Durham Astronomy Postgraduate Course: Stellar Structure & Evolution lectures

5. Stellar End Points

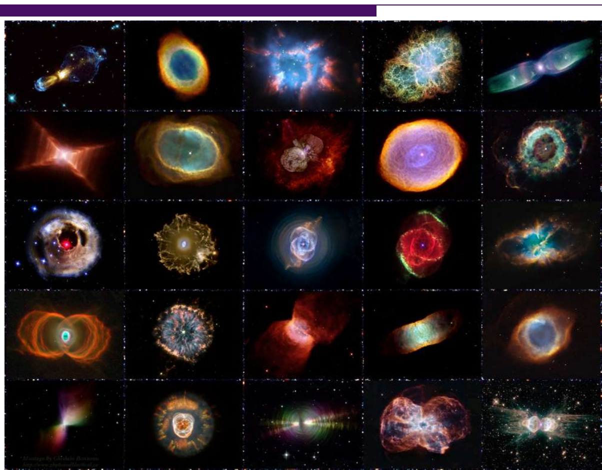
Aims

- Discuss the phenomenology associated with the end of stellar fusion
  - What happens when a star has burnt all available fuel?
- Discuss the phenomenology of stellar remnants
  - What's left behind? And how do we study it?

Death of a low mass star

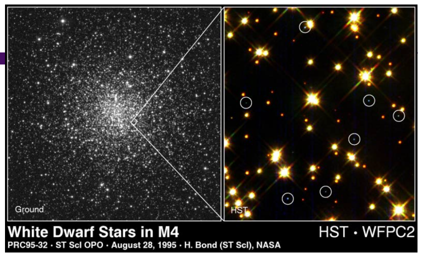
- Evolution of ~ 1 $M_\odot$ star described in previous lecture
- Eventually becomes unstable – stellar envelope lost in thermal pulsations
- Produces a 'superwind': drives the formation of a planetary nebula (PN)
- Leave compact remnant: C-O **white dwarf** (WD) with mass ~ 0.6 $M_\odot$

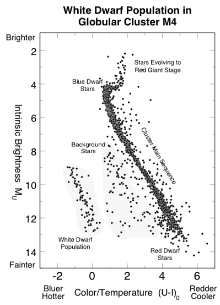
Planetary nebulae



White dwarfs

- White dwarfs are remains of stellar core – degenerate objects
- No fusion – electron degeneracy pressure prevents collapse
- Emit via remnant heat, cool as they age



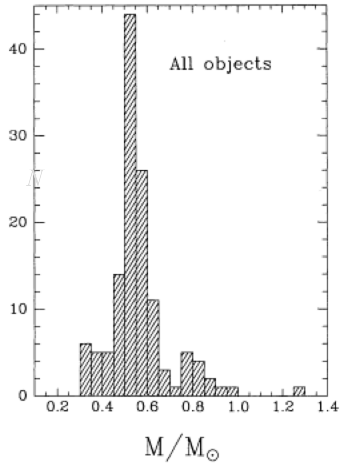


Chandrasekhar limit

- From equation of state for degenerate gas, polytropic stellar mass equation, obtain for non-relativistic limit $M \propto R^{-1/3}, \rho \propto M^2$
- So if increase mass → becomes relativistic
- Obtain Chandrasekhar mass limit for a WD

  $M_{Ch} = 5.86 \left(\frac{1+X}{2}\right)^2 M_\odot$ (*X* is fraction of mass in H)
- For $X \sim 0$, $M_{Ch} \approx 1.46\, M_\odot$

WD masses

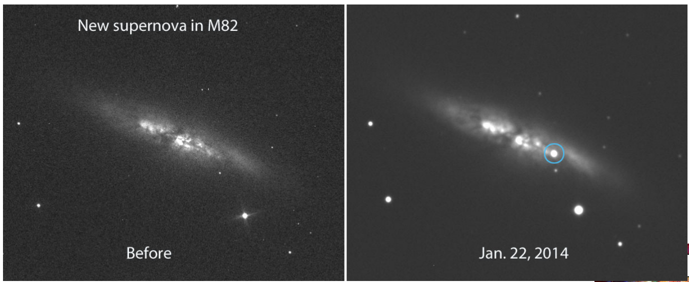


From Bergeron et al. (1992)

- Measured masses peak at ~ 0.6 $M_\odot$
- None larger than Chandrasekhar mass limit – real limit on mass of a WD

Death of a high mass star

- Star suddenly brightens such that its light is similar to that of the rest of its host galaxy – **supernova** (e.g. SN in M82)



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Supernova basics

- Last for a few months
- Typical (Milky Way-like) galaxies host 1 – 2 SNe per century
  - 6 recorded MW SNe in last ~1000 years
- Hot ejecta glows in X-rays, optical emission lines for > 10^3 years: supernova remnant

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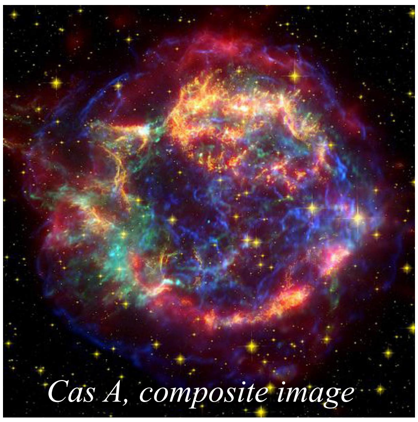
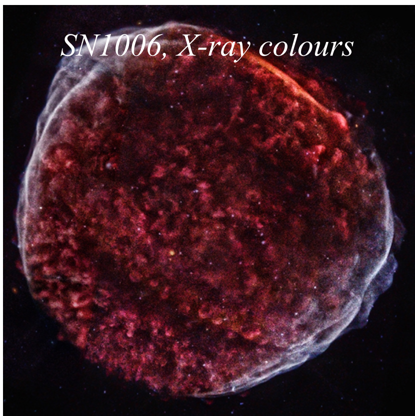
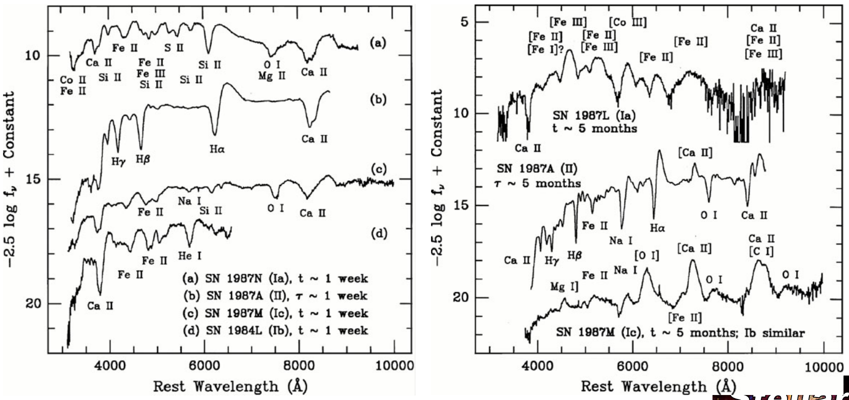
SN remnants





Red – Spitzer; yellow – HST; green/blue – Chandra

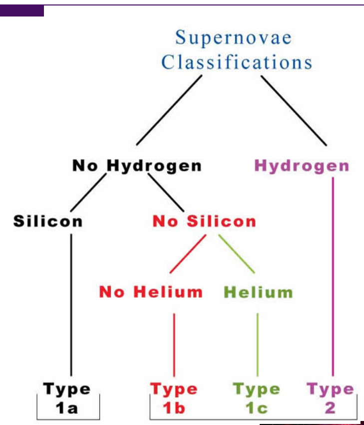
SN spectra - differences



From Filippenko (1997) ARA&A review

SN classification

- Old scheme: pre-dates physical understanding
- Type 1a seen in all stellar populations
- Other types only seen in young populations – massive stars present



Core collapse SNe

- Now think type 1b,c & type 2 SNe are from collapse of massive stars (> 8 $M_\odot$)
  - Type 1b,c from H-depleted objects
- At end of evolution Fe core forms – doesn't burn so cannot support outer layers via radiation pressure – contracts
- Exceeds Chandrasekhar limit ($M_{Ch} \approx 1.26 M_\odot$ for Fe): collapses

The big crunch

- T rises unchecked: Fe photodisintegrates
  $^{56}Fe \longrightarrow 13\times\ ^{4}He + 4n - 100$ MeV
- In near freefall, T rises, He photodissociates
  $^{4}He \longrightarrow 2p + 2n\ - 25$ MeV
- Core contracts until electron capture occurs
  $p + e^{-} = n + \nu_e$
- Neutron degeneracy at ~ 10^{18} kg m^{-3}: neutron star forms, outer layers 'bounce' off NS surface

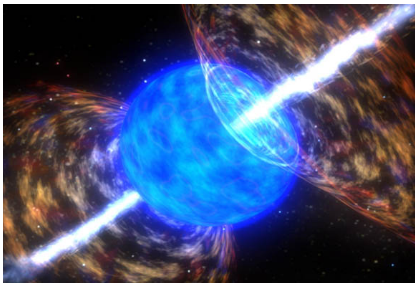
Neutrino-driven explosion

SN 1987A (left); pre-explosion image showing 17 $M_\odot$ progenitor

- Models show ‘bounce’ cannot disrupt star
- If 1% of neutrino energy release captured: enough to drive explosion
- SN 1987A in LMC: detect neutrino pulse for ~12 s at 2 detectors, precedes optical light

But if core really massive…

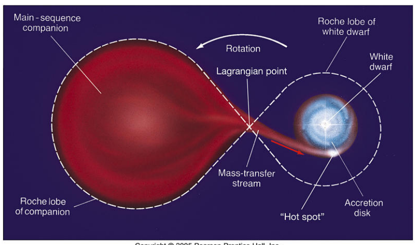
- Neutron degeneracy pressure insufficient to hold up bodies with > ~3 $M_\odot$
- Collapse to **black hole** (BH)
- If star massive & spinning fast – could form long **gamma ray burst** (GRB)



Type 1a SNe

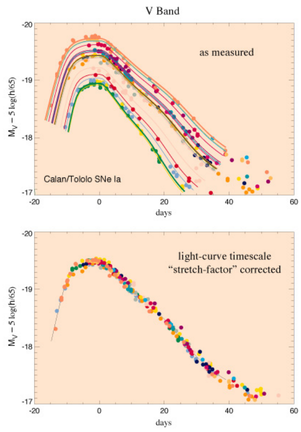
- Associated with older stellar populations
- Thought to be **thermonuclear runaway** explosion of a WD
- Accretion of material pushes WD to M_{Ch}
- As near limit – interior *T* rises, C ignites
  - C fuses to Mg, O to S, Si, Mg…
- WD completely destroyed

Physical models for type 1a SNe



- Three possible models
  - WD + MS star (accretion timescale too long?)
  - WD + red giant (novae remove too much material?)
  - WD + WD

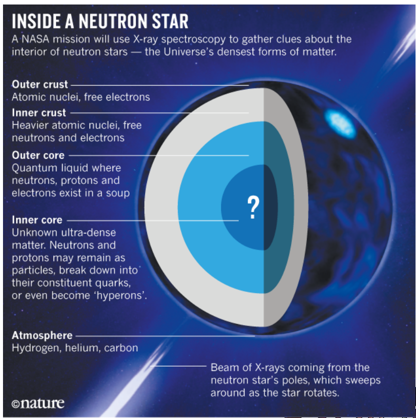
Standard candle



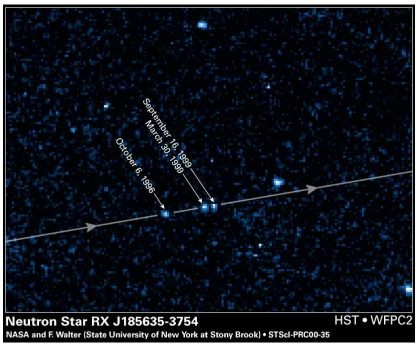
- Decay rate of 1a SNe light curves related to peak brightness
  - Phillips decline rate relation
- Constrain light curve → known peak *L* → can use as standard candle!

Neutron stars

- No fusion; supported by neutron degeneracy
  - Upper limit: Toller-Oppenheimer-Volkoff, 1.5 – 3 $M_\odot$
- Interior structure: uncertain. Studies aim to constrain mass-radius relation



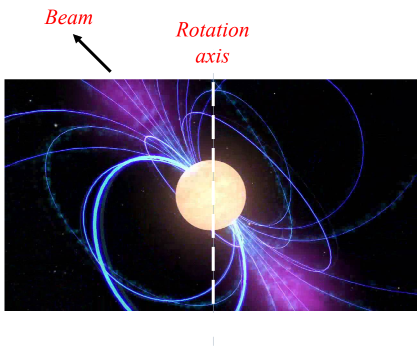
Observing neutron stars



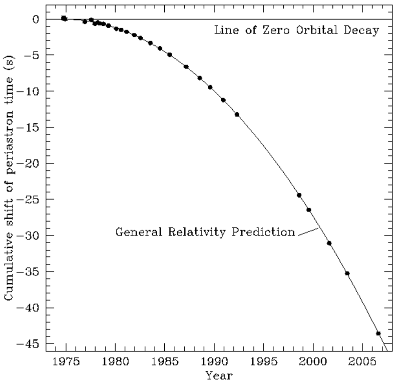
- Galaxy should be full of neutron stars
- But cool rapidly – if isolated difficult to see!
- If accrete material – emit X-rays
- Young NSs – often see as **pulsars**

Pulsars

- Young NSs can be highly magnetic (*B* ~ 10^{14} G), with field axis misaligned with fast rotation period (ms)
- Creates 'lighthouse'; pulses of radio & (in some cases) X-rays

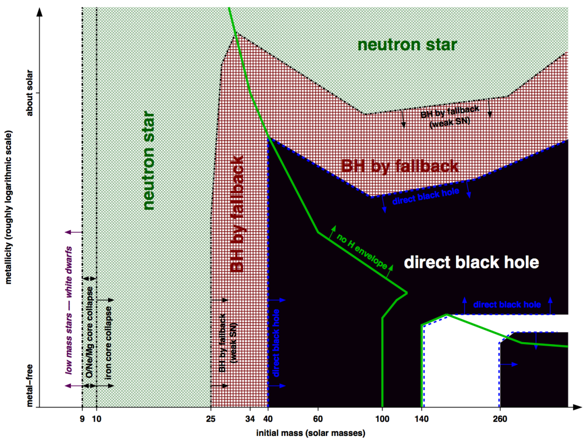


Hulse-Taylor pulsar



- Pulsar detected in close binary system (e = 0.62)
- Both with mass ~ 1.4 $M_{\odot}$ - double NS
- Orbital period shortens with time – gravitational radiation!

The remnants of massive stars



From Heger et al. (2003)

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Black holes

- General relativistic objects
- Possesses event horizon (where $v_{esc} = c$) – nothing seen within this radius
  - Contains singularity?
- ”No hair theorem” – BH properties defined by 3 observables:
  - Mass *M*
  - Angular momentum *J*
  - Charge *Q*

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Sizes of BHs

- Two main classes: stellar mass (4 – 18 $M_\odot$) and supermassive (10^6 – 10^9 $M_\odot$)
  - Stellar up to 100 $M_\odot$? SMBHs 10^5 – 10^{10} $M_\odot$?
  - Some good intermediate mass BH candidates now in 10^2 – 10^5 $M_\odot$ range
- Event horizon size depends on *M* and *J*
  - Non-rotating: Schwarzschild metric $R_S = \frac{2GM}{c^2}$
  - Rotating ($J \neq 0$): Kerr metric $R \rightarrow \frac{GM}{c^2}$

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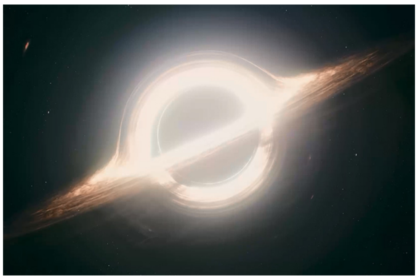
How do we observe BHs?

- Energy release from material falling into gravitational potential: accretion
- For NSs & BHs accretion discs form; sufficient energy release for thermal emission in UV/X-rays (Done lectures)



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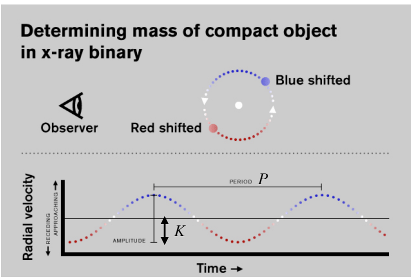
How do we know it's a BH?



Mass function f(M) from

$$f(M) = \frac{PK^3}{2\pi G} = \frac{M_{BH}^3 \sin^3 i}{(M_{BH} + M_*)^2}$$

- SMBHs – can't be anything else
- Stellar mass objects in binaries – radial velocity studies
- Obtain mass function from secondary star

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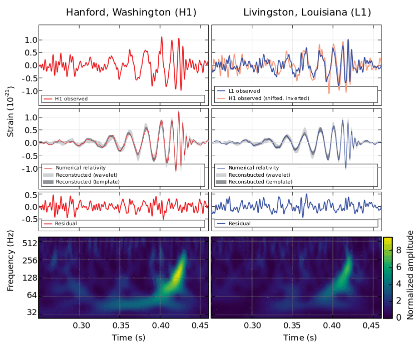
A new window on BHs

- GW150914 – first detection of GWs
- Merger of 29 + 35 $M_\odot$ BHs to form 62 $M_\odot$ BH: unprecedented!
- 3 subsequent BH+BH mergers (+1 marginal detection); 2/3 with massive stellar BHs



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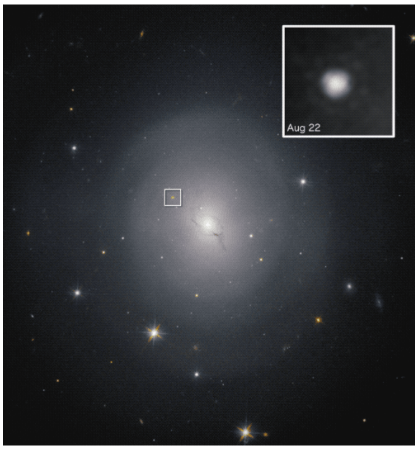
GW170817: multi-messenger astronomy



- First NS+NS merger
- Multi-wavelength counterpart!
- γ-rays detected 1.7 s after GWs
  - Off-axis short GRB – a *kilonova*
- Remnant unknown

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Summary

- The process of stellar death, and the remnants it leaves, include some of the most energetic and exotic processes known
- Phenomenology studied by full range of EM instruments (radio to γ-ray) – and now GW, even neutrino detectors
- Many theoretical challenges remain!