Astrophysics I: Stars and Stellar Evolution

AST 4001

Alexander Heger[1,2,3]

[1]School of Physics and Astronomy
University of Minnesota

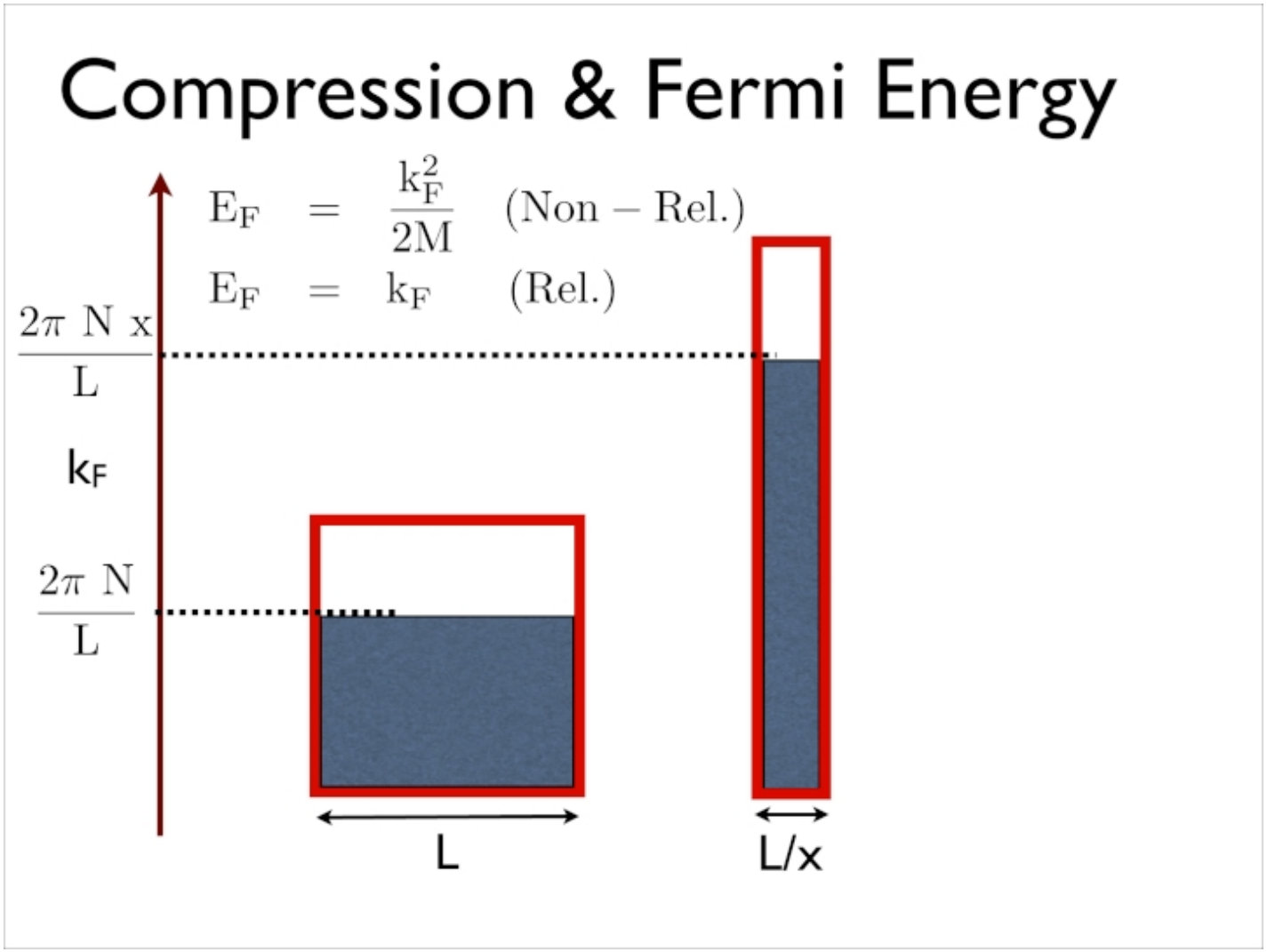
[2]Nuclear & Particle Physics, Astrophysics & Cosmology Group, T-2
Los Alamos National Laboratory

[3]Department of Astronomy and Astrophysics
University of California at Santa Cruz

Stars and Stellar Evolution, Fall 2008

Overview

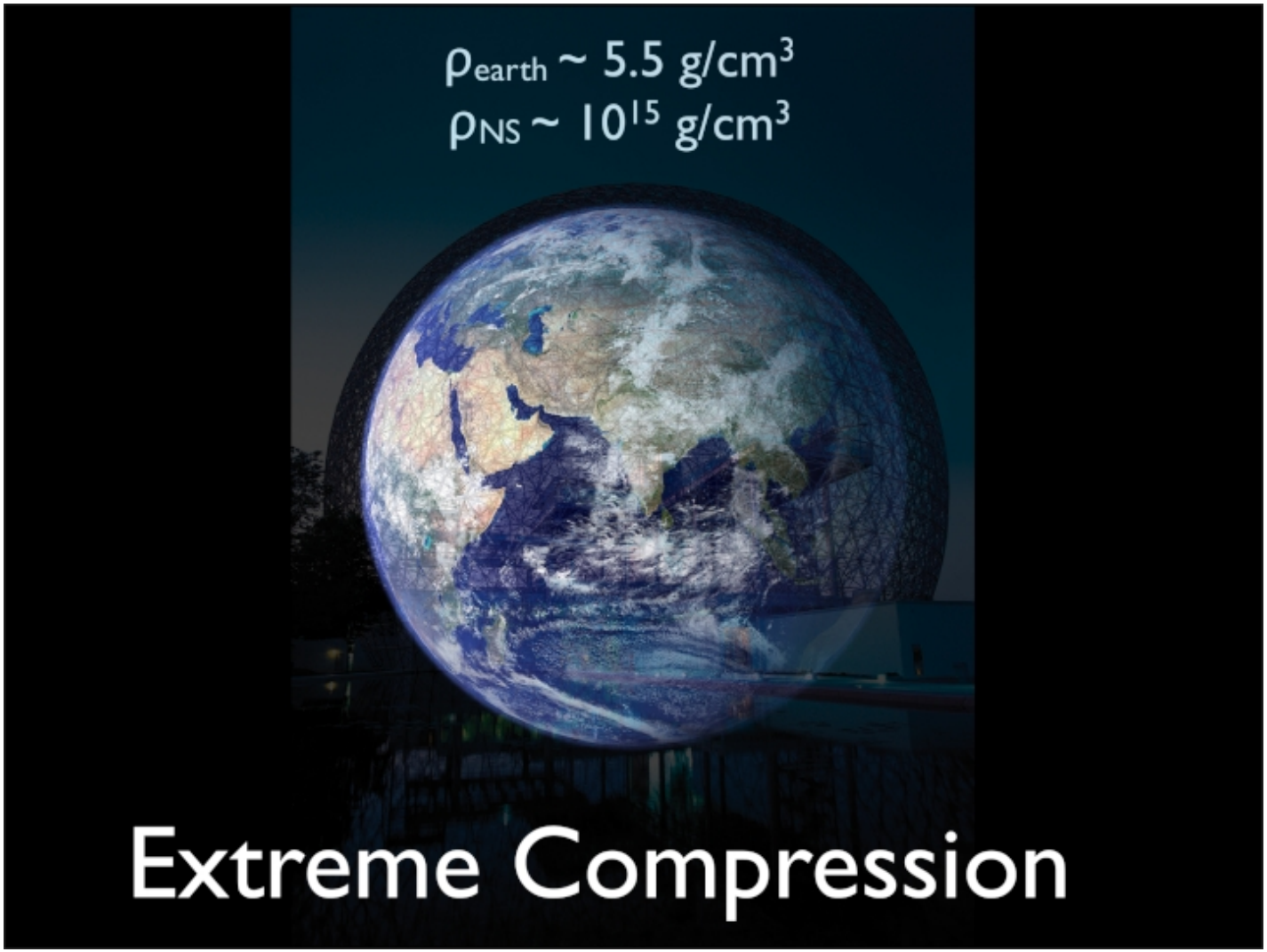
Fermi Energy & Compression



Overview

Extereme Compression

Extereme Compression



Overview - Comparison of Compact Remnants

Distinguishing Traits of Compact Objects

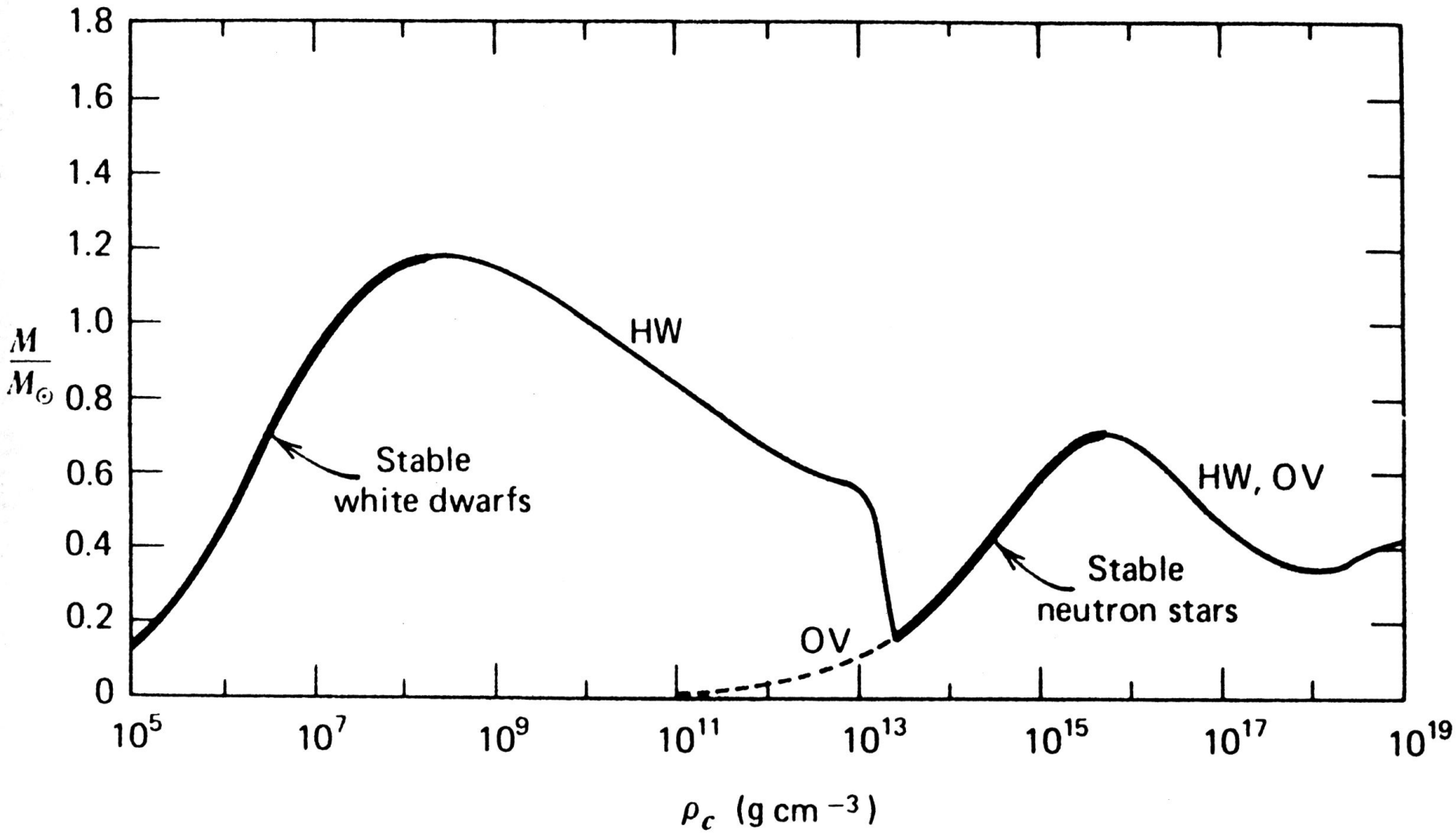
Object	Mass[a] (M)	Radius[b] (R)	Mean Density (g cm^{-3})	Surface Potential (GM/Rc^2)
Sun	$M_\odot$	$R_\odot$	1	10^{-6}
White dwarf	$\lesssim M_\odot$	$\sim 10^{-2} R_\odot$	$\lesssim 10^{7}$	$\sim 10^{-4}$
Neutron star	~ 1–$3 M_\odot$	$\sim 10^{-5} R_\odot$	$\lesssim 10^{15}$	$\sim 10^{-1}$
Black hole	Arbitrary	$2GM/c^2$	$\sim M/R^3$	~ 1

[a] $M_\odot = 1.989 \times 10^{33}$ g
[b] $R_\odot = 6.9599 \times 10^{10}$ cm

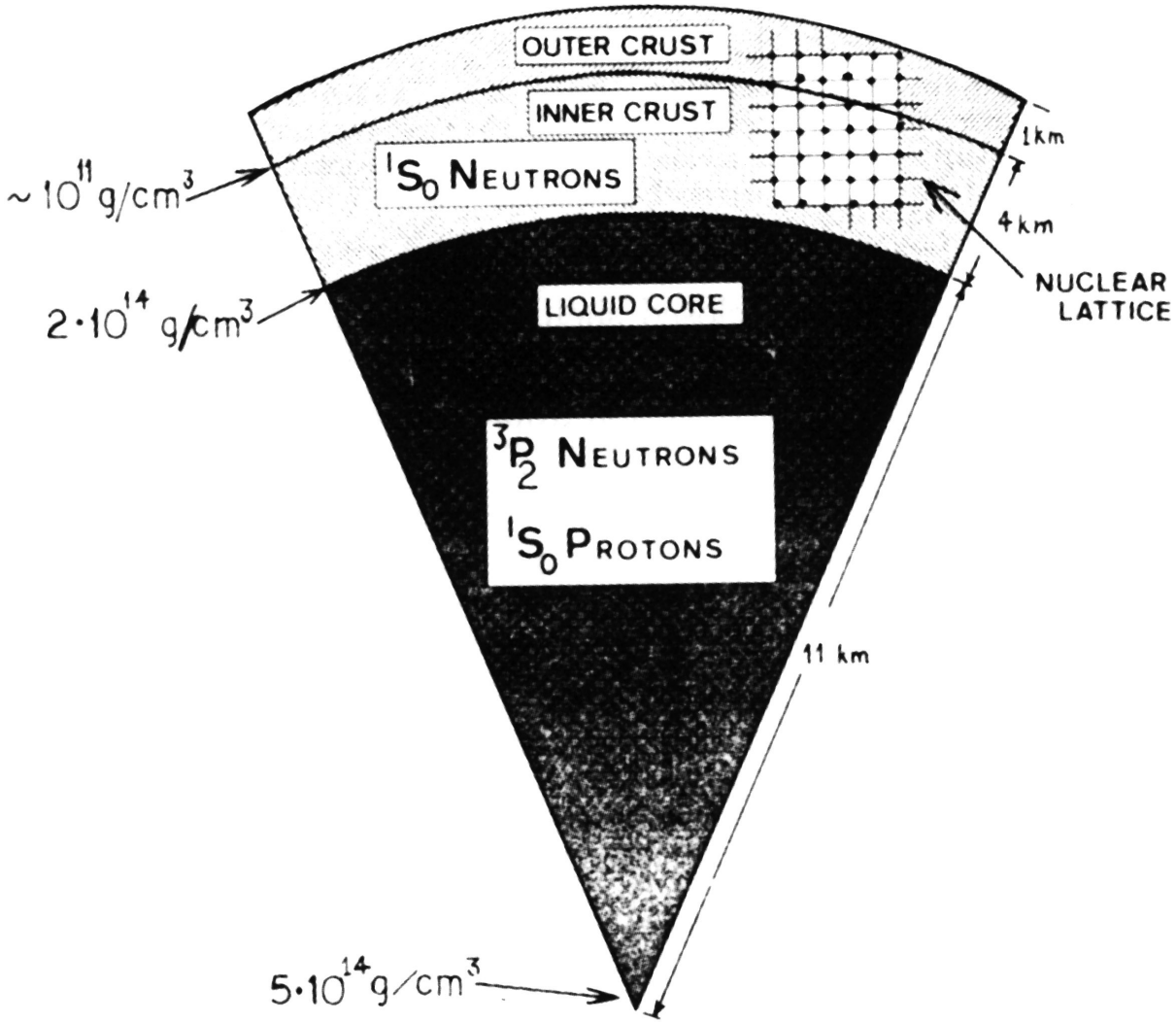
Compression Phenomena

Density	Fermi Energy	Phenomena
10^3 - 10^6 g/cm^3	Electron Fermi Enery μ_e= 10 keV– MeV	Ionization
10^6 - 10^{11} g/cm^3	Electron Fermi Energy μ_e= 1–25 MeV	Neutron-rich Nuclei $e+p \rightarrow n+\nu_e$
10^{11} - 10^{14} g/cm^3	Neutron Fermi Energy μ_n= 1–30 MeV	Neutron-drip
10^{14} - 10^{15} g/cm^3	Neutron Fermi Energy μ_n=30–1000 MeV	Nuclear matter Hyperons or Quarks ?

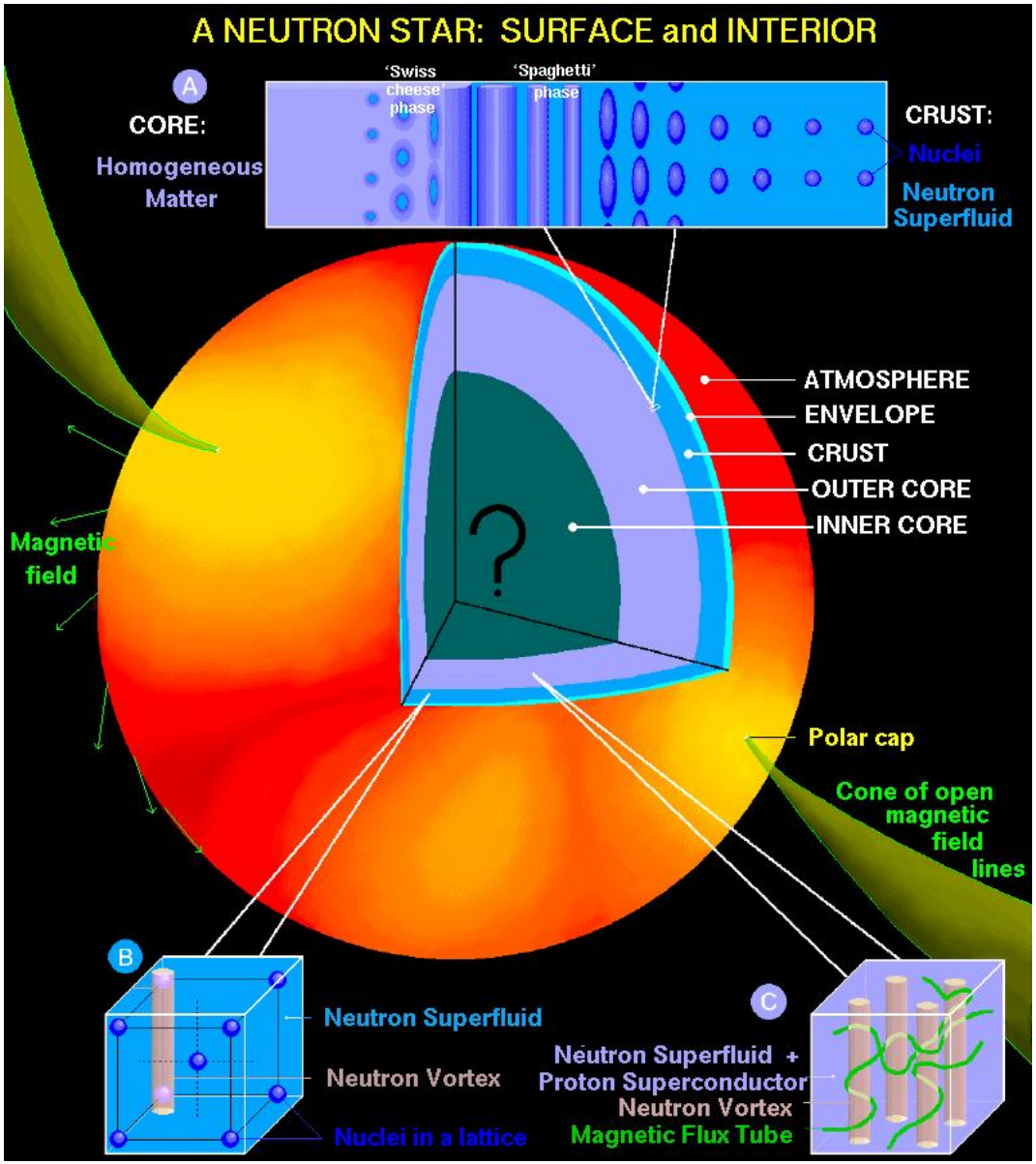
Neutron Stars and White Dwarf Mass-Radius Relations



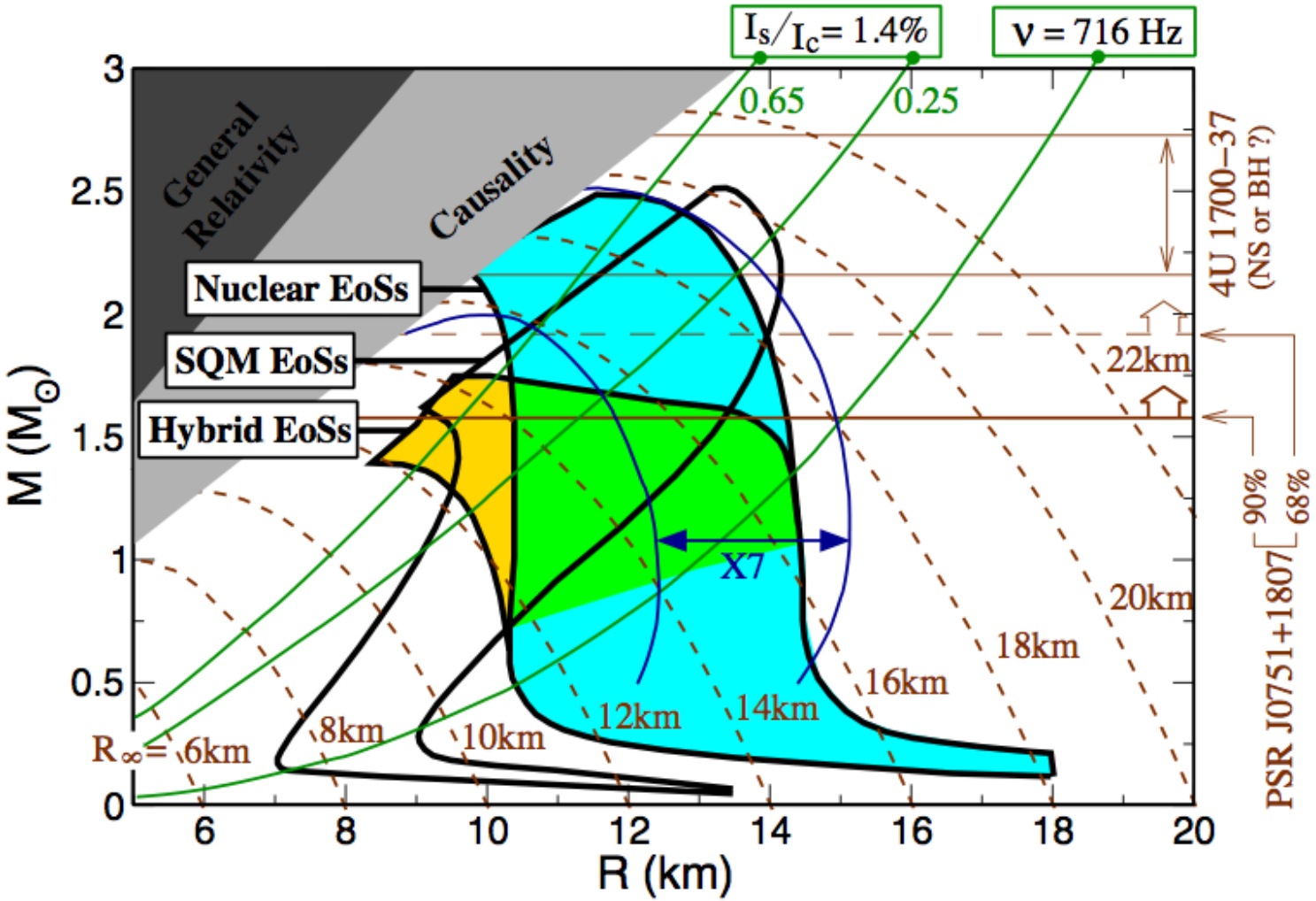
Neutron Star Structure



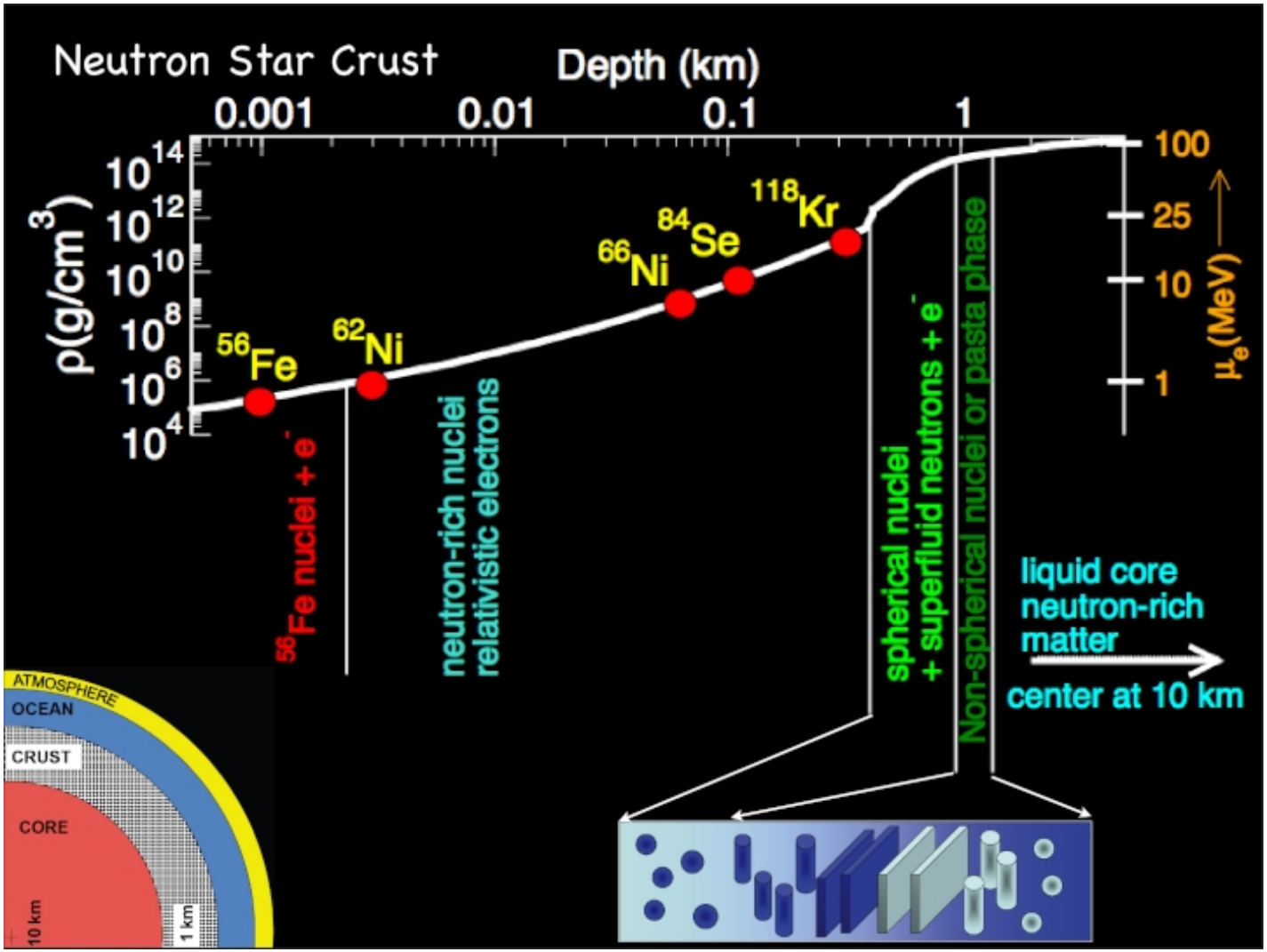
Neutron Star Structure



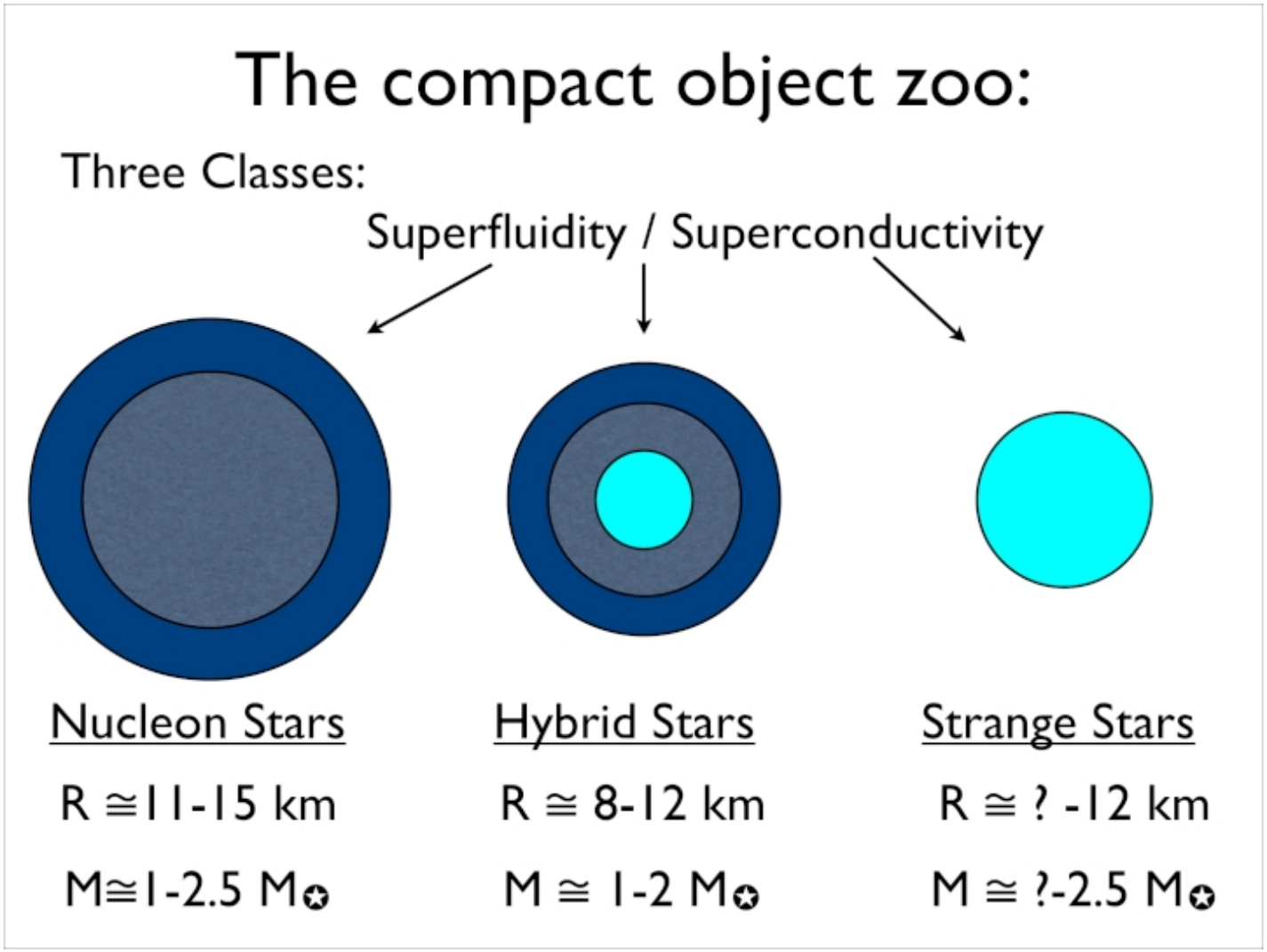
Neutron Star Equation(s) of State



Neutron Stars



Neutron Stars



Neutron Stars

- end point of evolution of (some) massive stars
- remain after supernova
- masses are $\sim 1.2 \ldots 2 M_\odot$, radii around 10 km
- maximum mass determined by uncertain neutron star and nuclear equation of state
- minimum mass determined by stellar evolution
- rotating neutron stars with magnetic fields appear as pulsars

Neutron Star Mass Determination in Binaries

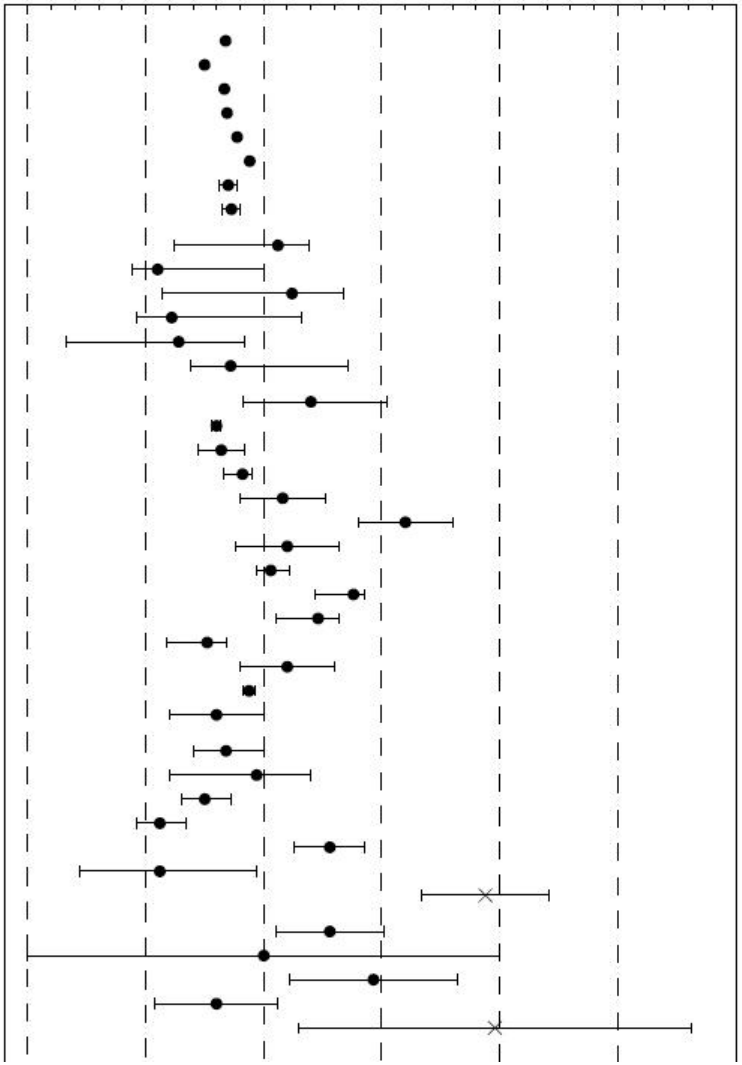
- assume system with two stars of masses M_1 and M_2, velocities v_1 and v_2, distances from center of mass a_1 and a_2
- doppler shift due to orbital motion if seen at inclination angle i is

$$v_1 = \frac{2\pi}{P} a_1 \sin i$$

- mass function

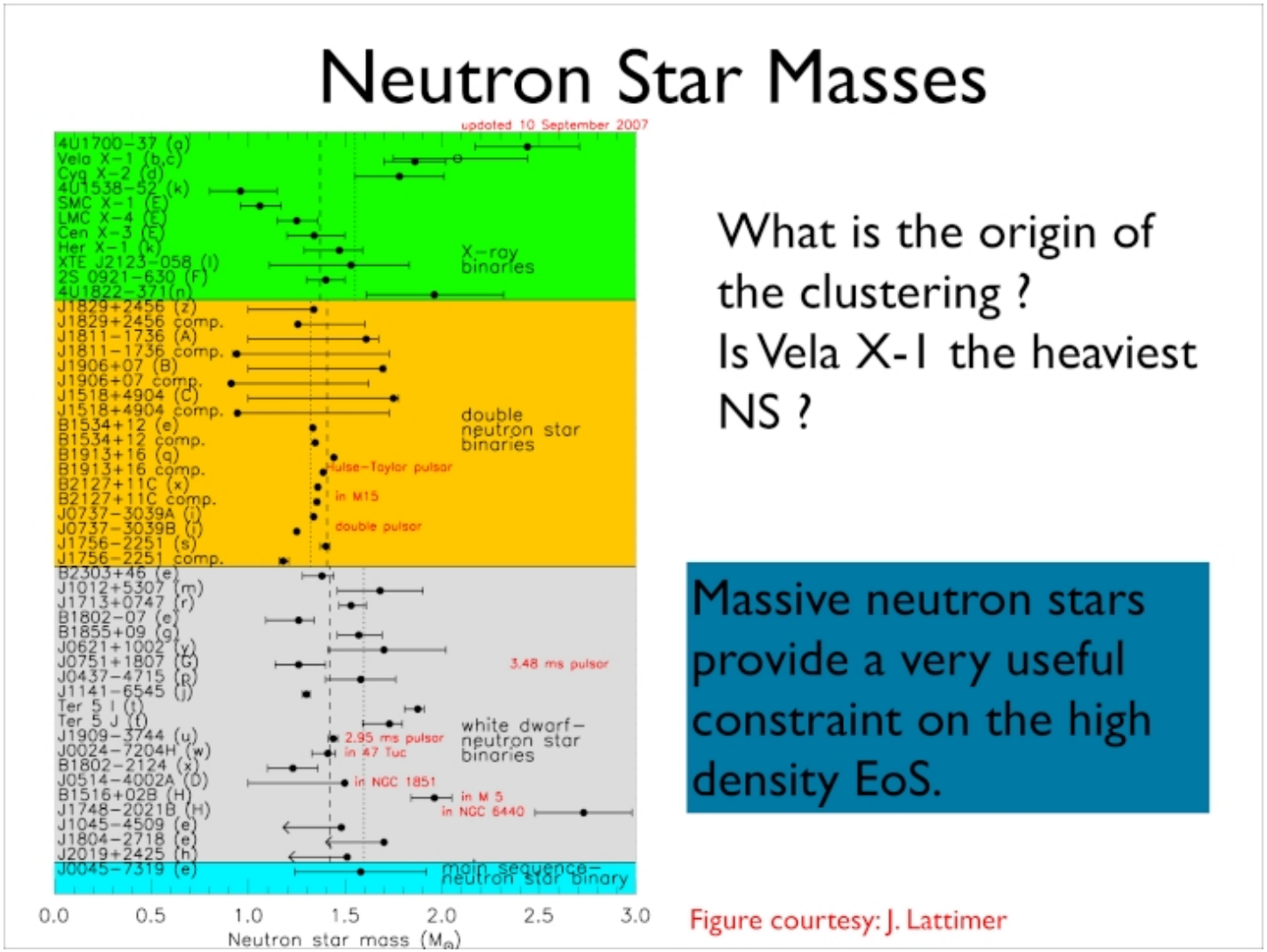
$$f(M_1, M_2, i) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P\, v_1}{2\pi G}$$

Neutron Stars Masses



PSR J0737−3039A	PSR+NS
PSR J0737−3039B	
PSR B1534+12	
PSR B1534+12 comp	
PSR B1913+16	
PSR B1913+16 comp	
PSR B2127+11C	
PSR B2127+11C comp	
PSR J1518+4904	
PSR J1518+4904 comp (?)	
PSR J1811−1736	
PSR J1811−1736 comp (?)	
PSR J1829+2456	
PSR J1829+2456 comp (?)	
PSR J0621+1002	PSR+WD
PSR J1141−6545	
PSR B2303+46	
PSR J0024−7204H	
PSR J0437−4715	
PSR J0751+1807	
PSR J1012+5307	
PSR J1713+0747	
PSR J1748−2446I	
PSR J1748−2446J	
PSR B1802−07	
PSR B1855+09	
PSR J1909−3744	
PSR J2019+2425	
Cen X−3	HMXB
Her X−1	
LMC X−4	
SMC X−1	
Vela X−1	
4U 1538−52	
4U 1700−37	
Cyg X−2	LMXB
Cen X−4	
X1822−371	
XTE J2123−058	
2S 0921−630	

Neutron Stars Masses

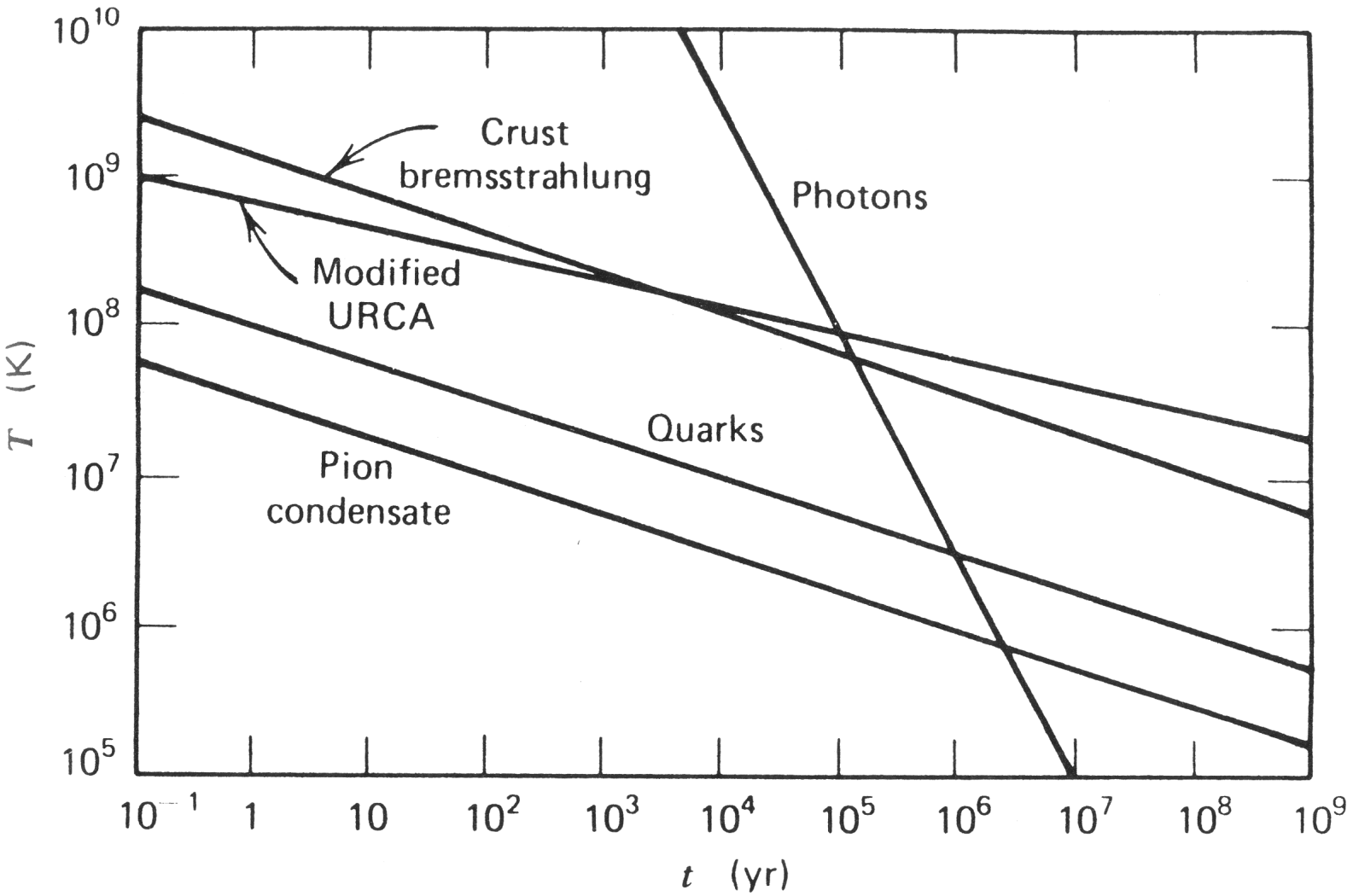


What is the origin of the clustering ?
Is Vela X-1 the heaviest NS ?

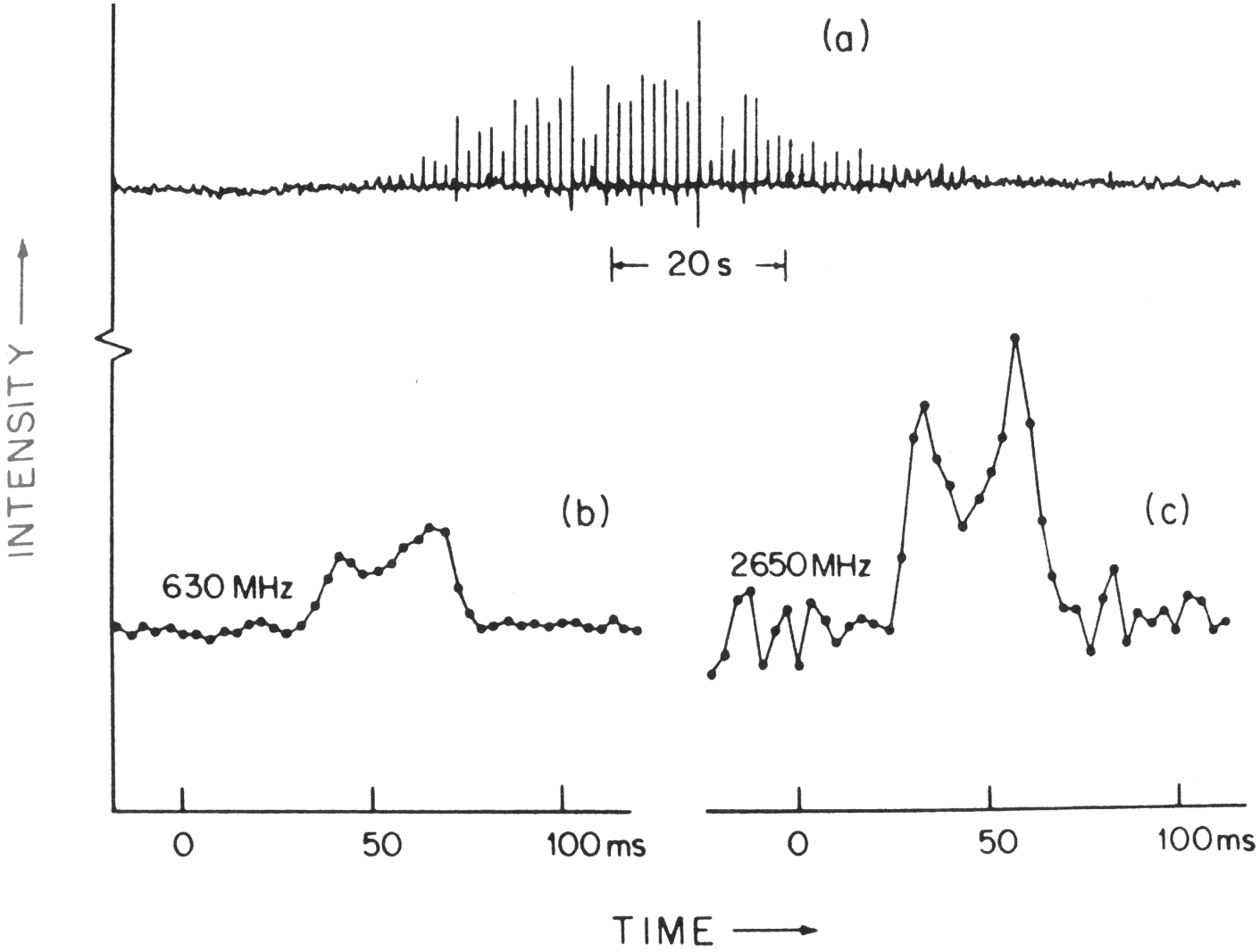
Massive neutron stars provide a very useful constraint on the high density EoS.

Figure courtesy: J. Lattimer

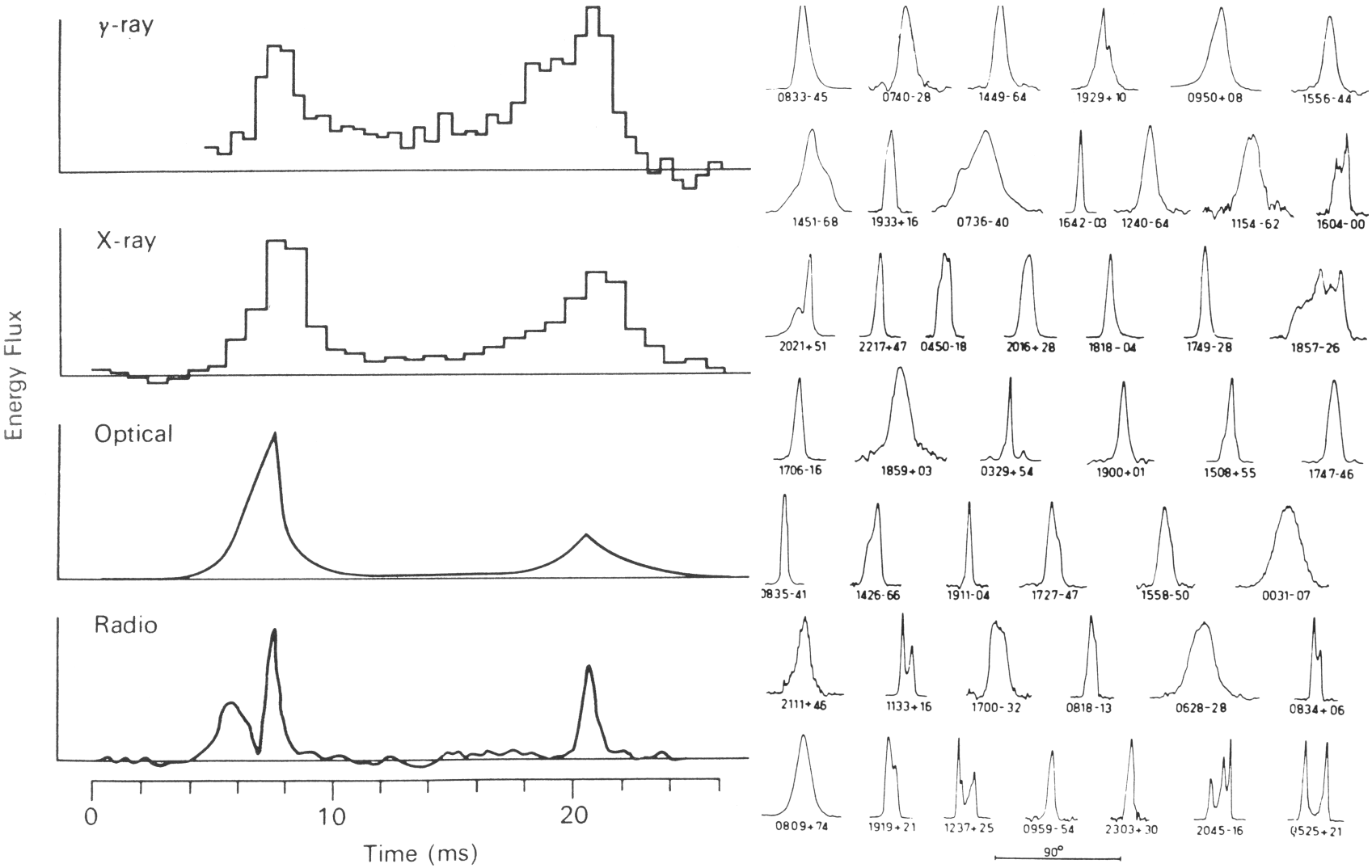
Neutron Stars Cooling



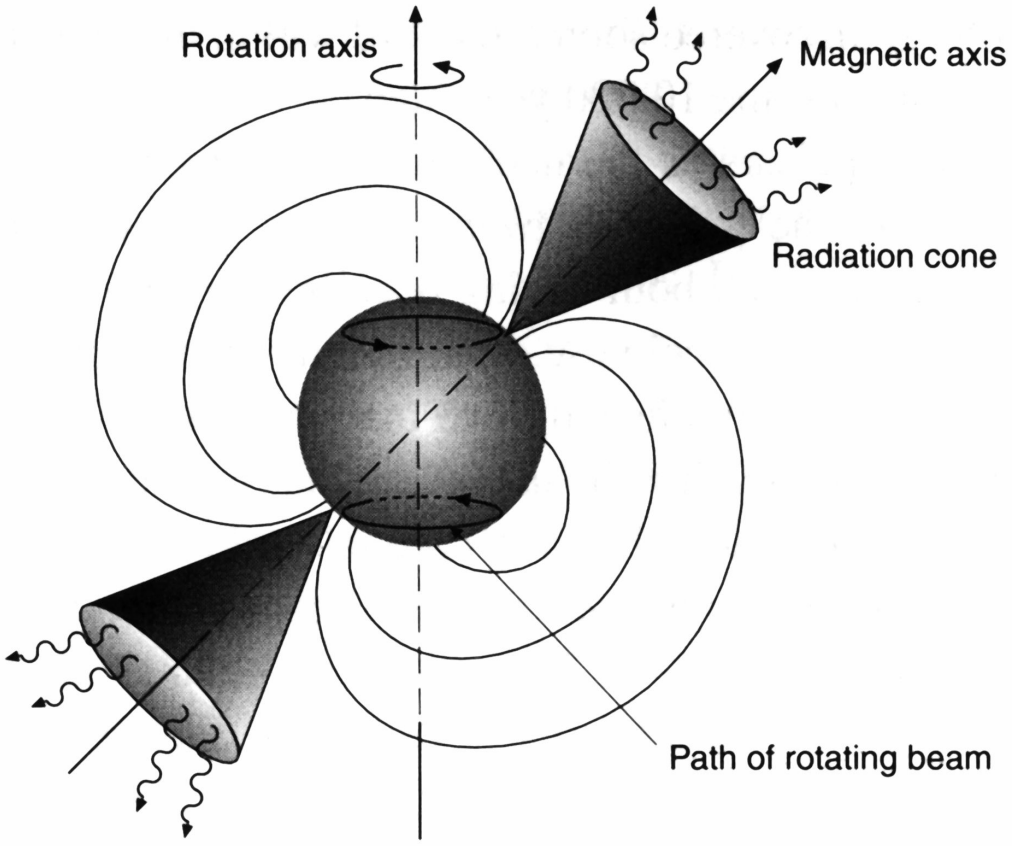
PSR 1919 - First Pulsar Found



Pulsar Radiation - Energy Bands, Zoo



Pulsars



moment of interia

$$I = \frac{8\pi}{3} \int_0^R r^2 \, \rho(r) \, \mathrm{d}r$$

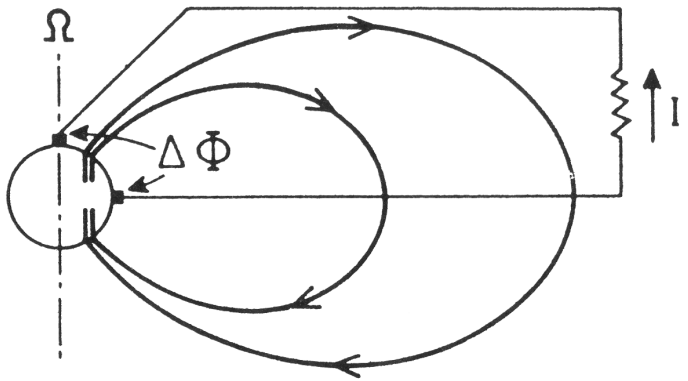
dipol radiation

$$L \sim \frac{1}{6c^3} \, B^2 \, R^6 \, \Omega^4$$

spindown

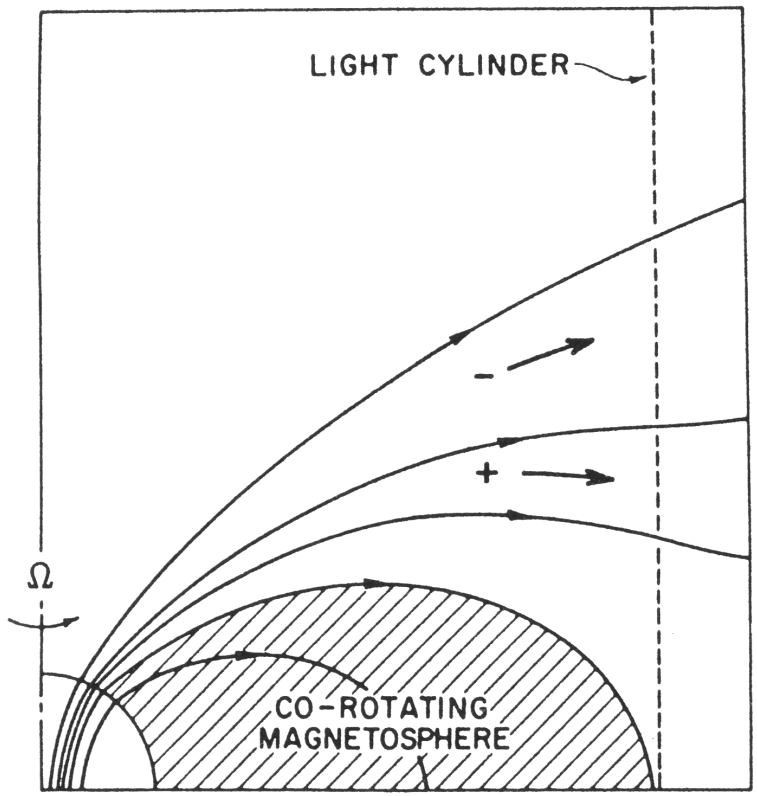
$$L = -\frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{1}{2} I \Omega^2 \right)$$

Pulsar - Magnets

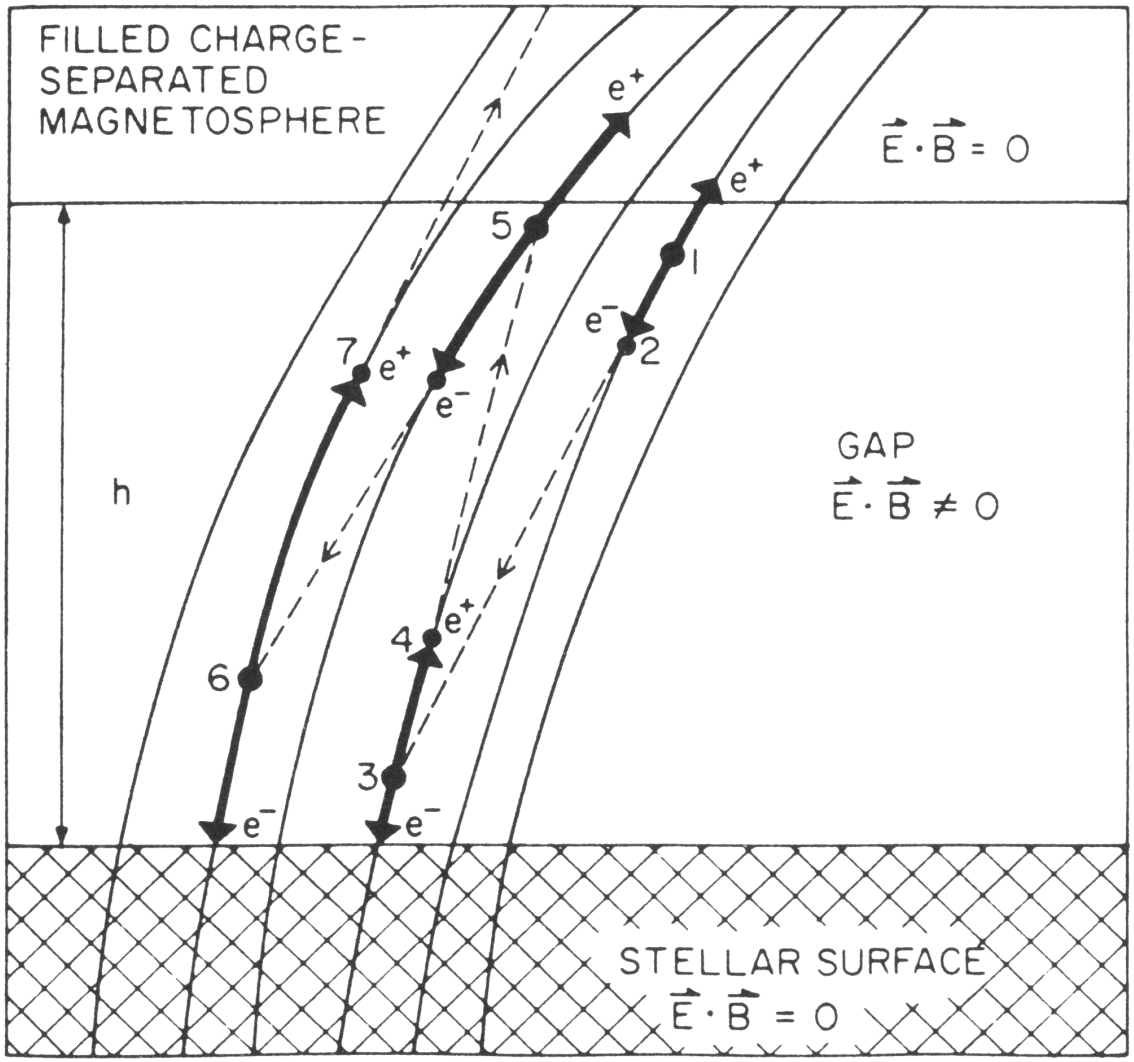


IRON MAGNET NEUTRON STAR

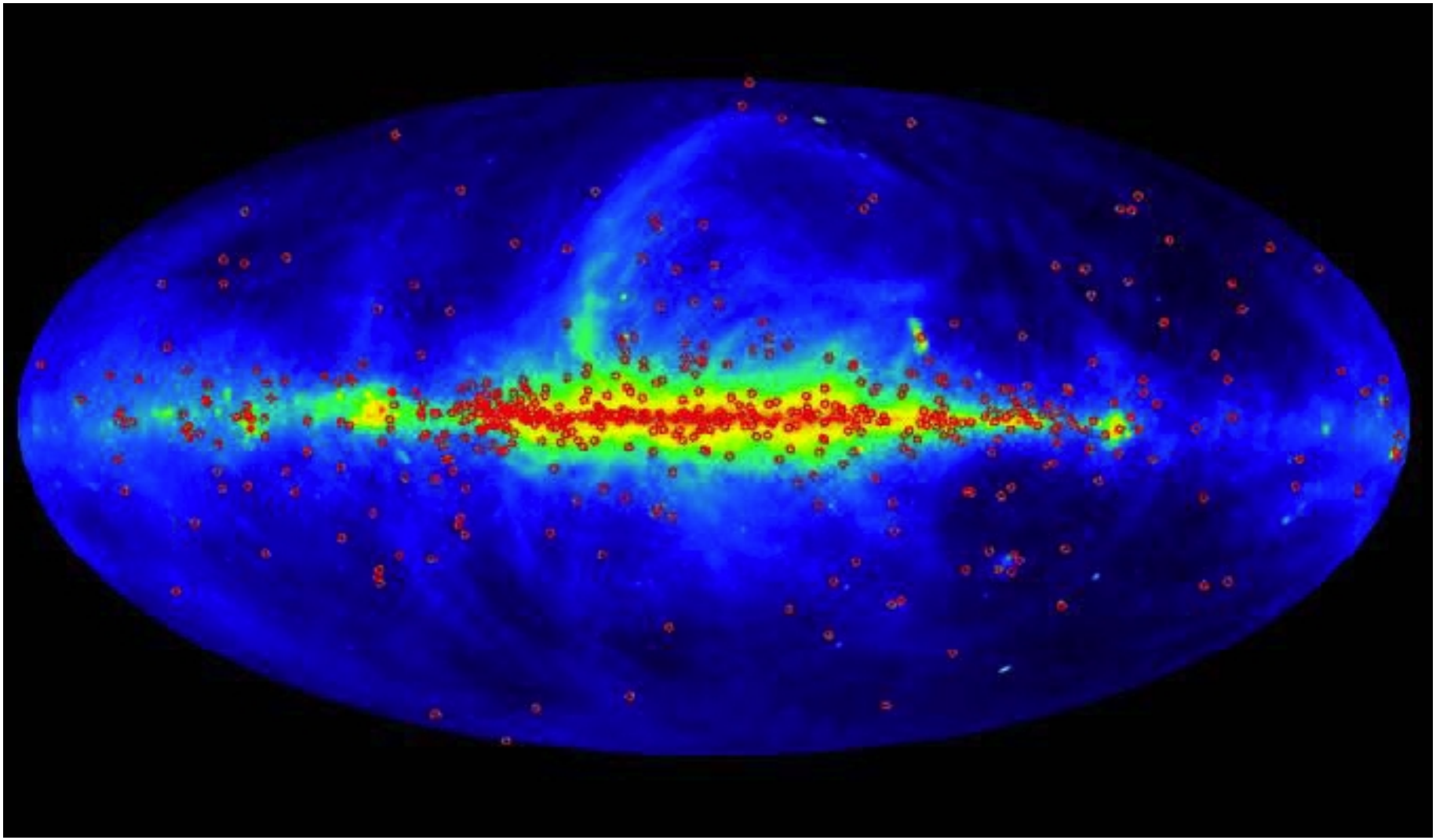
R (cm)	10	10^6
P (sec)	0.015	1
B (Gauss)	10^4	10^{12}
$\Delta\Phi$ (Volts)	5	3×10^{16}



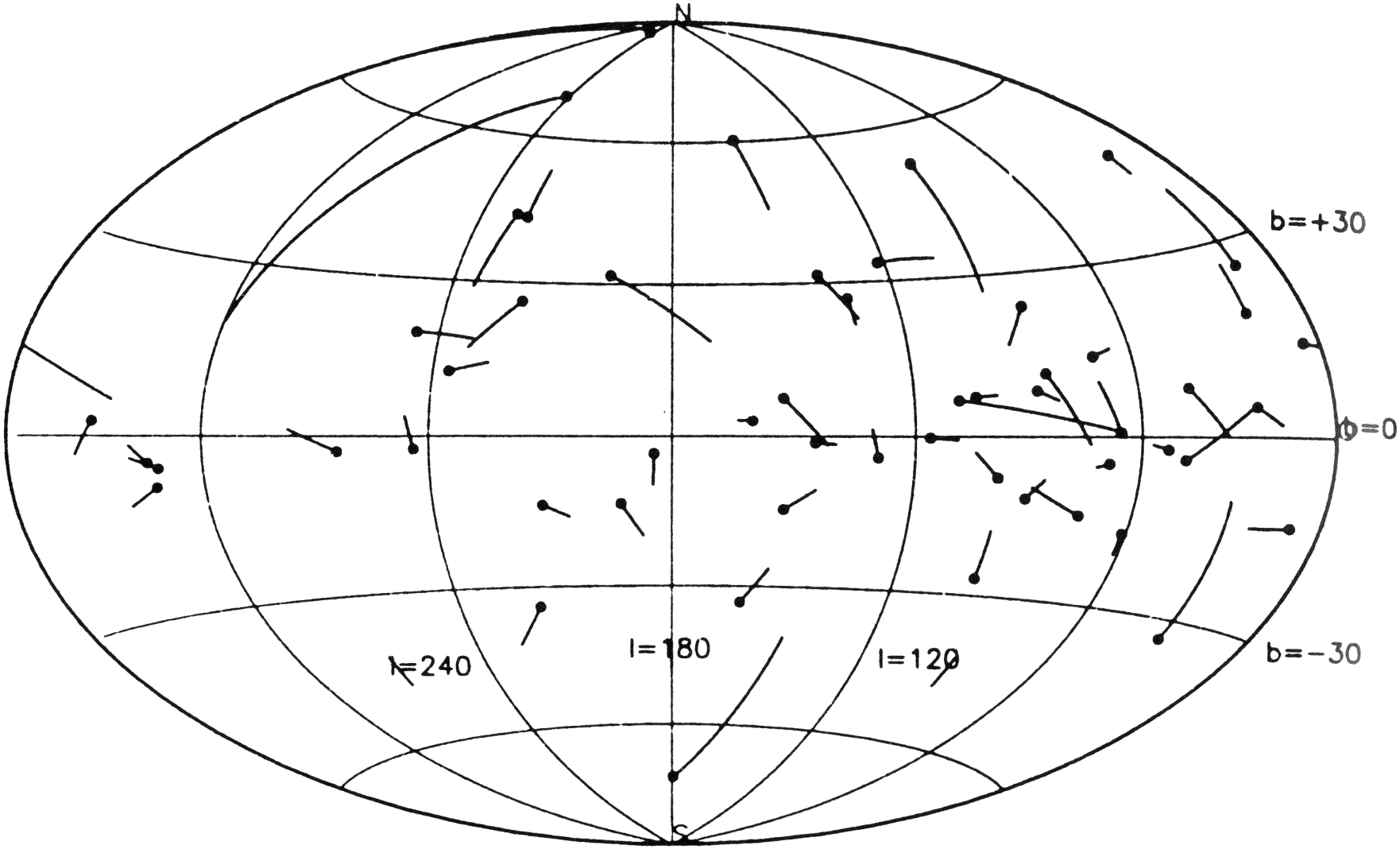
Pulsar - Magnetosphere



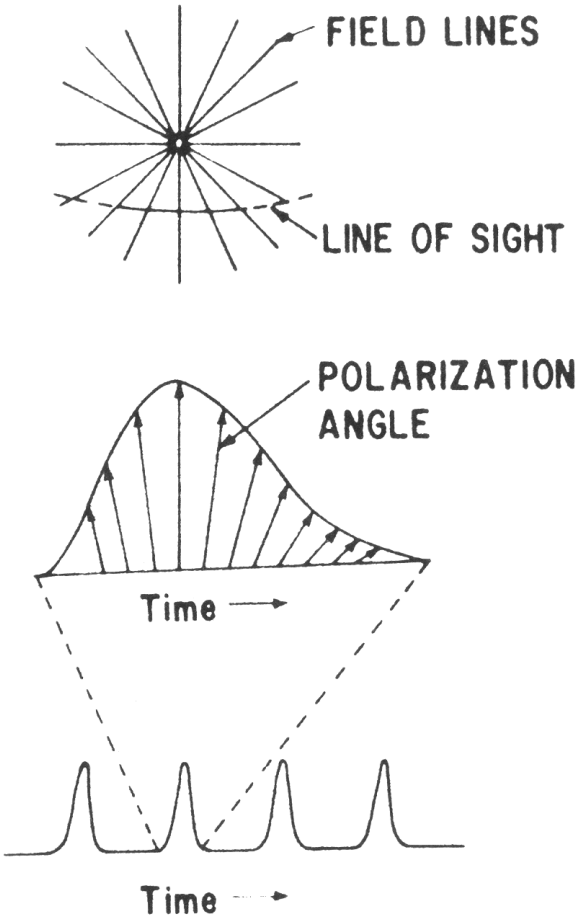
Pulsars in the Galaxy

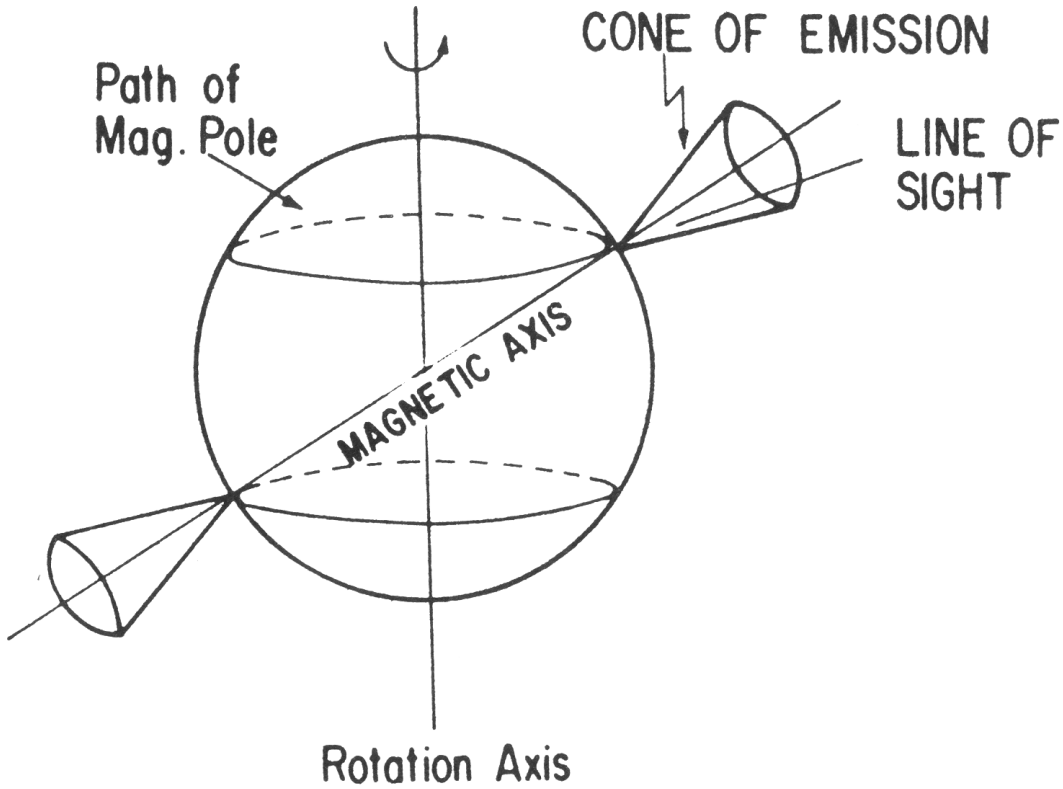


Pulsars in the Galaxy - Movement in Last Myr

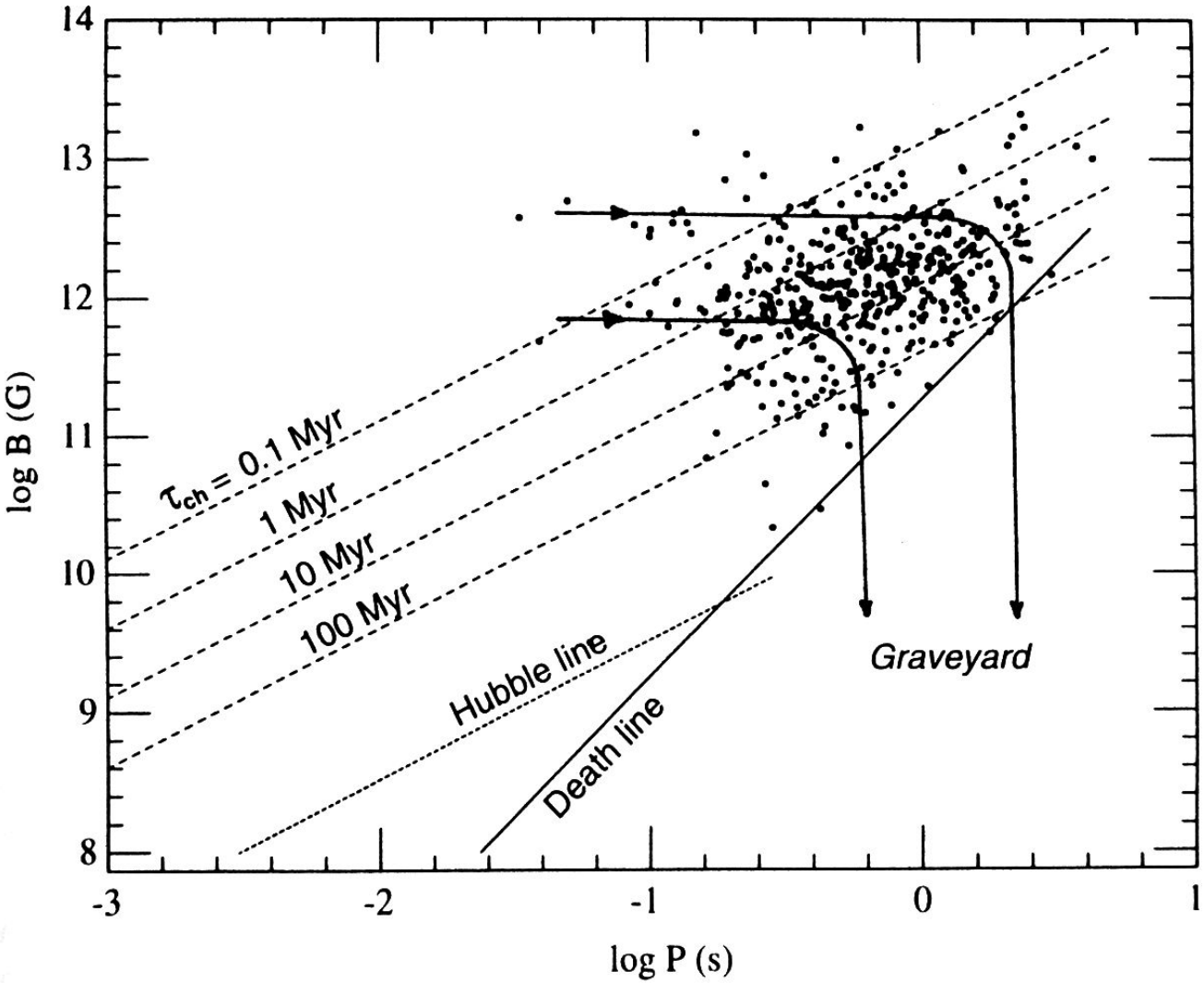


Pulsar Pulse and Polarization

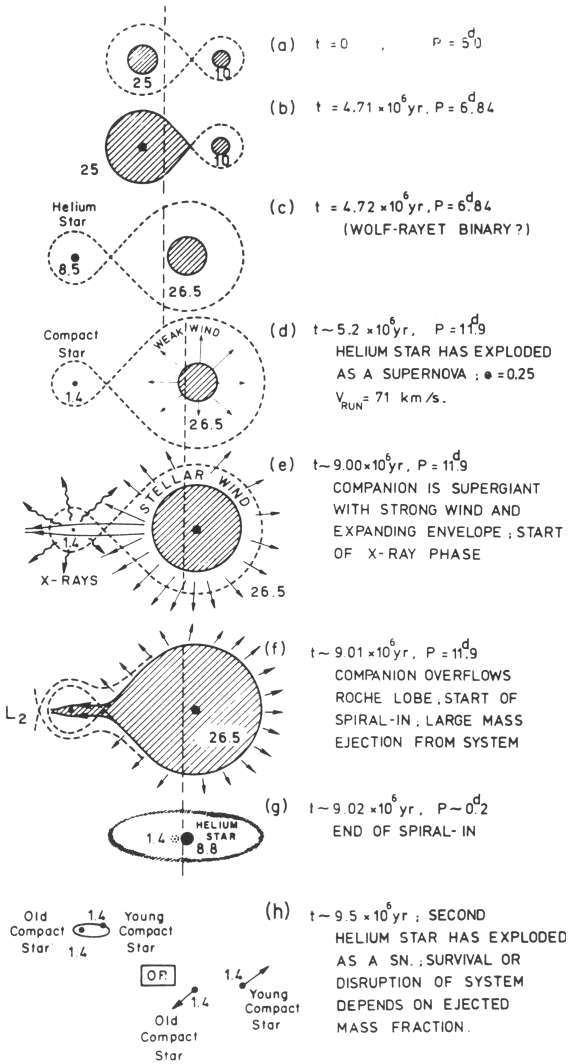


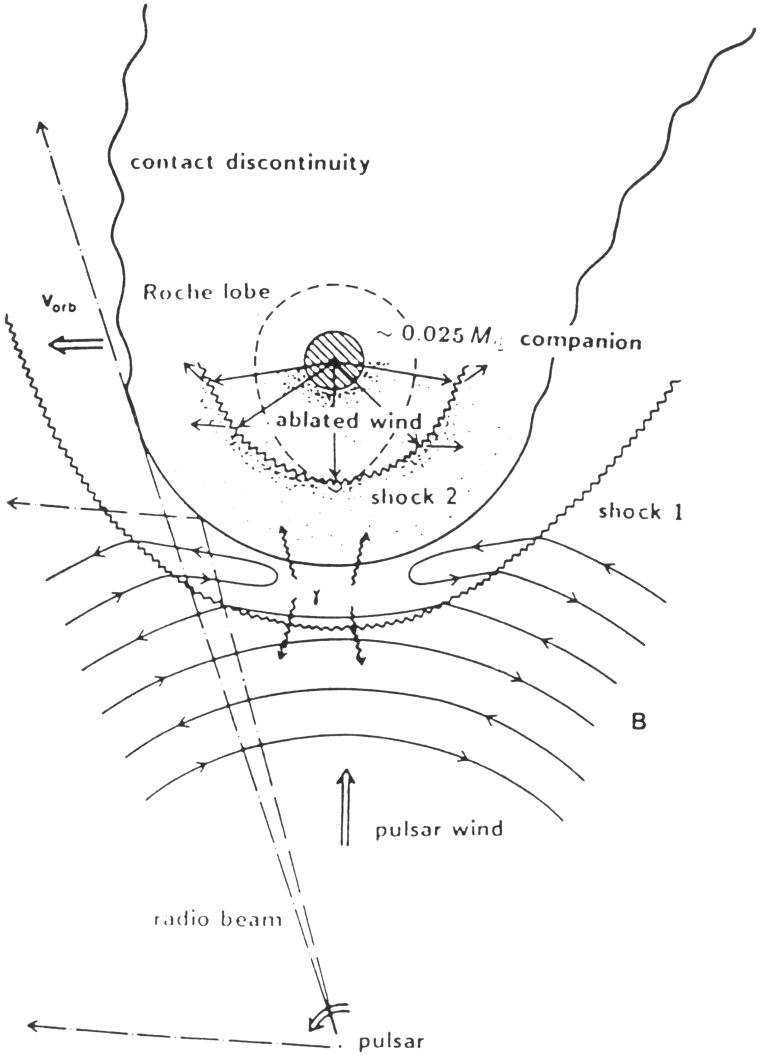


Pulsar Evolution

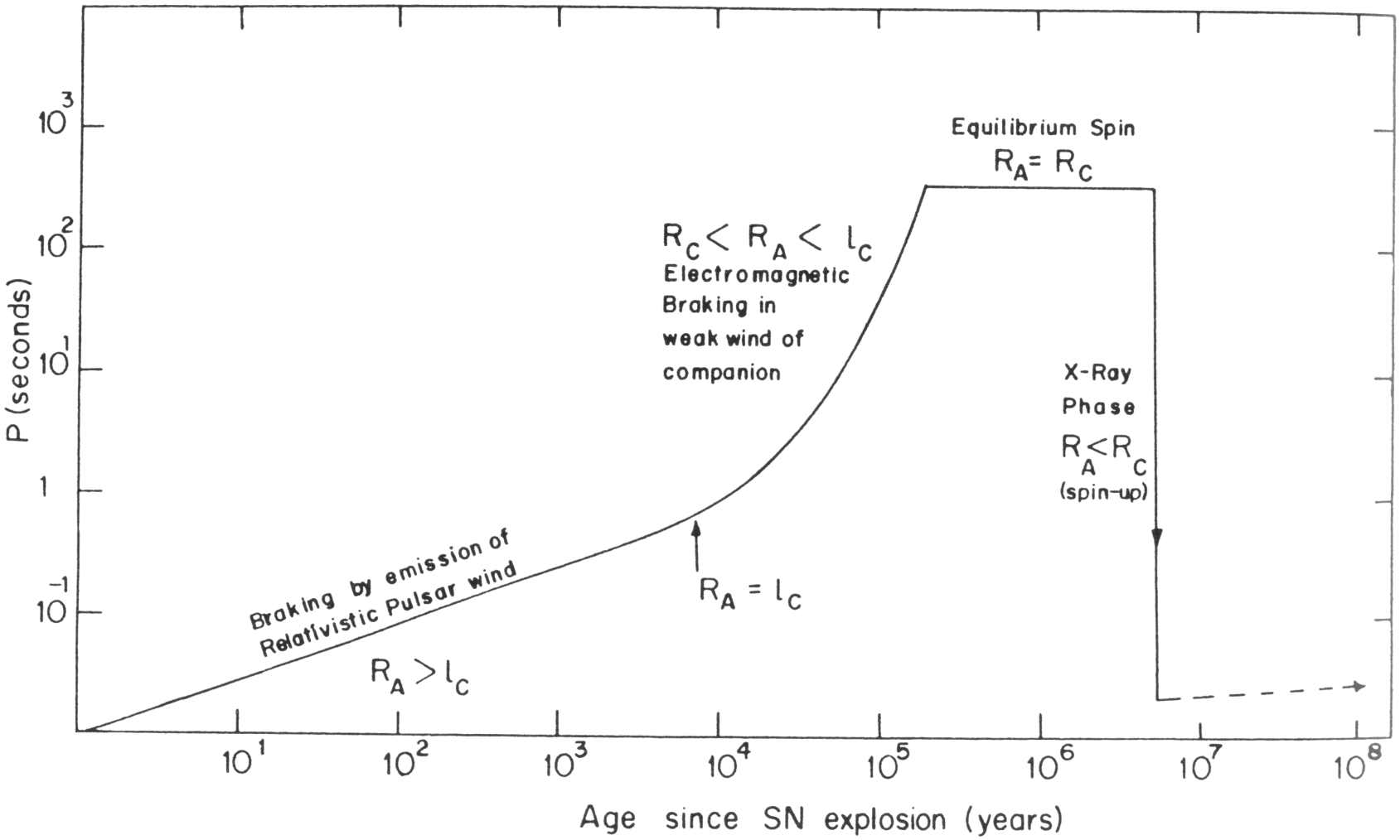


Pulsar Evolution - Binary Star System

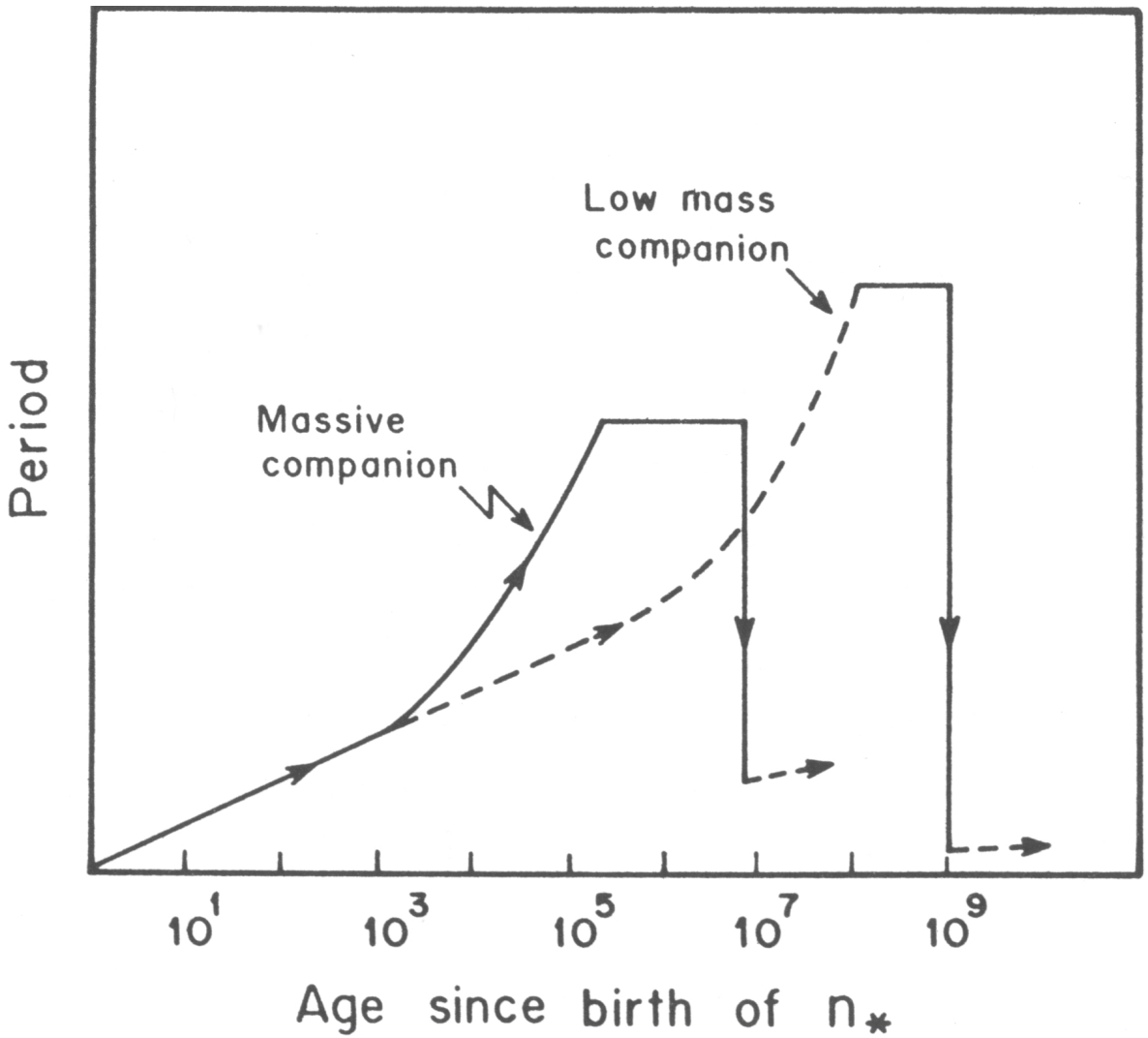




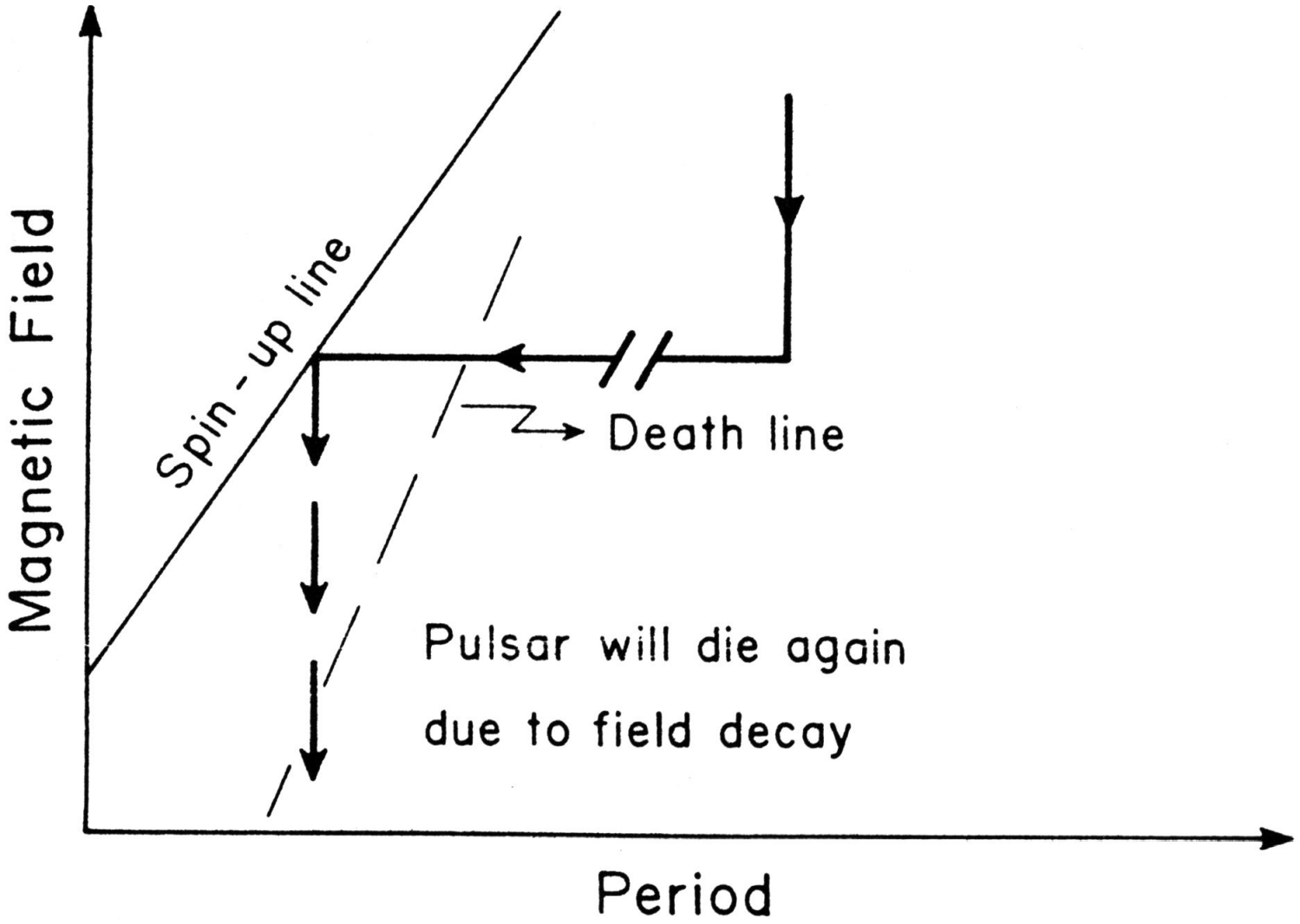
Pulsar Evolution - Spindown in Binary Systems



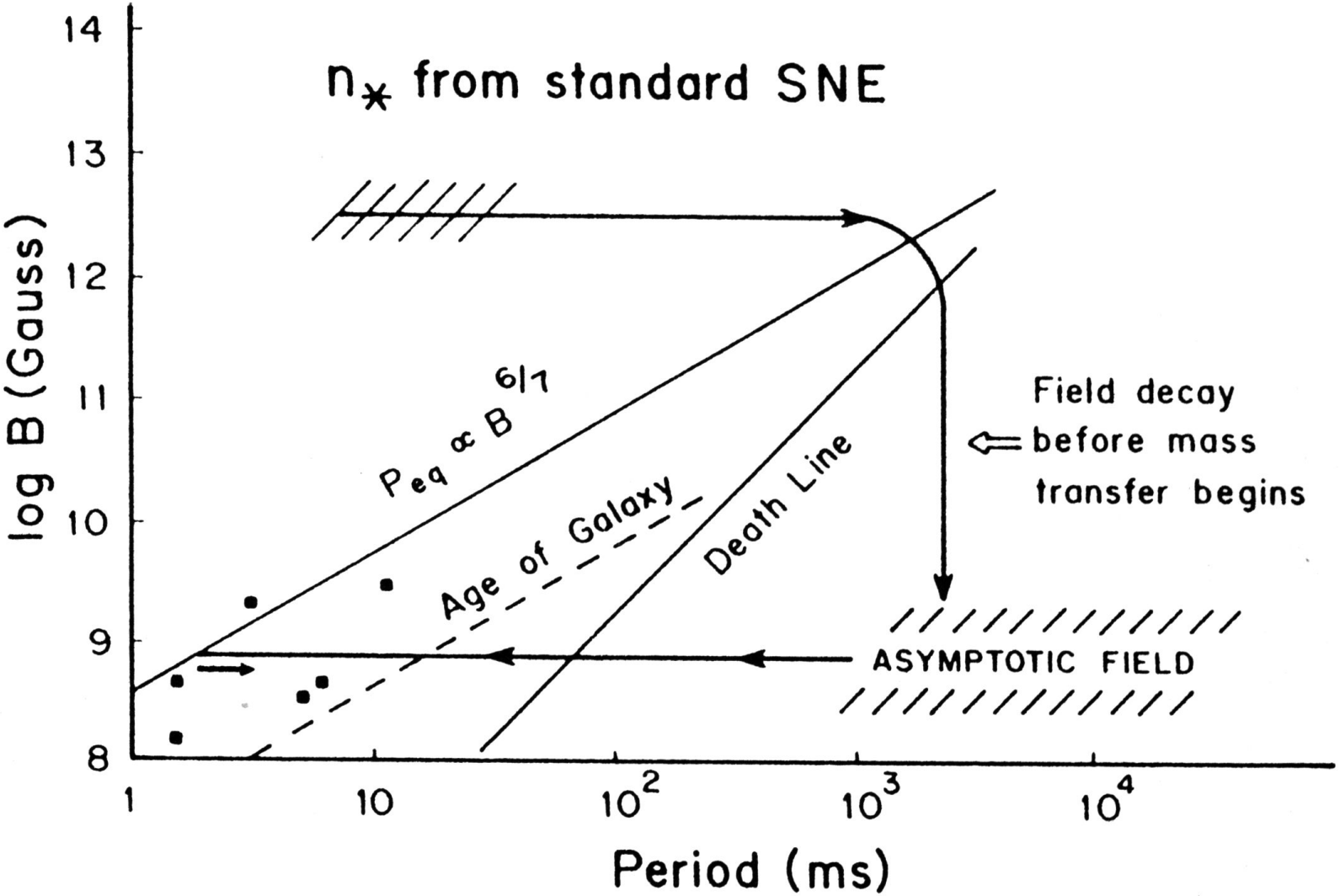
Pulsar Evolution - Spindown in Binary Systems



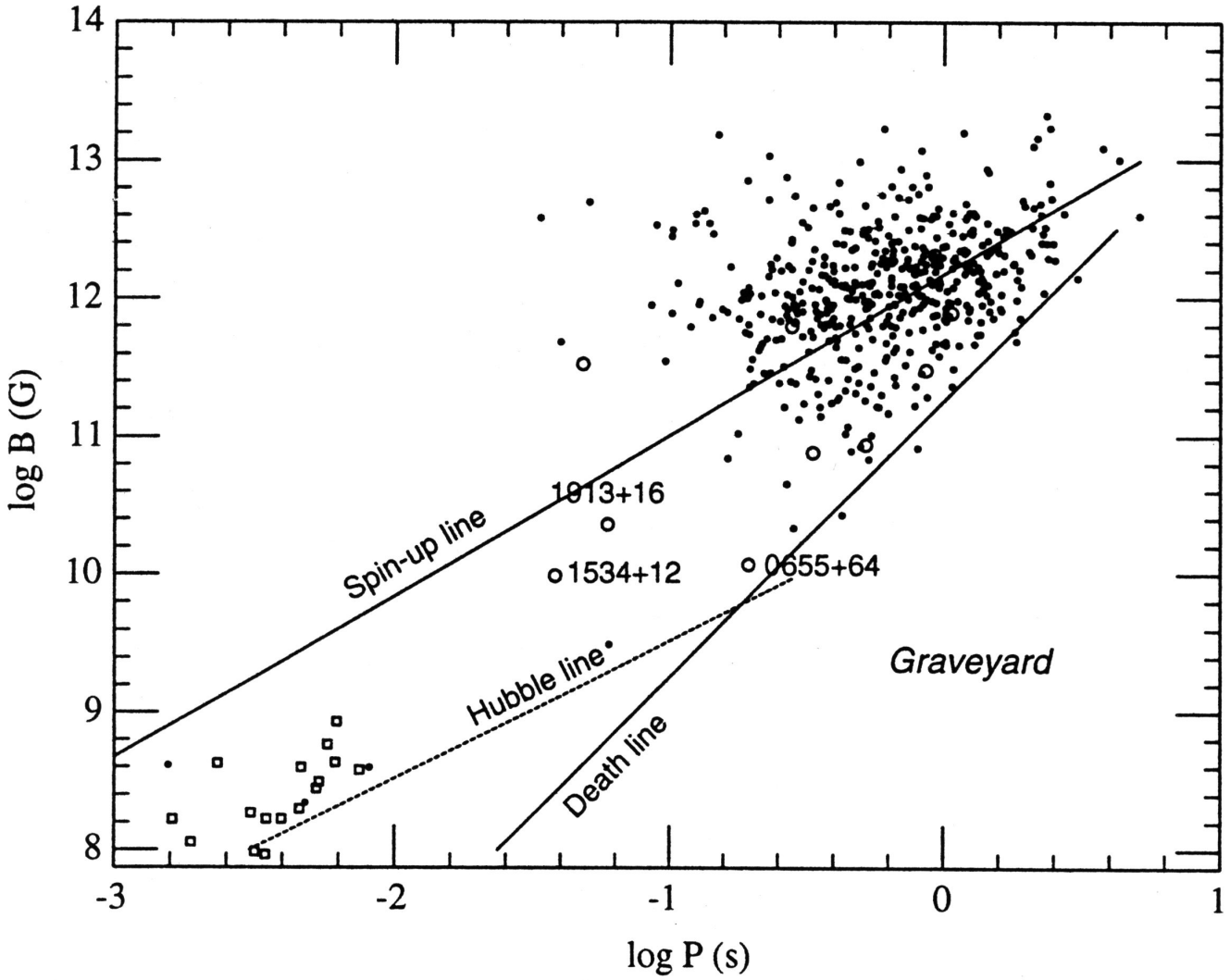
Pulsar Evolution - Spinup Due to Accretion



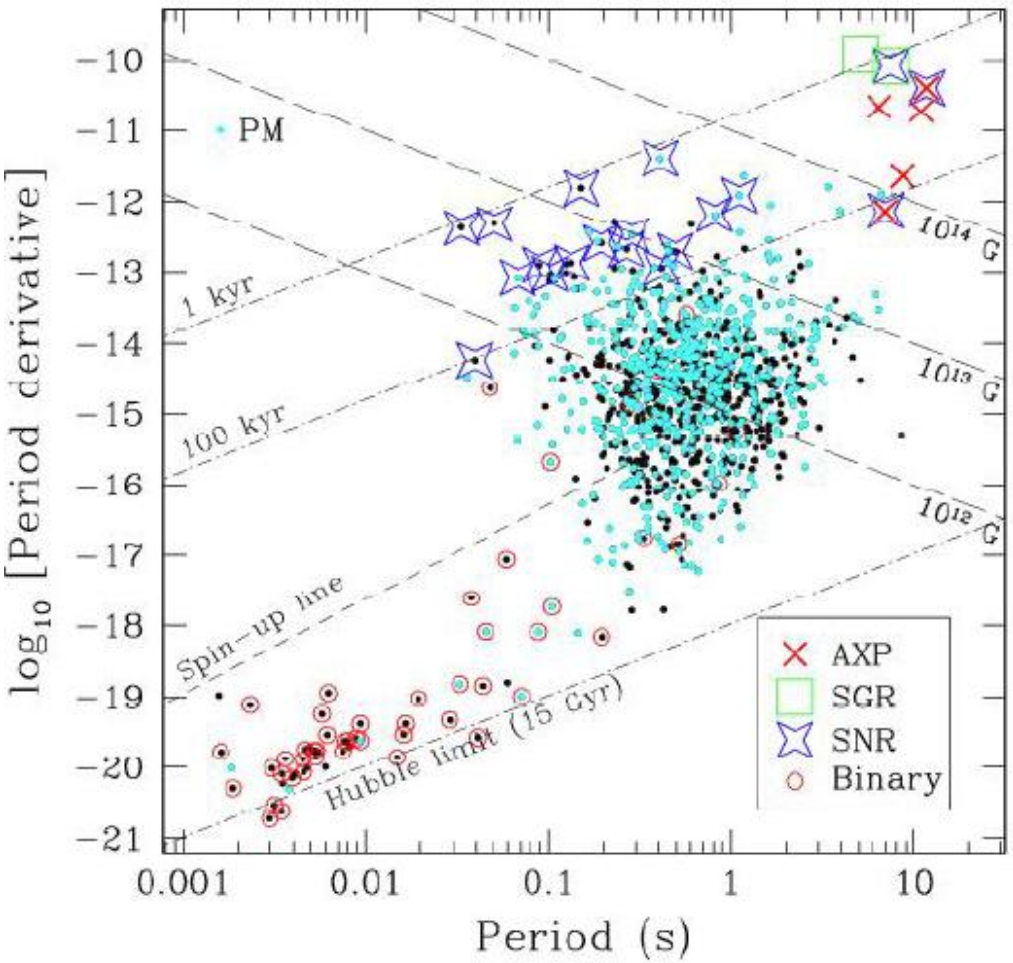
Pulsar Evolution



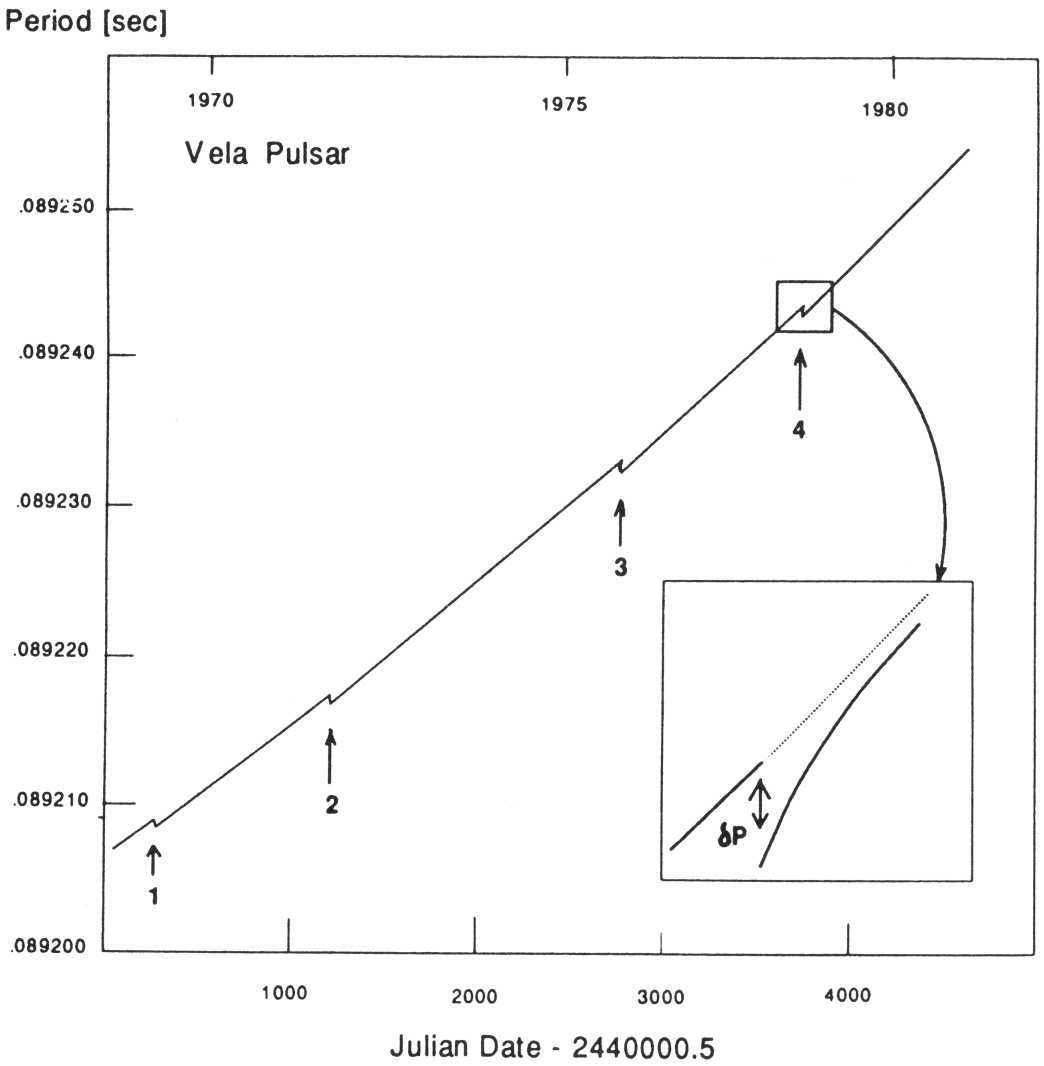
Observed Pulsar Populations



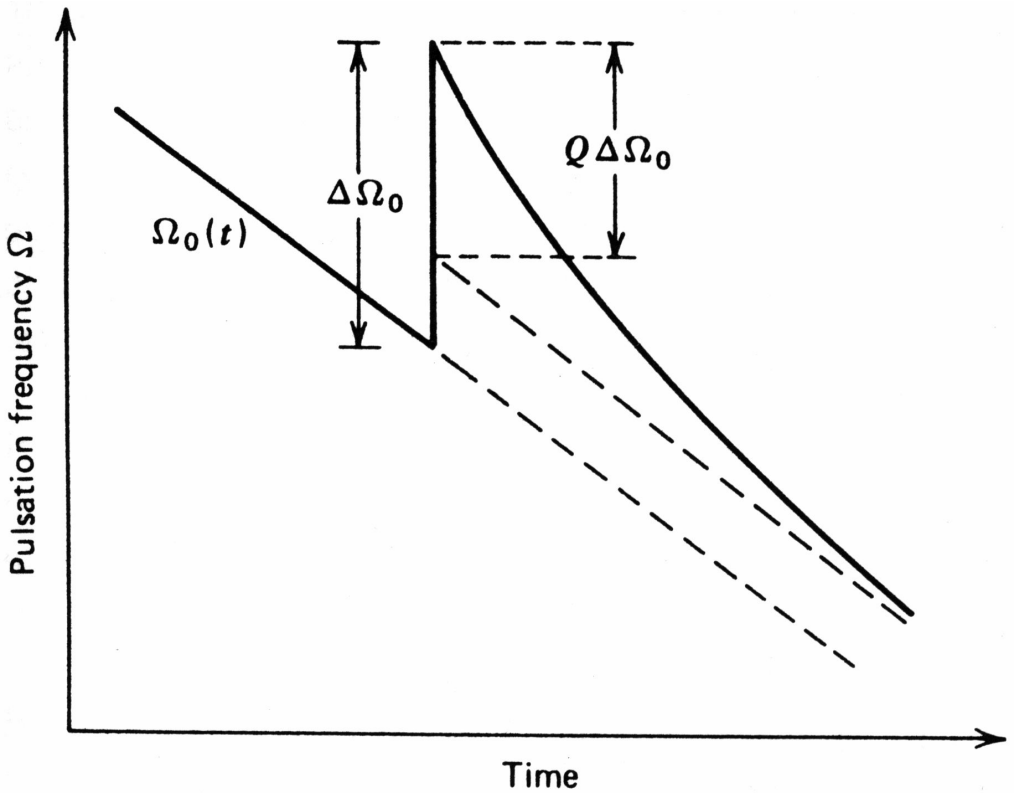
Pulsar Period and Spin-down

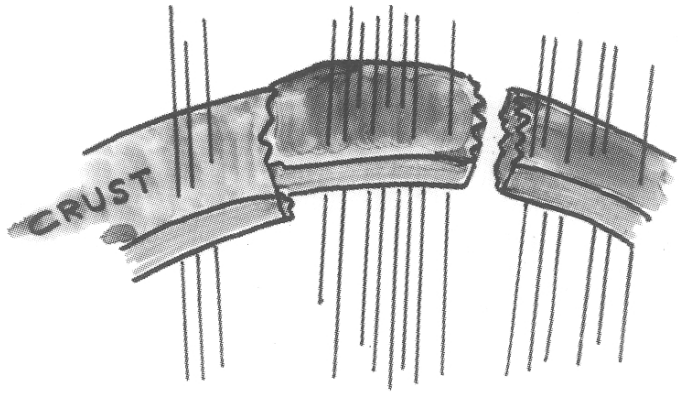


Pulsar Glitches



Pulsar Glitches





Change in rotation rate

$$\frac{\Delta\Omega}{\Omega} \sim 10^{-6}$$

change in spin-down rate

$$\frac{\Delta\dot{\Omega}}{\dot{\Omega}} \sim 10^{-2}$$