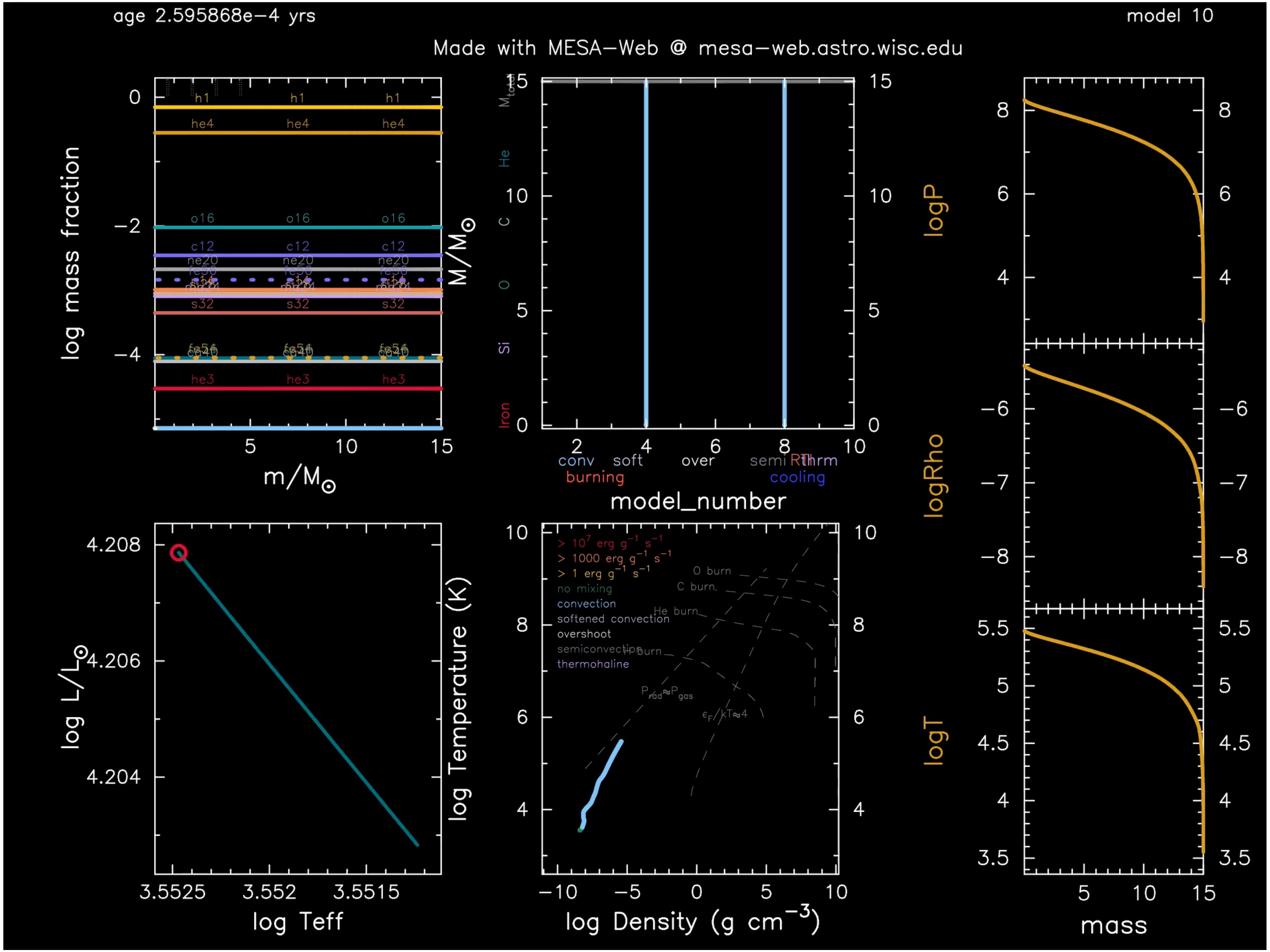
Core Collapse Supernovae and Neutron Stars

Zingale



15 $M_\odot$

Massive Star Evolution

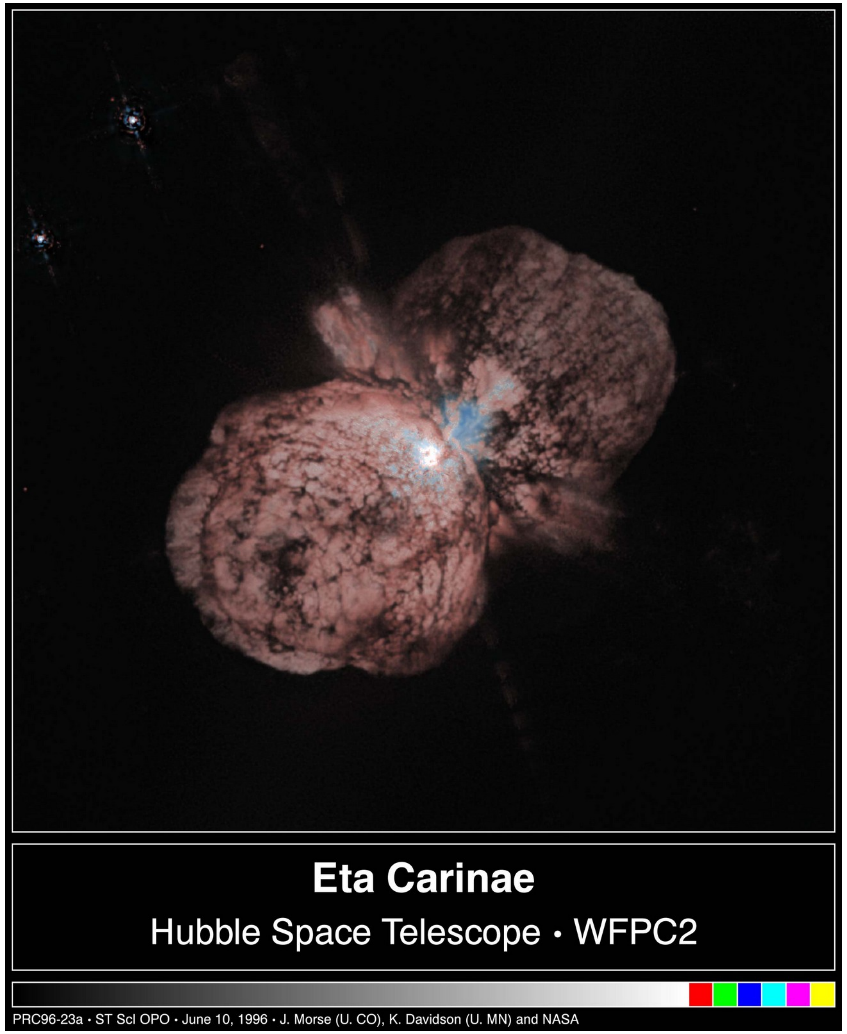
- $M > 10\ M_\odot$ ignite He and C under non-degenerate conditions
  - Electrons in core do not become degenerate until final burning stages with iron core
- Mass loss is important throughout evolution (including MS)
- Luminosity is near Eddington and remains roughly constant
  - Evolution on HR is horizontal
  - Shifts between low and high T occur when core burning begins / ends
- Stars $> 30\ M_\odot$ have very strong winds
  - Mass loss timescales shorter than main sequence lifetime—has dynamical impact
  - Mass loss is parameterized in stellar evolution codes—there is a lot of uncertainty
  - Evolution of these high mass stars converge to $\sim 30\ M_\odot$

Wolf-Rayet Stars

- Most massive stars lose H envelopes during MS phases
- Luminous, H depleted, high mass loss stars: Wolf-Rayet
  - Bare cores of stars initially more massive than 30 $M_{\odot}$

Potential Progenitors

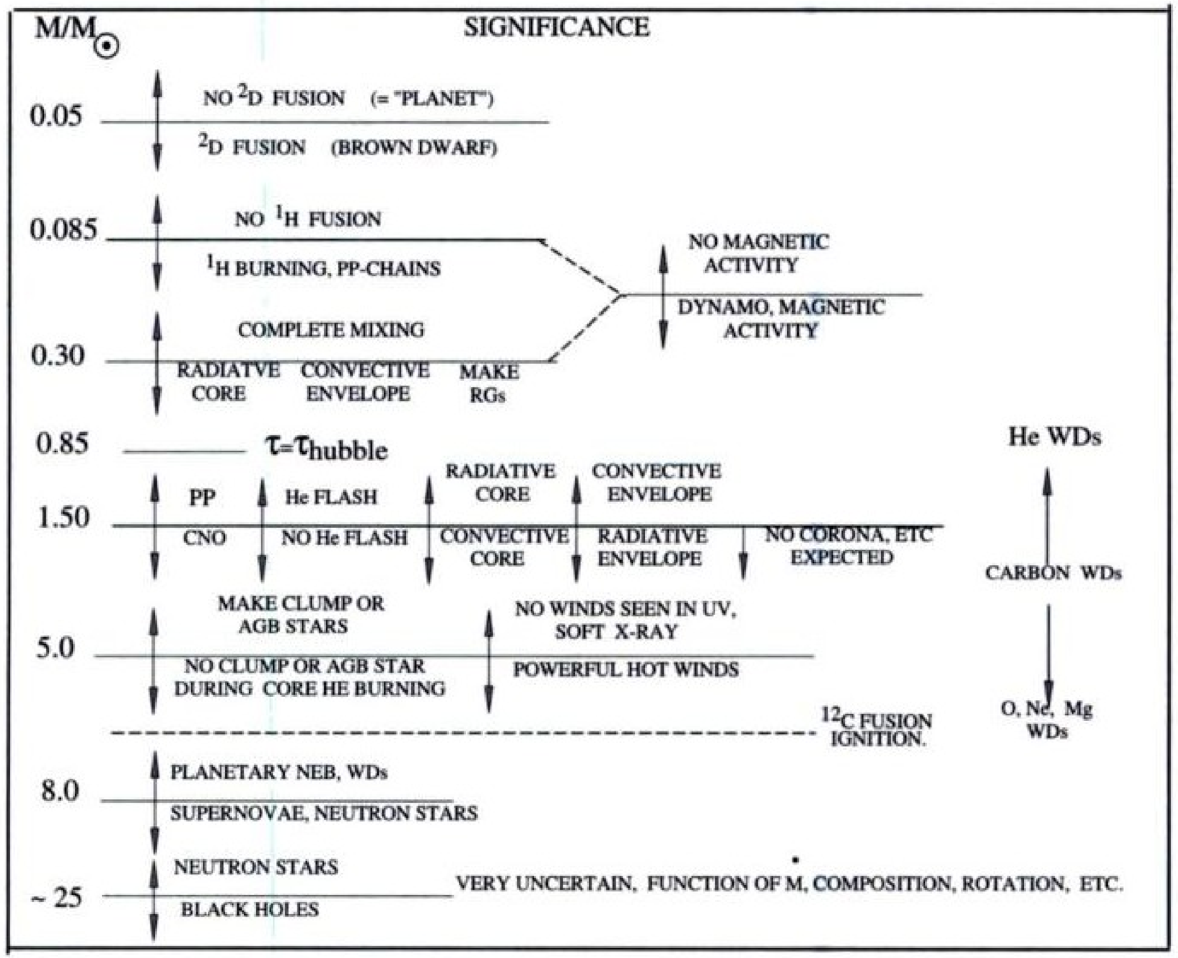
- Eta Carinae
  - > 100 solar mass star
  - 7000-8000 ly away
  - 2nd brightest star in the sky in 1843



http://antwrp.gsfc.nasa.gov/apod/ap060326.html

Mass Cuts

- Mass plays a big role in the outcome of stellar evolution

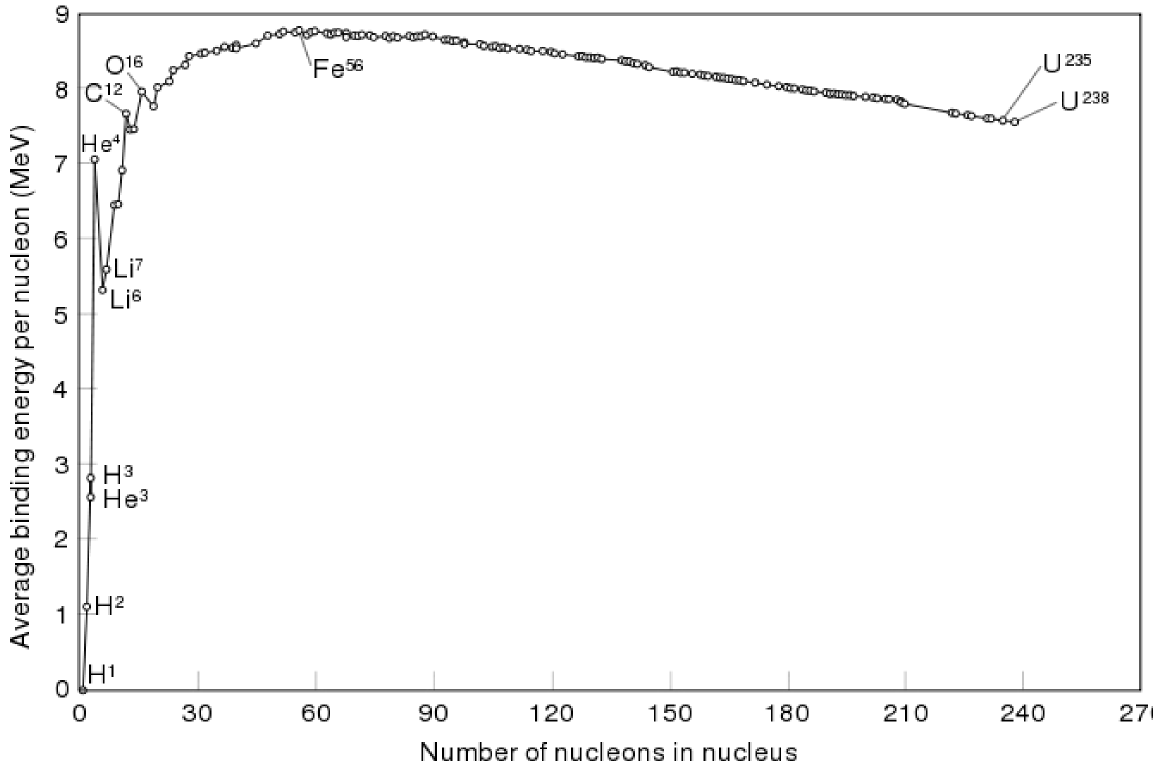


(Hansen, Kawaler, Trimble)

Fig. 2.4. Our "Mass Cut" diagram showing the fate of single stars in various mass classes. See text.

High Mass Evolution

- Evolution of higher mass stars
  - Burning can continue for stars with M > ~8 $M_\odot$
  - Lifetimes are VERY short
  - Remember: most of the energy available comes from H burning



(Wikipedia/Fastfission)

High Mass Evolution

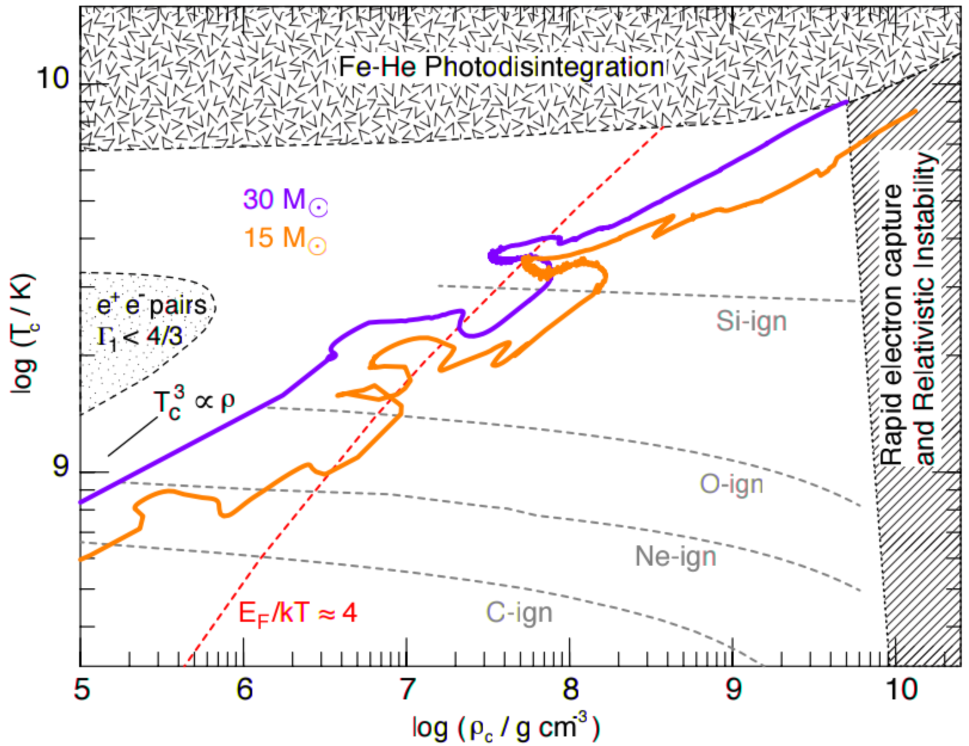


Figure 24. Evolution of T_c and ρ_c in solar metallicity, non-rotating $M_i = 15$ and 30 $M_\odot$ pre-supernova models. The curves are calculated using an in-situ 204 isotope reaction network. Locations of the core carbon, neon, oxygen, and silicon ignition are labeled, as is the scaling relation $T_c^3 \propto \rho_c$, and the $E_F/k_BT \approx 4$ electron degeneracy curve. Regions dominated by electron-positron pairs, photodisintegration, and rapid electron capture are shaded and labeled.

- Core evolution follows (roughly), $T^3 \sim \rho$
  - This is what we found with polytropes from the Eddington standard model
- Neutrino losses become important
  - Photo-neutrinos, plasma-neutrinos, pair-annihilation neutrinos
  - At T > 5×10^8 K, this dominates energy losses
  - Burning ignites where $\varepsilon_\nu \sim \varepsilon_{nuc}$
- Burning from C to Fe core is so fast that the outer layers don't really have time to adjust
  - We'll be mostly stationary on the HR diagram

(Paxton et al. MESA III paper)

Burning Lifetimes

- Lifetimes can be estimated using the energy generate rate where $\varepsilon \sim \varepsilon_{nuc}$

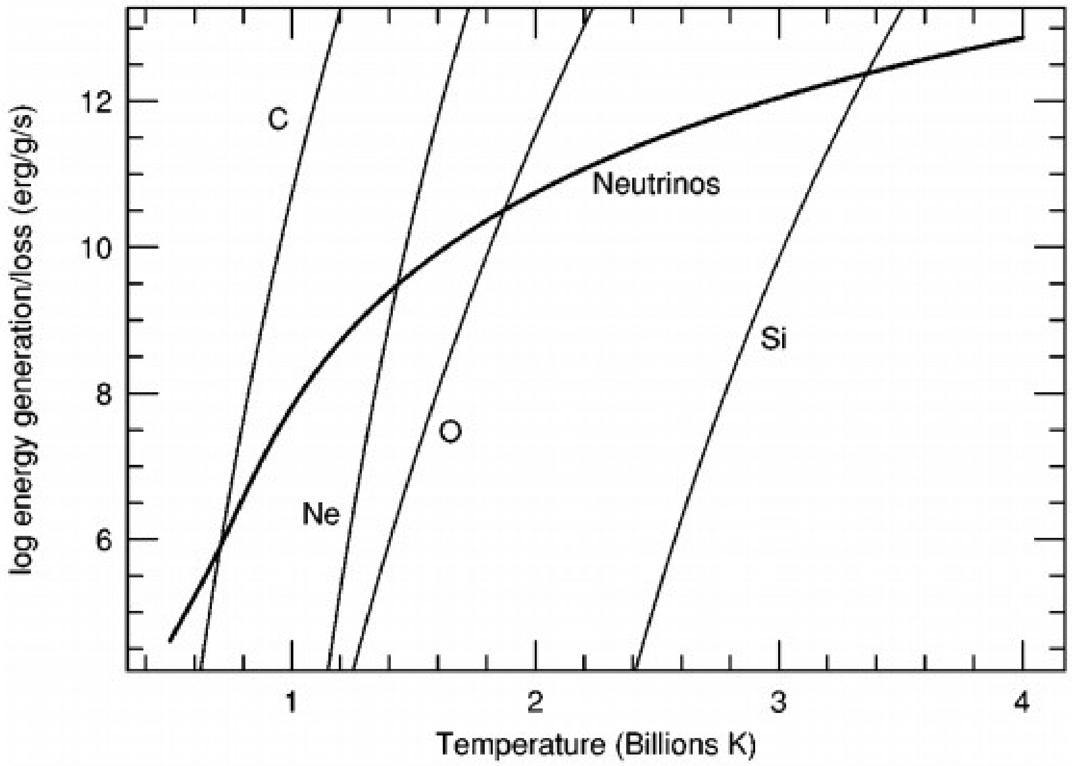


Figure 12.6. Energy generation rate and neutrino loss rate during the advanced evolution of a massive star. The stellar center is assumed to follow a track approximating that shown in Fig. 12.5. The intersections of the nuclear burning lines with the neutrino loss line define the burning temperature of the corresponding fuel. Figure from Woosley, Heger & Weaver (2002). (via Onno Pols notes)

High Mass Evolution

core burning state	*9 $M_\odot$ star*	*25 $M_\odot$ star*	*core temperature*
H burning	20 million years	7 million years	(3-10) $\times 10^7$ K
He burning	2 million years	700,000 years	(1-7.5) $\times 10^8$ K
C burning	380 years	160 years	(0.8-1.4) $\times 10^9$ K
Ne burning	1.1 years	1 year	(1.4-1.7) $\times 10^9$ K
O burning	8 months	6 months	(1.8-2.8) $\times 10^9$ K
Si burning	4 days	1 day	(2.8-4) $\times 10^9$ K

(table from Hester et al. Ch. 17)

C Burning

- Primary reactions:

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{23}\text{Na} + {}^{1}\text{H}$$
$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{20}\text{Ne} + {}^{4}\text{He}$$

- Less likely (due to structure of Mg nuclear levels)

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{24}\text{Mg} + \gamma$$

- Note that these are extremely T sensitive
  - Also note that electron screening can be important at high densities

- Transport:
  - Convective core in stars with M < 20 $M_\odot$
  - Radiative in higher mass cores (because initial C abundance is smaller, neutrinos carry a lot of energy)
- C exhaustion followed by core contraction + C shell burning

Ne / O Burning

- Neon burning follows (not O!)
  - Carbon burning makes lots of ^{20}Ne
  - Photodisintegration important → ^{20}Ne can α-capture

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}$$

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

  - Lots of ^{16}O builds up
  - Core is always convective
  - Shell burning follows (timescale short now: not significant burning in the shell)

- Oxygen burning primarily makes ^{28}Si and ^{32}S
  - Many n-rich isotopes are also produced
  - Si-S core has n/p > 1 ($\mu_e > 2$)

Si Burning

- Silicon burning is more complex
  - Coulomb barrier to large to directly fuse 2 ^{28}Si nuclei
  - Photodisintegration starts to occur
    - Photon energies ~ binding energy / nucleon—nuclei can break apart
  - Nuclear statistical equilibrium results
    - Burning proceeds by alpha-captures
    - Balance of forward and inverse reactions
    - Small imbalance leads to production of iron-group nuclei
    - Saha-like equation → most abundant nuclei have lowest binding energy
    - Neutron excess also dictates the products

High Mass Evolution

- Evolution of higher mass stars
  - Evolution of outer layers is pretty much decoupled from what's happening in the core (too fast)

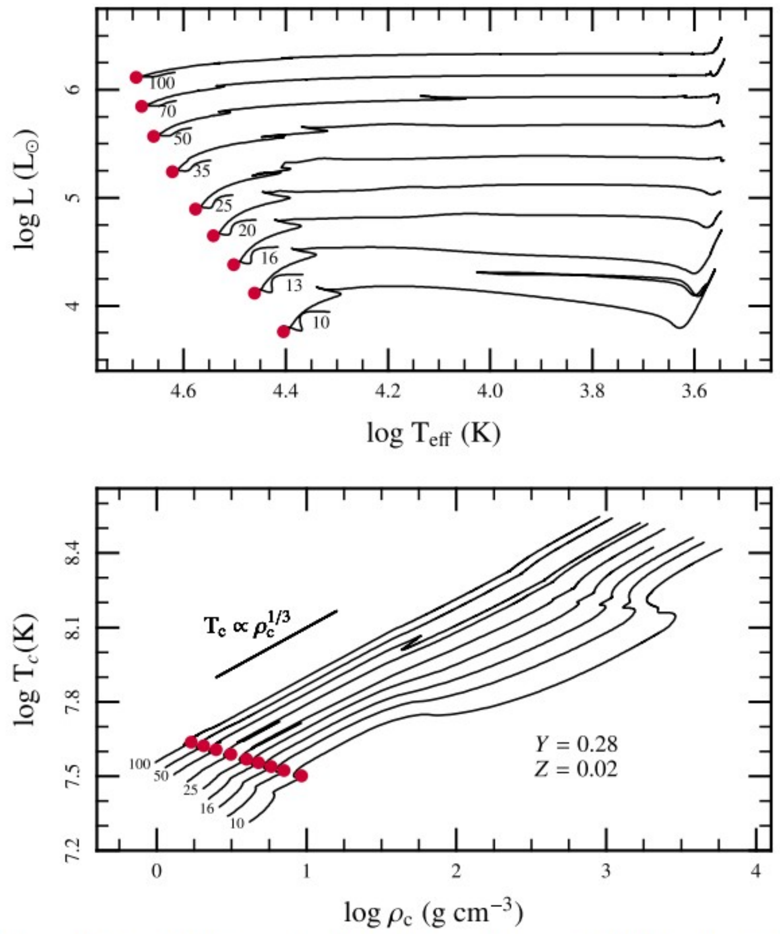
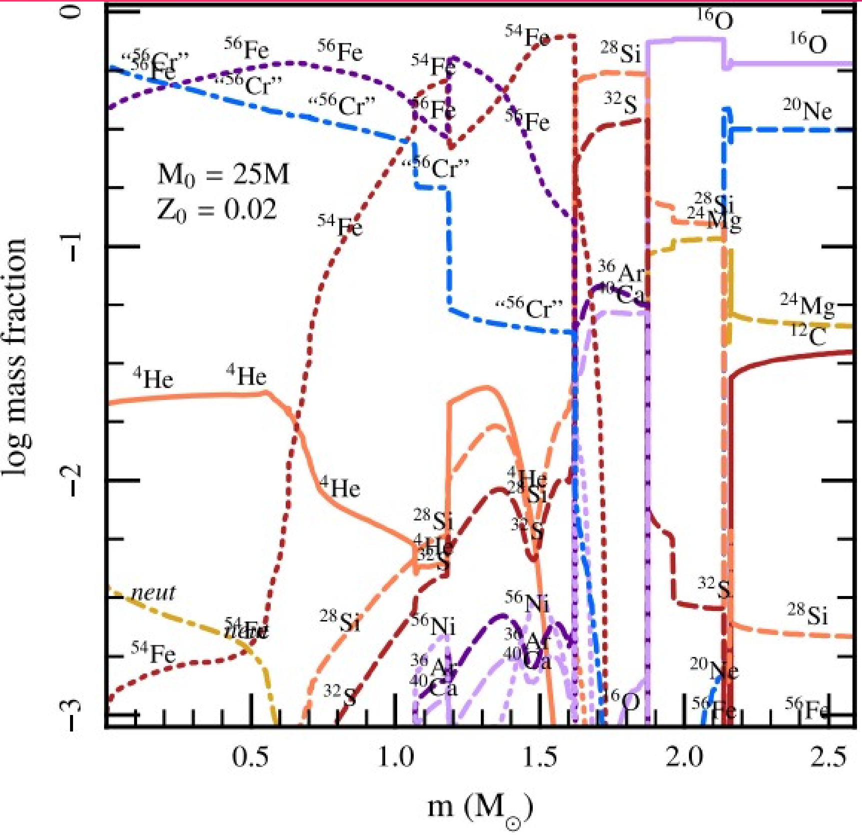


Figure 29. Top: H-R diagram for 10–100 $M_\odot$ models from the PMS to the end of core Helium burning for $Z = 0.02$ but with zero mass loss. Bottom: trajectories of the central conditions in the $T-\rho$ plane over this same evolutionary period.

(from Bill Paxton, MESA.)

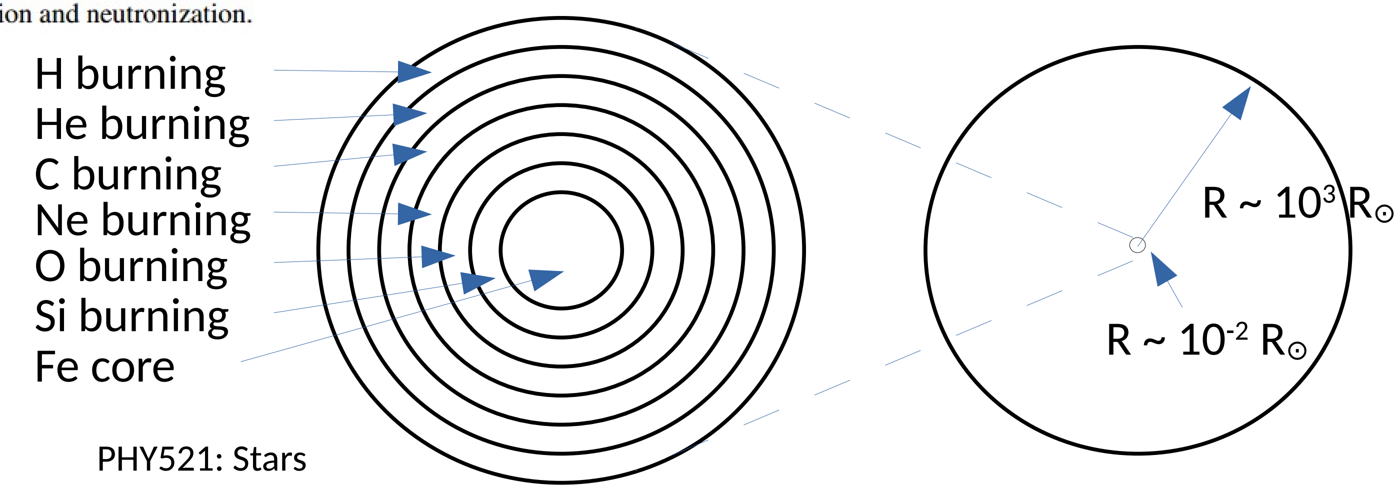
High Mass Evolution



- Advance burning stages lead to a "onion-skin" layering of nuclei

Figure 31. Mass fraction profiles of the inner 2.5 $M_\odot$ of the solar metallicity $M_i = 25\,M_\odot$ model at the onset of core collapse. The reaction network includes links between ^{54}Fe, ^{56}Cr, neutrons, and protons to model aspects of photodisintegration and neutronization.

(from Bill Paxton, MESA.)



Internal Structure

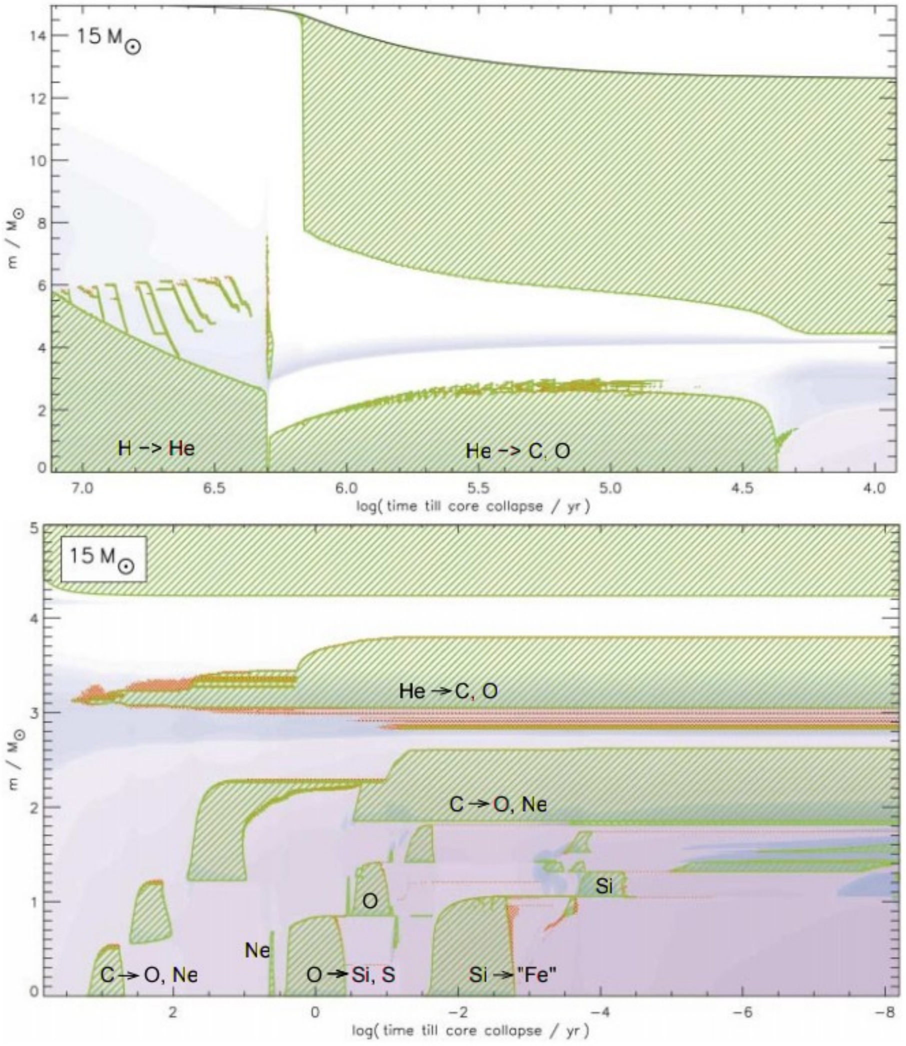
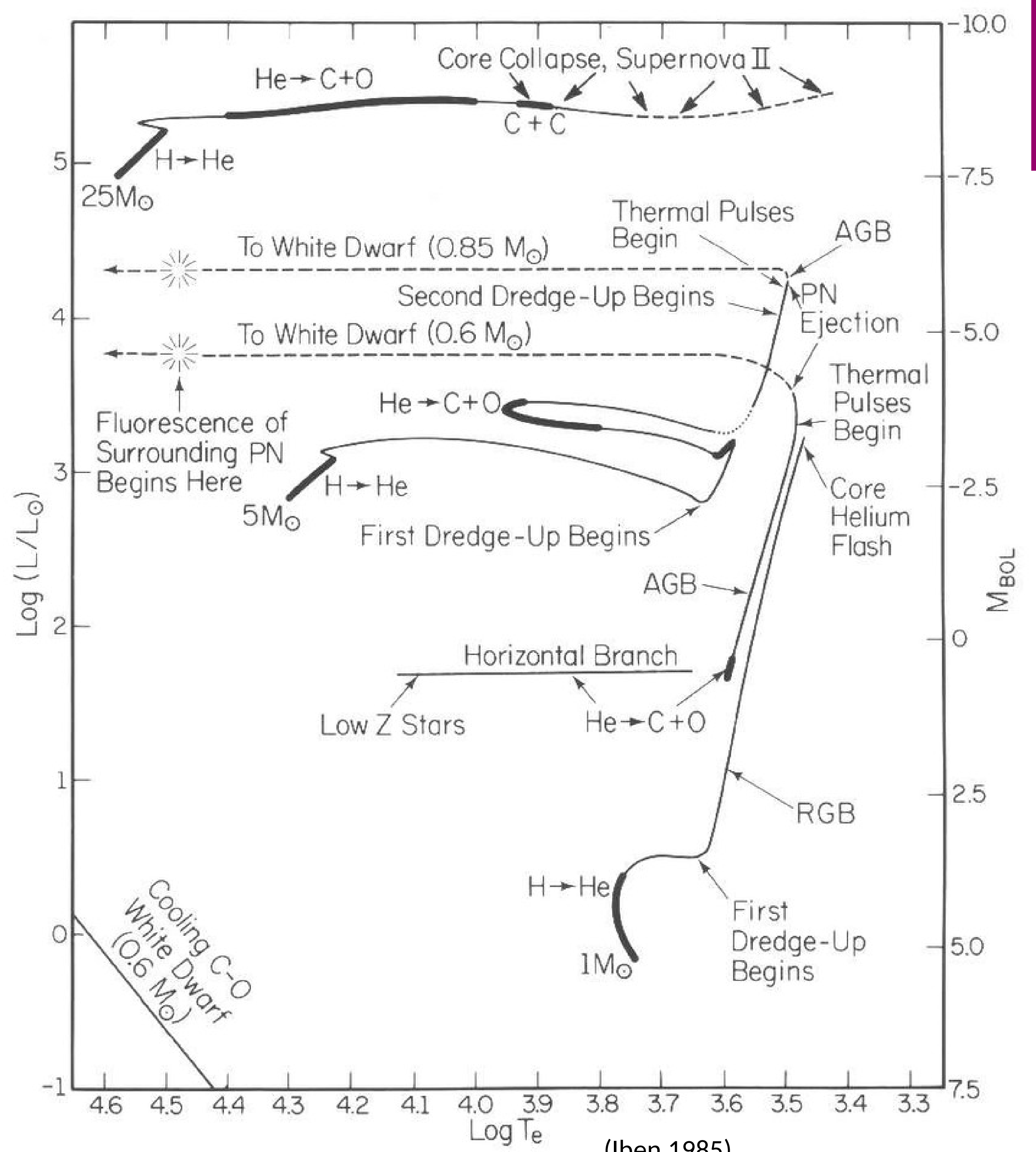


Figure 12.7. Kippenhahn diagram of the evolution of a 15 $M_\odot$ star showing convective regions (cross-hatching) and nuclear burning intensity (blue shading) during central H and He burning (top panel) and during the late stages in the inner 5 $M_\odot$ of the star (bottom panel). A complicated series of convective burning cores and shells appear, due to respectively carbon burning (around $\log t \sim 3$), neon burning (around $\log t \sim 0.6$), oxygen burning (around $\log t \sim 0$) and silicon burning (around $\log t \sim -2$). Figure from Woosley, Heger & Weaver (2002.)

- Convective shells of different burning phases abut one-another.
  - Mixing and can occur
  - Cannot be captured in one-dimension

Summary of Evolution



(Iben 1985)

Multi-dimensional Effects

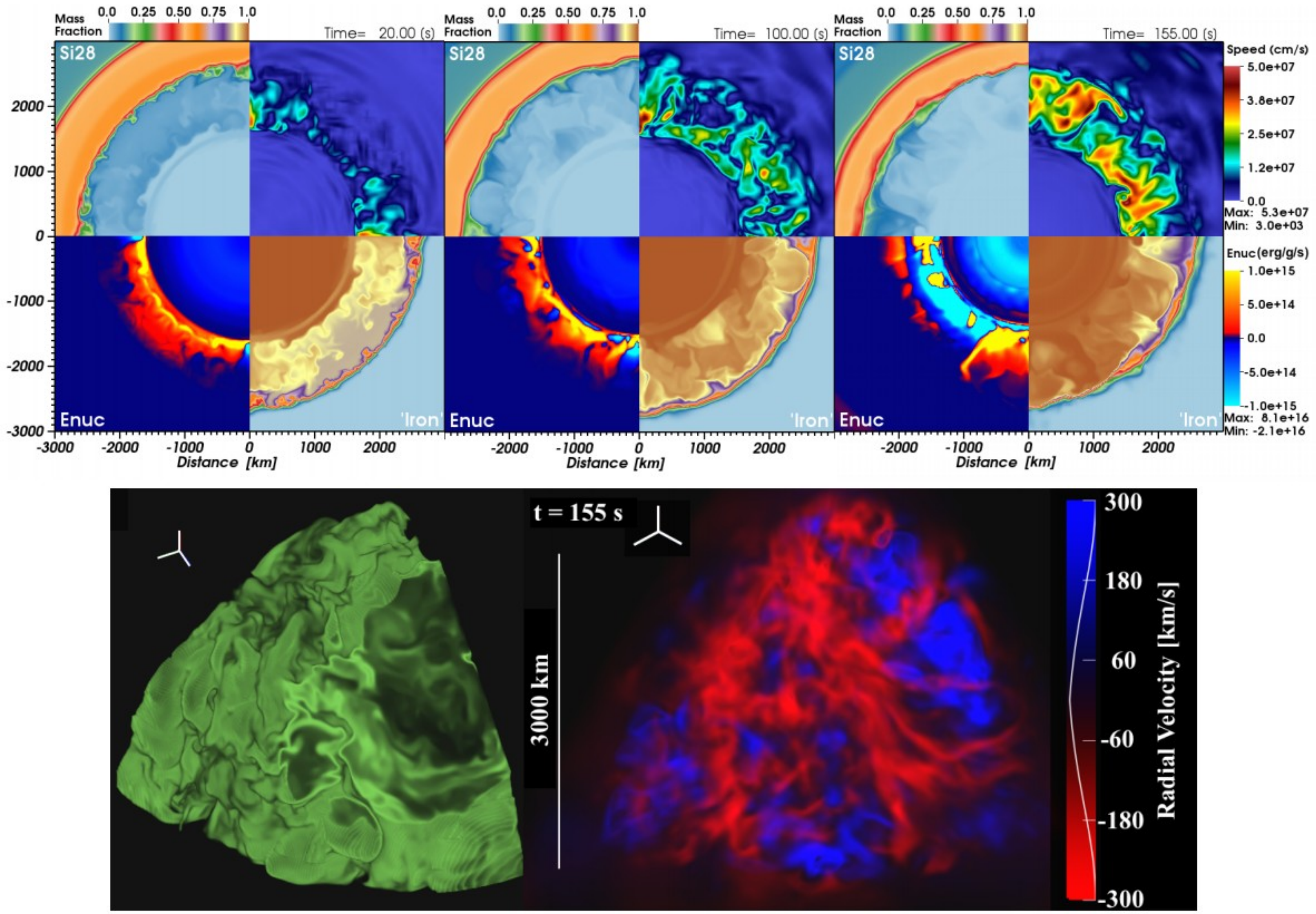
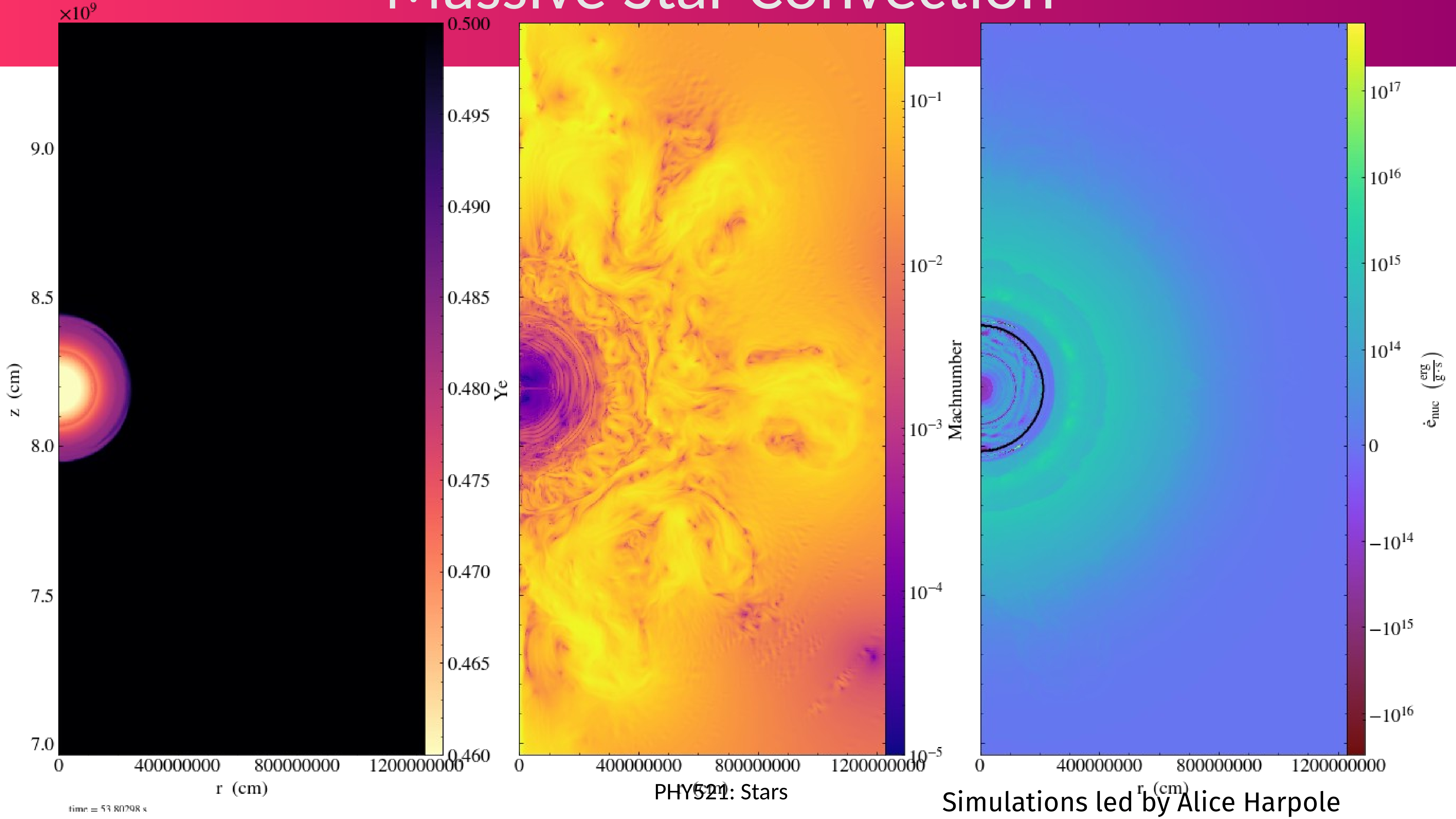


Figure 1. Visualizations of the 3D progenitor evolution simulation. The top row displays pseudocolor slices of the ^{28}Si mass fraction (top left), flow speed (top right), total mass fraction of iron group nuclei (bottom right), and specific nuclear energy generation rate (bottom left). The separate panels show different times since the start of the 3D simulation: 20 s (left), 100 s (middle), and 155 s (right). This final time is about 5 s before gravitational core collapse (see Figure 3). The bottom row shows volume renderings of the surface where the 'iron' mass fraction is 0.95 (left) and of the radial velocity (right) both at 155 s of 3D evolution.

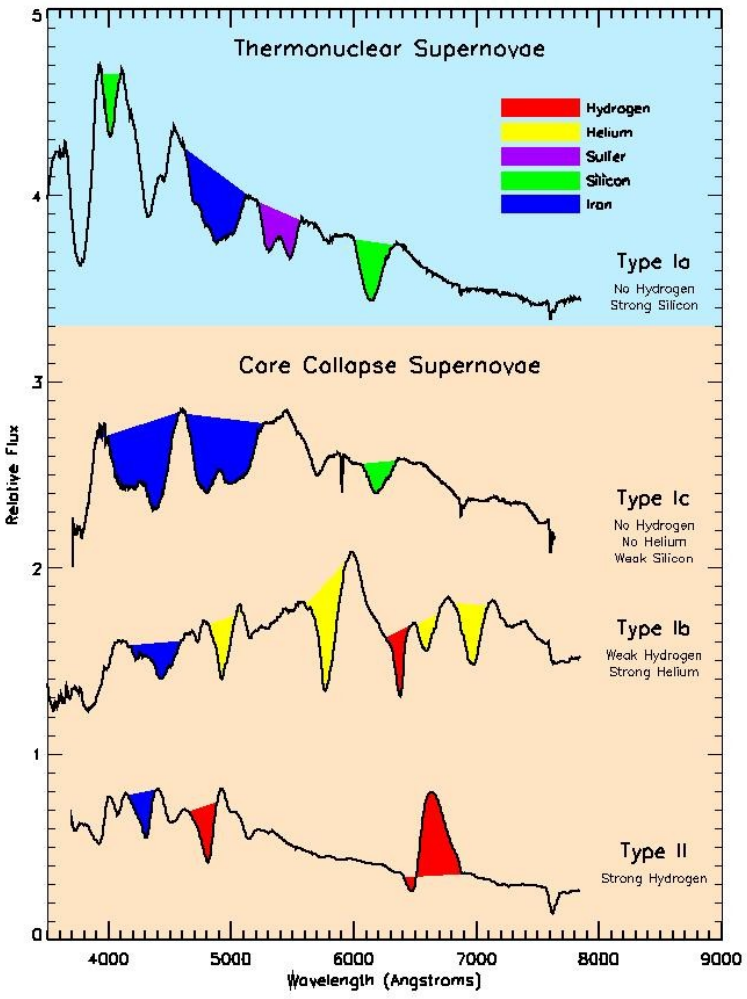
(Couch et al. 2015)

Massive Star Convection



Simulations led by Alice Harpole

Supernovae



Dan Kasen
http://panisse.lbl.gov/~dnkasen/tutorial/graphics/sn_types.jpg

- Fundamentally two types:
  - Gravitationally powered
  - Thermonuclear powered
- Observational classification more complicated
  - Type I: no H in spectrum
    - Ia: strong Si lines
    - Ib: strong He, weak Si
    - Ic: weak He
  - Type II: strong H in spectrum
- Observational pace is accelerating:
  - 1 per century in our galaxy
  - 1 – 10 per second in the observable Universe

Supernovae

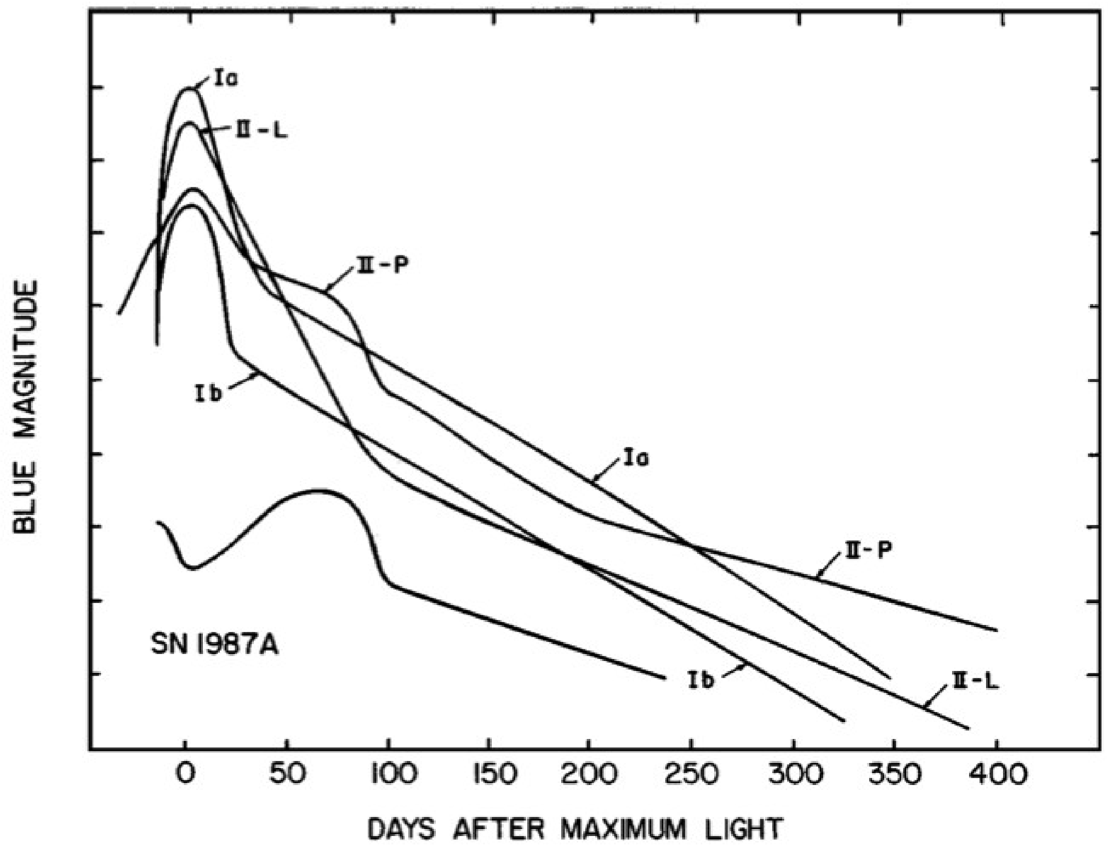


Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous.

Figure Credit: Wheeler, J. C., & Harkness, R. P. 1990, RPPh, 53, 1467

Instabilities

- We’ve already seen some instabilities that can lead to stellar death:
  - Dynamic instability can occur when the iron core forms and undergoes photodisintegration, leading to core-collapse
  - Chandra-mass white dwarfs are also dynamically unstable

Core-Collapse Supernovae

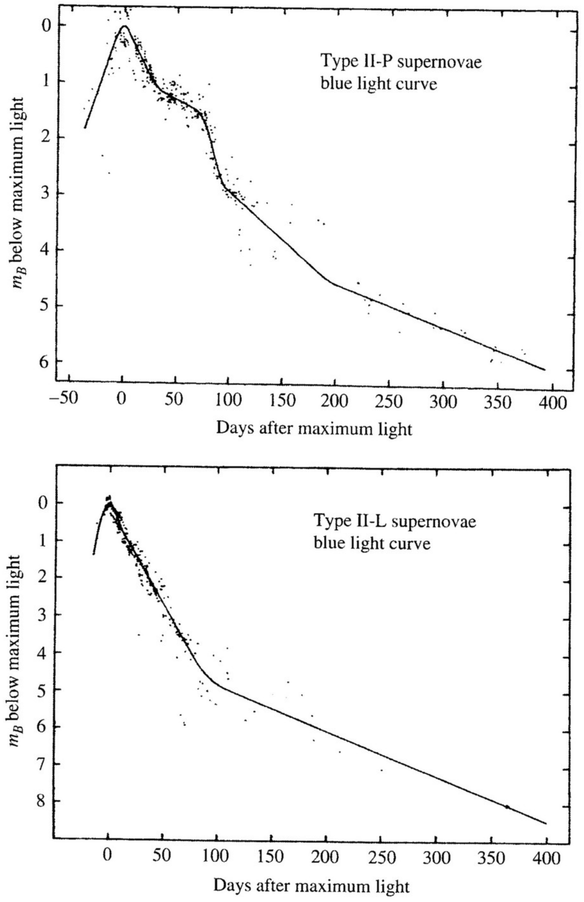


FIGURE 15.8 The characteristic shapes of Type II-P and Type II-L light curves. These are composite light curves, based on the observations of many supernovae. (Figures adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

(Carroll and Ostlie)

- Lightcurve—luminosity/magnitude vs. Time.
  - Quick rise followed by decay in brightness over ~ a month.
- Type II SNe are further divided into II-P (plateau) and II-L (linear):
  - Difference in shape due to time it takes for radiation to leak out.
- Type Ib, Ic, and II are all essentially the same mechanism
  - Collapse of the iron core
  - Difference among types is due to stripping the outer envelope off before core collapse

Core-Collapse Supernovae

(Pols, Ch 13)

- Since the star has run out of energy sources, it begins to cool.
- Core surrounded by different burning layers
- Core contracts (no energy generation)
  - Electrons become degenerate and relativistic
  - Chandra mass is slightly lower because of higher μ_e—$M_{Ch} \sim 1.2\ M_\odot$
  - There is nothing to stop the contraction
- Relativistic degenerate gas has $\gamma = 4/3$—we showed (a long time ago) that this is not dynamically stable

Core-Collapse Supernovae

- Instabilities help collapse
  - Electron capture
    - Free electrons capture onto β-unstable nuclei (inverse β-decay) and protons combine to neutrons
    - Material becomes more neutron-rich
    - Degenerate e pressure decreases
    - This leads to the collapse of the core (helped by decreasing Chandra mass)
  - Photo-disintegration
    - At 10^{10} K, photon energies are comparable to the binding energy of nuclei
    - Heavy nuclei are broken apart:

$$^{56}\mathrm{Fe} + \gamma \leftrightarrow 13\,^{4}\mathrm{He} + 4n - 124\ \mathrm{MeV}$$

    - Absorbs ~ 2 MeV / nucleon
    - Energy comes from the radiation field—cools star, pressure drops, aiding collapse

More on Electron Capture

- Naive estimate of density at which electron-capture can proceed:

$$\frac{p_F^2}{2m_e} = (m_n - m_p - m_e)c^2$$

  - This gives ρ ~ 10^7 g/cm^3
  - Surrounding nuclei modify this—real density is ~ 10^9 g/cm^3
- Why doesn't the neutron just decay back?
  - We are completely degenerate—there are no vacant states (below the Fermi momentum) for the electron to go into
- Neutron drip occurs around ρ ~ 4 × 10^{11} g/cm^3
  - mixture of free n, neutron rich nuclei, and degenerate electrons
  - superfluidity can occur (no viscosity)
  - a still higher densities, nuclei go away

Electron-capture SNe

- Note that stars that are < 10 $M_\odot$ don't make it to Fe.
  - Make ONeMg cores (from C burning)
  - Electron degenerary kicks in before Ne burning occurs
  - Electron capture becomes favorable → collapse is triggered.

Core-Collapse Supernovae

- Collapse becomes free-fall
  - Since $\gamma_a < 4/3$, increase in P from higher ρ cannot stop collapse
- ^{4}He breaks up too

$$^4_2\mathrm{He} + \gamma \rightarrow\ 2\,\mathrm{p} + 2\,\mathrm{n} - 24\ \mathrm{MeV}$$

  - ~ 6 MeV / nucleon
- Free p capture e and make n
  - More energy absorption
  - Fewer free particles

- Note that stars that are < 10 $M_\odot$ don't make it to Fe.
  - Make ONeMg cores (from C burning)
  - Electron degenerary kicks in before Ne burning occurs
  - Electron capture becomes favorable → collapse is triggered.

Core-Collapse Supernovae

(Pols, Ch 13)

- Collapse is rapid (~ 10 ms)
  - Dynamical timescale is

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}} \approx \frac{2100\ {\rm s}}{\sqrt{\rho}}$$

  - Continued electron captures occur
    - Full dissociation of Fe into p + n does not occur during the collapse

- Collapse halts when nuclear densities reached, $\rho \sim 10^{15}$ g cm^{-3}
  - Core is mostly neutrons now
  - Neutron degeneracy is part of the story, but strong nuclear force also comes into play
  - Equation of state “stiffens”
  - Proto-neutron star is formed

Core-collapse SNe & Neutron Stars

With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star. Such a star may possess a very small radius and an extremely high density…

—Baade & Zwicky (1934)

Core-Collapse Supernovae

(Kutner Ch. 11, Hester et al. Ch. 17)

- Strong force resists the collapse.
  - Outer layers of the core do not know that the inner core stopped.
- Outer layers of the core hit the compact inner core and bounce—shock wave moves outward through the star.

Core Collapse SNe

- Back of the envelope
  - Gravitational potential energy release
    - When the iron core collapses, it goes from the size of a WD down to ~ 20 km

$$\Delta\Omega = -\frac{GM^2}{R_{\rm WD}} + \frac{GM^2}{R_{\rm NS}} \approx \frac{GM^2}{R_{\rm NS}} \sim 10^{53}\ {\rm erg}$$

    - Note: not all this energy will come out in photons
  - Energy absorbed in nuclear processes

$$\Delta E_{\rm nuc} \sim 7\ {\rm MeV}\frac{M_c}{m_u} \sim 10^{52}\ {\rm erg} \ll \Delta\Omega$$

Core Collapse SNe

- Back of the envelope
  - Can we eject the envelope?

$$\Delta\Omega_{\rm env} \sim \frac{GM_c(M-M_c)}{R_c} \sim 5\times 10^{51}\ {\rm erg}$$

  - And can we give it KE w/ v ~ 10,000 km/s?

$$\Delta E_{\rm kin} \sim \frac{1}{2}(M-M_c)v_{\rm exp}^2 \sim 10^{52}\ {\rm erg}$$

- There is plenty of energy to explode the star
- Not all of it goes into photons:
  - $L \sim 10^{10}\ L_\odot$ over months → $\Delta E_{rad} \sim 10^{51}$ erg

Core-Collapse Supernovae

(Kutner Ch. 11, Hester et al. Ch. 17)

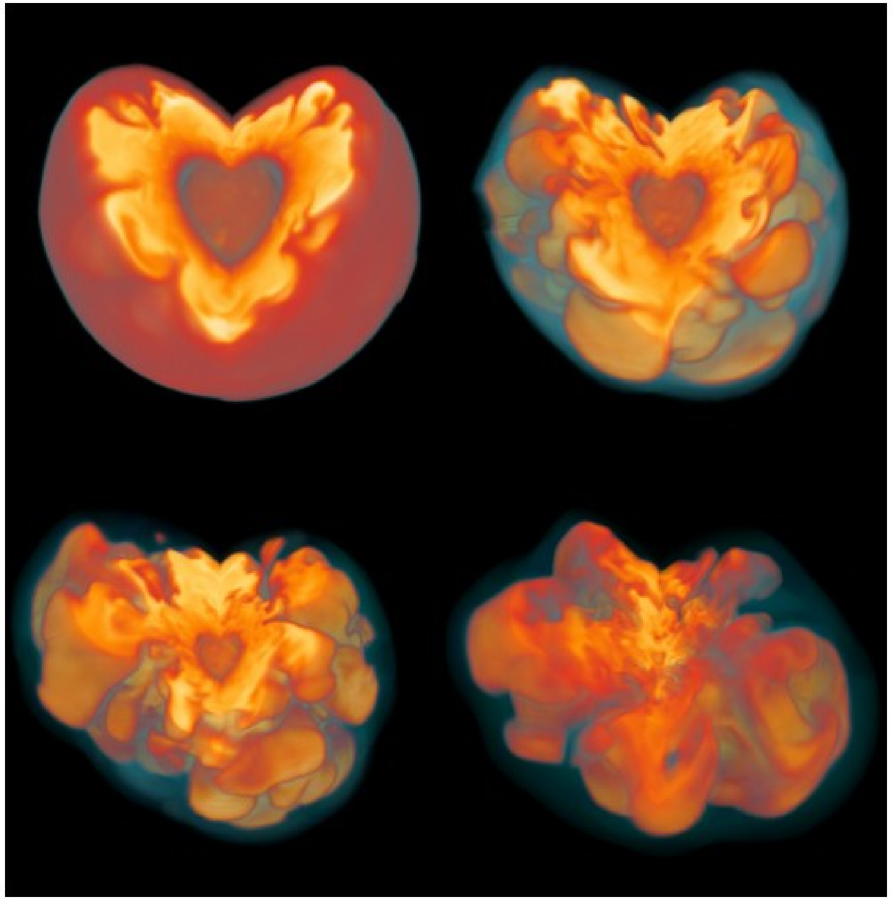
- Questions:
  - Where does the bulk of the energy go?
  - How is the energy deposited into the envelope?
- Neutrinos are produced at high rates during collapse.
  - $p + e^- \rightarrow n + \nu$
- Core and region outside is dense—neutrinos are trapped.
  - They create a bubble of hot gas behind the shock, which pushes the shock outward—this is really not well understood.
  - Most of the energy is carried by neutrinos

Explosion Mechanism

- Inner core bounces due to stiffness, rebounds
- Expanding inner core hits still-freefalling outer core
  - Outward propagating shock forms
  - Not enough energy for the shock to make it out through the entire star (a prompt explosion)
- Shock dissociates infalling matter (mostly Fe) into p + n
  - This consumes a large fraction of the gravitational binding energy released
  - Electron captures onto p create lots of neutrinos
    - Star is opaque to the neutrinos!
    - Neutrinos heat the material behind the shock—it becomes convective
    - Believed to revive the stalled shock

Modeling Core-Collapse Supernovae

- Most of our knowledge of core-collapse supernovae come from simulations
- Exceptionally difficult simulations
  - Need to follow matter, neutrinos, and interactions between them to get it right
- Models today can produce explosions, but some understanding and robustness still lacking



(Woosley and Janka)

Figure 2: *Looking into the heart of a supernova (14). Four snapshots show the vigorous boiling of the neutrino-heated, convective region around the nascent neutron star. Buoyant bubbles of hot matter moving outwards appear bright red and yellow. These are bounded by a shock wave, which expands outwards, disrupting the star. The images, from top left to bottom right, show the structure at 0.1, 0.2, 0.3, and 0.5 seconds after the shock is born. At these times, the shock has an average radius of about 200, 300, 500, and 2,000 kilometers, respectively.*

Neutrino Transport

- The transport of the neutrinos is described similarly to radiation
  - 6-dimensional (position + 2 directional angles + energy)
  - Computational expensive—this is where most approximations are made
- Microphysics requirements are opacity and scattering cross-sections for neutrino interactions

Modeling Core-Collapse Supernovae

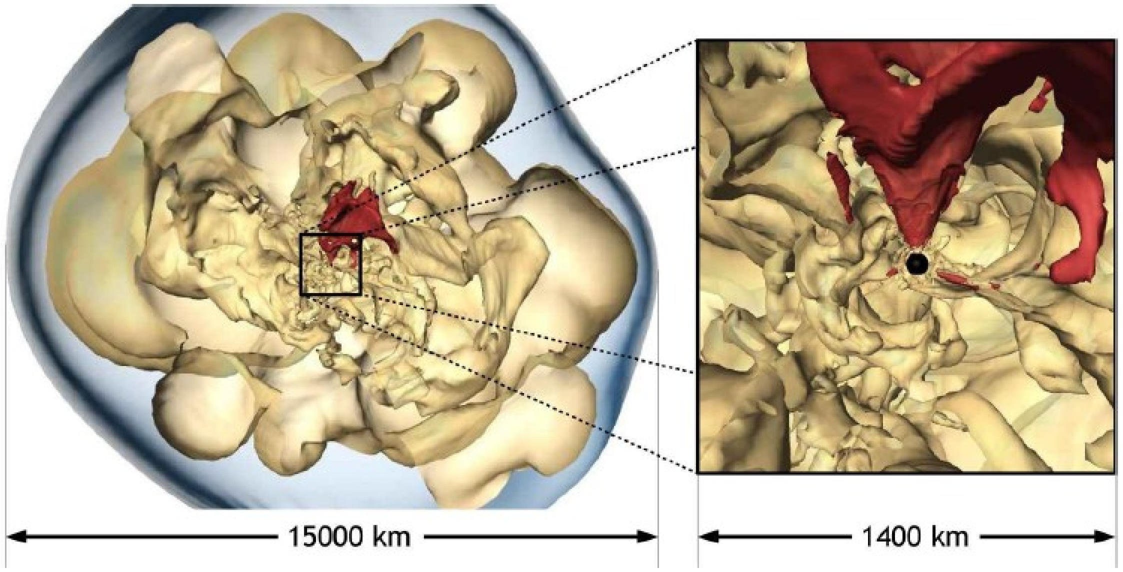


Figure 3: *Accretion onto the nascent neutron star shows a dipolar character (15). Cool matter (visible in red in the blow-up on the right) falls and is funnelled onto one side of the neutron star (black circle at the center), while neutrino-heated, hot ejecta flows out on the other. This 'jet engine' can accelerate the neutron star to velocities of several hundred kilometres per second within the first second of its life. At that same time, the supernova shock wave (blue, enveloping surface) is already well on its way through the exploding star (left panel), being pushed by the buoyant bubbles of neutrino-heated gas. Although the calculation was followed in three spatial dimensions, the initial model was spherically symmetric and was not rotating.*

(Woosley and Janka)

- Asymmetries in the accretion onto the proto-neutron star may give it a strong kick after the explosion.

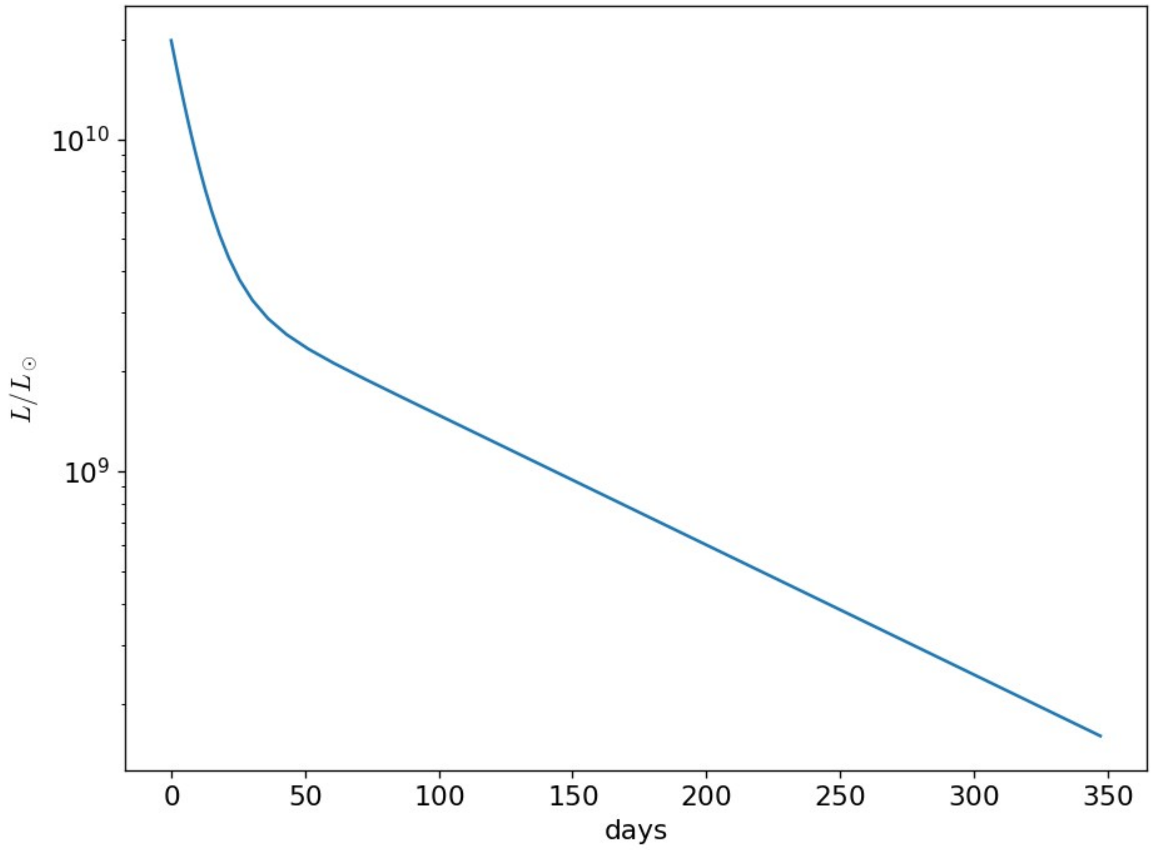
Lightcurve

- Shock from bounce breaks through the star's surface hours later
  - High T → most radiation is in UV
  - As envelope expands and cools, T drops, radiation is in visible spectrum

SN Nucleosynthesis

- Supernova are responsible for making a lot of heavy elements
  - Production occurs both before the collapse in the burning shells and after bounce, driven by the shock moving through the envelope
  - Shock wave produces $T > 5 \times 10^9$ K (nuclear statistical equilibrium)
    - ^{56}Ni produced ($Z/A \sim ½$ in envelope)
  - T drops below 2×10^9 K when shock reaches original Ne-O layer
    - lighter nuclei produced from pre-explosion burning
- Ejecta mix with ISM an enrich chemical composition

Supernovae Lightcurves



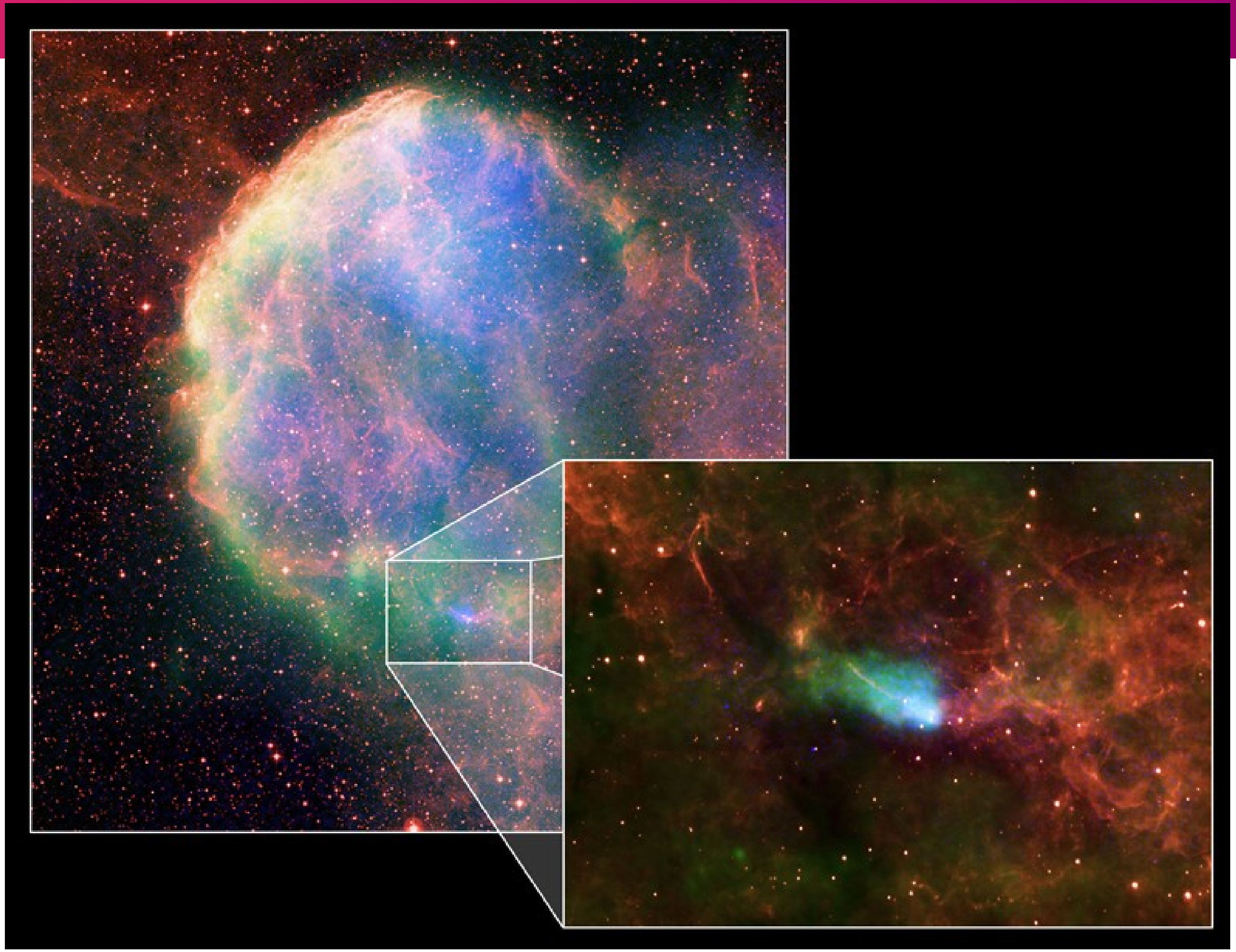
- Simple analytic model for a lightcurve:
  - Decay initial ^{56}Ni:
    - Half-life: 6.1 days
    - Q ~ 1.75 MeV in ɣ / decay
  - Decay ^{56}Co as produced:
    - Half-life: 77 days
    - Q ~ 3.73 MeV in ɣ / decay
- Remember half-life means:

$$N(t) = N_0 \left(\frac{1}{2}\right)^{t/\tau_{1/2}}$$

Remnant

The explosion leaves behind a remnant and a compact object (neutron star or black hole, depending on the progenitor mass).

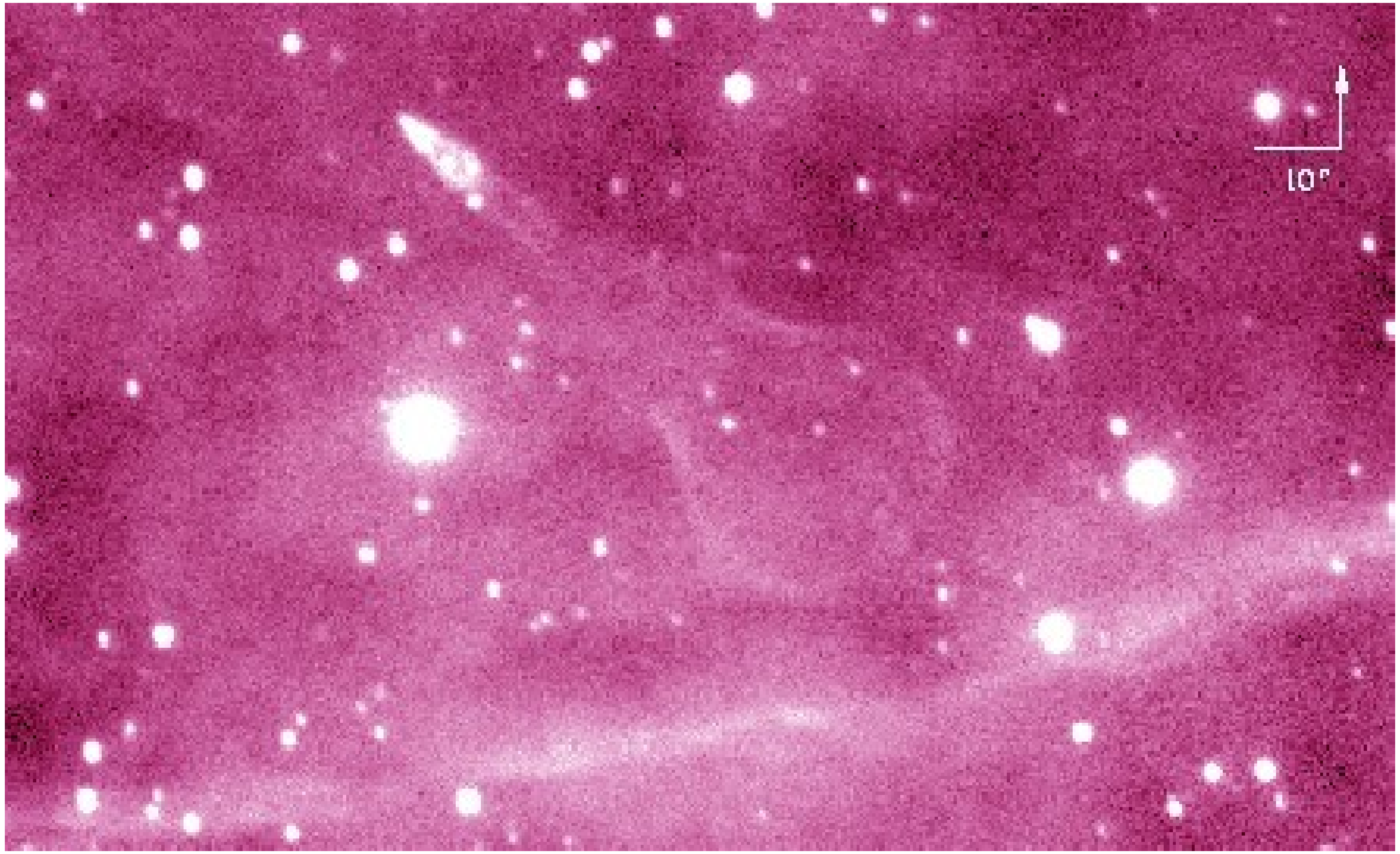
► IC 443, and the wake caused by the moving neutron star.



(NASA/CXC/B. Gaensler et al; NASA/ROSAT/Asaoka & Aschenbach; NRC/DRAO/D.Leahy; NRAO/VLA; DSS)

http://antwrp.gsfc.nasa.gov/apod/ap060602.html

Neutron Star Kick

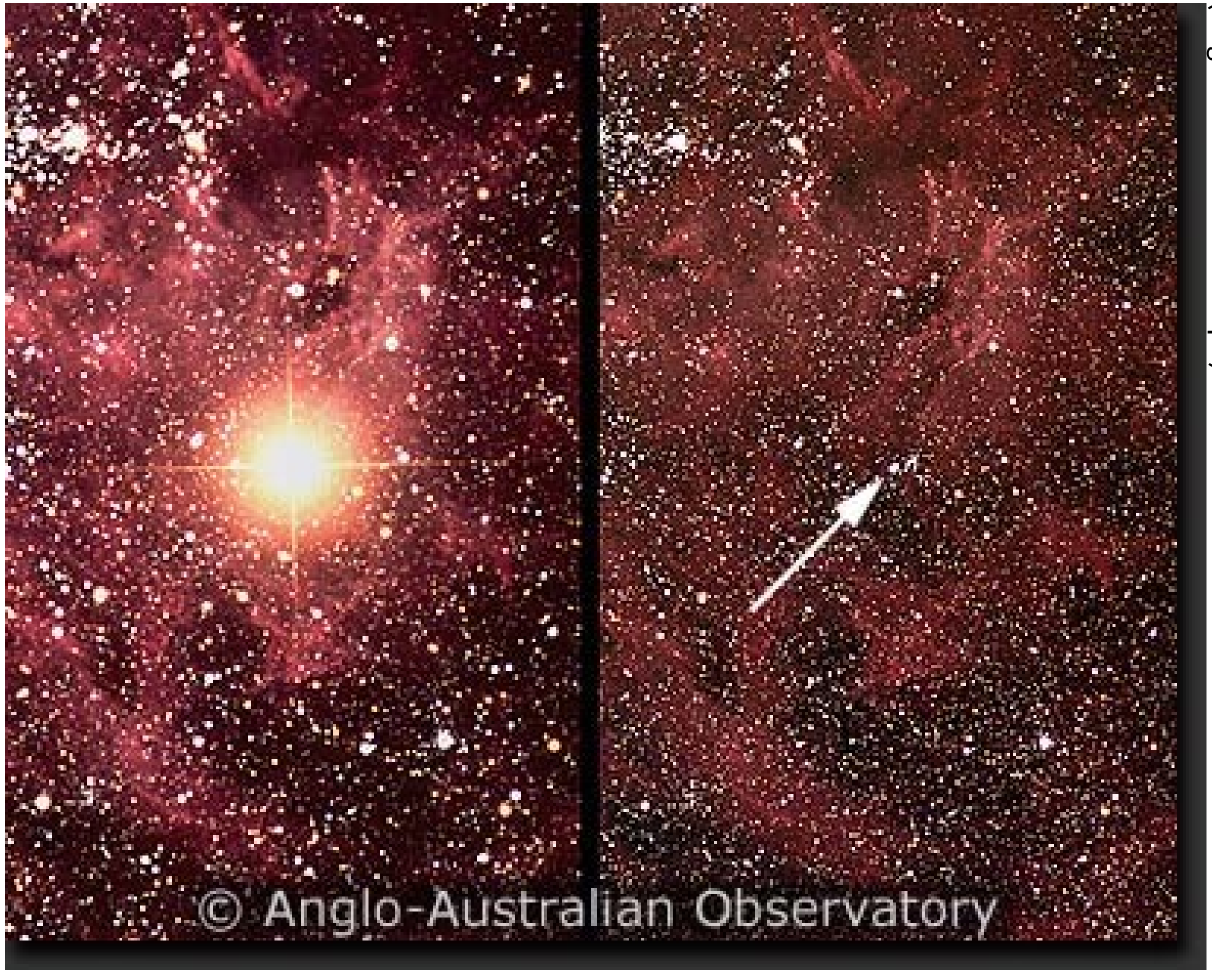


The guitar nebula—a bow shock from a 1600 km/s neutron star moving through the interstellar medium.

http://www.astro.cornell.edu/~shami/guitar/
Shami Chatterjee

SN 1987A

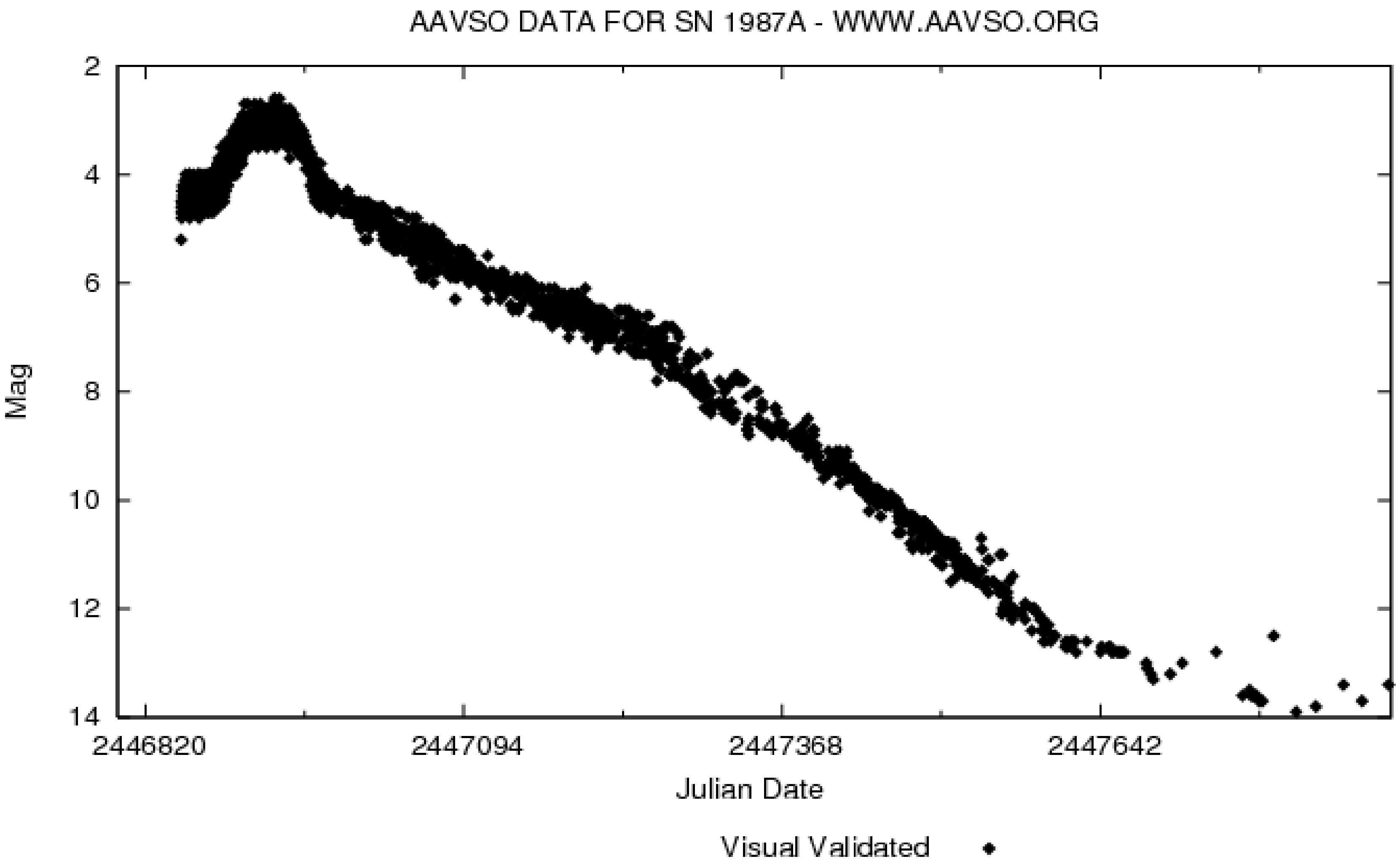
- One of the most famous core-collapse supernovae is 1987A
  - Exploded in the Large Magellanic Cloud—a satellite galaxy of ours.
  - Closest supernova (only 51.4 kpc away) since Kepler's (1604) in our galaxy.
- 1987A was so close that we detected 24 neutrinos coming from the event.



(Anglo-Australian Telescope)

The left image shows the supernova about 10 days after explosion and the right image shows the blue giant star before exploding.

SN 1987A


AAVSO DATA FOR SN 1987A - WWW.AAVSO.ORG
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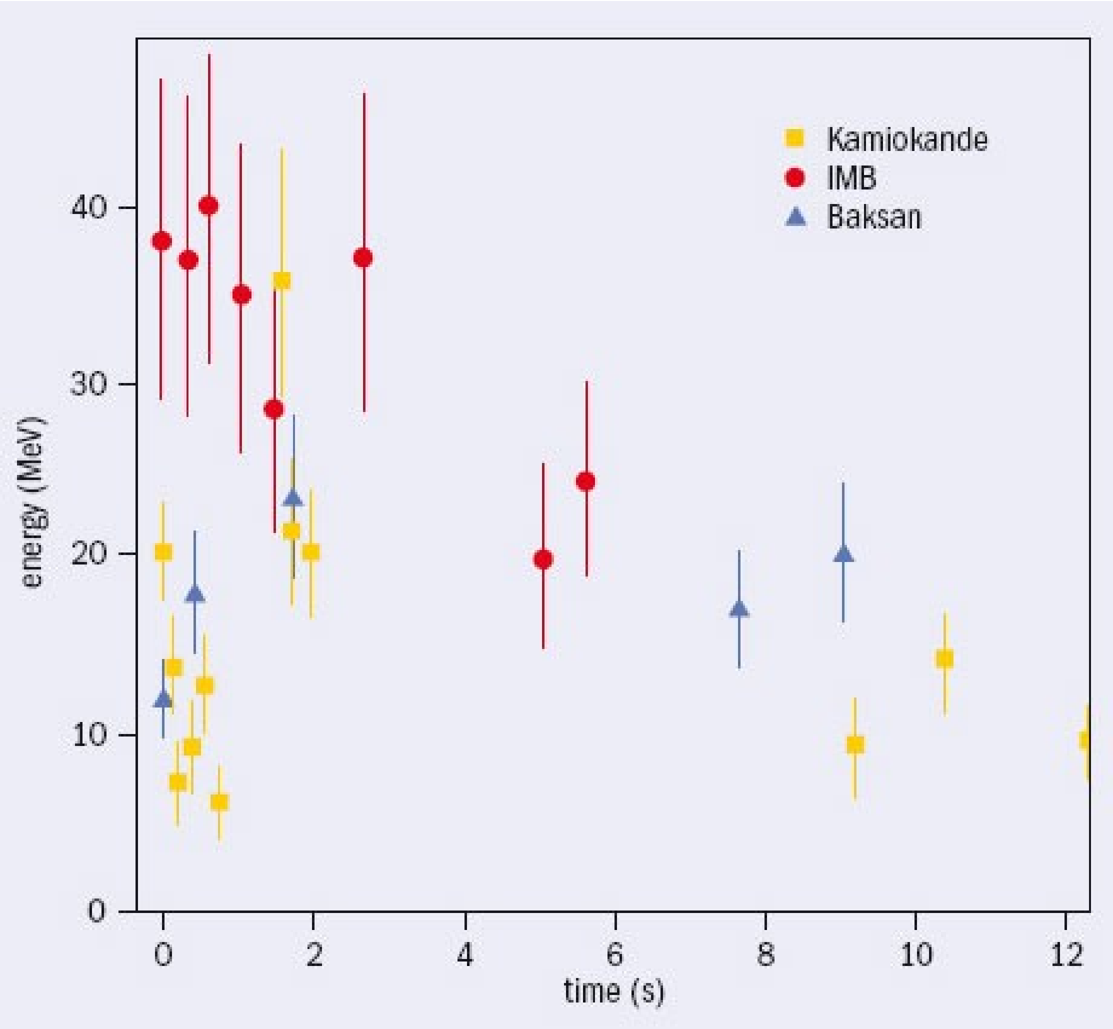
Visual Validated

SN 1987A Neutrinos

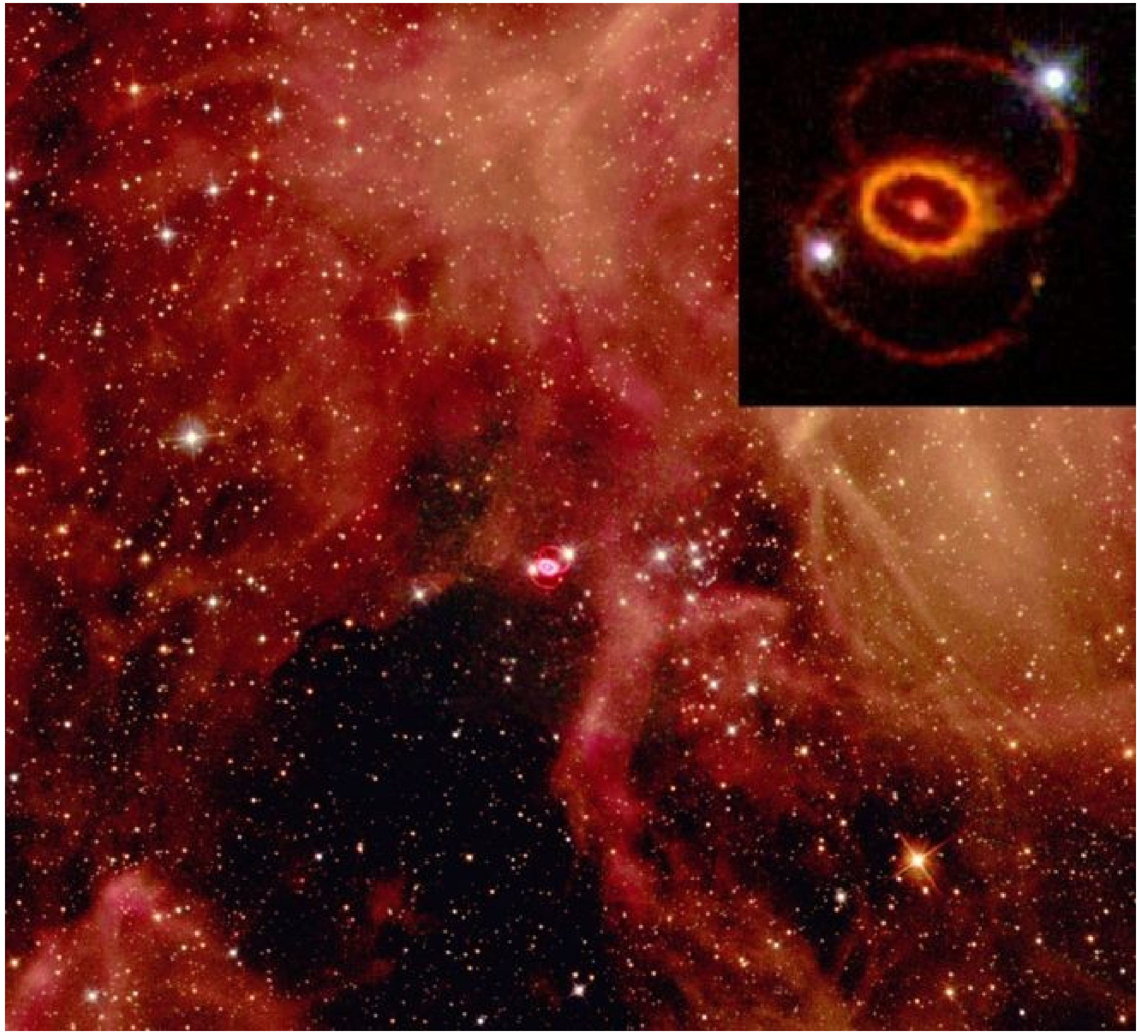


- Neutrinos preceeding the visible light to Earth
  - Photon emission awaits the shock breaking out of the surface of the star
  - Direct confirmation of our physical model for ccSNe.

(CERN Courier)

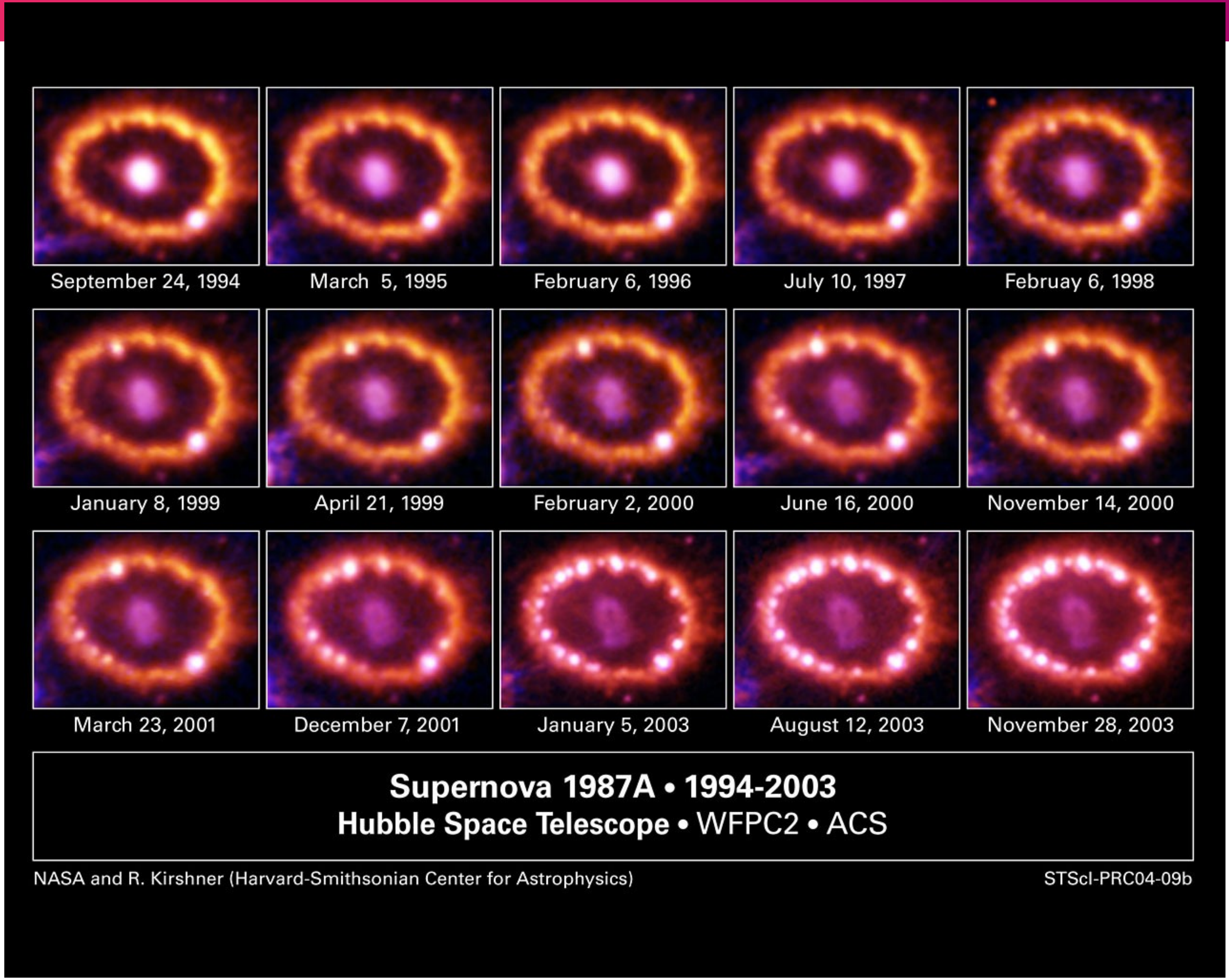
SN 1987A

- After the explosion, a remnant appears.
- Circumstellar material ejected from the progenitor is ionized by the explosion shock, making rings.
- So far, no neutron star has been discovered in the remnant.



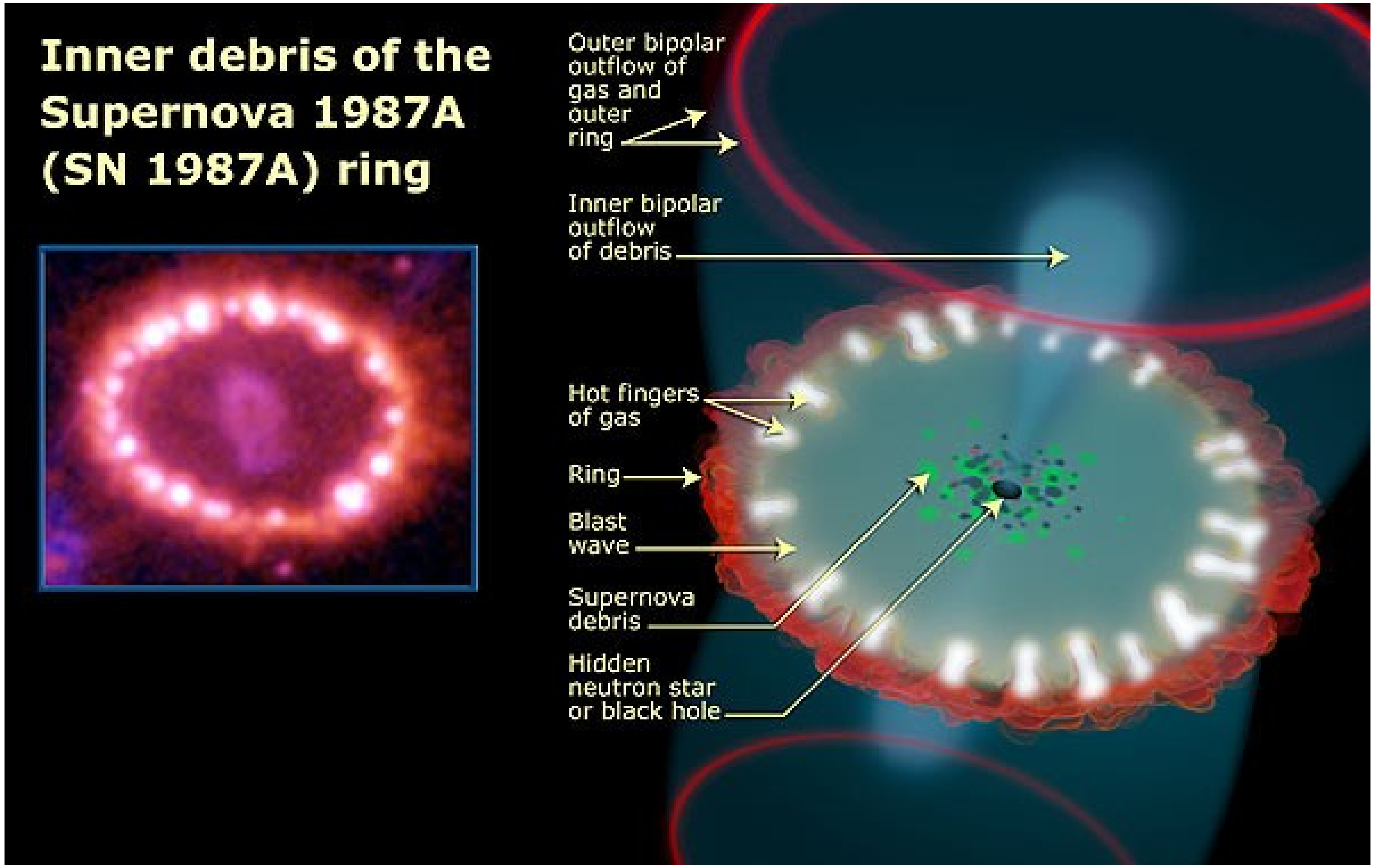
(NASA/ESA)

SN 1987A



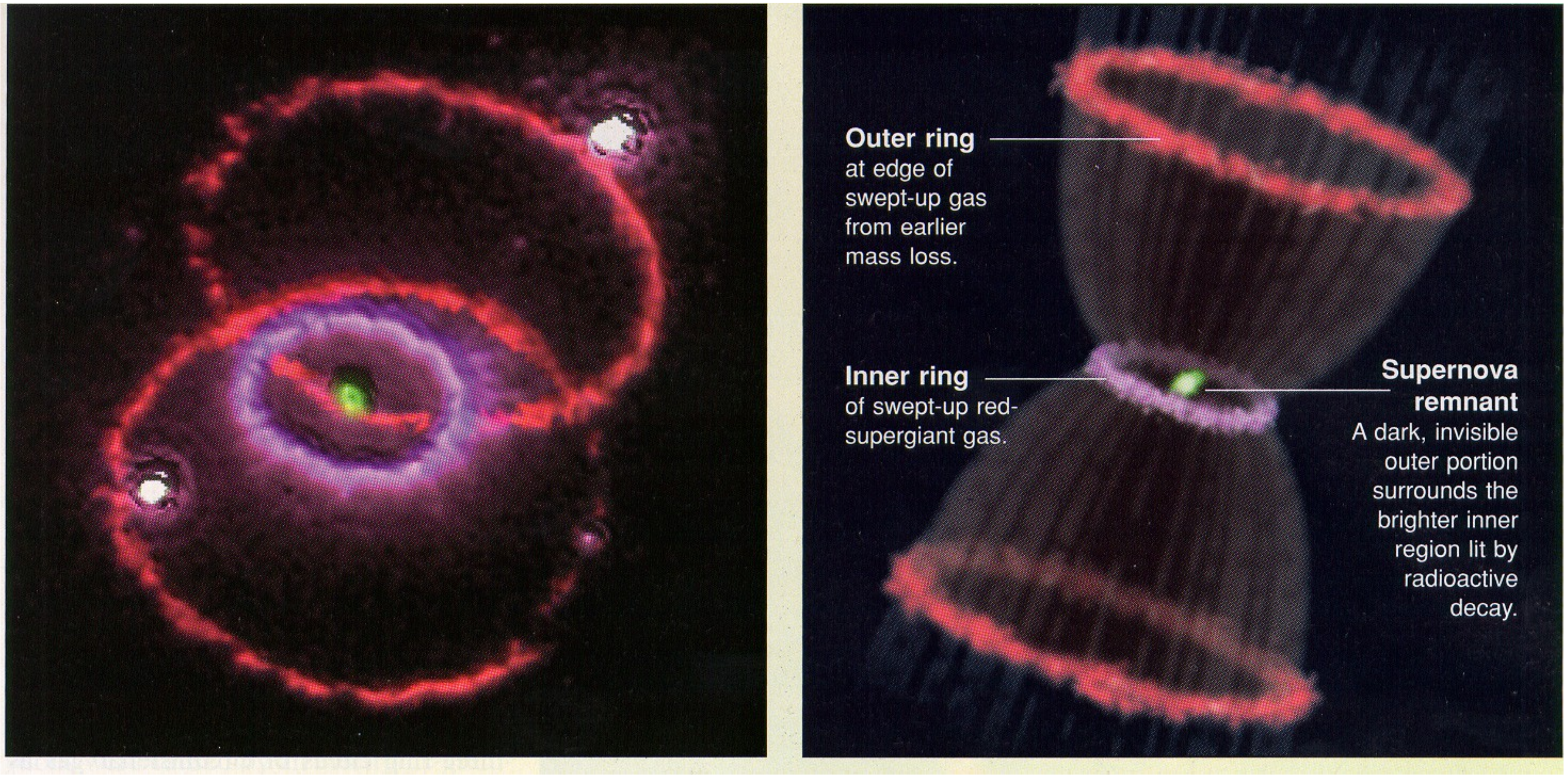
September 24, 1994
March 5, 1995
February 6, 1996
July 10, 1997
Februay 6, 1998
January 8, 1999
April 21, 1999
February 2, 2000
June 16, 2000
November 14, 2000
March 23, 2001
December 7, 2001
January 5, 2003
August 12, 2003
November 28, 2003
Supernova 1987A • 1994-2003
Hubble Space Telescope • WFPC2 • ACS
NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
STScI-PRC04-09b

SN 1987A



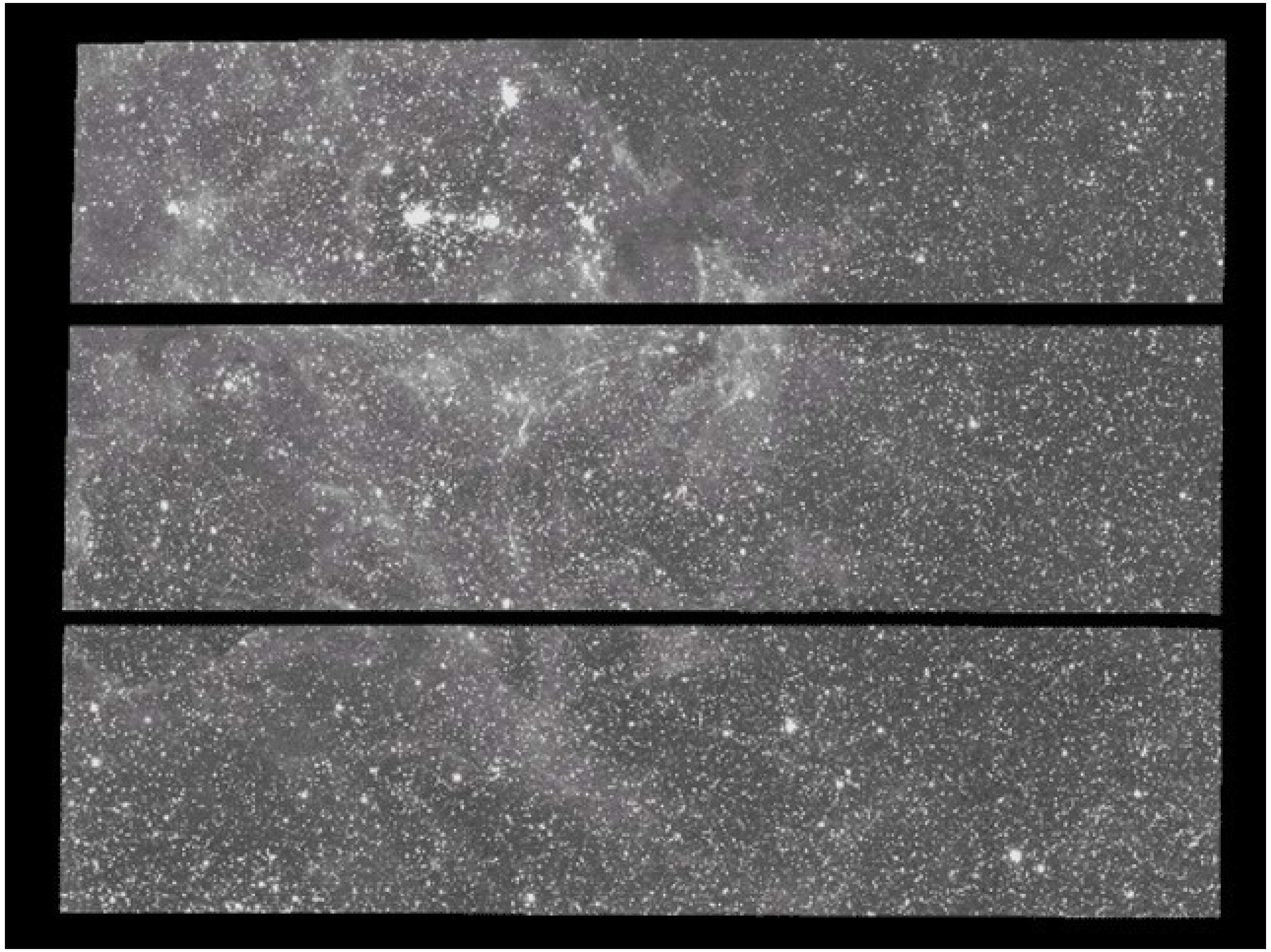
(Sky & Telescope)

SN 1987A



(Sky & Telescope)

SN 1987A



Light echos from SN 1987A. We can see light echos from older SN in the LMC as well—we can even take spectra of them!

Credit: The SuperMACHO Team, CTIO, NOAO, NSF
http://antwrp.gsfc.nasa.gov/apod/ap060125.html

Neutron Stars

- Neutron stars are supported by neutron degeneracy + the effects of the strong nuclear force
- Different equations of state give different mass-radius relations.
  - From some models, a 1.4 $M_\odot$ neutron star has R ~ 10 km!

$$\rho = \frac{M}{(4/3)\pi R^3} = 6.6 \times 10^{14}\ \mathrm{g\ cm^{-3}}$$

  - A neutron "radius" is ~10^{-13} cm and its mass is 1.67 x 10^{-24} g → density of a neutron is

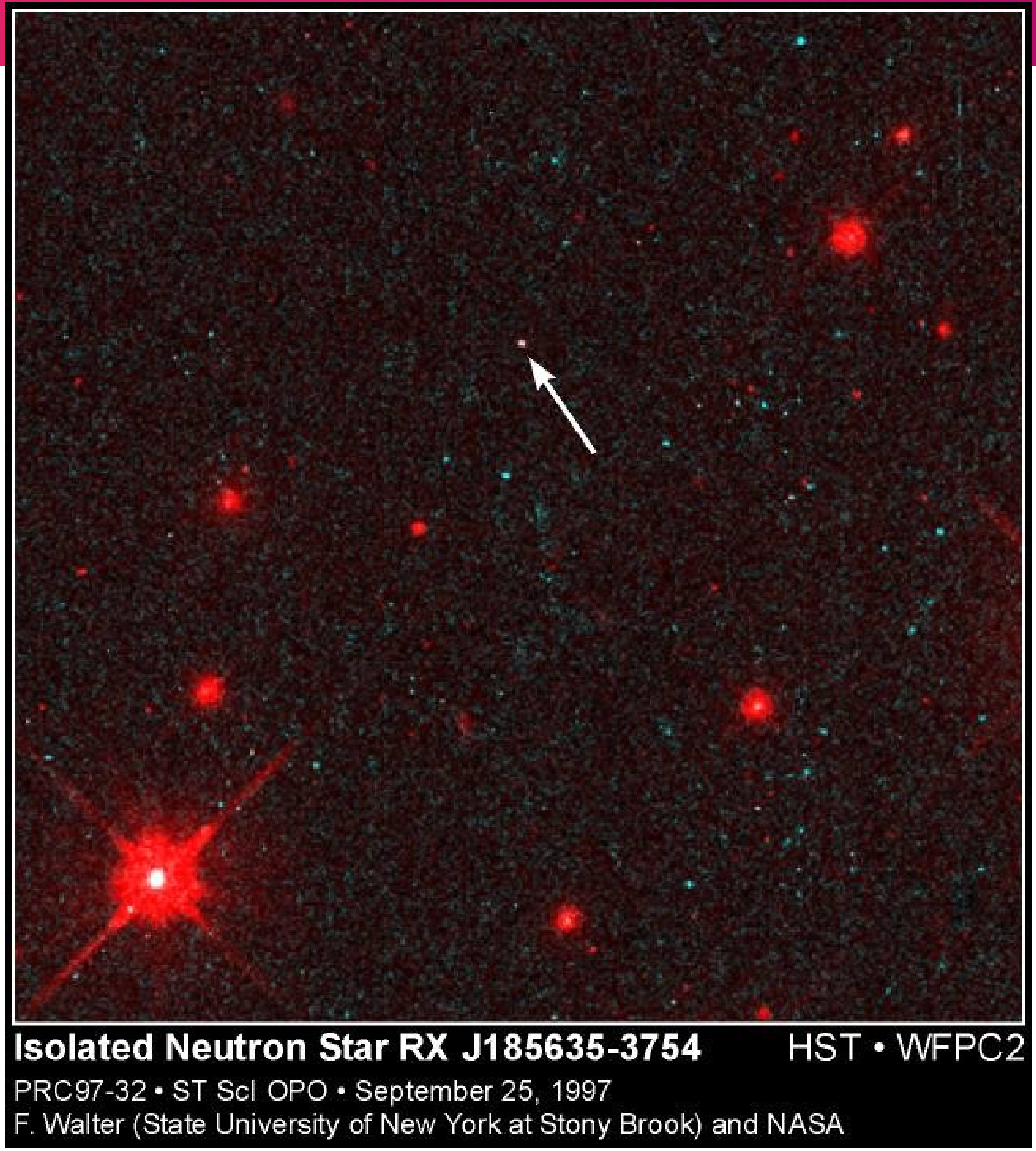
$$\rho = \frac{m_n}{(4/3)\pi r_n^3} = 4 \times 10^{14}\ \mathrm{g\ cm^{-3}}$$

Neutron Star Fun Facts

(from Jim Lattimer)

- Densest objects (outside of an event horizon), $\rho \sim 10^{15}$ g/cm^3
- Largest surface gravity: $g \sim 10^{14}$ cm/s^2
- Fastest known spinning objects: $\nu \sim 700$ Hz
  - PSR J1748-2446ad—equitorial velocity is ¼ c!
- Largest know magnetic field strengths: $B \sim 10^{15}$ G
- Highest T superconductor: $T \sim 10^{10}$ K
- Highest T at birth anywhere since the big bang: $T \sim 7 \times 10^{11}$ K
- Only place in the Universe (except for the big bang) where neutrinos become trapped

Neutron Stars



Neutron Stars

- If NS were supported by pure neutron degeneracy, we could use an $n = 3/2$ polytrope
  - We'd find $R \propto M^{-1/3}$ (non-relativistic)
    - 1.5 $M_\odot$ NS would have R = 15 km)
- We could also find a maximum mass in the same way we did for WDs
  - $M_{NS,max} = 5.83\ M_\odot$ ($\mu_n = 1$)
- This neglects important physics
- Relativistic neutron gas
  - KE of particles is comparable to rest-mass energy
  - HSE equation is modified (TOV equation)

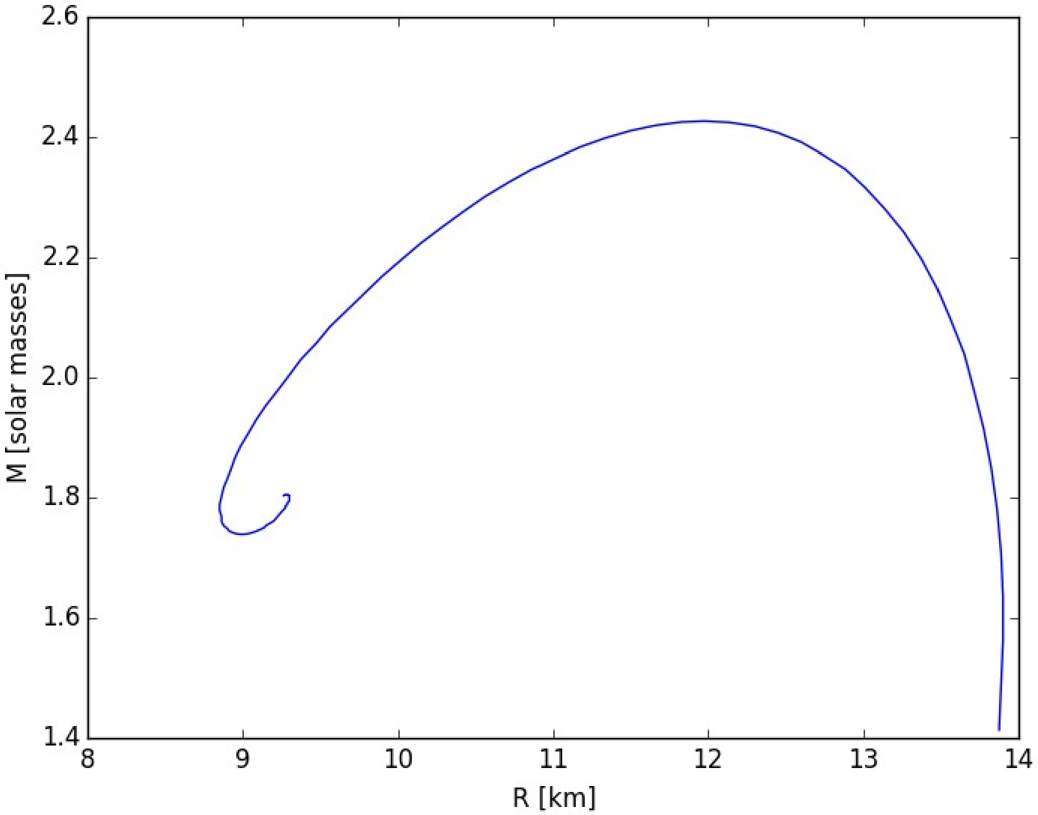
NS Structure

- TOV equation: GR version of HSE

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dp}{dr} = -\frac{G}{r^2}\left[\rho + \frac{p}{c^2}\right]\frac{M + 4\pi r^3 p/c^2}{1 - 2GM/(rc^2)}$$

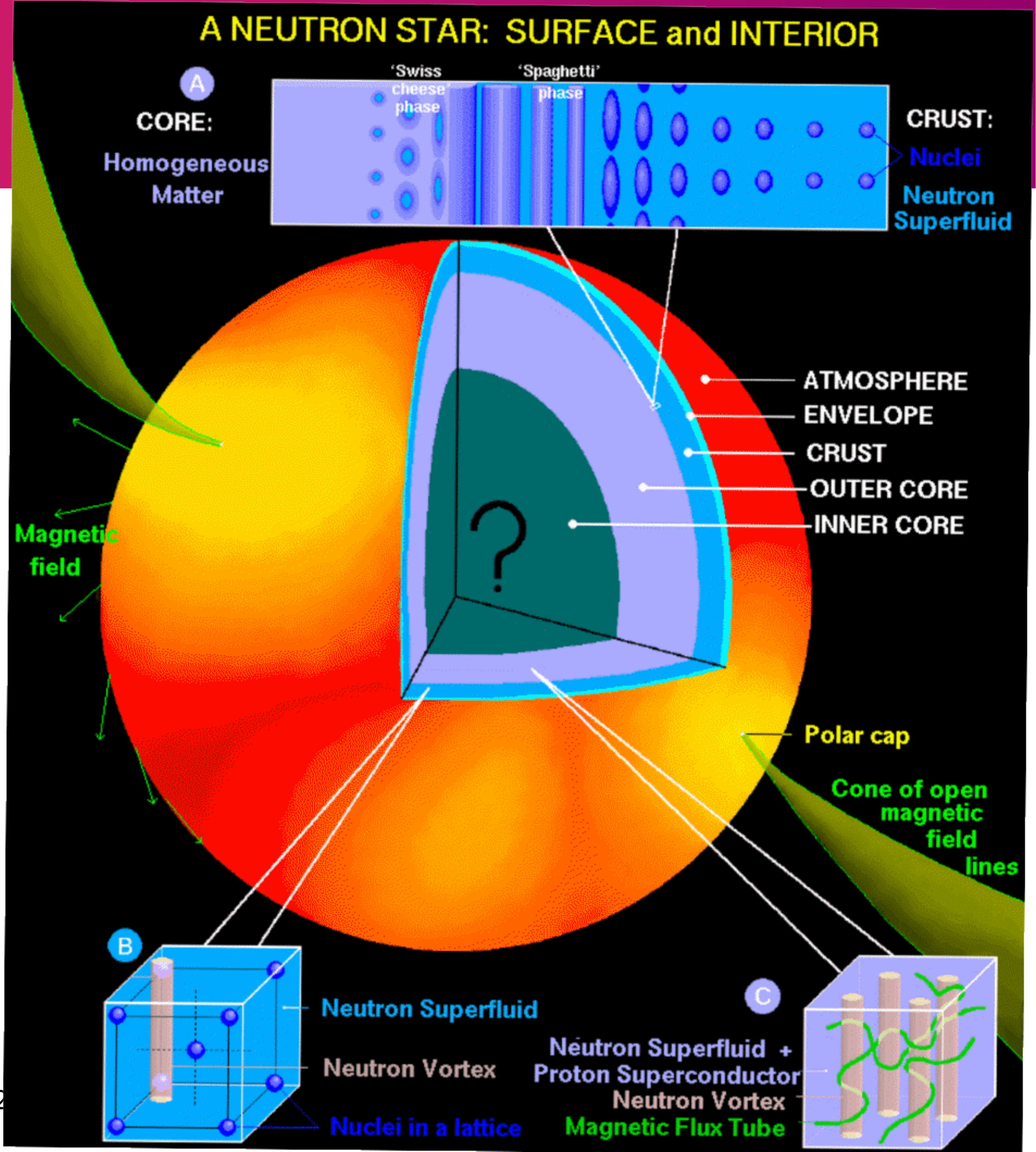
  - Pressure couples to gravity in GR
  - Metric factor



NS Structure

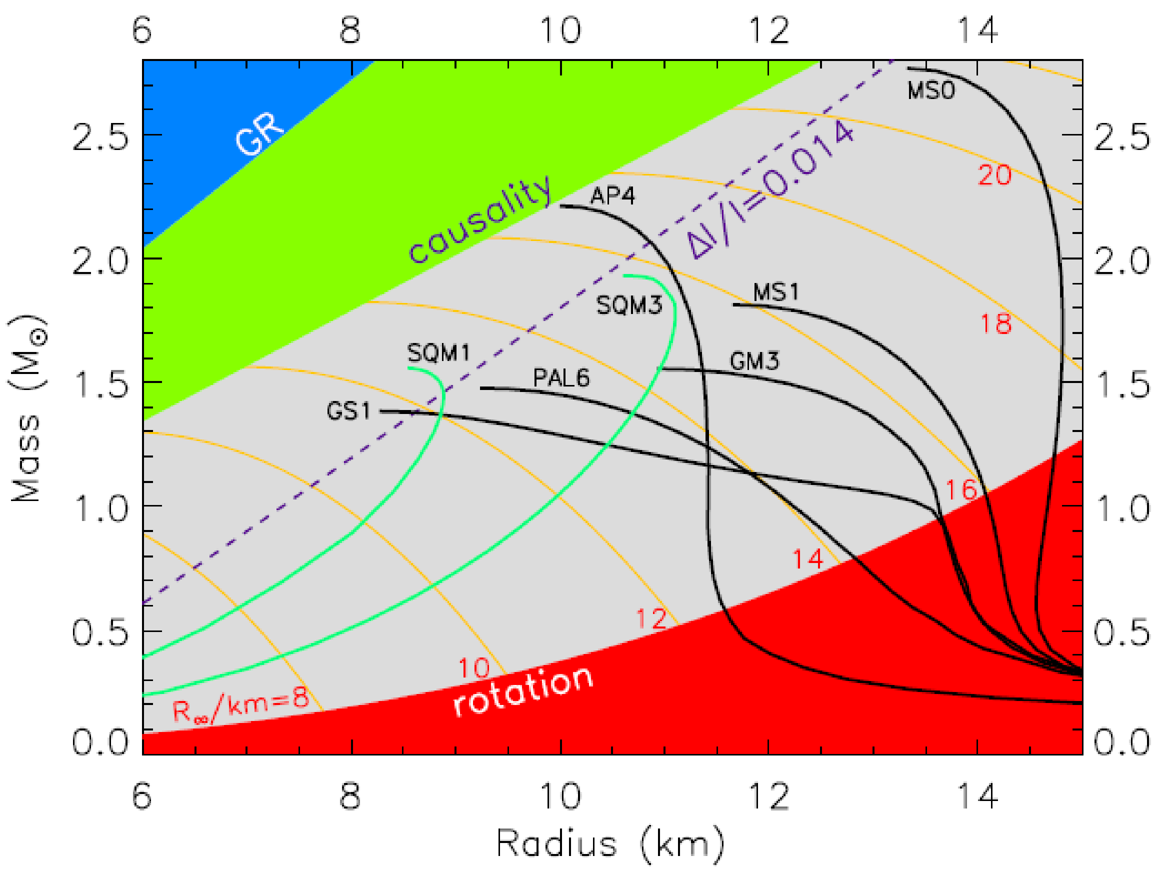
(following Guidry)

- Atmosphere: thin, hot gas
- Envelope / outer crust: lattice or dense liquid of heavy nuclei, e- degeneracy domniates pressure
- Inner crust: free superfluid neutrons "drip" out of nuclei
- Outer core: superfluid neutrons provide most of the pressure
- Inner core: might involve exotic matter



Neutron Stars

- Neutron gas is not a perfect gas
  - Interparticle distance is ~ range of strong force
  - Particles are not free
- Combined effects:
  - GR lowers maximum mass to 0.7 $M_\odot$
  - Strong interaction raises it



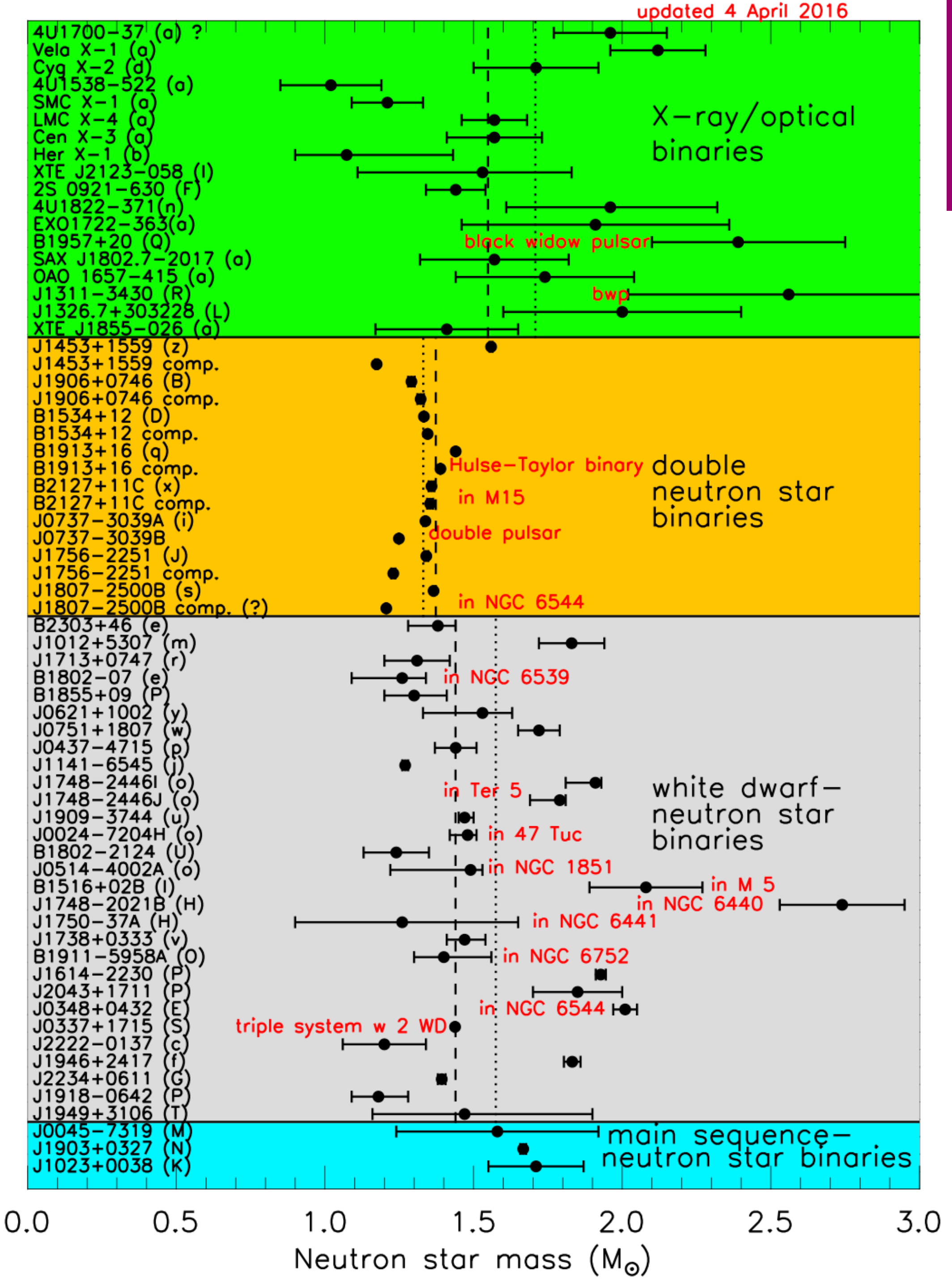
(Lattimer & Prakash, Science 304:536-542,2004)

Neutron Stars

- Neutron stars have a maximum mass—we don't know what it is.
  - Most theories of neutron star structure predict a maximum mass of $\leq 3\ M_{\odot}$.
  - Simultaneous observations of both the mass and radius of individual NSs can constrain the nuclear equation of state
- Above this, there is no other pressure that can kick in to halt the gravitational collapse of the star—a black hole is formed.

Maximum NS Mass

- Some neutron star masses have been found by observing binary systems.



Making Neutron Stars

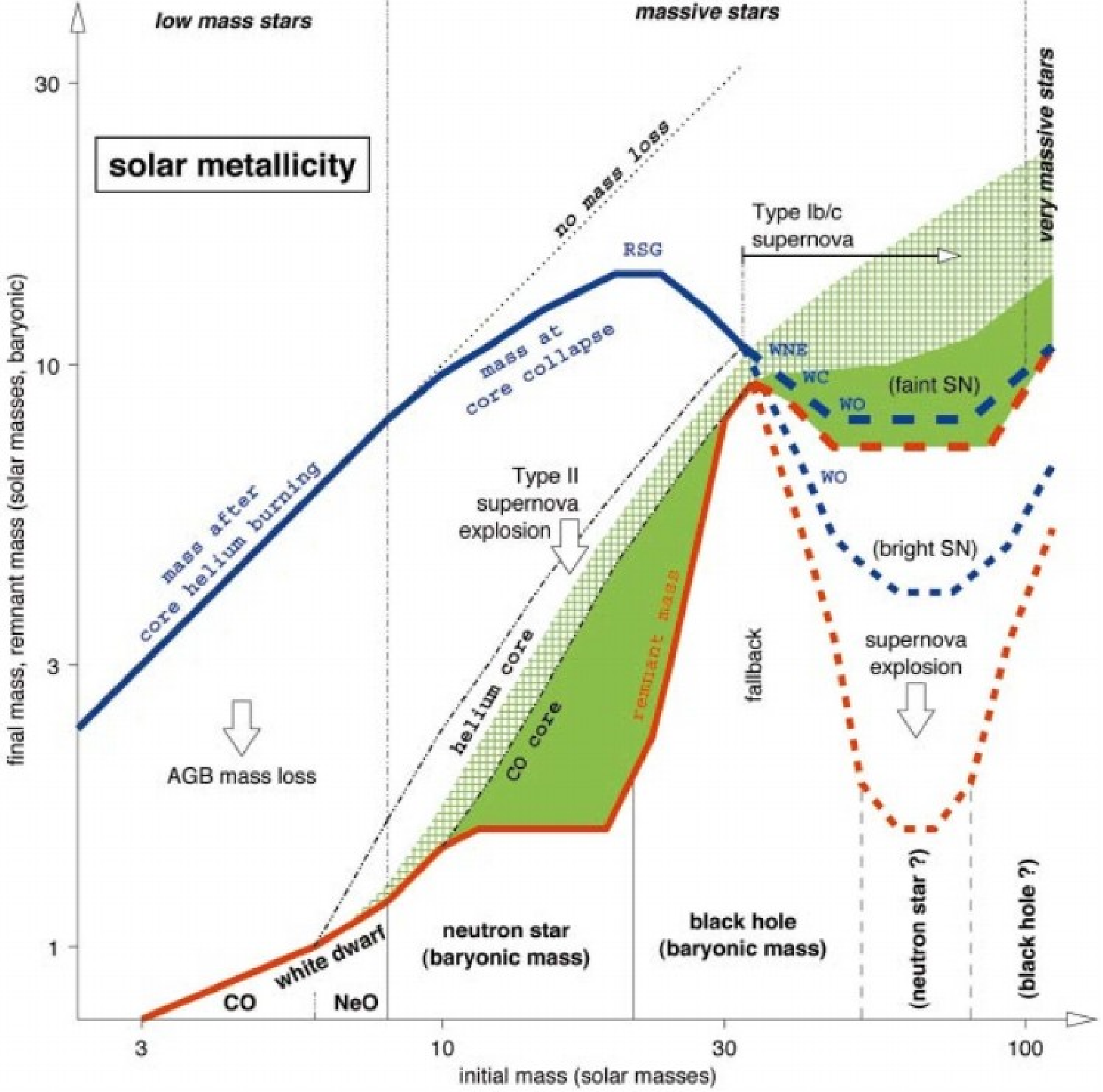
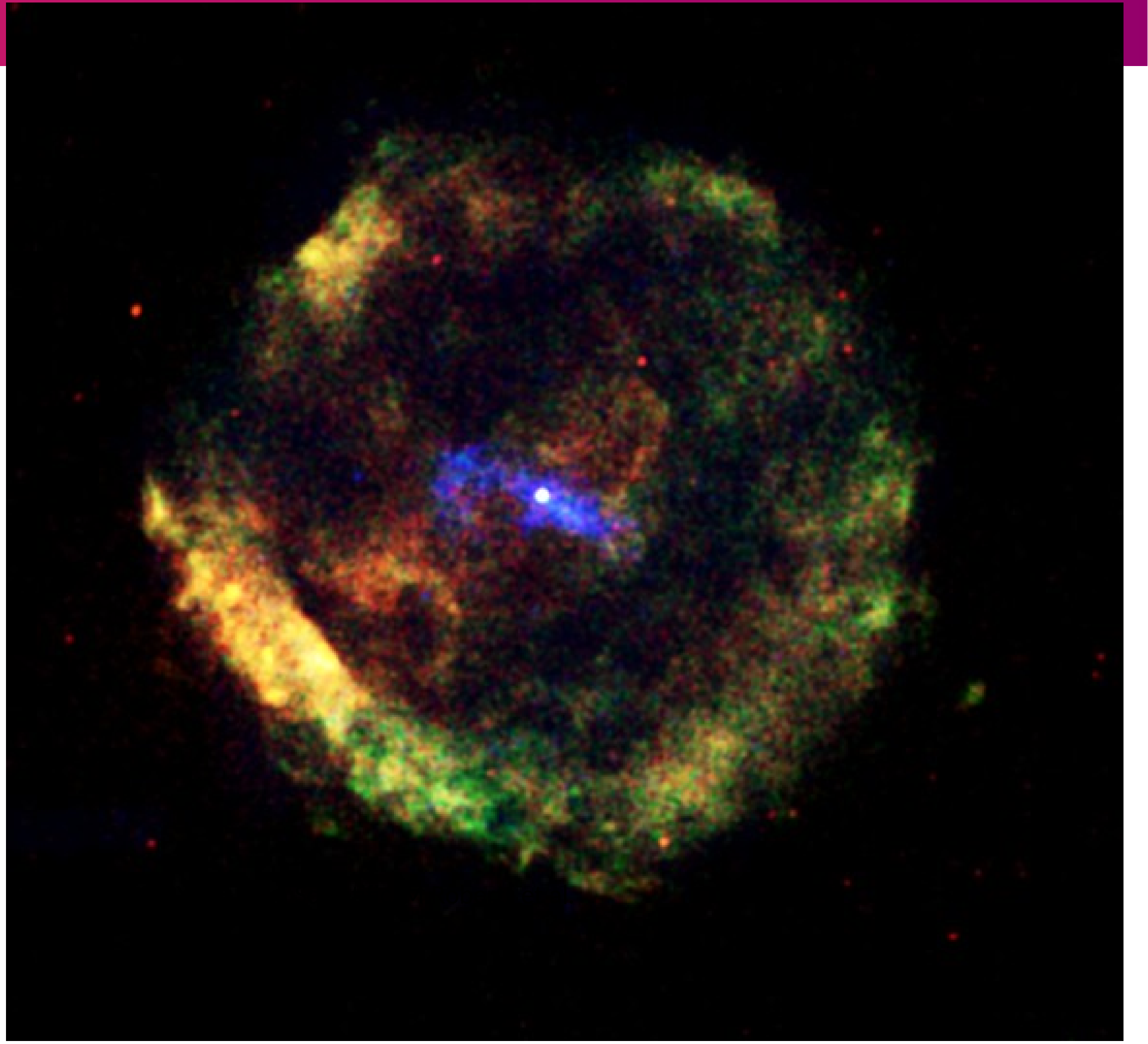


Figure 13.3. Initial-final mass relation for stars of solar composition. The blue line shows the stellar mass after core helium burning, reduced by mass loss during earlier phases. For $M \gtrsim 30\ M_\odot$ the helium core is exposed as a WR star, the dashed line gives two possibilities depending on the uncertain WR mass-loss rates. The red line indicates the mass of the compact stellar remnant, resulting from AGB mass loss in the case of intermediate-mass stars, and ejection of the envelope in a core-collapse supernova for massive stars. The green areas indicate the amount of mass ejected that has been processed by helium burning and more advanced nuclear burning. (Figure from Woosley et al. 2002).

Neutron Stars

- Neutron stars are one of the end states of massive star evolution.
- We know of a number of supernova remnants and sometimes we see a neutron star.
- The gas surrounding the neutron star is the outer layers that were ejected during the explosion.



Chandra image of the supernova remnant G11.2-03. This star exploded in 386 AD. The white dot in the center is a neutron star. (http://chandra.harvard.edu/photo/2007/g11/)

Supernova Remnants

(following Rosswog & Brüggen; Spitzer)

- Evolution of supernova remnants has several phases
  - Kinetic energy is about 1 Bethe (10^{51} erg)

$$v_{\mathrm{ejecta}} \sim 10^4 \text{ km/s} \left(\frac{E_{\mathrm{SN}}}{1 Bethe}\right)^{1/2} \left(\frac{M_{\mathrm{ejecta}}}{M_\odot}\right)^{-1/2}$$

- Phases of evolution
  - free expansion: v is constant
    - generally lasts until swept up mass ~ ejecta mass
    - r ~ v_{ej} t
    - ending condition:

$$M_{\mathrm{swept}} \sim \frac{4\pi}{3} r^3 \rho_{\mathrm{ISM}} \sim M_{\mathrm{ejected}}$$

    - this gives a timescale of ~200 yr

Supernova Remnants

(following Rosswog & Brüggen; Spitzer)

- Sedov-Taylor phase: assume E is constant
  - Energy: $E \propto \rho_{\rm ISM} r^3 v^2 \sim \rho_{\rm ISM} r^3 (\dot{r})^2$
  - Self-similar solution:

$$r \propto \left(\frac{E_{\rm SN}}{\rho_{\rm ISM}}\right)^{1/5} t^{2/5}$$

    - This is called a Sedov explosion
    - Deceleration as it expands
    - Strong heating behind the shock—you can get the post-shock state via jump-conditions
- Snowplow phase: momentum is constant
  - radiative cooling becomes important
  - momentum is constant, material piles on and shell slows
- Remnants merges with ISM

Supernova Remnants

(following Rosswog & Brüggen; Spitzer)

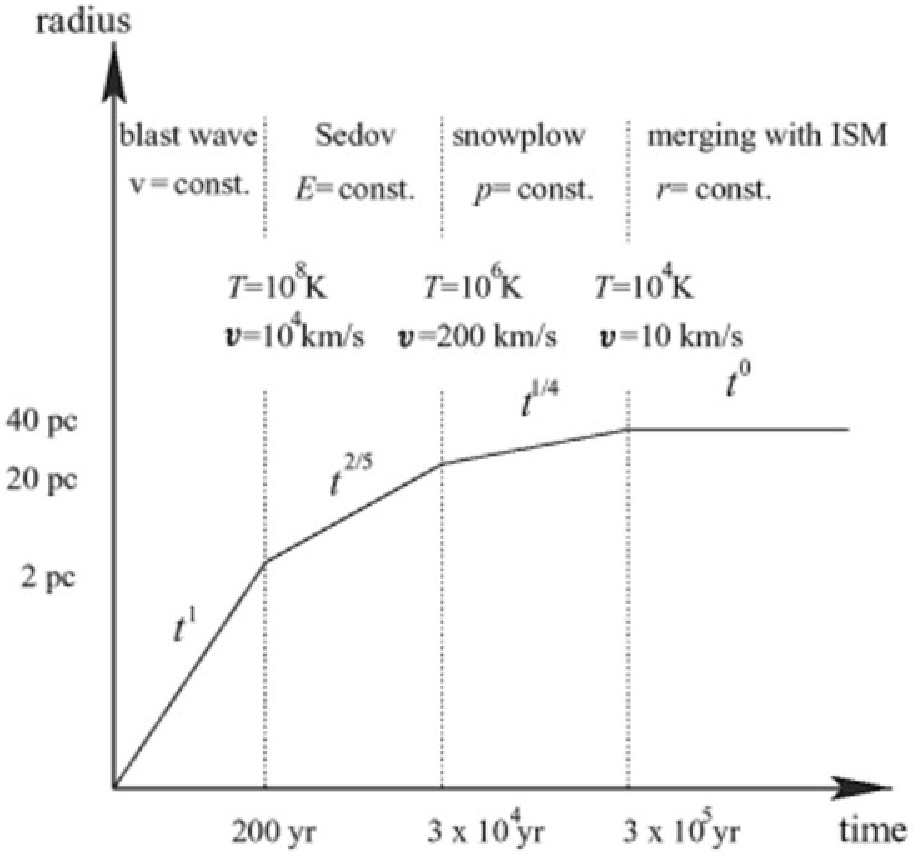
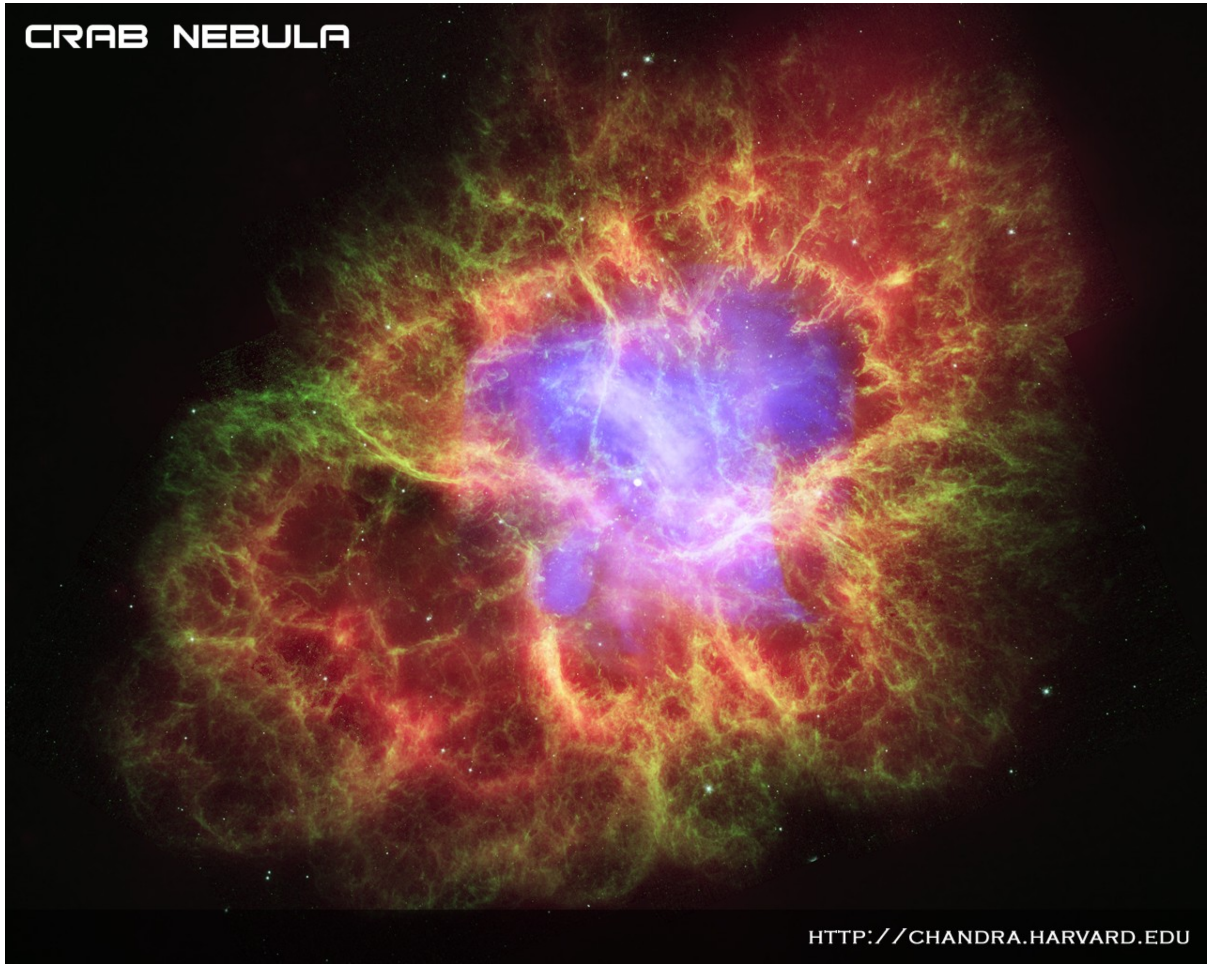


Figure 4.9 An illustration of the four different phases in the dynamics of a supernova remnant (SNR). As described in the text, we distinguish between the blast-wave stage, the Sedov phase, the snowplow phase, and the final phase where the SNR merges with the ISM. Rough estimates for the temperatures and velocities at the end of each phase are given.

(from Rosswog & Bruggen)

Supernova Remnants

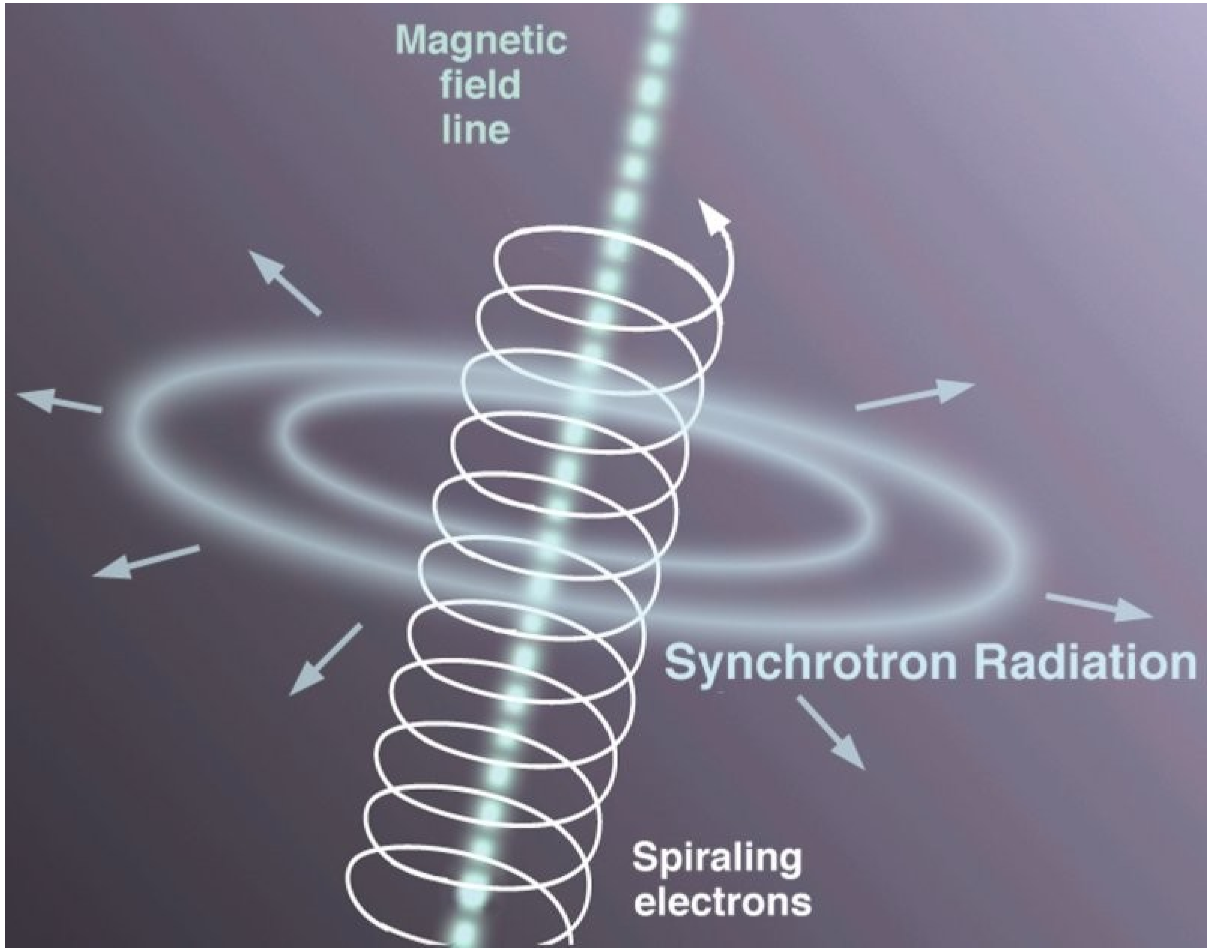
- Crab nebula—remnant of a core-collapse supernova (1054).
  - X-rays (blue/purple)
  - optical (green)
  - infrared (red)
  - Bright point at center: rapidly spinning neutron star.



Credit: NASA - X-ray: CXC, J.Hester (ASU) et al.; Optical: ESA, J.Hester and A.Loll (ASU); Infrared: JPL-Caltech, R.Gehrz (U. Minn)

Supernova Remnants

- Supernova remnants have strong magnetic fields.
- Synchrotron radiation: electrons interacting with B fields
  - Electrons spiral around the magnetic field lines.
  - Accelerating changes radiate
  - Radiation non-thermal (not a blackbody)
  - Radiation is polarized.
- Most of the radiation is in long wavelengths
  - Intensity falls off as power law.
- Spiraling electrons radiate energy—they must be slowing down.
  - Pulsar is energizing the nebula



(Gemini)

Spinning Neutron Stars

- Shrink Sun down to neutron star size, conserving angular momentum:

$$\left(\frac{\omega_{\rm NS}}{\omega_\odot}\right) = \left(\frac{R_\odot}{R_{\rm NS}}\right)^2 = \left(\frac{7\times10^{10}\ \rm cm}{1.5\times10^6\ \rm cm}\right)^2 = 2\times10^9$$

- The rotation period of the Sun is 30 days (2.6 x 10^6 s), and

$$P \sim 1/\omega$$

- So our neutron star period is $P_{\rm NS} \sim 1.3\times10^{-3}\ \rm s$

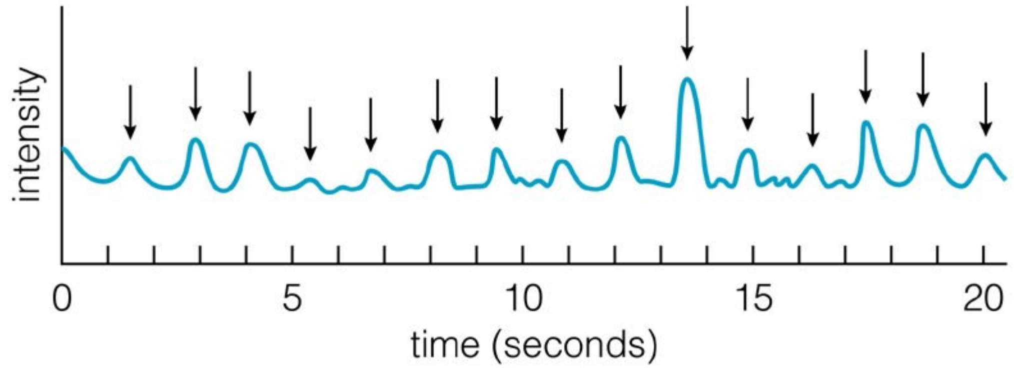
  A neutron star could be rotating 1000 times per second!

- Similarly, magnetic flux conservation gives:

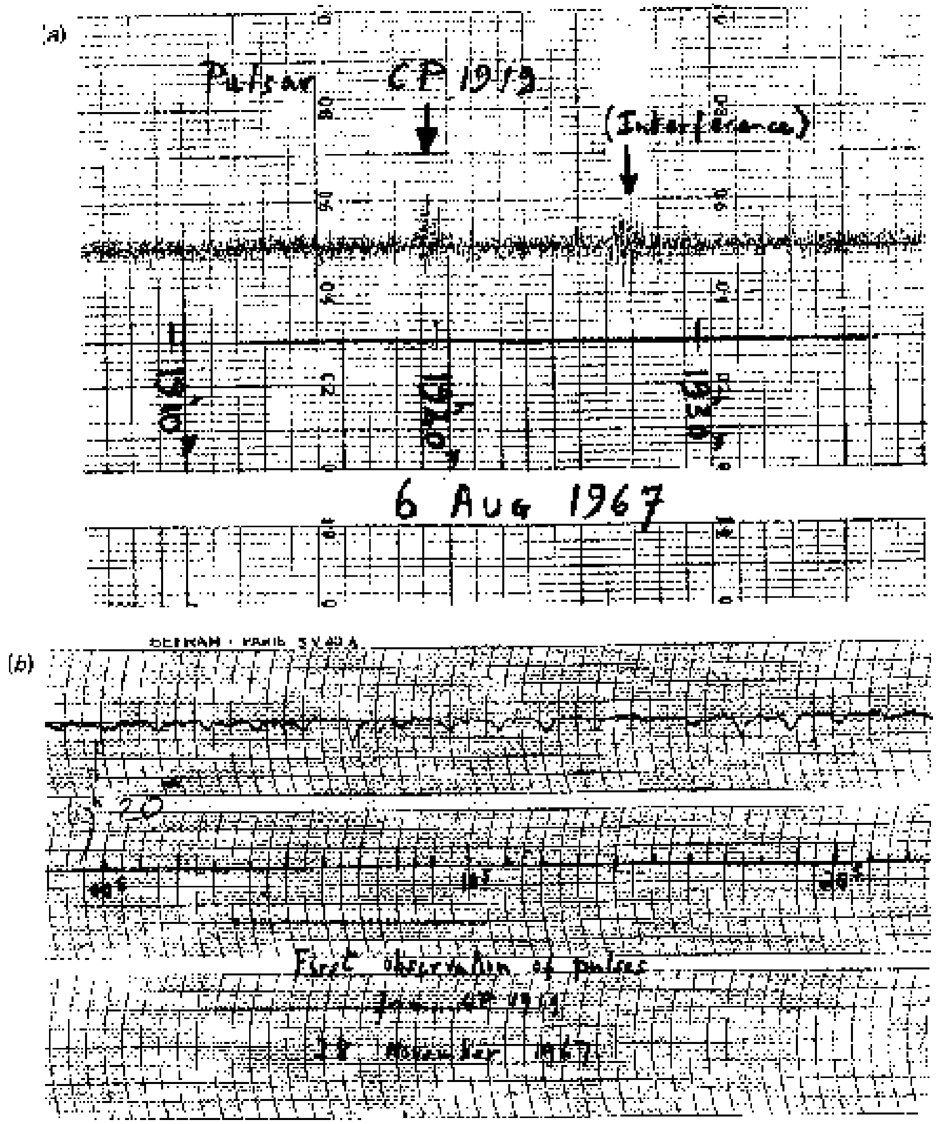
$$B_{\rm NS} = \left(\frac{R_\odot}{R_{\rm NS}}\right)^2 B_\odot \sim 2\times10^9\ B_\odot$$

Pulsars

- Jocelyn Bell Burnell and Antony Hewish found a rapidly varying radio source (1967).
  - Signal was composed of pulses, with a very regular period.
  - Eventually more such sources were found.
  - These sources were named pulsars.



(from Bennett et al.)



A. G. Lyne and F. G. Smith. Pulsar Astronomy. Cambridge University Press, 1990.; http://www.atnf.csiro.au/research/pulsar/Tutorial/tut/node3.html

Pulsars

- Distribution on the sky (in galactic plane) supports a Galactic origin

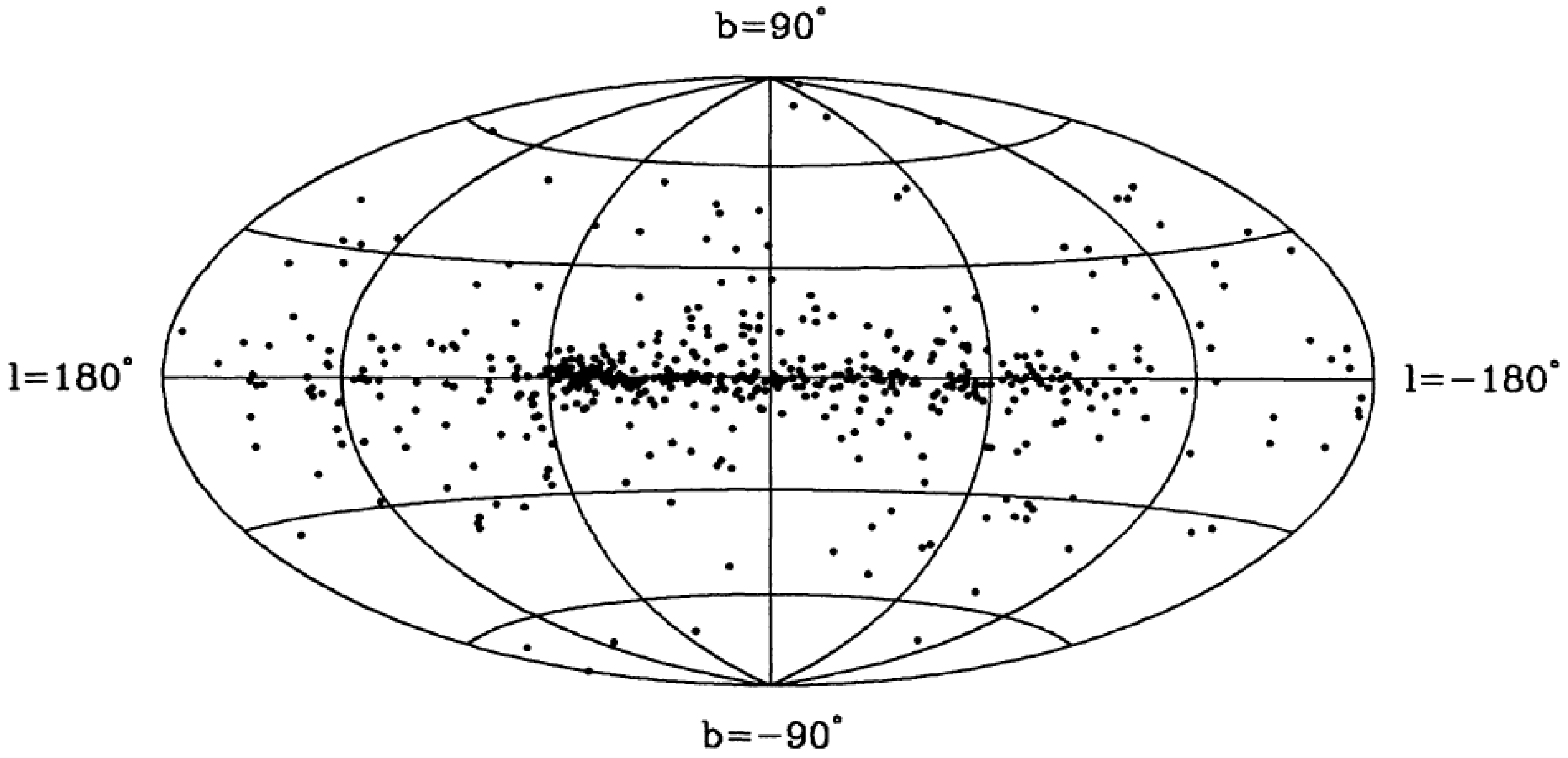


FIG. 1.—Distribution of 558 pulsars in Galactic coordinates, using the Hammer-Aitoff equal-area projection. The Galactic center is in the middle of the figure, and longitude increases toward the left.

What Are Pulsars?

- Pulsation:
  - Timescale is $t \sim (G\rho)^{-1/2}$
  - Densities needed is higher than a WD but lower than a NS
- Orbital motion (Kepler's laws):

$$\frac{4\pi^2 R^3}{G} = (m_1 + m_2)P^2$$

  - P = 1 s implies R ~ 2000 km, P = 0.1 s, R ~ 100 km.
    - These R < radius of a normal star or white dwarf.
    - Two neutron stars could work though.
  - Pulsar radiates → orbital E decreases → more bound (smaller R).
    - Decrease in R → decrease in P
    - GR also says that this system emits gravitational radiation
    - Observations: pulsars periods increase with time, not decrease

What Are Pulsars?

- Rotation:
  - Gravitational force on the outer layers > centrifugal force

$$\frac{GMm}{R^2} > \frac{mv^2}{R}$$

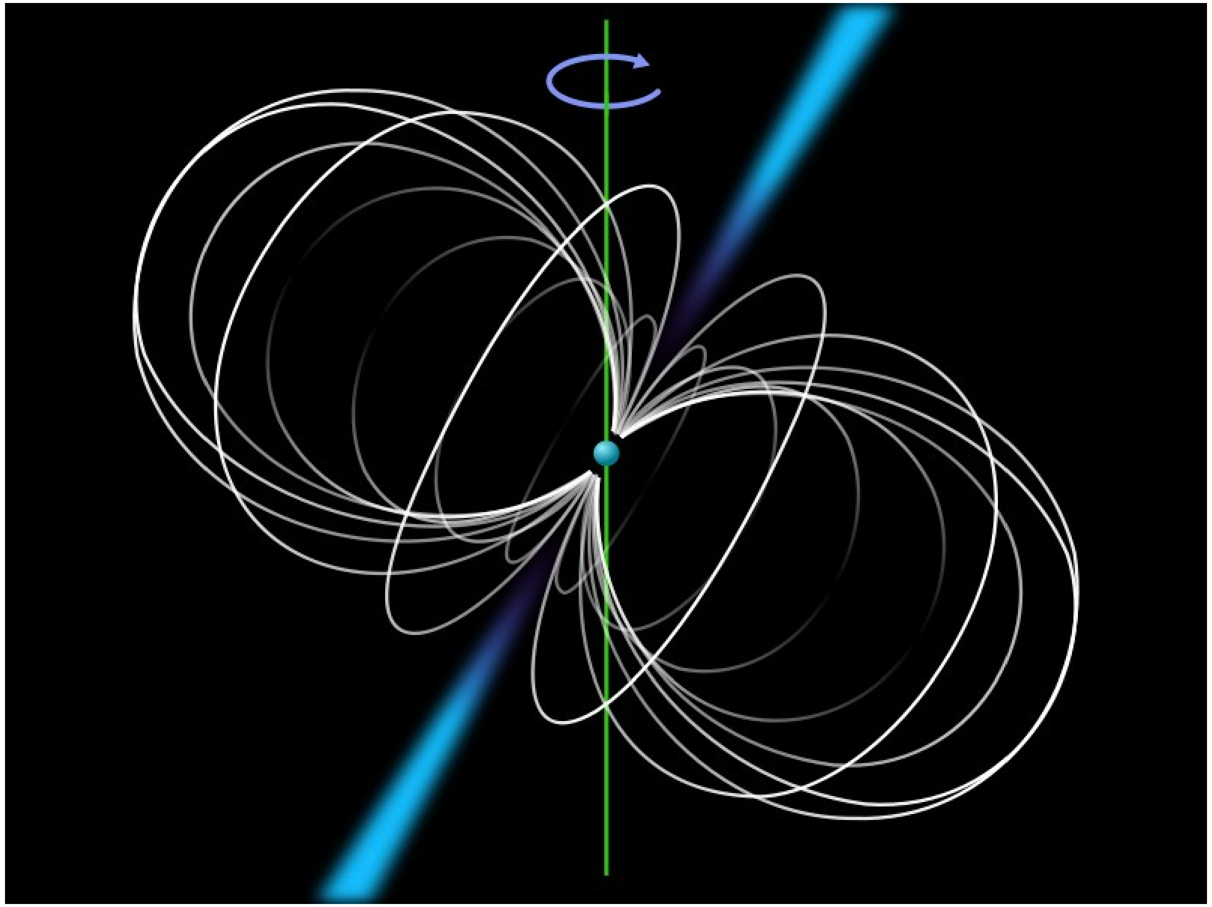
    - Now, $v = 2\pi R/P$, so

$$\frac{4\pi^2 R^3}{G} < MP^2$$

    - Normal stars and WDs cannot spin fast enough
    - Neutron stars work!

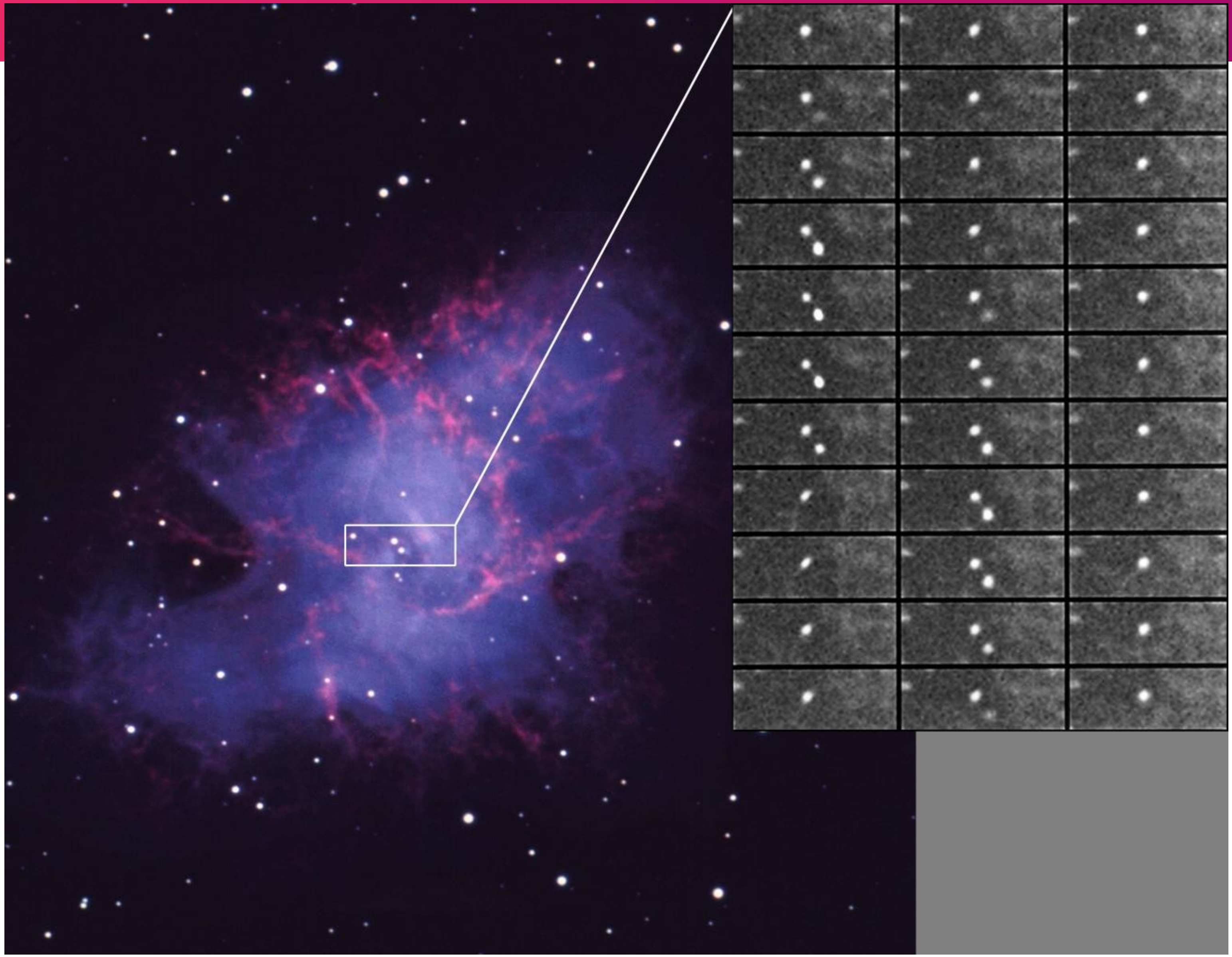
Pulsars

- Pulsar: beamed emission from the magnetic poles of NS, rotating in and out of our view.
  - Pulse period is rotation rate
- Emission not fully understood.
  - Strong, rotating magnetic field → electric field
  - Charged particles come off NS surface
  - Emission mechanism due to relativistic energies.
- Misalignment of the rotation and magnetic poles: magnetic poles come into and out of view.



(Wikipedia/User:Mysid, User:Jm smits)

Crab Nebula



N.A.Sharp/NOAO/AURA/NSF
http://www.noao.edu/image_gallery/html/im0565.html

Crab Nebula

Close up of the Crab pulsar showing activity surrounding the neutron star.

X-ray (blue) and optical (red) are shown.

(NASA/CXC/ASU/J. Hester et al.; http://hubblesite.org/newscenter/archive/releases/2002/24/image/a)

Pulsars

- Pulsars slow down—periods increase.
  - The faster the pulsar, in general, the faster it is slowing down.
  - Faster pulsars = youngest.
- Pulsar period increase = slower rotation—i.e. KE decreases.
- Eventually, they spin so slowly, that they can no longer generate the E fields to produce emission
- Pulsar lifetime can be estimated spin down rate
  - t ~ 10^4 yr

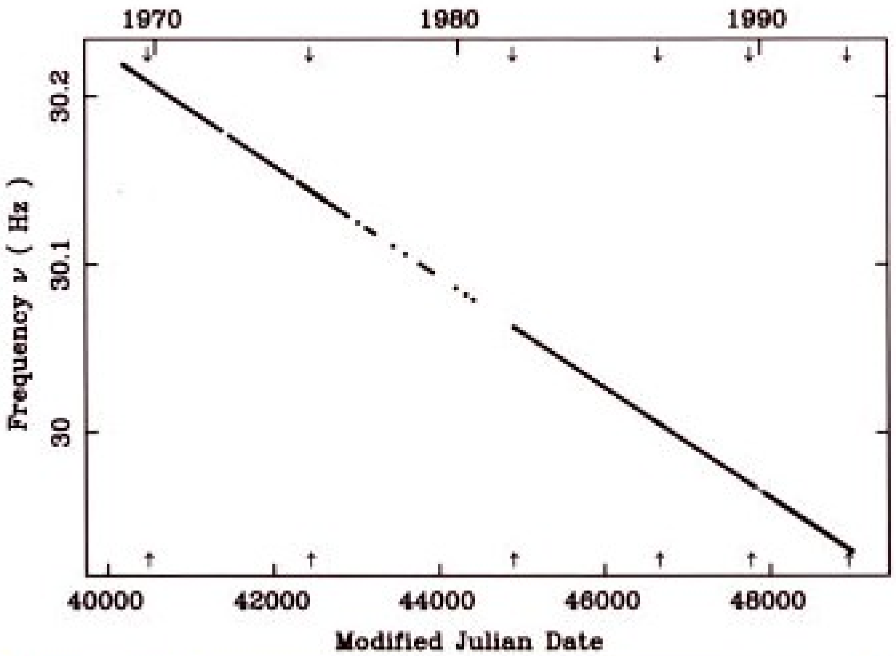


Fig 11.12. Period changes for the Crab pulsar. The general slowdown is clear. Glitches, brief period increases, are indicated by the locations of the arrows. [Michael Kramer/Lyne & Smith, Pulsar Astronomy, 2nd edn, CUP]

(from Kutner)

Pulsars

- Some pulsars also show period glitches—sudden changes likely due to sudden changes in the neutron star radius—star quakes.

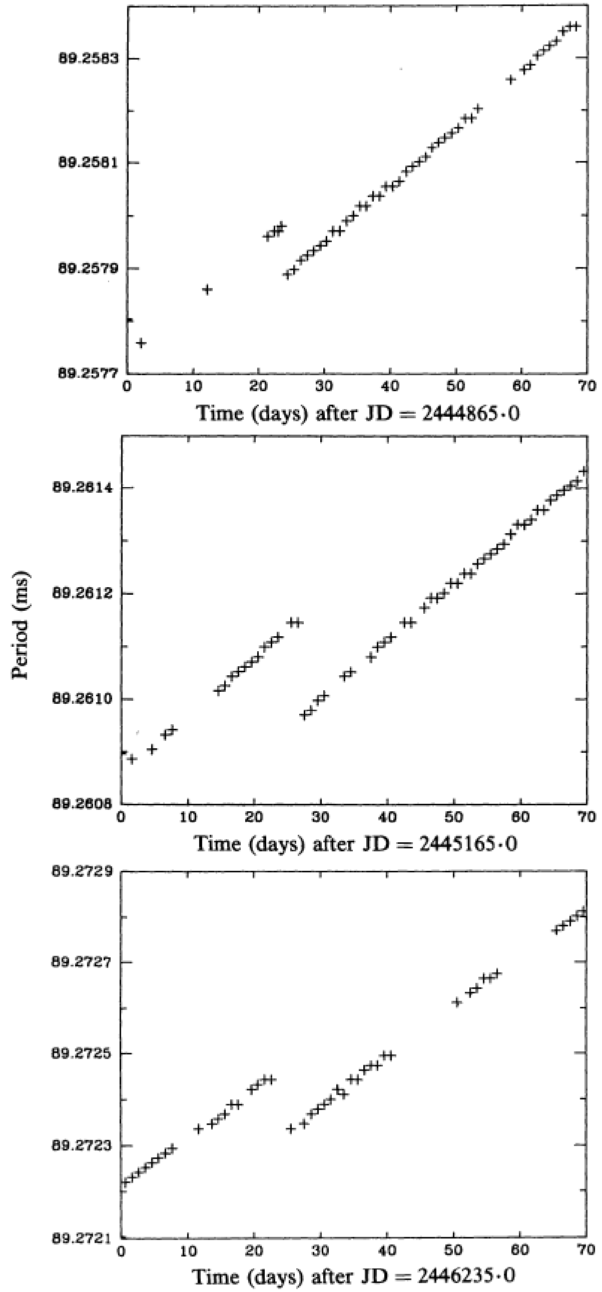


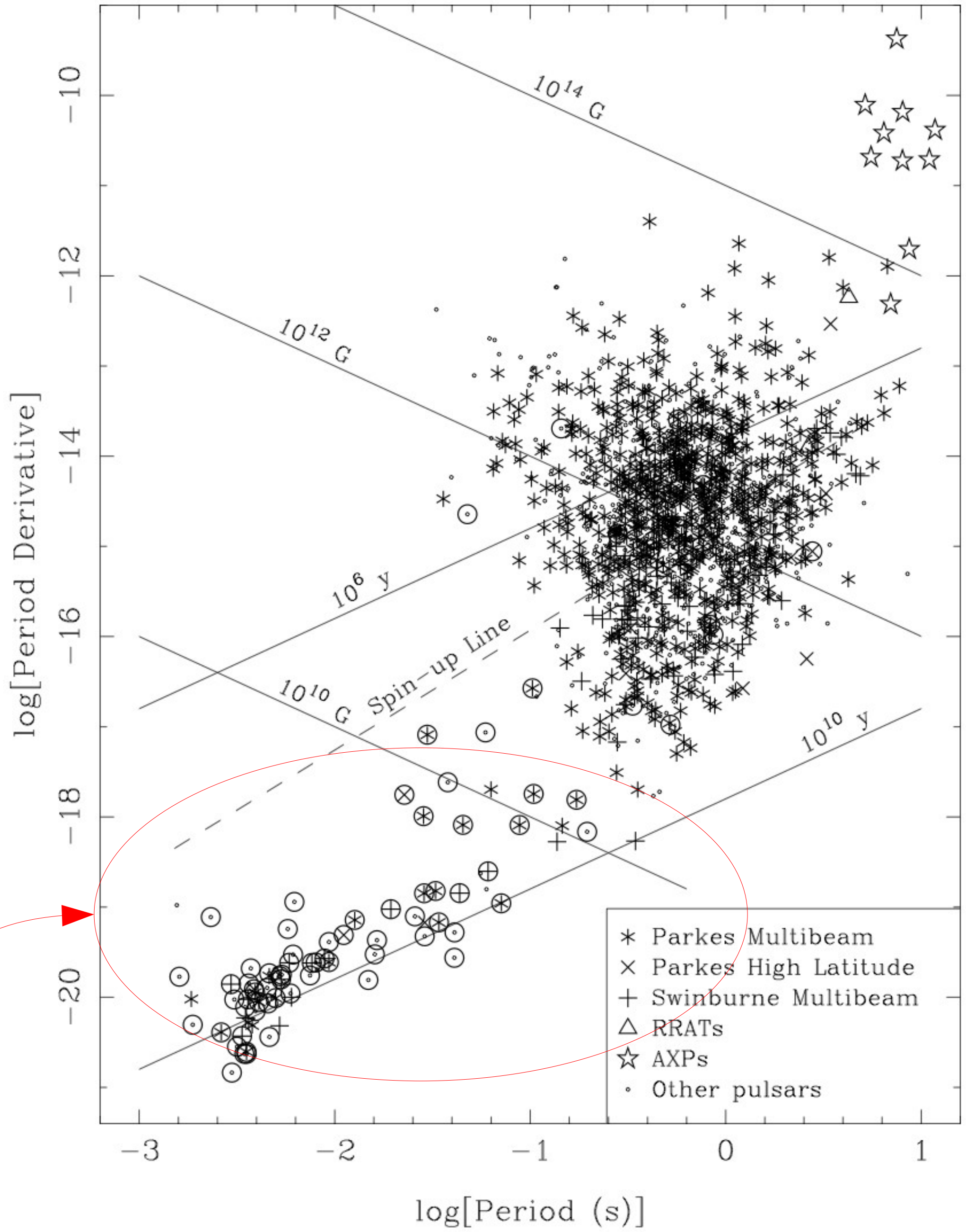
Fig. 1. Plots of the pulsar period determined daily about the time of occurrence of each of the three period jumps. (McCulloch, P. M. et al. 1987, Aust. J. Phys. 40, 725)

Pulsars

- A wide range of periods are observed in pulsars—from milliseconds to a second.
- Spin down is due to emission of magnetic dipole radiation
- Magnetic field strength can be shown to be

$$B \propto \sqrt{P\dot{P}}$$

  - Young pulsars have large magnetic fields
- Magnetars: extremely high B fields
  - powered by magnetic field decay, not rotation



These have been "spun-up" via accretion.

R. N. Manchester, CSIRO/ATNF
http://www.atnf.csiro.au/news/newsletter/jun06/RRATs.htm

Pulsars

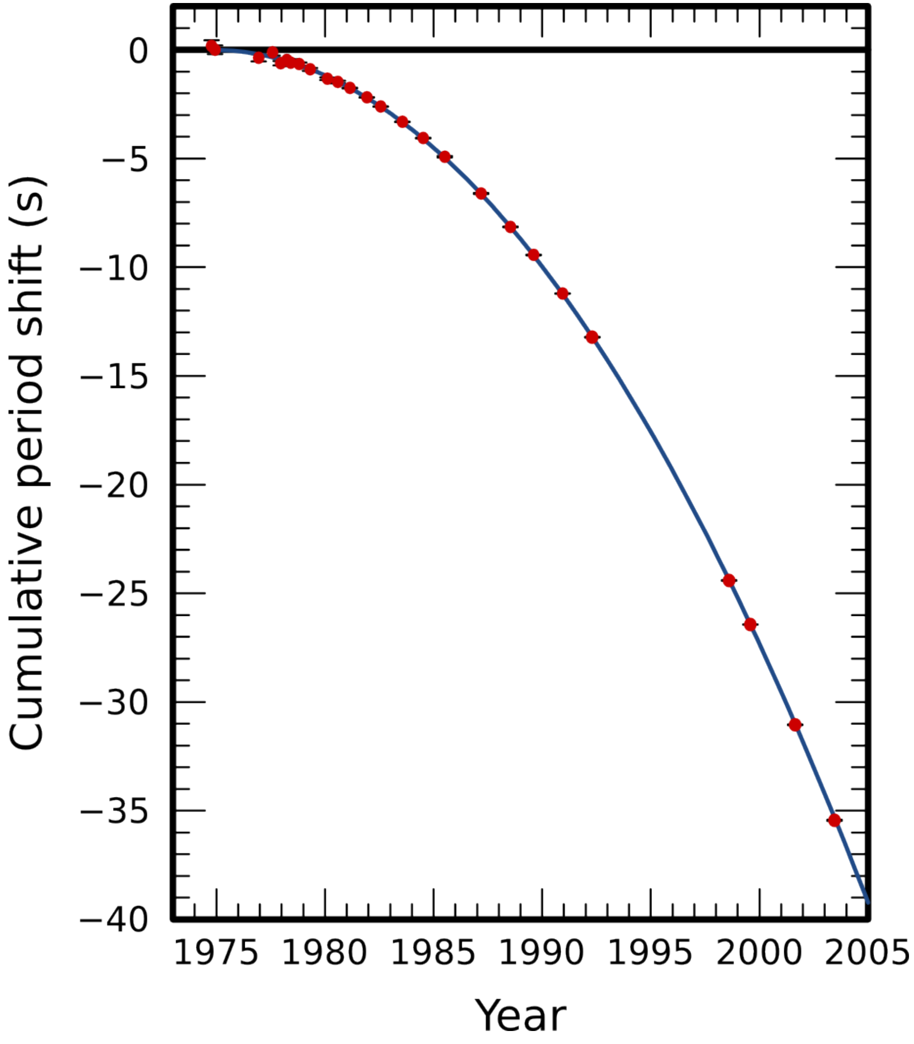
- Types:
  - Rotation powered pulsars—these are what we've mainly been talking about
  - Accretion powered pulsars: gravitational potential energy of accreted matter produces X-rays
  - Magnetars: decay of magnetic field
- Some gamma-ray-only pulsars have recently been discovered

Pulsars Uses

- The gold record on the Pioneer & Voyager probes indicated the location of our solar system using relative distances to pulsars
  - Pulsars are identified by unique timings
  - This same technique could be used for spacecraft navigation
- Pulsars can probe the ISM
  - Dispersion of the pulse as it travels to us allows us to infer the electron column density along the line of sight
- Pulsars are also being used as gravitational wave detectors
  - Delays in arrival times from millisecond pulsars can arise from gravitational waves

Binary Pulsars

- Some pulsars have been found in binary systems
  - companion often a white dwarf or neutron star
  - orbit decays due to gravitational radiation
- Important test of GR
  - Double pulsars exist.



binary star system PSR B1913+16 (Wikipedia / InductiveLoad)

End States of Massive Stars

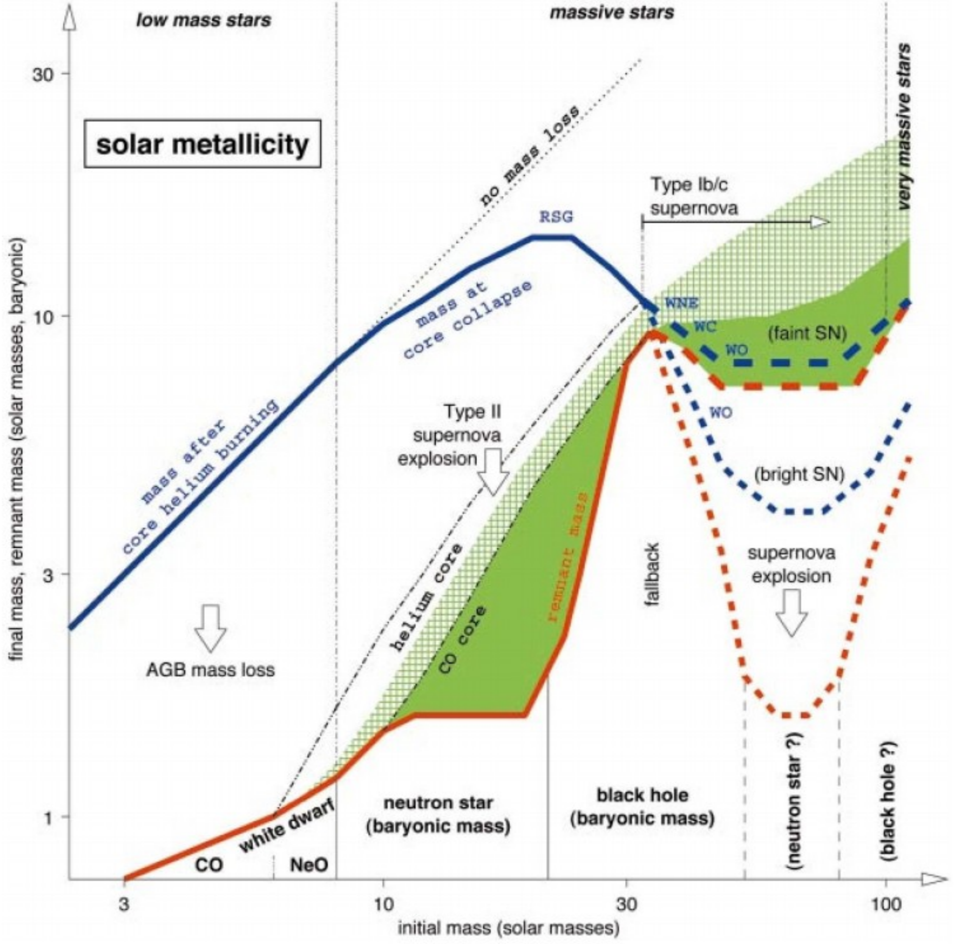


Figure 13.3. Initial-final mass relation for stars of solar composition. The blue line shows the stellar mass after core helium burning, reduced by mass loss during earlier phases. For $M \gtrsim 30\ M_\odot$ the helium core is exposed as a WR star, the dashed line gives two possibilities depending on the uncertain WR mass-loss rates. The red line indicates the mass of the compact stellar remnant, resulting from AGB mass loss in the case of intermediate-mass stars, and ejection of the envelope in a core-collapse supernova for massive stars. The green areas indicate the amount of mass ejected that has been processed by helium burning and more advanced nuclear burning. (Figure from Woosley et al. 2002).

Pair Instability Supernovae

- Really massive stars go unstable before the iron core forms
  - electron/positron pair production kicks
    - in our eos regime diagram, this is when $kT \sim 2\, m_e\, c^2$
      - $T \sim 10^9$ K
    - lowers adiabatic exponent to be < 4/3—dynamic instability kicks in
      - Similar to the effect that ionization has on the adiabatic index
  - core is massive—collapses into a black hole
  - 40 $M_\odot$ of ^{56}Ni may be produced
- May especially be important for the first stars (pop III)

Pair Instability Supernovae

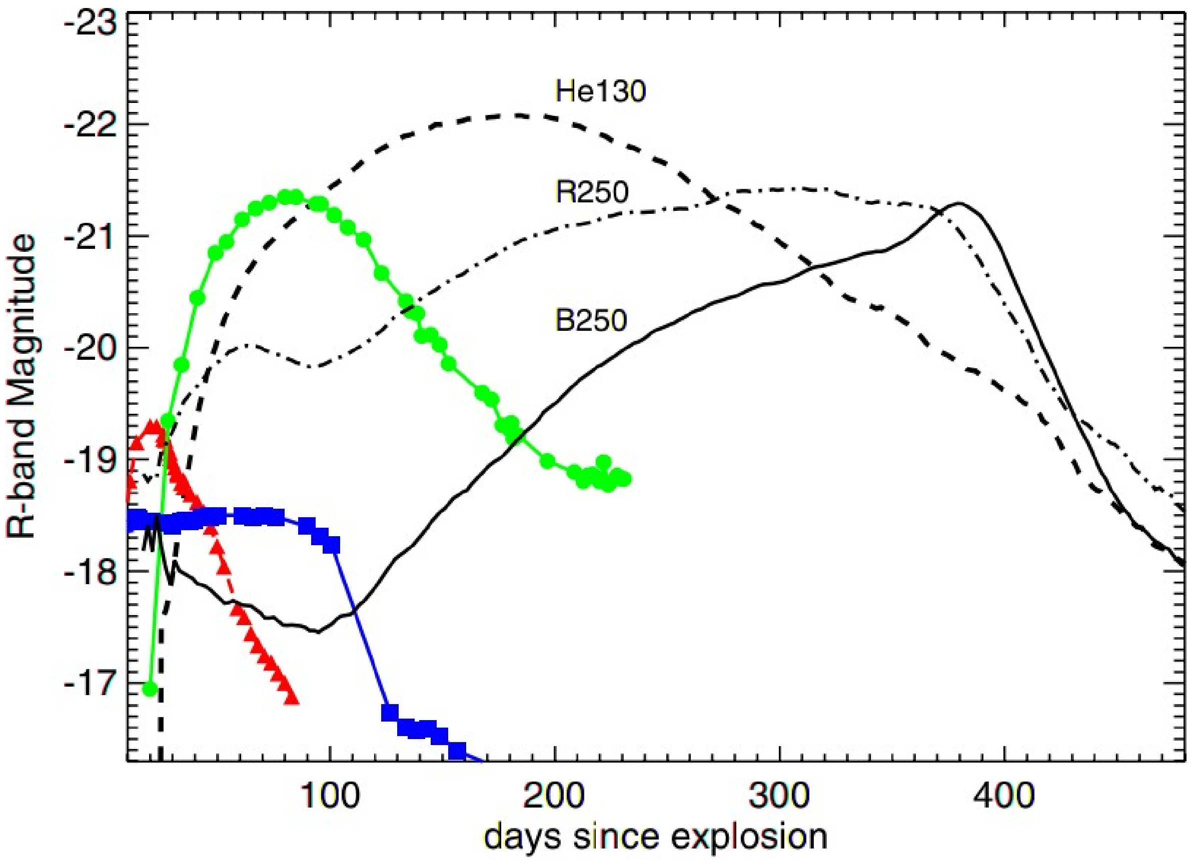


Figure 6. Synthetic *R*-band light curves (at $z = 0$) of bright PI SN models—R250 (dashed-dot), B250 (solid), and He130 (dashed)—compared to observations of a normal Type Ia supernova SN 2001el (red triangles; Krisciunas et al. 2003), a normal Type IIP supernova SN 1999em (blue squares; Leonard et al. 2002), and the overluminous core-collapse event SN 2006gy (green circles; Smith et al. 2007).

(Kasen, Woosley, & Heger, 2011)

Gamma-Ray Bursts

- 1960s spy satellites saw bursts of gamma-rays coming from space (not terrestrial thermonuclear explosions)
  - announcement of discovery waited until 1973 (Klebesadel et al.)
- Lots of initial ideas

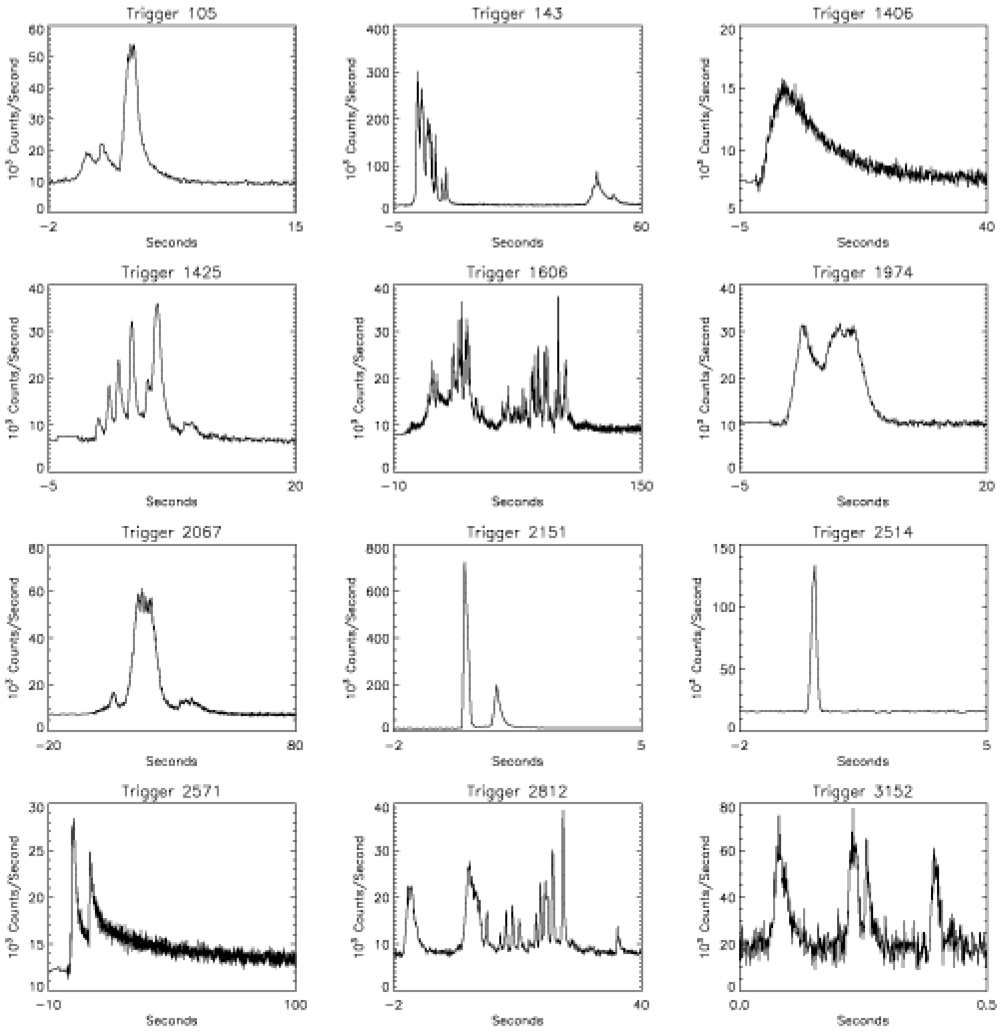
Ray Bursts

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E-field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS wanders though Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NS
88.	Trofimenko	1989	Ap & SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRBs
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapsed to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

Table from: Nemiroff, R. J. 1993, Comments on Astrophysics, 17, No. 4, in press

Gamma-Ray Bursts

- Lightcurves:

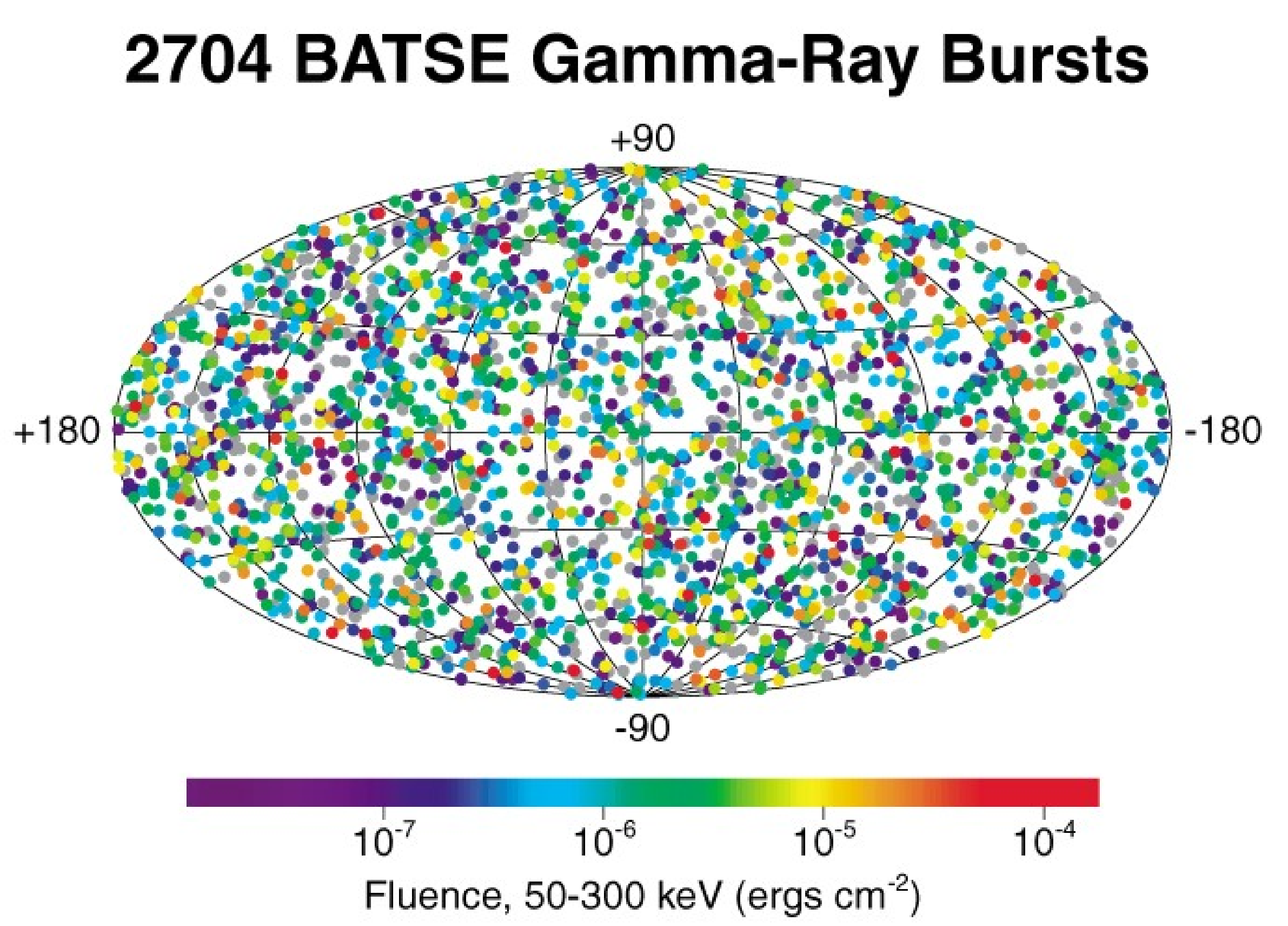


(Credit: J.T. Bonnell (NASA/GSFC))

Galactic or Cosmological?

- Gamma-ray observations are hard, and tend to have poor pointing (atleast for early instruments) making the identification of sources difficult
- What was know initially: short timescale of fluctuations implies that a compact object needed to be involved
- Main dilemma:
  - an enormous energy flux is recorded
  - galactic origin means that total energy release is a lot lower (and deemed more feasilble initially)
- Compton Gamma-Ray Observatory launched in 1991 had 8 gamma-ray detectors (at corners)

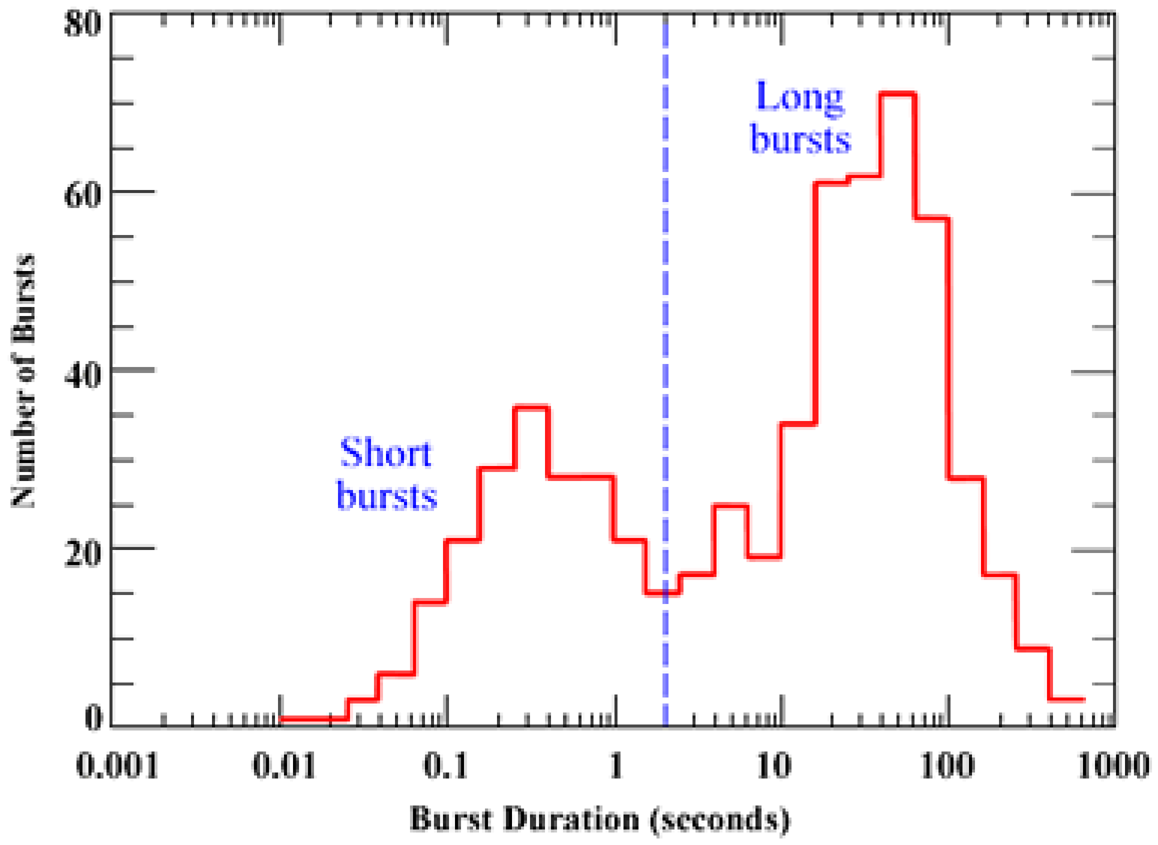
Gamma-Ray Bursts



http://heasarc.gsfc.nasa.gov/docs/cgro/cgro/batse_src.html

Gamma-Ray Bursts
(following Rosswog and Bruggen)

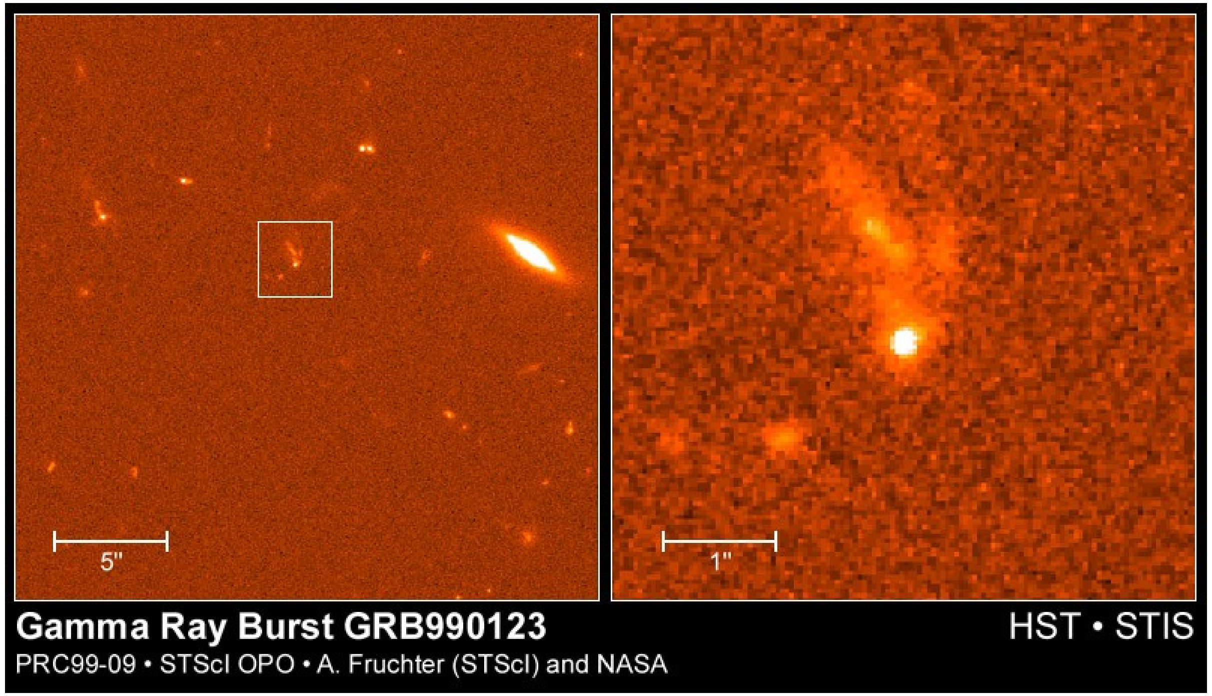
- Two populations
  - Long and short based on duration
  - Short burst spectra are harder (emission at higher energy photons / lower energy is larger)
- Note that spectra are non-thermal
- Two models
  - Relativistic jets in core-collapse supernova (long)
  - Merging neutron stars (short)



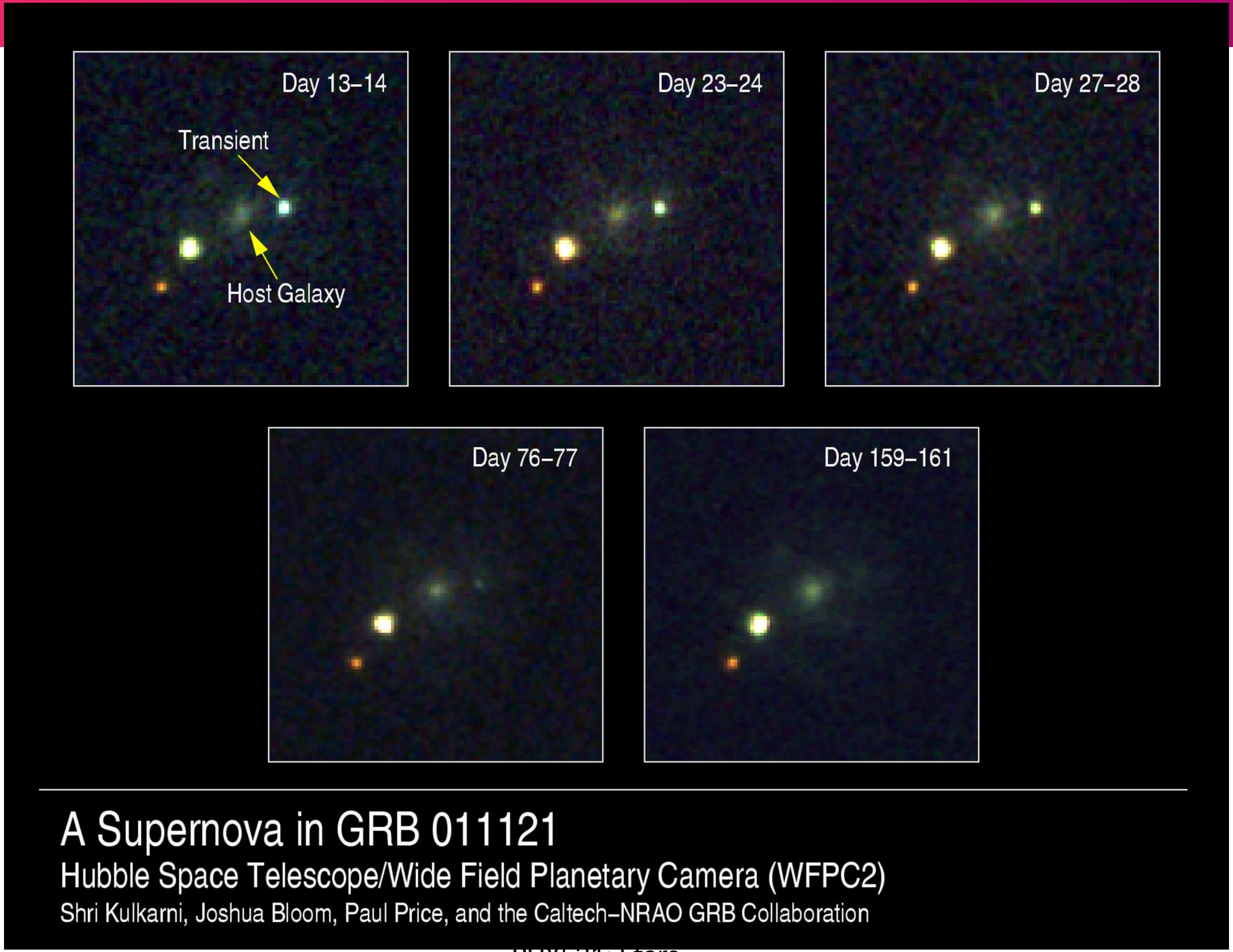
(Cosmos: SAO encyclopedia of Astronomy)

Gamma-Ray Bursts

- Debate for many years whether cosmological or galactic
  - An isotropic distribution could still be in the halo of our galaxy
- Energy budget for the two cases is vasty different
- Finally settled when an X-ray afterglow was detected
  - host galaxy could have redshift measured
  - Atleast long GRBs are cosmological



Gamma-Ray Bursts



Coincident GRB and SN!

GRB Energy Budget

(following Rosswog and Bruggen)

- Energy requirements can be dramatically lowered if the gamma-ray emission is collimated

$$E_{\rm true} = E_{\rm isotropic} \frac{\Delta\Omega}{4\pi}$$

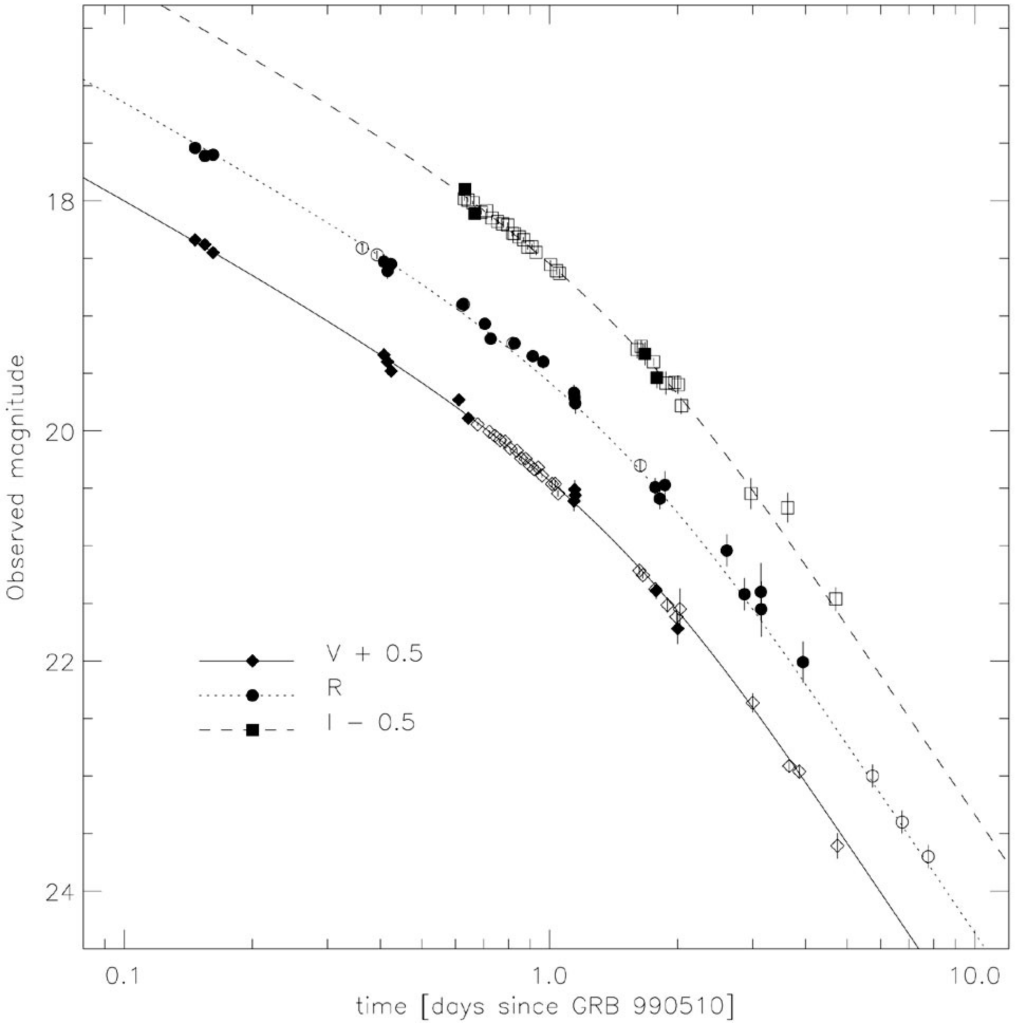
  – assuming a small angle:

$$\Delta\Omega \approx 4\pi \left(\frac{\theta_j^2}{2} \right)$$

- Beaming factor, $f \sim 4\pi/\Delta\Omega$, is small
  – burst only observed if we are looking down the beam
  – jet openning, $\theta \sim 1/\gamma$ (this is relativisitic beaming, aka, “headlight effect”)
  – relativistic beaming means that we can see more of the jet as the Lorentz factor drops
  – when we slow down enough, we can see more than the jet width—break in the lightcurve

GRB Jets

- Lightcurve breaks support jet model for long bursts
  - openning angles are ~4°
- Energy budget reduces to 10^{51} erg



(Harrison et al. 1999)

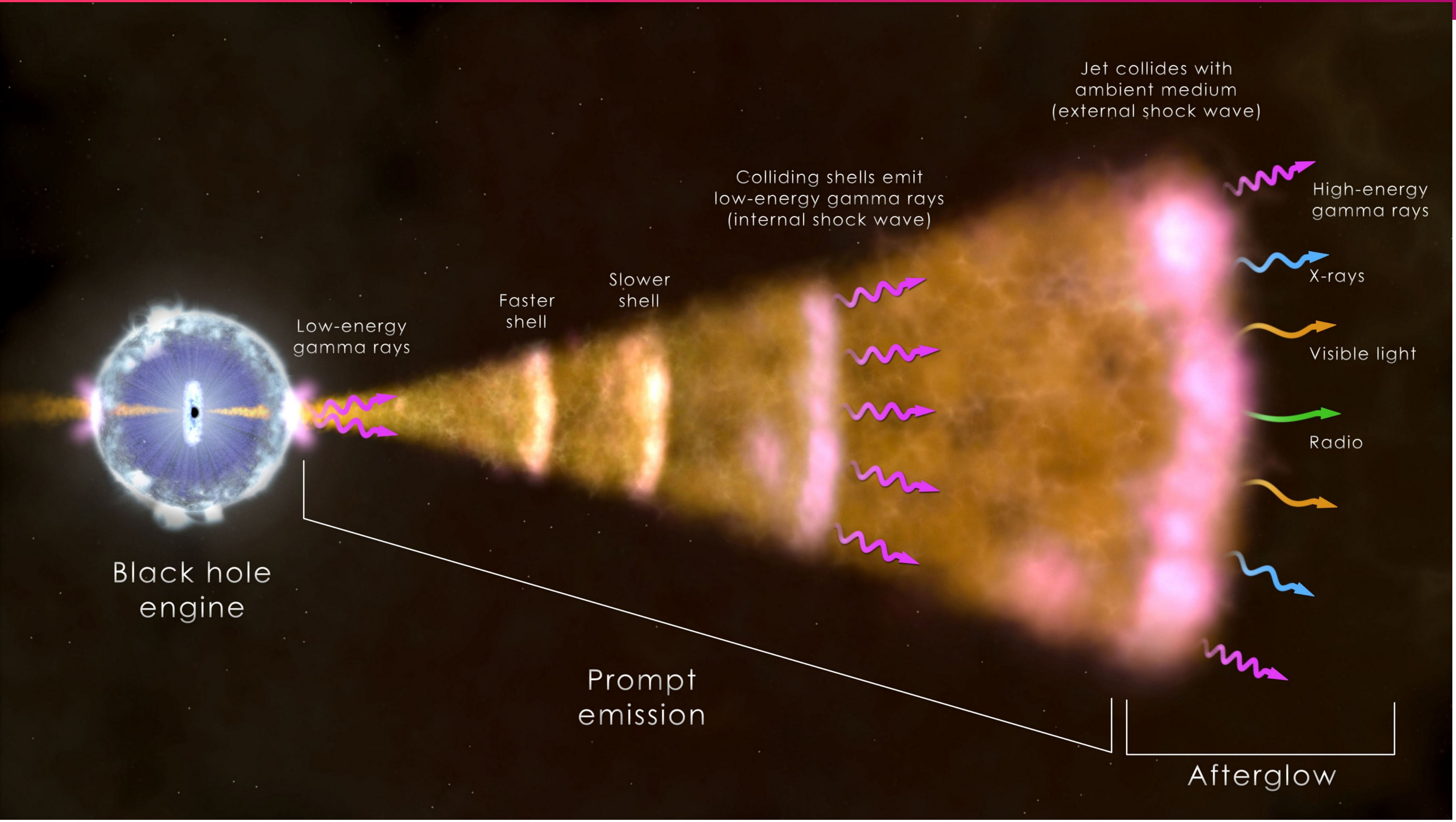
Short vs. Long

- Short bursts occur in all types of galaxies (even w/o star formation)
- Short have lower redshifts
- Short burst energies are several orders of magnitude smaller

Engines

- The collapsar is the standard model for long bursts
  - Rapidly rotating, massive star core-collapse SNe
    - Wolf-Rayet: stripped H envelope
  - Black hole forms, fed by accretion disk
  - Jet formation from energy deposition along rotation axis
  - Collimated shock breakout at relativistic speeds—highly beamed emission
  - Afterglow produced as shock slows via interaction with ISM
- Neutron star merger for short bursts
  - jet production likely involved as well.

Emission Mechanism

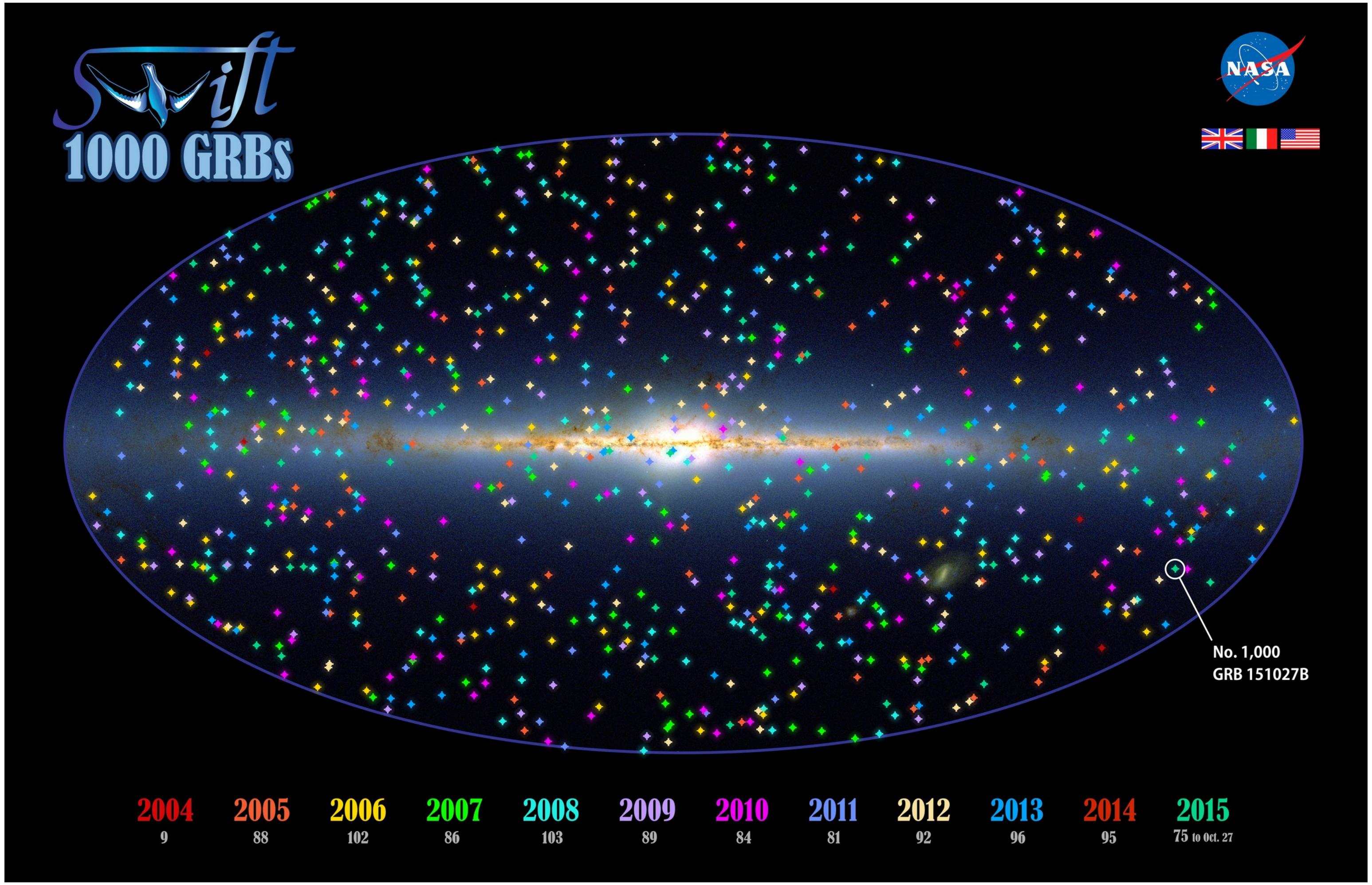


This illustration shows the ingredients of the most common type of gamma-ray burst. The core of a massive star (left) has collapsed, forming a black hole that sends a jet moving through the collapsing star and out into space at near the speed of light. Radiation across the spectrum arises from hot ionized gas in the vicinity of the newborn black hole, collisions among shells of fast-moving gas within the jet, and from the leading edge of the jet as it sweeps up and interacts with its surroundings. Credits: NASA's Goddard Space Flight Center

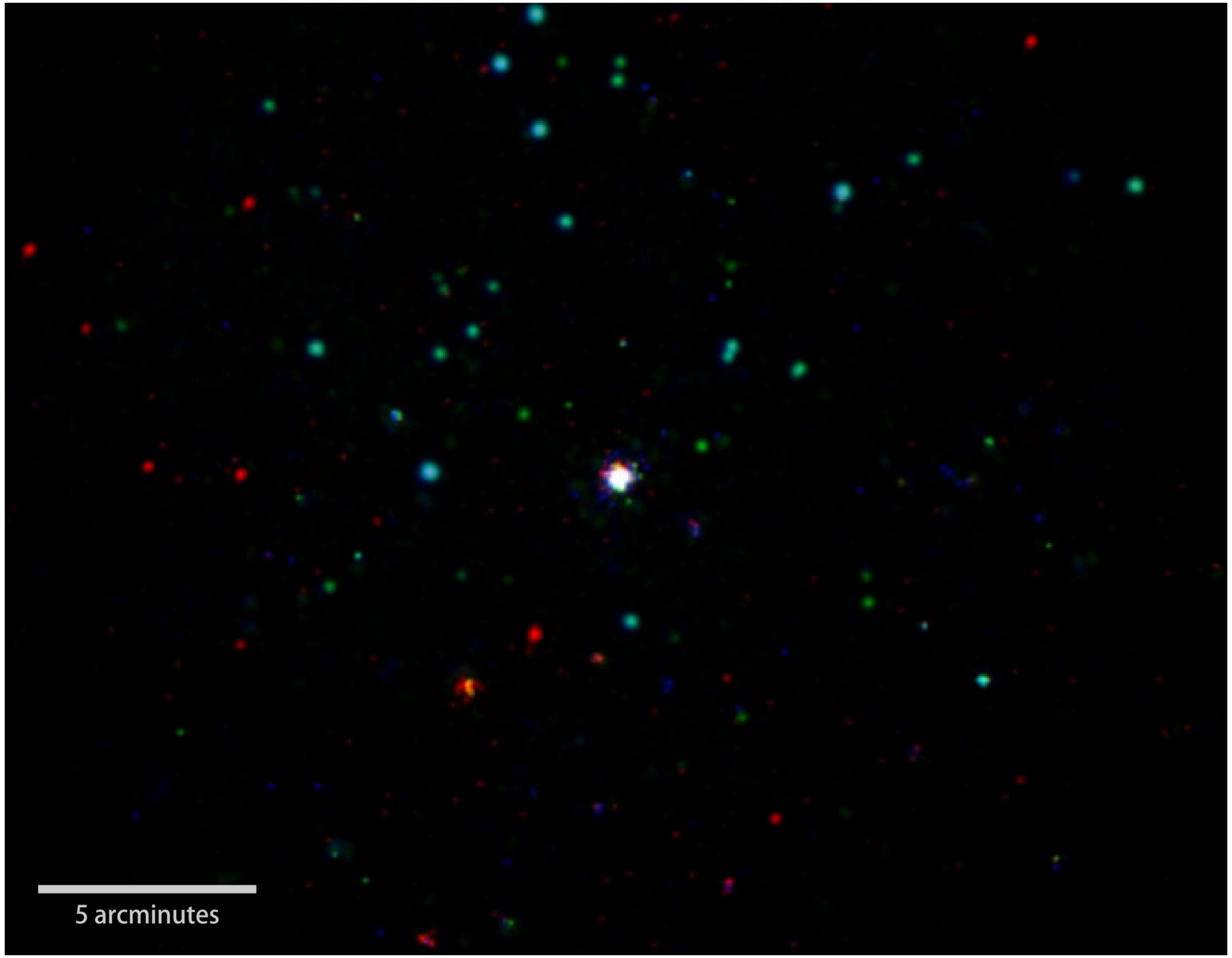
http://www.nasa.gov/feature/goddard/nasas-swift-spots-its-thousandth-gamma-ray-burst

Swift Mission

- Gamma-ray telescope that can pinpoint the locatoin of a burst in ~seconds and then take follow-up at other wavelengths + communicate to ground-based telescopes

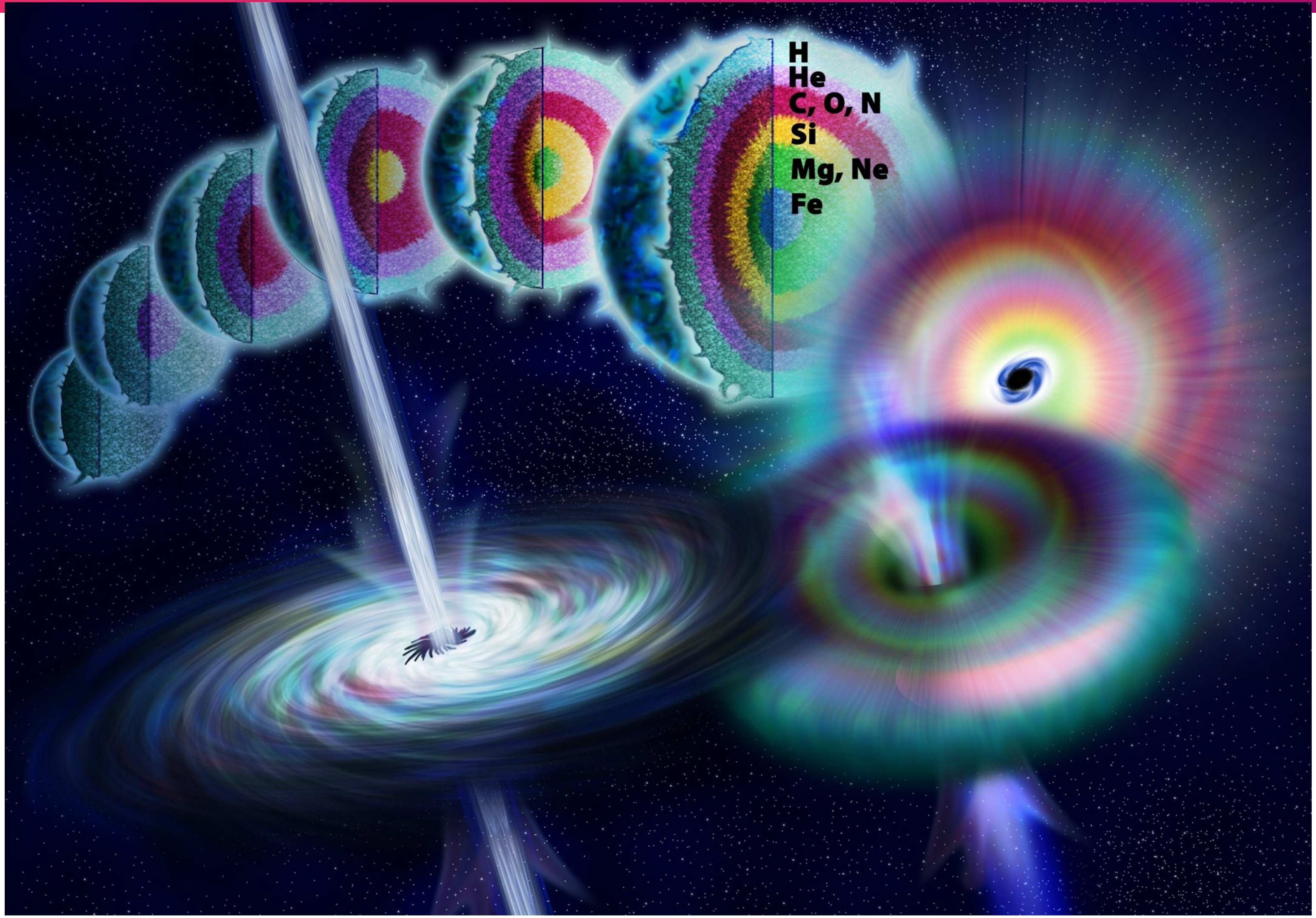


Swift Mission



GRB 151027B, Swift's 1,000th burst (center), is shown in this composite X-ray, ultraviolet and optical image. X-rays were captured by Swift's X-Ray Telescope, which began observing the field 3.4 minutes after the Burst Alert Telescope detected the blast. Swift's Ultraviolet/Optical Telescope (UVOT) began observations seven seconds later and faintly detected the burst in visible light. The image includes X-rays with energies from 300 to 6,000 electron volts, primarily from the burst, and lower-energy light seen through the UVOT's visible, blue and ultraviolet filters (shown, respectively, in red, green and blue). The image has a cumulative exposure of 10.4 hours. Credits: NASA/Swift/Phil Evans, Univ. of Leicester

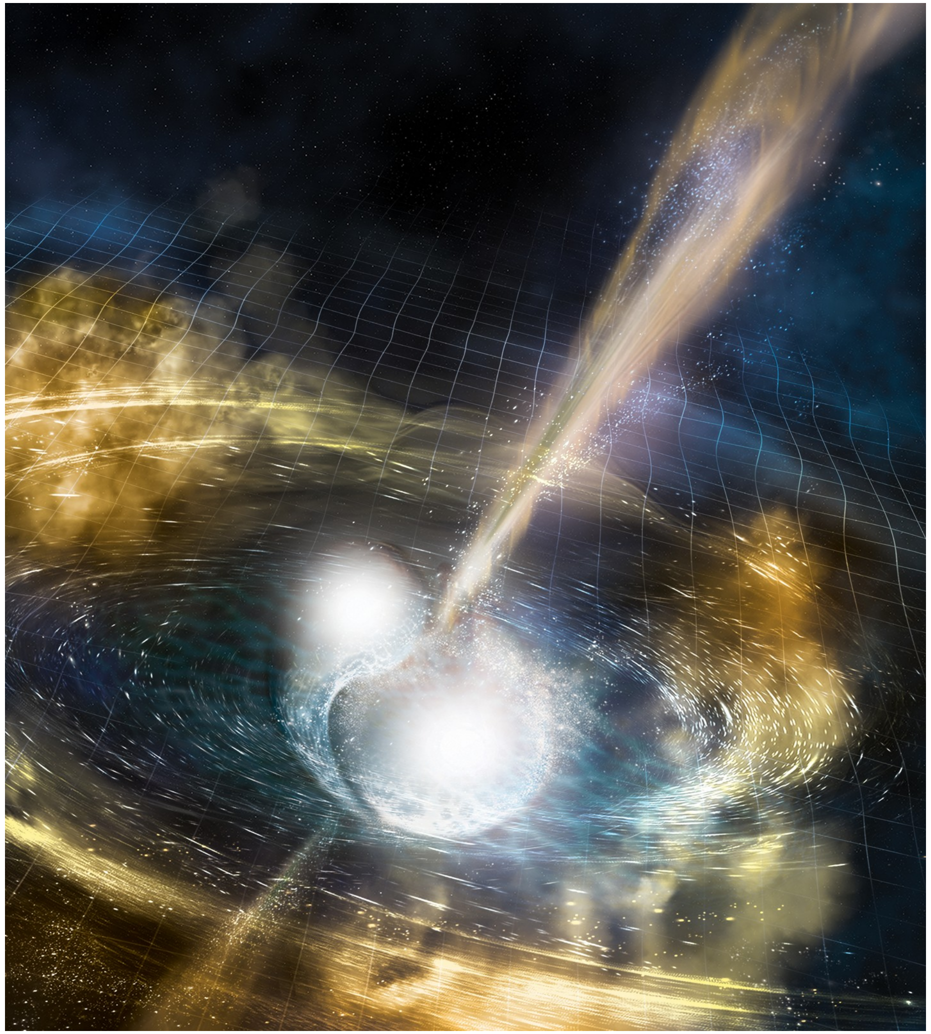
Collapsar



Nicolle Rager Fuller/NSF

Neutron Star Mergers

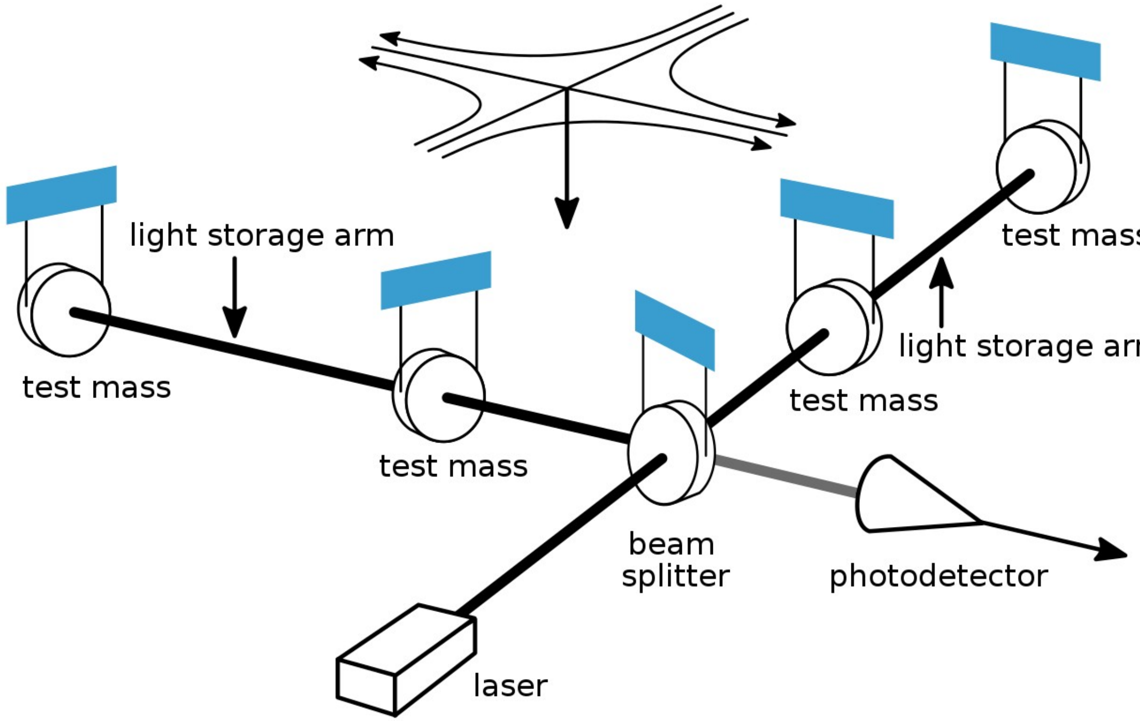
- What about 2 neutron stars in a binary?
  - Gravitational radiation takes energy from orbit
  - NSs inspiral and merge
  - Black hole formed
- Similar process for binary black holes
- We've detected the gravitational radiation of NS+NS and BH+BH with LIGO



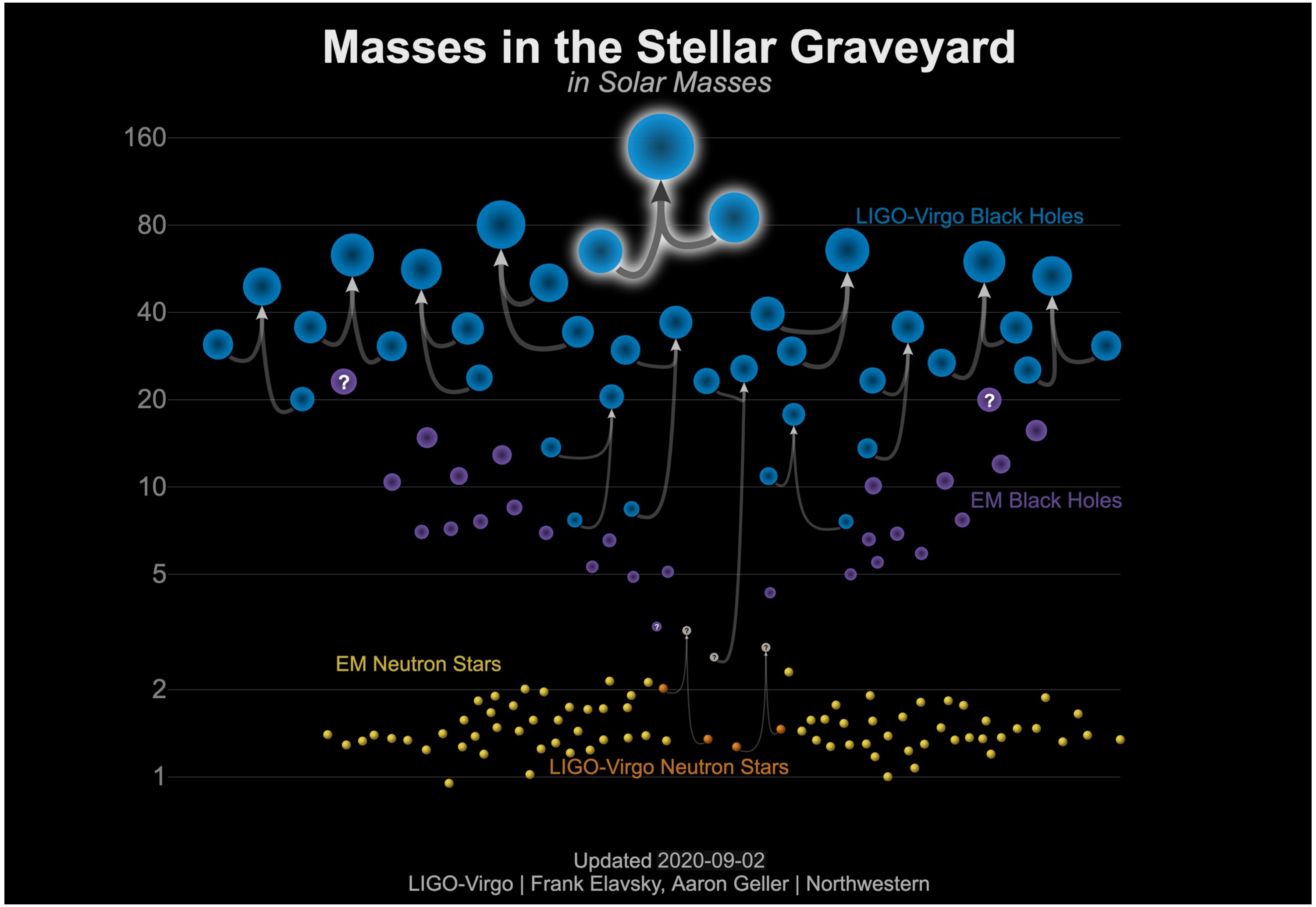
Credit: NSF/LIGO/Sonoma State University/A. Simonnet

LIGO

- Laser Interferometer Gravitational Wave Observatory
- Can detect changes in base length < 1/10000th of diameter of a proton

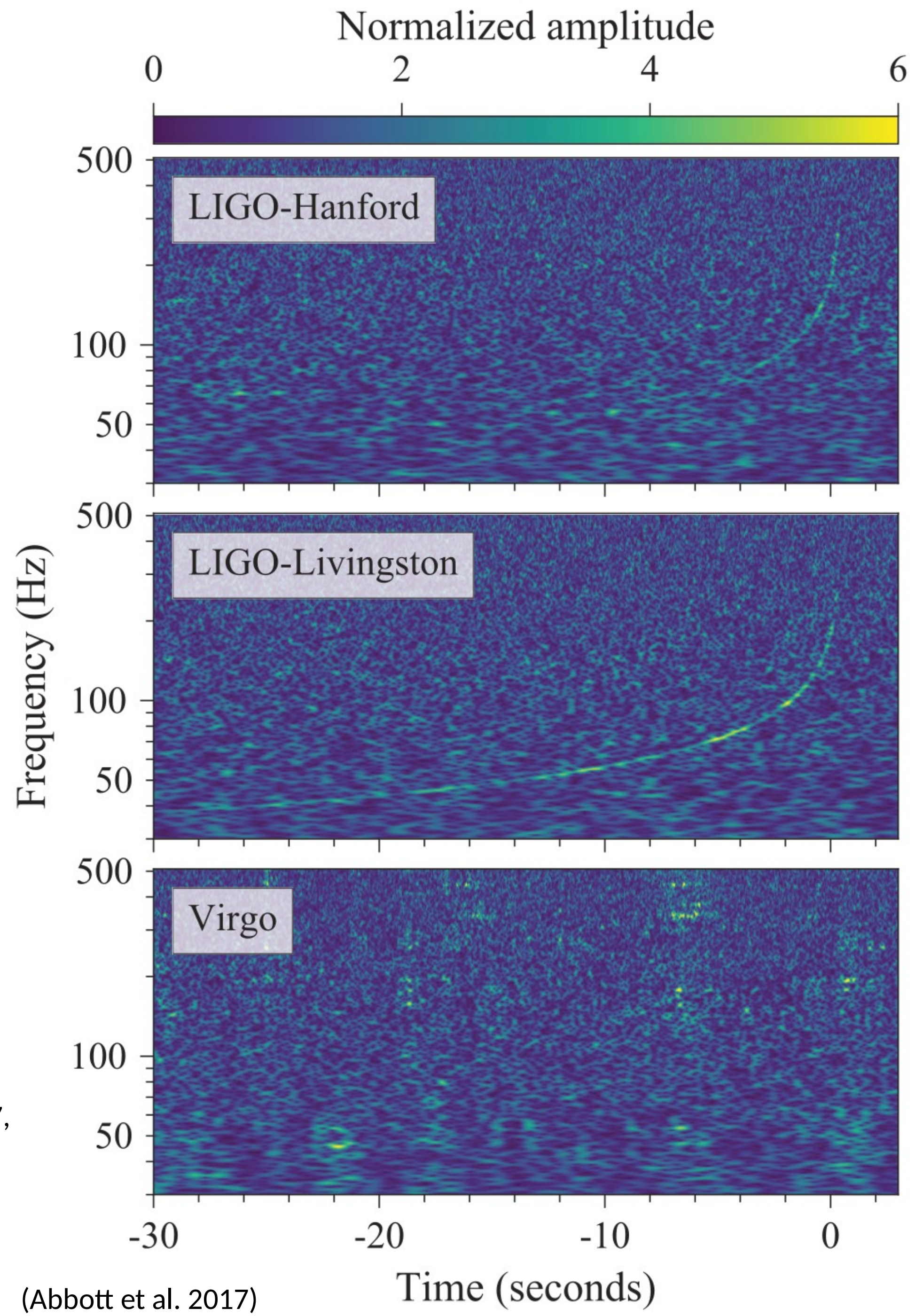


Observed Mergers



GW170817

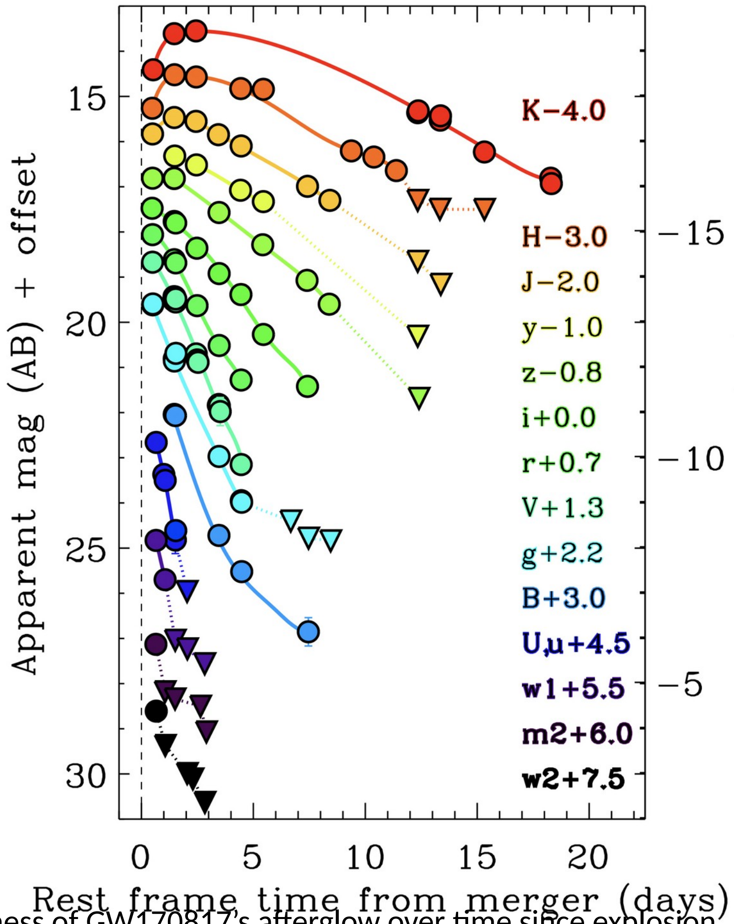
- LIGO measures strain as gravitational waves pass through earth, stretching the baseline of the detectors
- GW170817 is most consistent with merging NSs
- Electromagnetic counterpart detected



Time-frequency representations [65] of data containing the gravitational-wave event GW170817, observed by the LIGOHanford (top), LIGO-Livingston (middle), and Virgo (bottom) detectors. Times are shown relative to August 17, 2017 12:41:04 UTC. The amplitude scale in each detector is normalized to that detector's noise amplitude spectral density.

(Abbott et al. 2017)

GW170827



Change in brightness of GW170817's afterglow over time since explosion (merger), is shown in these light-curves. Brightness in 14 different optical wavelengths is shown, including invisible ultraviolet, and visible blue, green, and yellow, and invisible infrared wavelengths in orange and red. Afterglow fades quickly in all wavelengths, except infrared. In infrared, afterglow continues to brighten until ~3 days after explosion, before beginning to fade. CREDIT: Las Campanas Observatory, Carnegie Institution of Washington (Swope + Magellan)

Afterglow of GW170817 is shown in close-ups captured by the NASA Hubble Space Telescope, showing it dimming in brightness over days and weeks. CREDIT: NASA and ESA: A. Levan (U. Warwick), N. Tanvir (U. Leicester), and A. Fruchter and O. Fox (STScI)

https://www.universetoday.com/137629/gw170817-update-surprises-first-gravitational-wave-observed-independently/

GW170817

- Detected in gamma-ray (short GRB), optical, and IR
- Masses: 1.36 – 2.26 $M_\odot$ + 0.86 – 1.36 $M_\odot$
- Site of r-process nucleosynthesis (10 earth masses of gold and platinum produced)
- Believed to result in a black hole