Neutron stars
Giant atomic nuclei in the sky

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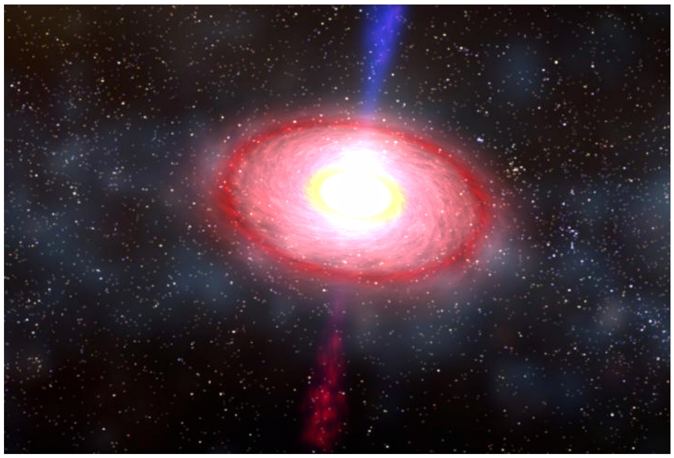
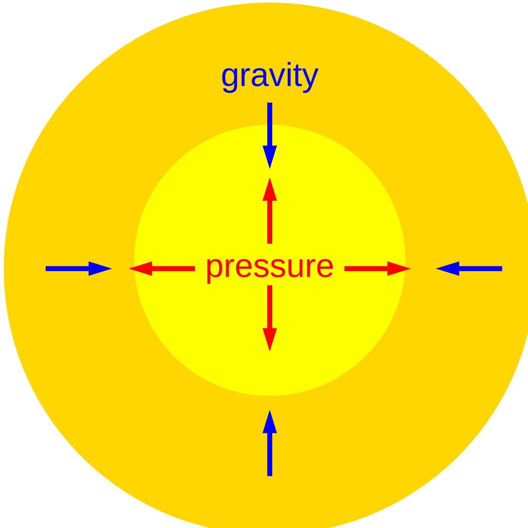


Outline

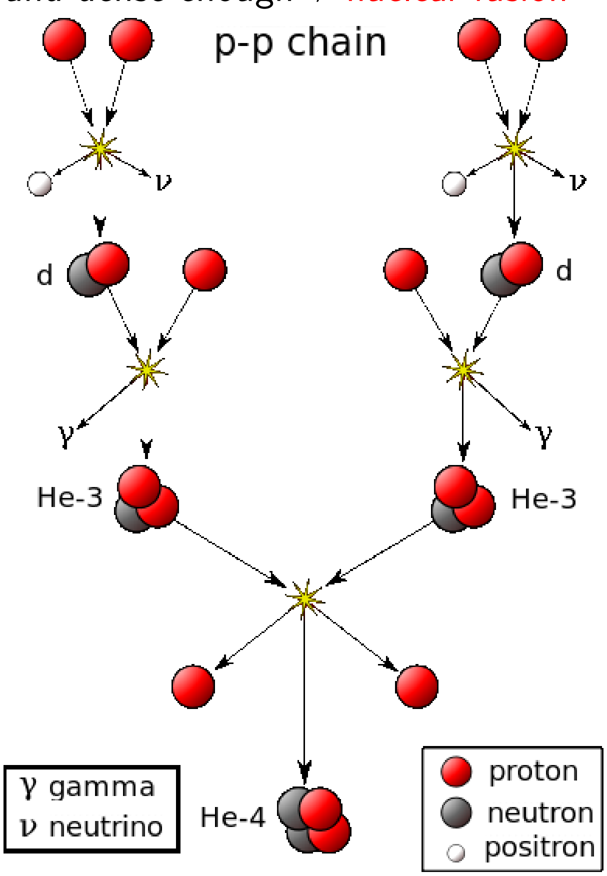
Structure of a "normal" star

- consists of a hot gas (plasma) of H, He,... (usual matter)
- it is held together by gravity ↔ gas pressure prevents collapse

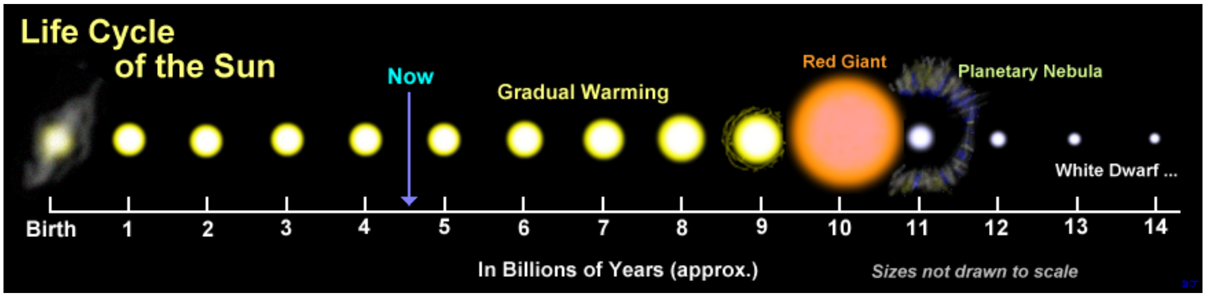


Structure of a "normal" star

- gas in core is hot and dense enough ⇒ nuclear fusion



Star formation

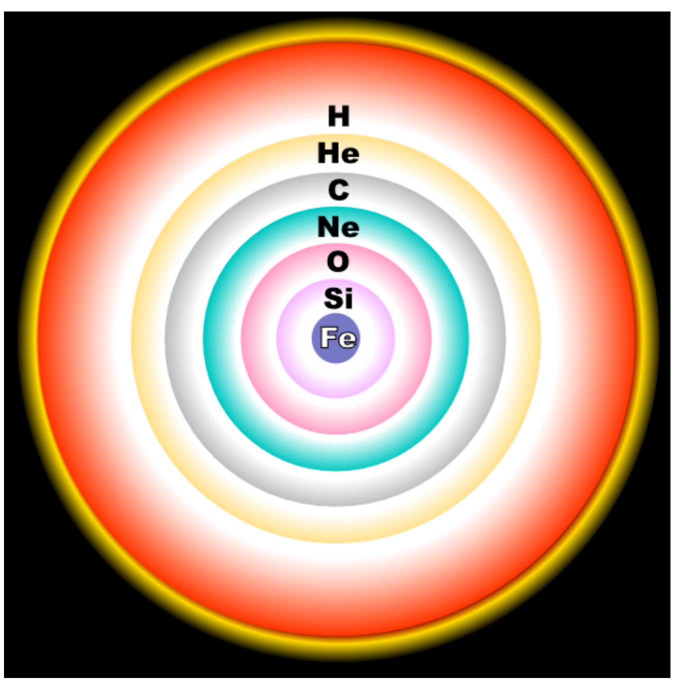


- star is born when a giant molecular cloud (GMC)
  - collides with another GMC (also in collisions of galaxies)
  - passes through dense regions of galaxies
  - is hit by shockwaves from a nearby supernova

  triggers gravitational collapse $\Rightarrow$ protostars are formed
- gravitational energy is transformed into heat
- if core becomes hot enough ($T > 10 \cdot 10^9$K) $\Rightarrow$ H-fusion chain reaction ignites
- pressure stabilizes star against gravitational collapse
- with time more and more He is built up in core $\Rightarrow$ higher pressure in H layer $\Rightarrow$ higher H-fusion rate $\Rightarrow$ higher temperatures/pressure star becomes larger
- through expansion star cools and becomes "redder" $\Rightarrow$ red giant

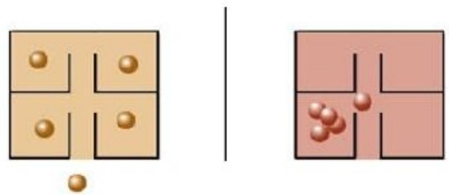
Evolution of a Star

- massive star $\Rightarrow$ He fusion to carbon and oxygen (see Dr. Banu's lecture)
- if the star is heavy enough, this can go on to form neon, magnesium, silicon
- sequence of fusion reaction definitely ends with iron (most tightly bound)



Death of a Star

- after all possible fusion reactions are ceased
  - pressure goes down ⇒ star cannot withstand gravitational collapse any longer
  - supernova explosion (see Prof. Krisciunas's lecture)
  - remnant becomes a white dwarf or a neutron star or a black hole
- to understand white dwarves and neutron stars ⇒ need quantum mechanics!
  - particles, nuclei, atoms,... are either bosons or fermions



  - Pauli principle: fermions can not occupy the same "hotel room" (quantum state) ⇒ gas of fermions withstands compression ⇒ "degeneracy pressure"
  - bosons like to occupy same state

Constituents of matter

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2		
Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	(0−0.13)×10⁻⁹	0
e electron	0.000511	−1
ν_M middle neutrino*	(0.009−0.13)×10⁻⁹	0
μ muon	0.106	−1
ν_H heaviest neutrino*	(0.04−0.14)×10⁻⁹	0
τ tau	1.777	−1

Quarks spin =1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

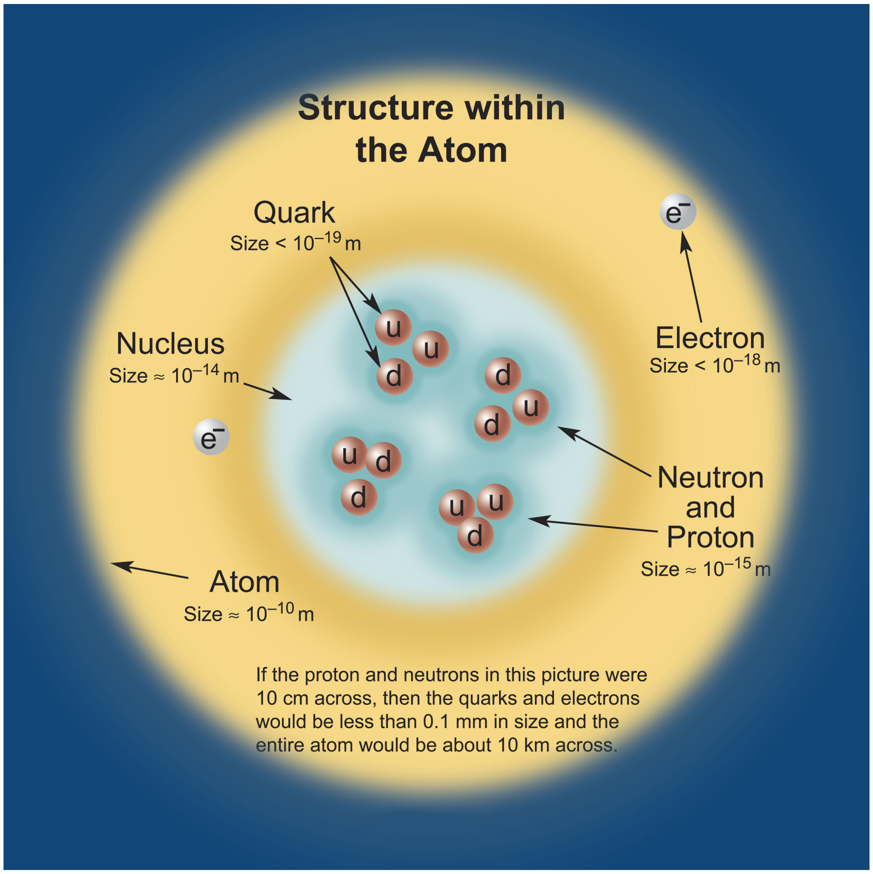
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

- Standard model of elementary particles describes successfully interactions ("forces") among elementary building blocks of matter
- quarks and leptons: fermions, constituents of matter
- "Force carriers" or fields: bosons
- one challenge of modern physics: understand matter from standard model

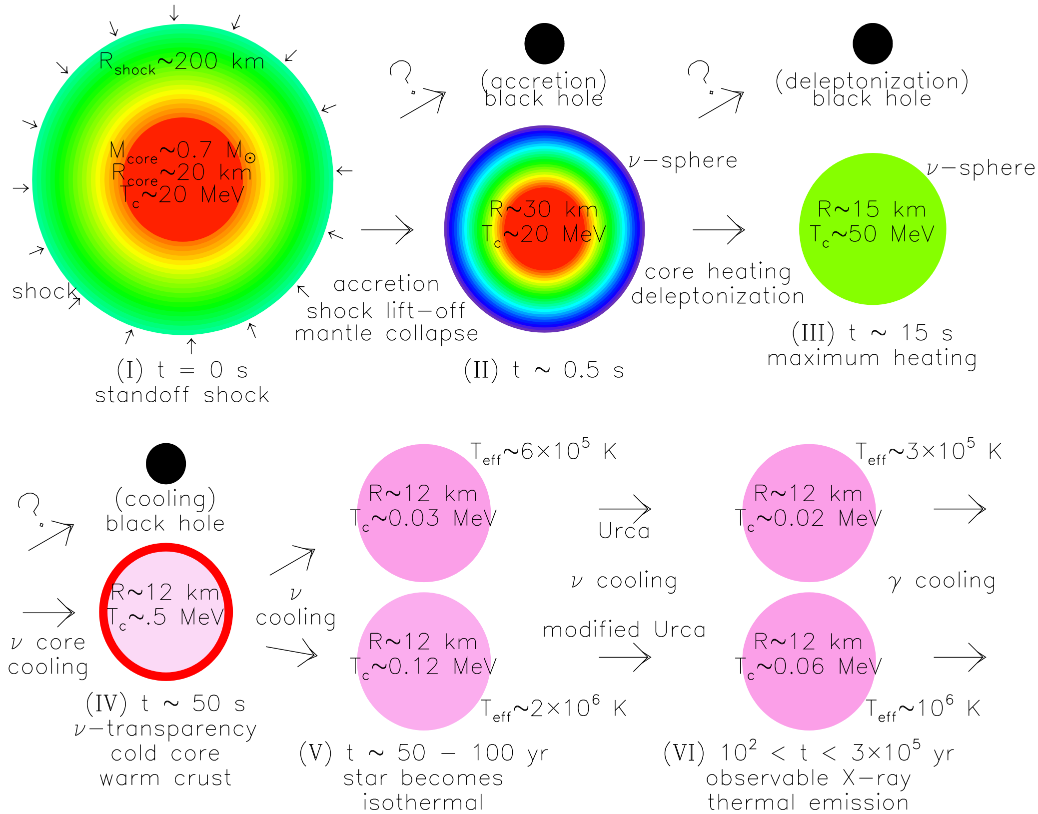
Constituents of matter



White dwarves, neutron stars, black holes

- White dwarves
  - remnant of a star composed of atomic nuclei and electrons (particular chemical composition depends on mass)
  - stabilized against further collapse by electron-degeneracy pressure
  - upper limit of mass $M_{\text{Chandrasekhar}} \simeq 1.4 M_{\odot}$ ($M_{\odot} = 1.9891 \cdot 10^{30}$ kg: mass of the sun)
- Neutron stars
  - $M_{\text{star}} > 1.4 M_{\odot} \Rightarrow$ pressure large enough to trigger electron capture reaction
$$p + e \rightarrow n + \nu$$
  - most protons become neutrons (neutrinos escape leading to effecient cooling)
  - stabilized against further collapse by neutron degeneracy pressure
  - some protons and electrons remain $\Rightarrow$ "Pauli blocking" of β decay
$$n \rightarrow p + \bar{\nu} + e$$
  - neutrons $\Rightarrow$ no repelling electric forces $\Rightarrow$ neutron star's $r \simeq 10$ km
- Quark stars or black holes?
  - Oppenheimer-Volkoff limit: $M_{\text{star}} \gtrsim (1.5\text{-}3) M_{\odot} \Rightarrow$ neutron star unstable!
  - collapse to a black hole or a quark star?
  - $M \gtrsim 5 M_{\odot} \Rightarrow$ for sure black hole!

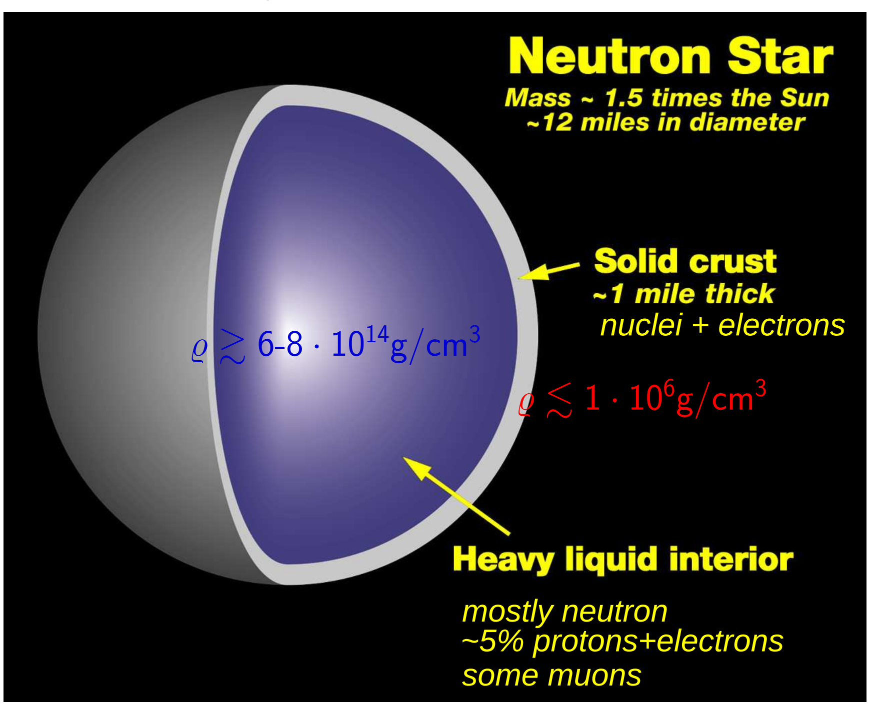
Neutron star evolution



from J.M. Lattimer, M. Prakash, Science **324**, 536 (2004)

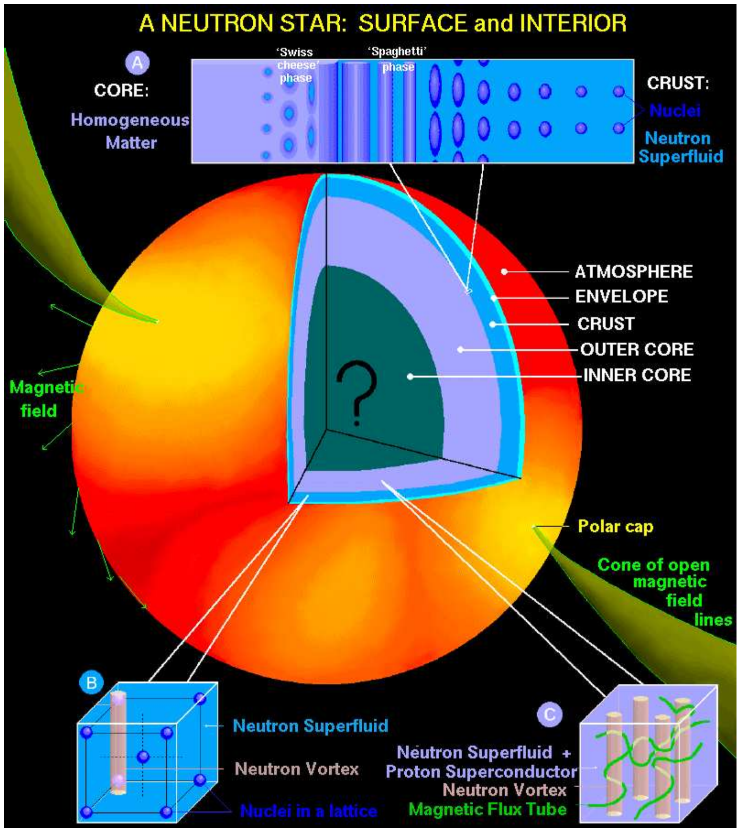
Characteristics of neutron stars

- "giant nuclei in the sky" (but bound by gravity rather than the strong force!)



- $M_{\text{NS}} = 1.35\text{-}2.1 M_\odot \Leftrightarrow r_{\text{NS}} = 20\text{-}10$ km
- density $\varrho_{\text{NS}} = 8.4 \cdot 10^{13}\text{-}1 \cdot 10^{15} \frac{\text{g}}{\text{cm}^3}$ $(\varrho_{\text{nucleus}} \simeq 3 \cdot 10^{14} \frac{\text{g}}{\text{cm}^3})$
- very dense $\Rightarrow$ general relativity needed to describe neutron star!

Neutron-star structure



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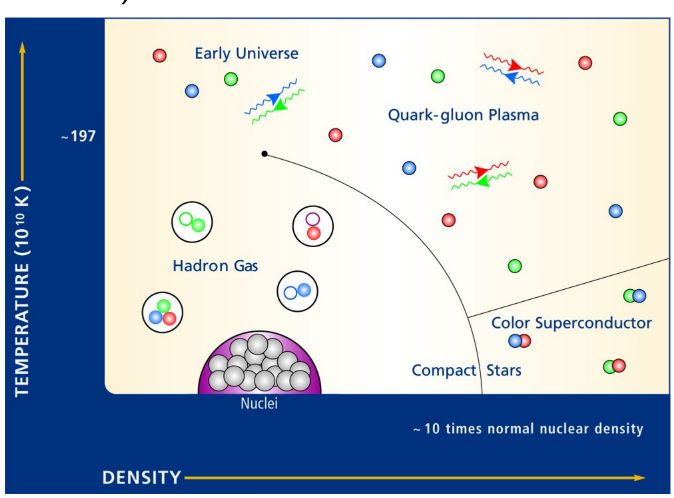
Core of neutron stars: particle/nuclear physics lab?

- properties like
  - maximal possible mass (Oppenheimer-Volkoff limit)
  - detailed decomposition and state of matter
  - temperature evolution (cooling)

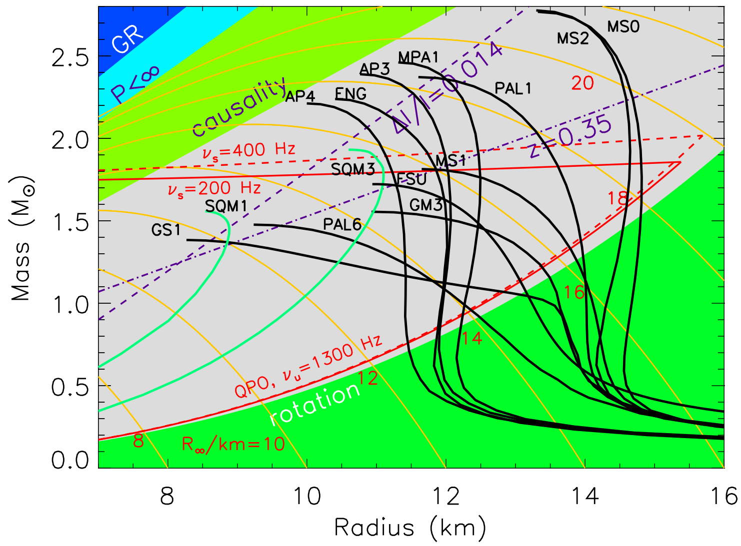
  depend on equation of state of nuclear/quark matter!
- above mass limit (Oppenheimer-Volkoff limit) only black holes or quark stars?
- neutron-star cores: "cold and dense" ⇒ state of matter not reachable in labs (heavy-ion accelerators) on earth!



How to relate to neutron-star properties?

Equation of state and neutron-star properties

- use hydrodynamics and general relativity to describe the matter in the neutron star ⇒ relation between mass and radius!
- need Equation of State (EoS): $p = p(\rho)$
- EoS can be determined from models about interacting particles

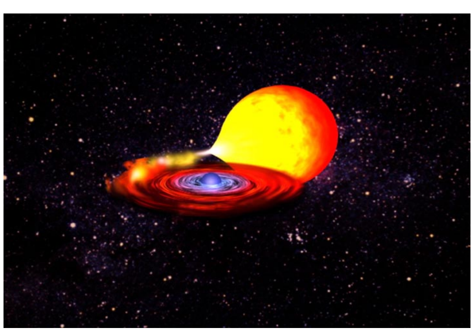


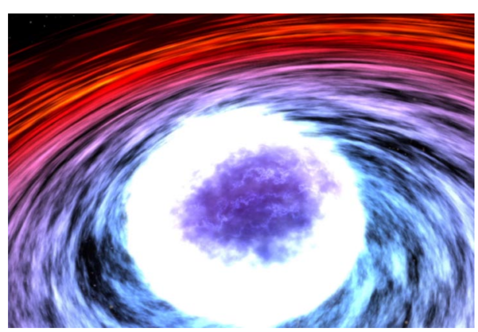
Symbol	Reference	Approach	Composition
FP	Friedman & Pandharipande (1981)	Variational	np
PS	Pandharipande & Smith (1975)	Potential	$n\pi^0$
WFF(1–3)......	Wiringa, Fiks & Fabrocine (1988)	Variational	np
AP(1–4)	Akmal & Pandharipande (1997)	Variational	np
MS(1–3)........	Müller & Serot (1996)	Field theoretical	np
MPA(1–2)......	Müther, Prakash, & Ainsworth (1987)	Dirac-Brueckner HF	np
ENG	Engvik et al. (1996)	Dirac-Brueckner HF	np
PAL(1–6)	Prakash et al. (1988)	Schematic potential	np
GM(1–3)	Glendenning & Moszkowski (1991)	Field theoretical	npH
GS(1–2)	Glendenning & Schaffner-Bielich (1999)	Field theoretical	npK
PCL(1–2)	Prakash, Cooke, & Lattimer (1995)	Field theoretical	npHQ
SQM(1–3)......	Prakash et al. (1995)	Quark matter	Q (u, d, s)

- SQM1 and SQM3: self-bound stars made of up, down and strange quarks
- challenge: meassure masses and radii of neutron stars!

Measurement of neutron-star mass and radius

- neutron star and "normal" (hydrogen) star in binary system
- neutron star accretes mass from companion
- gas becomes compressed and heated on surface ⇒ thermonuclear reaction
- X-ray burst
  (observed with Rossi X-ray Timing Explorer and XMM-Newton Satellite)
- rotation of neutron star ⇒ oszillations in burst ⇒ $f_{\text{rot}} = 45$ Hz

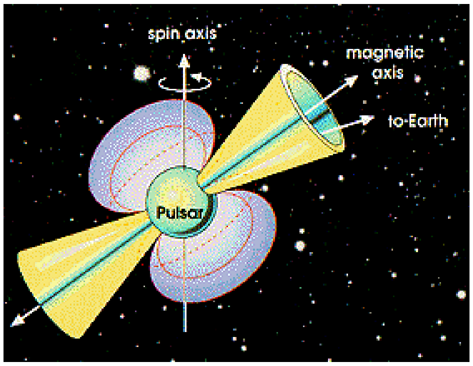




- Doppler broadening of spectral lines from hot gas near neutron-star surface ⇒ velocity of gas ⇒ $R = v/(2\pi f_{\text{rot}}) 11.5^{+3.5}_{-2}$ km
- spectral lines red-shifted due to gravity ⇒ M/R ⇒ $M = 1.75^{+0.55}_{-0.25} M_\odot$
- disfavors strange-quark EoS models for this star!
- more accurate measurements needed to learn about EoS of nuclear matter!

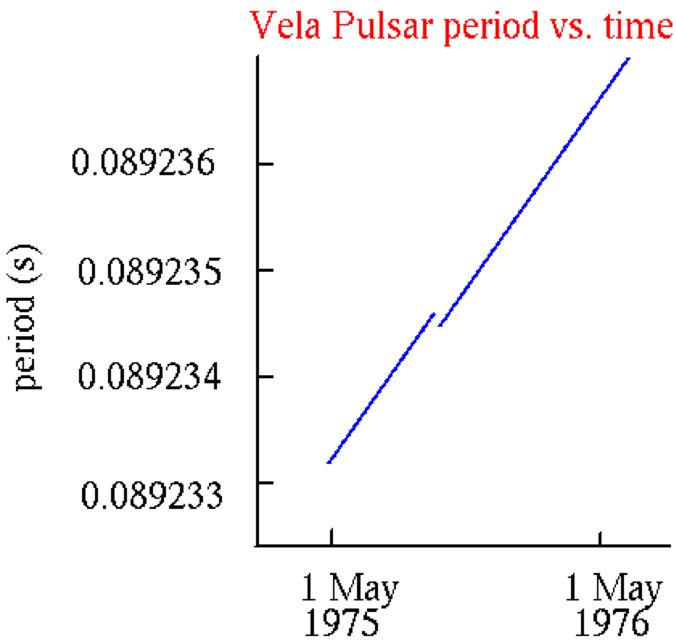
Discovery of neutron stars: Pulsars

- radio pulses in regular intervals (T=4 s-1.6 ms) ⇒ good clock ⇒ rotation
- surface can't be faster than speed of light ⇒ $R < 80$ km
- neutron star only possible object!



- explanations for pulsar properties
  - collapsing star rotates ⇒ radius becomes much smaller ⇒ angular momentum conservation ⇒ large rotation frequencies
  - magnetic fields of star trapped in small region ⇒ huge magnetic fields
  - axis of rotation ≠ axis of magnet ⇒ magnetic field rotates ⇒ em. waves of pulsar period emitted (NB that's not the radio wave making the pulses)
  - energy taken from rotation ⇒ rotation slows down!
  - radio waves from accelerated particles coming out along the magnetic axis ⇒ "light-house effect"

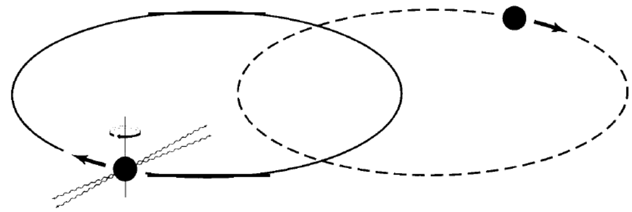
Slowing down of Vela pulsar



- becomes suddenly faster again ⇒ "glitch"
- reason for glitches under debate
  possible angular-momentum transfer from superfluid crust
- picture from the Chandra X-Ray Observatory: jet of electrons and positrons

Pulsar Timing

- measure very accurately the times of arrival (TOA) of radio pulses
- Hulse and Taylor discovered periodic variations in TOA's from PSR 1913+16 $\Rightarrow$ pulsar in orbit around accompanying star!



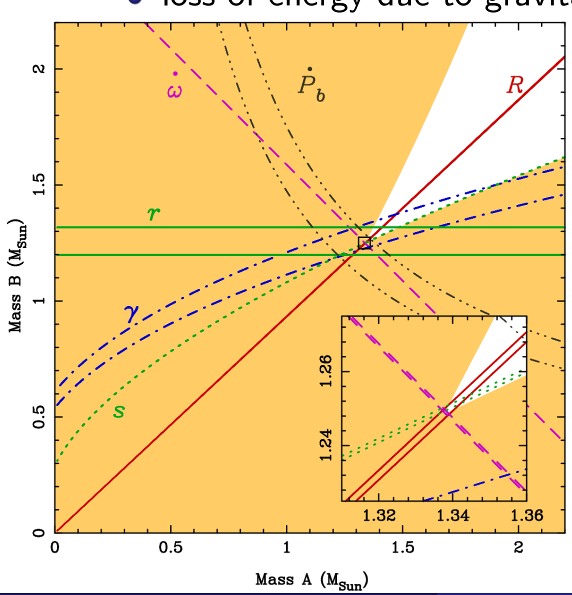
- if accuracy high enough $\Rightarrow$ relativistic effects allow determination of pulsar's and companion star's mass!

$$T = t_{\text{obs}} - t_0 + \Delta_{\text{clock}} - \Delta_{\text{DM}} + \Delta_{R\odot} + \Delta_{E\odot} + \Delta_{S\odot} + \Delta_R + \Delta_E + \Delta_S$$

- deviations from "true period" of pulses
  - Δ_{clock}: clock corrections
  - Δ_{DM}: signal goes through interstellar medium $\Rightarrow$ dispersion time delay
  - $\Delta_{R\odot}, \Delta_R$: Rømer delay due to light-travel time for different relative positions of pulsar and earth due to earth's motion and the pulsar's motion
  - $\Delta_{E\odot} + \Delta_E$: Einstein time-dilation due to motion of earth and pulsar + gravitational red-shift effect on the sun and the binary system
  - $\Delta_{S\odot}, \Delta_S$: light travels in curved space-time according to general relativity $\Rightarrow$ time delay of light-travel near our sun and the binary system (Shapiro effect)

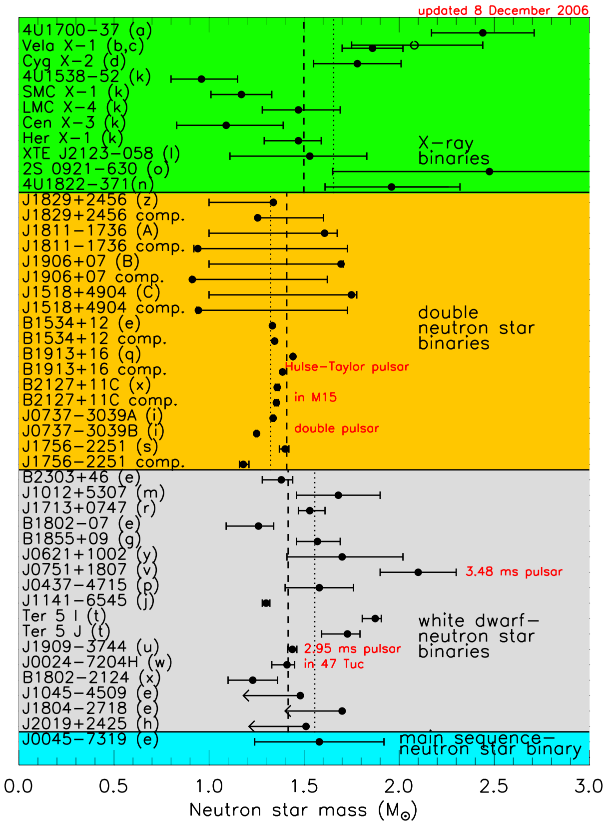
Measurement of neutron-star mass

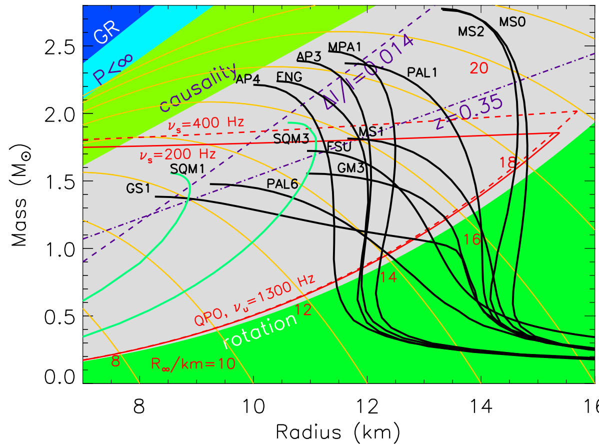
- Accurate pulsar timing $\Rightarrow$ Kepler orbits of the binary system
  - stars in binary system run in ellipses around their center of gravity
  - Kepler's 3rd Law: $P_{\text{orbit}}^2 = 4\pi^2 a^3/[G(m_A + m_B)]$, $a_A = a m_A/(m_A + m_B)$
- relativistic correction effects for orbits ("post-Keplerian parametrization")
  - shift of periastron (closest approach of body to center of gravity $\dot{\omega}$)
  - Einstein time dilation and redshift
  - parameters for Shapiro delay
  - loss of energy due to gravitational waves, $\dot{P}_b$



- model of gravity $\Rightarrow$ specific curves in plot
- any two curves $\Rightarrow$ m_A and m_B
- each additional curve tests model of gravity!
- here: Einstein's general relativity
- additional feature of this measurement: both stars in the binary system are pulsars $R = M_A/M_B$ from Kepler's 3rd Law

Measurement of neutron-star mass and radius





- highest observed masses may rule out exotic states like hyperons, Bose condensates, SQM
- not conclusive yet due to uncertainties in EoS's and large errors in mass measurements

History of discoveries

1932 J. Chadwick discovered the neutron (1935)

1933 W. Baade and F. Zwicky: neutron stars as remnants of supernovae

1939 J.R. Oppenheimer and G.M. Volkoff: general relativistic treatment of neutron stars; mass limit ⇔ Equation of State

1965 A. and S. Okoye: "source of high radio brightness" in the Crab Nebula

1967 J. Bell and A. Hewish: crab nebula radio source is a pulsar ("little green men")

1971 R. Giacconi, H. Gursky et al.: 4.8 sec pulsation in X-ray source

1974 J. Hulse and R. Taylor observe first pulsar in a binary system (1993)

2003 M. Burgay et al observe first double-pulsar system

Summary

- neutron stars are remnants of heavy stars from supernova explosions
- $M \simeq 1\text{-}2 M_{\odot}$, $r \simeq 10$ km
- prevented from gravitational collapse by degneracy pressure of neutrons
- upper limits for masses and mass-radius relations
  $\Leftrightarrow$ probe equations of state for "cold" nuclear and/or strange-quark matter under extreme densities
- pulsars identified as neutron stars
- accurate mass measurements with pulsar timing in binary systems
  - first constraints on equations of state
  - so far no observation of a self-bound quark star
  - enable high-precision tests of general relativity in large gravitational fields
  - only (indirect) hint for existence of gravitational waves yet
- a lot of fascinating work to do for both astronomers and nuclear physicists!

Appendix: details about effects, relevant for pulsar-timing measurements

Backup Slides

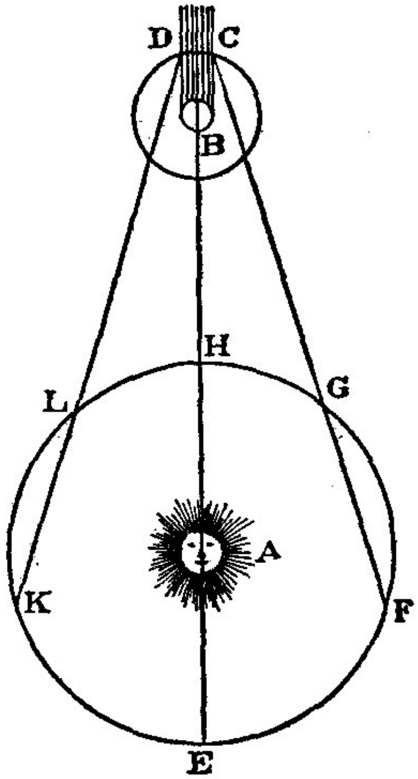
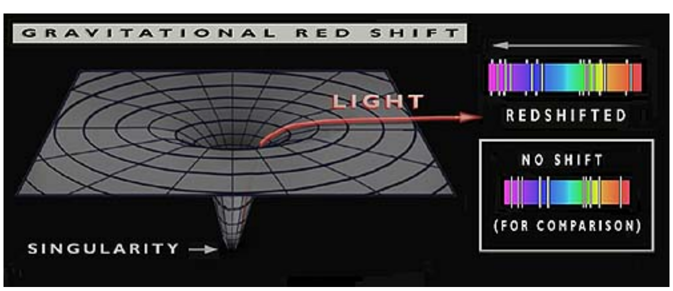


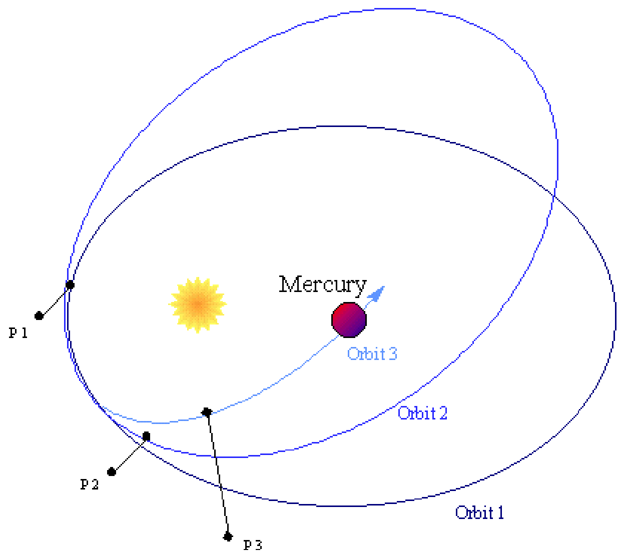
Fig. 70.

- time of arrival of periodic signal appears delayed or advanced due to finite time the light needs to travel along the diameter of the earth's orbit (depending on whether earth is far away from or close to signal source)
- In Rømer's time (1644-1710): first measurement of speed of light, using period of Jupiter-moon orbits
- in case of pulsar timing: effect for both the earth's orbit around the sun and the pulsar's orbit around the center of gravity of the binary system



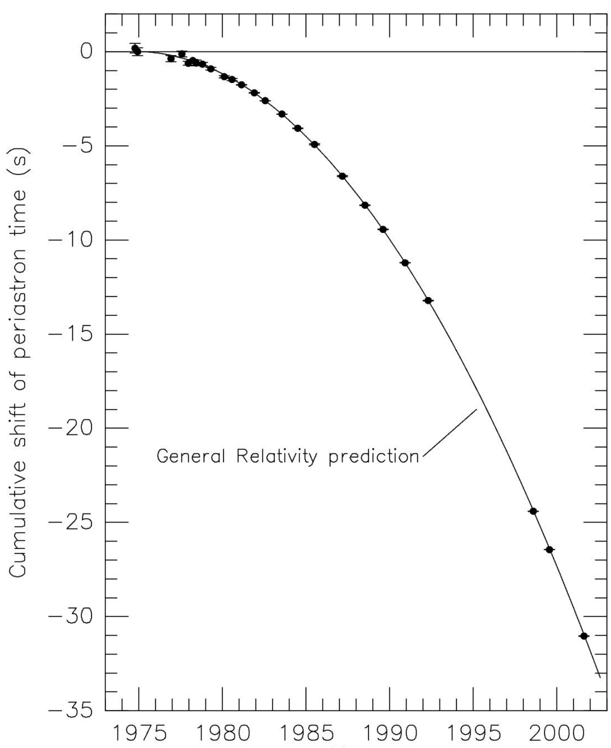
- time period of pulses from a source moving relative to observer appear to be longer by a time-dilation factor $\gamma = 1/\sqrt{1 - v^2/c^2}$ (v: velocity of object relative to observer, c: speed of light)
- general relativity: space-time curved $\Rightarrow$ light feels gravity and looses energy when travelling away from heavy object
- frequency of light becomes smaller $\rightarrow$ spectral lines of chemical elements appear "red-shifted"
- due to gravity curvature of space-time light signal needs longer to travel a distance than without gravity (Shapiro effect)

Precession of perihelion (periastron) of planets (stars)



- deviation of laws of motion from Newton's $F = ma$ and law of gravity $F = Gm_1 m_2/r^2$ due to general relativity ⇒ perihelion (closest approach to sun) of Mercury slowly rotates
- for stars in binary systems effect much larger due to stronger gravity ⇒ faster rotation of periastron

Gravitational waves and orbital-energy loss in pulsar binaries



- General relativity predicts existence of gravitational waves
- analogy to electromagnetism: accelerated charged objects radiate electromagnetic waves (radio waves, light, X-rays)
- massive accelerated bodies radiate gravitational waves
- binary stars loose orbital energy
- major axis (radius) of orbit becomes smaller ⇒ orbital period becomes shorter
- only (indirect) observation of gravitational waves
- 1993 for Hulse and Taylor