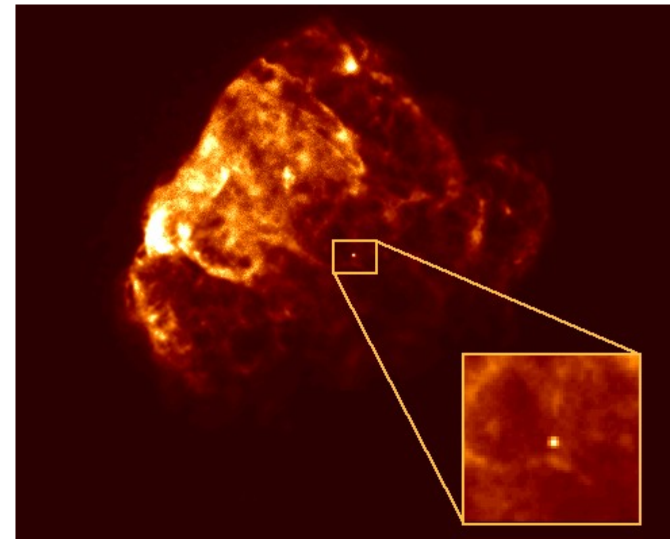
Stellar Graveyard

White Dwarfs

Neutron Stars

Black Holes



A neutron star in the Supernova Remnant Puppis A

A white dwarf in NGC2440 planetary nebula

Cygnus X-1 black-hole candidate (artist impression)

White Dwarfs (they are out there)

-- remaining cores of low-mass ($M < 8M_\odot$) stars

Very little H and He, mostly C and O
(some have mostly He)

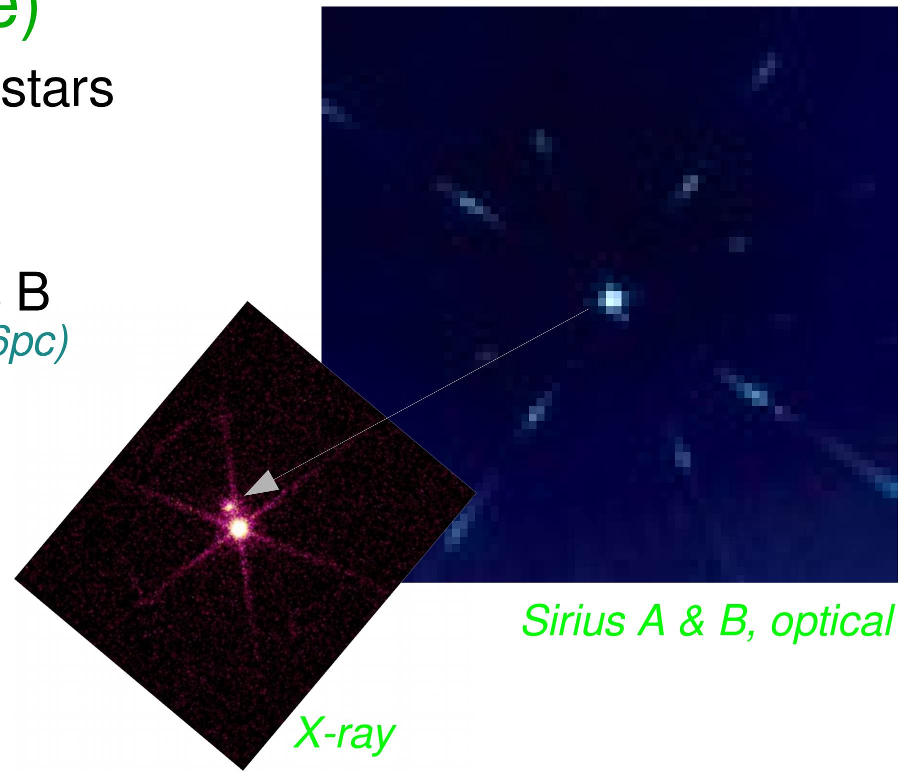
-- $\sim 10^{10}$ in the galaxy, closest known Sirius B

from movement of Sirius A (brightest on sky, 2.6pc)
--> Sirius B has $M \sim 1\ M_\odot$

-- white dwarfs are small

(and therefore dim; $L = 4\pi R^2\,\sigma T^4$)

Sirius A: main-sequence $T_A \sim 12{,}000$K
Sirius B: white dwarf $T_B \sim 25{,}000$K
Sirius B: $R \sim 4300$ km $\sim 1/200\ R_\odot$



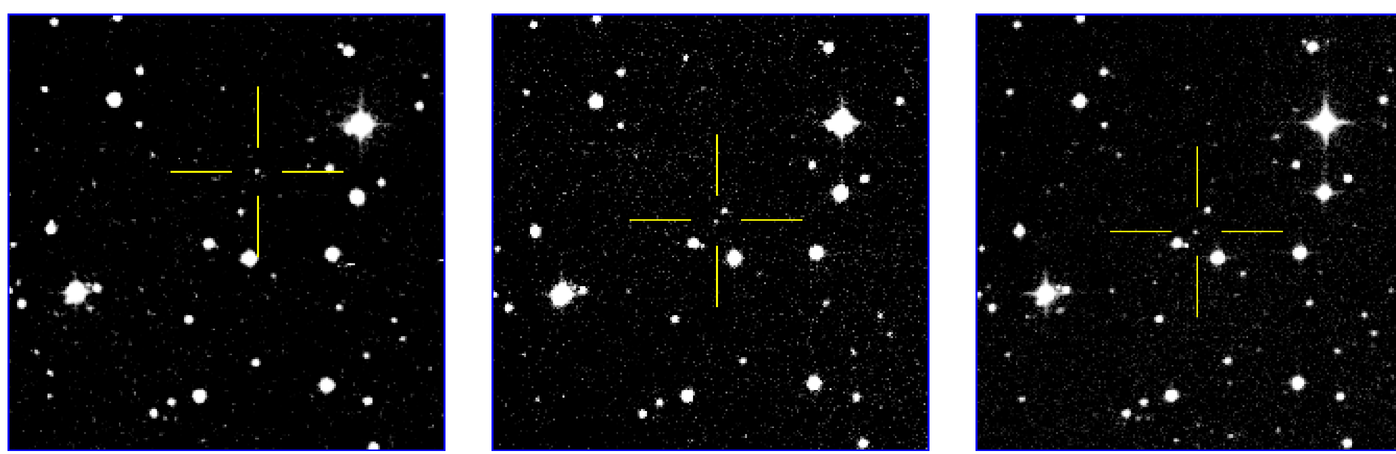
X-ray

Sirius A & B, optical

-- White dwarfs are dense

typically $M \sim 0.6\ M_\odot$
$R \sim R_\oplus \sim 0.01 R_\odot$
$\rho \sim 10^6$ g/cm^3
(1 sugar-cube = 1 tonne)

e^- pressure ionized
e^- degenerate



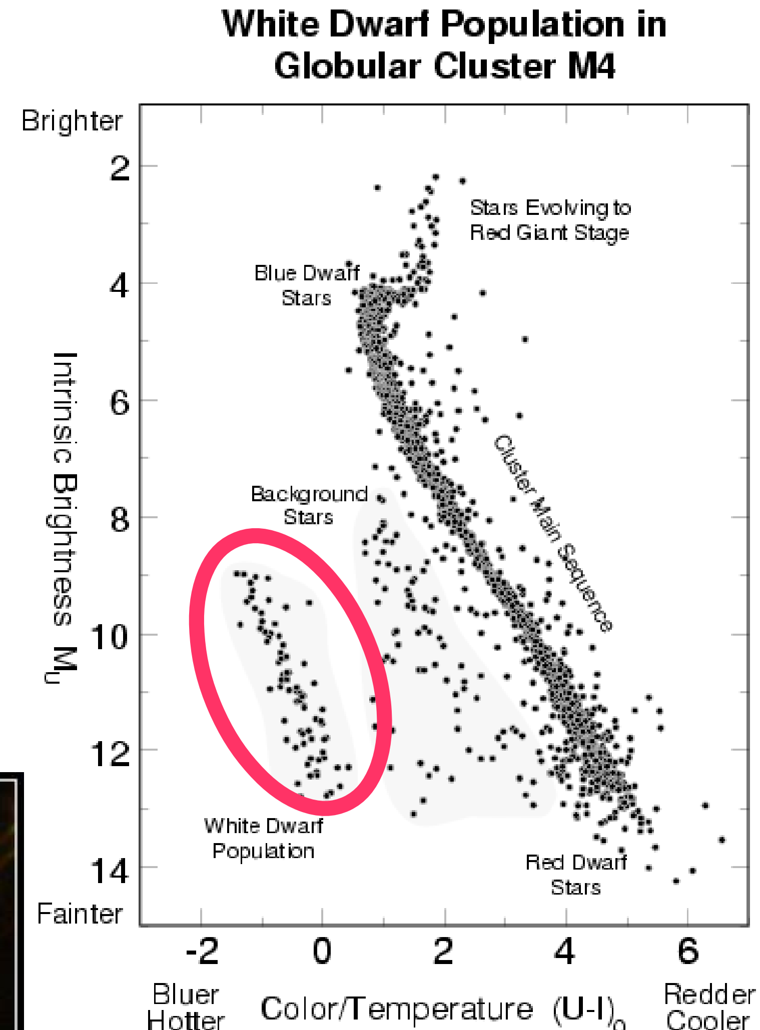
Finding white dwarfs by their fast proper motion

1951 1987 1994

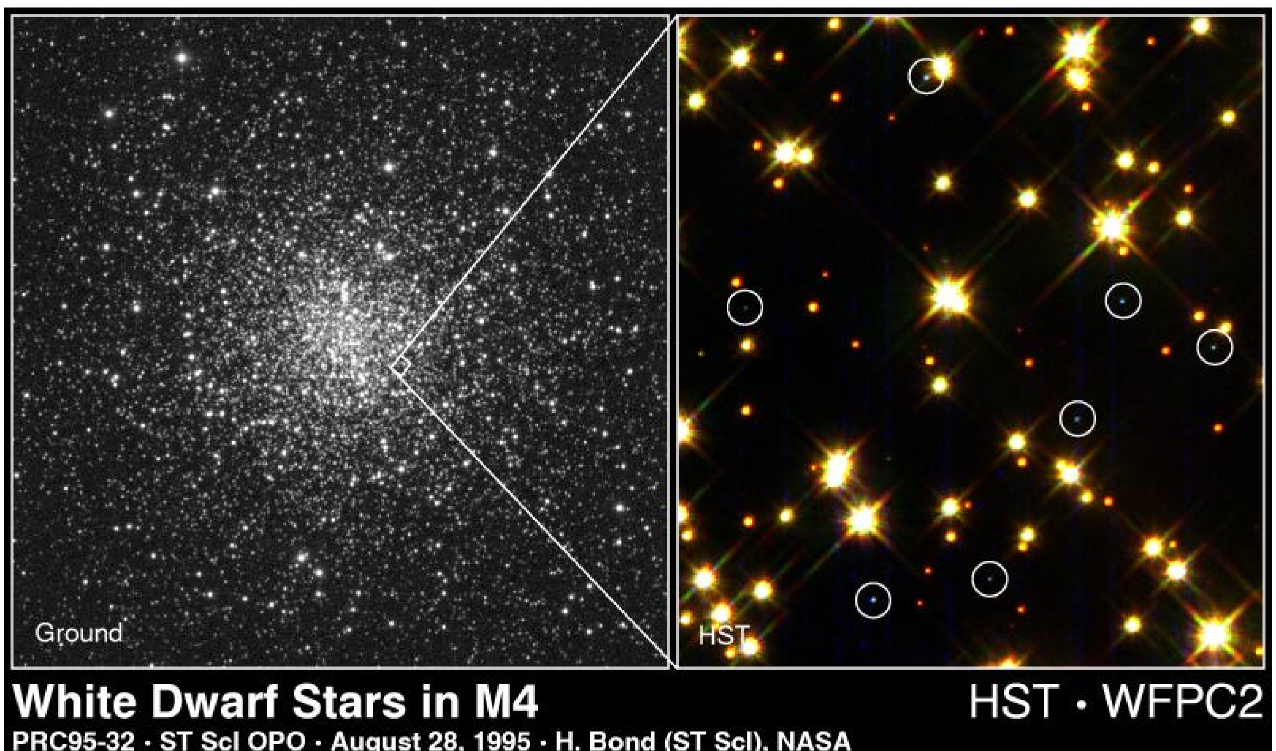
Cooling Death of White Dwarfs

Shines because of cooling of the star
--> thermal (Kelvin-Helmholtz) timescale
~ Hubble time (10 Gyr) to cool to few 10^3 K
(why do WDs not contract as they cool?)

Cooling may lead C/O core to crystallize
"stellar-mass diamond"



M4: a globular cluster
13 Gyr in age (older than the Galaxy),
all stars > 0.8 $M_\odot$
are white dwarfs now



Neutron Stars

-- core collapse at end of massive star ($8\ M_\odot < M < 25\ M_\odot$?)

-- produces a “huge nucleus,” mostly made of neutrons $p^+ + e^- \rightarrow n + \nu_e$

$M \sim 1.4\ M_\odot$, $R \sim 10$ km, $\rho \sim 3\times10^{14}$ g/cm^3 *(extremely dense, > nuclear density)*

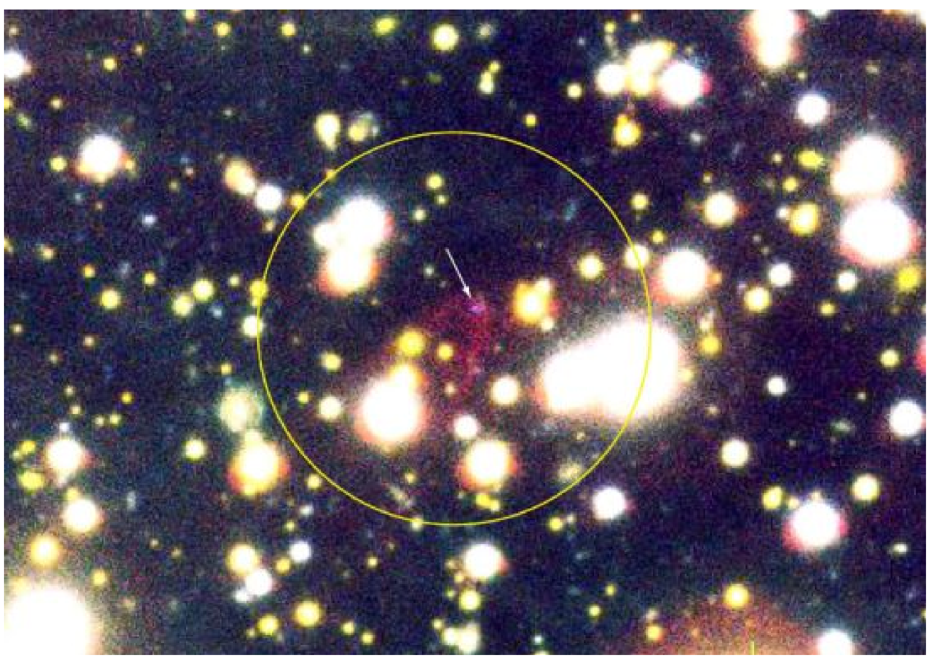
-- supported by pressure from degenerate neutrons *(fermions)* $\hbar/m_n v > d \sim 1/n_n^{1/3}$

and by strong-force repulsion   *why much denser than a white dwarf?*

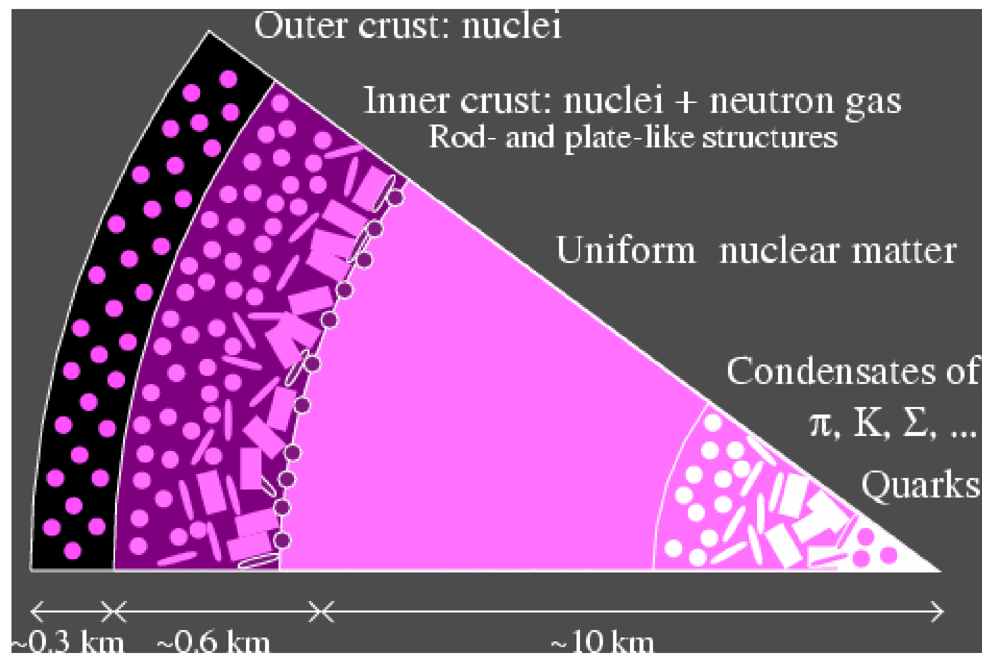
-- exotic physics: superfluid, superconductor + pions, Kaons, quarks?

-- $10^7 \sim 10^8$ in the galaxy, nearest @ ~ 10 ~ 20 pc (nearest known @ 150 pc)

$L = 4\pi R^2 \sigma T^4$ *very difficult to find by thermal radiation in optical, but....*



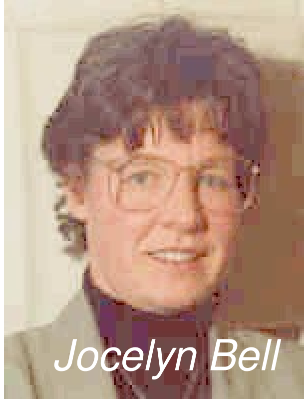
A near-by neutron star (your prof., 2000)

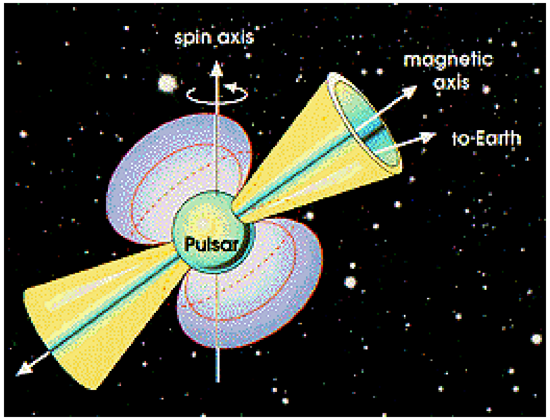


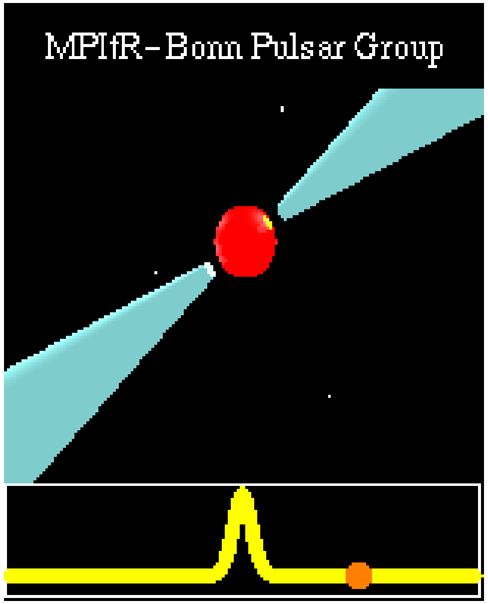
Sketch of structure of neutron star (Heiselberg 2002)

Neutron Stars (pulsars)

first discovered as '**pulsars**' (1967):
many (all?) neutron stars are somehow endowed with both a fast spin and a strong magnetic field







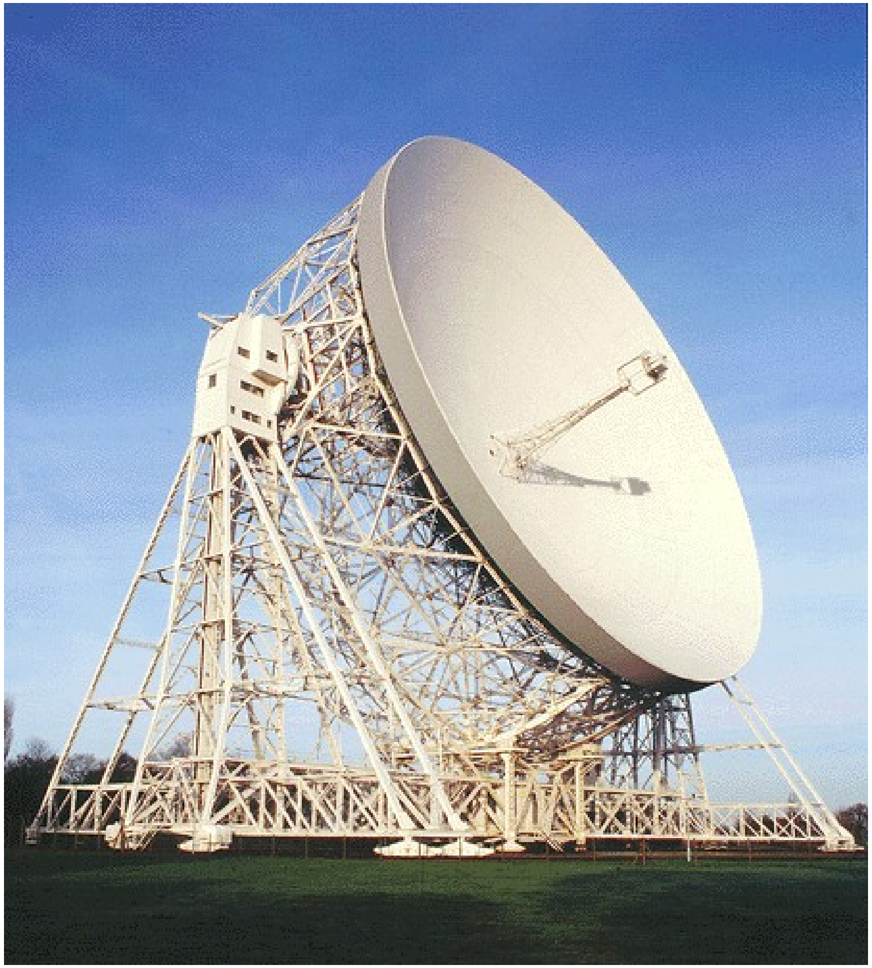
radio photons produced in the magnetic cone

rotation periods: 1.6 ms – 10 s

B-field: ~10^9 ~10^{13} G

rotation + B --> shines like a lighthouse beacon

Now know few thousand pulsars
pulsar astronomy: neutron star physics
binary star evolution, galactic structure,
interstellar medium....



Jodrell Bank 72m radio telescope

Neutron Stars (Magnetic fields)

The Crab Pulsar-wind Nebula

Pulsar field strengths at birth 10^{12}~10^{13} G

Earth field ~ 1 G
Solar field ~ 1 G (strongest point ~10^3 G)
strongest man-made field ~ 10^5 G
galaxy field ~ 10^{-6} G
universe field ~ ?

How does the pulsar B arise?
Flux conservation? Dynamo?

Magnetars (C. Thompson, UofT):
~ 10^{14} – 10^{15} G , rotate ~ 10 s, $B^2R^3 >> I\,\Omega^2$, QED field...
Sudden detwisting of the field (crust cracking; star quakes) produces γ-ray outbursts
First one seen on 1979 March 8.

Also slightly less magnetized varieties (possibly descendants):
~ half a dozen known, young and nearby, cooling radiation seen by X-ray satellites

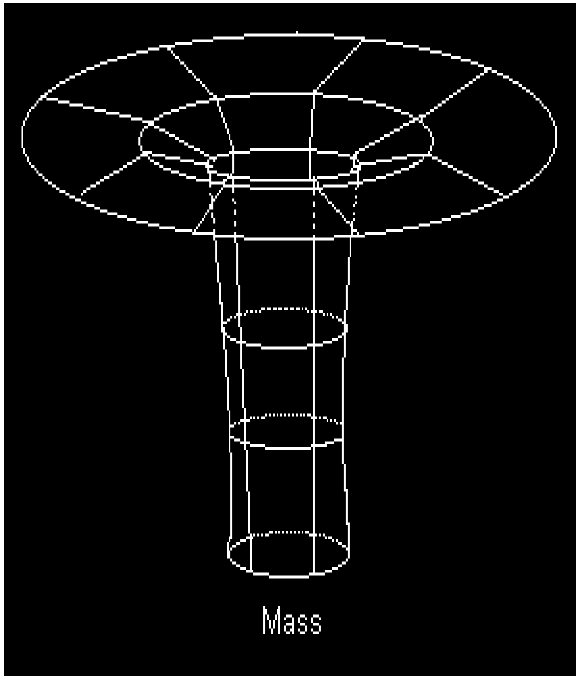
Black Holes – a space-time singularity

Cyg X-1 (Bolton, UofT)

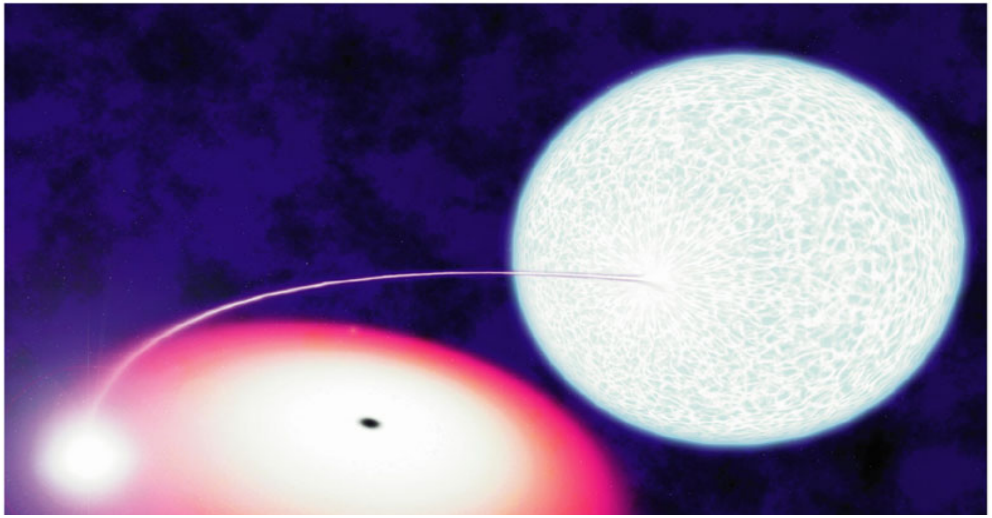
How do stellar-mass black-holes come about?
- More massive stars -> more massive neutron stars(?)
- When NS mass > critical mass, no known pressure support
- Further collapse into a BH (SN1987A?)

Black-Hole: even photons can't escape:
$v_{esc}^2 = 2GM/R > c^2$ within a certain distance
(photons have no mass, why care about grav. potential?)

Define Schwarzschild radius $R_S = 2GM/c^2$
“event horizon” (definition)
textbook: who kills the astronaut with a torch-light?
tidal stretching, photon redshift, time dilation



– Discovered as they are accreting gas from a companion
Gas gets hot and radiates *before* it disappears.



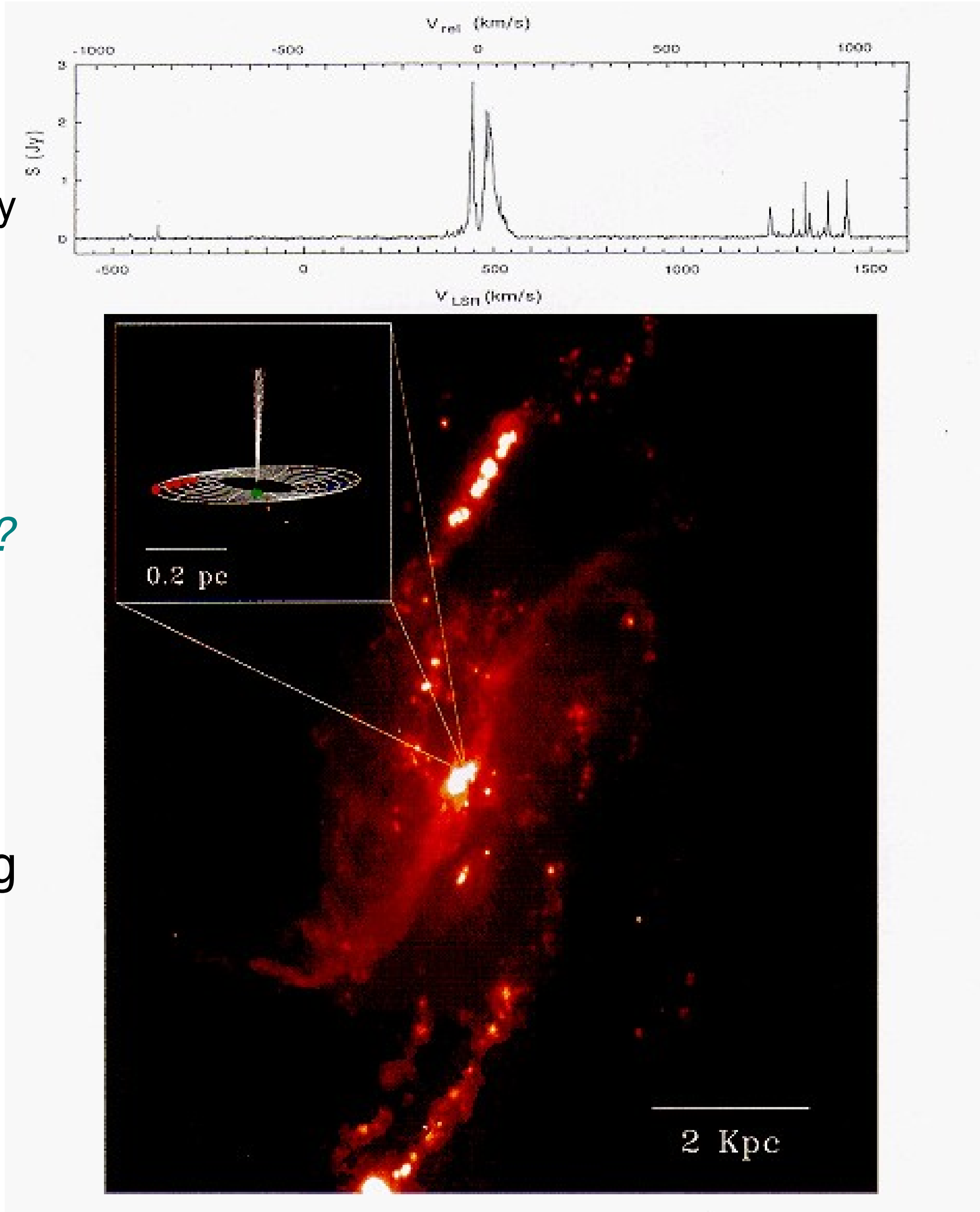
Black Holes (Active Galactic Nuclei)

New: ~ every galaxy harbors a massive BH at its center

1) BH mass $10^6 - 10^{10}\ M_\odot$, rises with M_{galaxy}
2) How to find? How to measure mass?
   Active galactic nuclei:
   accrete gas & stars, and shines
   (if outshines the galaxy – quasar)
4) Center of Milky Way, $M_{BH} \sim 3\times10^6\ M_\odot$
5) Origin? *Amalgamation of stellar mass BHs?*
   Heavy BHs form in early universe?

Bizarre effects associated with BHs

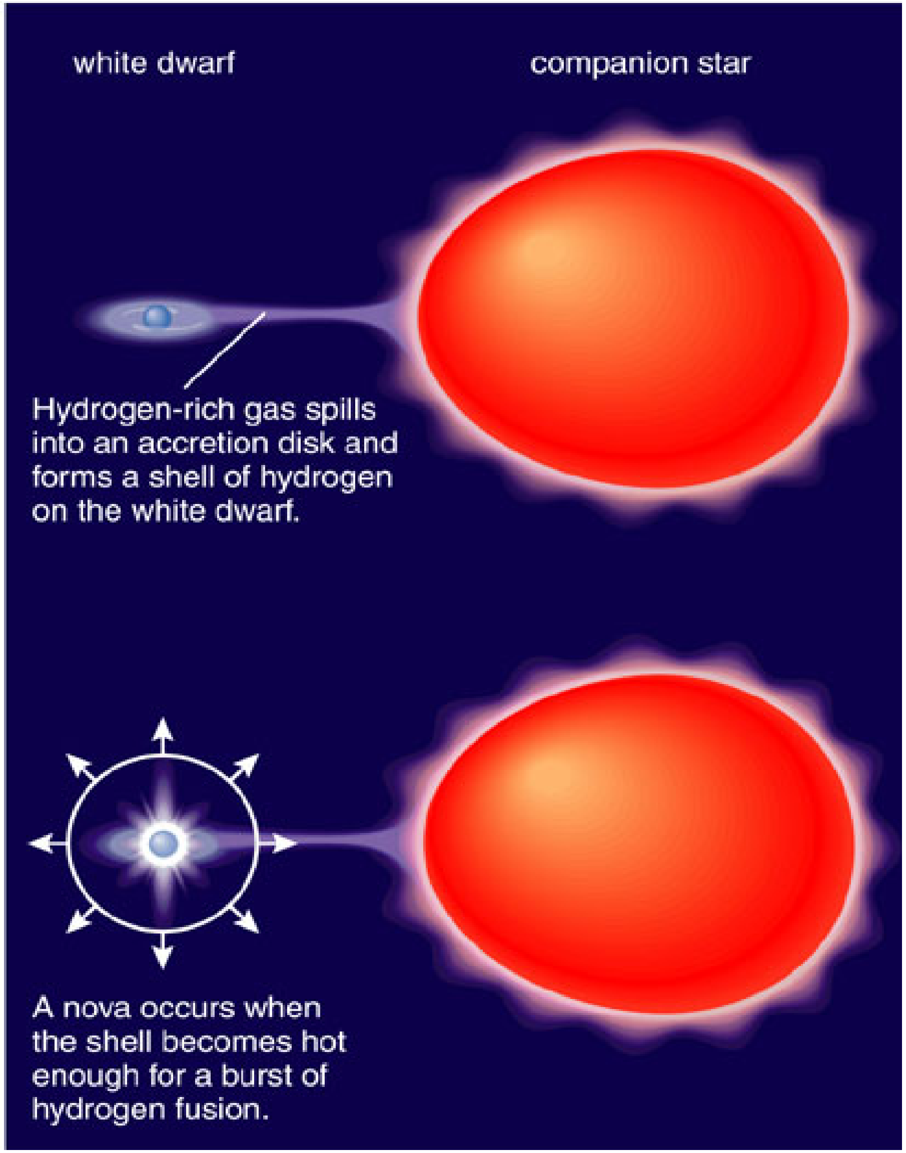
1) Centre: GR fails, need quantum gravity
2) Spinning black hole – space-time dragging
3) Quantum fluctuation of the vacuum &
   the evaporation of a black hole
   (Hawking Radiation)
4) Magnetic field threading the BH?
5) Warp-drive?



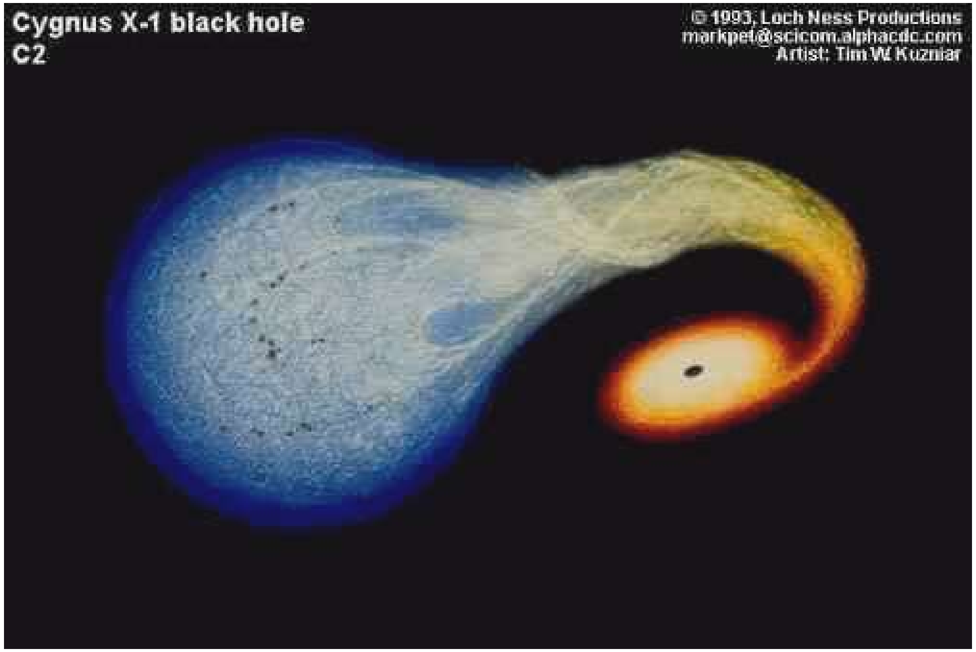
NGC 4258, the maser disk

Rejuvenation of Compact Objects

cataclysmic variable (around a WD)

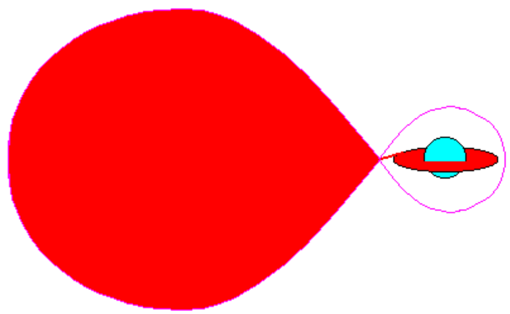


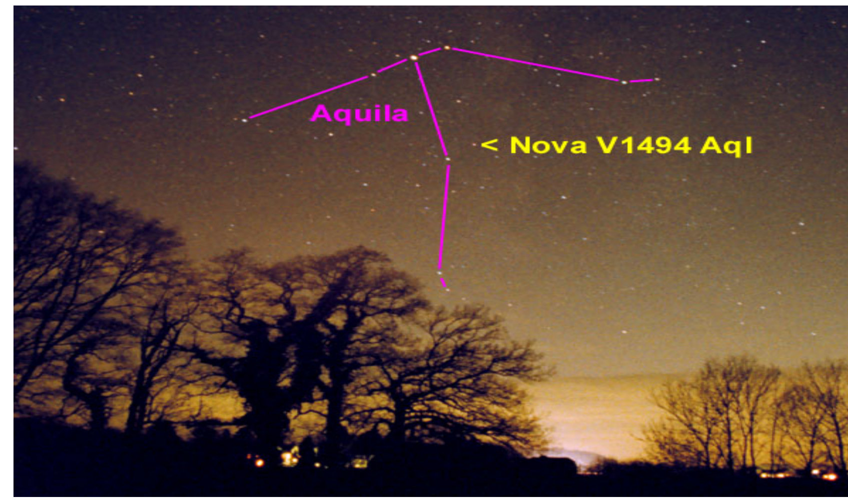
X-ray binary (around a NS or a BH)



Resurgence of old white dwarfs

Novae: binary = WD + giant star, mass transferred to WD
thermal nuclear run-away at surface of WD,
$L \sim 10^5 L_\odot$, gradual decline, recursive



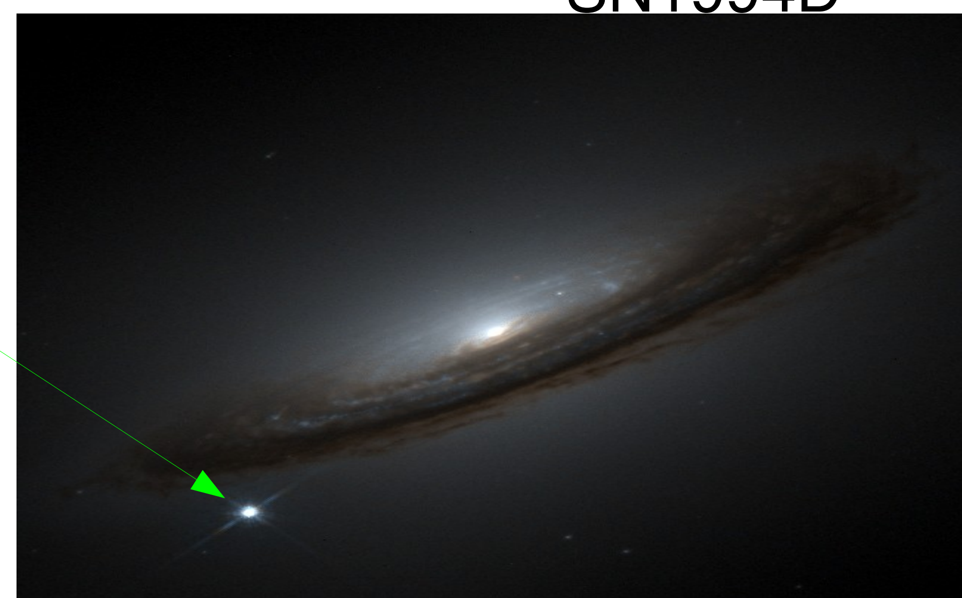


Second death of degenerate objects

Type Ia supernova
binary = WD + ? (giant, WD, MS...),
Fusion ignited when WD ~ $1.4 M_\odot$?
Or by heat from merger?
$L \sim 10^{10} L_\odot$

WD destroyed, all metals returned to ISM
"standarizable candle" to measure cosmological distances

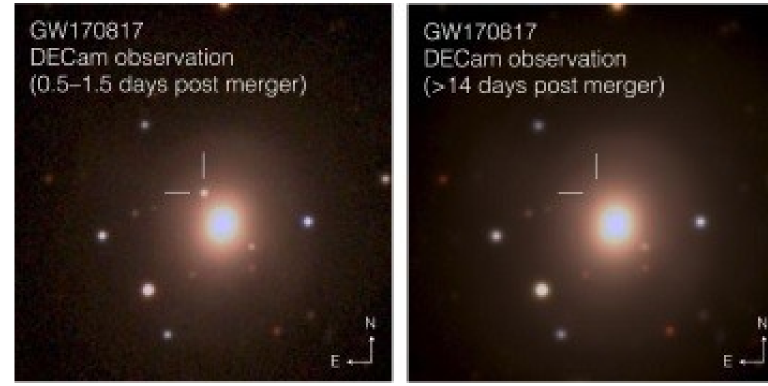
SN1994D

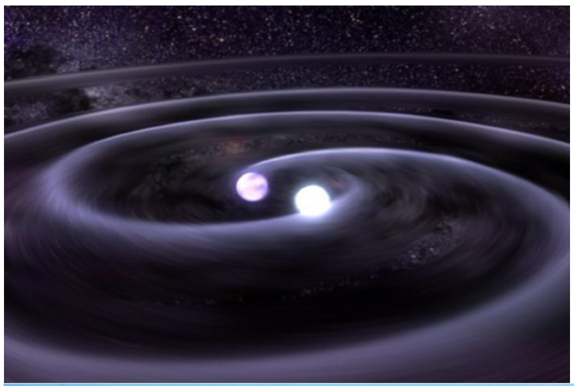


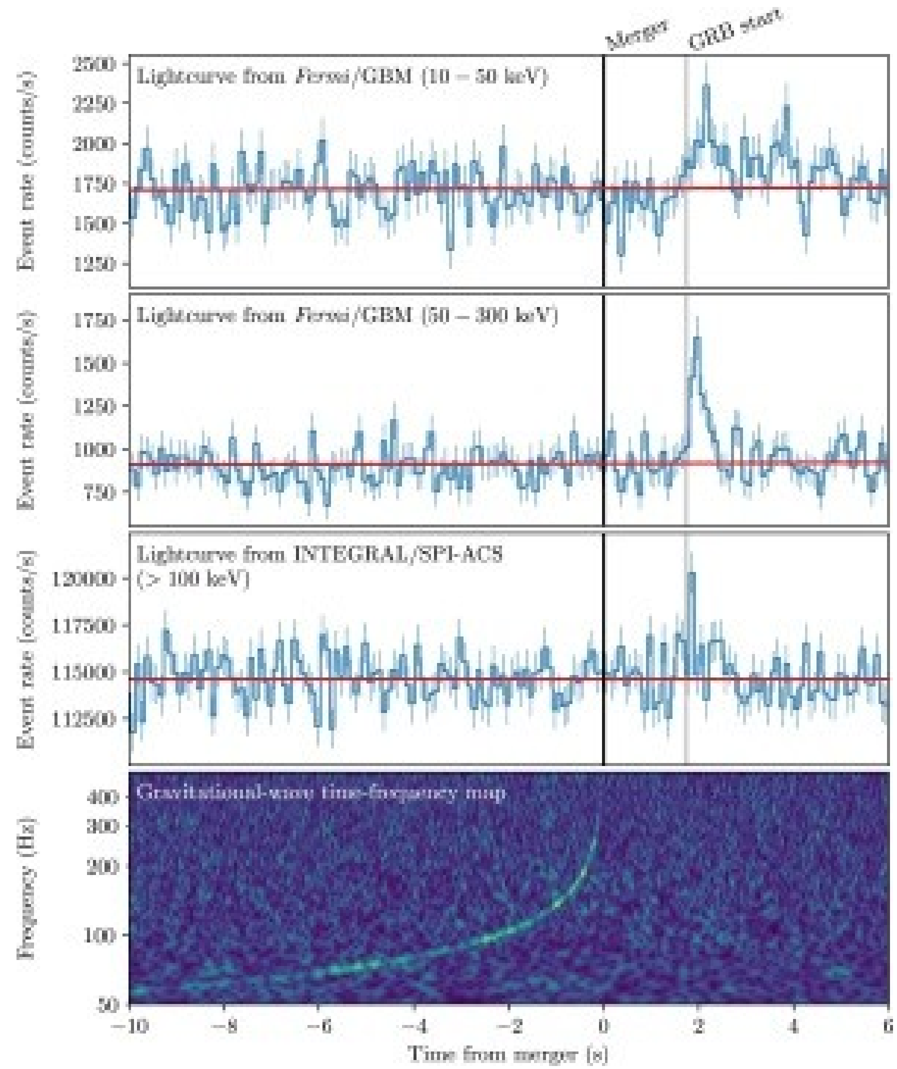
Second death of degenerate objects (cont'd)

– Mergers of NS+NS and NS+BH
 → gamma-ray burst, "kilonova"
  creation/dispersion of heavy elements

– Now detected by Gravitational wave observatories!

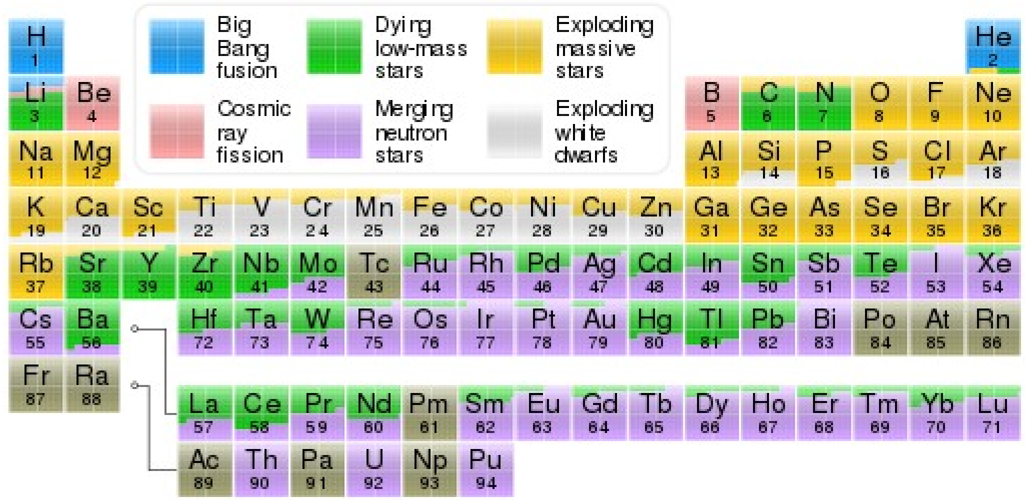






Laser Interferometer Gravitational-wave Observatory (LIGO). Also VIRGO.
And space (LISA) coming along...

Extra Notes: Origin of the Elements



https://en.wikipedia.org/wiki/Nucleosynthesis

1) Big Bang
Hydrogen, helium, and a smattering of Li.

2) Low mass stars
Outer envelope ejected when white dwarf is formed. Heavier elements formed by slow bombardment with neutrons during helium shell burning.

3) High mass stars
Outer envelope ejected during supernova explosion. Intermediate mass elements made beforehand; further ones made during explosion.

4) Exploding (merging?) white dwarf
Whole object disrupts. Fusion powering explosion produces Si and Fe group elements (most stable given density/temperature).

5) Merging neutron stars
About a percent of neutron-star material escapes and decays to the heaviest still stable nuclei.

6) Cosmic rays
Breaks elements apart. Only important for those present in trace quantities.