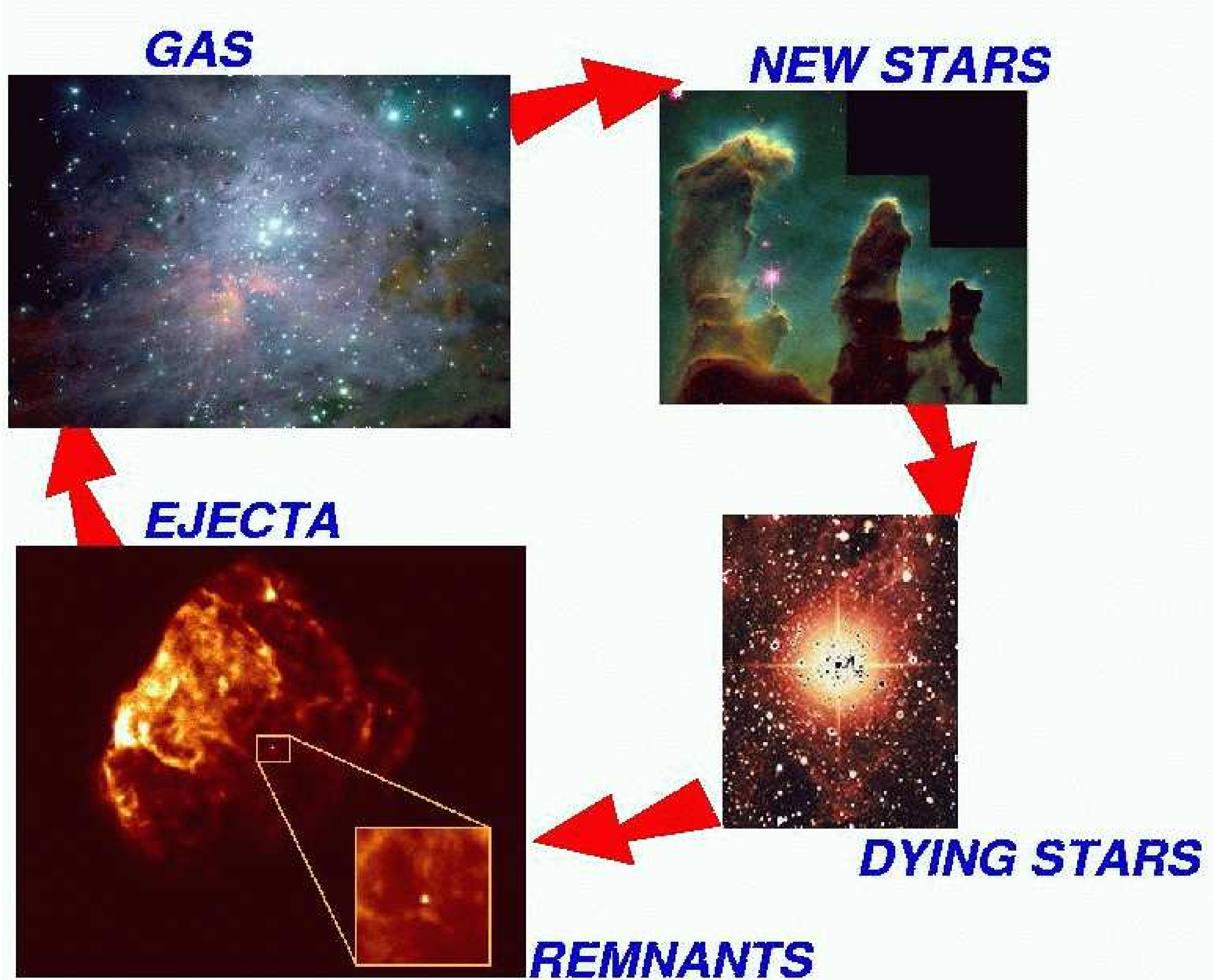
Cassiopeia A (shell-like)



The role of supernovae in the Universe

- after the main supernova phase, the ejecta expand and ultimately mix with the interstellar medium (over $\sim 10^5$ yr)
- energy injection into the medium

  $\rightarrow$ regulates star formation (and hence galaxy evolution)
- increasingly enriches the interstellar medium with elements produced in stars/supernovae


GAS
NEW STARS
DYING STARS
REMNANTS
EJECTA

The Origin of the Elements

- supernovae eject nuclei that were produced in their progenitors or explosively in the supernova → key agent to enrich the interstellar medium and the next generation of stars

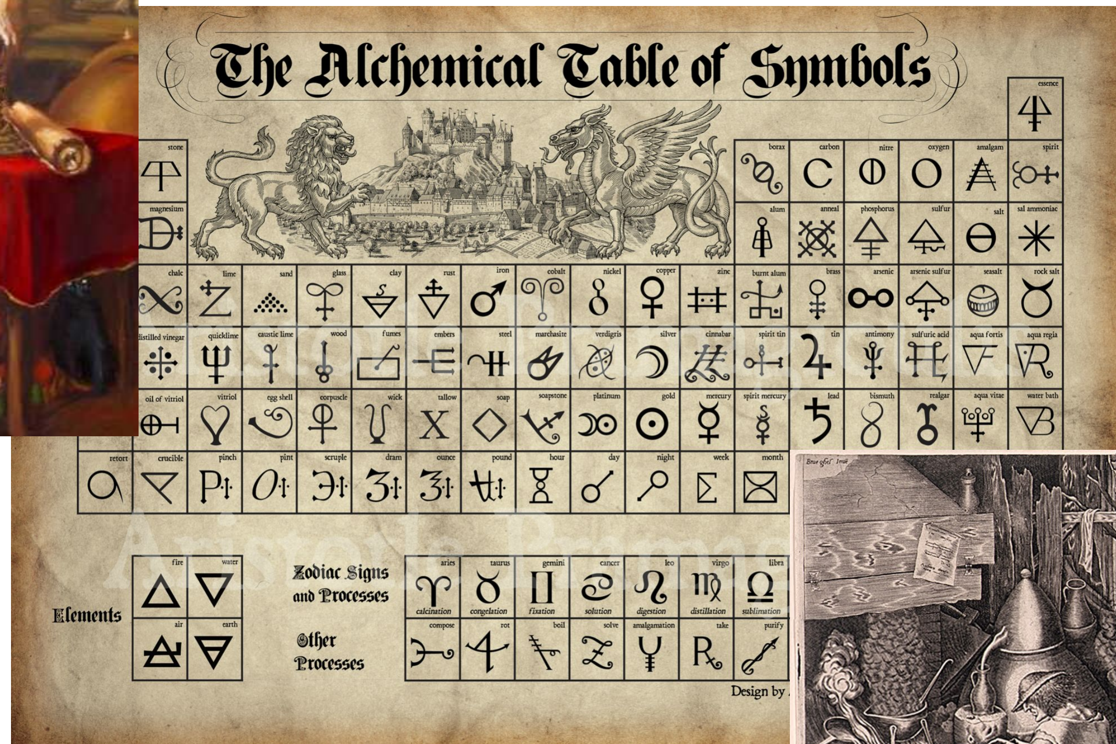
Core-collapse supernovae

- eject progenitor material rich in O, Mg, Ne (note: most of the Fe core collapses and is locked up in the compact remnant)
- produce only some ^{56}Ni that decays to ^{56}Fe
- time scale of injection is determined by the lifetime of the massive progenitor $(10^6 - 10^7\,\mathrm{yr})$

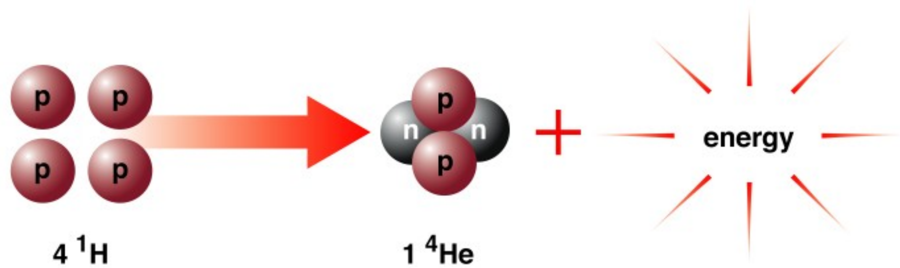
Thermonuclear supernovae

- produce/eject intermediate-mass elements (Si, S, Ca) and ^{56}Ni (→ main producer of ^{56}Fe)
- time scale till the explosion depends on binary evolution: $\sim 10^9\,\mathrm{yr}$

- difference in abundance pattern (e.g. O/Fe) and different timescales → O/Fe signature of star-formation/enrichment timescale in galaxy evolution
- big remaining puzzle: origin of very neutron-rich elements (such as gold, platinum)
- major breakthrough in 2017 with aLIGO


The Alchemical Table of Symbols
Elements
fire
water
air
earth
Zodiac Signs
and Processes
Other
Processes
Design by

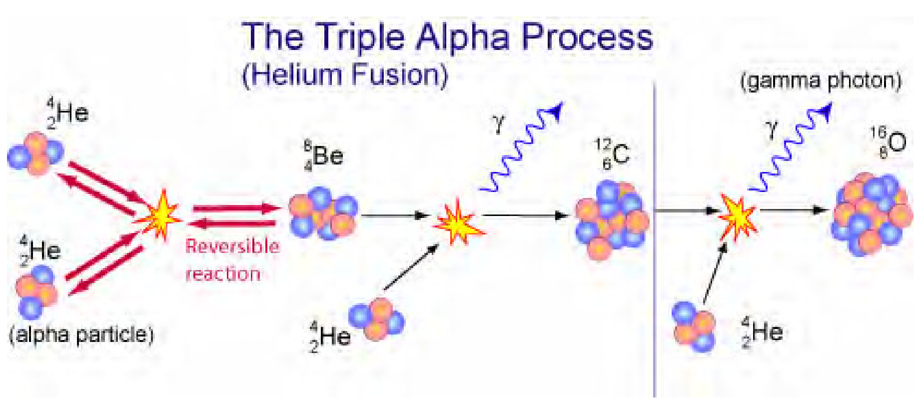
Hydrogen Fusion (present Sun)



$$4\,{}^1\mathrm{H} \to {}^4\mathrm{He} + \mathrm{energy},$$

$$T \simeq 15 \times 10^6\,\mathrm{K},$$
$$\Delta E = \eta_H\, M_H\, c^2,$$
$$\eta_H = 0.7\,\%$$

Helium Fusion (future)



$$3\,{}^4\mathrm{He} \to {}^{12}\mathrm{C} + \ \mathrm{energy},$$
$$+{}^4\mathrm{He} \to {}^{16}\mathrm{O} + \mathrm{energy},$$

$$T \sim 100 \times 10^6\,\mathrm{K},$$
$$\eta_{He} = 0.1\,\%$$

EVOLUTION OF MASSIVE STARS
($M \gtrsim 10\,M_\odot$)

- massive stars continue to burn nuclear fuel beyond H and He and ultimately form an **iron core**
- alternation of nuclear **burning and contraction** phases
  - ▷ carbon burning ($T \sim 6 \times 10^8\,K$)

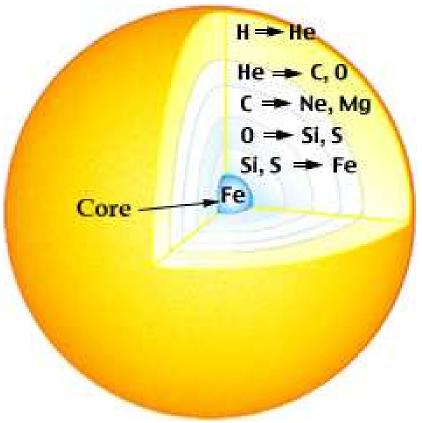
$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + {}^{1}H \\
&\rightarrow {}^{23}Mg + n
\end{aligned}
$$

  - ▷ oxygen burning ($T \sim 10^9\,K$)

$$
\begin{aligned}
{}^{16}O + {}^{16}O &\rightarrow {}^{28}Si + {}^{4}He \\
&\rightarrow {}^{31}P + {}^{1}H \\
&\rightarrow {}^{31}S + n \\
&\rightarrow {}^{30}S + 2\,{}^{1}H \\
&\rightarrow {}^{24}Mg + {}^{4}He + {}^{4}He
\end{aligned}
$$

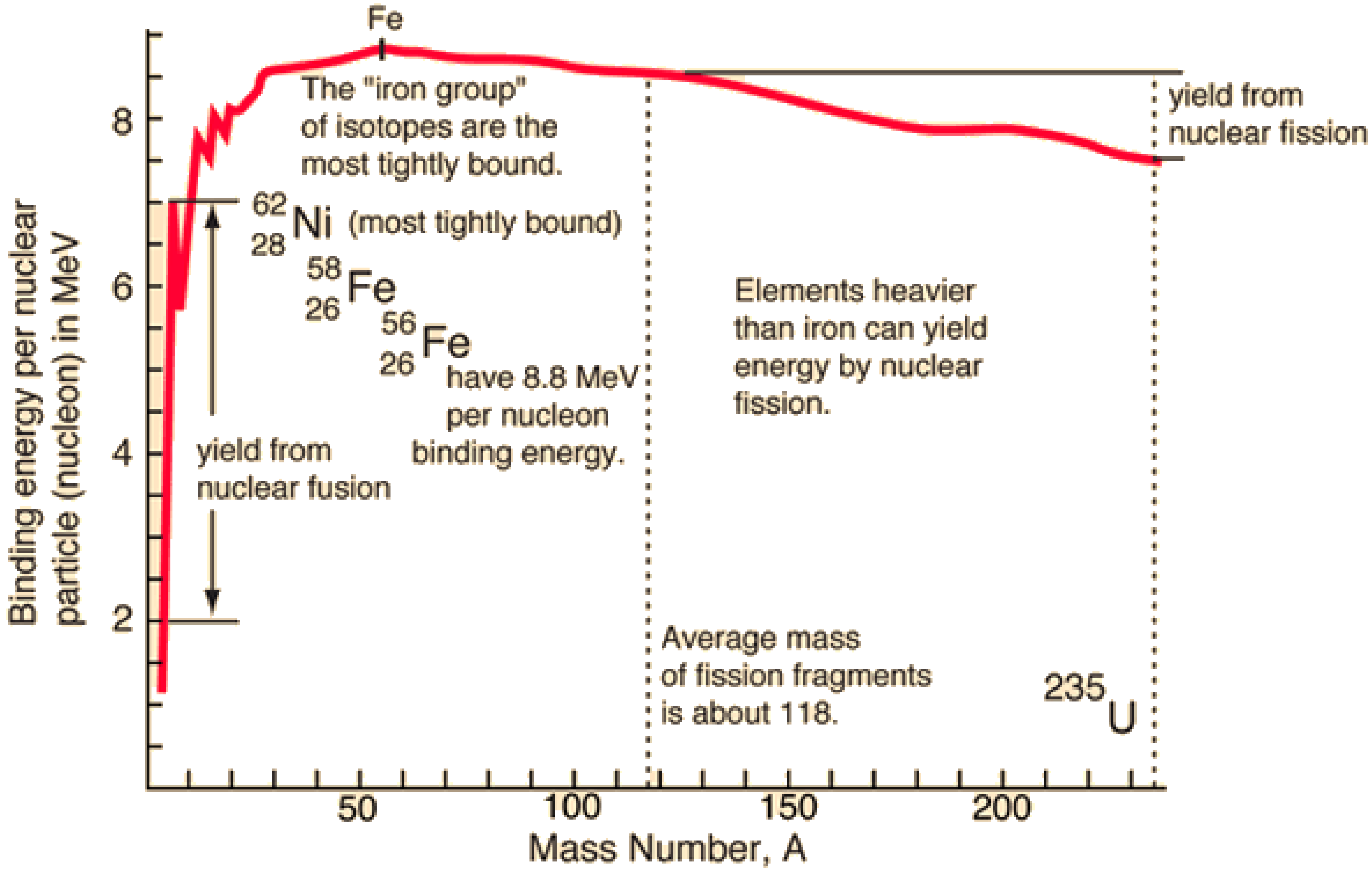
  - ▷ silicon burning: photodisintegration of complex nuclei, 100s of reactions → iron

Final Structure

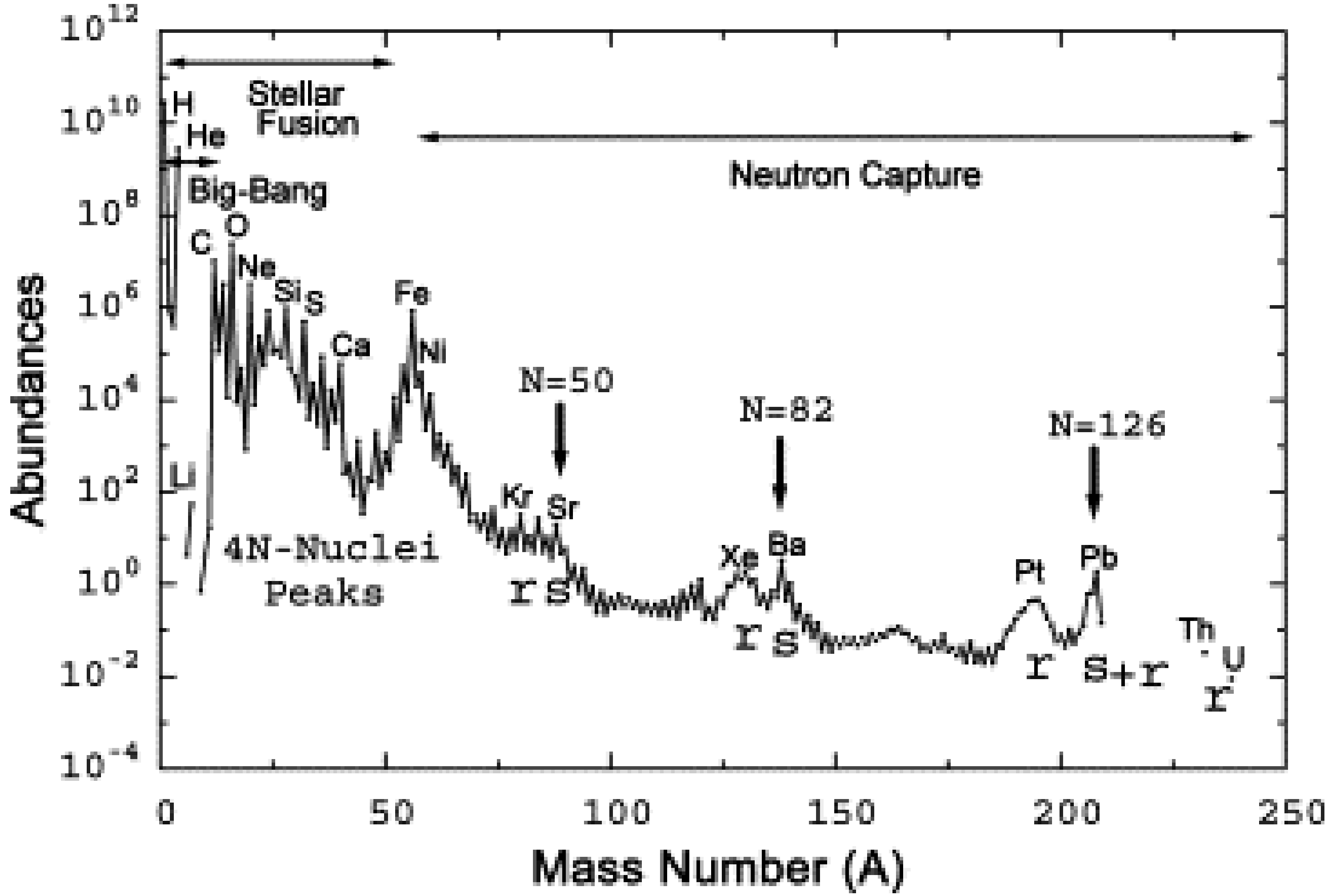


- ▷ form **iron core**
- ▷ **iron** is the most tightly **bound nucleus** → no further energy from nuclear fusion
- ▷ iron core surrounded by **onion-like shell structure**

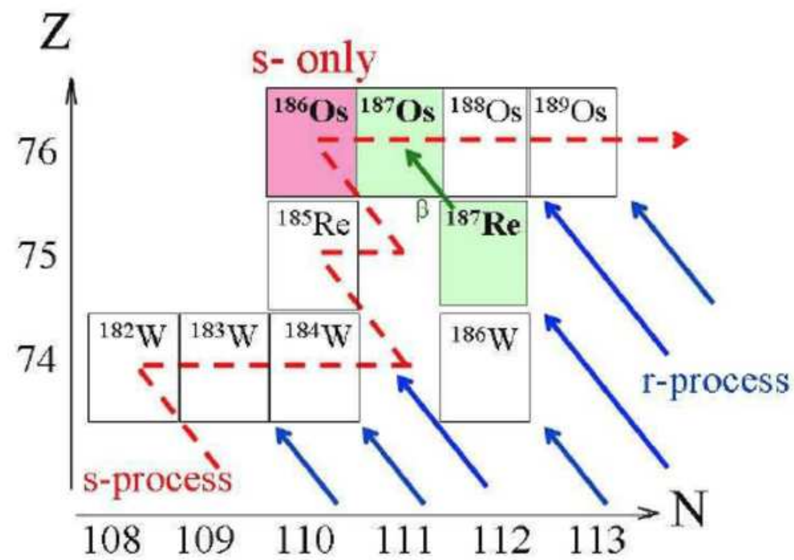
→ **core collapse**



- iron (Fe) most tightly bound nucleus
- generate energy
  - ▷ by nuclear fusion for elements lighter than Fe
  - ▷ by nuclear fission for elements heavier than Fe



Stellar Fusion
Neutron Capture
H
He
Big-Bang
Li
C
O
Ne
Si
S
Ca
Fe
Ni
4N-Nuclei Peaks
N=50
Kr
Sr
r
s
N=82
Xe
Ba
r
s
N=126
Pt
Pb
r
s+r
Th
U
r
Abundances
Mass Number (A)

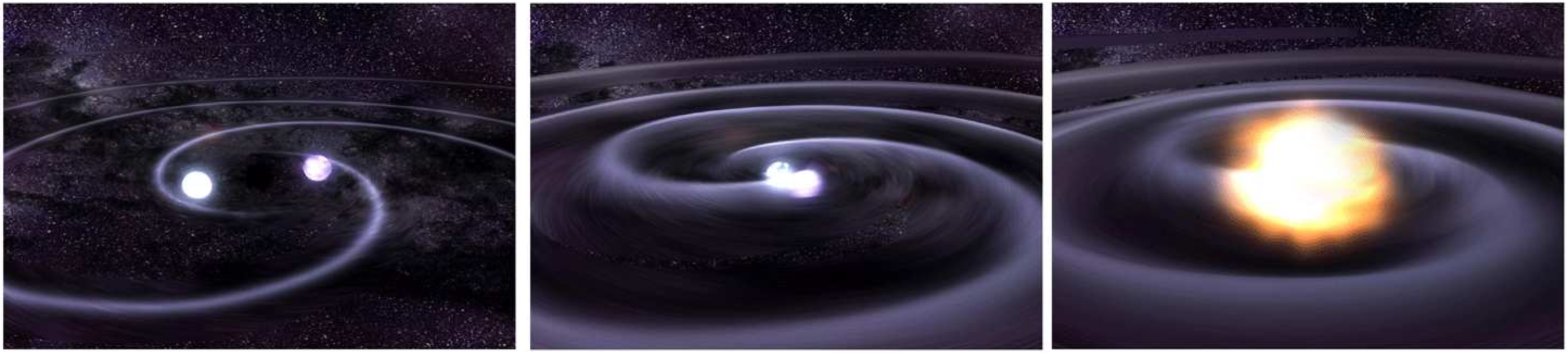


- production of neutron-rich, heavy elements (gold, platinum, . . .) requires special conditions
- high temperatures
- neutron-rich environment

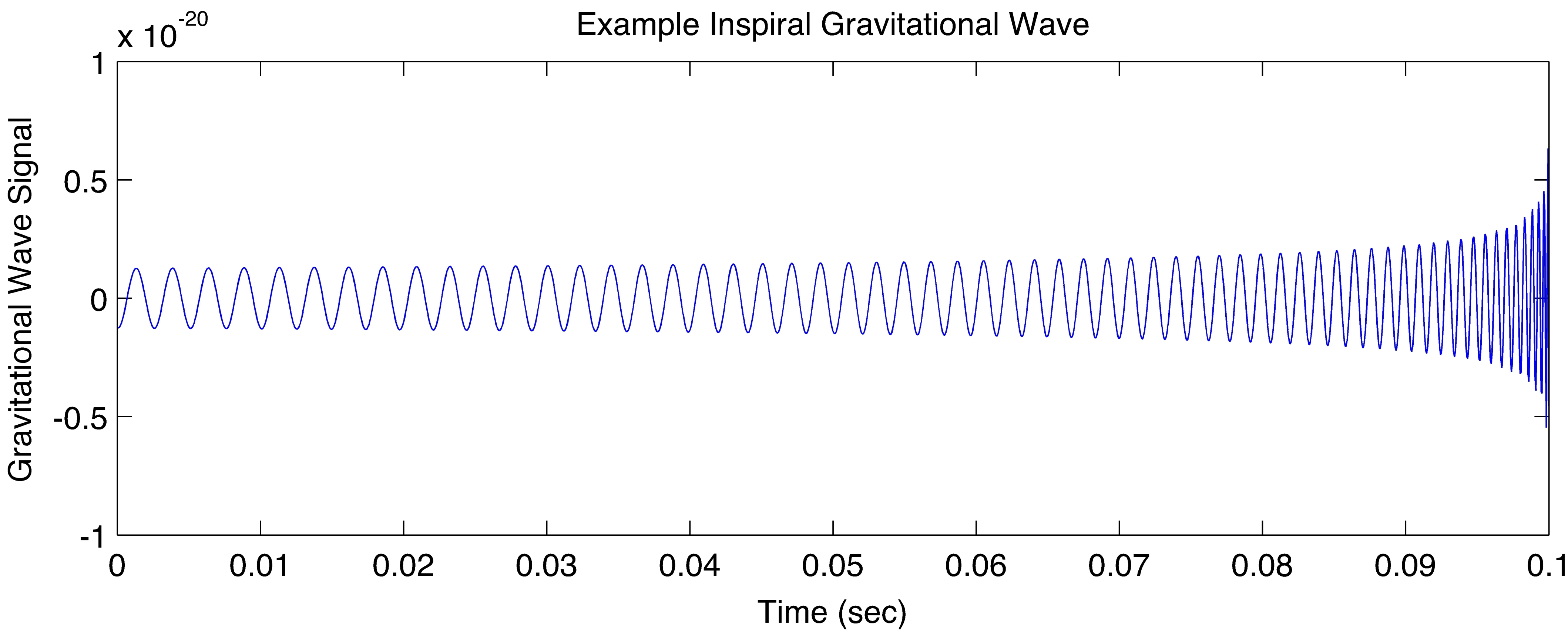
candidates:

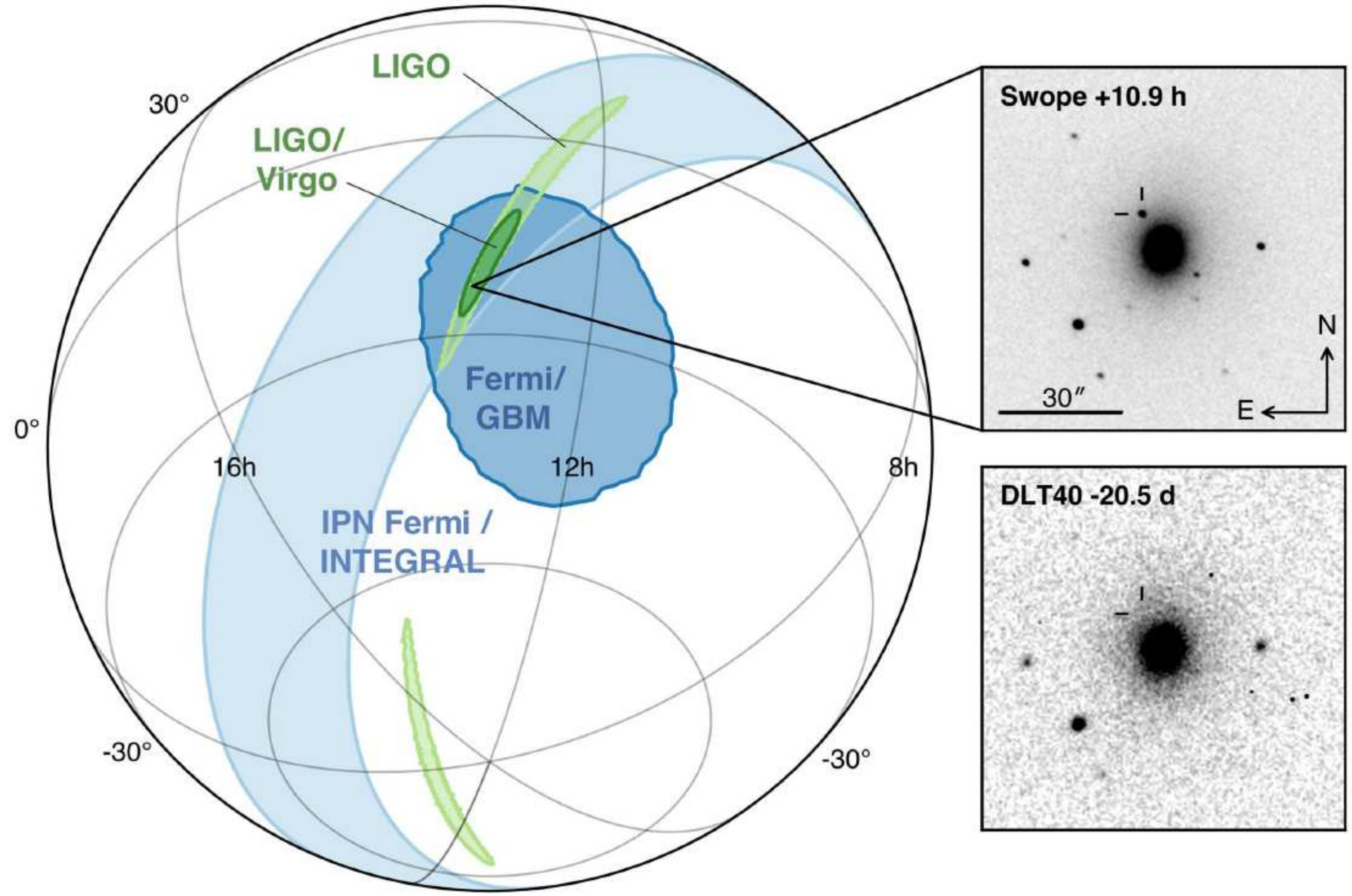
- supernova explosions (but unusual ones)
- merging neutron stars

Compact Binary Inspiral and Final Merger



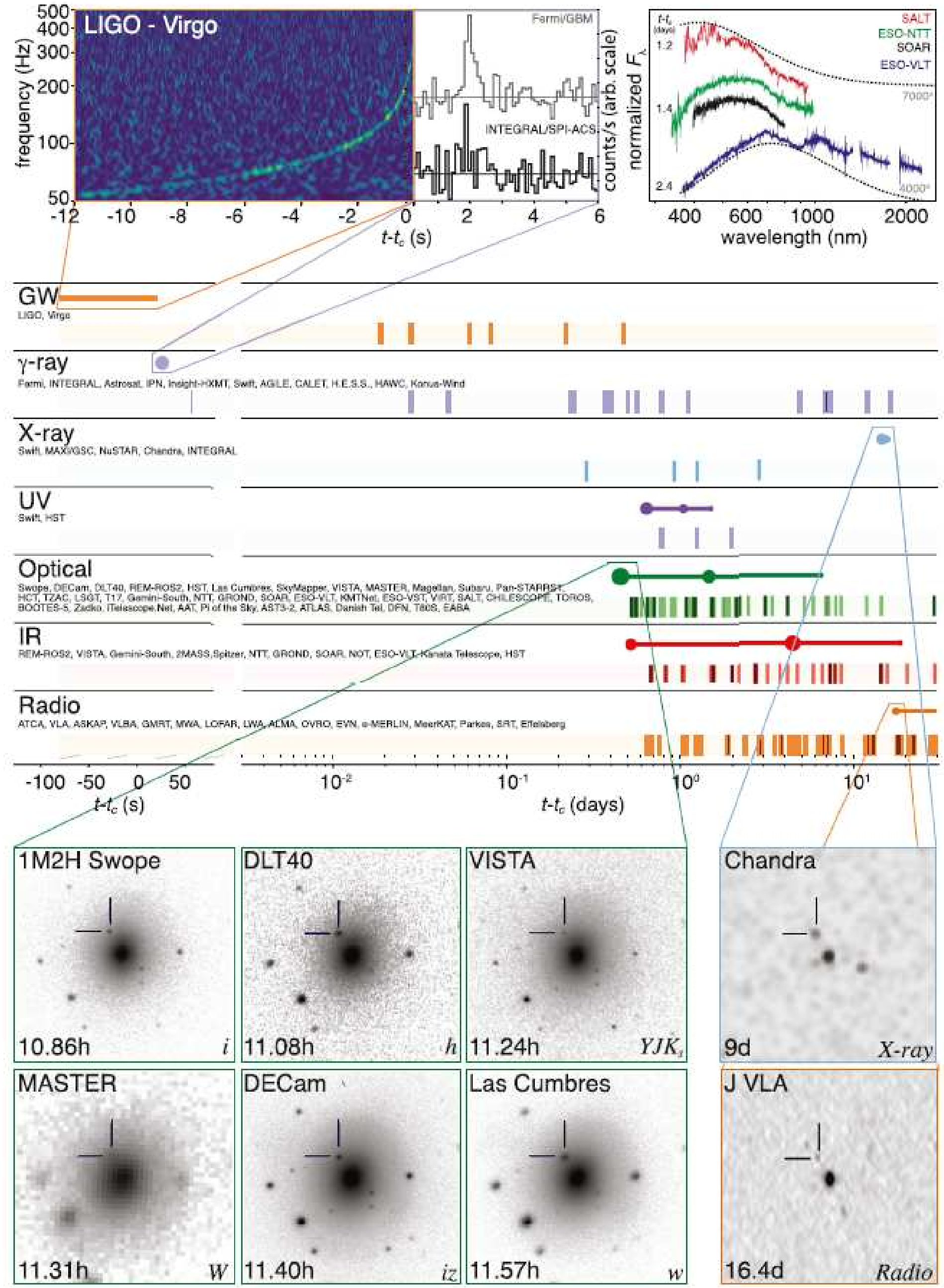
(Strohmayer)



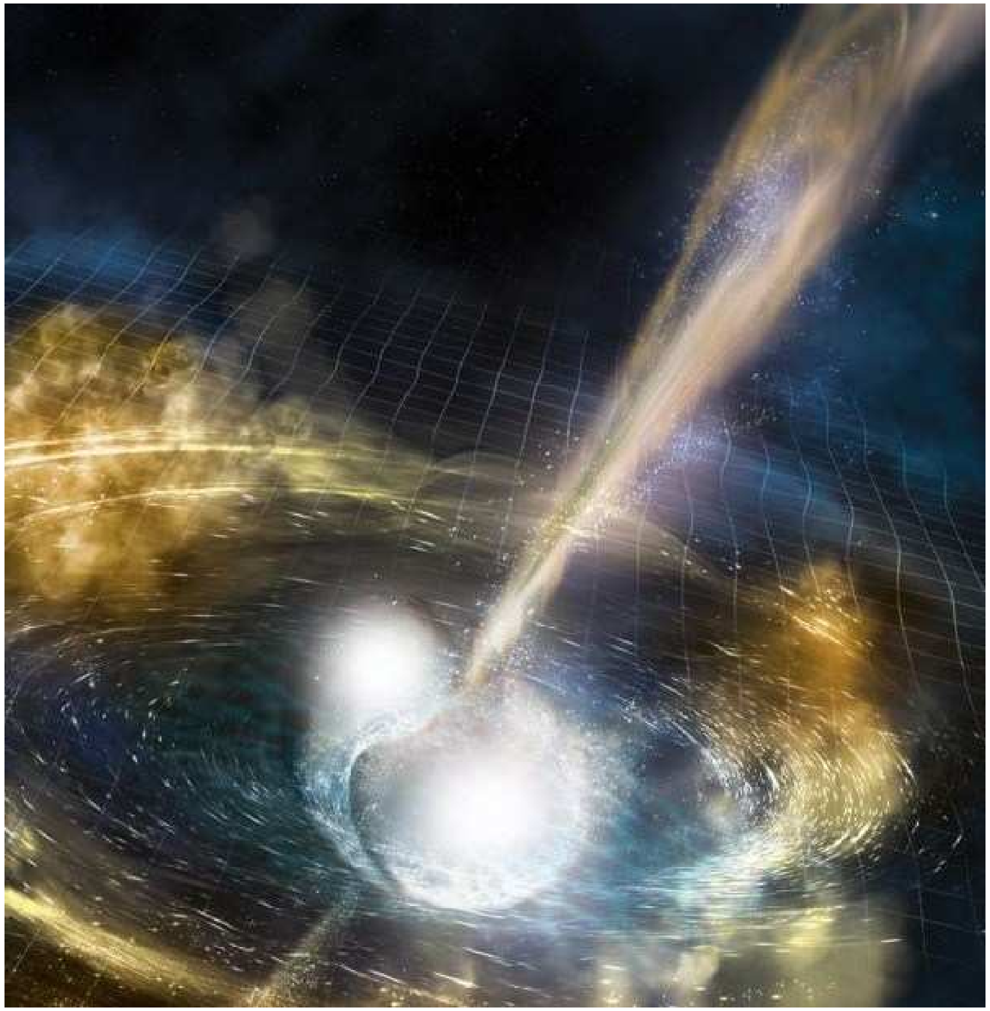


Abbott+ (2017b)

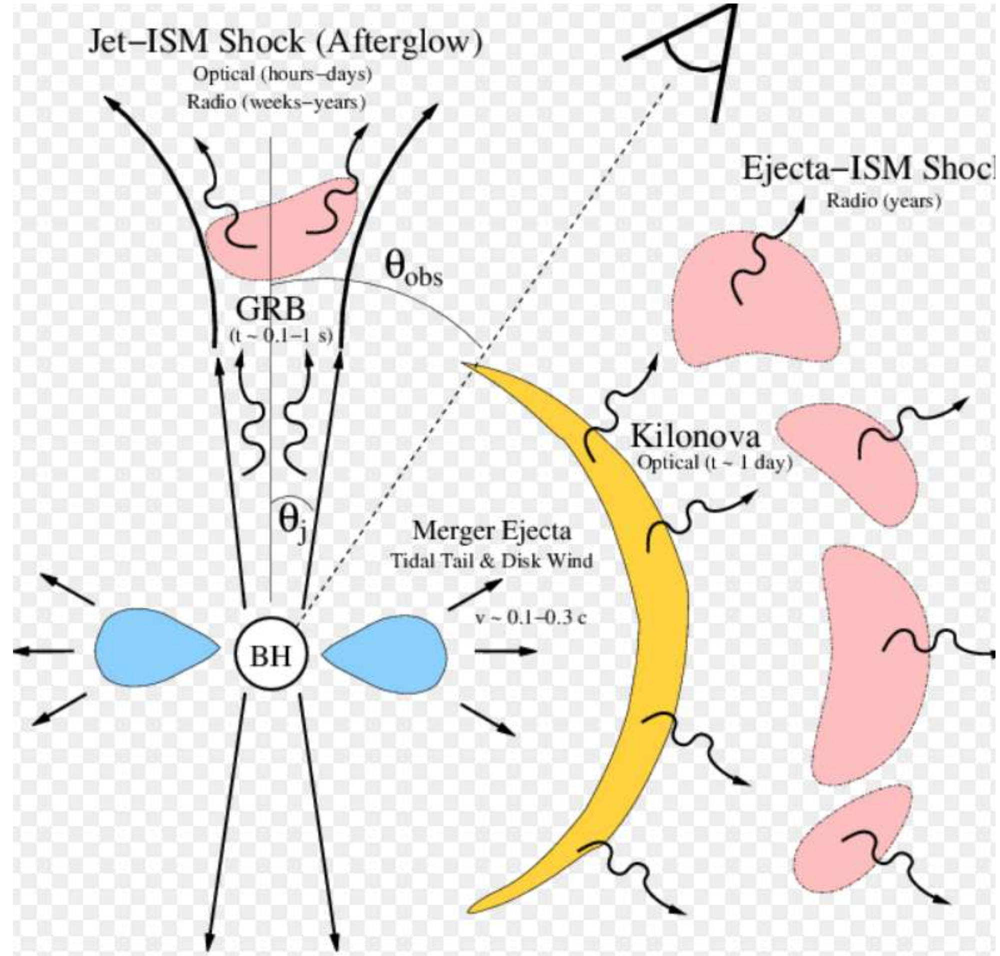
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.



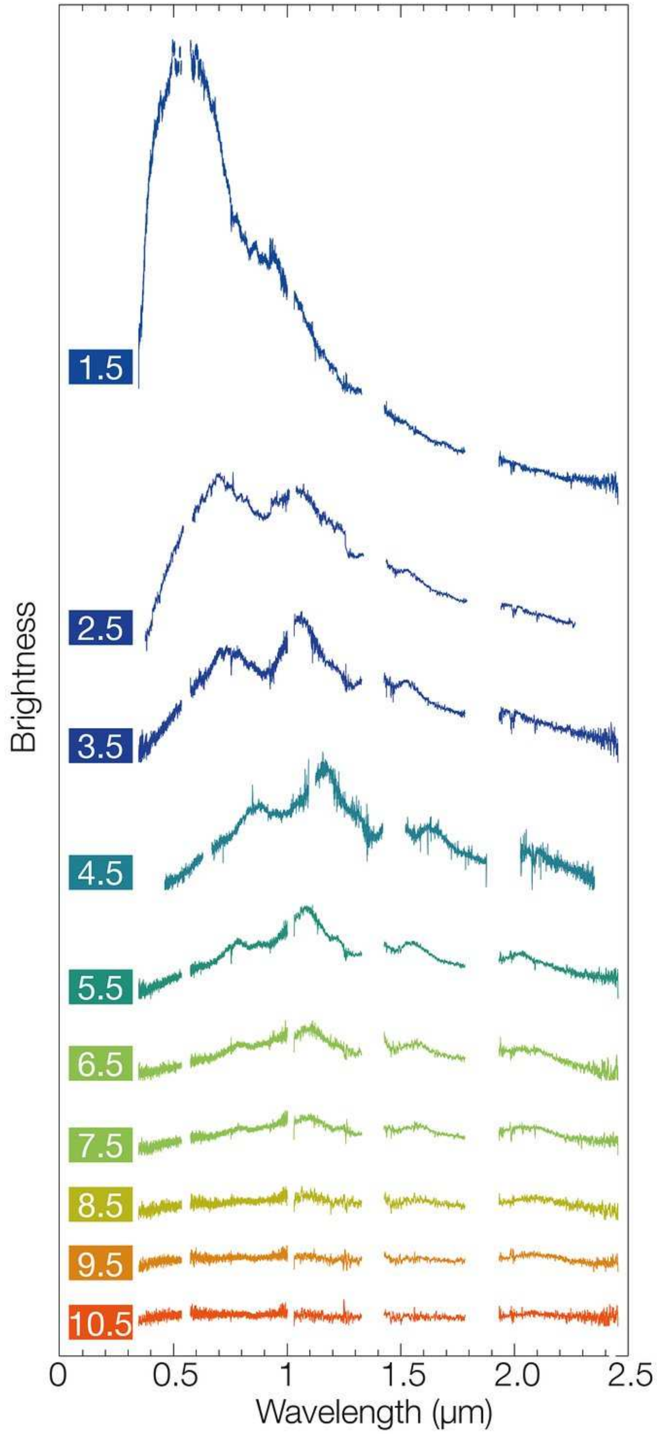
Multi-messenger astronomy (Abbott+ 2017b)



kilonova



Brian Metzger



ESO X-Shooter spectra

GW170817 breakthrough

- spectra require large abundance of neutron-rich heavy elements
- ejecta mass larger than expected: $0.03 - 0.05\,M_\odot$
- neutron-star mergers more common than expected
- consistent with forming all r-process elements in the Universe (preliminary)