Compton Lecture #4: Massive Stars and Supernovae

- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets
    - please fill one out only if you're not already on the Compton Lectures mailing list or need to change your address

Stars: Their Life and Afterlife

Massive Stars and Supernovae

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68th Series, Compton Lecture #4

November 1, 2008

Outline

- Evolution of Massive Stars
- Supernova Zoo
- White dwarfs and thermonuclear supernovae
- Core-Collapse Supernovae

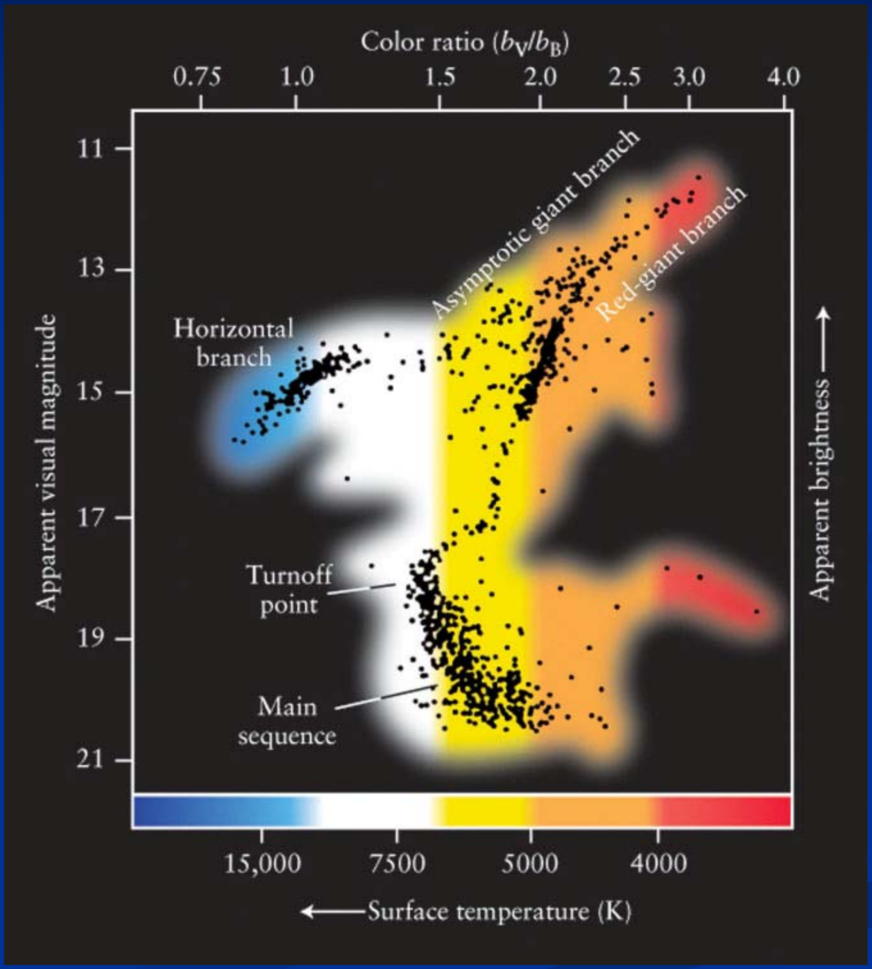
Key Points to Take Away

- Light/moderate mass stars form white dwarfs.
  - Isolated: fusion ends, heat slowly radiates away…
  - Close Binary: mass transfer can cause novae and/or Type Ia Supernovae.
- Runaway fusion reaction powers supernova explosion.
  - (no neutrinos)
- Massive stars burn until they form an iron core.
- Core collapse powers neutrino-driven supernova explosion.
  - $\lesssim$ 1% of energy is transferred from neutrinos into visible supernova!
- SN 1987A confirmed general picture of core-collapse supernovae.
- Both types release as much kinetic energy as Sun releases starlight in its lifetime!

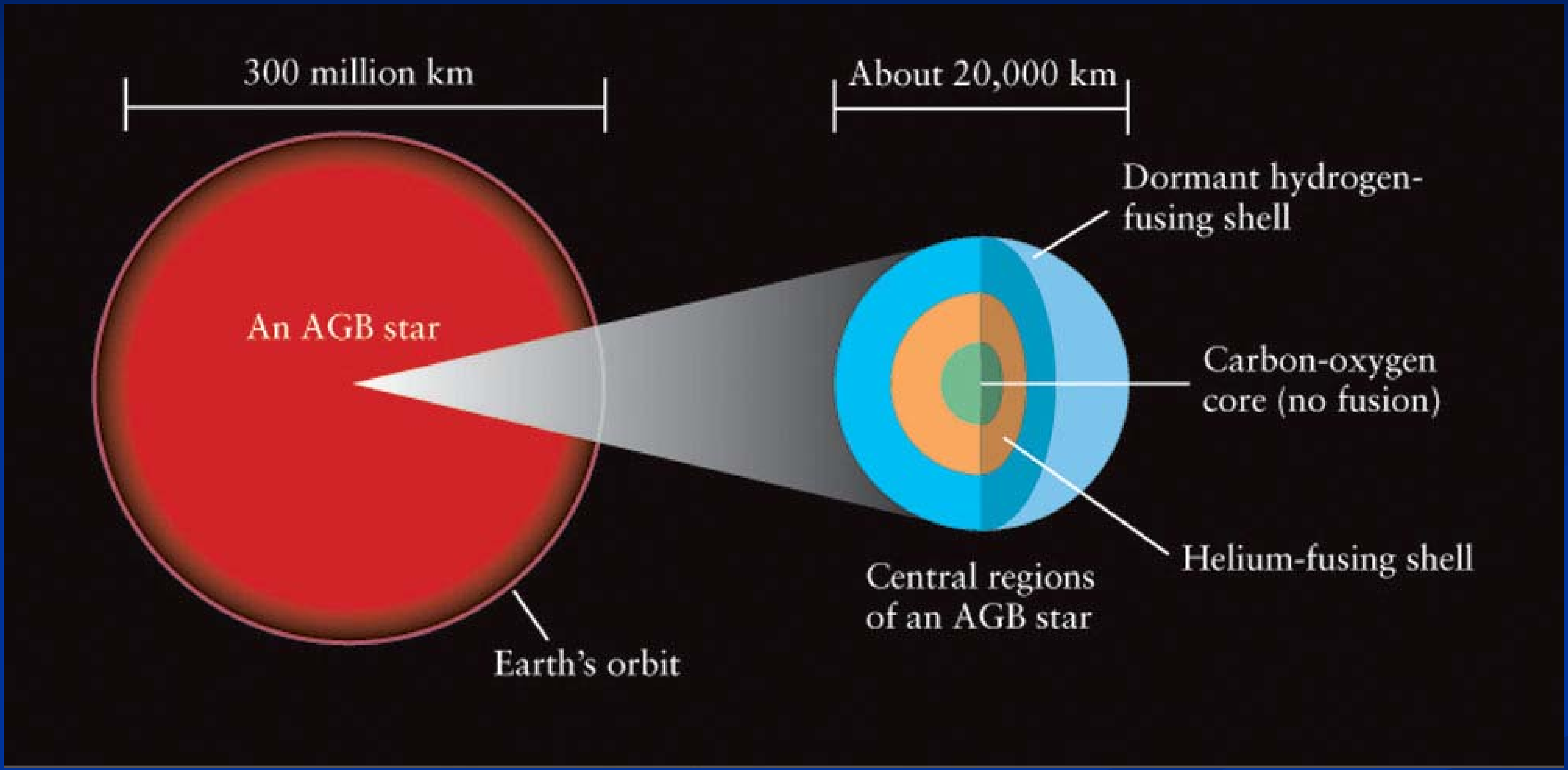
Evolution of Massive Stars

Second Red Giant Stage

- When core supply of ^{4}He runs out, history repeats itself:
- Core contracts until degenerate-electron pressure takes over.
- Fusion in ^{4}He shell.
- Star moves to Asymptotic Giant Branch.



Structure of an Asymptotic Giant Branch Star



Summary of Solar-Mass Stellar Evolution

- Core hydrogen fusion for 12 billion years (main sequence)
- Shell hydrogen fusion for 250 million years (red giant)
- Core helium and shell hydrogen fusion for 100 million years (horizontal branch)
- Shell helium and hydrogen fusion (asymptotic giant phase)
- White dwarf phase, fusion completed

- This series of stages is similar for all stars with initial masses in the range 0.4 – 4.0 $M_{\odot}$.

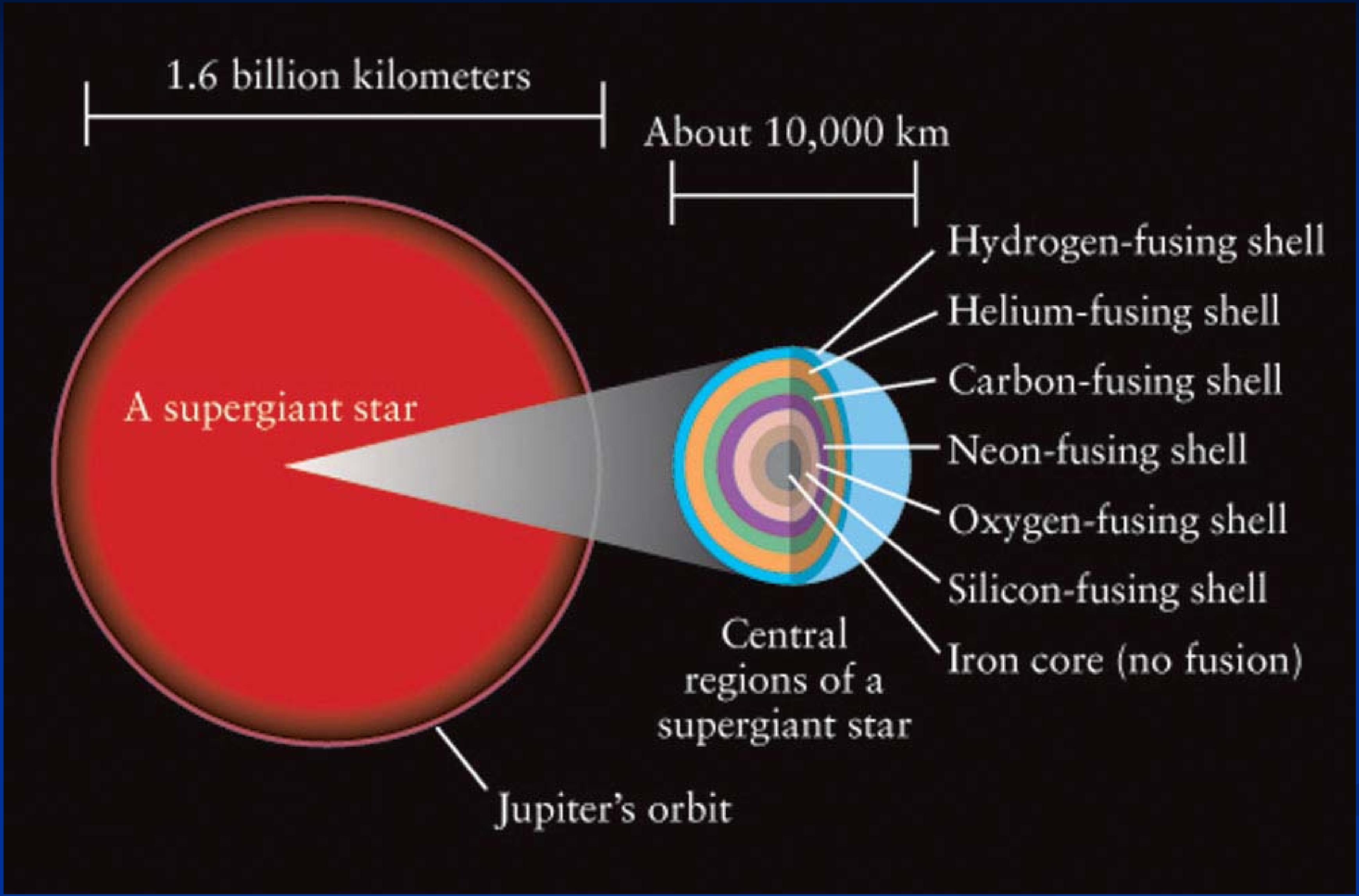
Fusion in Massive Stars

- Massive stars ($\gtrsim 8\ M_\odot$) go through many fusion stages beyond ^4He:
  - For a 25 $M_\odot$ star
  - Compare: water density is 1000 kg/m^3 = $1 * 10^3$ kg/m^3

Fusion Stage	Core Temp (K)	Core Density (kg/m^3)	Duration of Stage	Notes
Hydrogen	$4 * 10^7$	$5 * 10^3$	$7 * 10^6$ years	Main sequence
Helium	$2 * 10^8$	$7 * 10^5$	$7 * 10^5$ years	
Carbon	$6 * 10^8$	$2 * 10^8$	600 years	Neutrino cooling
Neon	$1.2 * 10^9$	$4 * 10^9$	1 year	
Oxygen	$1.5 * 10^9$	$1 * 10^{10}$	6 months	
Silicon	$2.7 * 10^9$	$3 * 10^{10}$	1 day	Produces iron

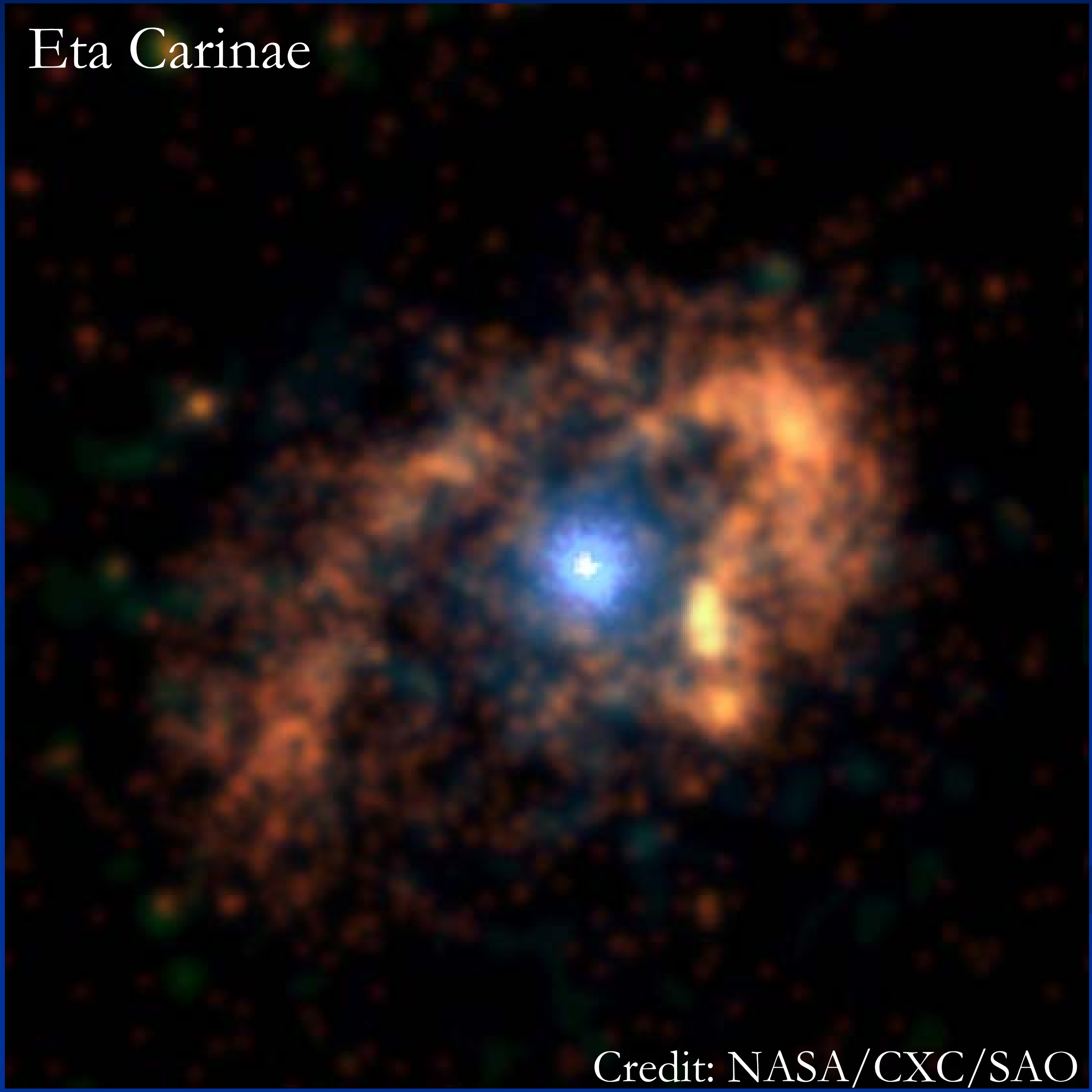
- Stages require increasingly higher temperatures and densities
- Star exhausts each fuel increasingly rapidly
  - less energy yield per reaction
  - energy losses – star gets very luminous in neutrinos!

Heavy Stars as Onions



Stellar Winds, Mass Ejection

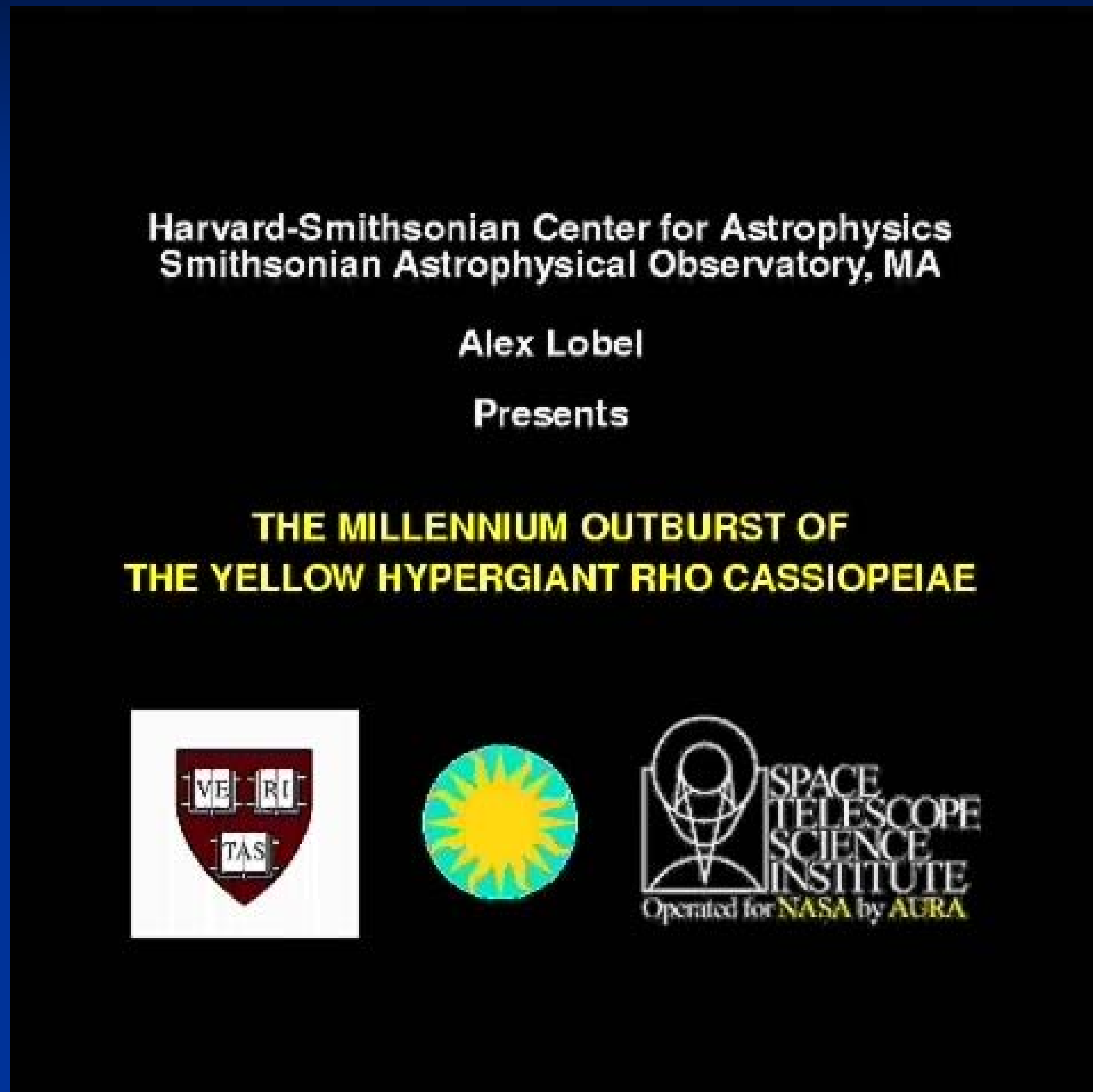
- Late-stage massive stars are unstable, lose mass
  - steady winds: 10^{-4} $M_{\odot}$/yr
  - ejection events
- Eta Carinae shows evidence of past outbursts and a wind
  - ~ 100 – 150 $M_{\odot}$



Credit: NASA/CXC/SAO

ρ Cassiopeiae

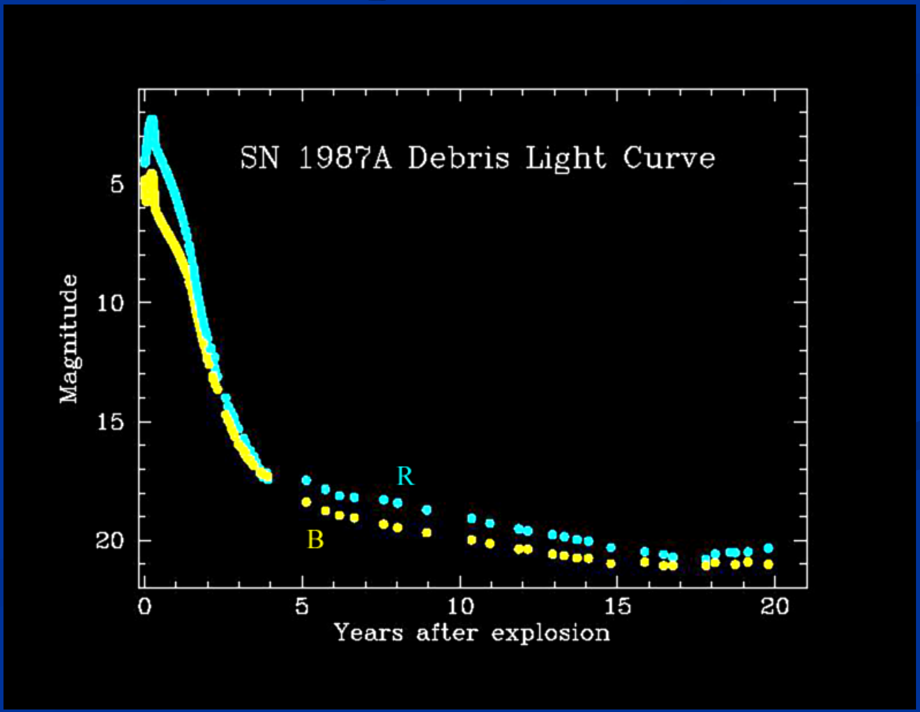
- ρ Cas is a yellow supergiant
  - ~ 40 $M_\odot$
  - SN candidate
  - Major outburst in 2000-2001



Supernova Zoo

Common features of SNe

- Rate: Roughly ~2/century total in our galaxy
- High-speed outflow of majority of star's mass
  - speeds of 10 – 20 million m/s, few % speed of light
- Synthesis of heavy elements
- Radioactive isotopes of heavy elements (especially ^{56}Ni and ^{56}Co) power the emission we see at late times
  - SNe are nonthermal emitters!
- Similar kinetic energy release
  - ~ 10^{51} ergs ≈ Sun's lifetime!
- Understanding SNe relies heavily on simulations!



Differences Amongst Supernovae

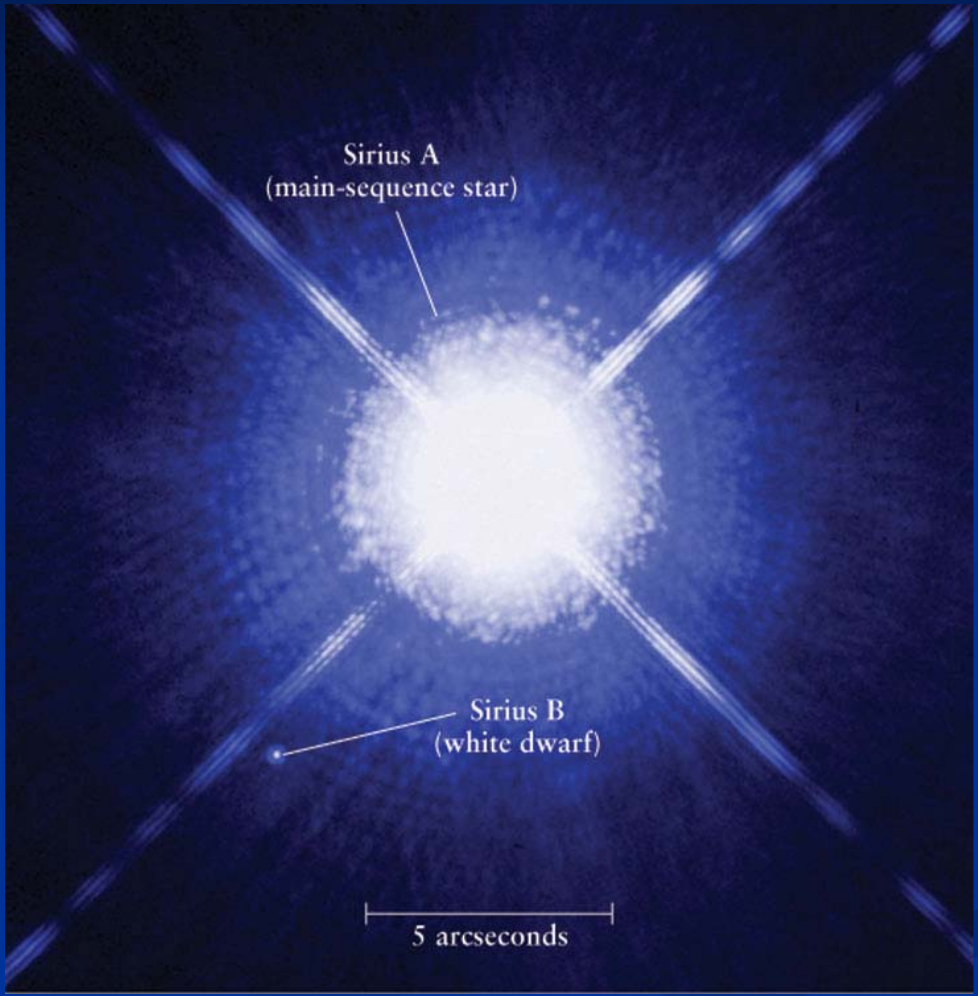
	Thermonuclear	Core Collapse
Progenitor	White dwarf in a binary system	$\gtrsim 8\ M_{\odot}$ star
Location	Anywhere	Star-forming regions
Fraction of SNe	~ 20%	~ 80%
Local Environment	Low-to-average density	Complex
Final Result	Complete disruption	Neutron star or black hole

Also: shape, spectrum of optical light curve varies

White Dwarfs and Thermonuclear Supernovae

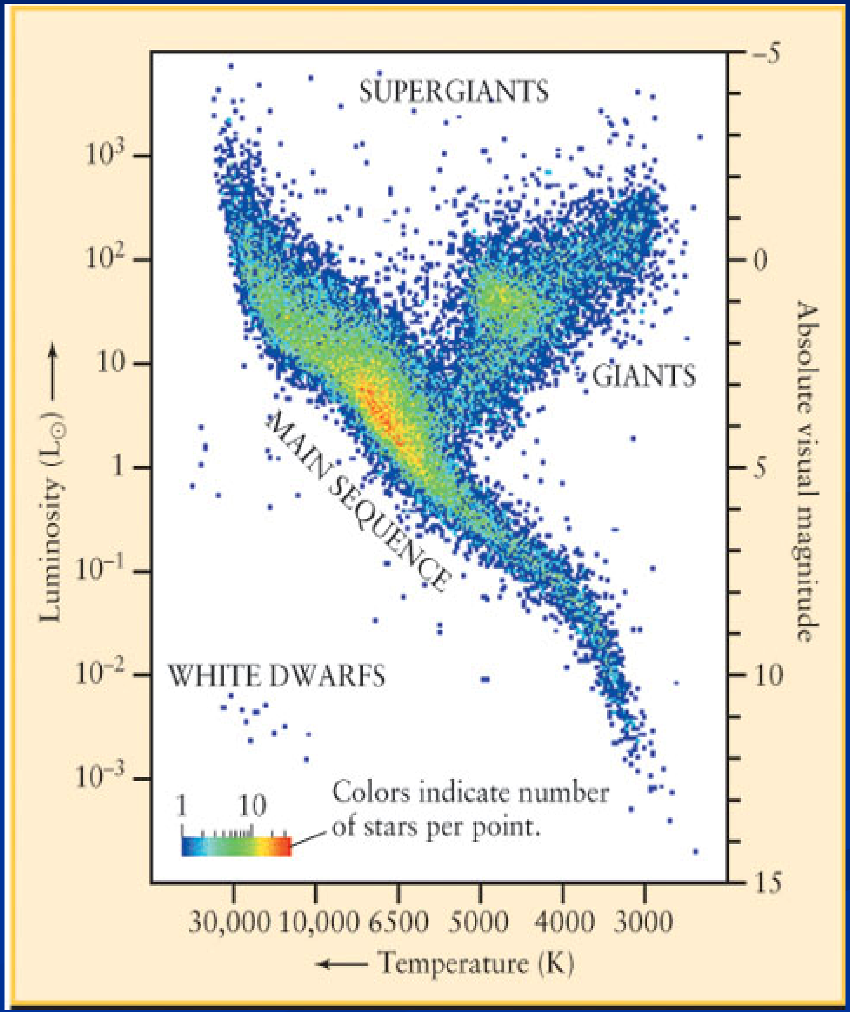
White Dwarf Stars

- Post-fusion, hot core left behind is supported by a degenerate-electron sea.
  - masses $\lesssim 4\ M_\odot$: carbon/oxygen
  - masses $\sim 4 - 8\ M_\odot$: oxygen/neon
- (nearly) The end of their evolution.



White Dwarfs Again – Isolated Evolution

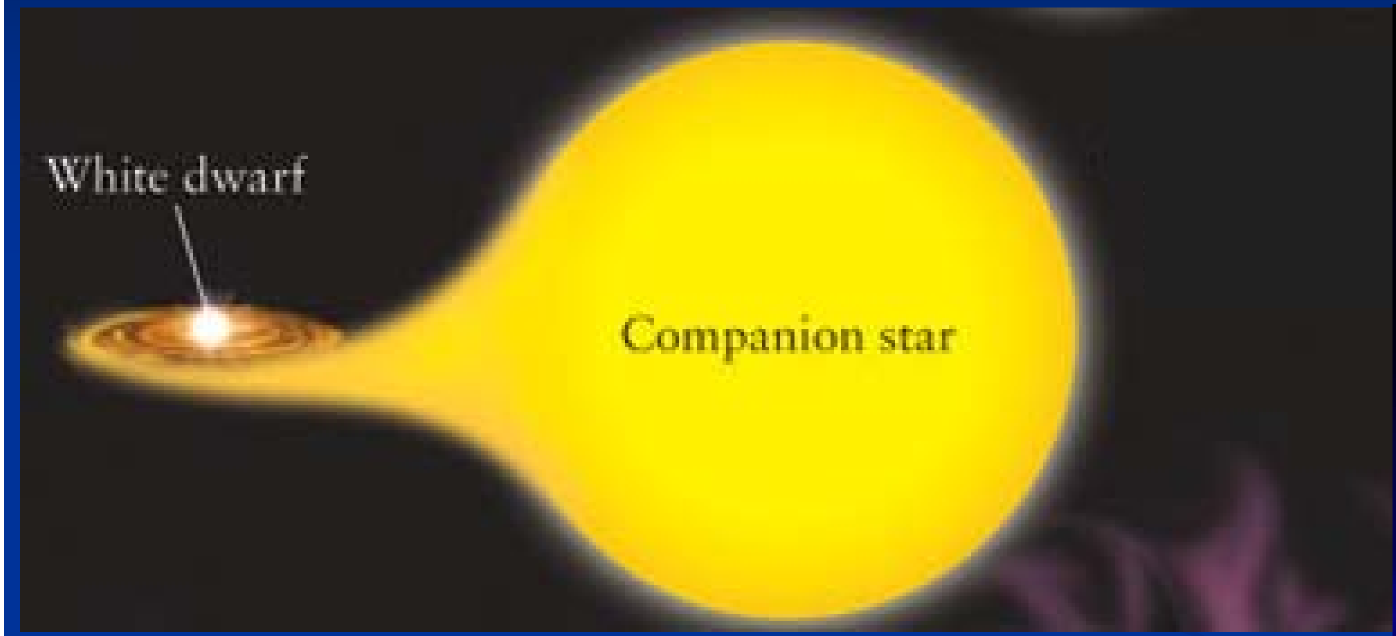
- Slowly radiate away their heat.
- The Sun will eventually form a white dwarf with ~10% its current luminosity, or 0.1 $L_\odot$.
- After 5 Gyr as a white dwarf, the Sun's luminosity will be ~10^{-4} $L_\odot$ and dropping…

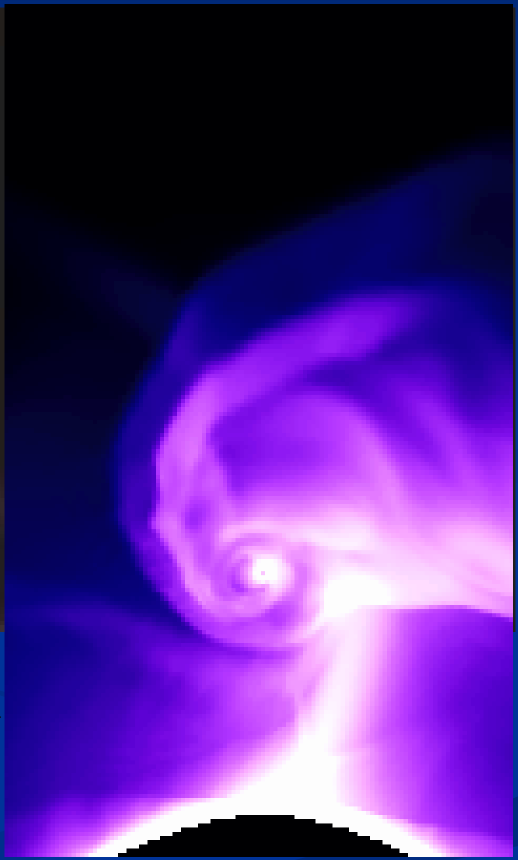


White Dwarfs in Binary Systems

- More massive star evolves more rapidly – becomes a white dwarf first.
- Less massive star evolves along the main sequence, but if the two stars are close enough…

White Dwarfs in Binary Systems

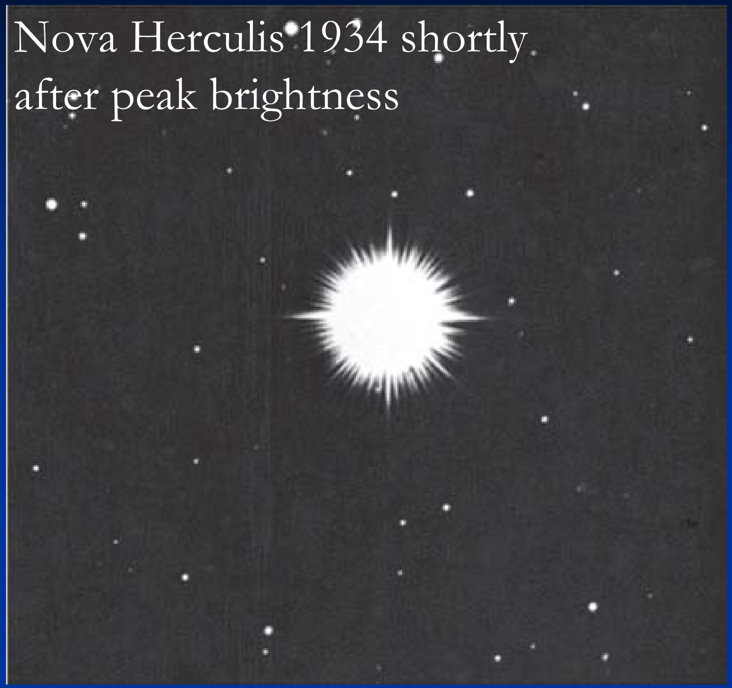




John Blondin, NCSU

- … White dwarf sucks in (accretes) gas from companion, eventually reaching a critical mass.

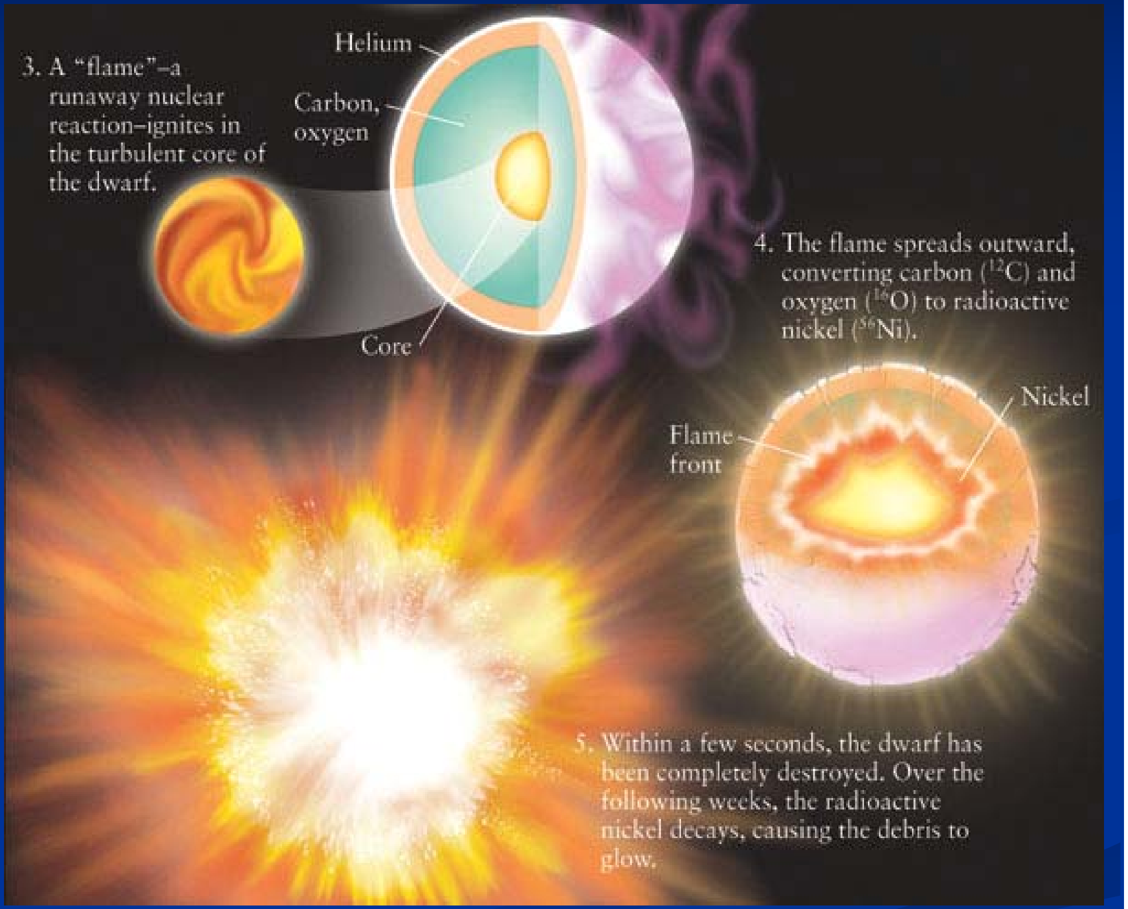
Classical Novae



- Novae occur when a white dwarf accretes hydrogen very slowly from a neighbor.
- At a critical temperature, the entire surface burns at once.
- Novae release as much energy as the Sun does in 1000 years.
- White dwarf and companion survive; repeat performances are possible!

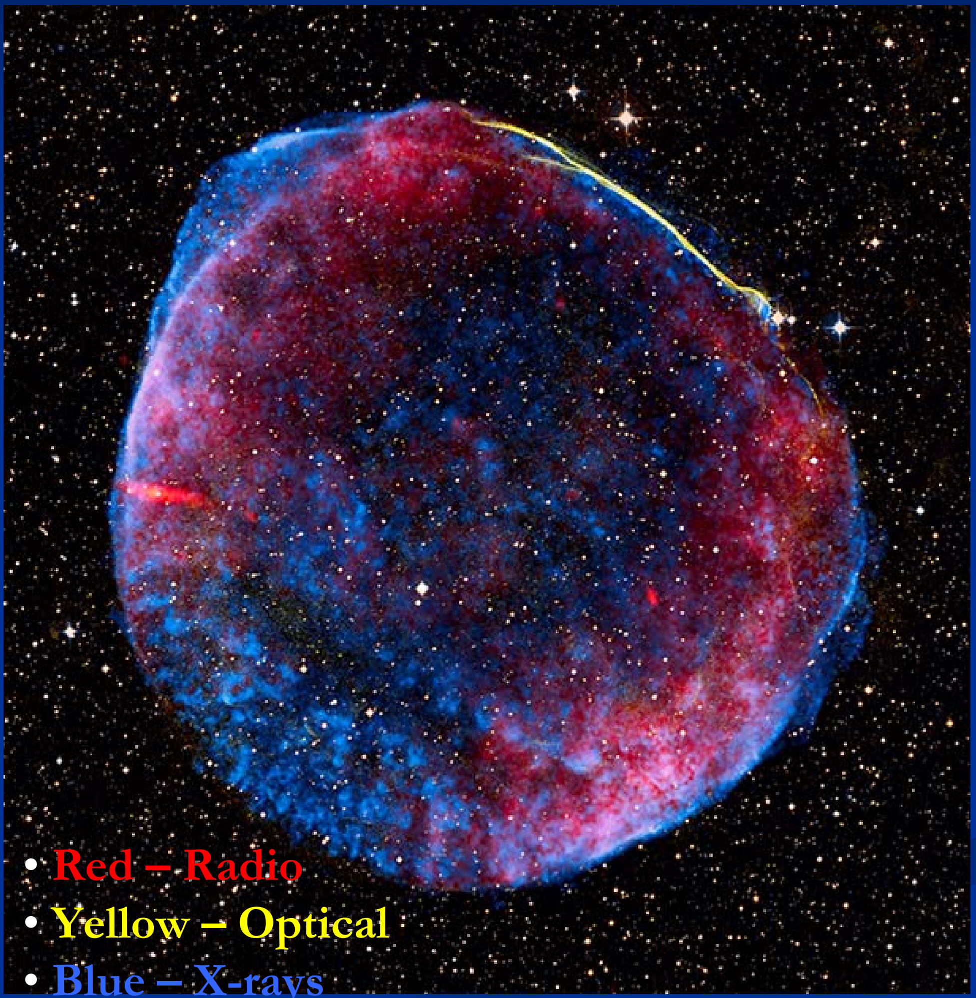
Type Ia Supernovae

- Similar mechanism to Novae, details still unclear.
  - Mass accretion till near Chandrasekhar limit.
- Runaway fusion in carbon/oxygen core (similar to helium flash)
- 10 million times more energetic than a nova.
  - Equal to lifetime output of Sun
  - White dwarf is completely destroyed



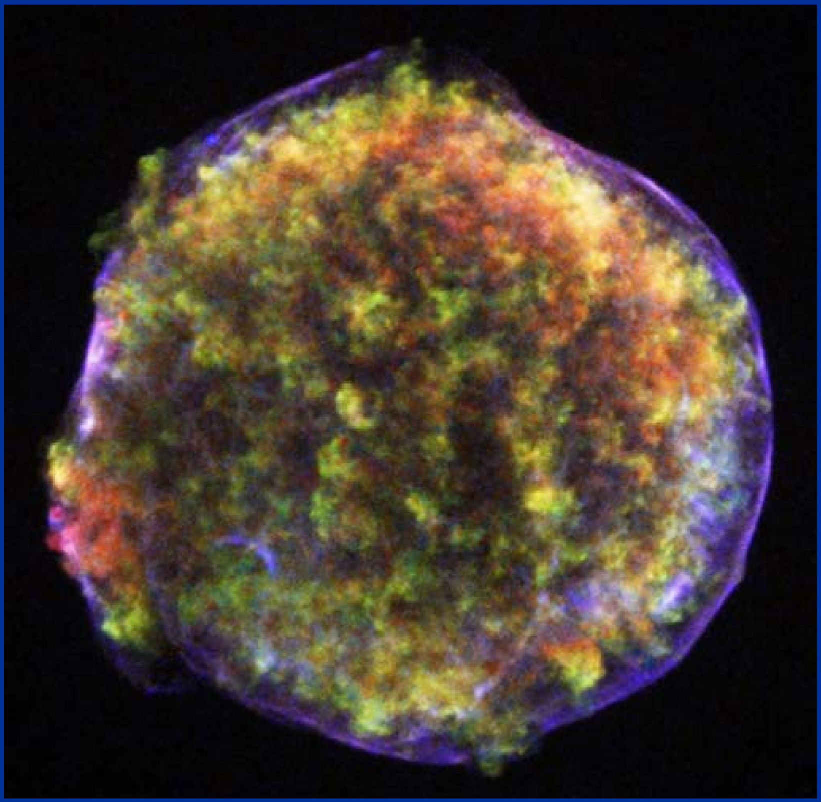
Remember SN 1006?

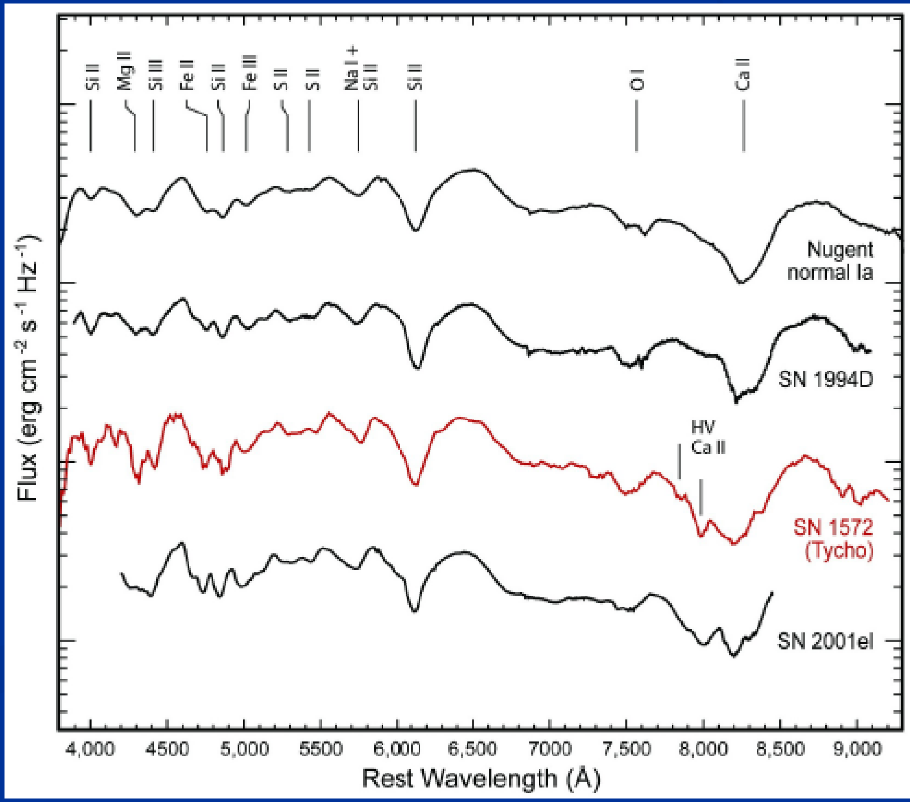
- Young – only 1002 years
- Type Ia
  - no compact remnant detected
  - no companion star detected either
- Nearly uniform low-density environment
  - nearly symmetrical development (except NW)
  - no nearby star formation



Tycho's Supernova

- Similar to SN 1006 in a lot of ways
  - Young, observed by Tycho Brahe in 1572, low-density medium
- Recently confirmed as Type Ia by observing reflections of its original explosion!





Type Ia Supernovae as Standard Candles

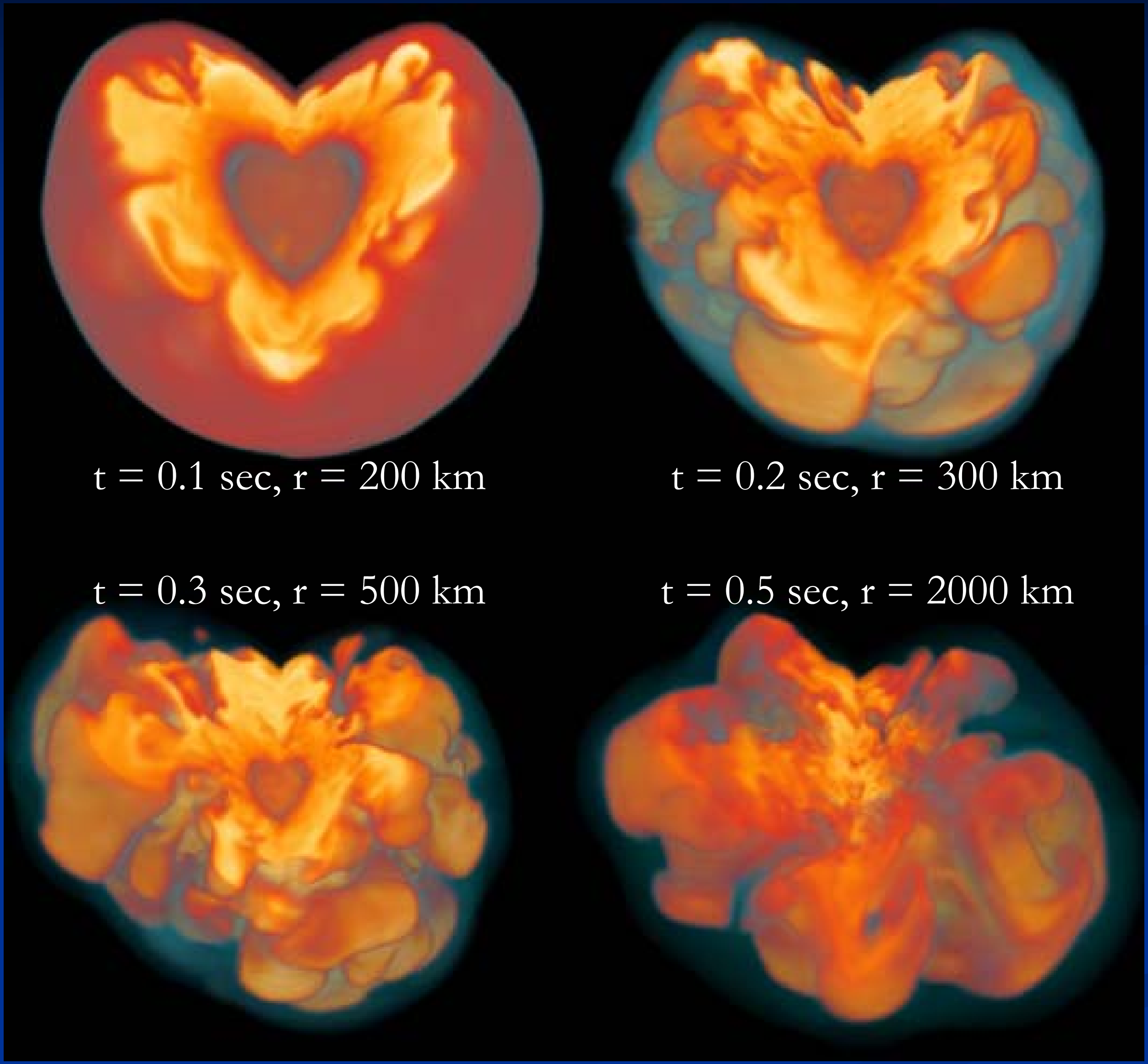
- Some SN Ia occur in nearby galaxies where we can measure distance accurately by other means – calibrating distance/brightness scale
- Then can use SN Ia to measure distance to farther galaxies.
- Independently measure redshift using spectral lines.
- Comparison measures expansion history of the universe – provided first indication that expansion of universe is accelerating!
  - confirmed by measurements of CMB, large-scale structure
  - but identity of the "dark energy" driving this acceleration remains a mystery

Core-Collapse Supernovae

What happens when the burning ends?

- Core cools rapidly
  - neutrino cooling
  - lose degeneracy pressure: $e + p \rightarrow n + \nu$
- Free fall inward in ~ 0.25 seconds at 25% speed of light
  - Gravity unleashed: collapse from earth-size to ~ 30 km radius!
- "Bounce"
  - inner core becomes rigid at nuclear density
    - proto-neutron star
  - outer core bounces off
  - outgoing shockwave heats infalling matter, dissipates
- Neutrinos + convection revive outgoing shockwave
  - outer layers blown off – explosion!
  - 25-$M_{\odot}$ star: over 90% of mass ejected

Boom.



Woosley and Janka, arXiv:astro-ph/0601261

Core Collapse and Explosion: the Movie

- Credit: NASA/CXC/D.Berry

Supernova Animation – Outside View

- NASA HEASARC
  - http://heasarc.gsfc.nasa.gov/docs/snr.html

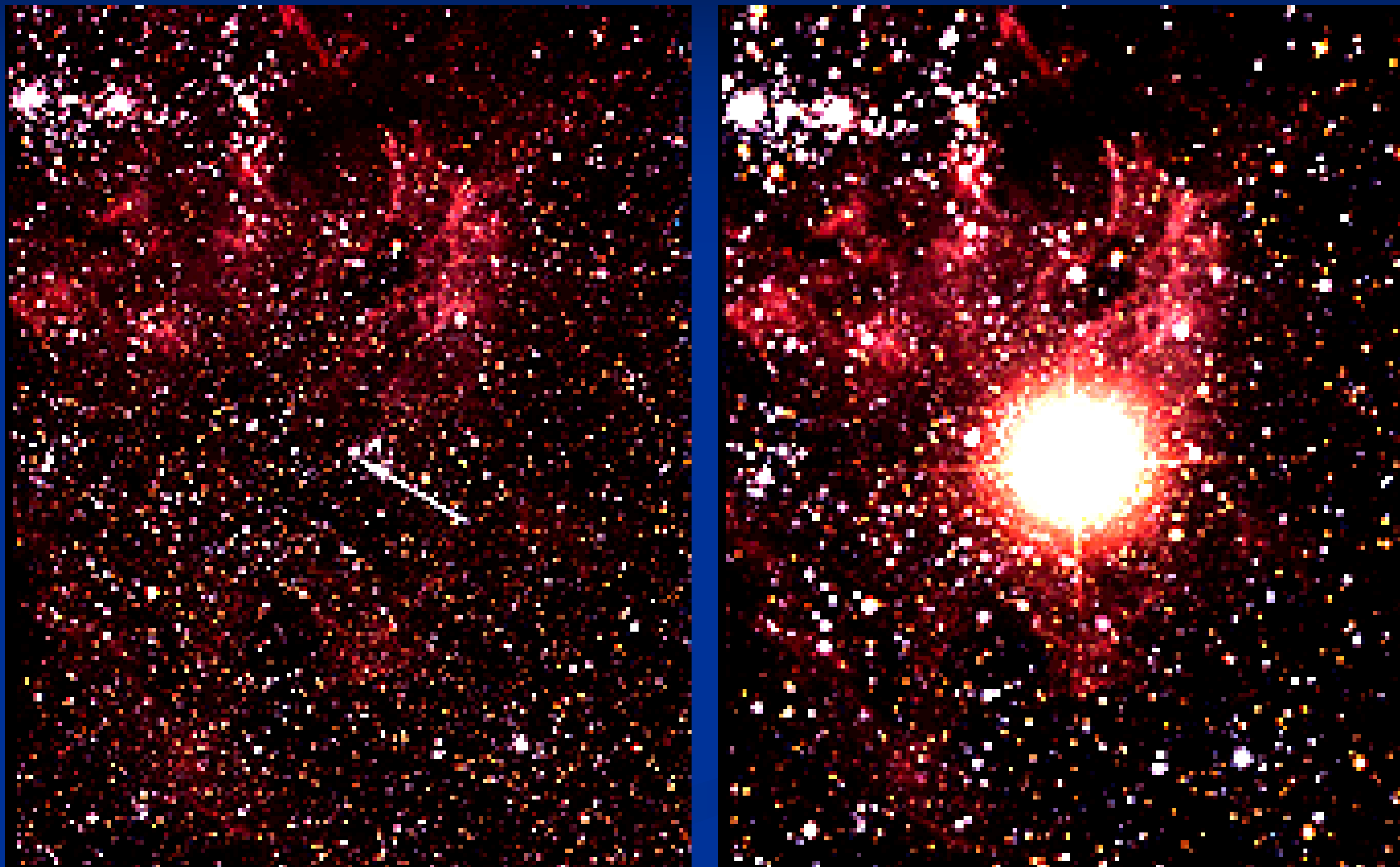
How does the Explosion *Explode?*

- Powered by gravitational potential energy released by *core*.
- Basic picture validated by SN 1987A.
- Detailed understanding requires detailed computer models:
  - Nuclear reactions, convection, rotation, magnetic fields….

- If proto-neutron star cools and/or accretes matter too quickly, it collapses → black hole
  - No explosion!
  - Otherwise, condenses into neutron star, ~ 10-km radius
- Can also form a black hole post-explosion
  - as matter falls back onto neutron star

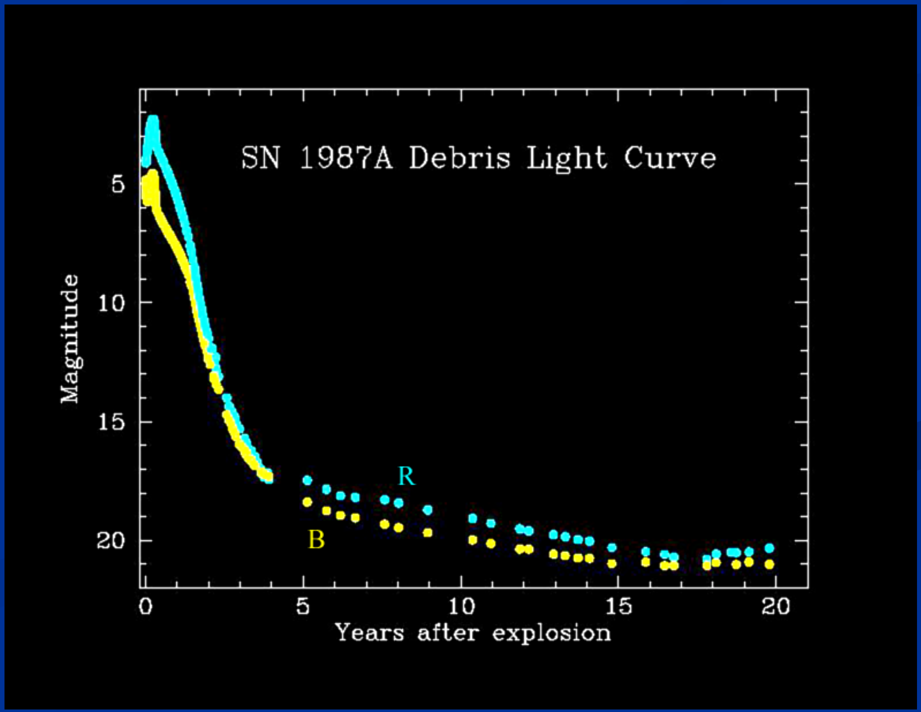
SN 1987A Before and After

- http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html



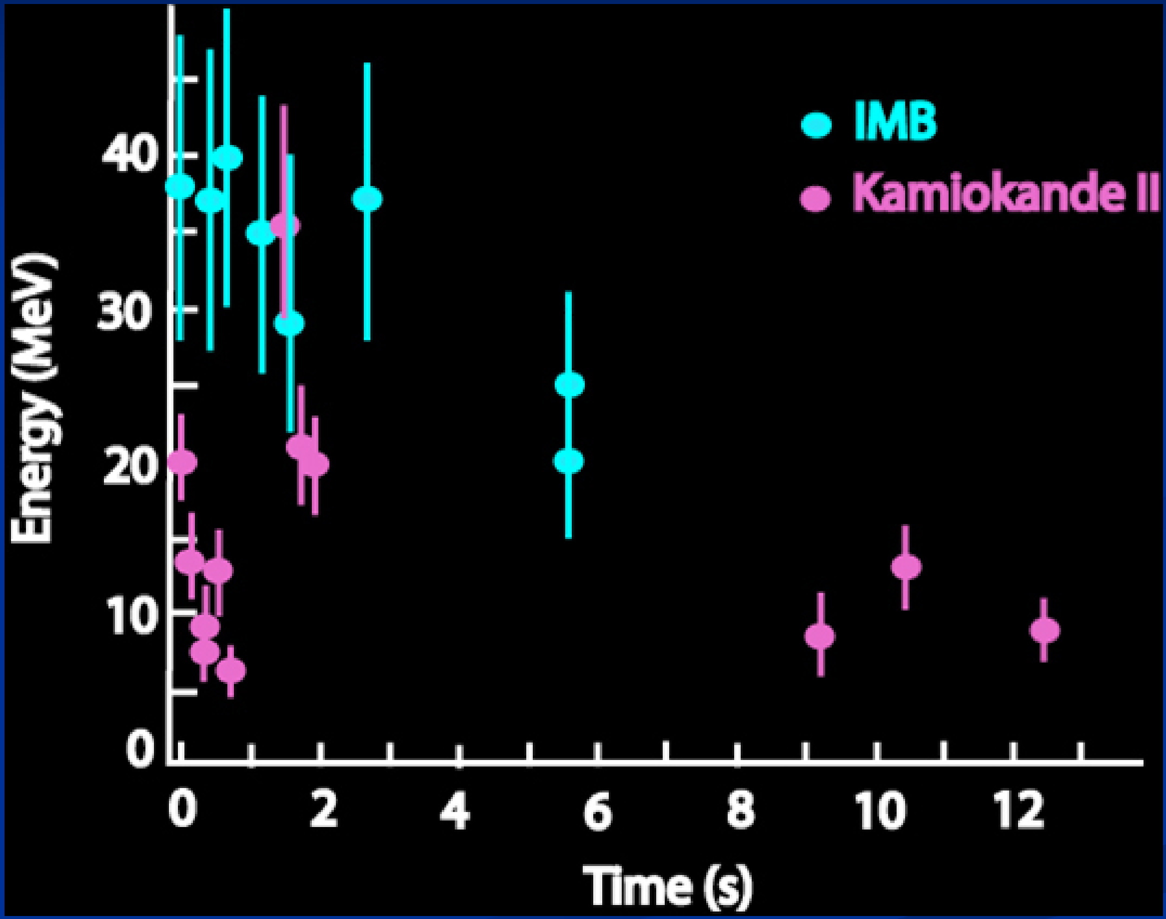
SN 1987A

- Core collapse of a massive star
- Progenitor was Sanduleak -69 202, in the Large Magellanic Cloud
  - 160,000 light years distant
  - discovered by Shelton, Duhalde, and Jones on Feb 23, 1987
  - surprisingly, a blue supergiant instead of red
  - mass ~ 20 $M_\odot$ prior to supernova
- Optical light curve dimmer than expected
  - but explained by progenitor



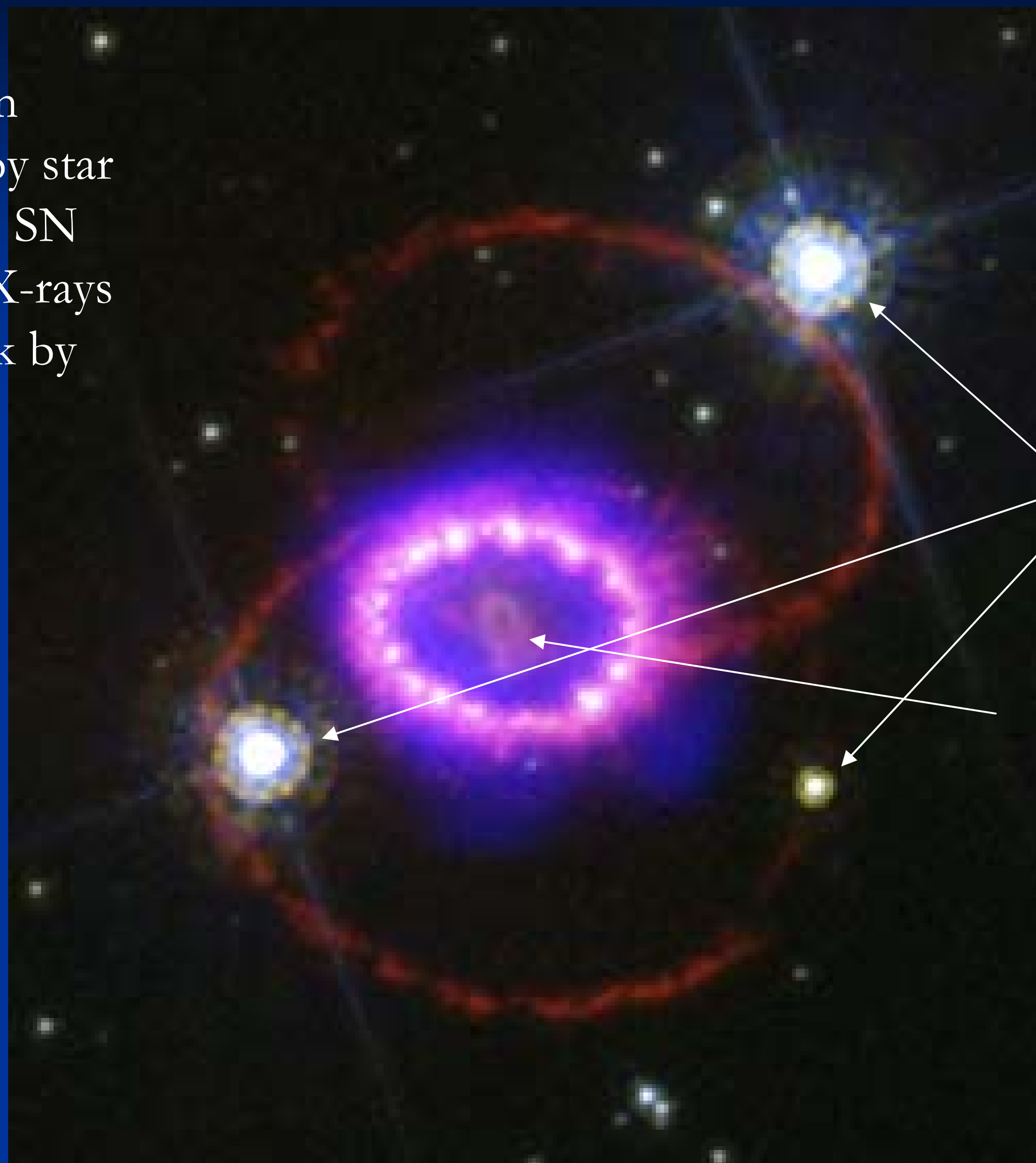
SN 1987A in Neutrinos

- Two neutrino detectors saw a total of 19 neutrinos
  - exactly consistent with theory!
  - → $3 * 10^{53}$ ergs released by SN in neutrinos
  - $1.5 * 10^{51}$ ergs released in kinetic energy
- Neutrinos arrived ~ 3 hrs before optical SN began
- Today, bigger/better neutrino detectors wait for the next supernova!



SN 1987A Today

Three-ring system
- matter ejected by star 10-20kyr before SN
- ionized by SN X-rays
- inner ring struck by shock wave



foreground stars

Center: no neutron star seen yet
- obscured?
- too dim to see?
- black hole?

Summary

- Light/moderate mass stars form white dwarfs.
  - Isolated: fusion ends, heat slowly radiates away…
  - Close Binary: mass transfer can cause novae and/or Type Ia Supernovae.
- Runaway fusion reaction powers supernova explosion.
  - (no neutrinos)
- Massive stars burn until they form an iron core.
- Core collapse powers neutrino-driven supernova explosion.
  - $\lesssim$ 1% of energy is transferred from neutrinos into visible supernova!
- SN 1987A confirmed general picture of core-collapse supernovae.
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- Next week: Following the supernova remnant – where does all that energy go and how does it affect the interstellar environment?