# Reminders

- Midterm 2 will be next Tuesday, 10/30
  - Today I'll give a study guide/brief in-class review after chapter 18
  - This test will be a little different, hopefully in a good way
    - Work as much in class as you can (no books/notes)
    - Then, take it home. Open book/note, don't work together
    - Due following Tuesday, 11/6
- Extra credit (5% toward final grade) Three College Observatory visit nights just for A235 students:
  - Thursday, 11/1; Sunday, 11/4; Monday, 11/5; Thursday, 11/8
  - **Only if clear!!** Observatory phone number (336-334-5700) will have on/off announcement by 5:30pm those dates
  - We will arrange carpools in Petty main foyer at 6pm (~40min drive to TCO). I can only take 3- volunteers with cars much appreciated!

Dress warmly, no heat at observatory!

# The Bizarre Stellar Graveyard

Chapter 18, The Cosmic Perspective

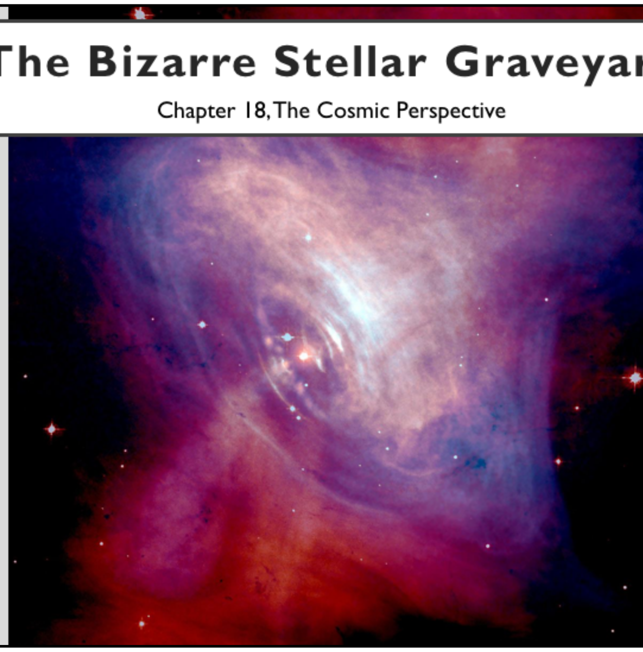



*Image 1: Supernova 1987A after exploding in February 1987 (left), and an image taken before the explosion (right). Credit: David Malin / Australian Astronomical Observatory.*
Image 2: NASA/CXC/ASU/J. Hester et al.[1]
image 3: still from Gargantua simulation, produced for the movie Interstellar: https://io9.gizmodo.com/the-truth-behind-interstellars-scientifically-accurate-1686120318

# Recap: summary of stellar lives

**Low mass stars (~1$M_{\odot}$)**

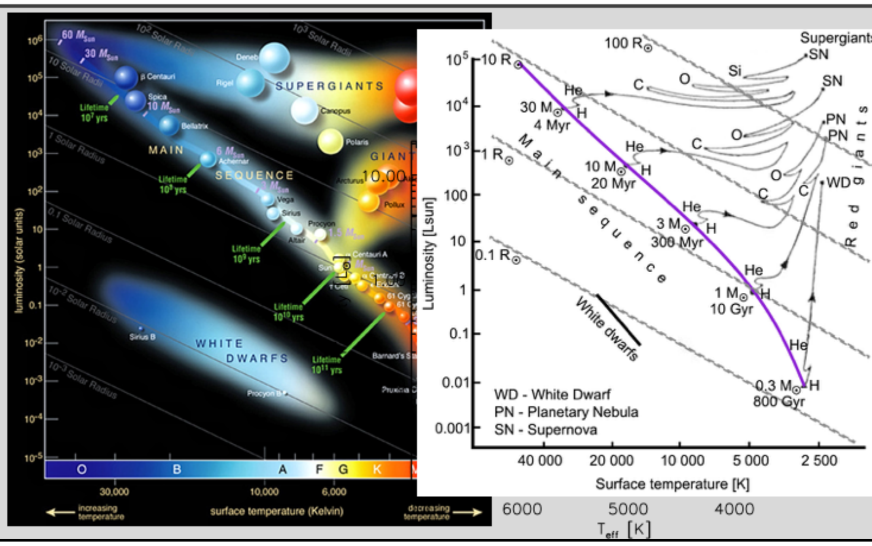
- 11.5 billion year lifetime
  - protostar,
  - yellow main sequence star,
  - red giant star,
  - helium core-fusion star,
  - double shell-fusion red giant,
  - planetary nebula,
  - white dwarf

**High mass stars (~25$M_{\odot}$)**

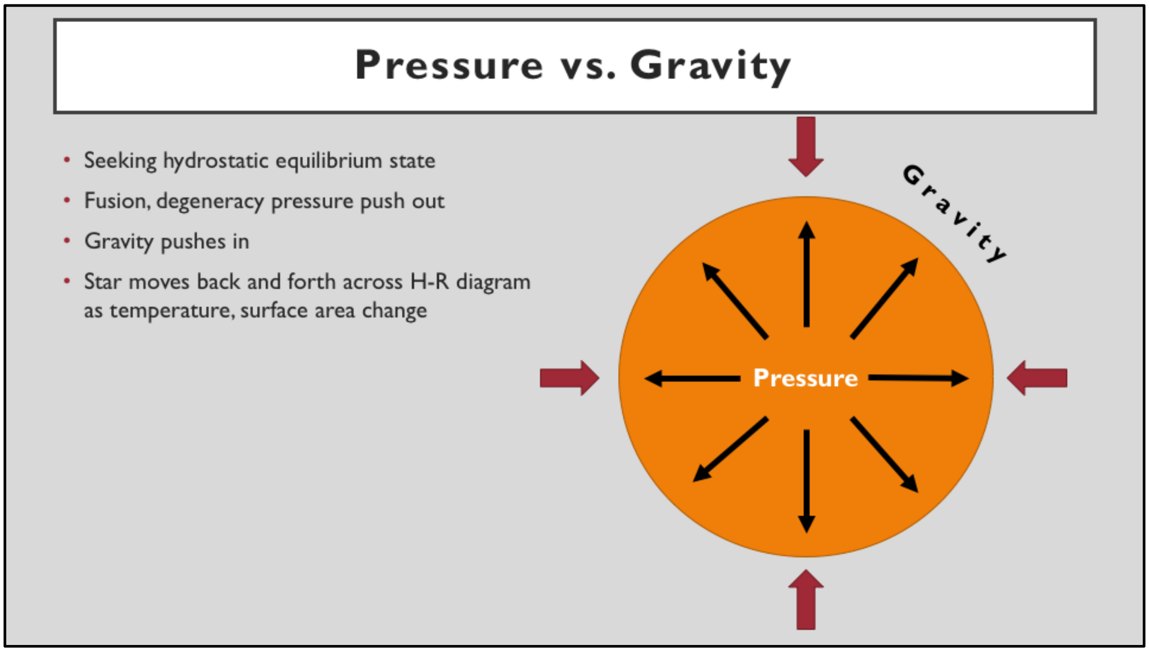
- 6 million year lifetime
  - protostar,
  - blue main sequence star,
  - red supergiant,
  - helium core-fusion supergiant,
  - multiple shell-fusion supergiant,
  - supernova,
  - neutron star or black hole

Pg 550 in the textbook
11.5billion years = 10 months on cosmic calendar
6 million years = 4 hours on cosmic calendar

# H-R Diagram, in time




I'm going to really lean on some things you've already heard a number of times today as a way of reviewing for the test..

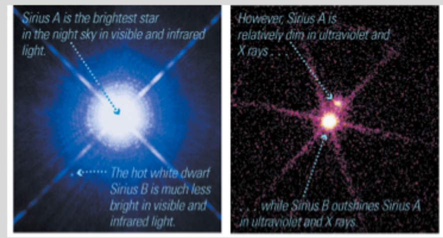


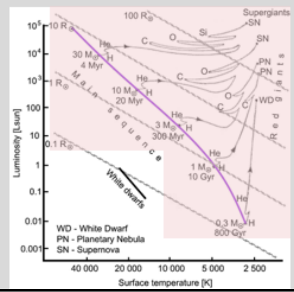

This is really important- most of the rest of class will have to do with the balancing (or not) of pressure and gravity

# White Dwarfs

- When conditions aren't hot/dense enough to burn…
- Pressure source becomes electron degeneracy pressure
- Since it isn't fusing any more, the light emitted is thermal emission because it's still hot
- White dwarfs gradually cool

  (and move along this locus in the H-R diagram)
- Radii are about the same as the Earth
  - More massive white dwarfs *smaller* in radius
- Temperatures typically ~20,000+ K

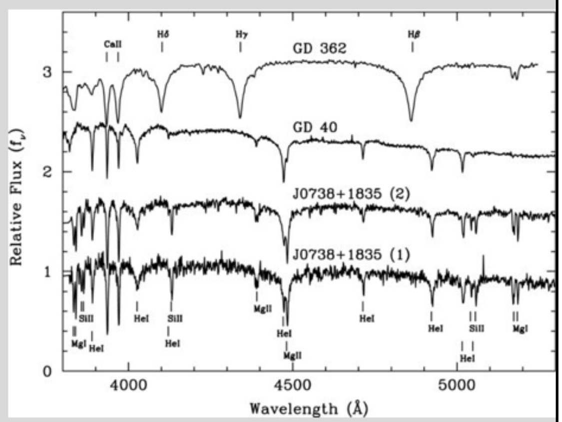



Electron degeneracy pressure is a consequence of the Pauli Exclusion Principle; it's a resistance to quantum state degeneracy and not an electrostatic repulsion. Remember that question from the first midterm about stars you can see in a blue filter as well as in a red one, vs one you can see in just the red? This white dwarf example is exactly the same, but the filters are ultraviolet and visible light. The star you can see in the UV and the visible (the white dwarf) is hotter than the star that's dim in the UV and bright in the visible.

## White Dwarfs

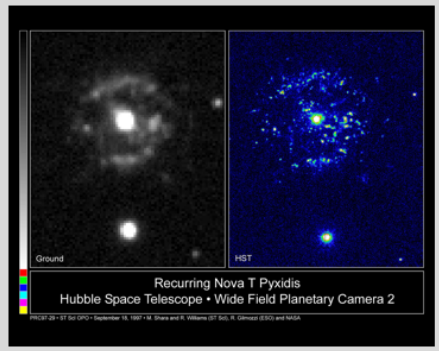
- Still have absorption lines in their spectra!
- A white dwarf's composition reflects the products of the star's final nuclear burning stage
  - The lowest mass stars leave helium white dwarfs
  - The remnant of a 1 $M_\odot$ star contains mostly carbon
  - Intermediate-mass stars end their lives as oxygen white dwarfs or those containing heavier elements
- The mass of a white dwarf cannot exceed 1.44 $M_\odot$ – beyond this mass (the Chandrasekhar limit), electron degeneracy pressure can be overcome by gravity




So if you observe a white dwarf, you have a pretty good idea what its mass may be.
http://iopscience.iop.org/article/10.1088/0004-637X/719/1/803
In the figure, that lowest spectrum is of a metal-rich white dwarf- astronomers think the metals are from a planet or asteroid-like object the star accreted (ate. Yum, burrp.).

# White dwarf novae

- If a companion is close enough, white dwarf can accrete material
- Fusion can briefly reignite in a shell if enough H accretes, 10 million K temperature reached
- Hot, fast, burst of fusion blows the accreted material right off
- Accretion can resume, novae could periodically happen
- For comparison, novae are ~100,000$L_{\odot}$, supernovae ~$10^9$ $L_{\odot}$



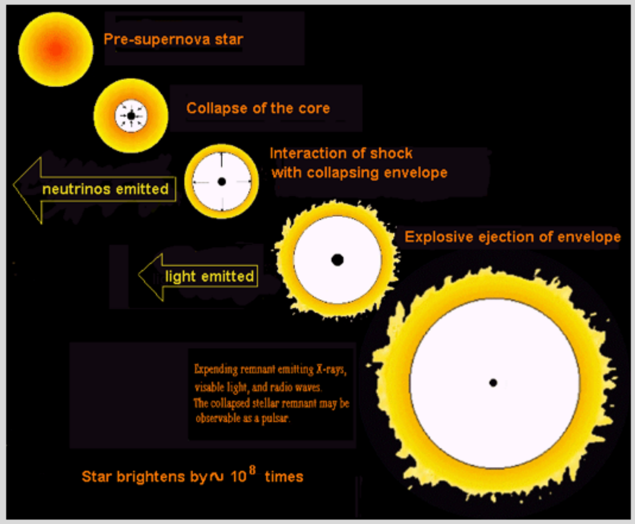

‘nova’ just means ‘new’
https://www.spacetelescope.org/images/opo9729a/

# Supernovae

- If electron degeneracy pressure is overcome, electrons combine with protons to become neutrons
- In a fraction of a second, an iron core collapses into a ball of neutrons a few kilometers across
- The collapse stops, since neutrons have their own degeneracy pressure
- Collapse releases a huge amount of energy and results in an explosion – a **supernova**

## Supernovae

- Explosion could be driven by a neutrino shock wave, propagating through the star's outer layers
- Some part of acceleration/driving away star's envelope could be 'bouncing' effect of the core




http://astrosun2.astro.cornell.edu/academics/courses/astro201/sn.htm

# Supernovae

- Three types of supernova (depending on how limit is exceeded):
  - White dwarf (explosion in a binary system)
    - Accretion
    - Merger
  - Intermediate-mass (leaves a neutron star as remnant)
  - Massive (leaves a black hole as remnant)

- Supernovae shine as bright as ~10 billion Suns for a few weeks
- The neutron core is called a neutron star
- If gravity overcomes neutron degeneracy pressure, the core continues to collapse → black hole

Supernova 1987a, observed by HST
http://www.spacetelescope.org/images/potw1142a/

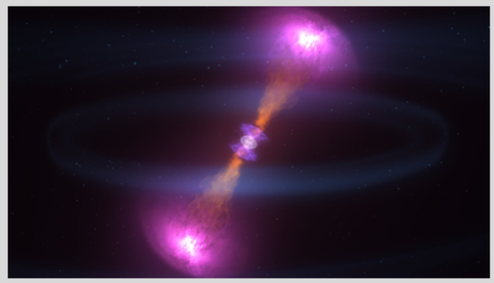
## White dwarf supernova

- Something (two white dwarfs merging, or a white dwarf accreting material from its companion) pushes white dwarf over Chandrasekhar limit
- Inert, electron degeneracy pressure-supported C core reaches 600 MK, C ignites
- But wait, there's not enough mass to counteract the outward pressure from C fusing!
  - *Ka-boom!*

- Because of the magic 1.4 $M_{\odot}$ number, all white dwarf supernovae have comparable brightnesses
  - If we observe the apparent brightness and know what its luminosity should be, can calculate a distance!

# Neutron Stars

- Product of intermediate mass stars' supernovae
- A neutron star is created by the collapse of the iron core: electrons and protons combine
- Neutron stars are supported by neutron degeneracy pressure
- Neutron stars resemble atomic nuclei, but:
  - are made of neutrons
  - are held together by gravity
  - emit photons gravitationally redshifted
    - photons lose energy overcoming the strong gravitational field



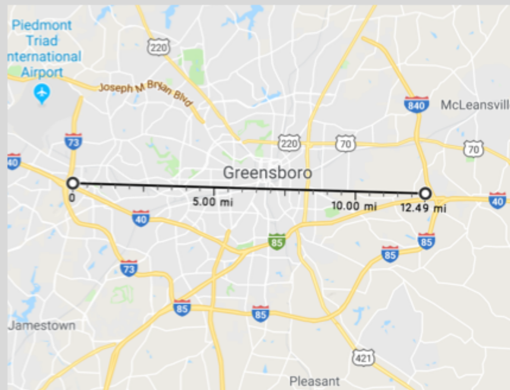
https://phys.org/news/2018-05-spectacular-neutron-star-merger-gravitational.html

# Neutron Stars

- Hold on to your hats, these things are bizarre…
  - Typical size: R ~10 km (~6.21mi)
  - Mass: M ~1.4 – 3 $M_\odot$
  - Density: ρ ~$10^{14}$ g/cm$^3$

→ Piece of neutron star matter of the size of a sugar cube has a mass of ~ 100 million tons!!!
→ A paper clip as dense as a neutron star would weigh more than Mt Everest

Thought to have "crusts" of electrons, ions, near surface where pressure is like a white dwarf



# Pulsars

- How do we know neutron stars exist?
- First detection of a pulsar: Jocelyn Bell, 1967; radio observations
- Fast (1.337301 second), regular pulses detected from the constellation Cygnus
  - Called "LGM-1" (Little Green Man)
- 1968: More pulsars! Found in Crab, Vela Nebulae, gaseous remnants of supernovae

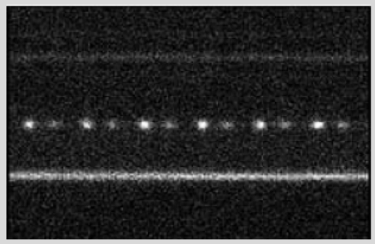


Image: Crab nebula observed with VLT (on page 563 in book)

## Story time…

- In 1967, Dame Jocelyn Bell Burnell discovered pulsars when she was a graduate student (age 24!)
- Her thesis advisor won the Nobel Prize in 1974 for the discovery
  - He originally thought it was interference from human-produced radio signals, suggested s
- Recently, she won the $3 million Breakthrough Prize
  - Has donated it all to the Institute of Physics to fund studentships (fellowships and scholarships) for physics students from traditionally excluded groups

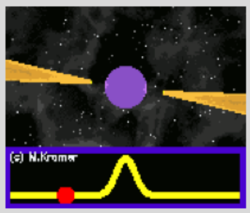
"It was a very, very small signal. It occupied about one part in 100,000 of the three miles of chart data that I had," Bell Burnell said. "I noticed it because I was being really careful, really thorough, because of impostor syndrome."

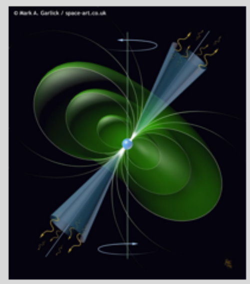
Impostor syndrome strikes when people doubt their own achievements and develop a deep sense that they will be outed as a fraud. In Bell Burnell's case the condition manifested as a fear she would be thrown out of Cambridge: "I'm a bit of a fighter, so I decided that until they threw me out I would work my very hardest. Then, when the time came, I wouldn't have a guilty conscience. I'd know I had done my best."

Story time!!! Can you guess what I'm going to tell you about Jocelyn Bell (Burnell)? She discovered something cool, her work wasn't believed, she continued to work and confirm it, then others got credit for the discovery, she wasn't acknowledged by Nobel prize committee … story's getting a little familiar, isn't it?
https://www.nature.com/articles/d41586-018-06210-w
https://www.theguardian.com/science/2018/sep/06/jocelyn-bell-burnell-british-astrophysicist-overlooked-by-nobels-3m-award-pulsars

# Pulsars

- Found at the centers of supernova remnants: A-ha!
- Pulsations are due to rapid spinning of the neutron star (angular momentum conservation!)
- Pulsars also have extremely strong magnetic fields.
- The magnetic field directs beams of radiation out along the magnetic poles.
- Pulsars slow down with time
- All pulsars are neutron stars, but not all neutron stars are pulsars



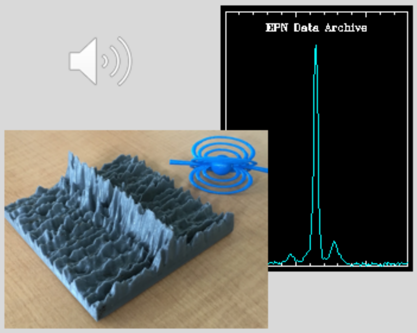



http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_deathhigh.html

# Pulsars - examples

## PSR B0329+54

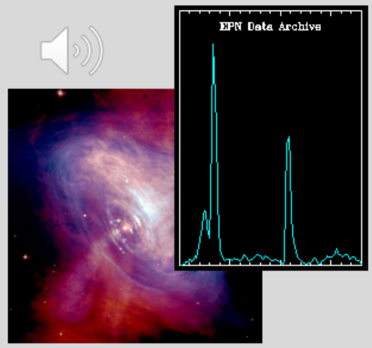
- Period 0.714519 seconds, i.e. close to 1.40 rotations/sec



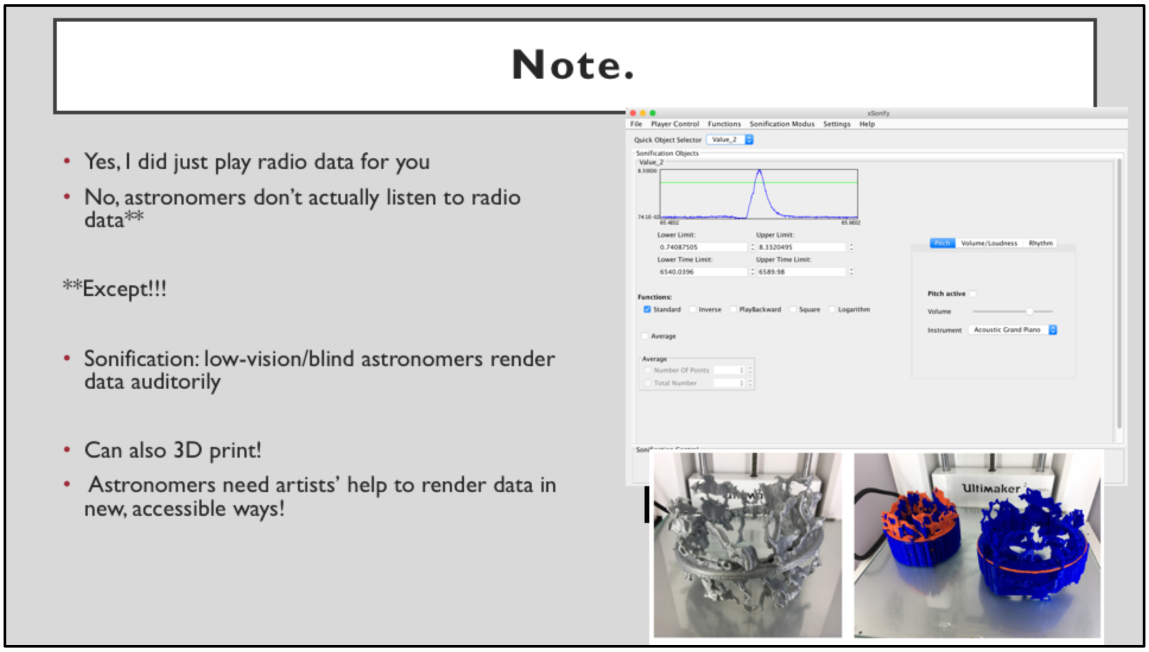

Credit: Dawn Erb (found on Thingiverse)

## PSR B0531+21, The Crab Pulsar

- Rotates about 30 times a second

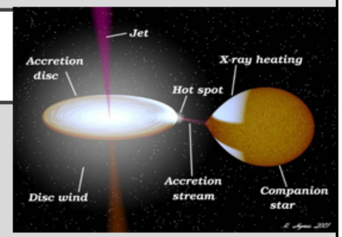



http://www.jb.man.ac.uk/pulsar/Education/Sounds/sounds.html




X-sonify:
https://www.cfa.harvard.edu/sed/projects/star_songs/pages/xraytosound.html
3d printed model, Salvatore Orlando:
http://chandra.harvard.edu/deadstar/sn1987a.html

# Neutron stars in pairs

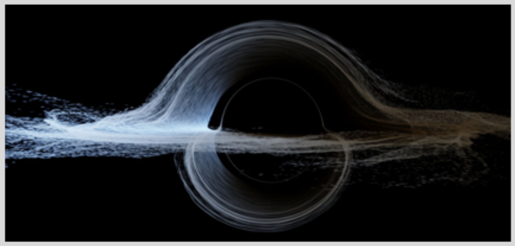



- Just like white dwarfs accreting from companions, neutron stars can, too
- Material falling in releases a lot of gravitational potential energy
  - Not because of the distance, but because of the G! (recall, PE = mgh)
- Accretion disk so hot, emits X-rays
- Called an X-ray binary
- A pair of neutron stars could exist, orbit each other; even merge:
  - resulting energy release could form elements heavier than iron: more energy involved than in a massive star supernova
  - lots of neutrons around, rare elements could be formed
  - models show most of rare-earth elements in universe (like gold!) produced by neutron star mergers

https://www.cosmos.esa.int/web/cesar/x-ray-binaries-monitoring

# Black holes

- So far, degeneracy pressure has thwarted gravity- can gravity ever win?



- Rev. John Michell (1783), Pierre-Simon Laplace (1796) wondered: do "Dark Stars" exist? So small, escape velocity ~ speed of light?

# Escape velocity

- Speed needed to escape an object's gravitational pull

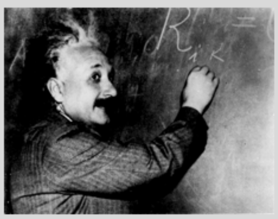
$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

- Examples:
  - Earth: $V_{esc}$ = 27,000 miles/hour (11 km/s)
  - Sun: $V_{esc}$ = 1.4 million miles/hour (600 km/s)

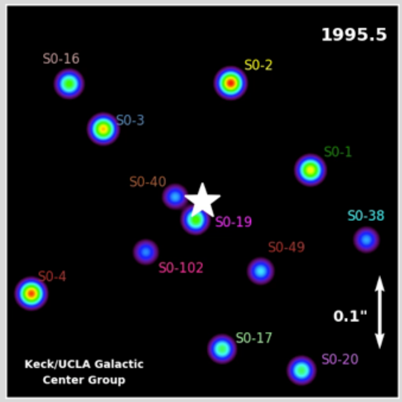
- Keeping their masses the same, for $v_{esc}$ to be the speed of light,
  - Earth's radius R ~ 1 inch
  - Sun's radius R ~ 2 miles

# Historical note

- 1915: General Relativity, Einstein's Theory of Gravity
- 1916: Karl Schwarzschild's discovery of black holes in General Relativity
- ~1960s: Black holes understood and generally accepted
- 1967: term "black hole" coined by John Wheeler
- Mid-1990's-present: Prof. Andrea Ghez observing stars' orbits around Milky Way (supermassive) BH



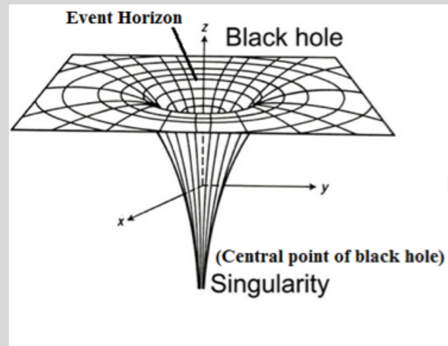
# Our friendly Milky Way BH




http://www.galacticcenter.astro.ucla.edu/animations.html

# Black holes

- The neutron star limit is ~3 $M_\odot$
- A collapsing stellar core >3 $M_\odot$ becomes a black hole
- The event horizon is where the escape velocity = c
- Schwarzschild radius: $2GM/c^2$
  - For a 10 $M_\odot$ black hole, it is 30 km
- The center of a black hole is called a singularity; this is where all the black hole mass resides
- If the escape velocity is ~c, gravitational force is so strong, not even light can escape




http://astrosun2.astro.cornell.edu/academics/courses/astro201/bh_structure.htm

## Black hole myth-busting

- BHs are not cosmic vacuum cleaners: only inside the event horizon is matter pulled inexorably inward
- Far away from a BH, gravity is no different than for any other object with the same mass
- If a BH were to replace the sun, the orbits of planets, asteroids, moons, etc., would be unchanged (though it would get really really cold)


Yep, black holes can have accretion disks, just like stars, white dwarfs .. Physics is the same ☺

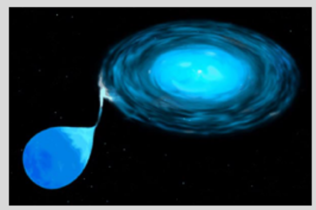
# Where to find black holes?

## Galaxy Centers

- Millions of solar masses ("supermassive" black holes)
- Generally 1 per galaxy
- We don't know how they form

## Binaries

- Likely millions of black holes per galaxy of ~10 $M_\odot$ or more
- Formed via massive star collapse
- One example: Cygnus X-1: 18 $M_\odot$ + unseen ~10 $M_\odot$ object



## Black holes: concluding thoughts

- The theory of relativity predicts that time should run more slowly as the force of gravity grows stronger
- The light coming out of a strong gravitational field should show a gravitational redshift (recall: neutron stars do this, too)
- A body falling through the event horizon will be stretched and squeezed
- Black holes produce among the most dramatic and energetic phenomena in the universe
  - Gamma ray bursts
  - Black hole-black hole mergers
  - Galactic center black holes accrete, drive energetic outflows

For now…

# Lecture recap

- **A star's mass determines its fate.**
- Low-mass stars (0.5 – 5 $M_{sun}$) end their lives as white dwarfs expelling planetary nebulae. The core mass does not exceed 1.44 $M_{sun}$
- Intermediate-mass stars (5 – 10 $M_{sun}$) end their lives exploding as supernovae, leaving neutron stars behind. The core mass does not exceed 3 $M_{sun}$
- High-mass stars ($M > 10$ $M_{sun}$) end their lives as exploding as supernovae, leaving black holes behind. The core mass exceeds 3 $M_{sun}$
- Binary systems with a white dwarf and mass transfer may end up as supernovae, if the white dwarf mass becomes higher than 1.44 $M_{sun}$