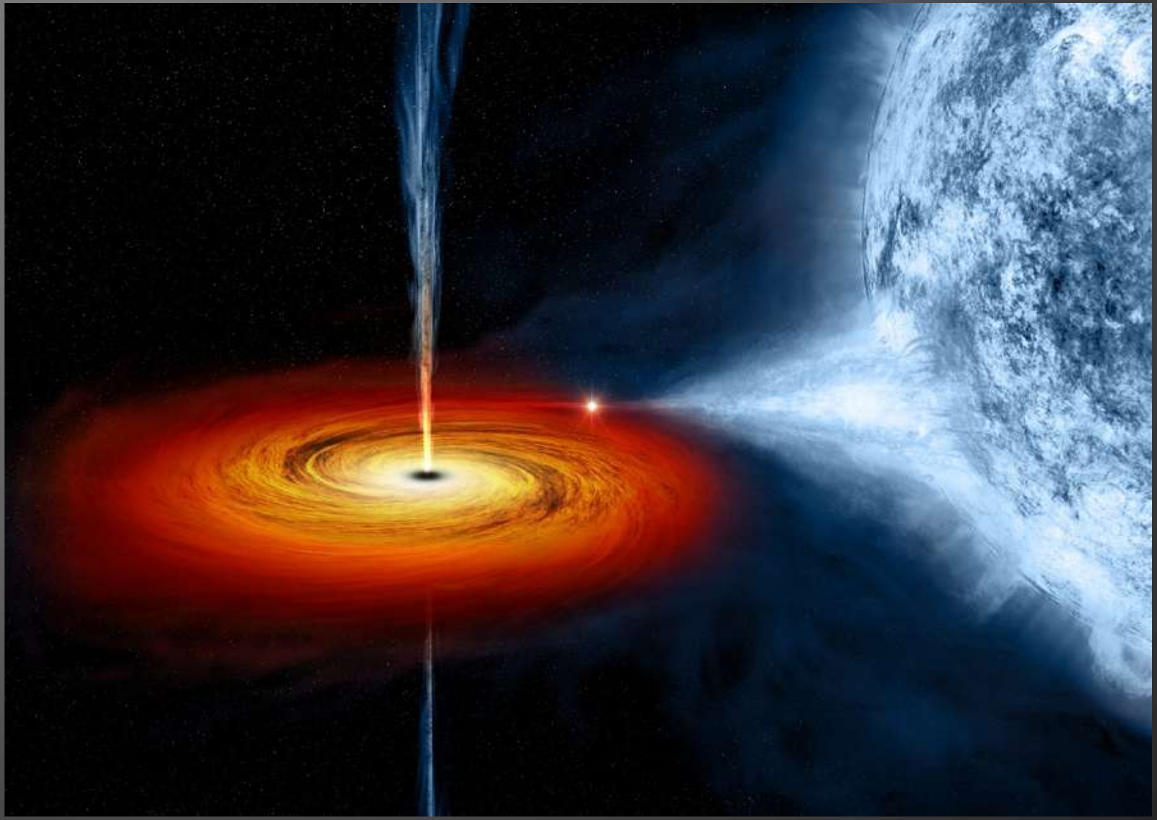
PHYSICS OF COMPACT OBJECTS
AND THEIR BINARY INTERACTIONS



AALBORG
UNIVERSITY

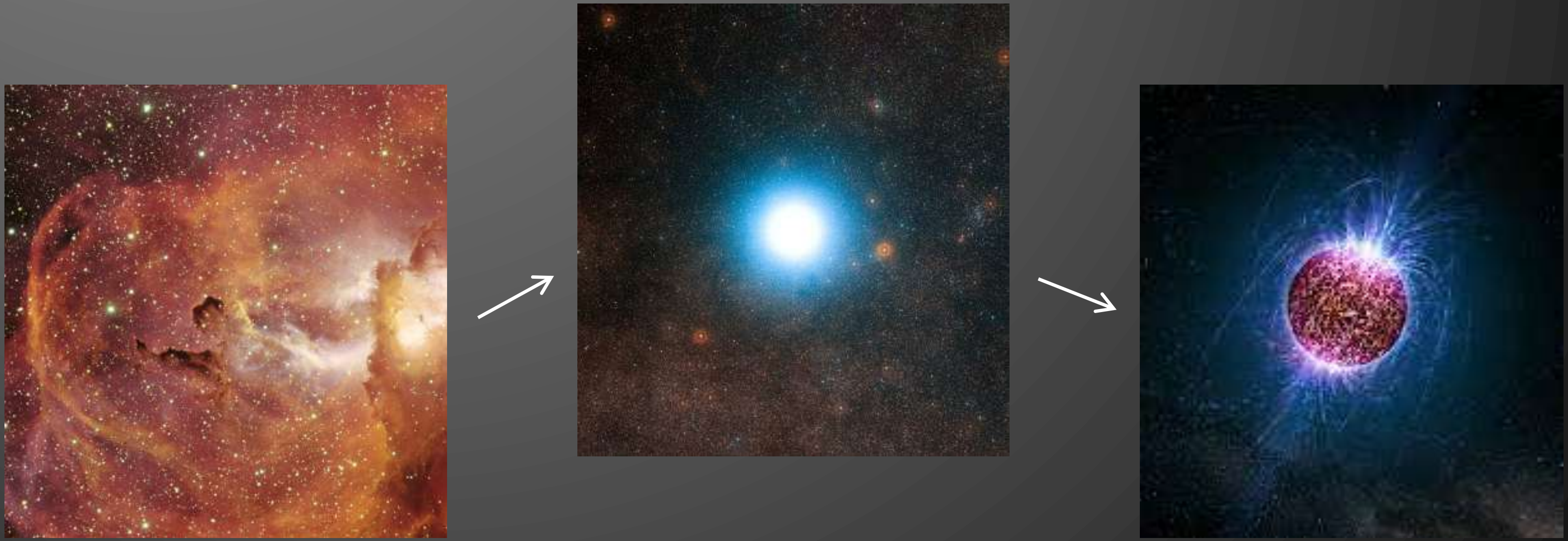
Thomas Tauris – Physics, Aalborg University

Programme

- ▣ ∗ **Introduction**
- ▣ ∗ **Degenerate Fermi Gases**
  Non-relativistic and extreme relativistic electron / (n,p,e^-) gases
- ▣ ∗ **White Dwarfs**
  Structure, cooling models, observations
- ▣ ∗ **Neutron Stars**
  Structure and equation-of-state
- ▣ ∗ **Radio Pulsars**
  Characteristics, spin evolution, magnetars, observations, timing
- ▣ ∗ **Binary Evolution and Interactions**
  X-ray binaries, accretion, formation of millisecond pulsars, recycling
- ▣ ∗ **Black Holes**
  Observations, characteristics and spins
- ▣ ∗ **Gravitational Waves**
  Sources and detection, kilonovae
- ▣ ∗ **Exam**

Introduction

The ”stellar life” is just an intermezzo in the transition from a gas cloud to a compact object



Why do stars shine?

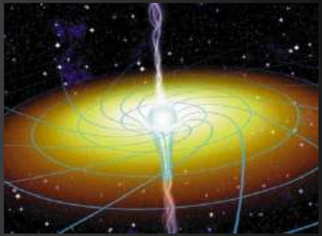
Why do stars shine? ”Stars shine because of nuclear burning”.	No, stars shine because they are hot!
Why are stars hot? ”Stars are hot because of nuclear burning”.	No, stars undergo nuclear burning *because* they are hot!

The ”stellar life” is just an intermezzo in the transition from a gas cloud to a compact object

1) Gas cloud contracts under gravity.
   Temperature increases due to release of gravitational binding energy and increasing density.
2) When the temperature is high enough (~10 mill. K) hydrogen fusion is ignited. The star is born!
   When hydrogen is exhausted the star contracts further until the temperature is high enough to ignite helium fusion (~100 mill. K), etc. until an iron core is formed (max. E_bind per nucleon).
3) Gravitational collapse leads to a supernova explosion and fomation of a NS or a BH.

Star forming region, M17 (5000 light years away)

Stellar death → Formation of compact objects



(IMF) initial mass function:

$$f(M) \propto M^{-2.35}$$

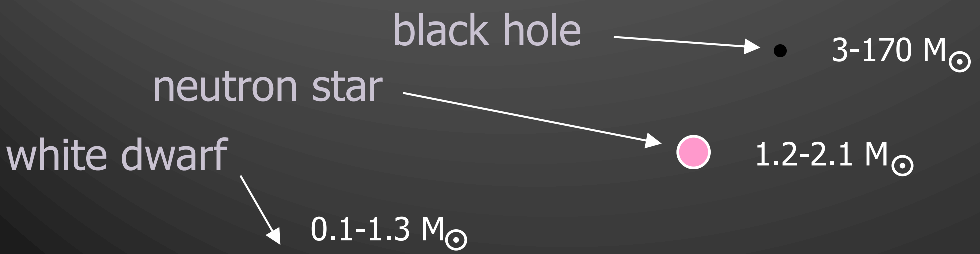
time scale of evolution:

$$\tau_{nuclear} \propto M^{-2.5}$$

$M < 8\ M_\odot$	→	white dwarf	~ 140	~ 10 billion yr
$8 < M/M_\odot < 25$	→	neutron star	~ 4	~ 10 million yr
$M > 25\ M_\odot$	→	black hole	~ 1	~ 1 million yr

(A bit more complicated…)

Formation rate of neutron stars in Milky Way: 1-2 / 100 yr

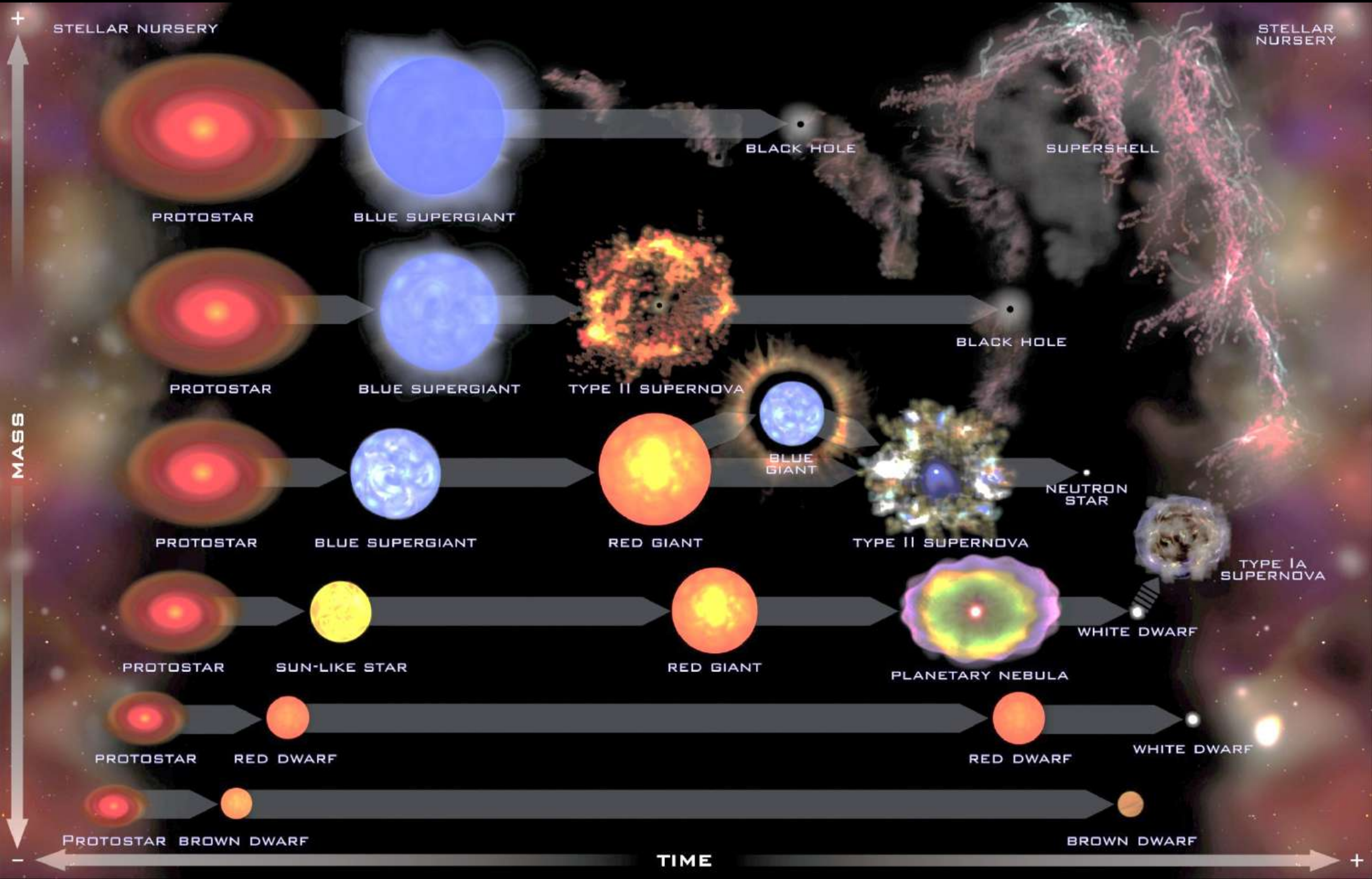


black hole → 3-170 $M_\odot$

neutron star → 1.2-2.1 $M_\odot$

white dwarf → 0.1-1.3 $M_\odot$

Stellar evolution in a nutshell



White Dwarfs

Sirius B: Discovered in 1917 (companion star to Sirius A, the brightest of all stars)

$$\Rightarrow \quad \bar{\rho} = 300 \ kg\, cm^{-3} \qquad (\text{Sun}: \ \bar{\rho}_\odot = 1.4 \ g\, cm^{-3})$$

$$T_{eff} = 17000 \ K \qquad (\text{Sun}: \ T_\odot = 6000 \ K)$$

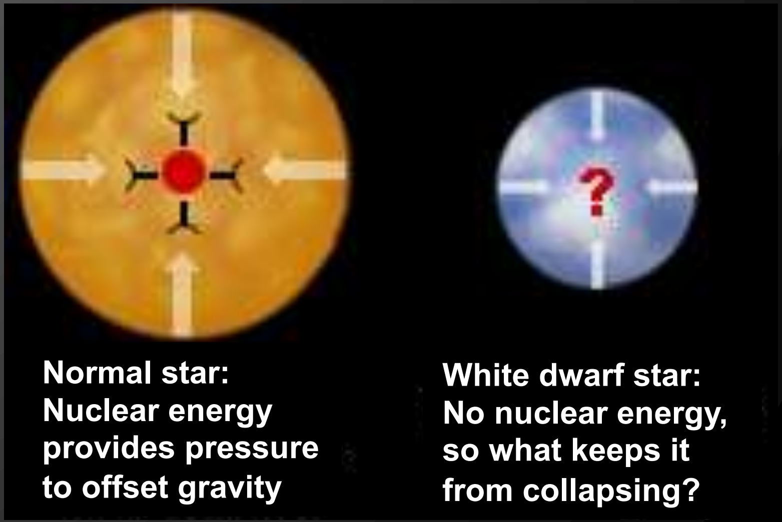
$$R \approx 7000 \ km \quad \approx R_\oplus \ = 1/109 \ R_\odot$$

high temperature + small radius: white dwarf

Paradox: White dwarfs are "dead" stars! with no burning processes.

So, what keeps it from collapsing? (low pressure → collapse with time)

The paradox was not resolved until the quantum theory of matter was developed in the 1920s.



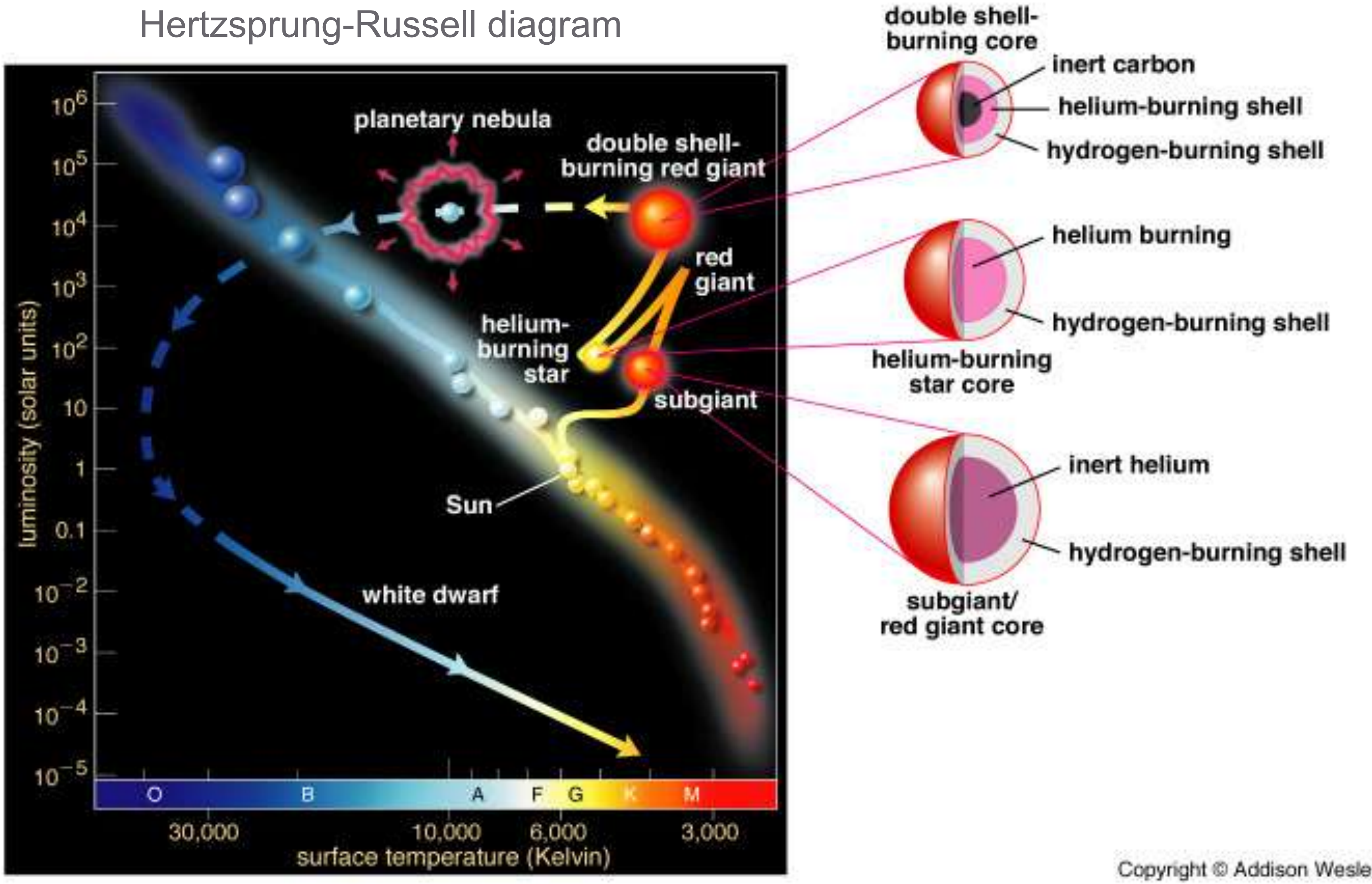
Normal star:
Nuclear energy provides pressure to offset gravity

White dwarf star:
No nuclear energy, so what keeps it from collapsing?


Ziggy
..o. LOOK, I'M JUST A WHITE DWARF ! FOR A WISH THAT BIG...YOU'LL NEED A RED GIANT !
2/2 TOM WILSON & TOM II

Formation of White Dwarfs

Hertzsprung-Russell diagram



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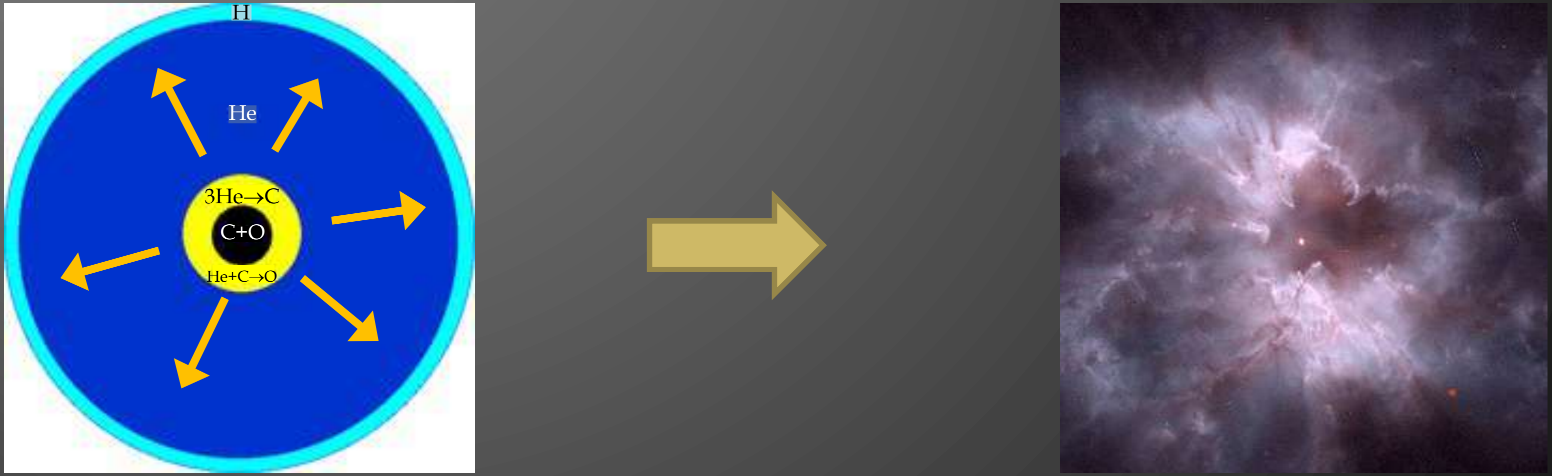
Formation of White Dwarfs

The planetary nebula is formed by the dissipation of the entire envelope at a random *thermal pulse* on the AGB

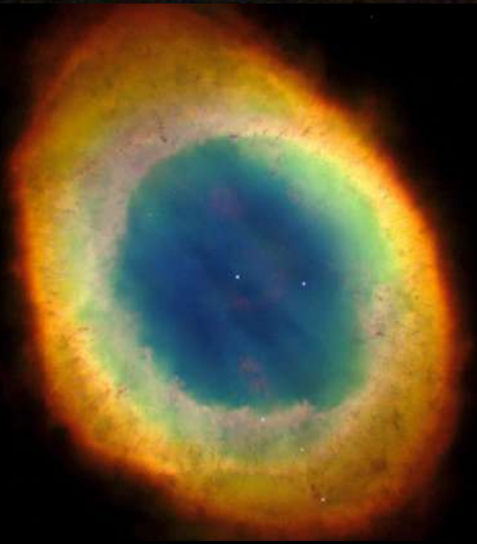
(alternate burning of hydrogen or helium in thin shells)

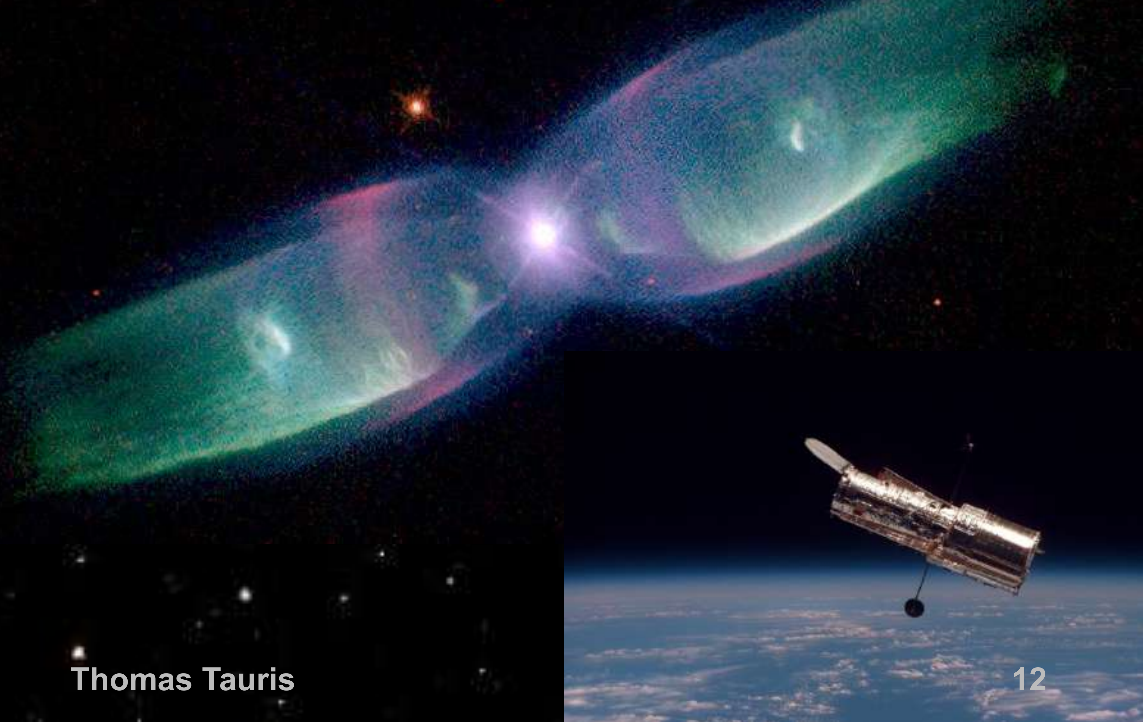
Shortly thereafter the nuclear burning ceases in the core (WD)



$1 < M/M_\odot < 5$ ⟶ Carbon-oxygen (CO) white dwarf $0.7\ M_\odot$
$6 < M/M_\odot < 8$ ⟶ Oxygen-neon-magnesium (ONeMg) white dwarf $1.2\ M_\odot$
in binaries also: ⟶ Helium (He) white dwarf $0.2\ M_\odot$

planetary nebulae





James Webb Space Telescope (JWST)

NGC 3132 Near-infrared (NIR)

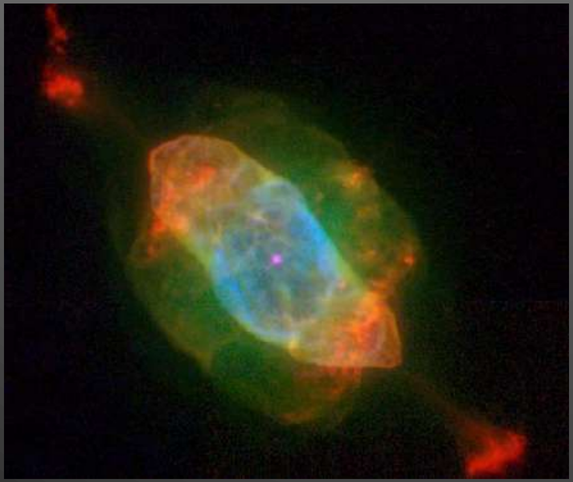
NGC 3132 Mid-infrared (MIR)

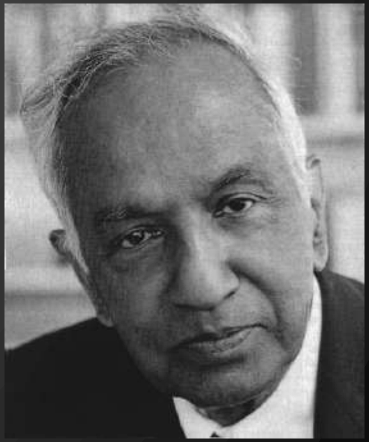
Structure and Cooling of White Dwarfs

The pioneering work of Chandrasekhar (1931) and Mestel (1952)

The structure of white dwarfs is characterised by:

1. A thin envelope which engulfs an isothermal core
2. Degenerate electrons are responsible for the interior pressure
3. Thermal energy is stored in ions and is released gradually as radiation and hence the white dwarf cools down with time





Chandrasekhar

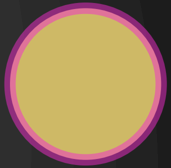
Structure and Cooling of White Dwarfs

The relationship between luminosity and the interior temperature is given by:

$$T_C \approx 4\times10^{7}\left(\frac{L/L_\odot}{M/M_\odot}\right)^{2/7} K$$

or

$$L \propto M\,T_C^{3.5}$$



The luminosity is equal to the dissipation rate of thermal energy:

$$L = -\frac{dU_I}{dt} \qquad \wedge \qquad U_I = \frac{3}{2}\frac{\Re}{\mu_I} M\,T_C$$

Hence the cooling rate and the cooling timescale is given by:

$$\tau_{cool} \approx 2.5\times10^{6}\left(\frac{M/M_\odot}{L/L_\odot}\right)^{5/7} yr$$

(correction effects from e.g. coulomb interactions, crystalization at late stages)

Late stages of cooling of white dwarfs

At very low temperatures the following effects become important:

- Coulomb interactions between ions become important
- The ions crystallizes into a lattice
- Below the Debye temperature (few million K) the cooling accelerates due to quantum mechanical effects

$$\tau_{cool} \propto L^{\alpha} \qquad \begin{cases} \alpha = -5/7 & L \geq 10^{-3}\, L_{\odot} \\ \alpha > 0 & L < 10^{-4}\, L_{\odot} \end{cases}$$

Observations of and knowledge about cooling white dwarfs is used to determine the age of clusters

The concept of Black Holes

Laplace (1795):
"Light cannot escape from an object of suffuciently large mass and small radius"

Schwarzchild (1916):
Found analytical solution for a gravitational field surrounding a spherical mass from Einstein's (1915) GR

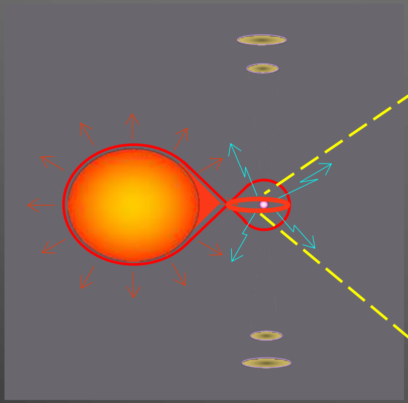
Chandrasekhar (1931):
Found an upper limit to the mass of a completely degenerate configuration

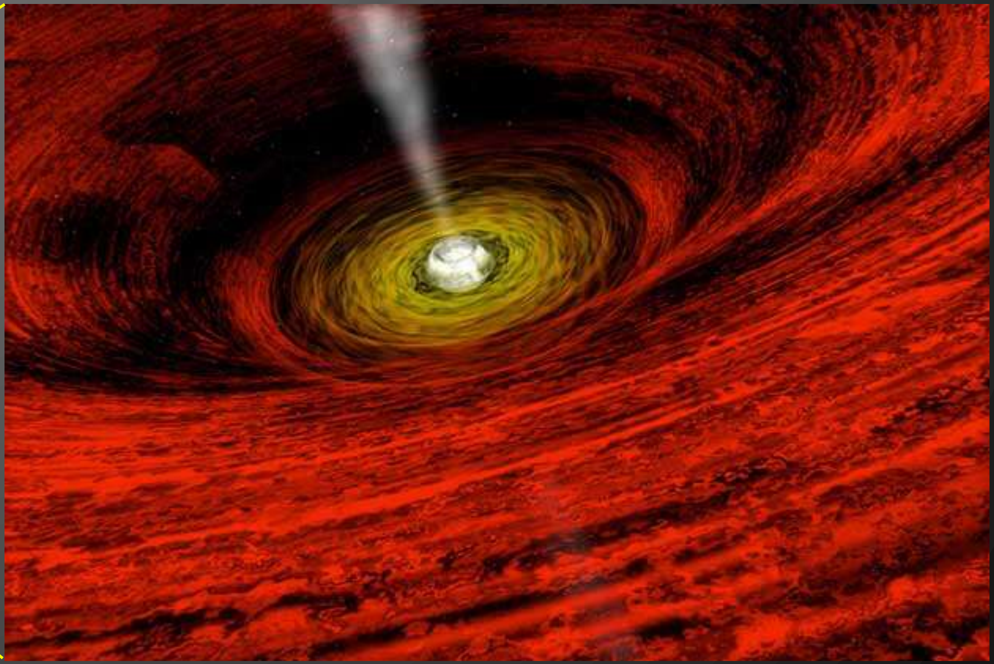
Eddington (1935):
Black holes would be the inevitable fate of the evolution of massive stars:
"The star apparently has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few kilometers radius when gravity becomes strong enough to hold the radiation and the star can at last find peace" But he didn't believe in it!

Oppenheimer, Snyder, Kerr, Wheeler (1968): coined the name "black hole"

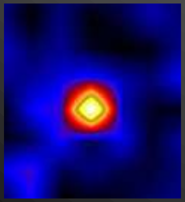
Observations of Black Holes

Observations: Cygnus X-1, beginning of 1970’s
Today: ~30 stellar mass black holes identified in the Milky Way and local galaxies
(besides 100 LIGO-Virgo-KAGRA detections of double BH mergers in distant galaxies)





X-ray emission!!



Black Holes: masses, radii and spin

Mass: "stellar mass BHs" have masses in the interval: $6 < M_{\mathrm{BH}}/M_\odot < 21$
determined via Kepler's 3. law in X-ray binaries

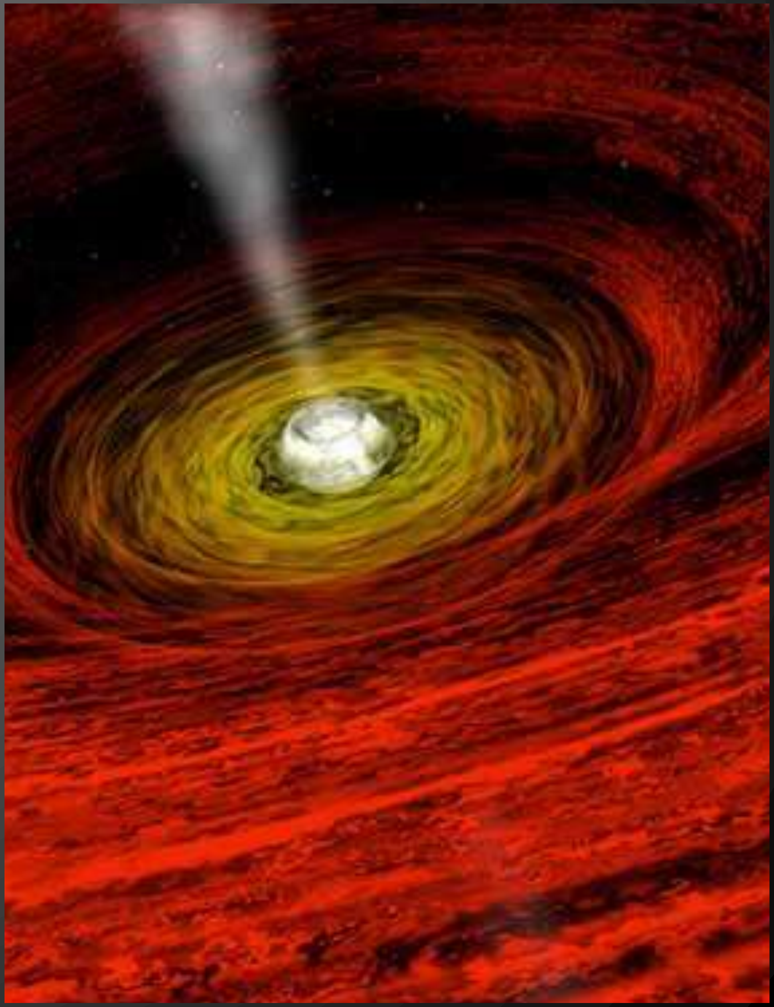
Radius:

$$R_{Sch} = \frac{2GM_{BH}}{c^2}$$

$$R_{Sch} = 3\,km\ \ (M_{BH}/M_\odot)$$

Spin: $0.1 < a_* < 0.99$

Evidence for existence:
(black holes versus neutron stars)
- mass of compact object above NS threshold
- features of X-ray emission
  (hard surface or not)
- gravitational wave sources detected by LIGO



The Schwarzchild radius
defines the event horizon

The history of neutron stars

Theoretical prediction:

Landau (1932), in Copenhagen in a meeting with Bohr and Rosenfeld:

”…. the possibility of cold, dense stars composed principally of neutrons”

Baade & Zwicky (1934):

"With all reserve we advance the view that supernovae represent the transitions from ordinary stars into neutron stars, which in their final stages consist of extremely closely packed neutrons"

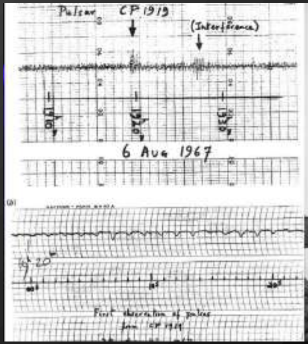
Discovery of neutron stars in 1967

Known neutron stars in the Milky Way today:

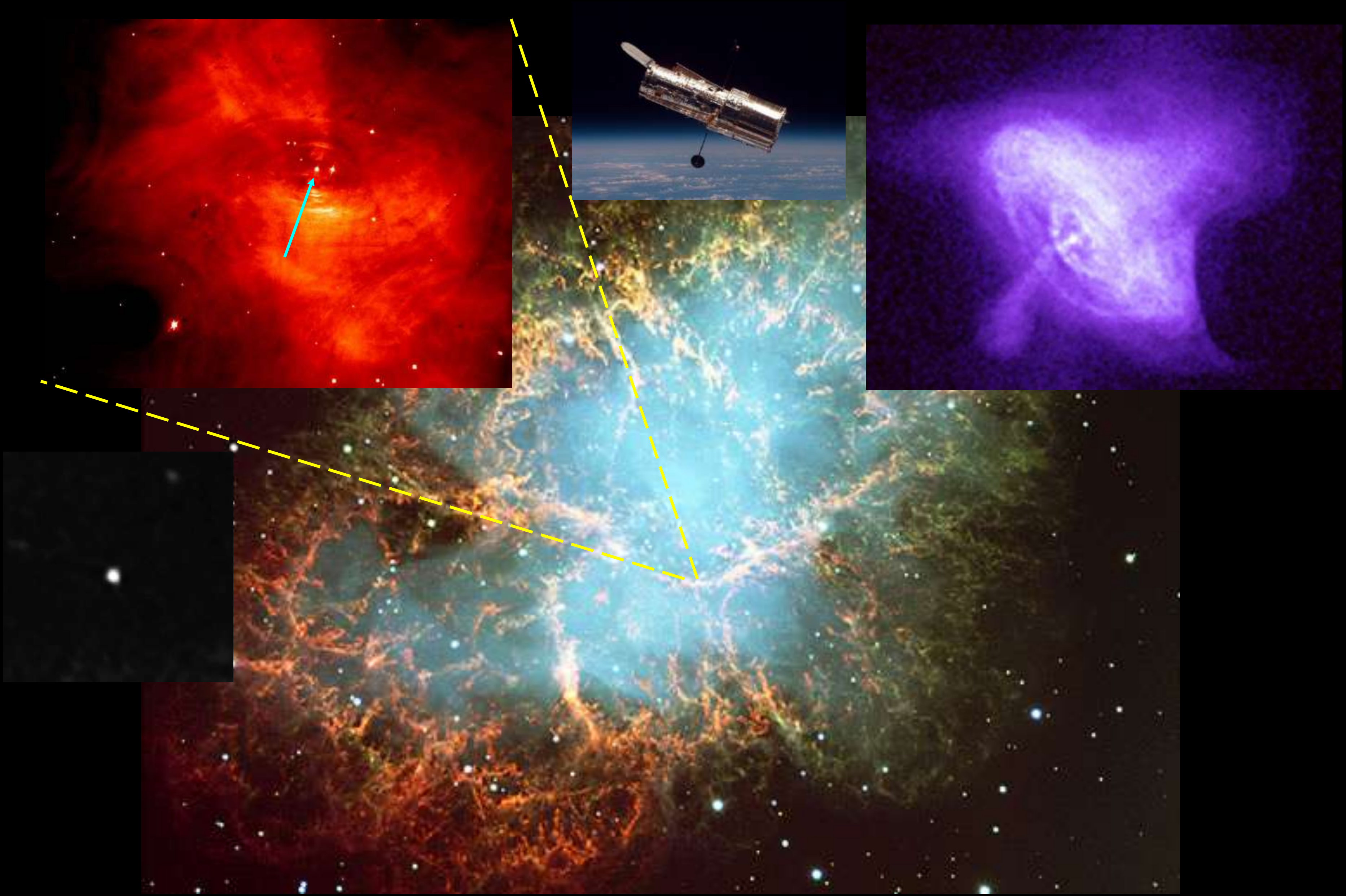
~ 3500 radio pulsars

~ 100 X-ray pulsars

~ 400 neutron stars in X-ray binary systems

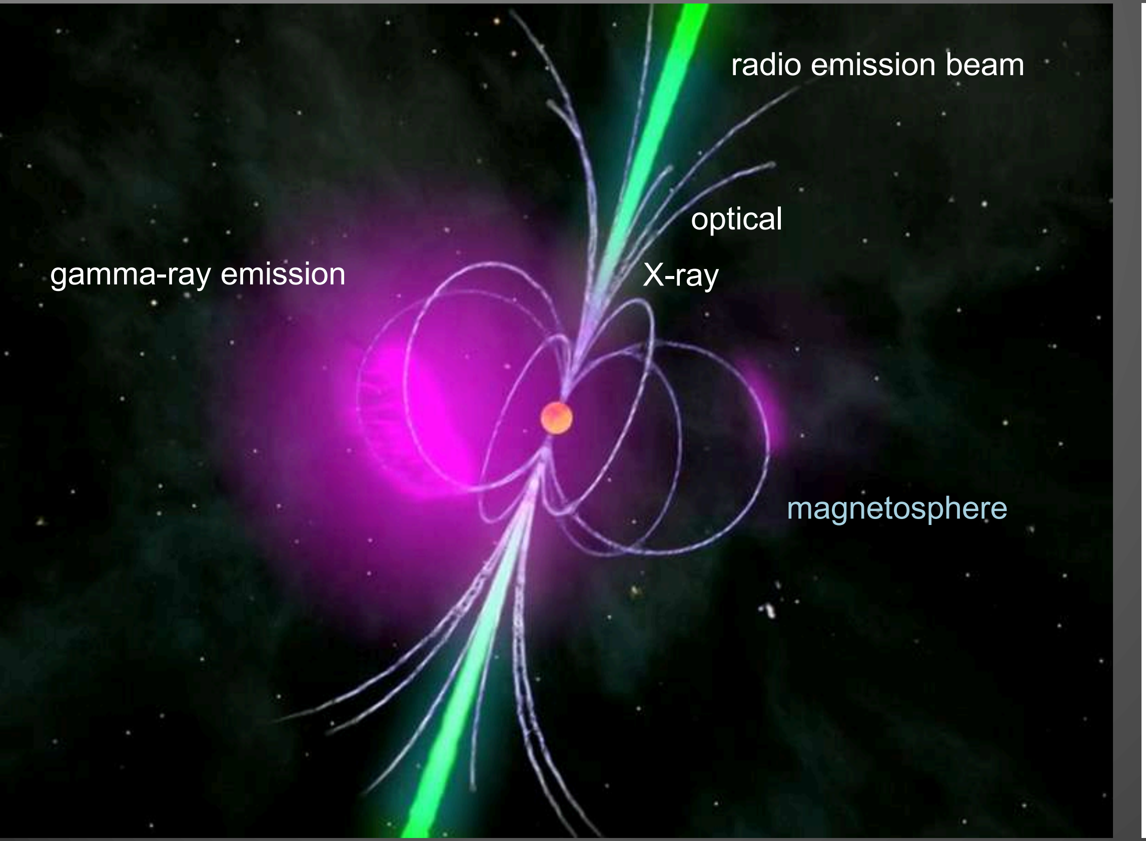


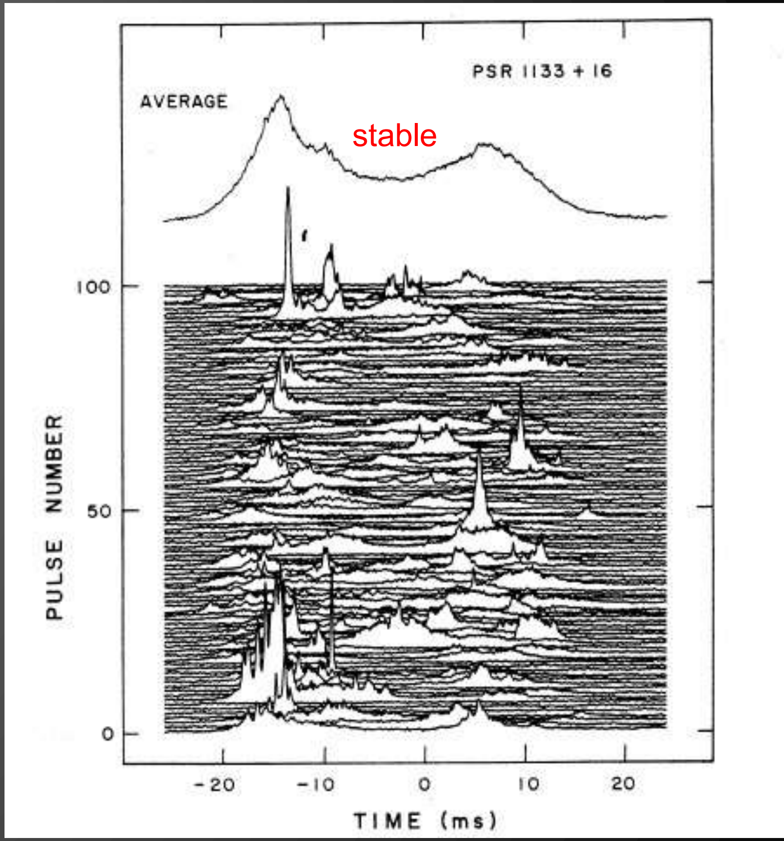
Credit: Daily Herald Archive/SSPL/Getty Images



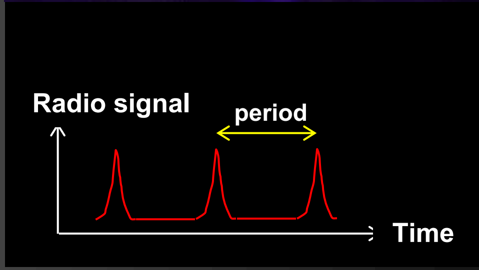
This supernova was observed by Chinese astronomers in 1054 a.d.
Today we observe a rapidly rotating neutron star (pulsar) with a period of 33 ms.

Radio Pulsars





Radio Pulsars



A pulsar is a perfect physics laboratory:

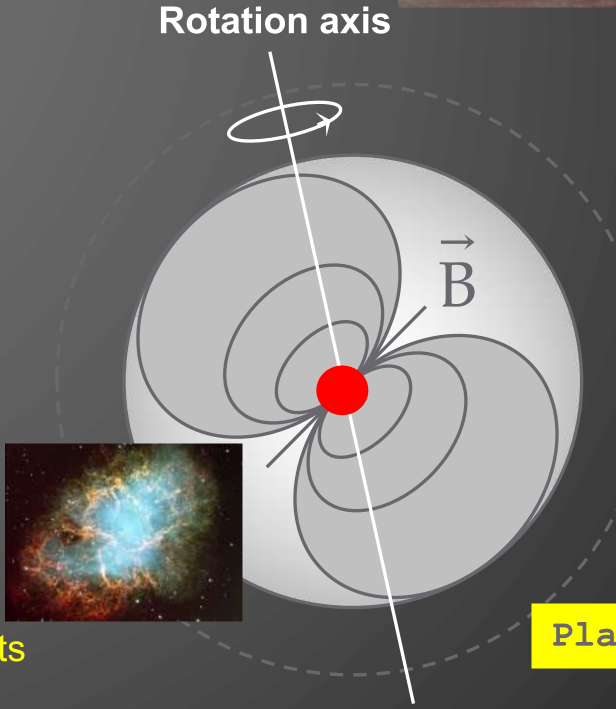
- ✓ ν = 700 Hz (P=1.4 ms – 23 sec.)
- ✓ B = 10^{13} G
- ✓ $\dot{E}_{rot} = 10^5\ L_\odot$ (F = $10^{14}\ F_\odot$)
- ✓ M = 1.4 $M_\odot$
- ✓ R = 10 km

Giant atomic nucleus:

- ✓ A=10^{57} baryons, ρ_{core} = 2-10 $\rho_{nuclear}$

Magnetosphere:

- ✓ production of 10^{38} (e^-, e^+) per second
- ✓ TeV γ-rays
- ✓ e^- accelerated to 10^{16}eV, $\Delta\phi$ =10^{16} Volts



Particle physics

Nuclear physics

Solid state physics

Atom physics

Plasma physics

Relativity

a unique physics laboratory

Perfect clock:

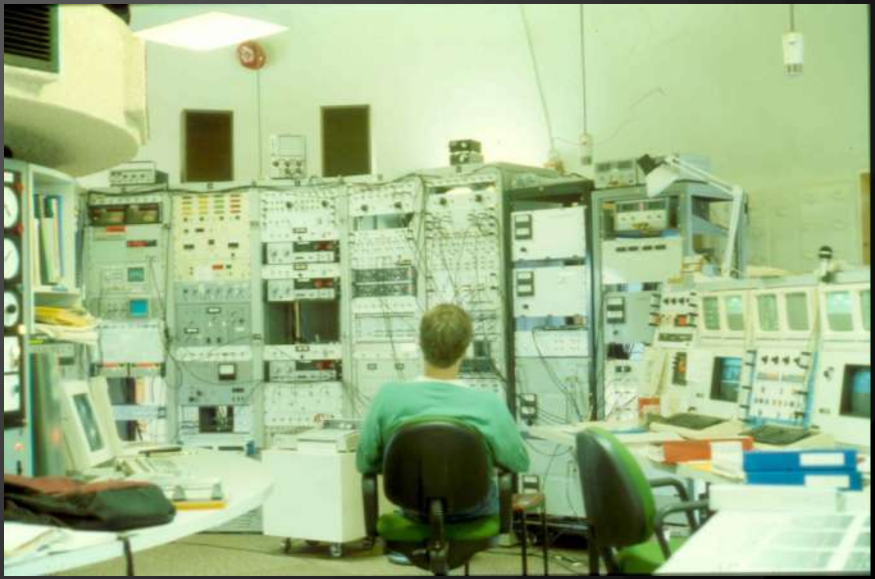
- ✓ P = 0.001 557 806 448 872 75 seconds (PSR 1937+21)

Challenge atomic clocks

Vela supernova remnant (~11000 yr old)
Today we observe a pulsar with a spin period of 89 ms.

Pulsar speeds (kicks): 30-1200 km/s
(asymmetric supernova explosions)

Parkes (64 meter) Radio Telescope (NSW, Australia)

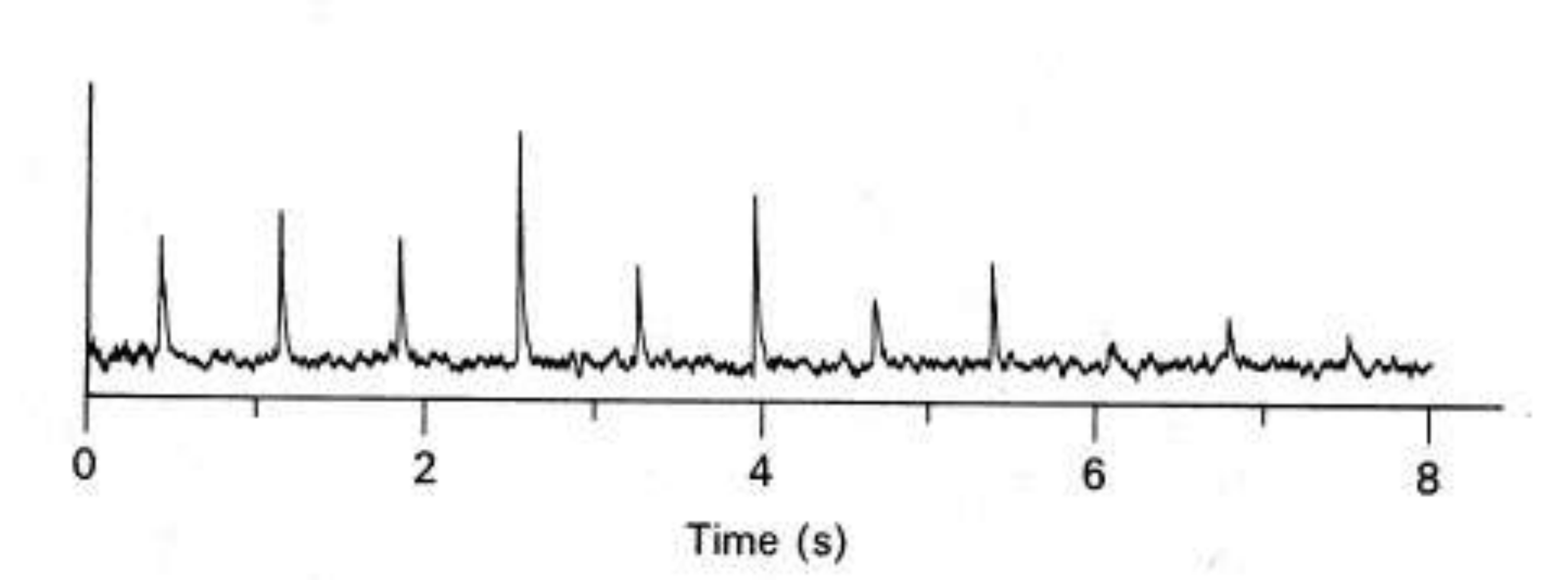


ATCA, Narrabri
(NSW, Australia)
6 km. baseline

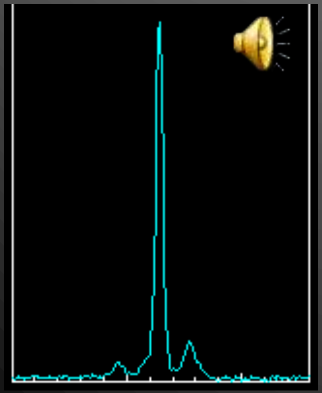
Bonn Effelsberg 100-m radio telescope

Dr. David Champion (MPIfR)

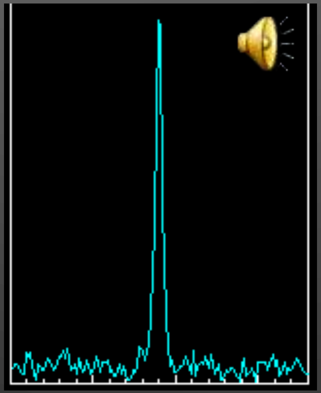
Pulsar pulse profiles



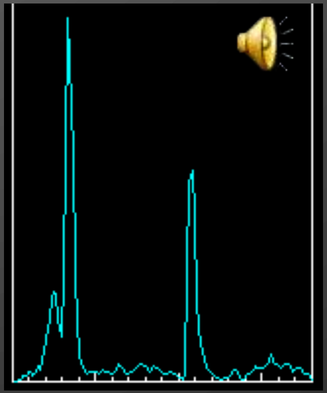
PSR 0329+54



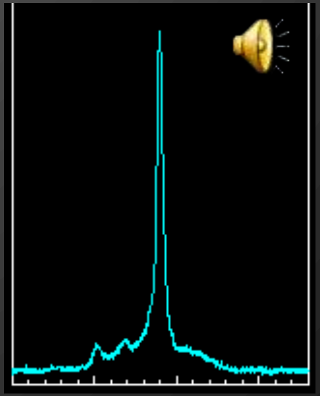
Vela



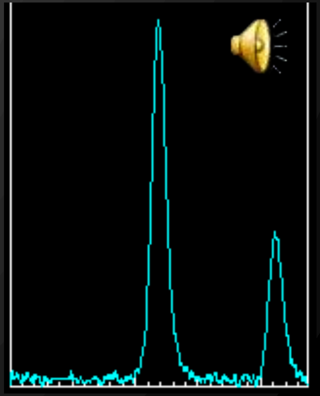
Crab



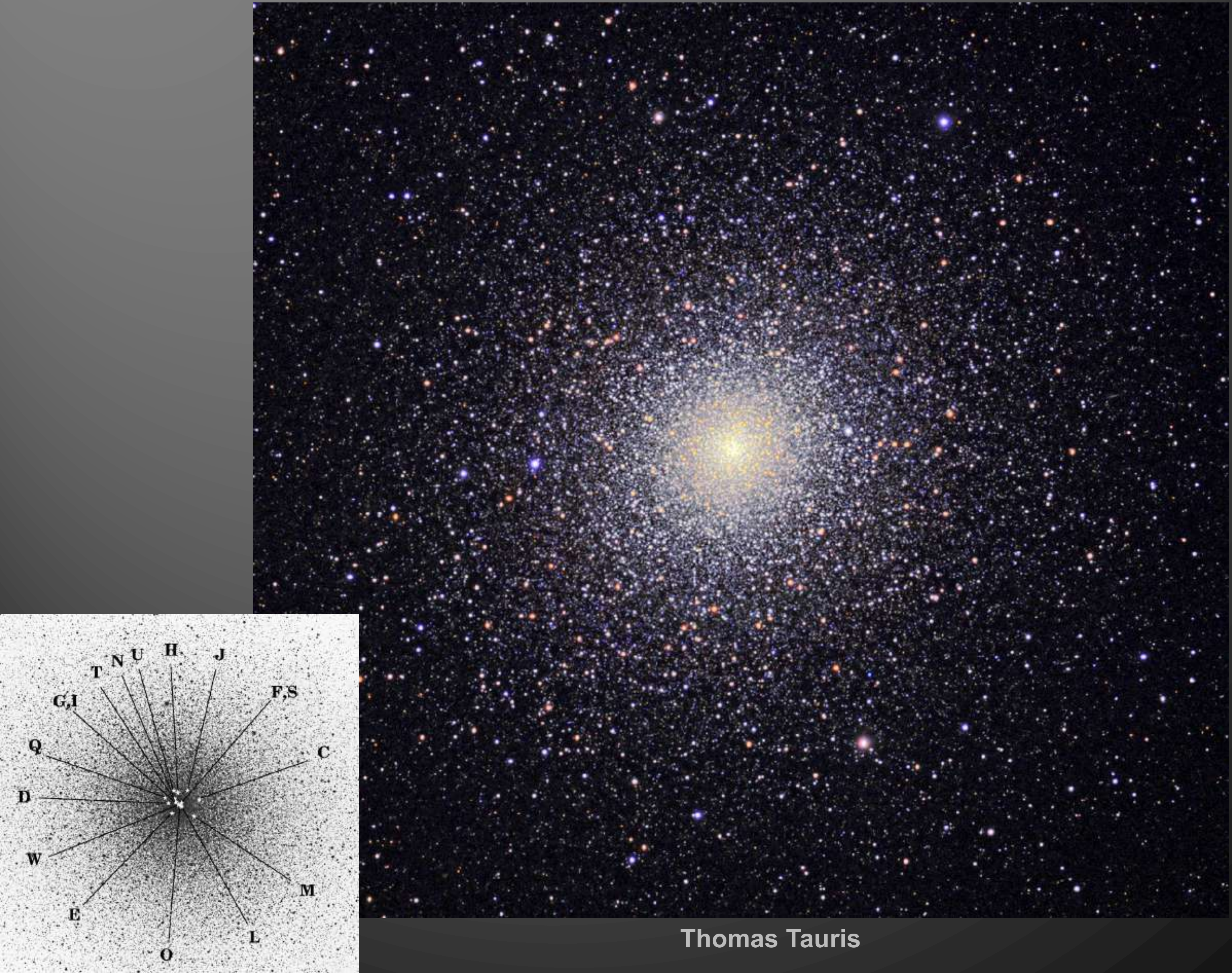
PSR 0437-4715



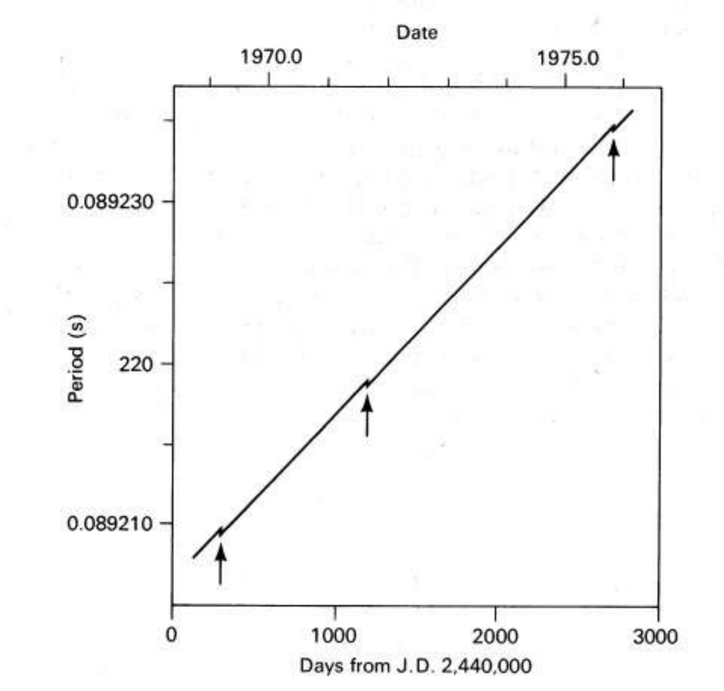
PSR 1937+21



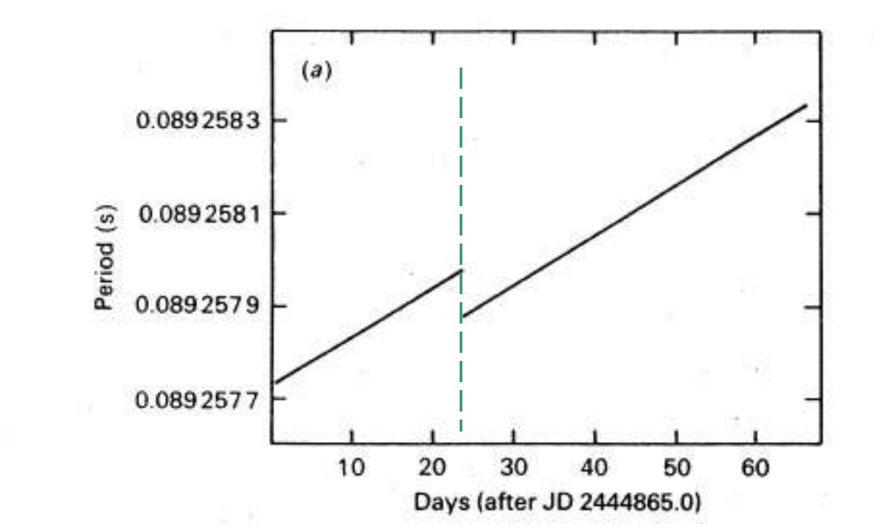
Cosmic orchestra in 47 Tuc

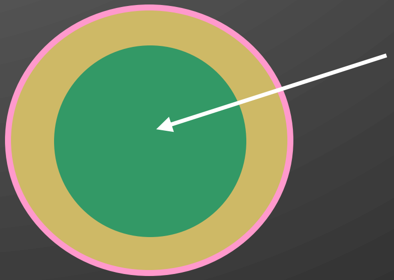


Glitches (neutron star quakes)



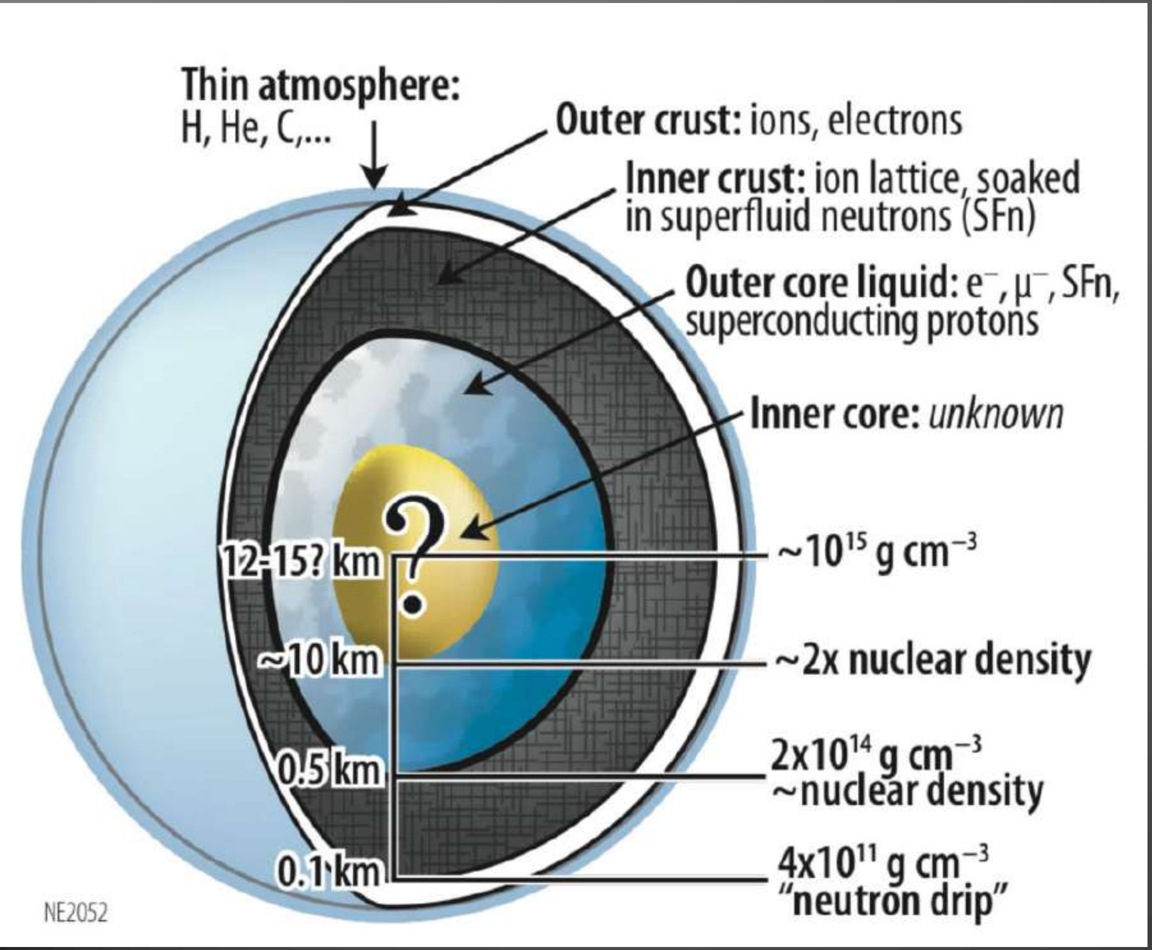
Vela (89 milliseconds)

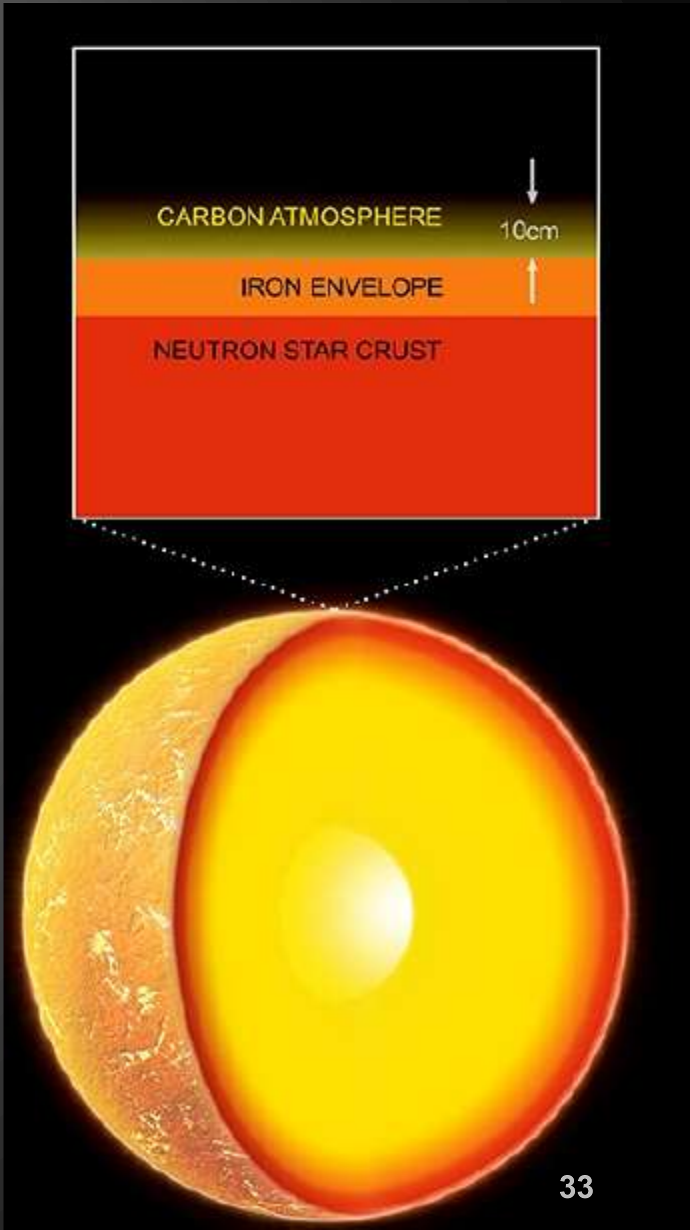




core of superfluid neutrons

Neutron Star cross section





The magnetic dipole model

$$\dot{E}_{dipole} = -\frac{2}{3c^3}|\ddot{m}|^2$$

$$|\ddot{m}| \sim BR^3\Omega^2 \sin\alpha$$

second derivative of magnetic moment

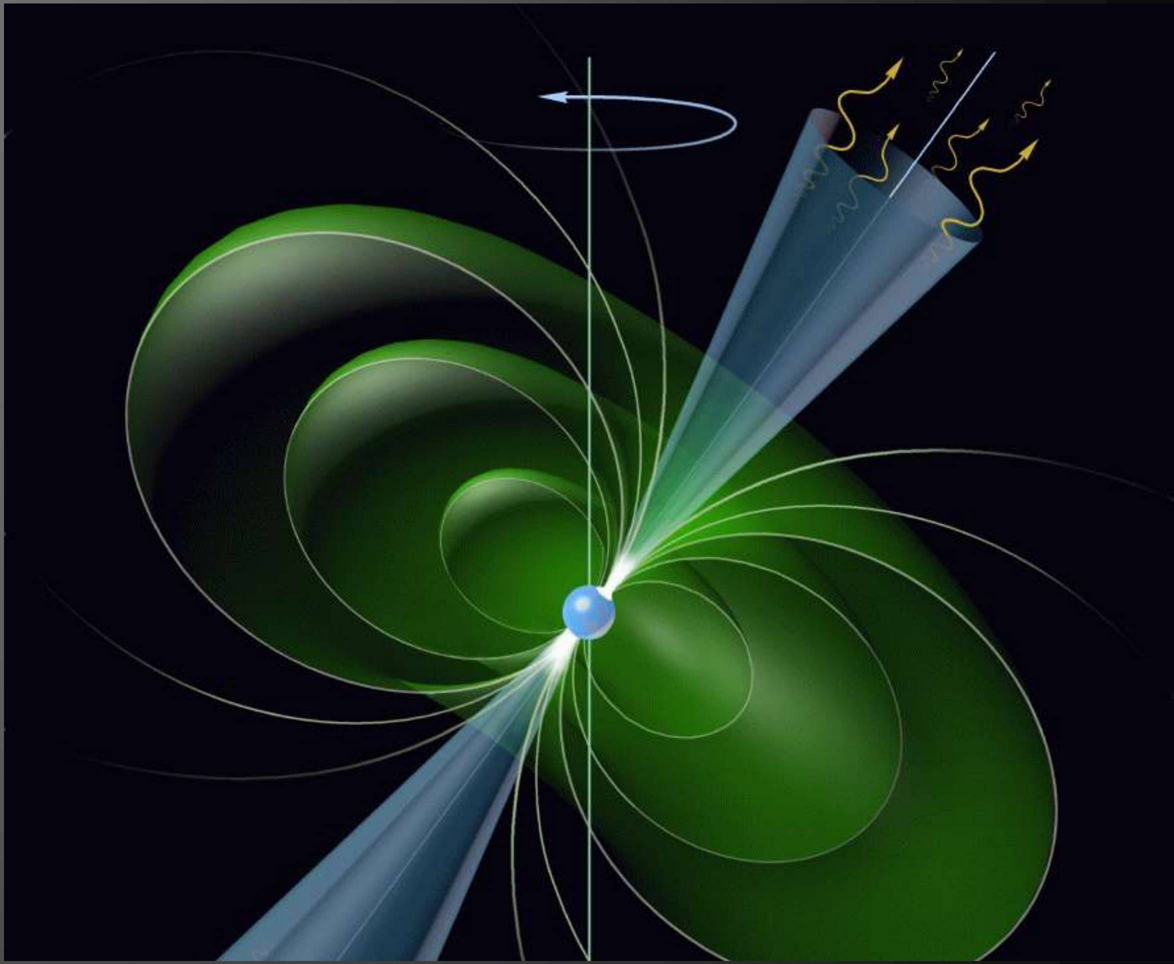
$$E_{rot} = \frac{1}{2} I_{NS}\Omega^2 \quad (\Omega = 2\pi / P)$$

$$\dot{E}_{rot} = I_{NS}\Omega\dot{\Omega}$$

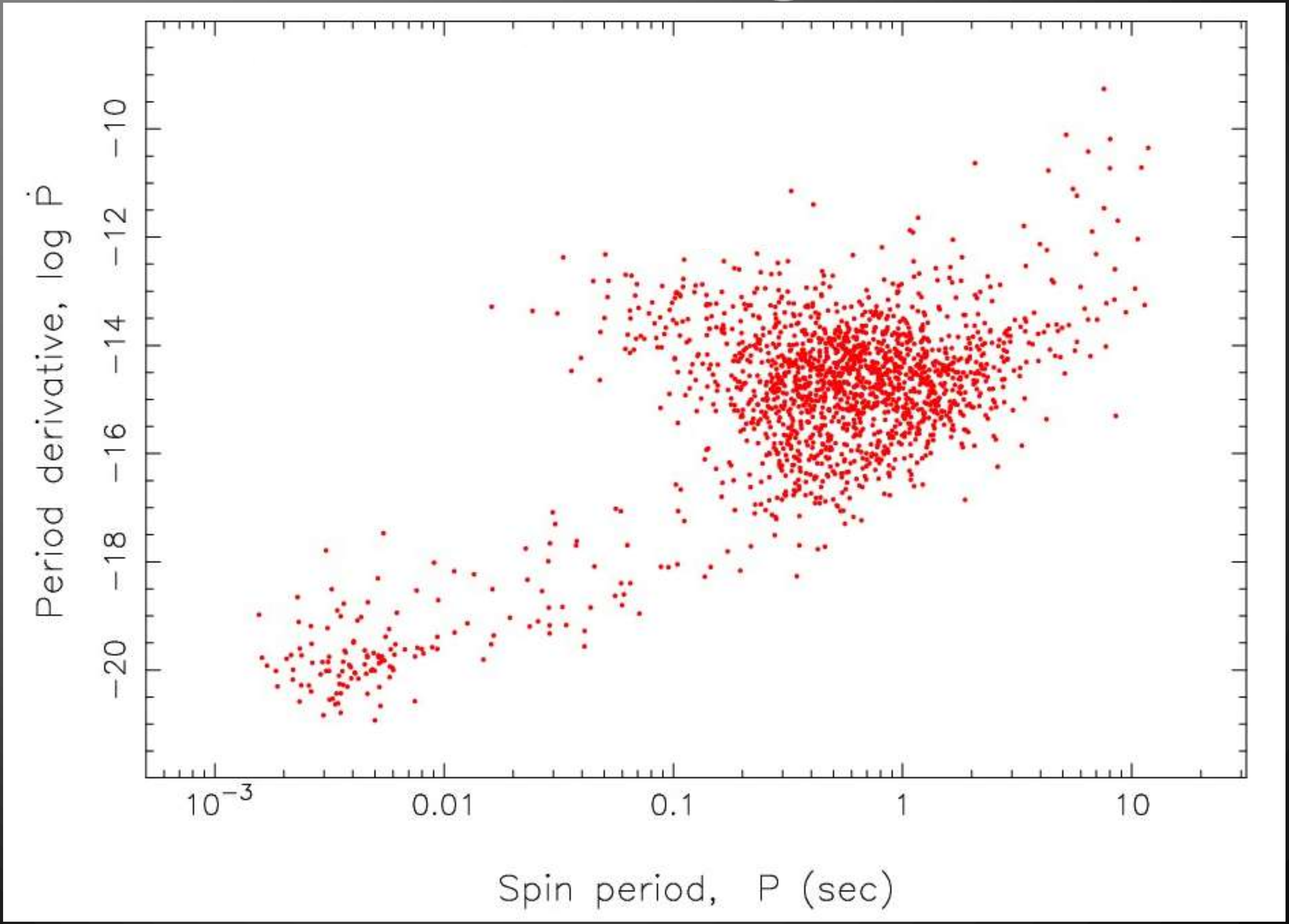
$$\Updownarrow$$

$$\boxed{B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6} P\dot{P}}}$$

Pacini (1967)



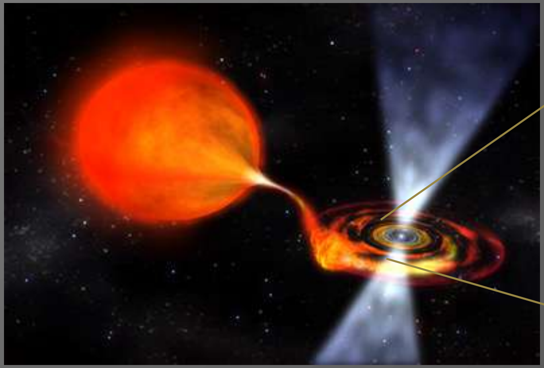
The P-$\dot{P}$ diagram

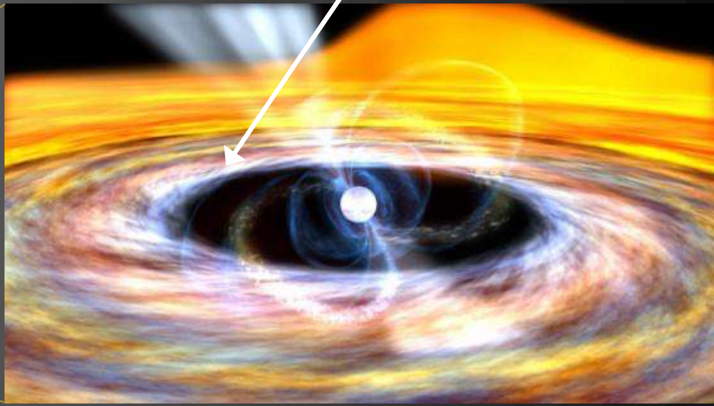


MILLISECOND PULSARS

- Rapid spin: $P < 50\,ms$
- Small period derivative: $\dot{P} < 10^{-17}\,\mathrm{s\,s^{-1}}$

Origin:





$J = |\vec{r} \times \vec{p}|$

- Accretion of mass and angular momentum from a companion star in a binary system

$$N = \dot{J}_* \equiv \frac{d}{dt}(I\Omega_*) = \dot{M}_* \sqrt{GM_* r_{\mathrm{A}}}\,\xi$$

Lamb, Pethick & Pines (1973)
Ghosh & Lamb (1979, 1992)

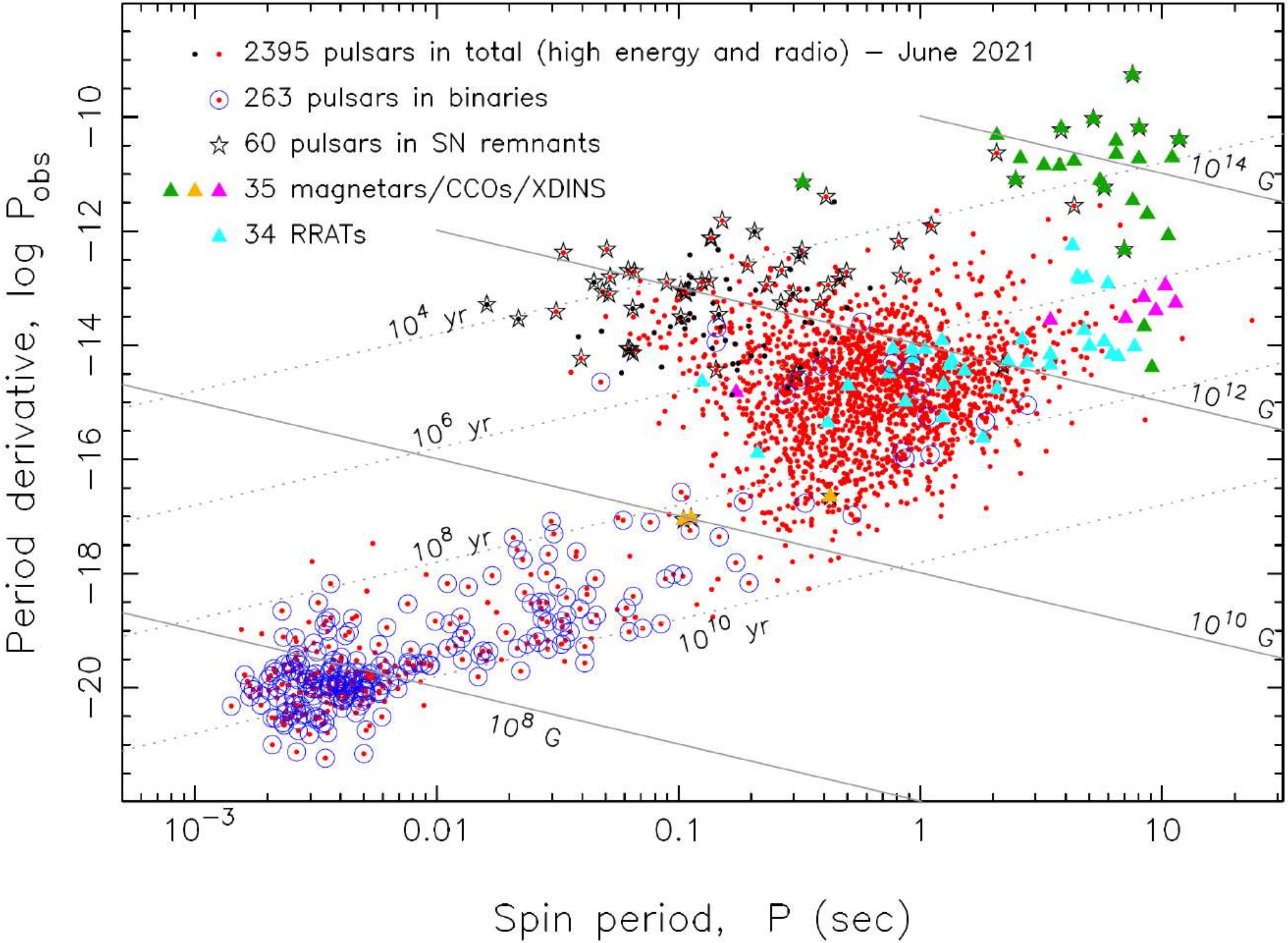
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{c^2}{4\pi}\nabla \times \left(\frac{1}{\sigma} \times \nabla \times \vec{B}\right)$$

Geppert & Urpin (1994); Konar & Bhattacharya (1997)

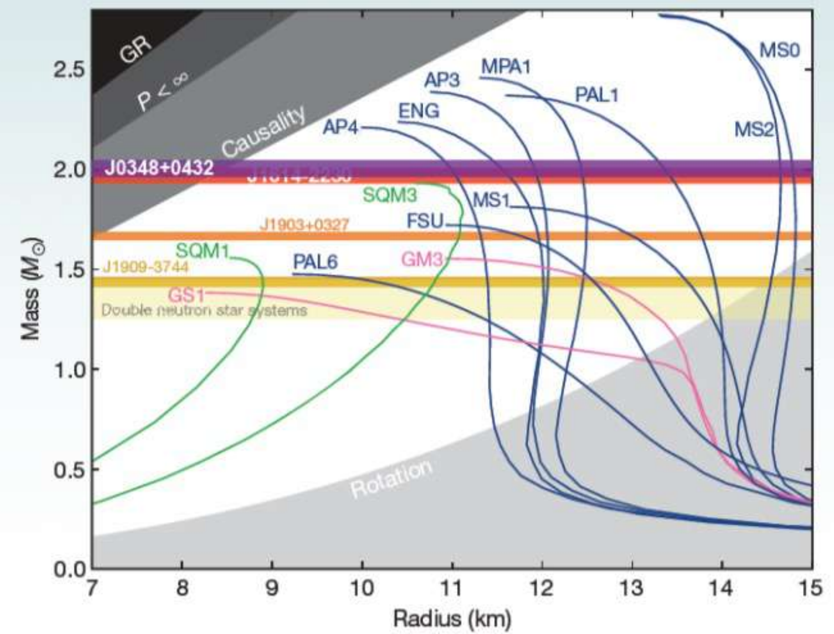
$$B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6} P\dot{P}}$$

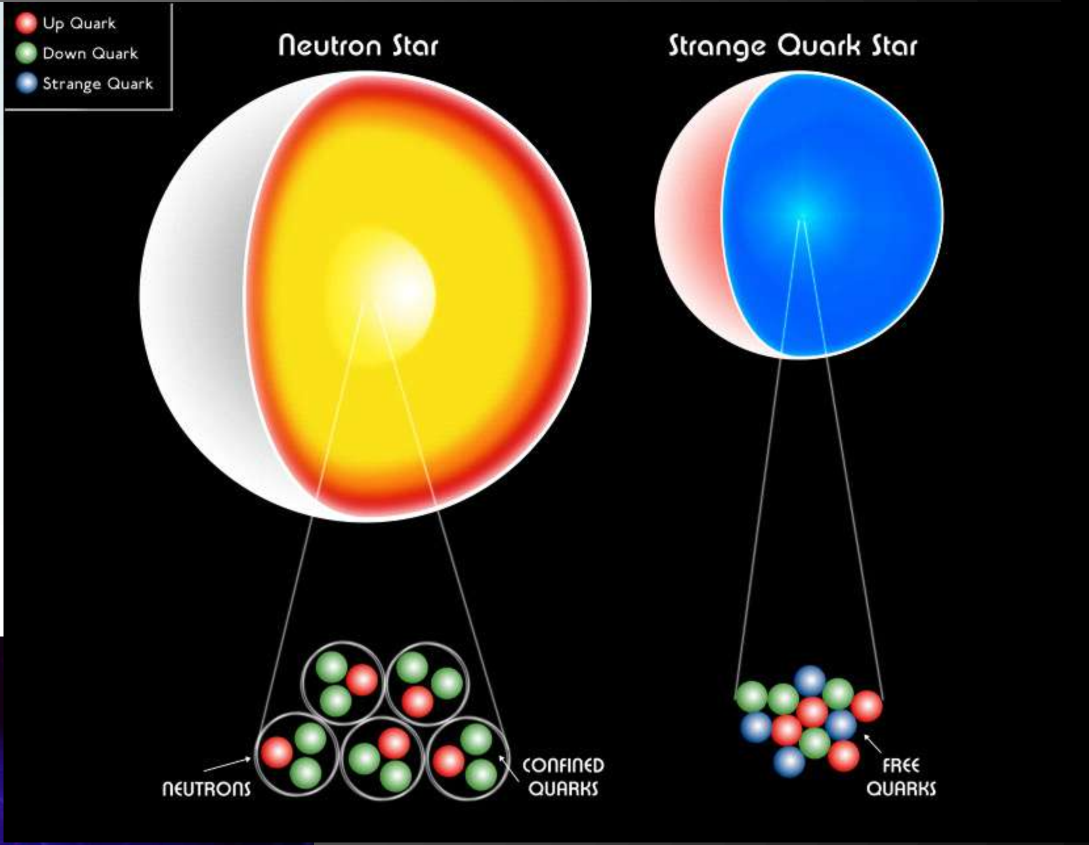
Magnetic-dipole model

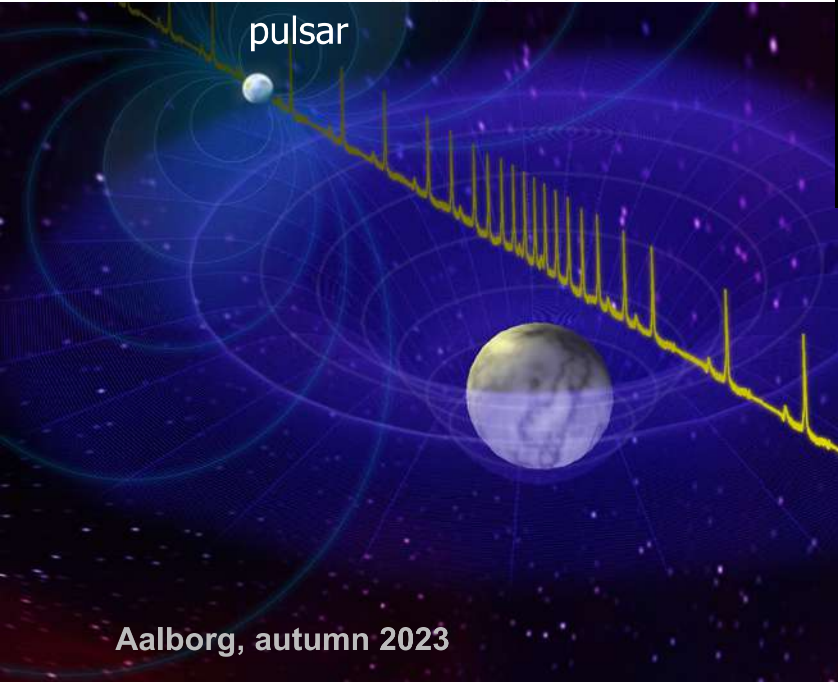
Tauris & van den Heuvel (2023)



The neutron star equation of state

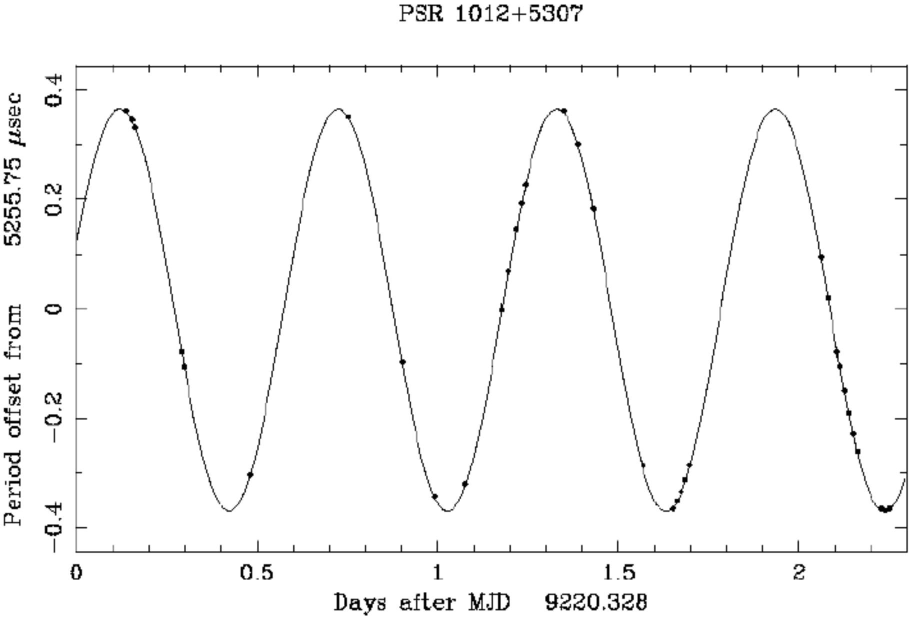




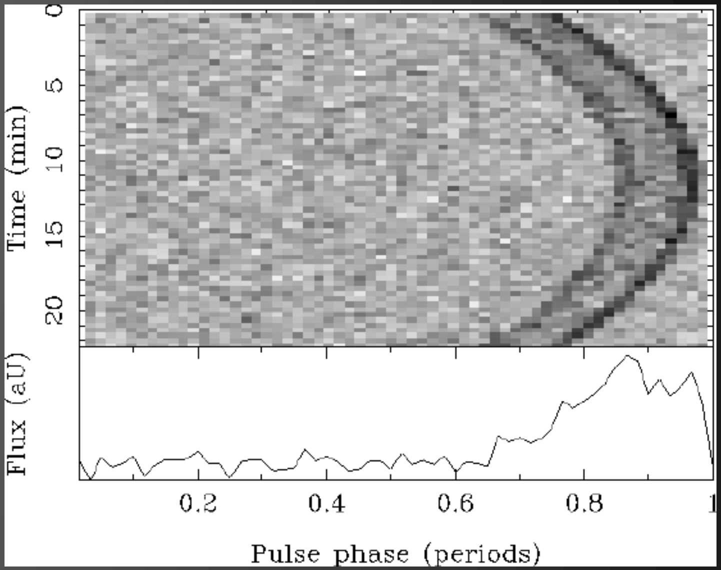


Hessels et al. (2006)
Demorest et al. (2010)
Freire et al. (2011)
Lattimer (2012)
Antoniadis et al. (2013)

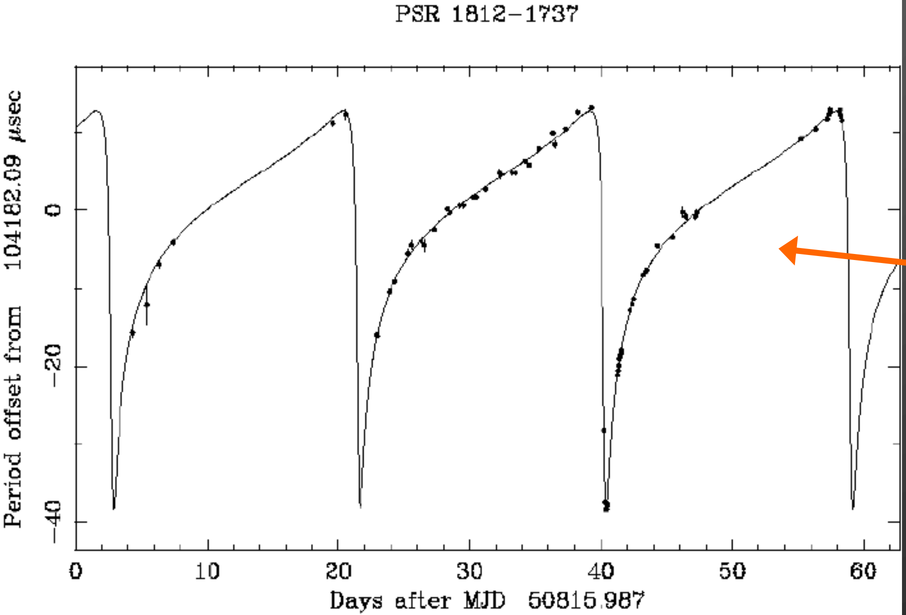
Detection of binary pulsars



binary pulsar



Doppler shift of the signal



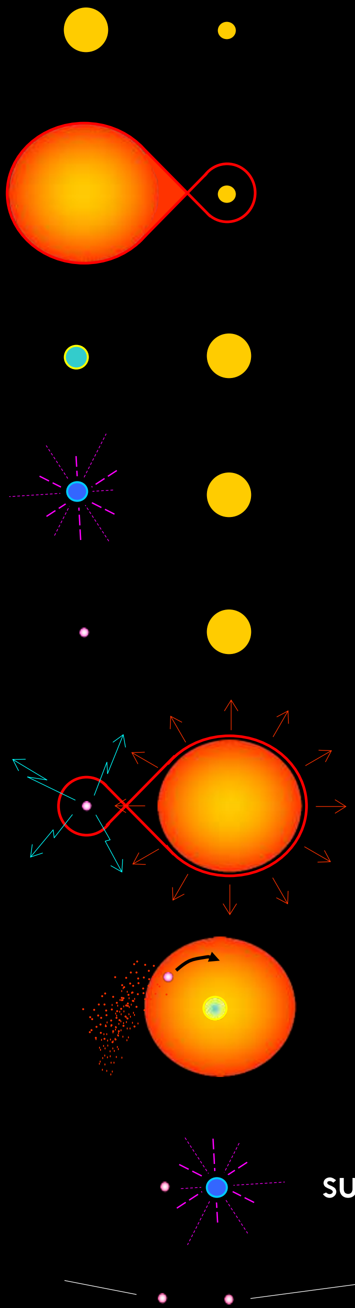
elliptical orbit
(double neutron star system)

DOUBLE PULSAR

Burgay et al. (2003), Lyne et al. (2004), Kramer et al. (2006)

Pulsar J0737-3039A: P=22.7 ms
Pulsar J0737-3039B: P=2.77 sec

Formation of PSR J0737-3039
- a double pulsar



ZAMS

Roche-lobe overflow

helium star

supernova

neutron star

HMXB

common envelope
+ spiral-in

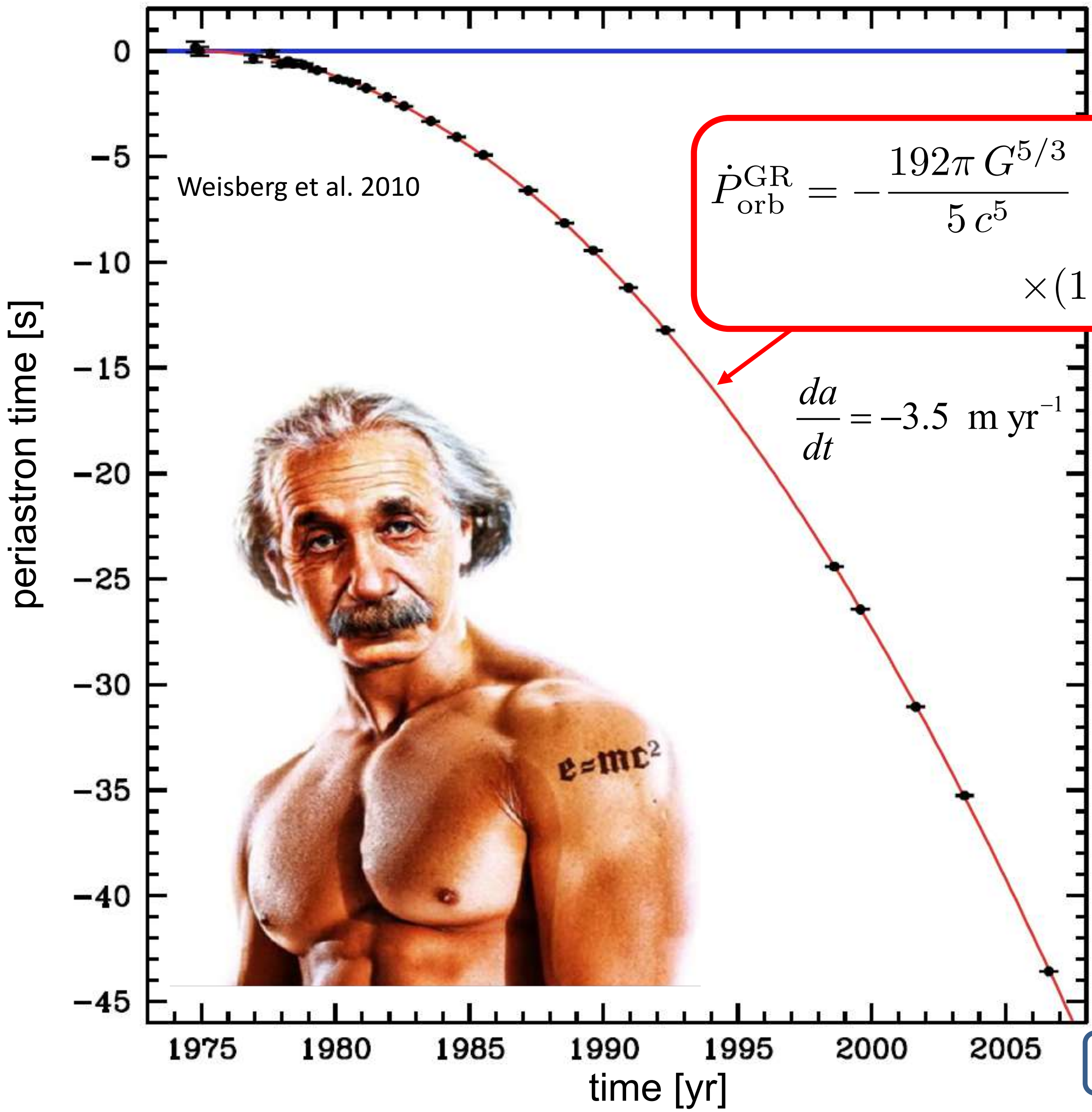
supernova

<u>recycled pulsar</u>

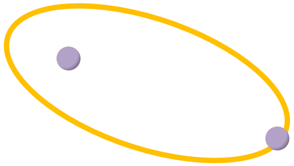
<u>young pulsar</u>

MERGING NEUTRON STARS

PSR B1913+16 (Hulse-Taylor pulsar, $P_{\rm orb}$=7.75 hr, ecc=0.61)



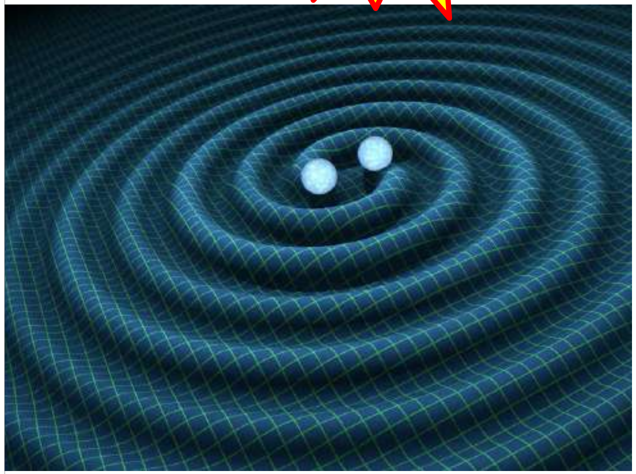
$$\frac{da}{dt} = -3.5 \ \text{m yr}^{-1}$$



Peters (1964)

$$\dot P_{\rm orb}^{\rm GR} = -\frac{192\pi\, G^{5/3}}{5\, c^5}\left(\frac{P_{\rm orb}}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\times(1-e^2)^{-7/2}\, M_1 M_2\,(M_1+M_2)^{-1/3}$$

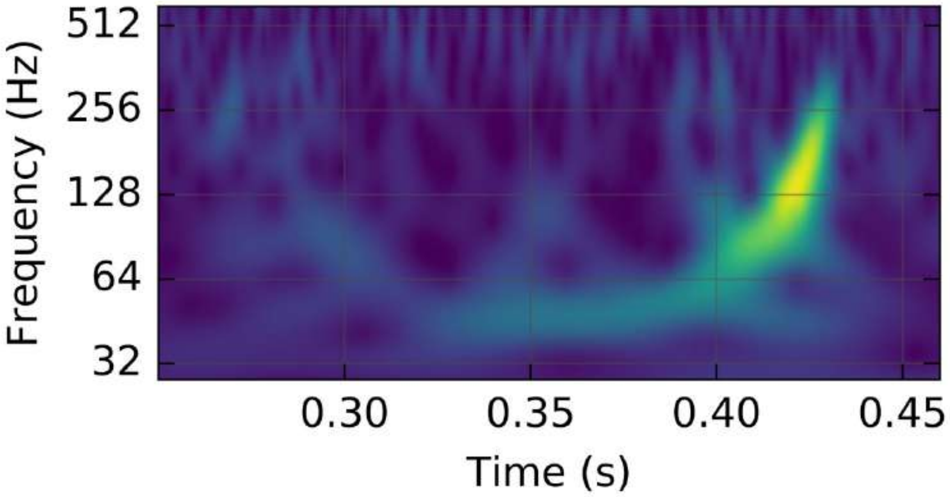
Merge in
τ = 300 Myr



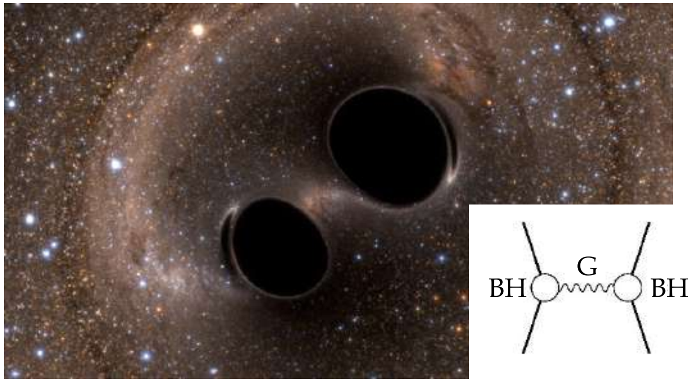
$L_{\rm GW} = 7\times10^{24}$ W $\qquad (L_{{\rm GW},\odot} = 5000$ W)

GRAVITATIONAL WAVES: *The Discovery!* Sept.14, 2015 @ 09:50 UTC

A brief chirp from a galaxy 1.4 billion light years away…



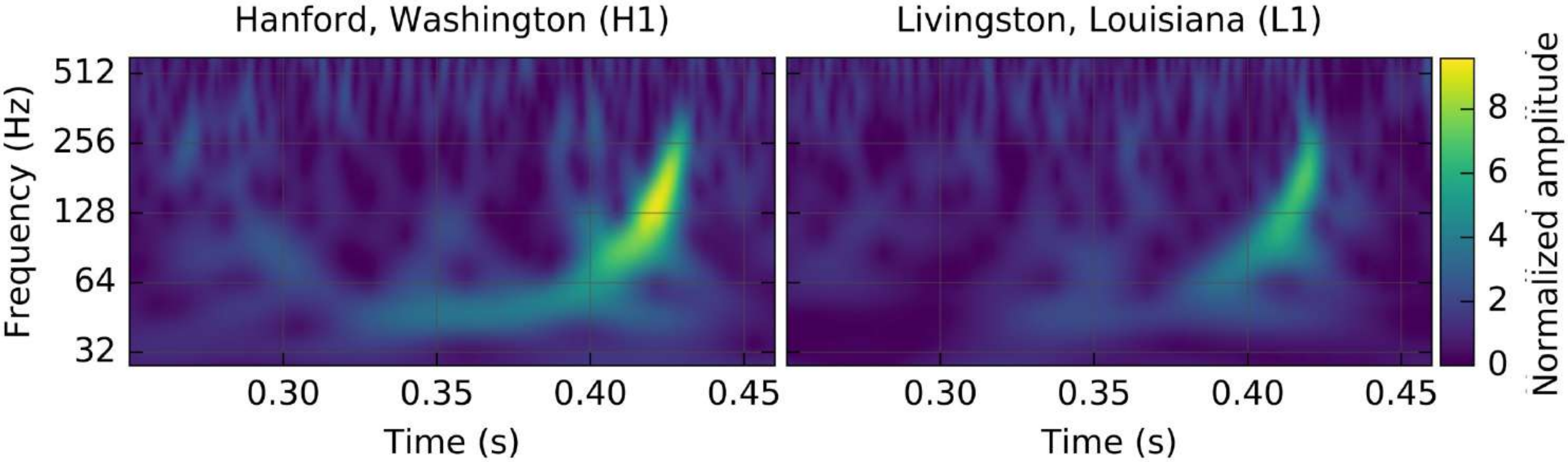
Detection of gravitational waves!

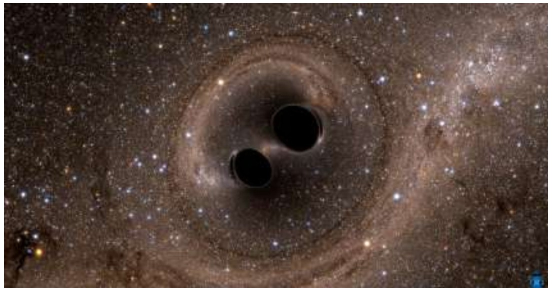


GW150914, GW151012, GW151226, GW170104, GW170608, GW170729, GW170809, GW170814, GW170817, GW170818, GW170823 (GW151216,…)

DETECTION OF GRAVITATIONAL WAVES: GW150914

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$





Collision of two black holes:

$36\ M_{sun} + 29\ M_{sun} \neq 65\ M_{sun}$

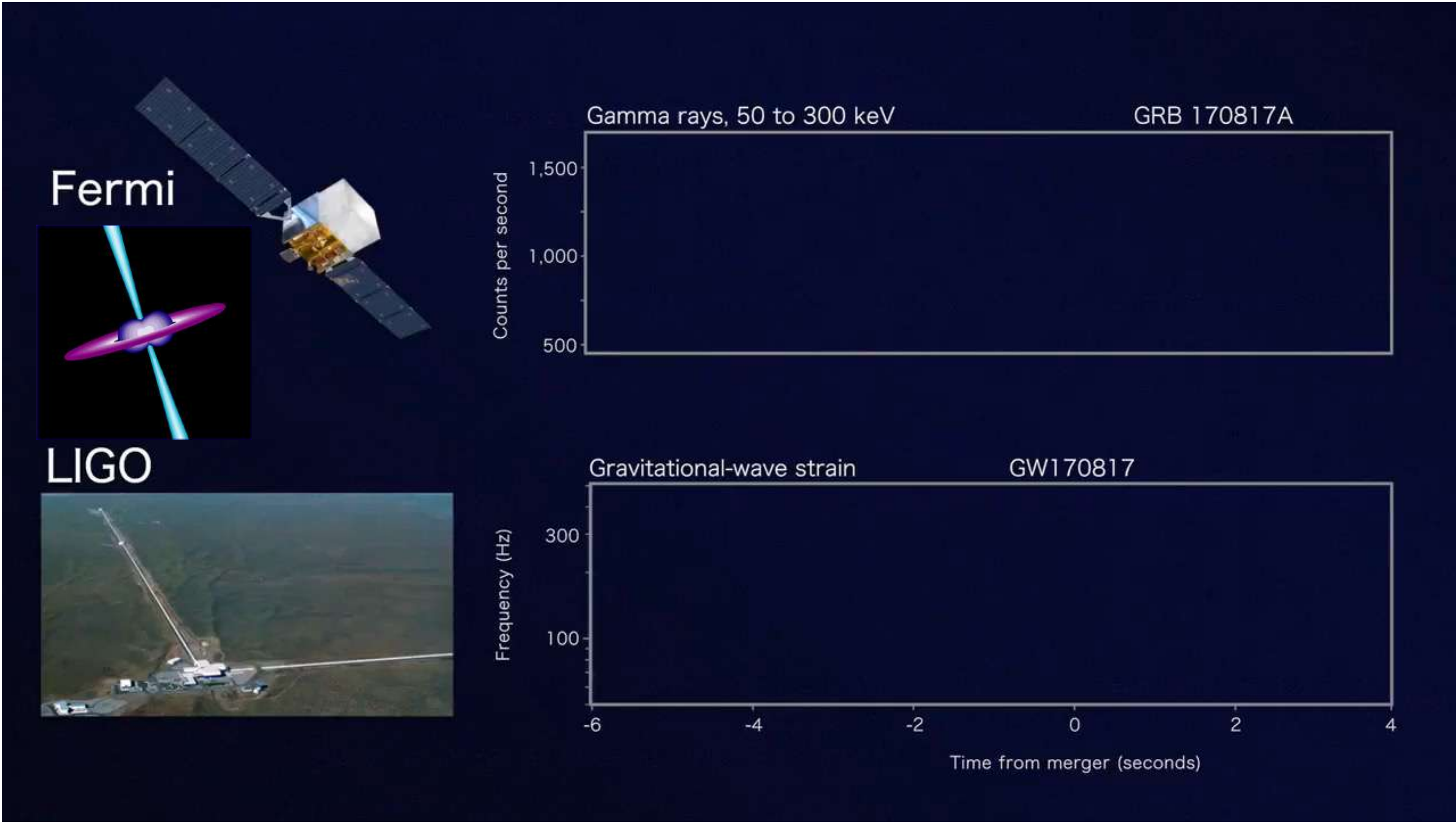
$M_{merger} = 62\ M_{sun}$! (3 $M_{sun} \cdot c^2$ emitted as GWs)

35–250 Hz (8 cycles)

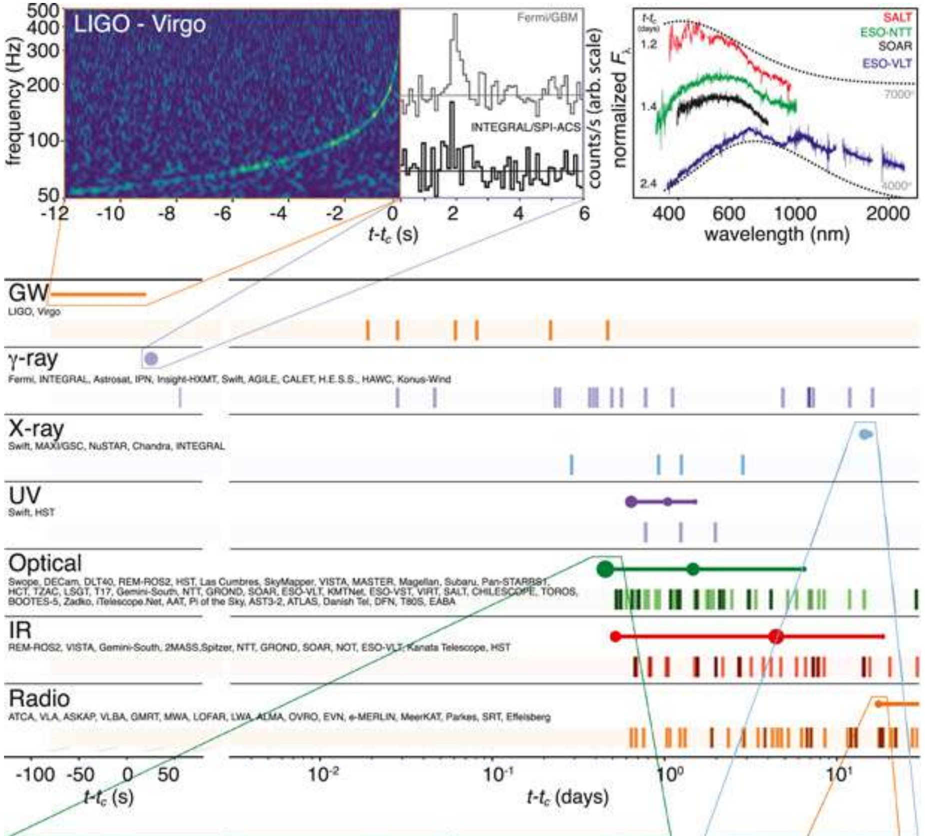
$h_{top} = 3.4\text{x}10^{-22}$

Z=0.09 (400 Mpc = 1.4 bill. light years)

NS merger: GW170817 + EM follow up



New era of **multi-messenger** astrophysics

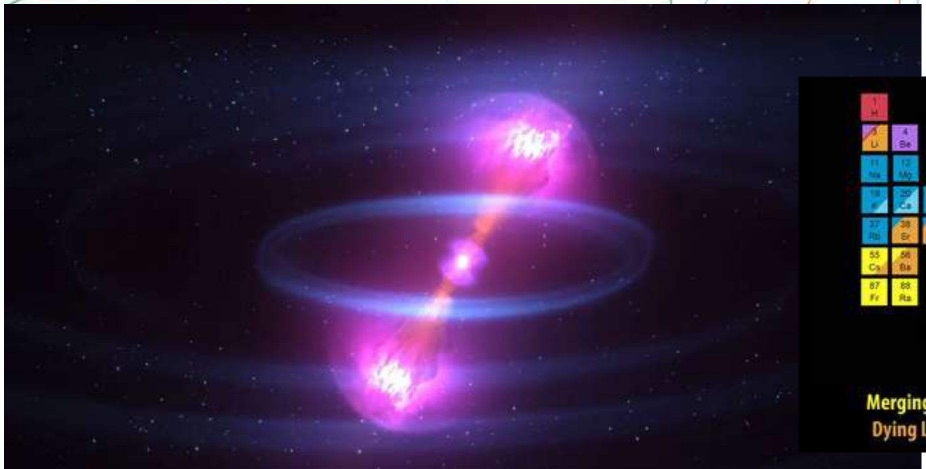


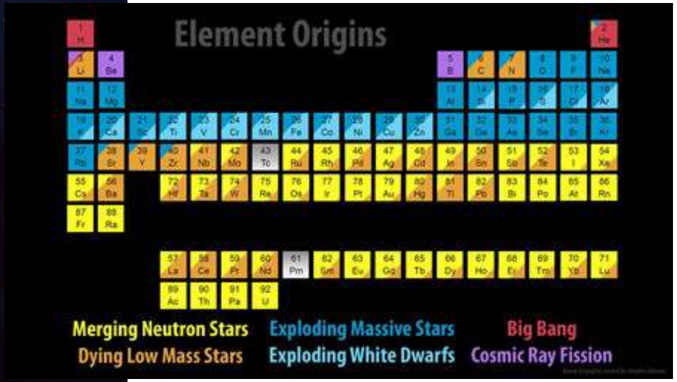
physicsworld

BREAKTHROUGH OF THE YEAR

2017

Detection of a **kilonova** (radioactive decay of heavy r-process elements)

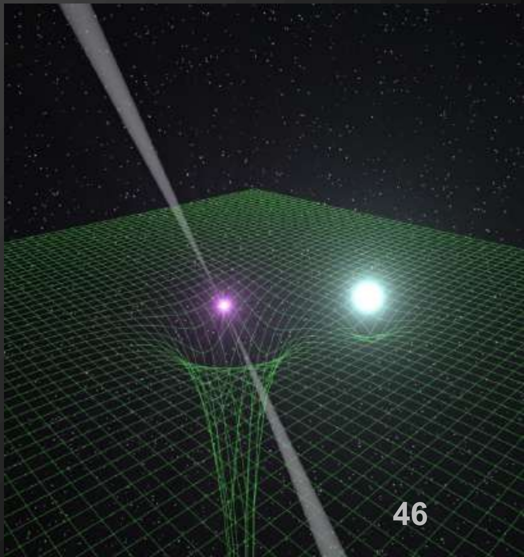




Physics of Compact Objects

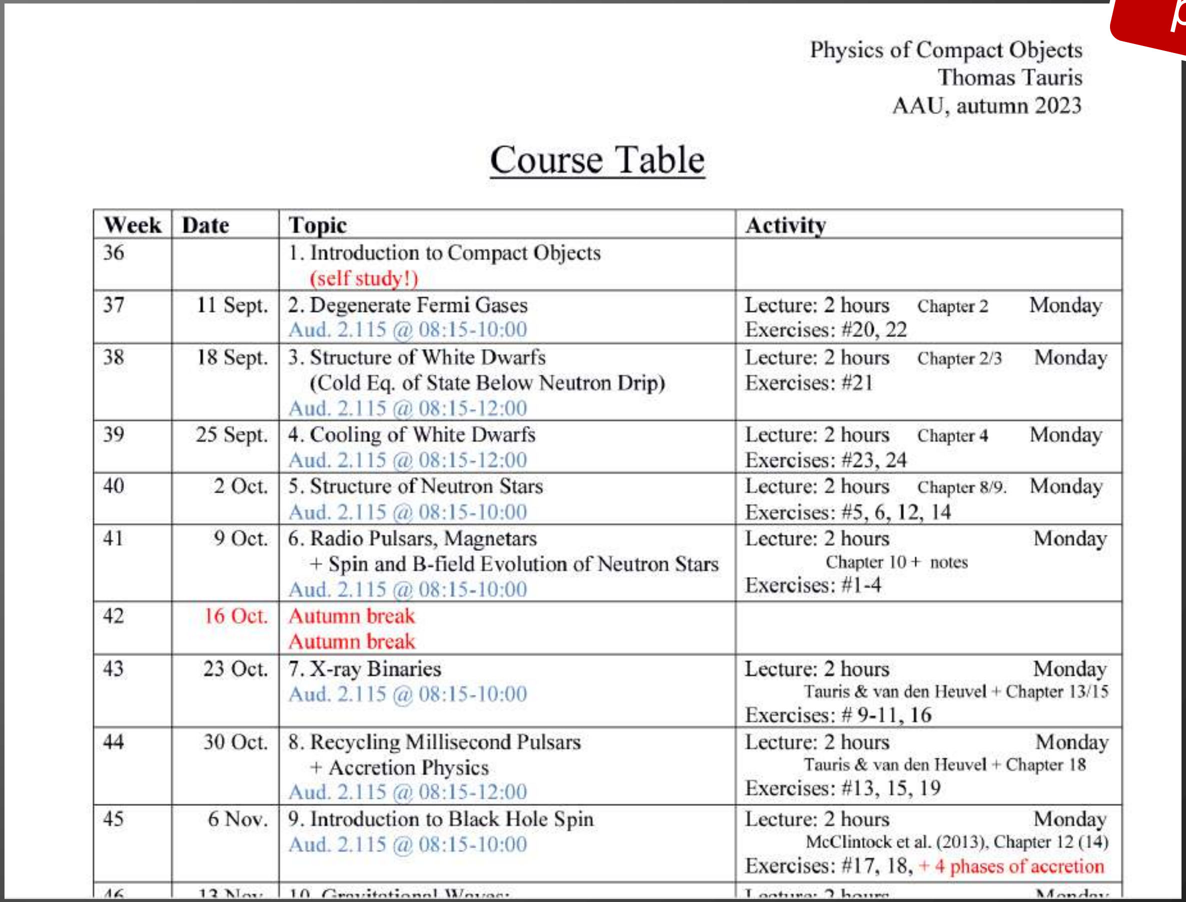
- Degenerate Fermi Gases
- Cold Eq.-of-state Below Neutron Drip
- Structure and Cooling of White Dwarfs
- Cold Eq.-of-state Above Neutron Drip
- Structure of Neutron Stars
- Radio Pulsars
- Spin and B-field Evolution of Neutron Stars / Magnetars
- Binary Evolution
- Recycled Millisecond Pulsars
- X-ray Bursts
- Black Hole Spin
- Gravitational Waves and Kilonovae

Oral Exam:
January



Physics of Compact Objects

preliminary

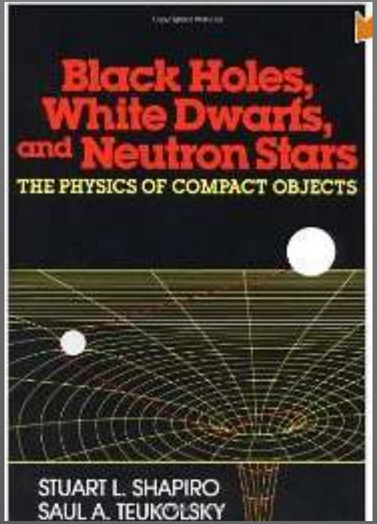


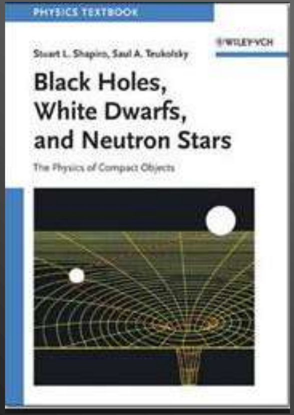
Physics of Compact Objects
Thomas Tauris
AAU, autumn 2023

Course Table

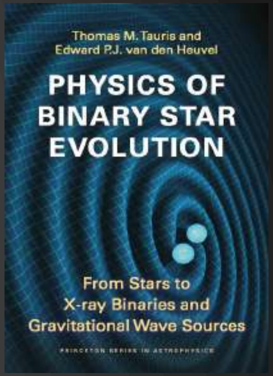
Week	Date	Topic	Activity
36		1. Introduction to Compact Objects (self study!)	
37	11 Sept.	2. Degenerate Fermi Gases Aud. 2.115 @ 08:15-10:00	Lecture: 2 hours Chapter 2 Monday Exercises: #20, 22
38	18 Sept.	3. Structure of White Dwarfs (Cold Eq. of State Below Neutron Drip) Aud. 2.115 @ 08:15-12:00	Lecture: 2 hours Chapter 2/3 Monday Exercises: #21
39	25 Sept.	4. Cooling of White Dwarfs Aud. 2.115 @ 08:15-12:00	Lecture: 2 hours Chapter 4 Monday Exercises: #23, 24
40	2 Oct.	5. Structure of Neutron Stars Aud. 2.115 @ 08:15-10:00	Lecture: 2 hours Chapter 8/9. Monday Exercises: #5, 6, 12, 14
41	9 Oct.	6. Radio Pulsars, Magnetars + Spin and B-field Evolution of Neutron Stars Aud. 2.115 @ 08:15-10:00	Lecture: 2 hours Monday Chapter 10 + notes Exercises: #1-4
42	16 Oct.	Autumn break Autumn break	
43	23 Oct.	7. X-ray Binaries Aud. 2.115 @ 08:15-10:00	Lecture: 2 hours Monday Tauris & van den Heuvel + Chapter 13/15 Exercises: # 9-11, 16
44	30 Oct.	8. Recycling Millisecond Pulsars + Accretion Physics Aud. 2.115 @ 08:15-12:00	Lecture: 2 hours Monday Tauris & van den Heuvel + Chapter 18 Exercises: #13, 15, 19
45	6 Nov.	9. Introduction to Black Hole Spin Aud. 2.115 @ 08:15-10:00	Lecture: 2 hours Monday McClintock et al. (2013), Chapter 12 (14) Exercises: #17, 18, + 4 phases of accretion
46	13 Nov.	10. Gravitational Waves:	Lecture: 2 hours Monday

The Physics of Compact Objects





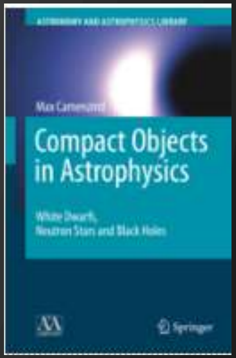
Shapiro & Teukolsky (1983), Wiley-Interscience
Tauris & van den Heuvel (2023)



Review articles:

- McClintock, Narayan & Steiner (2013)
- Riles (2013)

- Camenzind (2007)
- Giacomazzo et al. (2019)
- Haensel, Potekhin & Yakovlev (2006)
- Reynolds (2020)

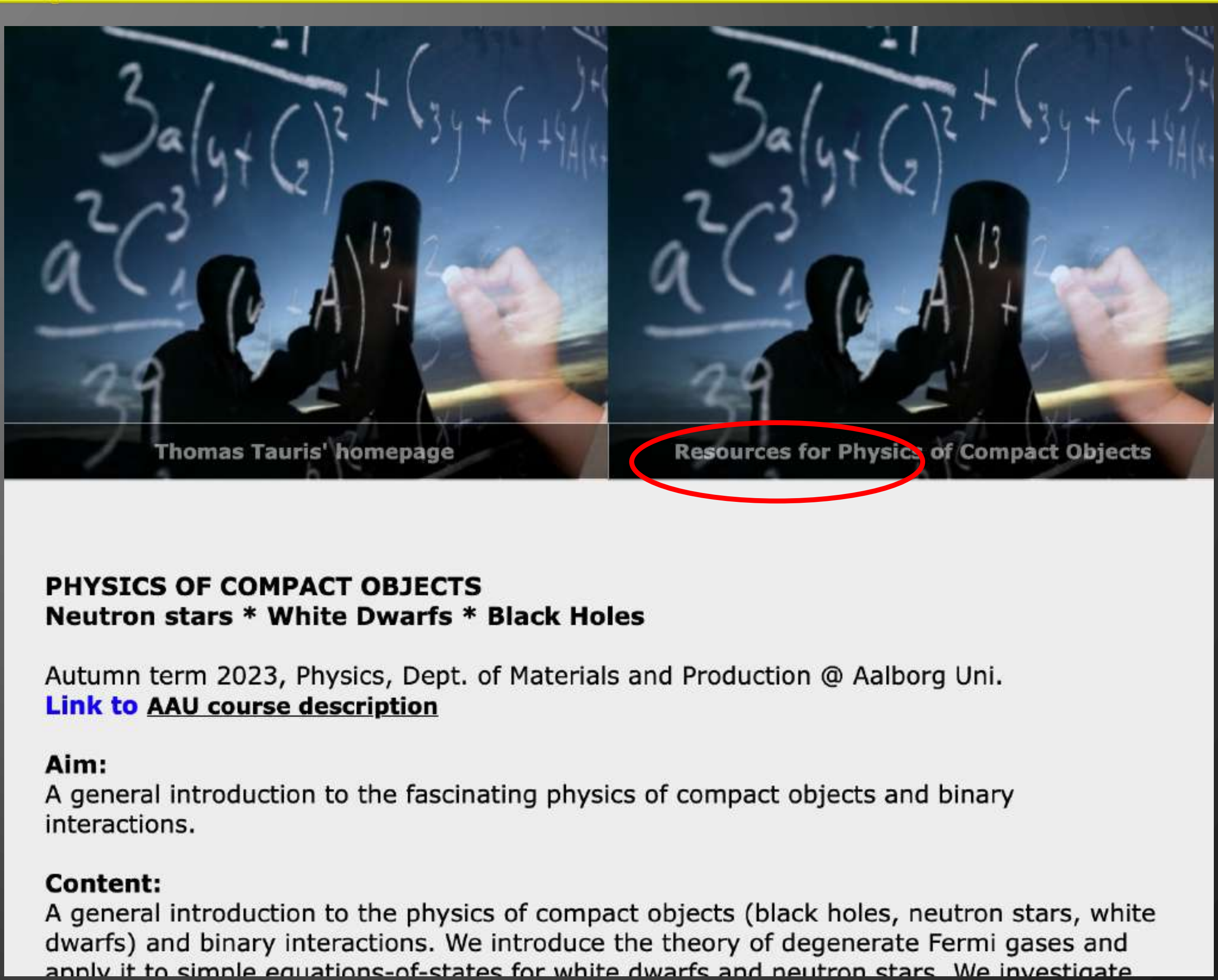


Check resources on:
https://homes.m-tech.aau.dk/~tauris/course_resources.html
weekly notes, lecture notes, literature, exercises

Exercises: First time Sep. 11

Webpage

https://homes.m-tech.aau.dk/~tauris/course.html



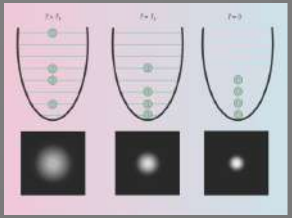
PHYSICS OF COMPACT OBJECTS
Neutron stars * White Dwarfs * Black Holes

Autumn term 2023, Physics, Dept. of Materials and Production @ Aalborg Uni.
Link to **AAU course description**

Aim:
A general introduction to the fascinating physics of compact objects and binary interactions.

Content:
A general introduction to the physics of compact objects (black holes, neutron stars, white dwarfs) and binary interactions. We introduce the theory of degenerate Fermi gases and apply it to simple equations-of-states for white dwarfs and neutron stars. We investigate

Programme



- ▣ * Introduction
- ▣ * **Degenerate Fermi Gases**
  Non-relativistic and extreme relativistic electron / (n,p,e$^-$) gases
- ▣ * **White Dwarfs**
  Structure, cooling models, observations
- ▣ * **Neutron Stars**
  Structure and equation-of-state
- ▣ * **Radio Pulsars**
  Characteristics, spin evolution, magnetars, observations, timing
- ▣ * **Binary Evolution and Interactions**
  X-ray binaries, accretion, formation of millisecond pulsars, recycling
- ▣ * **Black Holes**
  Observations, characteristics and spins
- ▣ * **Gravitational Waves**
  Sources and detection, kilonovae
- ▣ * **Exam**