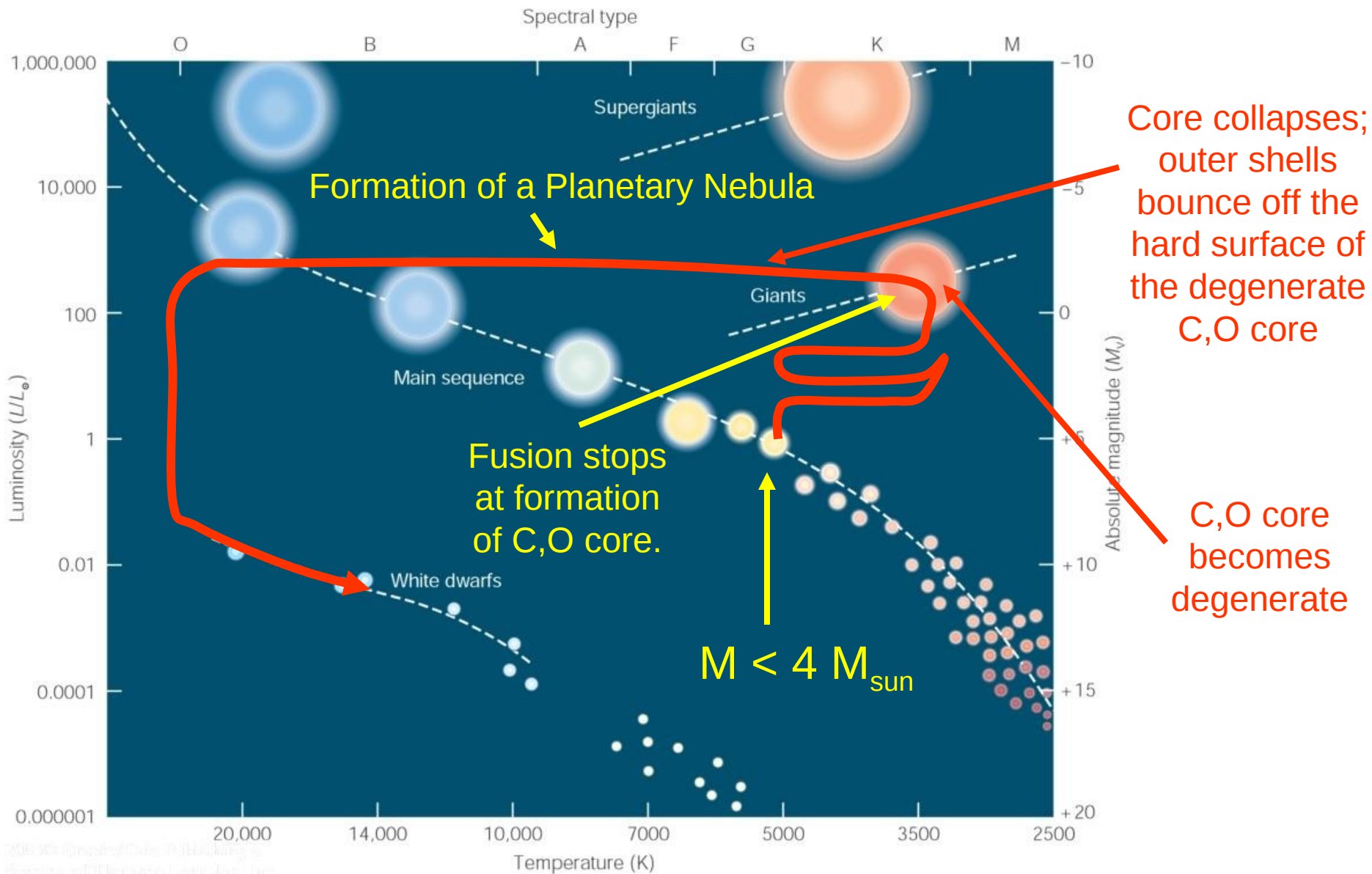


Degenerate Matter and White Dwarfs



Summary of Post-Main-Sequence Evolution of Sun-Like Stars



The Remnants of Sun-Like Stars: White Dwarfs



First example:

Sirius B (Astrometric
binary; discovered 1862)

$$M \approx 1 M_0$$

$$L \approx 0.03 L_0$$

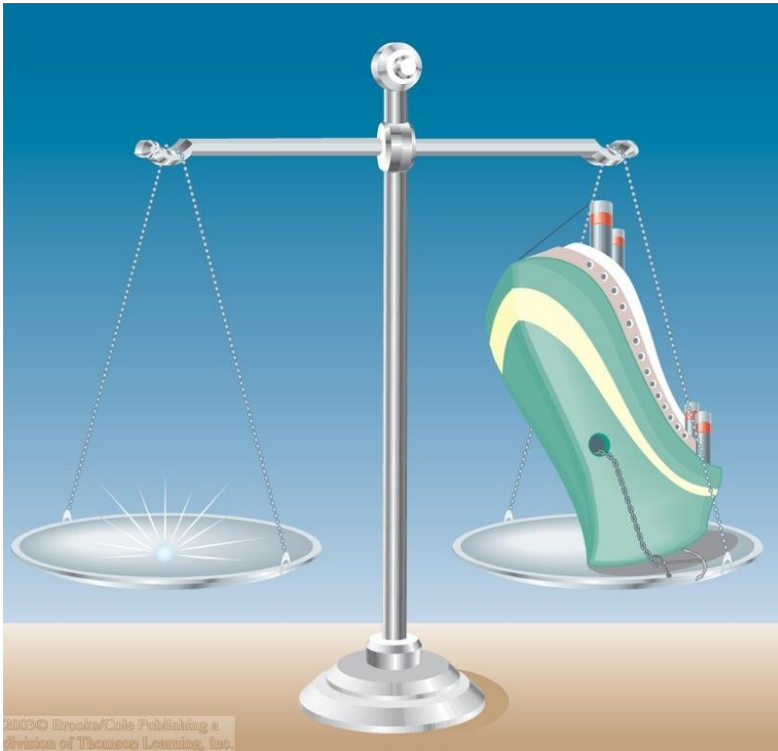
$$T_e \approx 27,000 \text{ K}$$

$$\Rightarrow R \approx 0.008 R_0$$

$$\Rightarrow \rho \approx 3 \times 10^6 \text{ g/cm}^3$$

White Dwarfs

Degenerate stellar remnant (C,O core)



Extremely dense:

1 teaspoon of WD material:

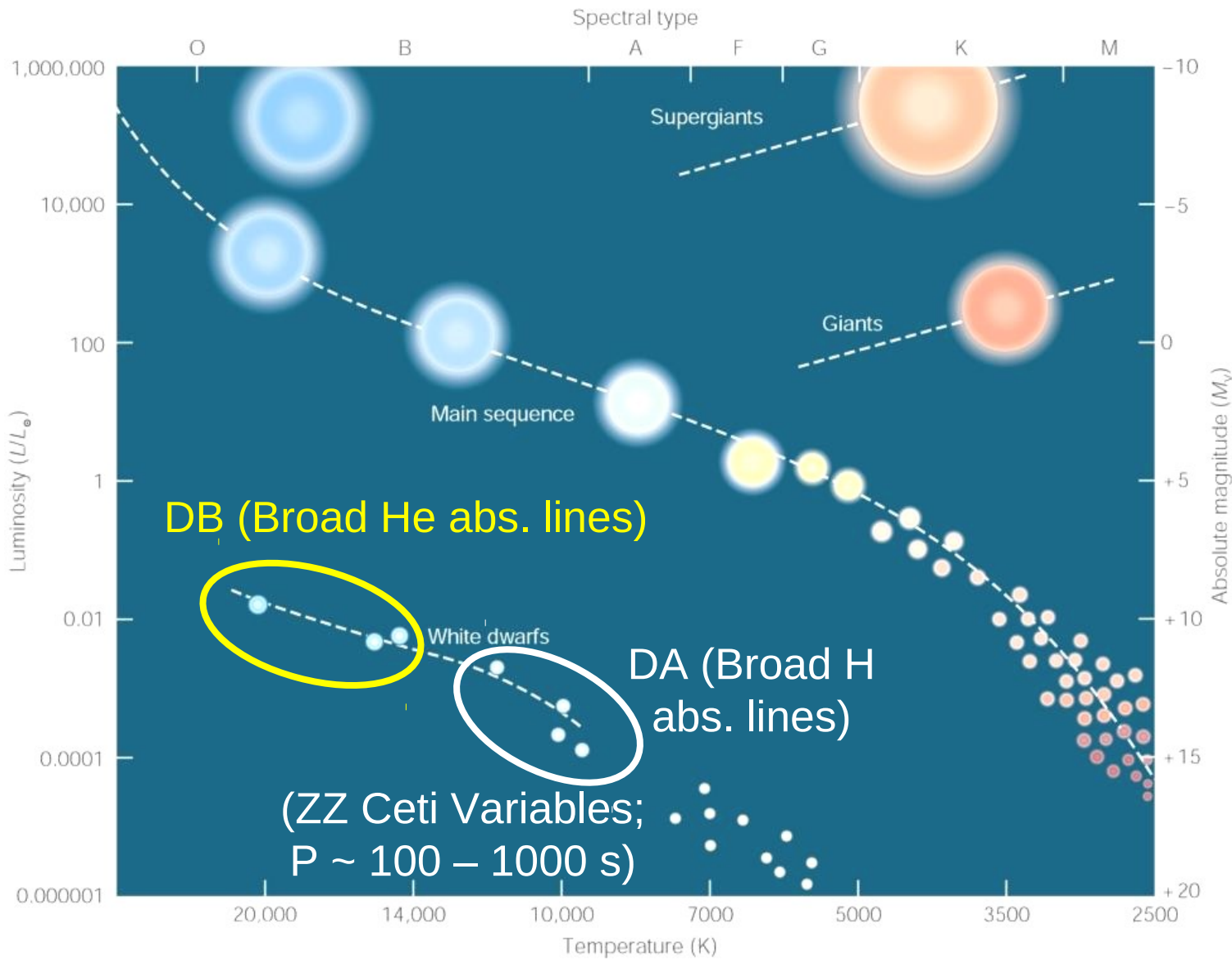
mass \approx 16 tons!!!

Chunk of WD material the size of a beach ball would outweigh an ocean liner!

Central pressure:

$P_c \sim 3.8 \times 10^{23}$ dynes/cm² $\sim 1.5 \times 10^6 P_{c,\text{sun}}$ for Sirius B

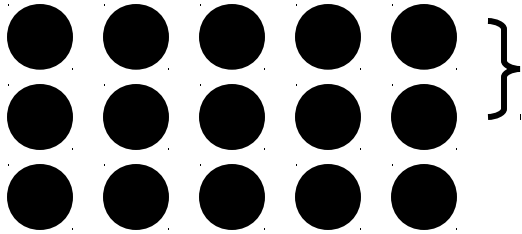
Central temperature: $T_c \sim \text{several} \times 10^7$ K



Thin remaining surface layers of He and H produce absorption lines;

Low luminosity; high temperature => Lower left corner of the Hertzsprung-Russell diagram.

Degenerate Matter

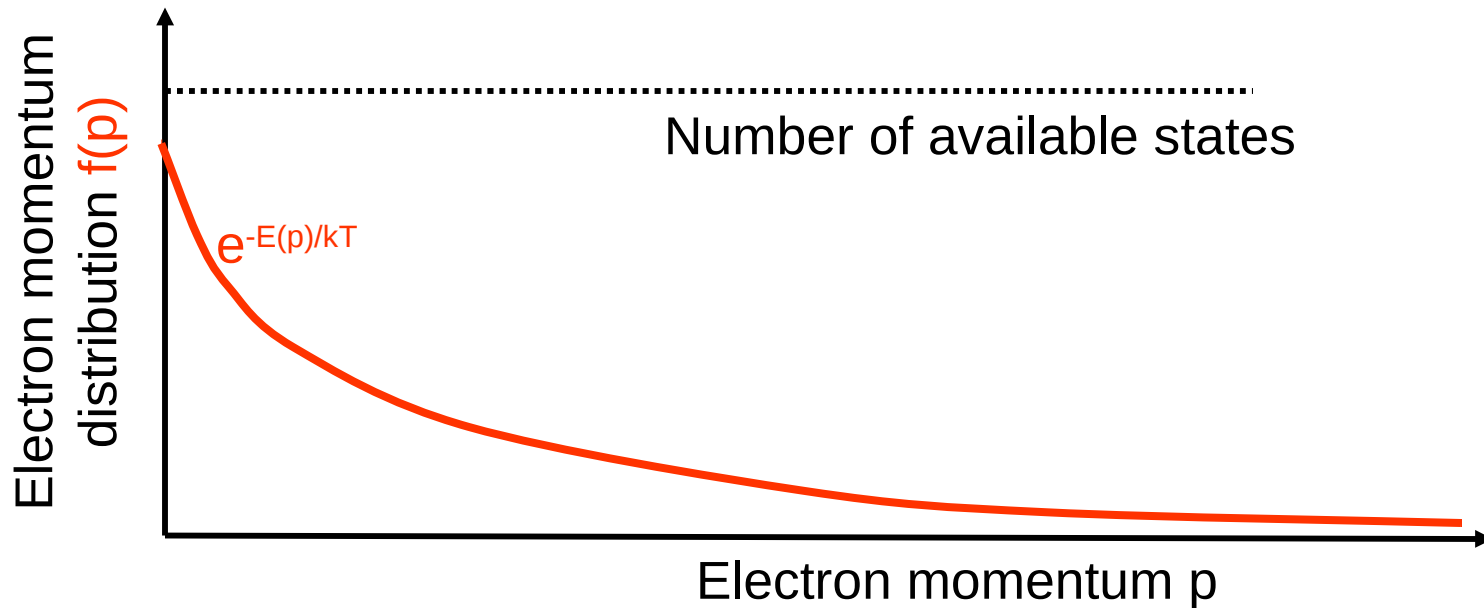


$$\Delta x \sim n^{-1/3}$$

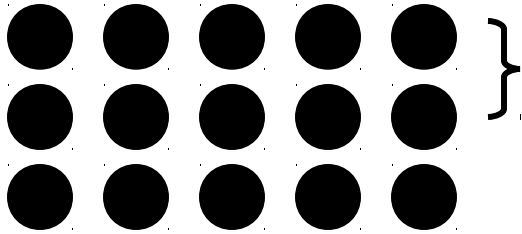
Heisenberg Uncertainty Principle:

$$(\Delta x)^3 (\Delta p)^3 \sim h^3 \Rightarrow (\Delta p)_{\min}^3 \sim n h^3$$

Non-degenerate matter (low density or high temperature):



Degenerate Matter

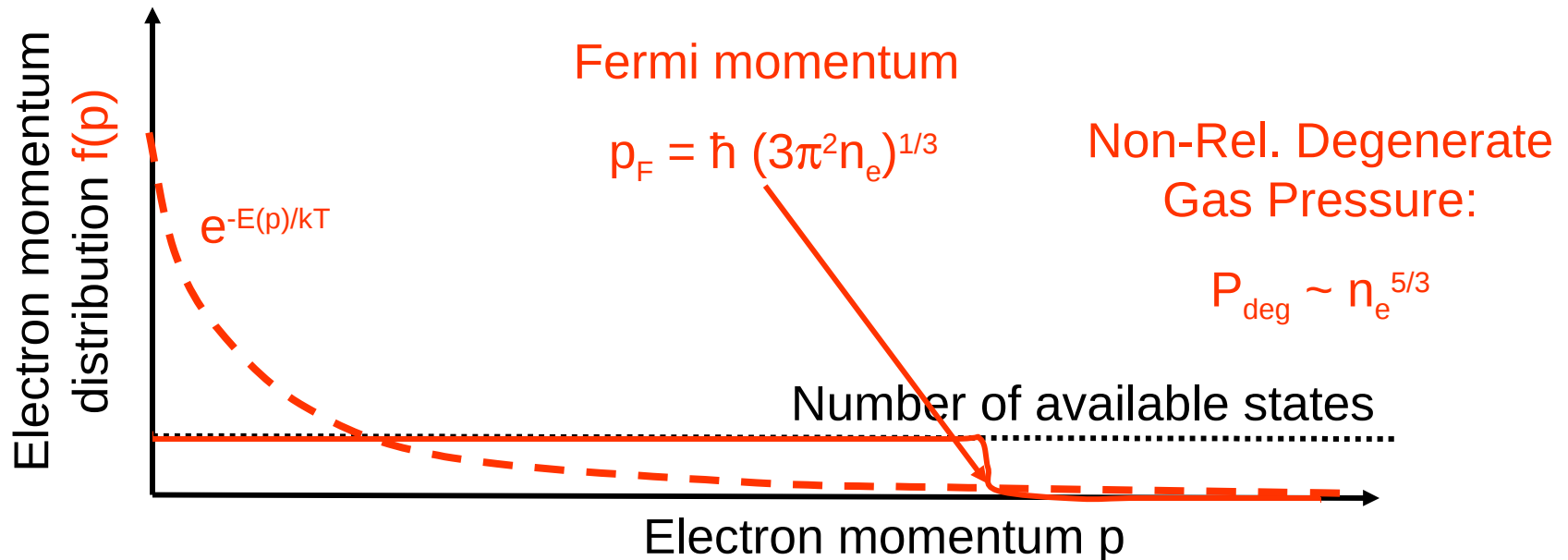


$$\Delta x \sim n^{-1/3}$$

Heisenberg Uncertainty Principle:

$$(\Delta x)^3 (\Delta p)^3 \sim h^3 \Rightarrow (\Delta p)_{\min}^3 \sim n h^3$$

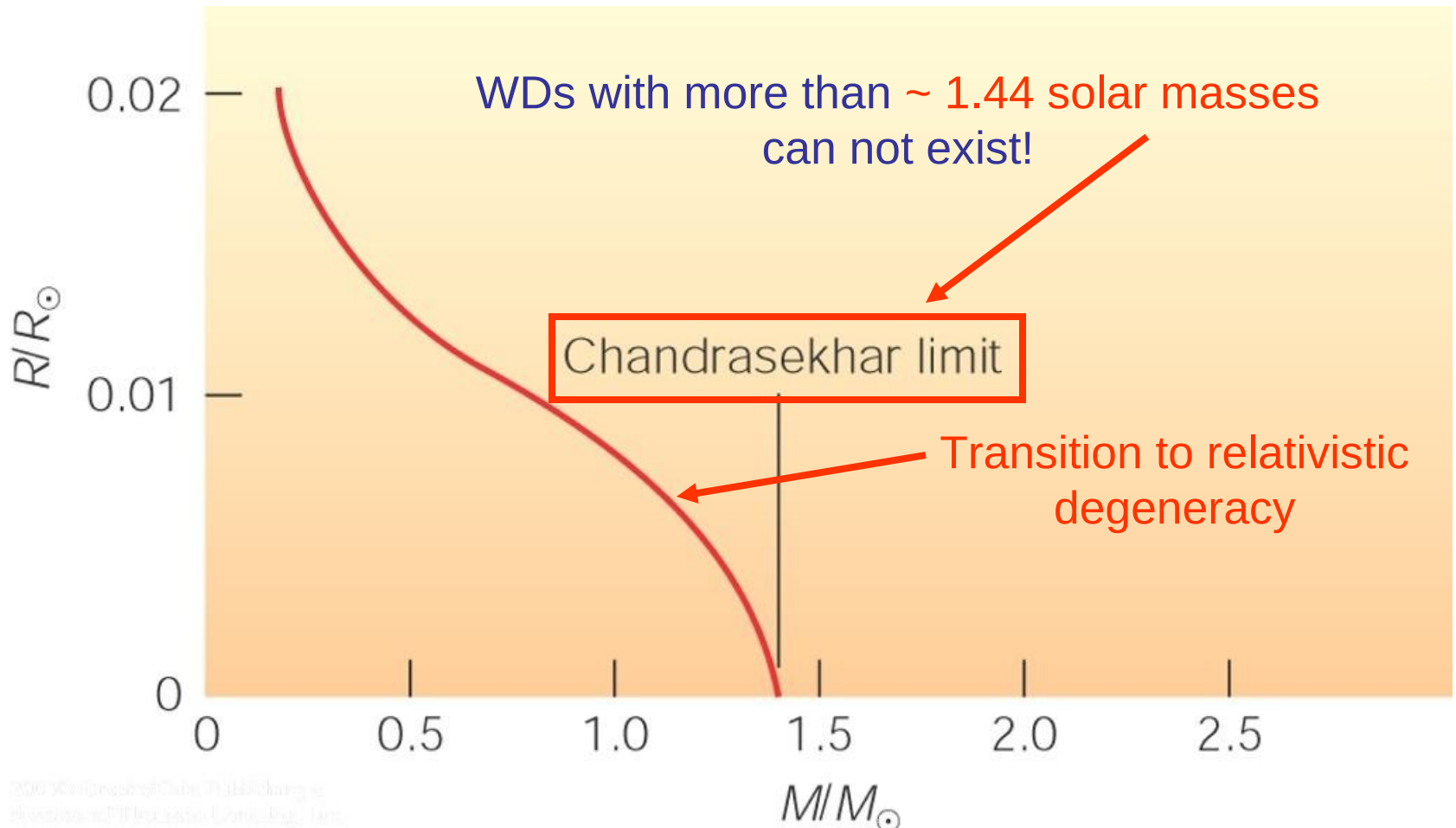
Degenerate matter (High density or low temperature):



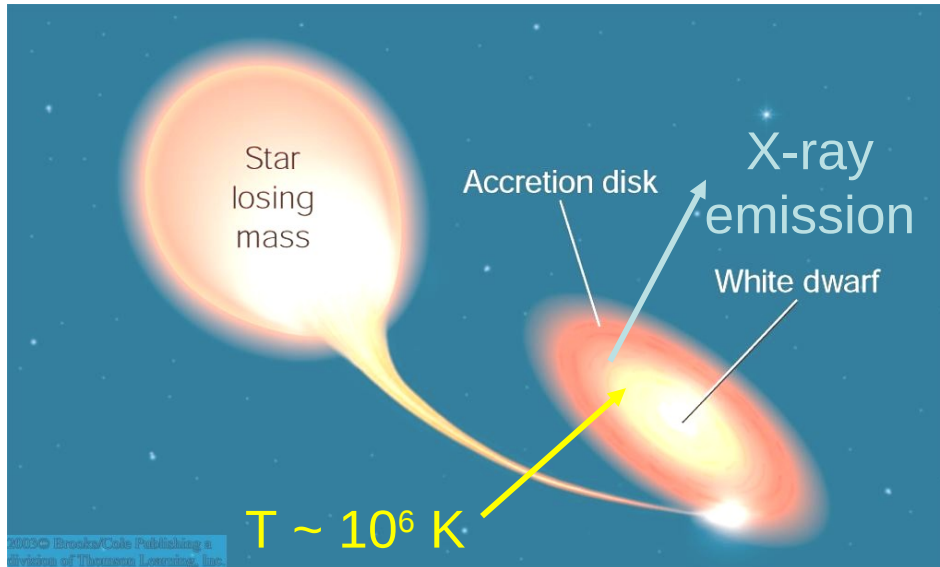
The Chandrasekhar Limit

The **more massive** a white dwarf, the **smaller** it is.

$$R_{\text{WD}} \sim M_{\text{WD}}^{-1/3} \Rightarrow M_{\text{WD}} V_{\text{WD}} = \text{const.} \quad (\text{non-rel.})$$



White Dwarfs in Binary Systems



Cataclysmic Variables (CVs)

Binary consisting of WD + MS or Red Giant star

=> WD accretes matter from the companion

Angular momentum conservation => accreted matter forms a disk, called **accretion disk** (see Monday's lecture for the physics of accretion disks).

Matter in the accretion disk heats up to ~ 1 million K => X-ray emission

Accreted Material builds up on the WD surface, heats up

=> High density, high temperature => Explosive onset of H \rightarrow He fusion

=> Nova

Novae

Hydrogen accreted through the accretion disk accumulates on the surface of the WD

⇒ Very hot, dense layer of non-fusing hydrogen on the WD surface

⇒ Explosive onset of H fusion

⇒ Nova explosion

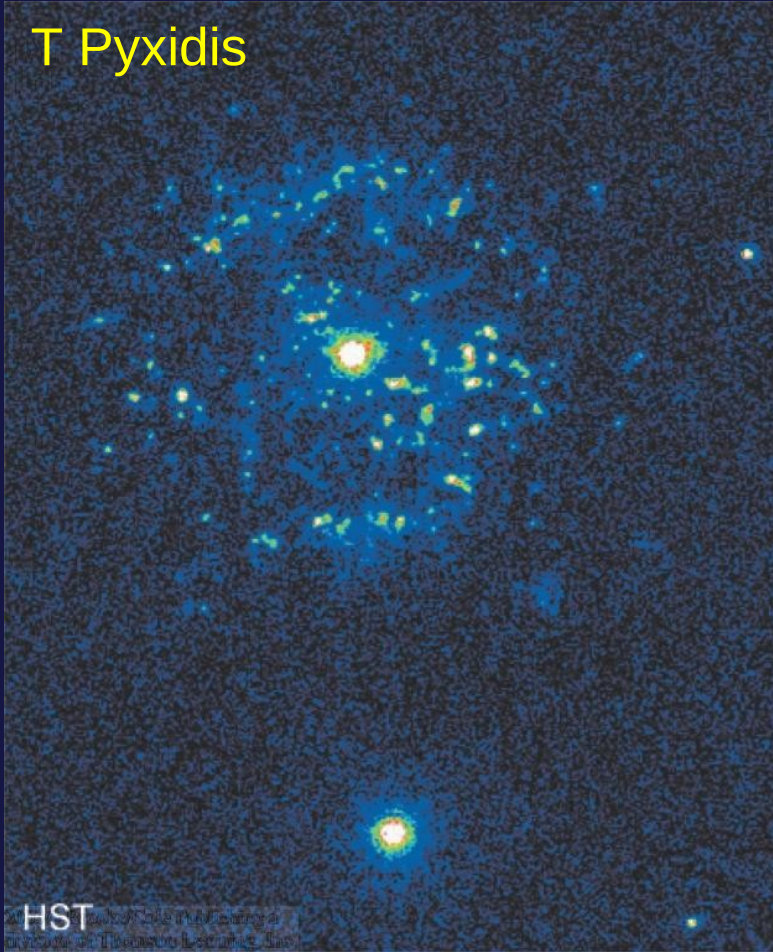
In many cases: Cycle of repeating explosions every few years – decades.



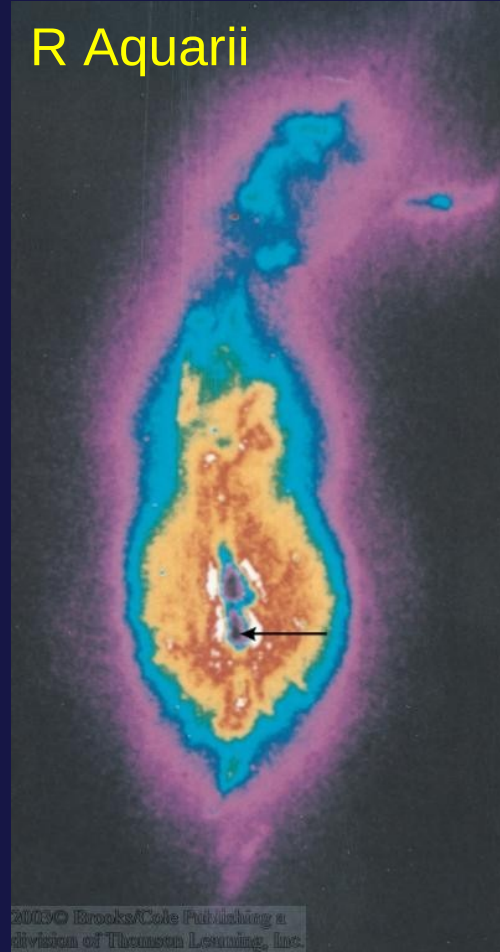
Nova Cygni 1975

Recurrent Novae

T Pyxidis



R Aquarii



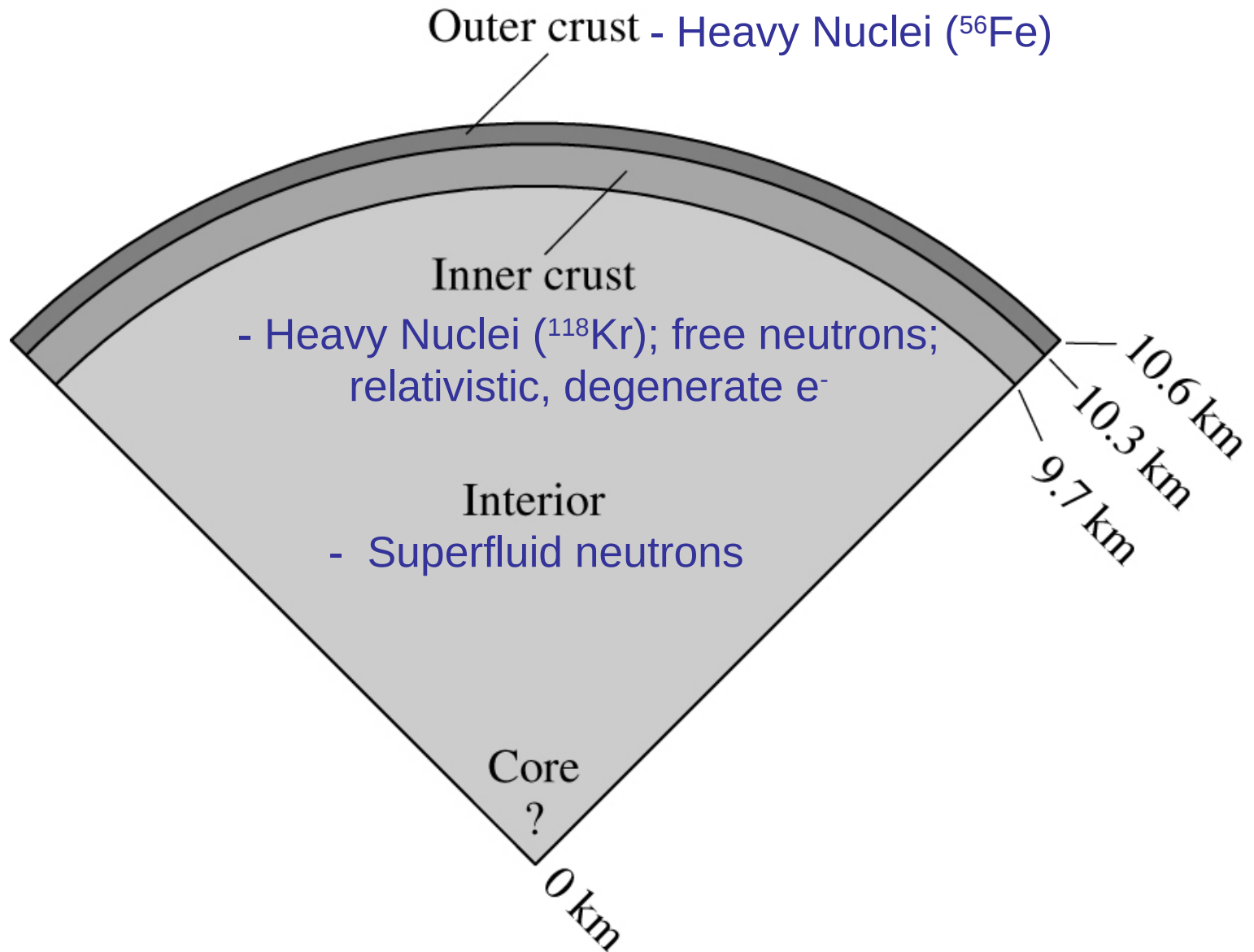
In many cases, the mass transfer cycle resumes after a nova explosion.

→ Cycle of repeating explosions every few years – decades.

Neutron Stars and Pulsars



Radial Structure of a Neutron Star



Properties of Neutron Stars

Typical size: $R \sim 10 \text{ km}$

Mass: $M \sim 1.4 - 3 M_{\text{sun}}$

Density: $\rho \sim 4 \times 10^{14} \text{ g/cm}^3$

→ **1 teaspoon** full of NS matter has a
mass of ~ 2 billion tons!!!

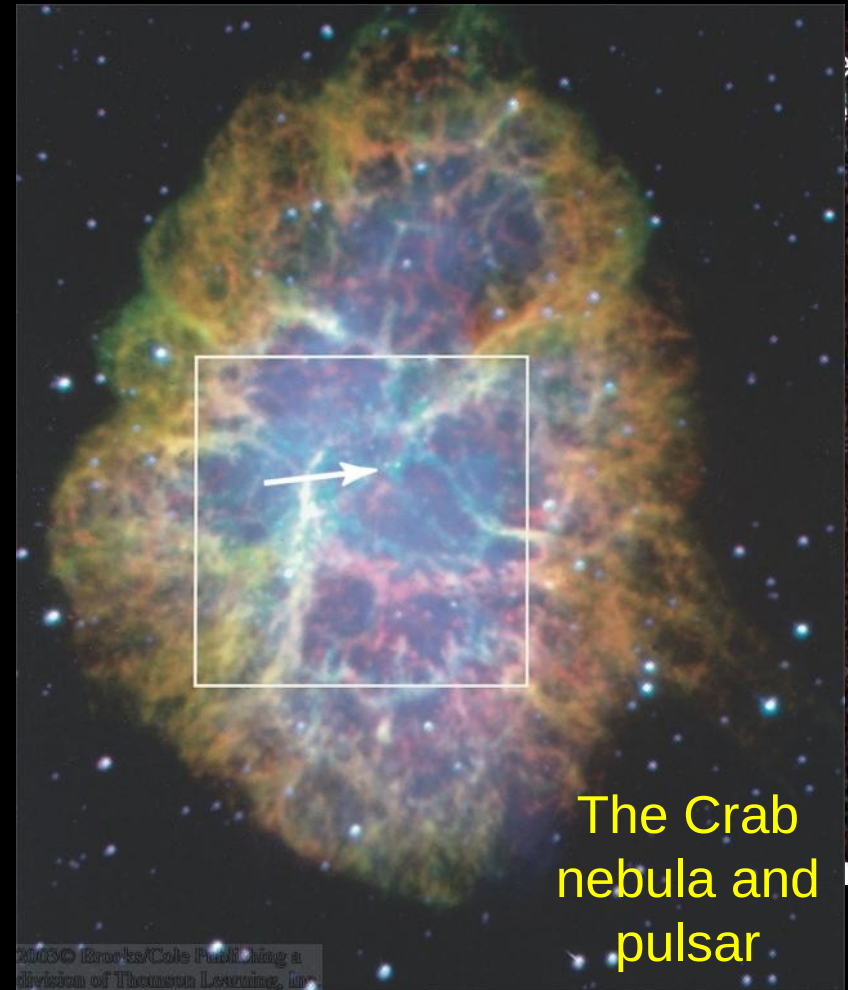
Rotation periods: ~ a few ms – a few s

Magnetic fields: $B \sim 10^8 - 10^{15} \text{ G}$

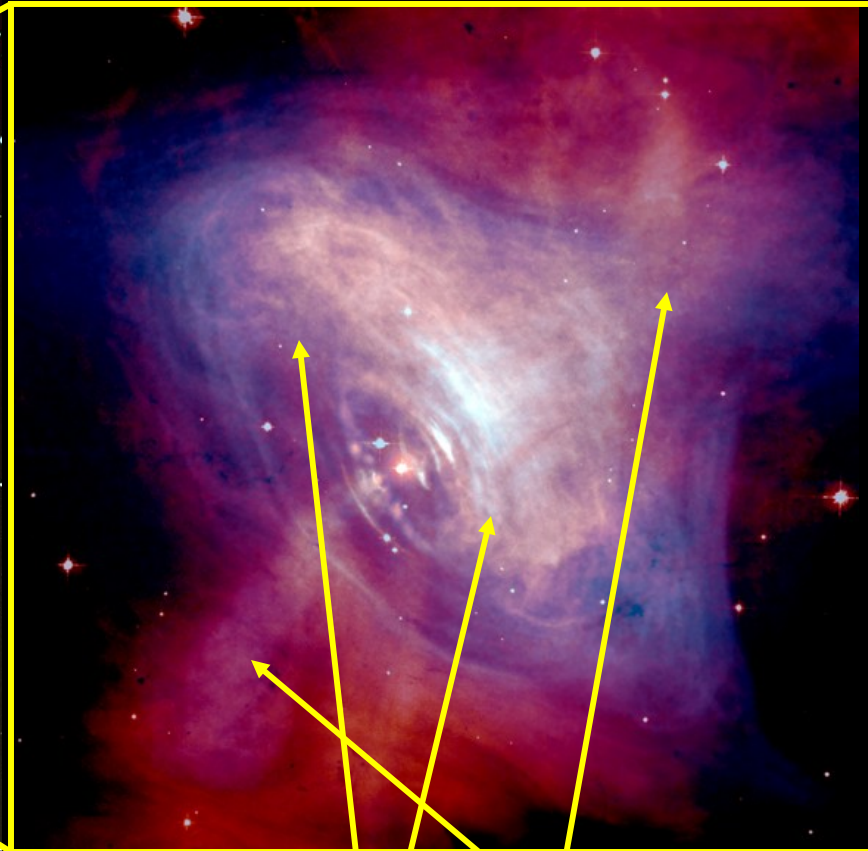
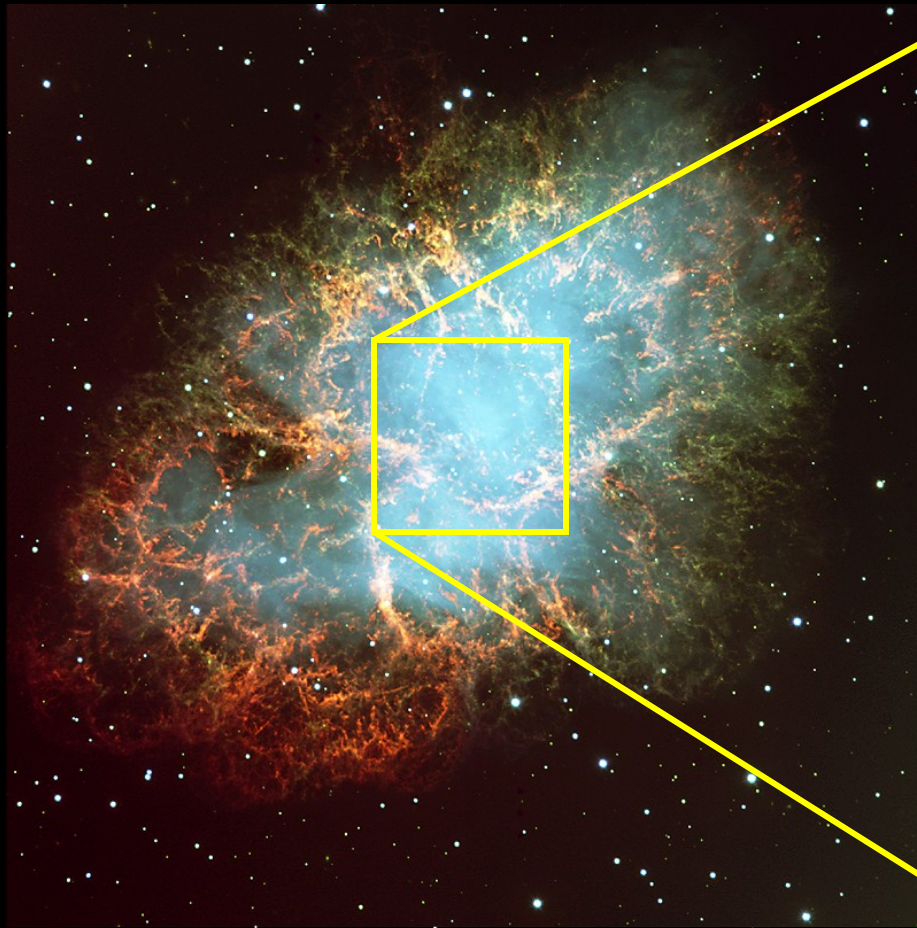
(millisecond
pulsars)

(magnetars)

Images of Pulsars and other Neutron Stars



The Crab Pulsar



Pulsar wind + jets

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

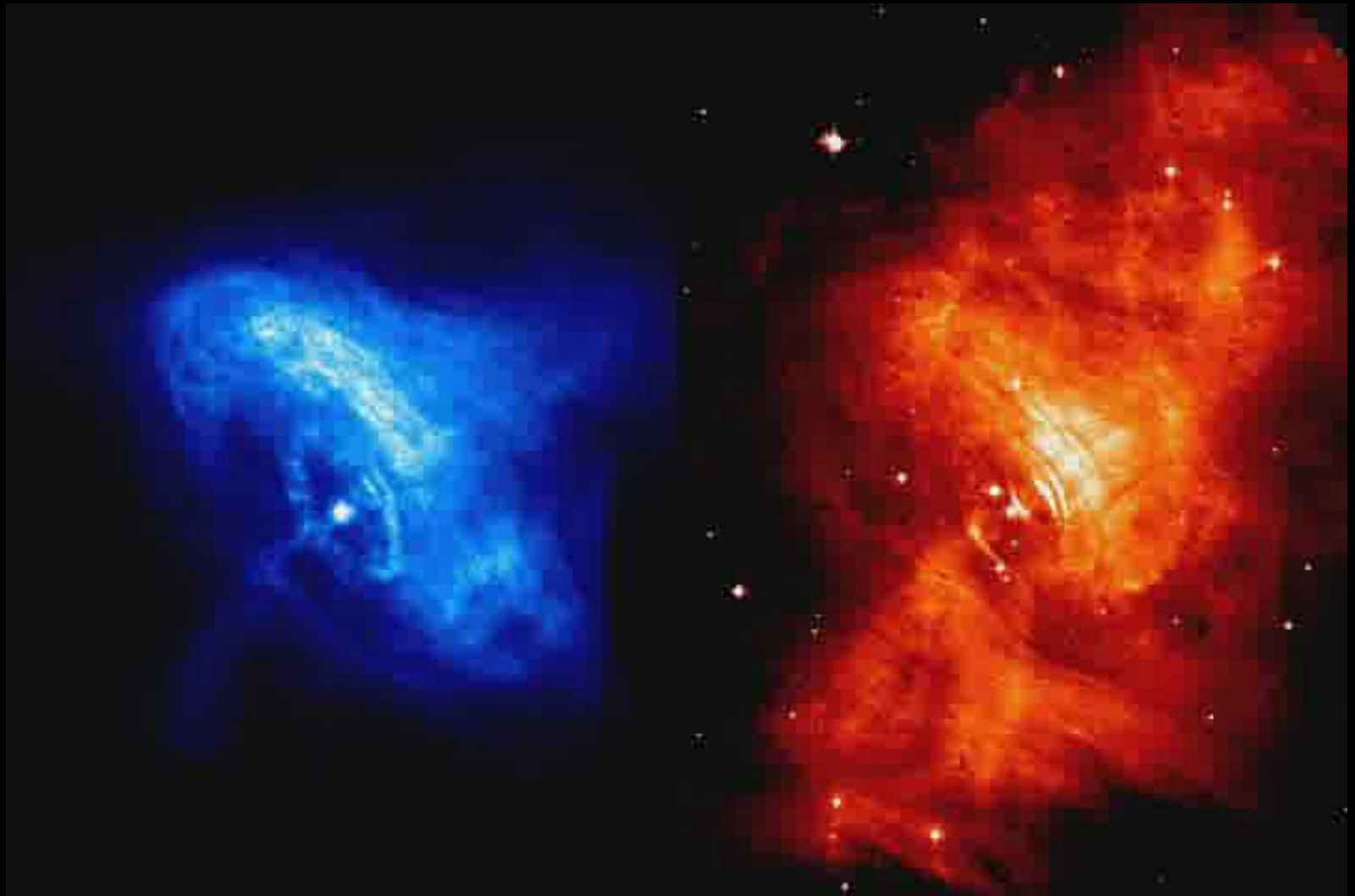
ESO PR Photo 40f/99 (17 November 1999)

© European Southern Observatory



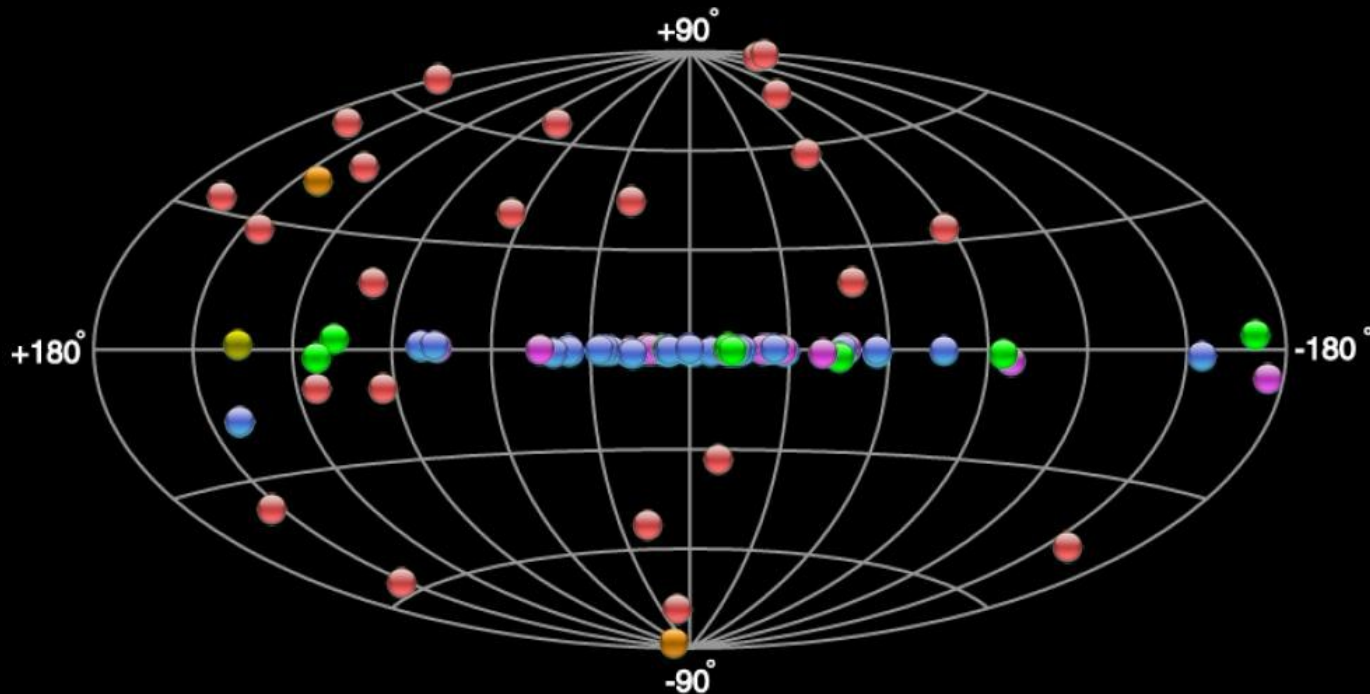
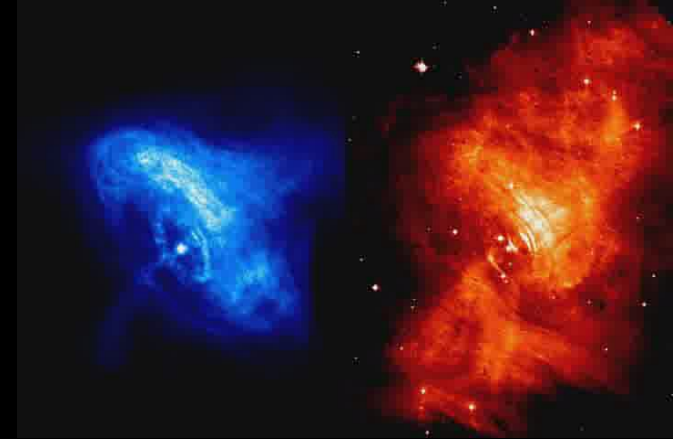
Remnant of a supernova observed in A.D. 1054

The Crab Pulsar and Pulsar-Wind Nebula

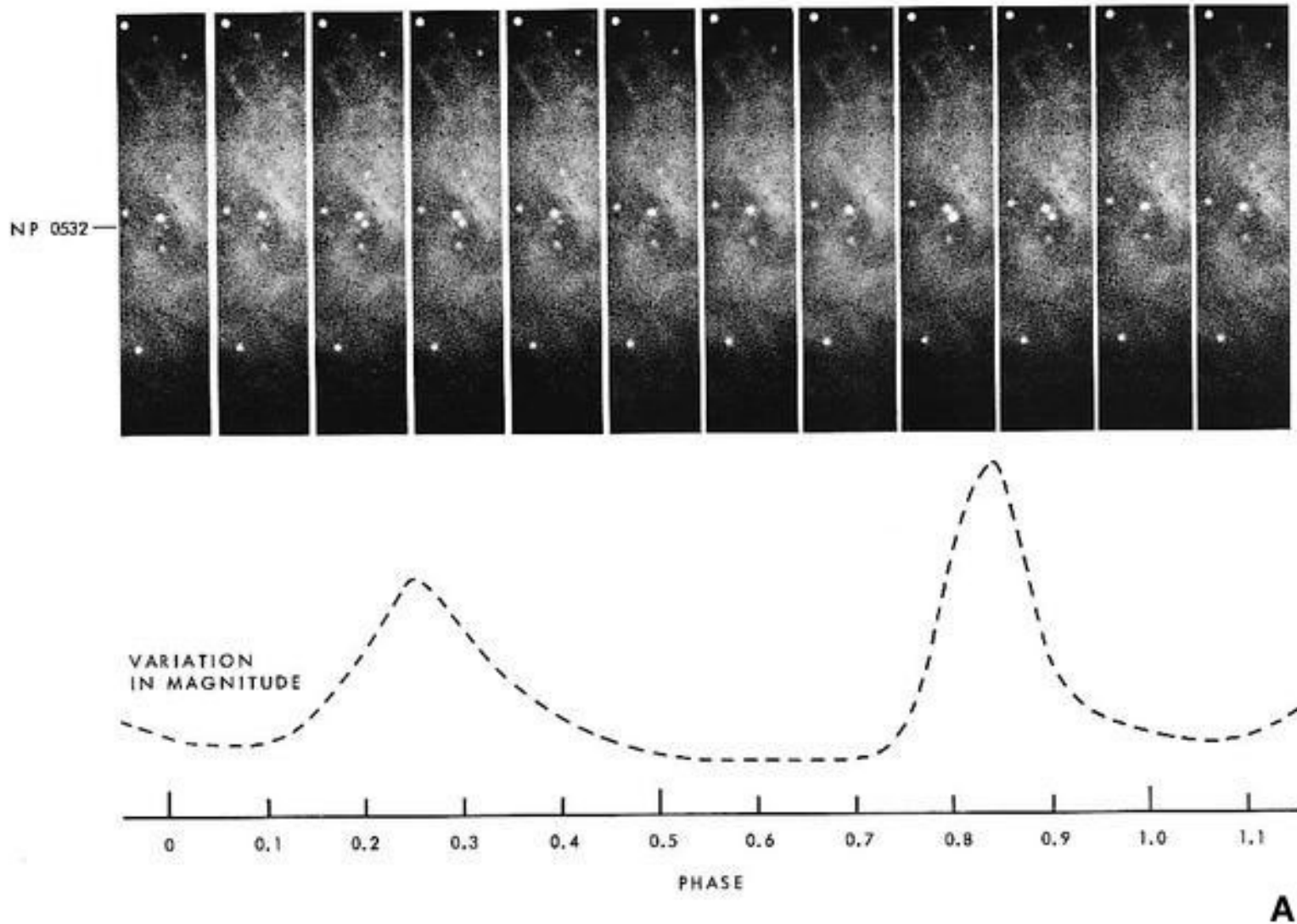


Pulsar Wind Nebulae

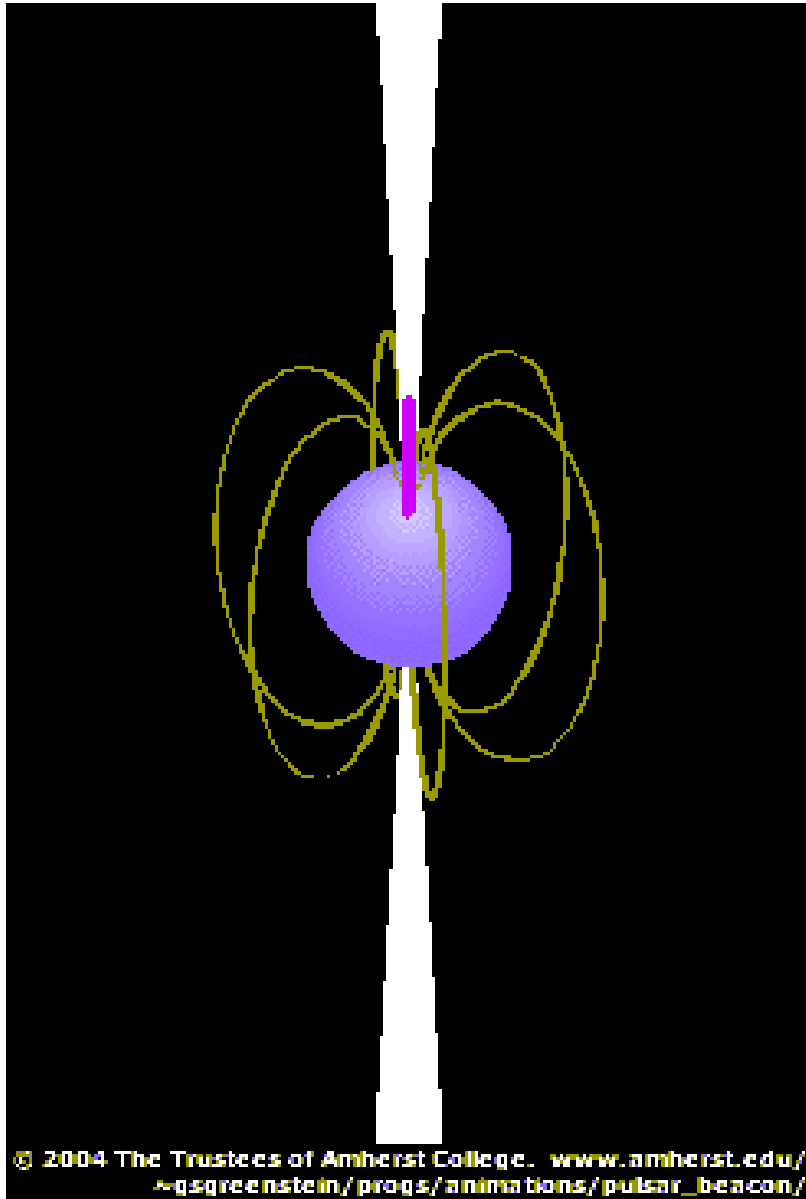
- Relativistic Wind from the Pulsar interacting with its environment
- Most numerous class of VHE gamma-ray sources in our Galaxy



The Discovery of Pulsars



The Lighthouse Model of Pulsars



A Pulsar's magnetic field has a dipole structure, just like Earth.

Radiation is emitted mostly along the magnetic poles.

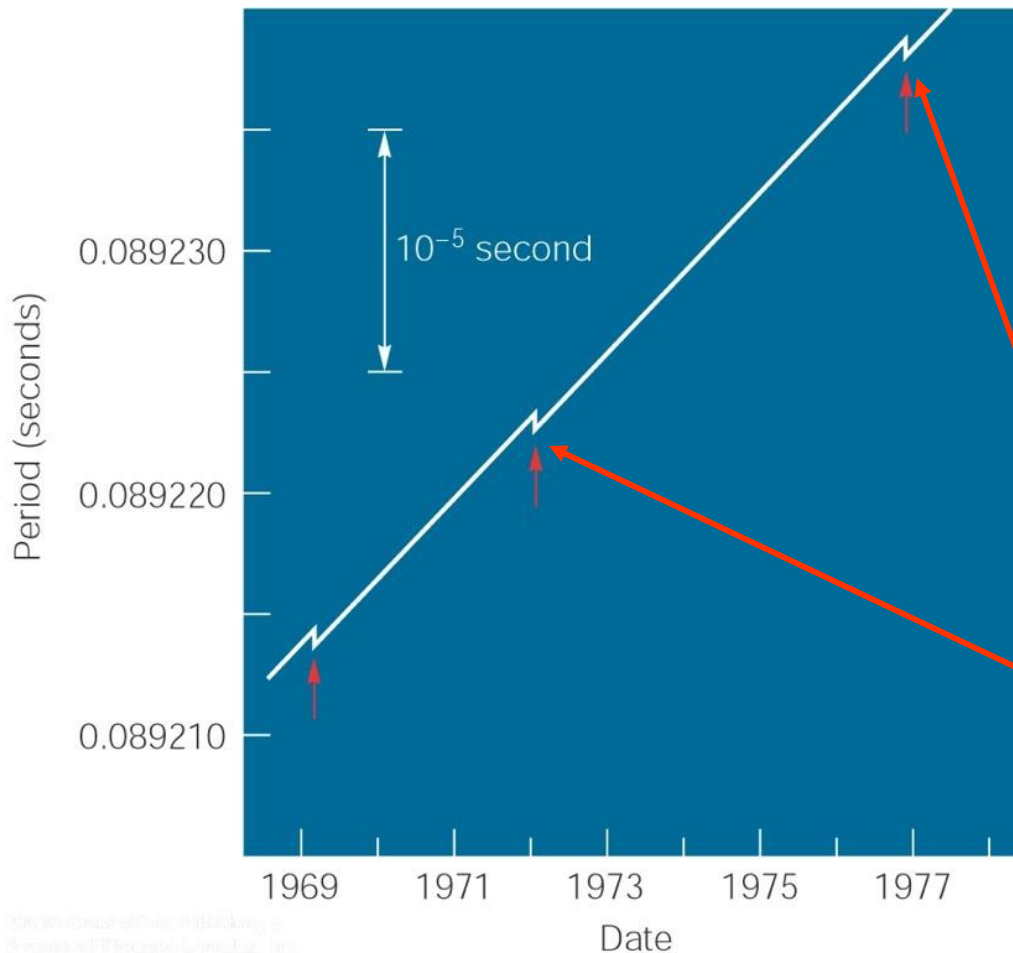
Rapid rotation along axis not aligned with magnetic field axis

→ Light house model of pulsars

Pulses are not perfectly regular

→ gradual build-up of average pulse profiles

Pulsar periods



Over time, pulsars lose energy and angular momentum

=> Pulsar rotation is gradually slowing down.

$$dP/dt \sim 10^{-15}$$

Pulsar Glitches:

$$\Delta P/P \sim 10^{-7} - 10^{-8}$$

Energy Loss of Pulsars

From the gradual spin-down of pulsars:

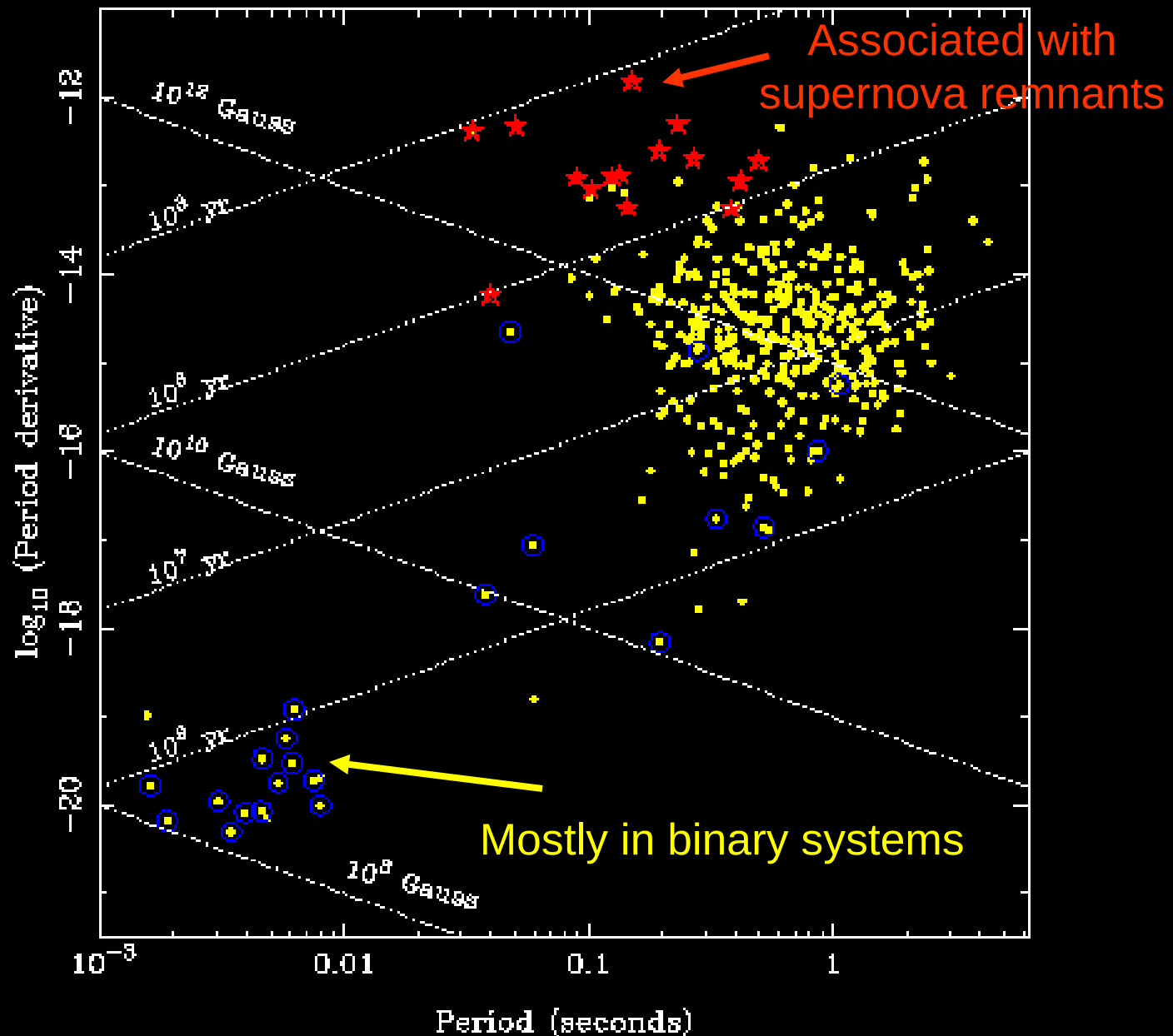
$$dE/dt = \frac{d}{dt} \left(\frac{1}{2} I \omega^2 \right) = I \omega \dot{\omega} = - \frac{2}{3} \mu_{\perp}^2 \omega^4 c^{-3}$$

$$\mu_{\perp} \sim B_0 r \sin \alpha$$

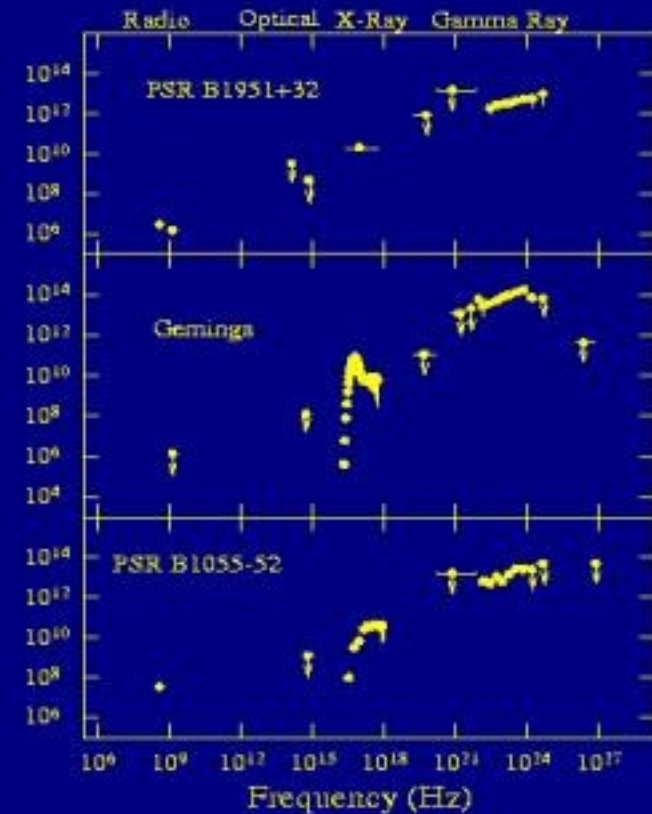
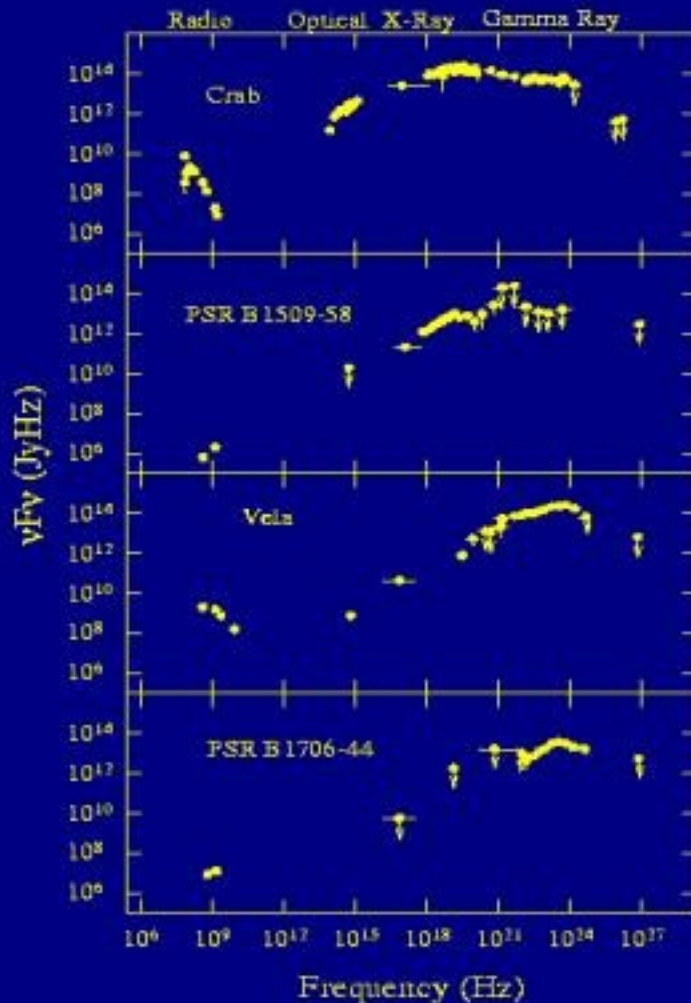
One can estimate the magnetic field of a pulsar as

$$B_0 \approx 3 \times 10^{19} \sqrt{\dot{P} P} \text{ G}$$

Pulsar periods and derivatives



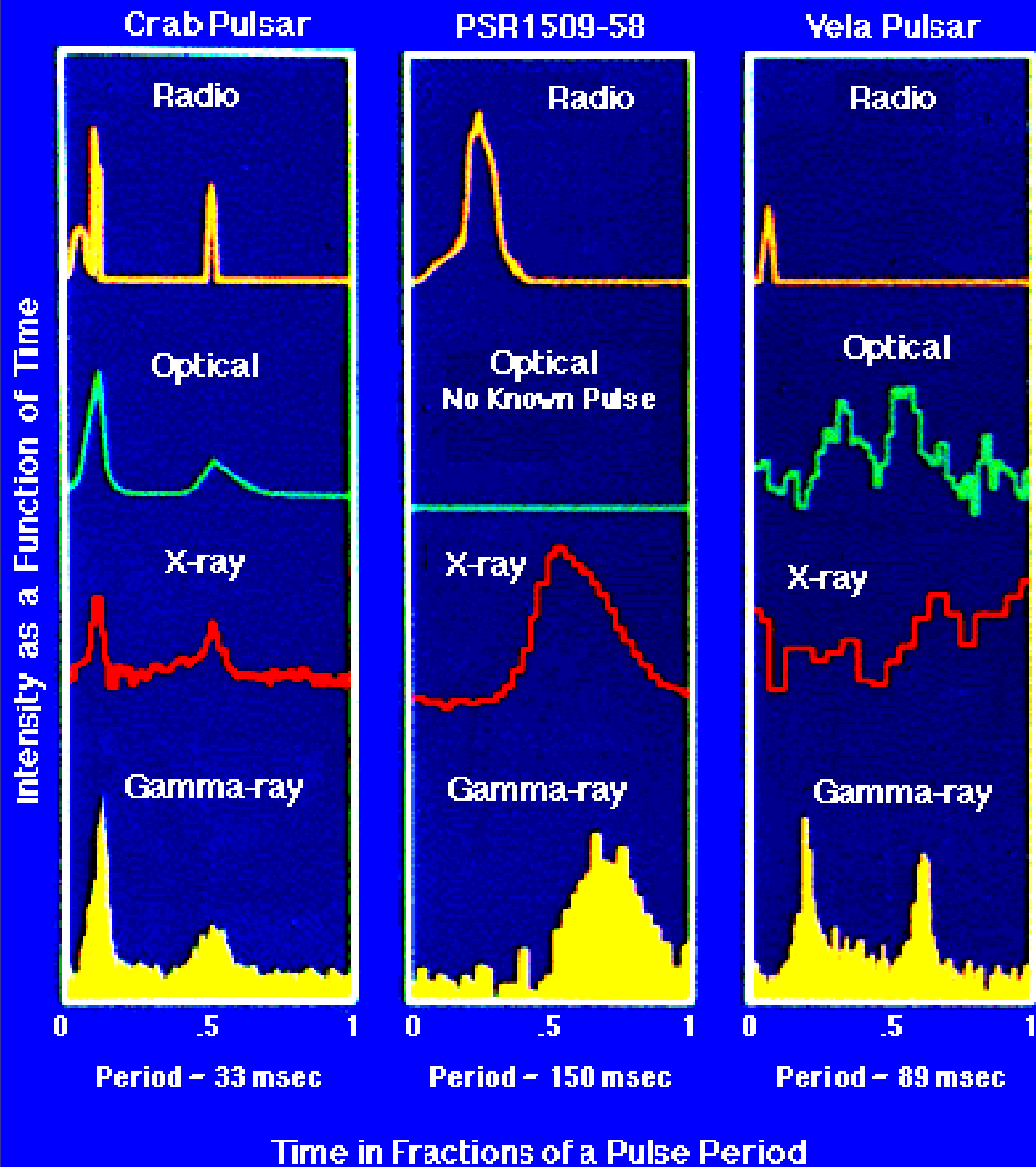
γ -Ray Pulsars



Multiwavelength Energy Spectra
of Pulsars

(Summary from Thompson, 1996)

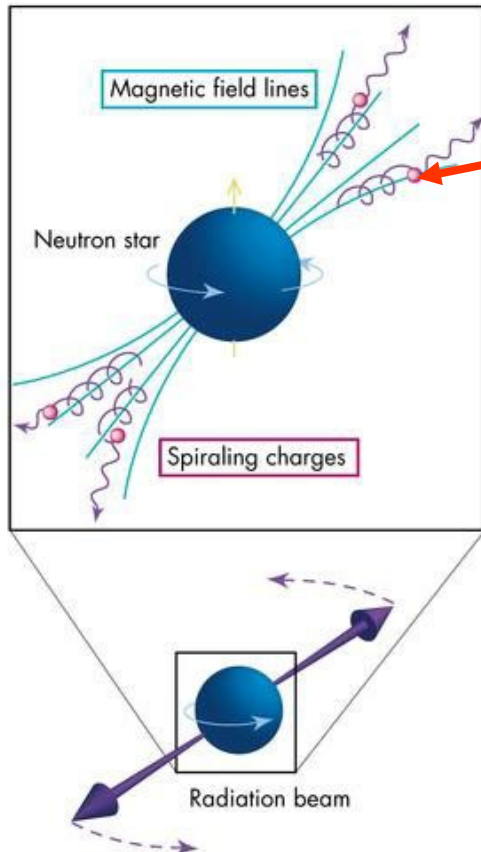
- Detected pulsars have highest $\dot{E} = I \cdot \Omega \cdot \dot{\Omega}$!



Pulsar Emission Models

Particles can be accelerated to ultrahigh energies in two regions in pulsar magnetospheres:

A) Polar Cap Models



Particle acceleration along the extremely strong magnetic field lines (close to the surface) near the polar cap

Synchrotron emission

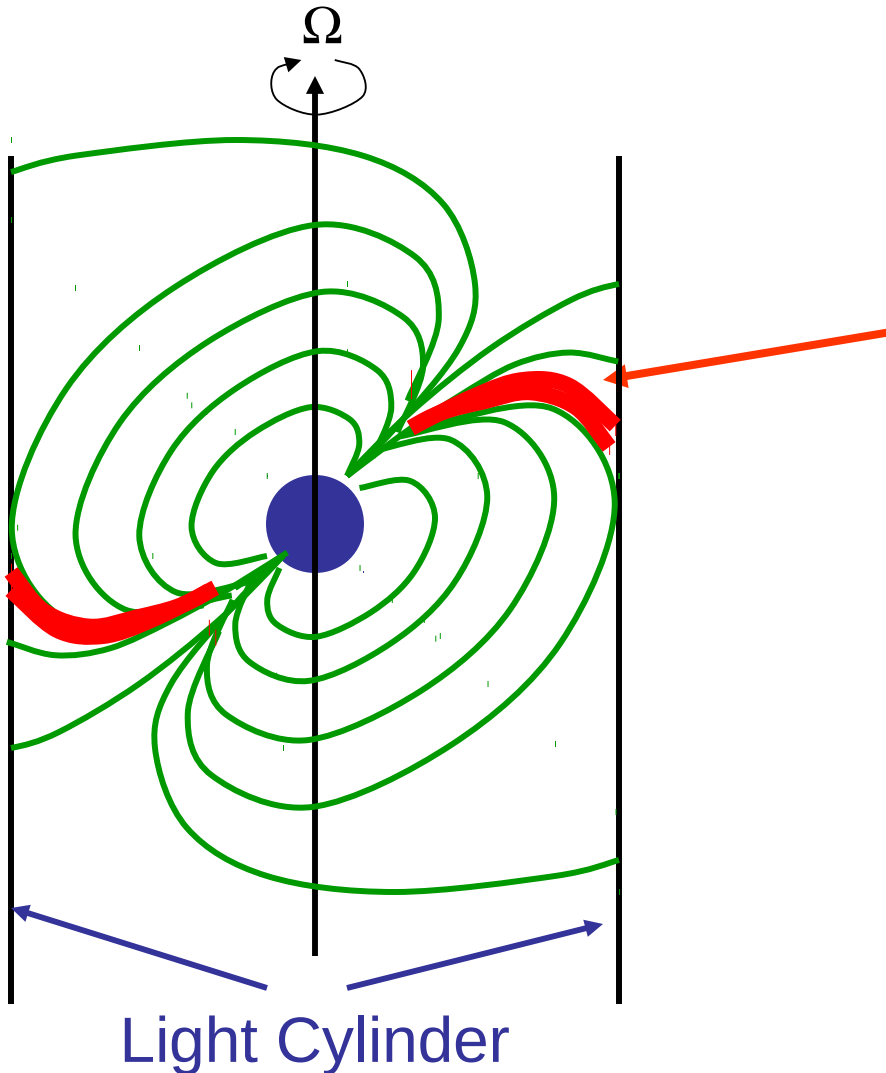
Curvature radiation

Pair production

Electromagnetic cascades

Pulsar Emission Models (cont.)

B) Outer Gap Models



Particles follow magnetic field lines almost out to the light cylinder

=> Acceleration to ultrarelativistic energies

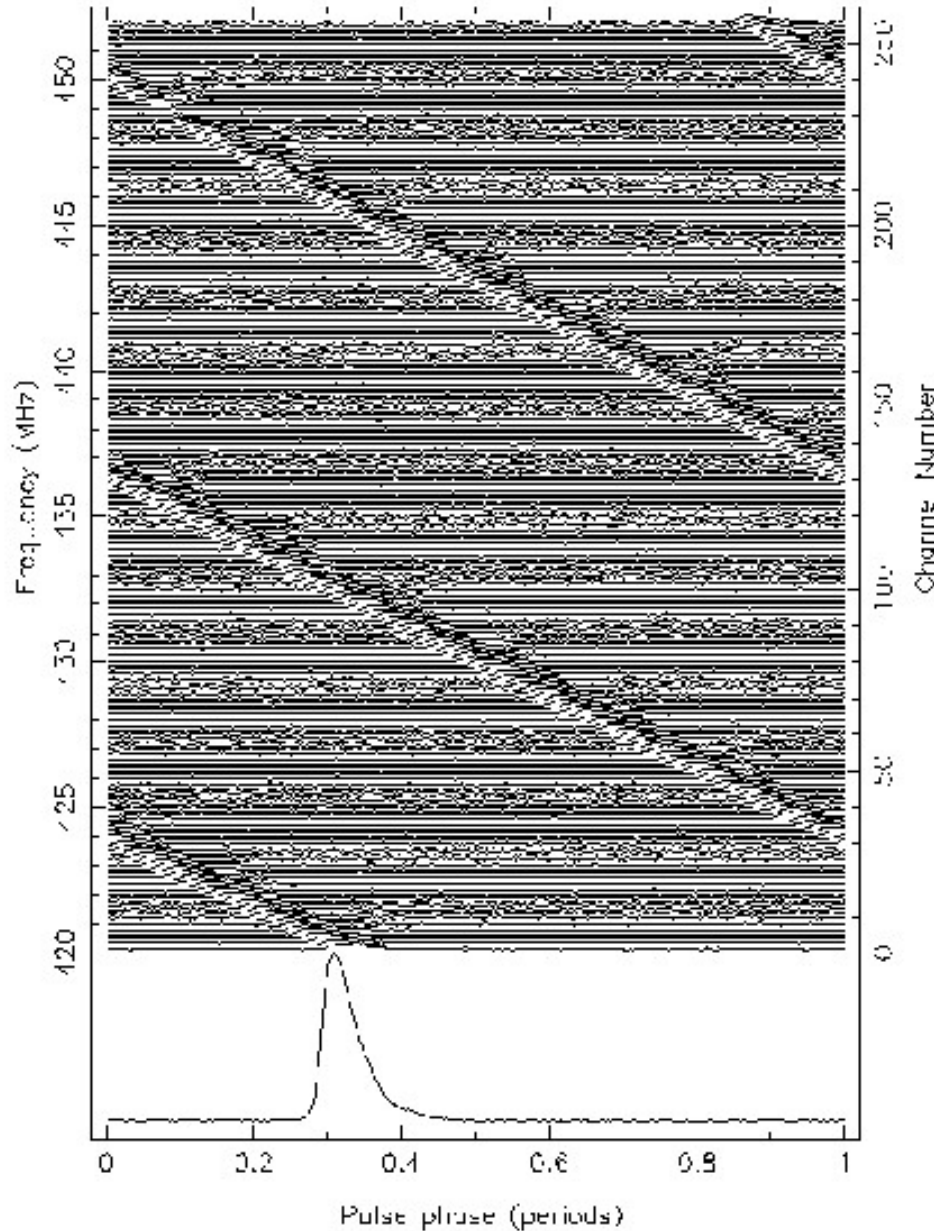
Synchrotron emission

Curvature radiation

Pair production

Electromagnetic cascades

Dispersion of Pulsar Signals



$$\delta t = (4\pi e^2 / m_e c \omega_1^3) \delta \omega \text{ DM}$$

$$\text{DM} = \int_0^d n_e(s) ds$$

DM = Dispersion Measure