Einführung in die Astronomie II
Teil 10

Peter Hauschildt
yeti@hs.uni-hamburg.de

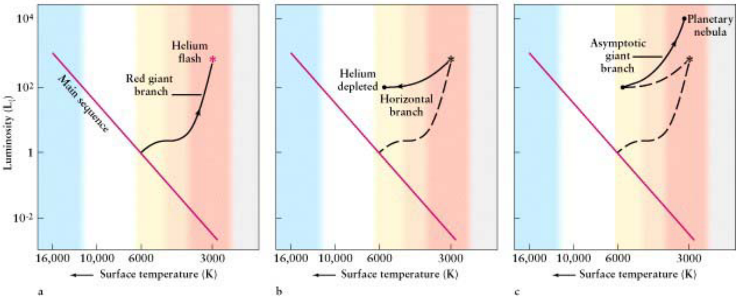
Hamburger Sternwarte
Gojenbergsweg 112
21029 Hamburg

13. August 2019

Overview part 10

- Death of stars
  - AGB stars
  - PNe
  - SNe
  - neutron stars
  - stellar black holes

Post-MS: 1 $M_\odot$!!



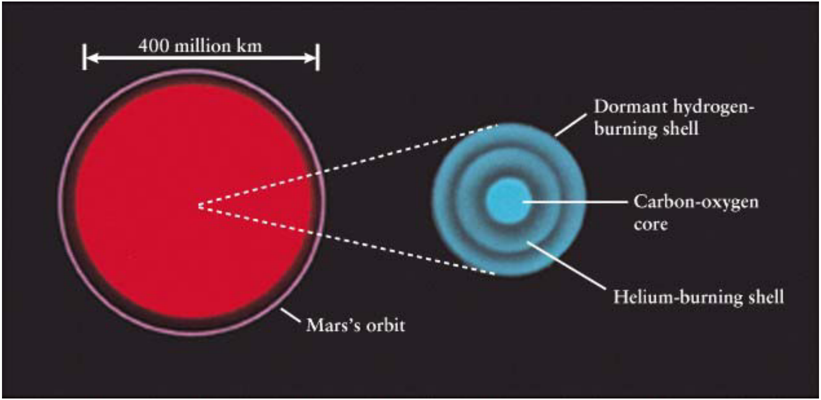
Asymptotic Giant Branch

- core He burning → cooling of the core and H shell source
- *L* goes down a bit, *R* shrinks and surface temperature increases
- stars moves horizontally through HRD
  → *horizontal branch*
- core He burning lasts $\approx 10^8\,\mathrm{yr}$ ($1\,\mathrm{M}_\odot$ star)
- core consists of C and O
- core shrinks until it becomes (electron) degenerate

Asymptotic Giant Branch

- He burning re-starts in a shell
  $\rightarrow$ *shell helium burning*
- same effect as earlier
  $\rightarrow$ energy output from He burning shell expands star
- $\rightarrow$ it moves again toward the red giant region
- $\rightarrow$ *asymptotic giant branch (AGB)*
- AGB star initially has a C-O core &
  He and H shell burning
- star reaches R of $\approx 1.5\,\mathrm{AU}$ (Mars orbit)
- $1\,M_\odot$ AGB star has $10^4\,L_\odot$

old AGB star !!


400 million km
Dormant hydrogen-
burning shell
Carbon-oxygen
core
Helium-burning shell
Mars's orbit

Dredge up

- convection can dredge up material from the core to the surface
- *first dredge up* after core H burning ends and the star becomes a first time RG
- CNO cycle ashes can reach the surface area
  $\rightarrow$ changes in the observed abundances

Dredge up

- *second dredge up* after core He burning ends
- also enhances CNO in the atmosphere
- *third dredge up* during AGB stage ($> 2\,M_\odot$ stars)
- large amounts of C reach the surface
  $\rightarrow$ *carbon star*
- strong stellar winds of AGB stars eject large amounts of C into the ISM

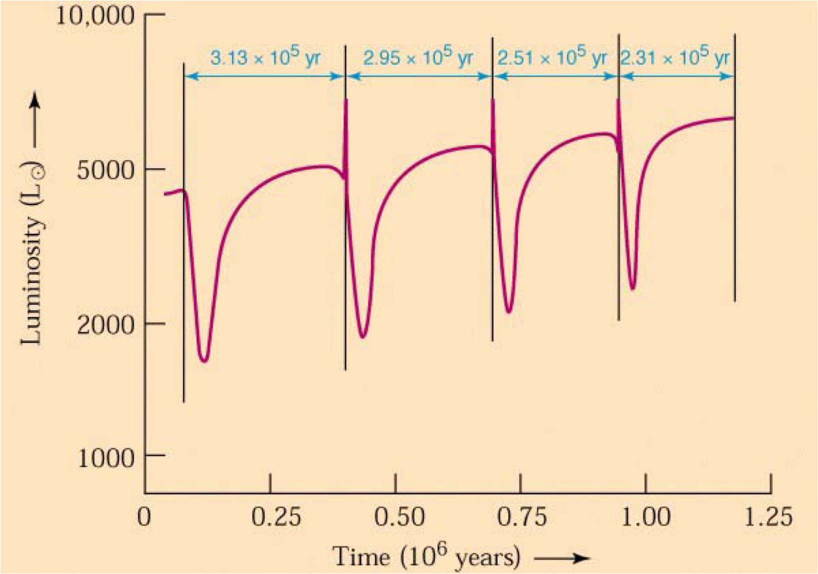
Planetary Nebulae

- low mass stars: $< 4\,M_\odot$
- AGB phase $\rightarrow$ huge mass loss rates
- He core runs out of He
- contracts $\rightarrow$ heats up H shell source $\rightarrow$ more output

Planetary Nebulae

- He rains on the core
- it shrinks and heats up even more
- eventually a *helium shell flash* ignites a temporary He shell source
- this expands the H shell source layers
- they cool and H shell source turns *off*
- process repeats
  $\rightarrow$ *thermal pulses* (300,000 year intervals)

thermal pulses

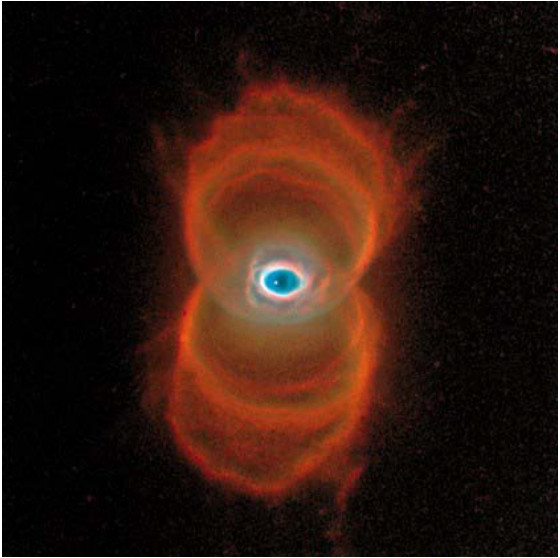


Planetary Nebulae !!

- bursts of energy output $\rightarrow$ bursts of mass loss
- ejects all the envelope material
- only hot core remains ($100,000\,\mathrm{K}$)
- ejected material is excited by high-energy photons to glow
- $\rightarrow$ *planetary nebula*

NGC 7293

Hourglass Nebula



Planetary Nebulae

- common objects, 20,000–50,000 in the Galaxy
- bright emission lines of H, O, N
- expand at $10 - 30\,\mathrm{km\,s^{-1}}$
- typical diameter is $1/3\,\mathrm{pc} \rightarrow$ about 10,000 years old
- eventually remnant (core) cools off too much and gas disperses
- 50,000 years lifetime of a PN
- PN deliver about $5\,\mathrm{M_\odot/yr}$ into the ISM
- about 15% of the total input
- $\rightarrow$ important for the chemical evolution of the Galaxy

White Dwarfs

- stars $< 4\,\mathrm{M}_\odot$
- He burning is the last thermonuclear reaction
- core of C+O becomes the remnant of the star
- core inert, just cools down over time
- material in the core is degenerate
  $\rightarrow$ doesn't shrink when cooling
- cooling WD can crystallize!

High Mass Stars !!

- larger mass produces more compression in the core
- $\rightarrow$ higher temperatures
- MS mass $> 4\,M_{\odot}$: C-O core $> 1.4\,M_{\odot}$
- $\rightarrow$ continues to compress
- $T > 600 \times 10^6$ K: *carbon burning*
- produces O, Ne, Na, Mg

High Mass Stars !!

- MS mass $> 8\,M_\odot$: after C burning: temperatures reach 10^9 K
- $\rightarrow$ Ne burning produces O and Mg
- then: O burning ($T > 1.5 \times 10^9$ K) produces S and Si
- $T > 2.7 \times 10^9$ K $\rightarrow$ *Si burning* produces S to Fe
- each phase of core thermonuclear burning has a shell source associated with it

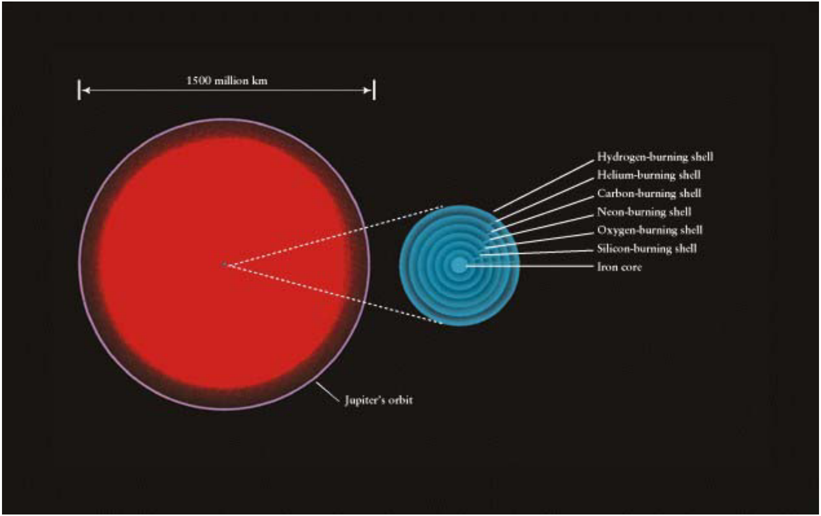
High Mass Stars

- also causes several red giant phases!
- $\rightarrow$ star moves back and forth in the HRD
- star is also losing mass at high rates
- some nuclear reactions produce neutrons
- these react easily with nuclei
  $\rightarrow$ *neutron capture*
- $\rightarrow$ produces rarer elements

High Mass Stars

- each successive reaction lasts shorter
- 25 $M_\odot$ star:
  $\rightarrow$ C burning 600 years
  $\rightarrow$ Ne burning 1 year
  $\rightarrow$ Si burning 1 day
- resulting structure looks like an onion

old massive star !!



High Mass Stars !!

- high L expands outer layers $\rightarrow$ *supergiant*
- up to $1000\,\mathrm{R}_\odot$
- sequence of thermonuclear reactions end with Si burning
- ^{56}Fe is the most stable element (26 protons, 30 neutrons)
- adding protons or neutrons requires energy!!
- $\rightarrow$ inert Fe core
- all energy production by shell sources within 1 Earth radius

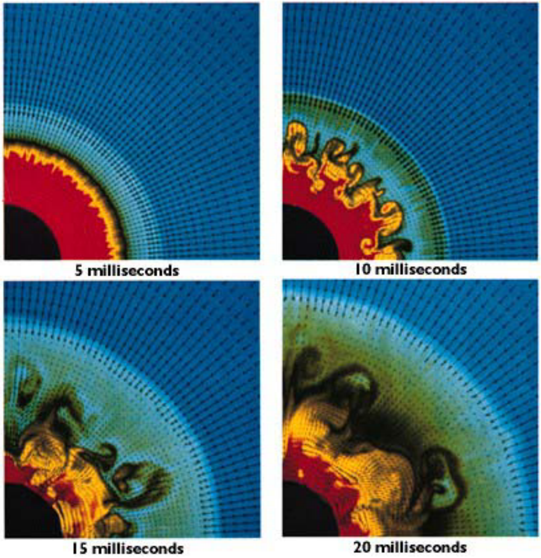
Supernovae !!

- Fe core very hot (100's million K)
- $\rightarrow$ photons set off nuclear reactions that produce neutrinos
- these leave the star
- to compensate, core contracts within 1/10 s
- heats to $> 5 \times 10^9$ K
- $\rightarrow$ photons energetic enough to break up nuclei $\rightarrow$ *photodisintegration*
- breaks up elements to He!

Supernovae !!

- this *costs* the core energy $\rightarrow$ more contraction
- core becomes so dense that electrons and protons combine to produce neutrons and neutrinos
- these leave the core/star $\rightarrow$ more contraction
- after about 0.25s the core reaches 20km diameter
- density comparable to that of nuclei!
- this changes the behavior of the material:
- very rigid
- contraction stops and core bounces back

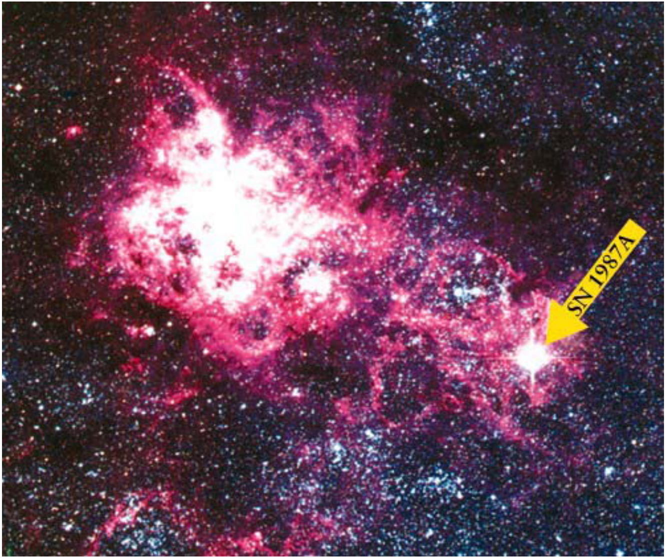
SN simulation



Supernovae !!

- this creates a powerful pressure (sound) wave
- encounters outer material trying to fall onto the collapsed core (at speeds of 0.15c!)
- the pressure wave reverses the motion of the falling material (aided by neutrinos)
- reaches supersonic speed and becomes a shock wave
- drives the material outwards and reaches surface after a few hours

SN 1987A



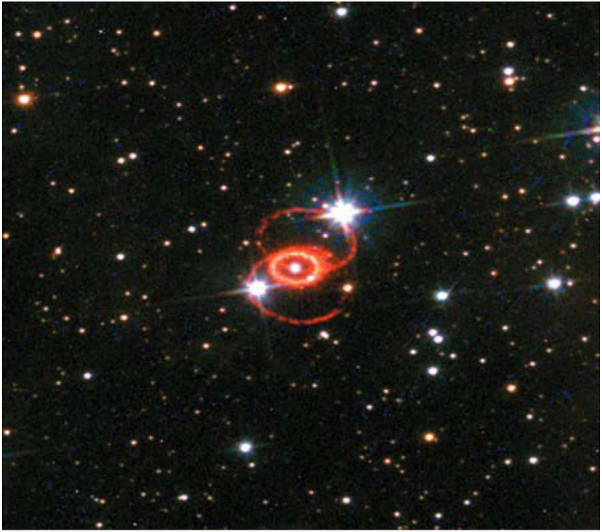
Supernovae

- total energy released is 10^{46} J
- 100 times more than the Sun has emitted during its lifetime
- red giant star becomes a *Supernova*
- reaches $10^{9}\,L_{\odot}$ for a few months after explosion
- most material ejected into space at speed in excess of $10^{4}\,\mathrm{km\,s^{-1}}$

SN 1987A

- closest recent SN: 1987A in the LMC
  - bright enough to be seen directly
  - reached only $10^8\,L_\odot$: blew up as a blue supergiant
  - neutrino emission detected!
  - 3h *before* optical detection!
- SNe emit most of their energy as neutrinos (99%)

SN 1987A

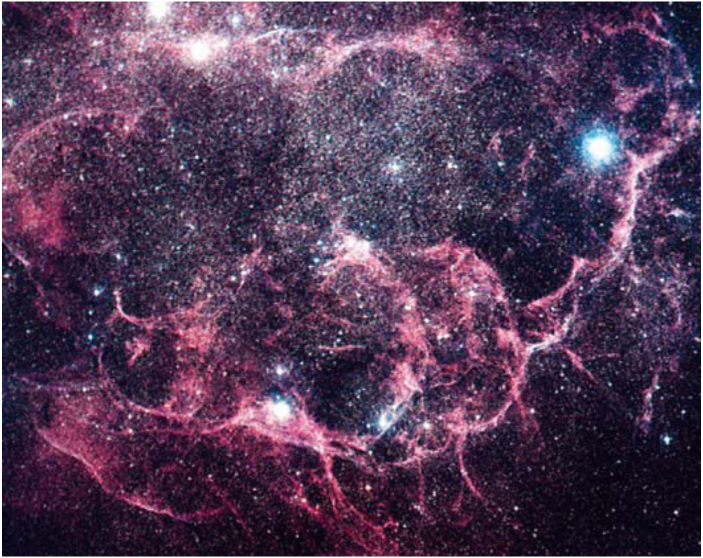


a

Supernova Remnants

- debris ejected by SN explosion
- plows into ambient gases and produces glowing nebula
- many *supernova remnants* are known
- Gum nebula:
  - 60° in the sky (largest)
  - near side 100pc from Earth!
  - center about 460pc away
  - exploded about 9000 B.C.
  - parent SN as bright as the quarter moon!

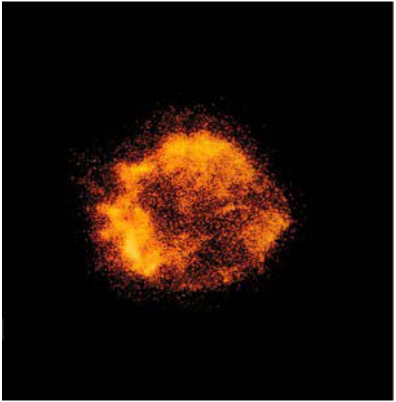
Gum nebula

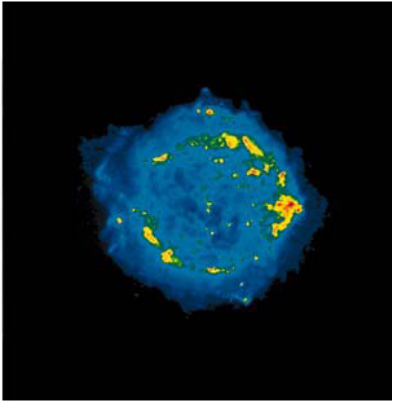


Supernova Remnants

- SN remnants best searched via radio observations
- Cas A: exploded about 300 years ago (unseen!)
- last galactic SNe: 1572 (Tycho), 1604 (Kepler)
- next earlier: $\approx$ 1000 years earlier!
- Galaxy should show about 5 SNe per century
- most are hidden by dust in the ISM!

Cas A: X-ray & radio

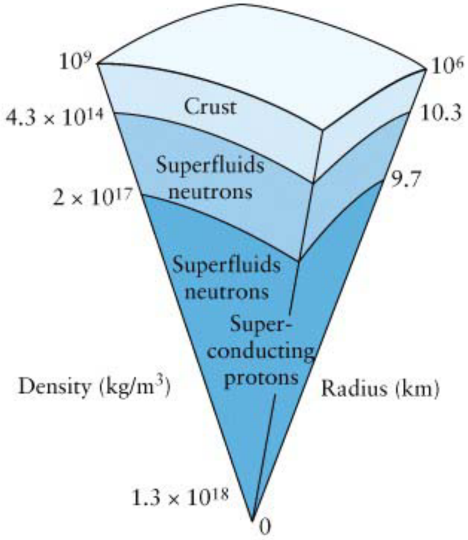




Neutron stars !!

- compact remnant of SN explosion
- $M \approx 1\,\mathrm{M}_\odot$
- $R \approx 10\,\mathrm{km}$
- density of nuclear matter!
- shrinks with larger M
- $\rightarrow$ limiting mass $\approx 3\,\mathrm{M}_\odot$

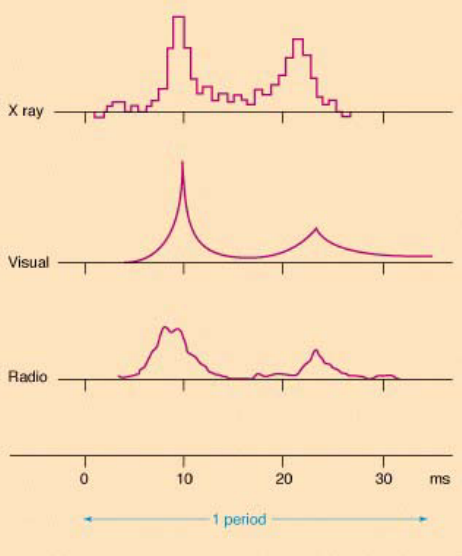
neutron star structure



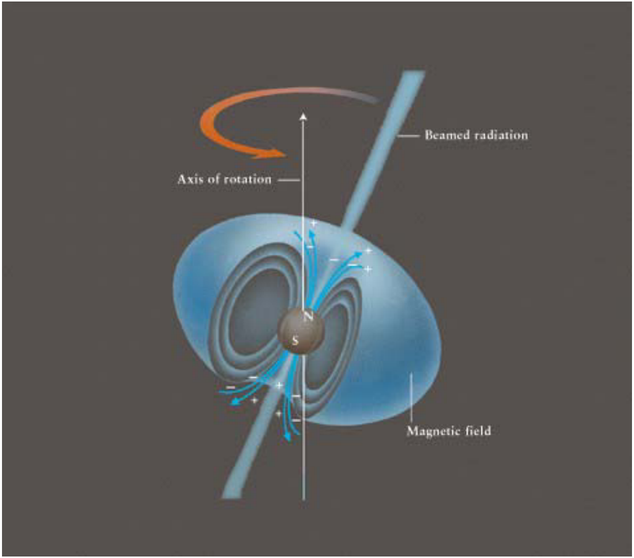
Neutron stars

- predicted in 1930!
- observed as *pulsars*

Pulsars



Pulsars !!

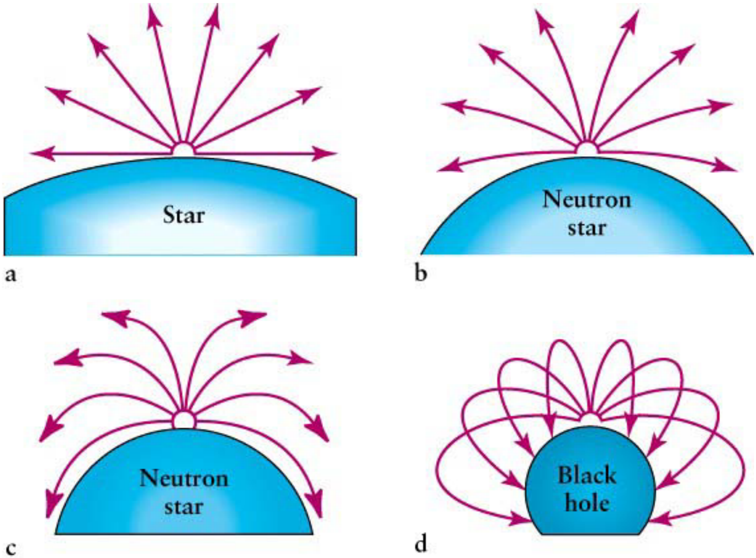


Vela Pulsar

Black Holes

- stellar remnant too massive to become a WD or neutron star?
- collapses due to extremely strong gravity
- distortions of space-time increase dramatically
- light follows curved path due to huge distortions
- eventually, the escape speed from the surface reaches c

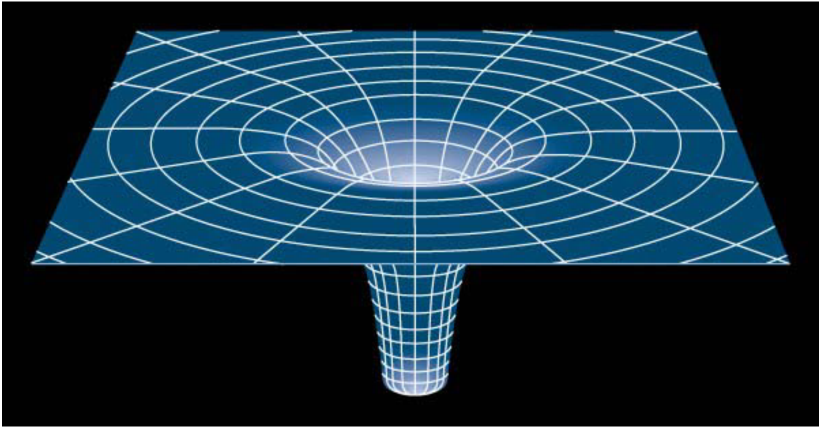
Black Holes



Black Holes !!

- at this stage, a "hole" is punched into space-time by the enormous gravity
- $\rightarrow$ collapsing objects disappears from the universe and becomes a *black hole*
- *event horizon*: location where the escape speed from the hole is equal to the speed of light
- nothing inside of the event horizon can ever leave the hole!
- can be considered "surface" of the BH

Black Holes



Black Holes

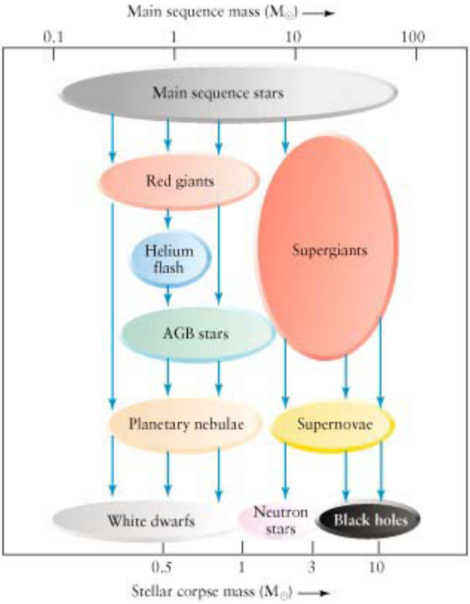
- inside the event horizon the mass of the collapsing star is concentrated at zero volume at the center of the BH
- $\rightarrow$ *singularity*
- distance singularity to event horizon:
  $\rightarrow$ *Schwarzschild radius*

$$R_S = \frac{2GM}{c^2}$$

Black Holes

- inside a BH, directions of space and time interchange
- observer could affect time but cannot move in space!
- at the singularity, space and time completely lose identity
- singularity behaves randomly (unpredictable)
- all this is completely shielded from the universe by the event horizon!
- GR effects strong only within a small distance from the event horizon!

Overview



Main sequence mass (M☉)
0.1
1
10
100
Main sequence stars
Red giants
Supergiants
Helium flash
AGB stars
Planetary nebulae
Supernovae
White dwarfs
Neutron stars
Black holes
0.5
1
3
10
Stellar corpse mass (M☉)