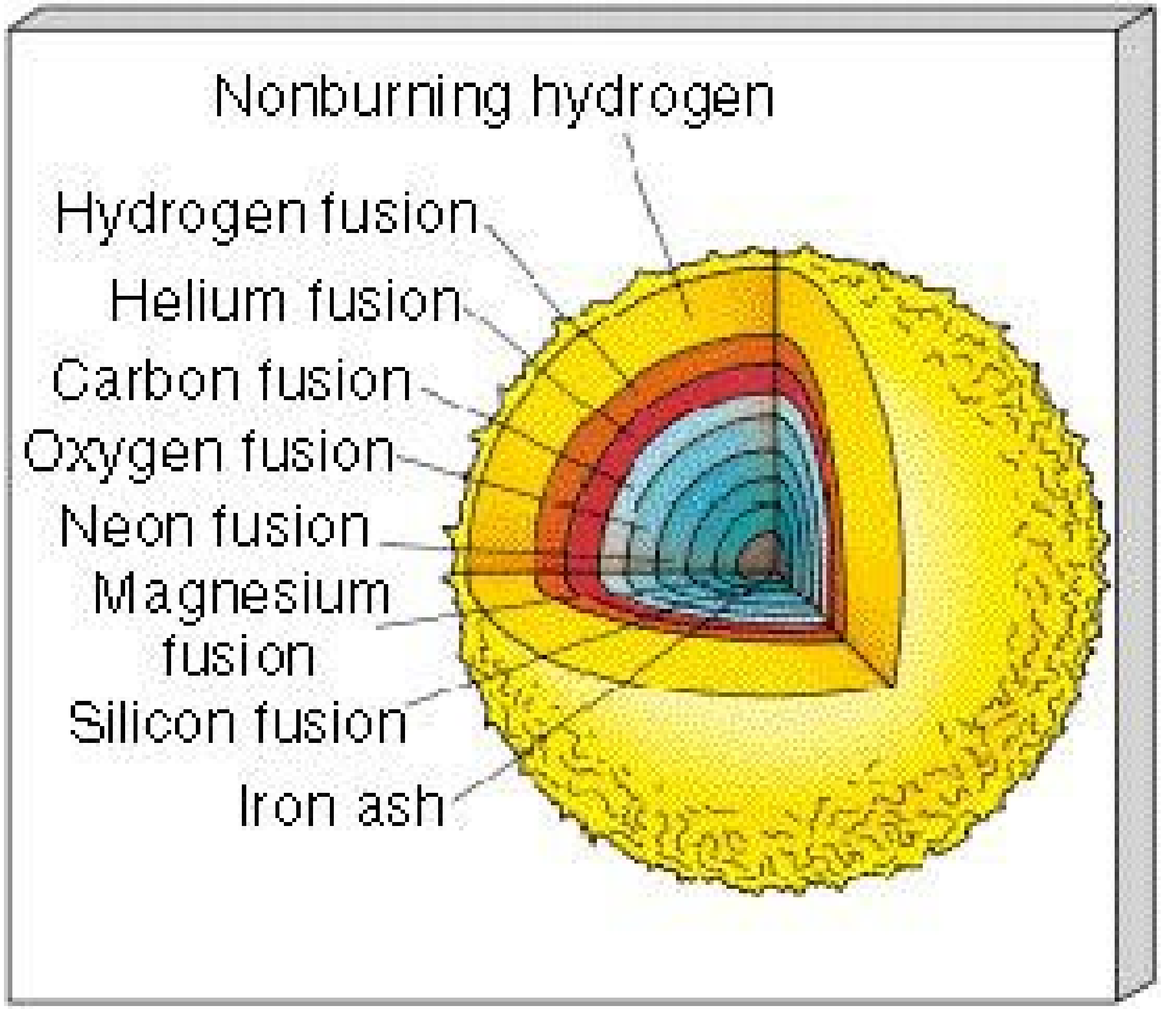
Neutron Stars & Pulsars

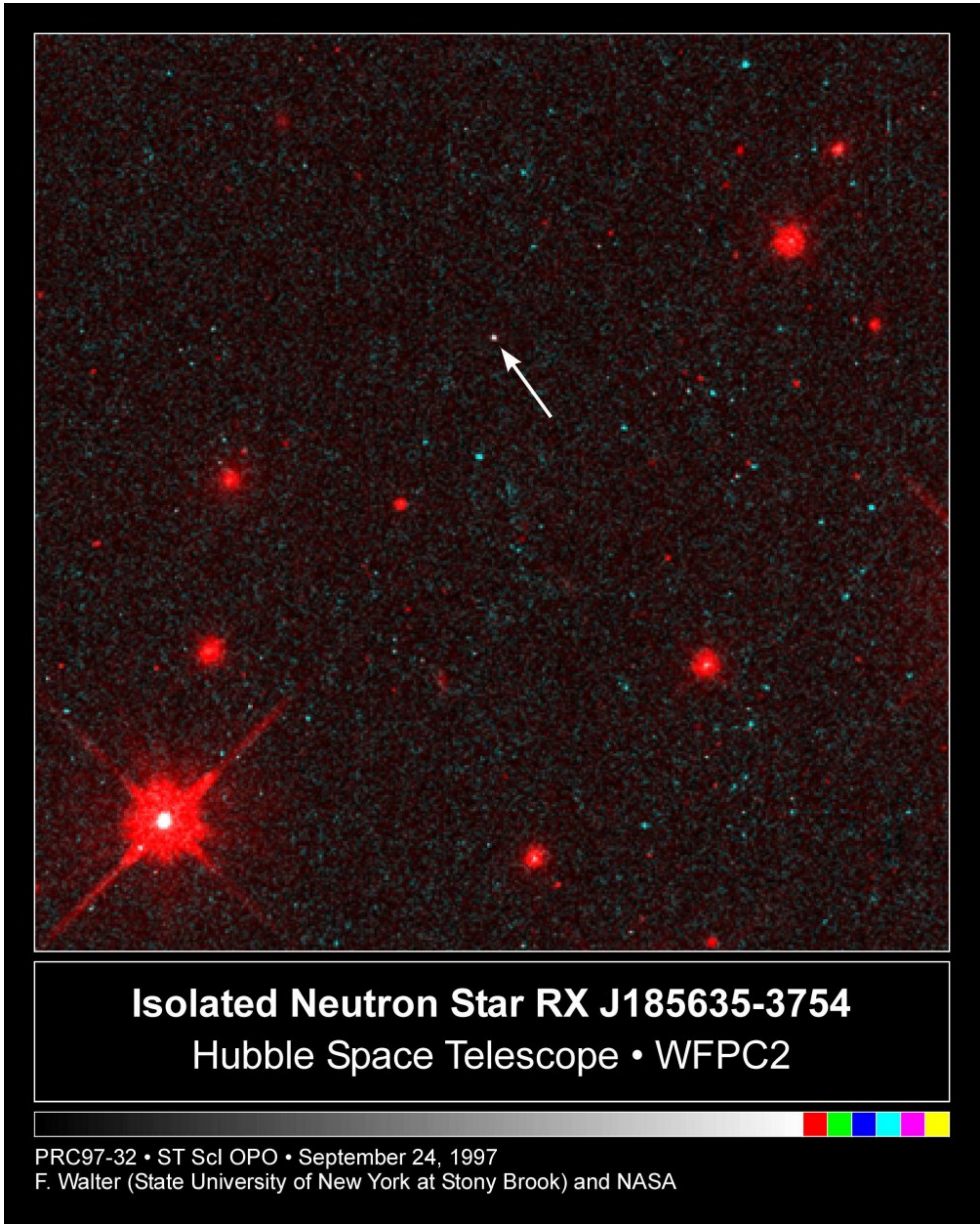
Stellar Evolution in 1 slide



- in the 1920s, Chandrasekhar showed that quantum mechanics allowed the weight of a star to be held up by *electron degeneracy pressure*
- However, beyond a mass of 1.4 $M_{\odot}$ (the Chandrasekhar limit) the electrons would have to be moving faster than the speed of light, so the white dwarf would again collapse

- in 1932 Chadwick discovered the neutron
- 1 year later, Zwicky (left) and Baade proposed that supernovae were powered by the gravitational collapse of a star to a neutron star
- in 1939, Oppenheimer & Volkoff showed that neutron degeneracy pressure could support a star up to $\sim 3\ M_{\odot}$ (still unknown)
- above that limit, there is no known support mechanism, and the star collapses to a BH

- After they are formed, neutron stars are very hot, but then cool off
- Isolated NS are often very dim and hard to detect



Pulsars

Discovered by Burnell & Hewish in 1967 in Cambridge

Extremely regular radio pulses every second

the stability of the 1 s pulse argued for a cosmic origin

others were soon discovered

rotating NS proposed for explanation

- The observed spin rate of the object can be used to determine a minimum average density…

- The minimum period (P) of a star is that for which the surface layers are “in orbit”…

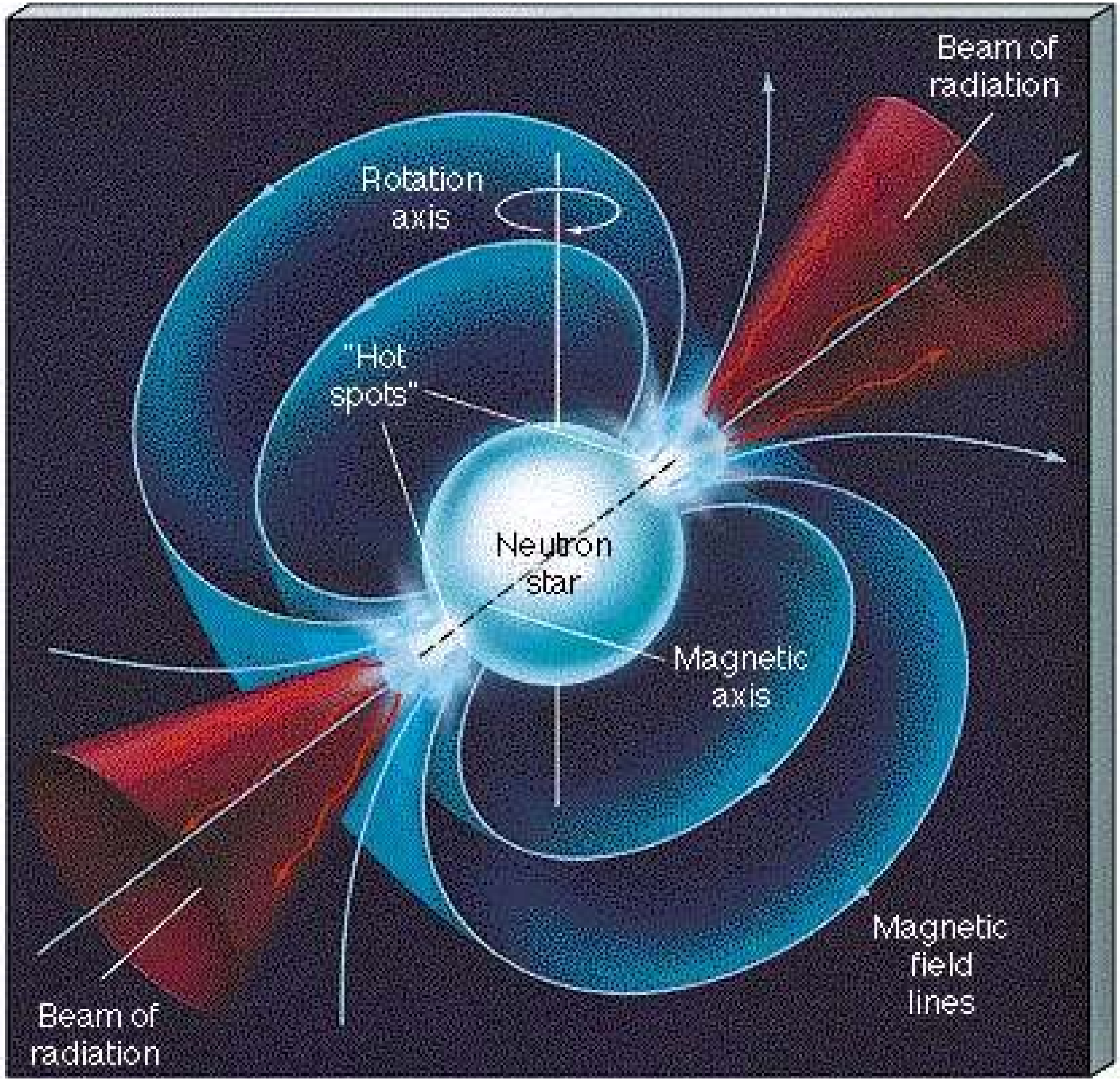
$$\frac{v_{\rm rot}^2}{R} < \frac{GM}{R^2}$$

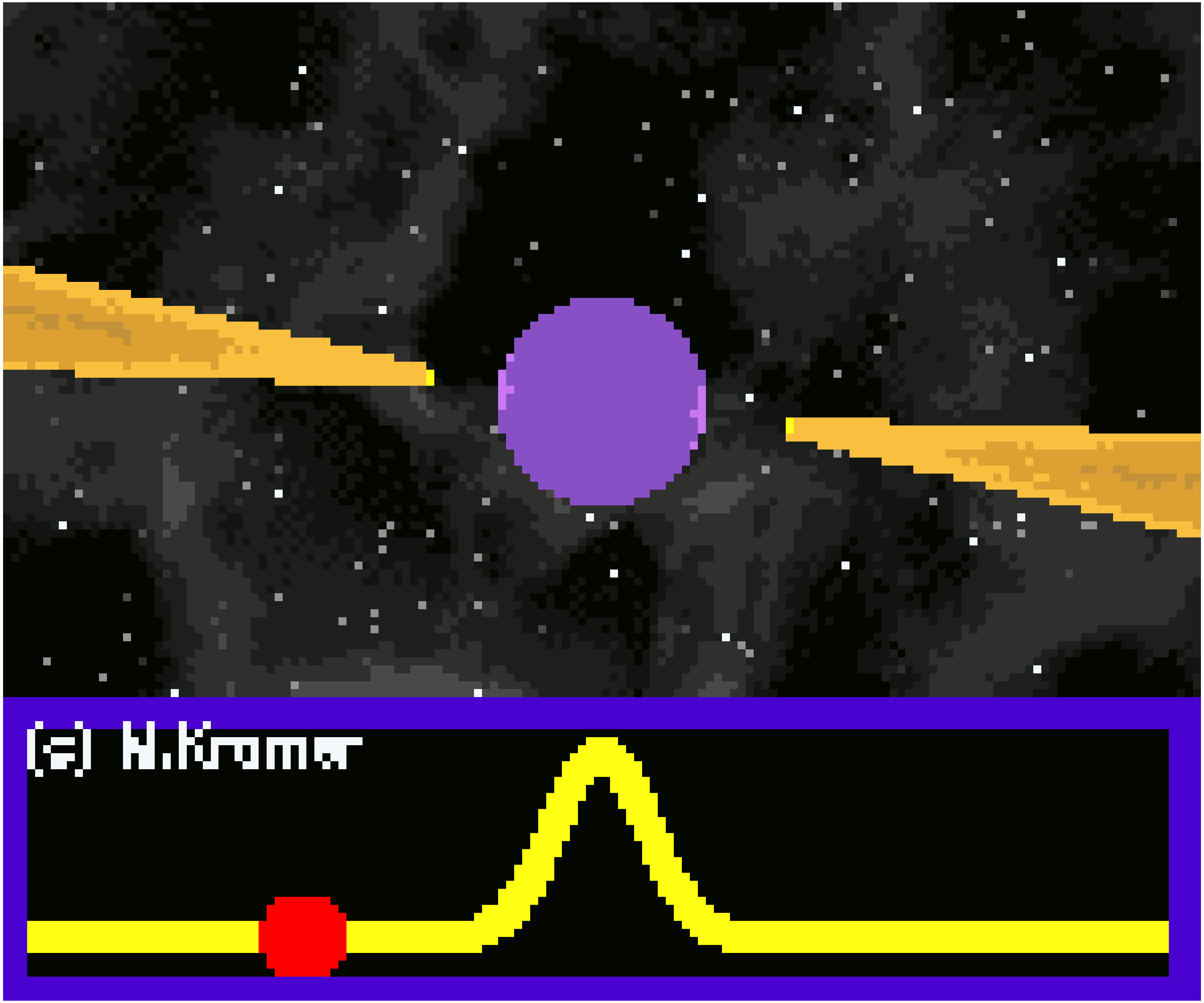
$$\frac{4\pi^2 R}{P^2} < \frac{GM}{R^2}$$

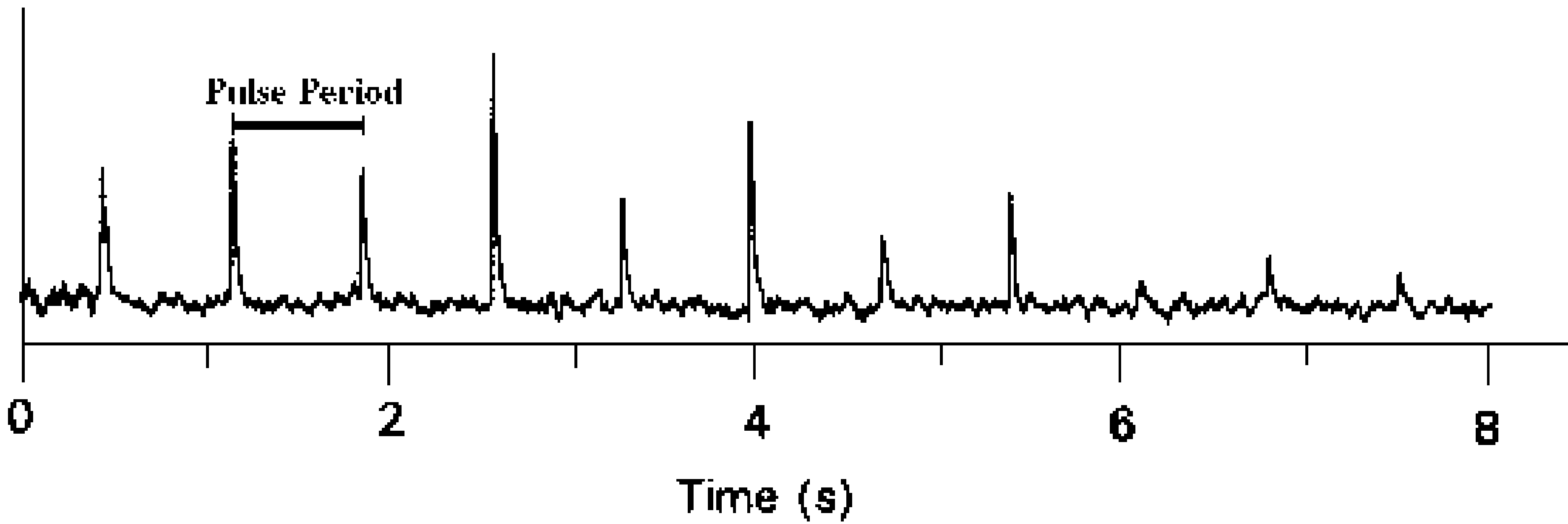
$$\bar{\rho} \equiv \frac{3M}{4\pi R^3} > \frac{3\pi}{GP^2}$$

- $P = 1\,s \Rightarrow \rho > 1 \times 10^{11}$ kg/m^3
- $P = 10^{-1}\,s \Rightarrow \rho > 1 \times 10^{13}$ kg/m^3
- $P = 10^{-2}\,s \Rightarrow \rho > 1 \times 10^{15}$ kg/m^3

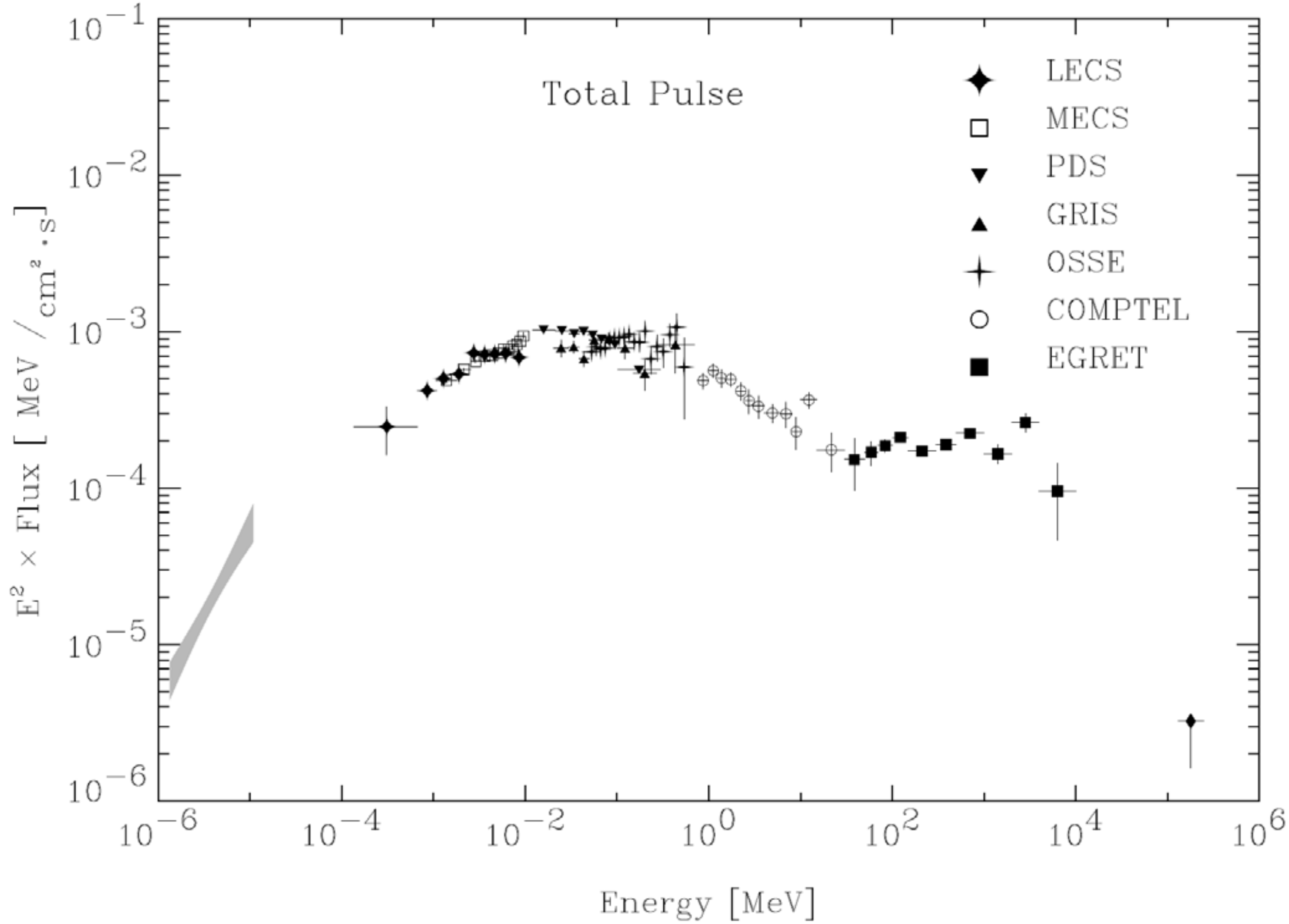
- So the measured periods imply neutron star densities!


Beam of radiation
Rotation axis
"Hot spots"
Neutron star
Magnetic axis
Magnetic field lines
Beam of radiation

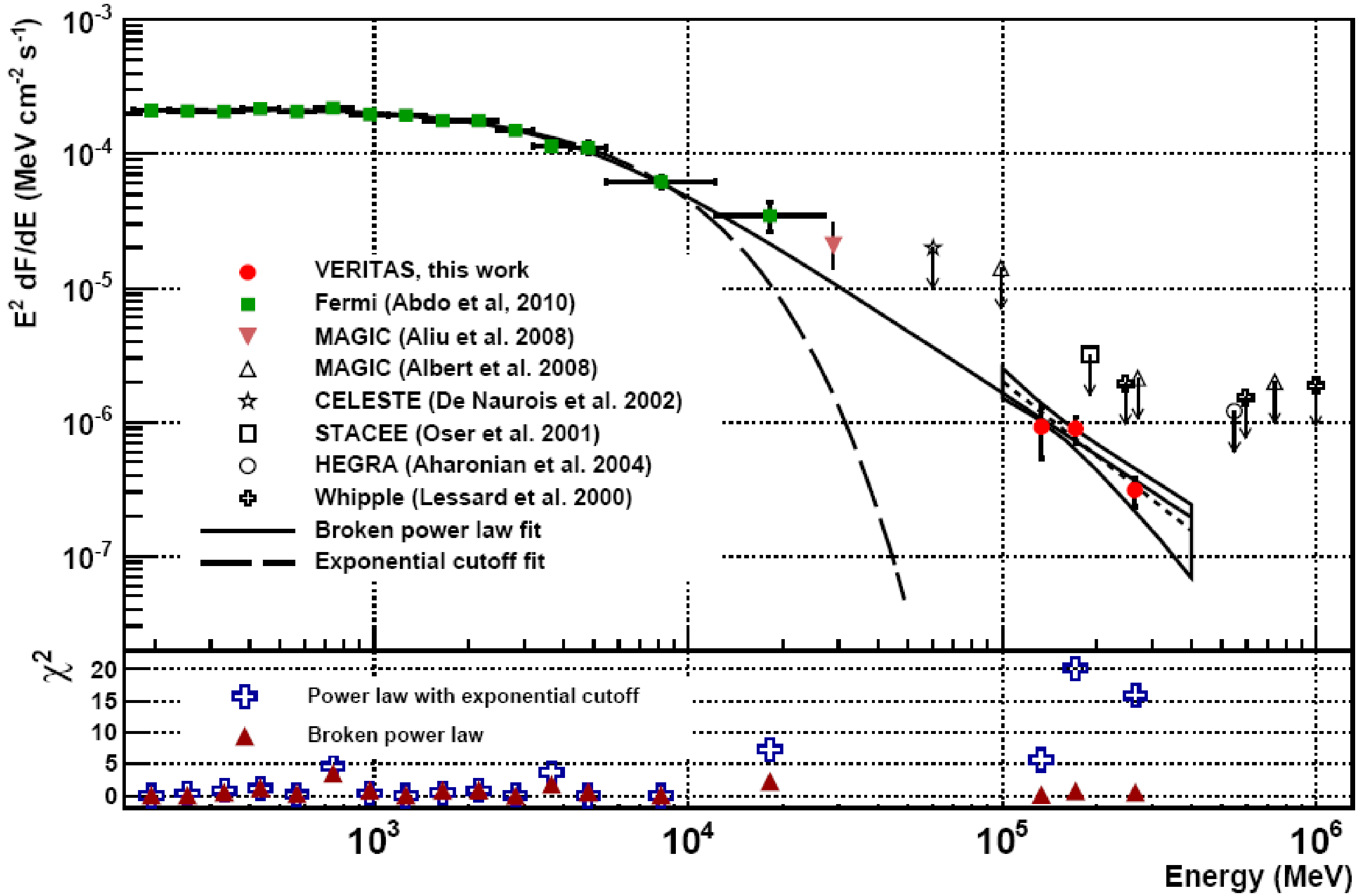

(c) N.Kramer



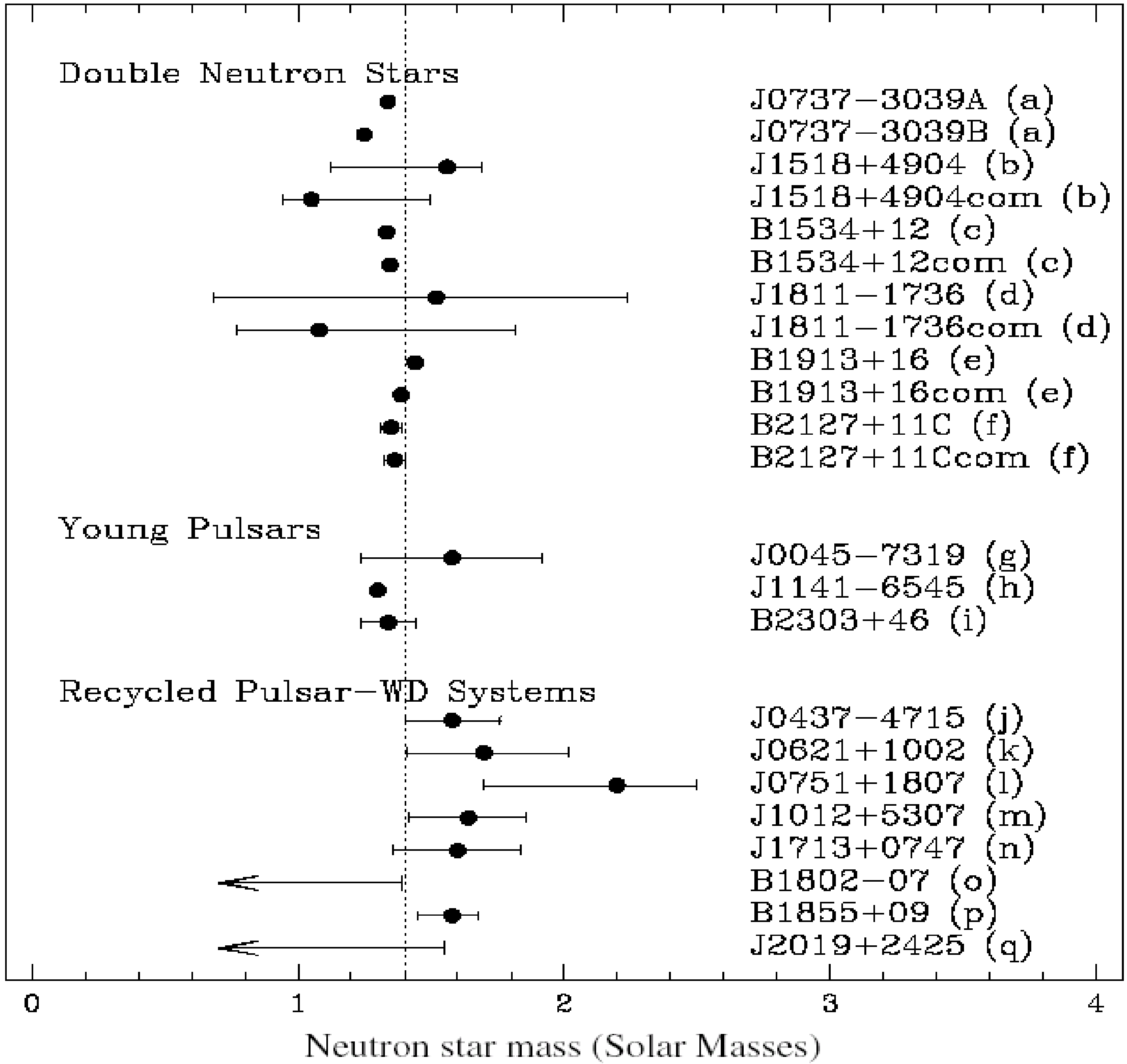
Pulse Period
0
2
4
6
8
Time (s)



Broadband pulsed spectrum of the Crab.



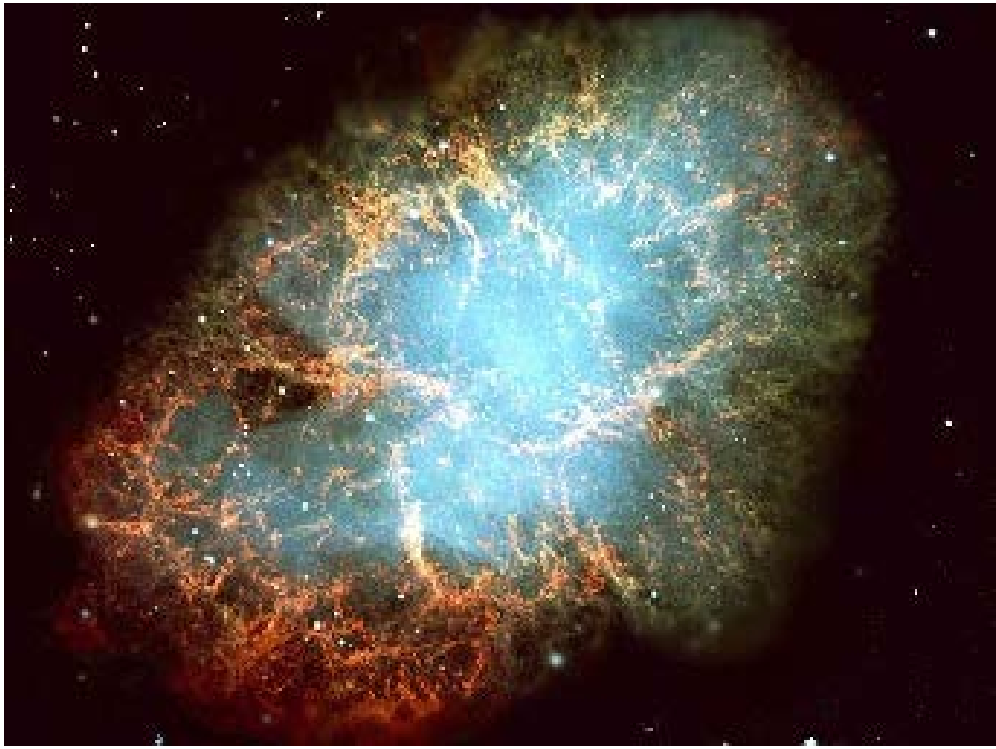
ig. 2. Spectral energy distribution (SED) of the Crab pulsar in gamma rays. VERITAS flux measurements are shown by the solid d circles, Fermi-LAT data (*13*) by green squares, and the MAGIC flux point (*16*) by the solid triangle. The empty symbols are upper nits from CELESTE (*25*), HEGRA (*26*), MAGIC (*17*), STACEE (*27*), and Whipple (*29*). The bowtie and the enclosed dotted line ve the statistical uncertainties and the best-fit power-law spectrum for the VERITAS data using a forward-folding method. The sult of a fit of the VERITAS and Fermi-LAT data with a broken power law is given by the solid line and the result of a fit with a ›wer-law spectrum multiplied with an exponential cutoff is given by the dashed line. Below the SED we plot χ^2 values to visualize e deviations of the best-fit parametrization from the Fermi-LAT and VERITAS flux measurements.

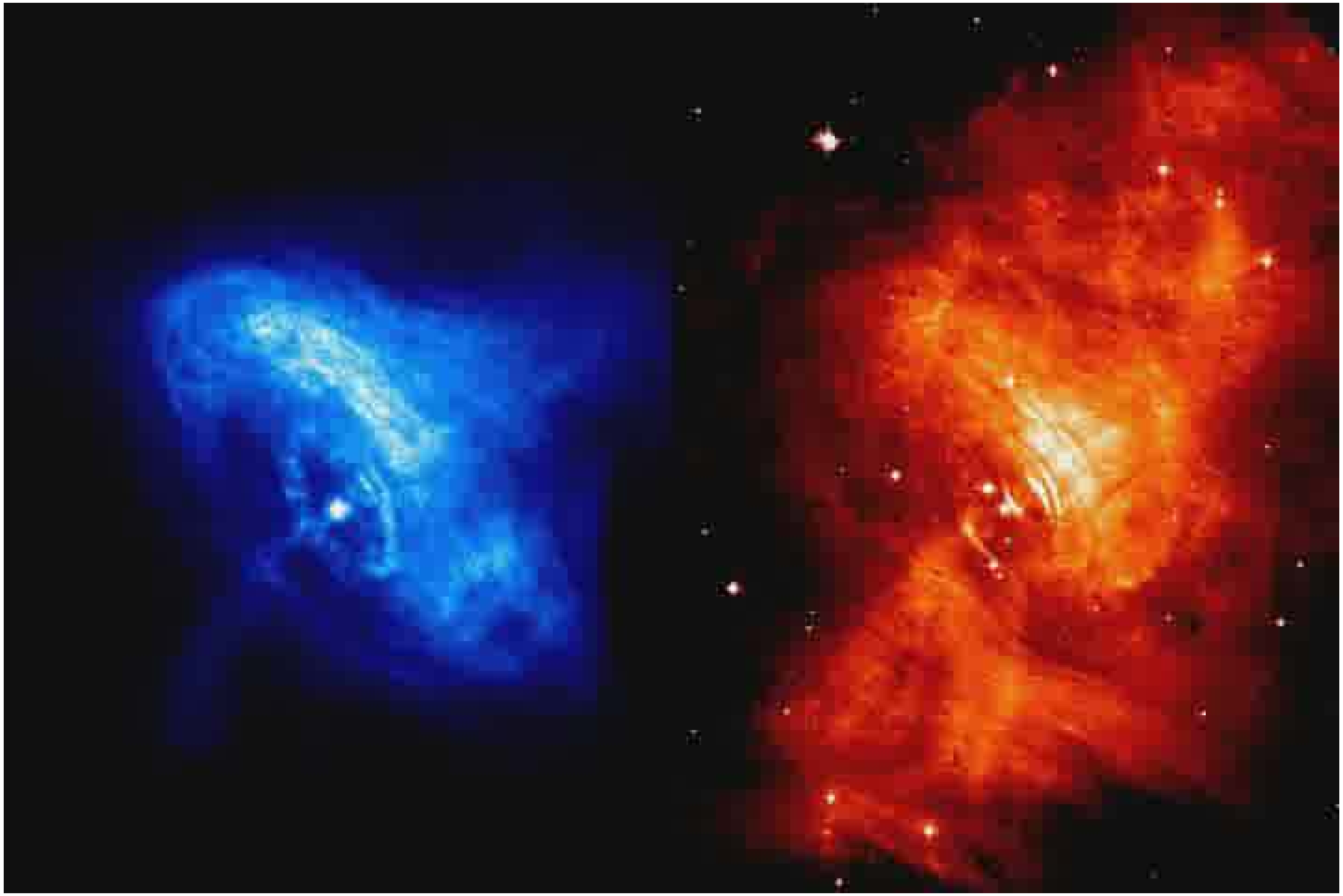


Double Neutron Stars
J0737−3039A (a)
J0737−3039B (a)
J1518+4904 (b)
J1518+4904com (b)
B1534+12 (c)
B1534+12com (c)
J1811−1736 (d)
J1811−1736com (d)
B1913+16 (e)
B1913+16com (e)
B2127+11C (f)
B2127+11Ccom (f)
Young Pulsars
J0045−7319 (g)
J1141−6545 (h)
B2303+46 (i)
Recycled Pulsar−WD Systems
J0437−4715 (j)
J0621+1002 (k)
J0751+1807 (l)
J1012+5307 (m)
J1713+0747 (n)
B1802−07 (o)
B1855+09 (p)
J2019+2425 (q)
0
1
2
3
4
Neutron star mass (Solar Masses)

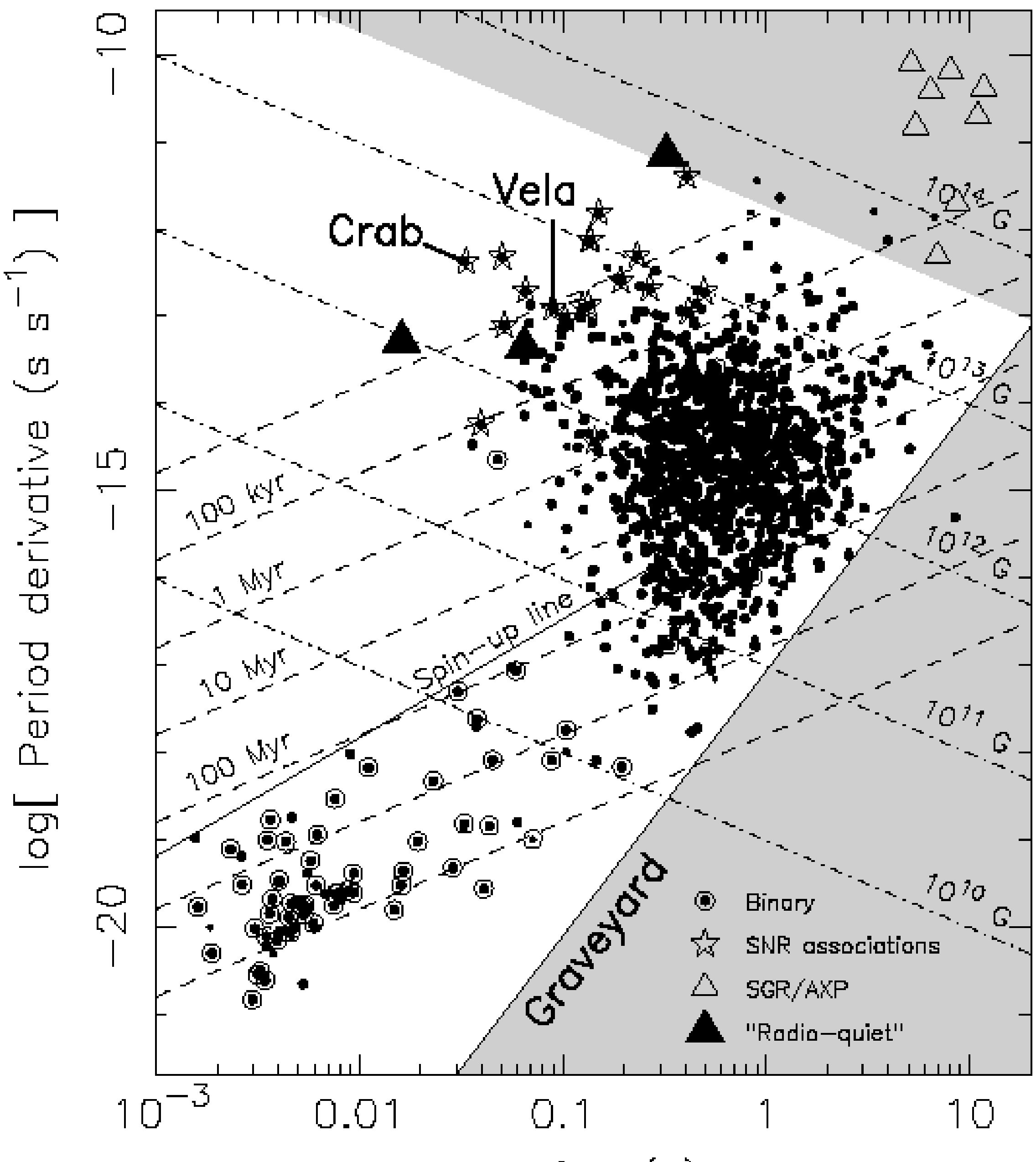
The Crab Pulsar

- Pulsar in Crab nebula discovered in 1969
- Nebula the remnants of a supernova observed in 1054
- Confirmed that NS were formed in supernova explosions
- Energy of the nebula is powered by the rotation of the NS





Chandra (X-ray) Hubble (Optical)



log[Period derivative (s s^{-1})]
−10
−15
−20
Period (s)
10^{-3}
0.01
0.1
1
10
Crab
Vela
100 kyr
1 Myr
10 Myr
100 Myr
Spin-up line
Graveyard
10^{14} G
10^{13} G
10^{12} G
10^{11} G
10^{10} G
Binary
SNR associations
SGR/AXP
"Radio-quiet"

Still many mysteries remain about the composition of neutron stars (the eqn. of state)

is now a test for some of the most exotic physics ever considered

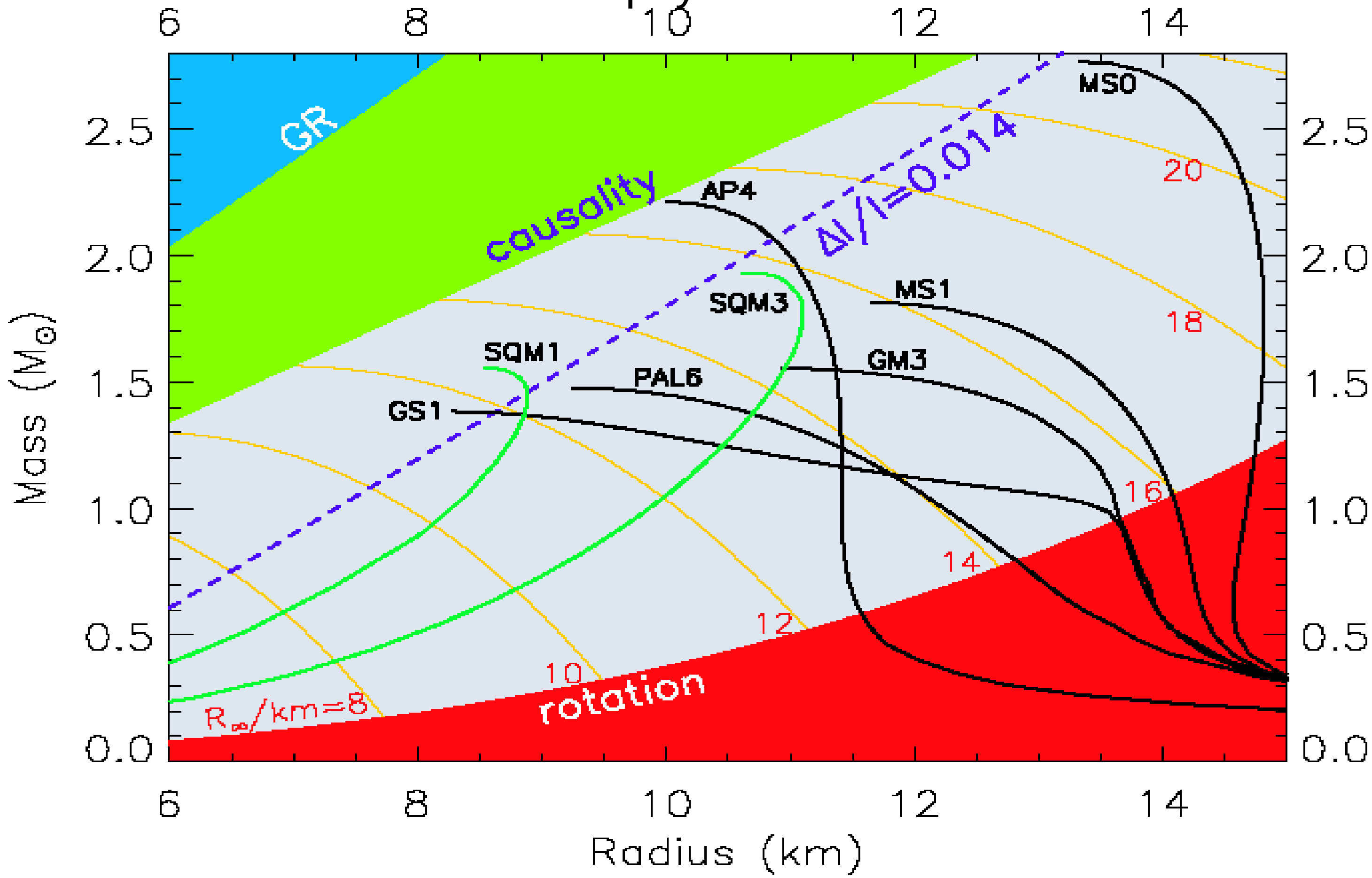
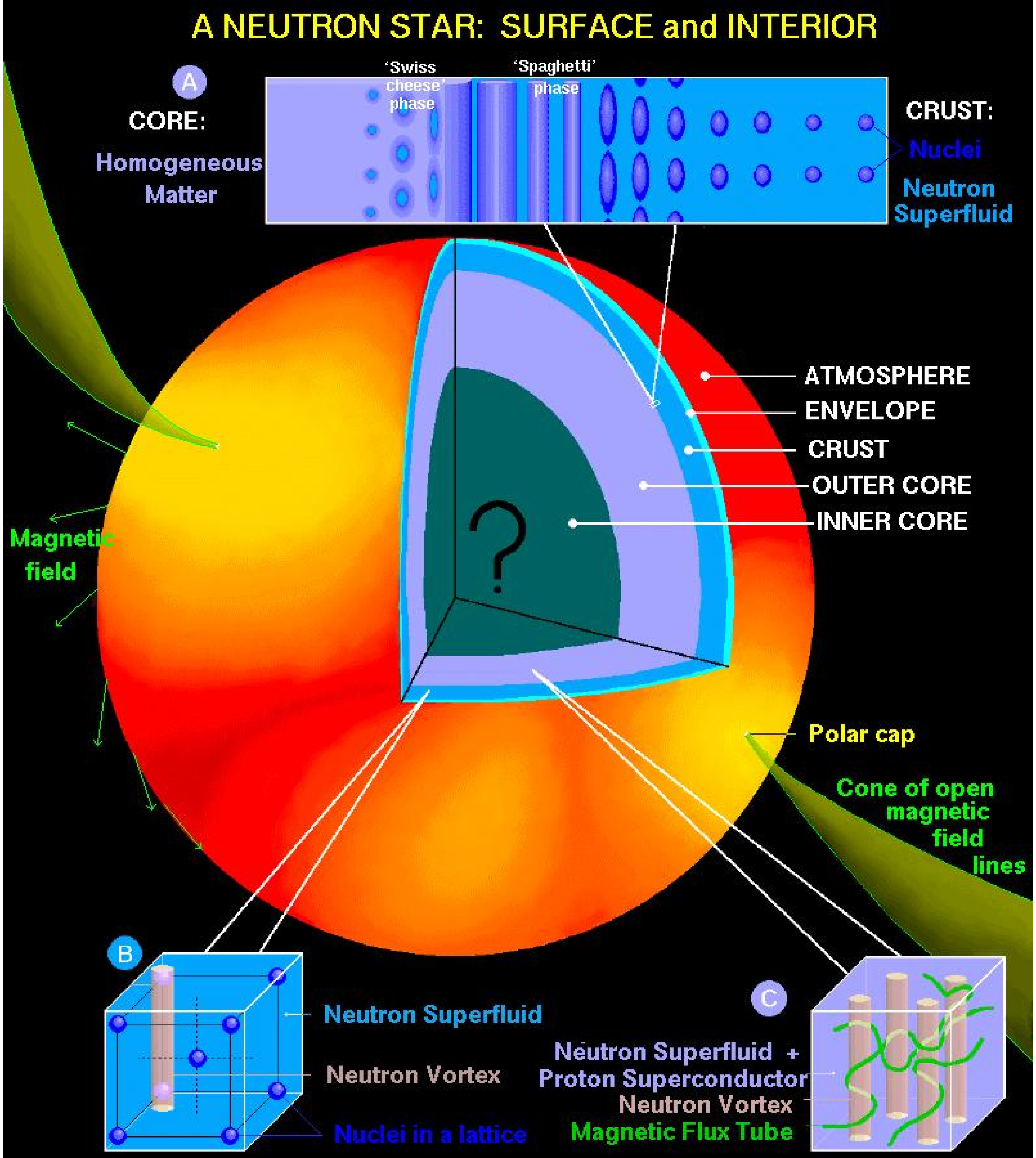
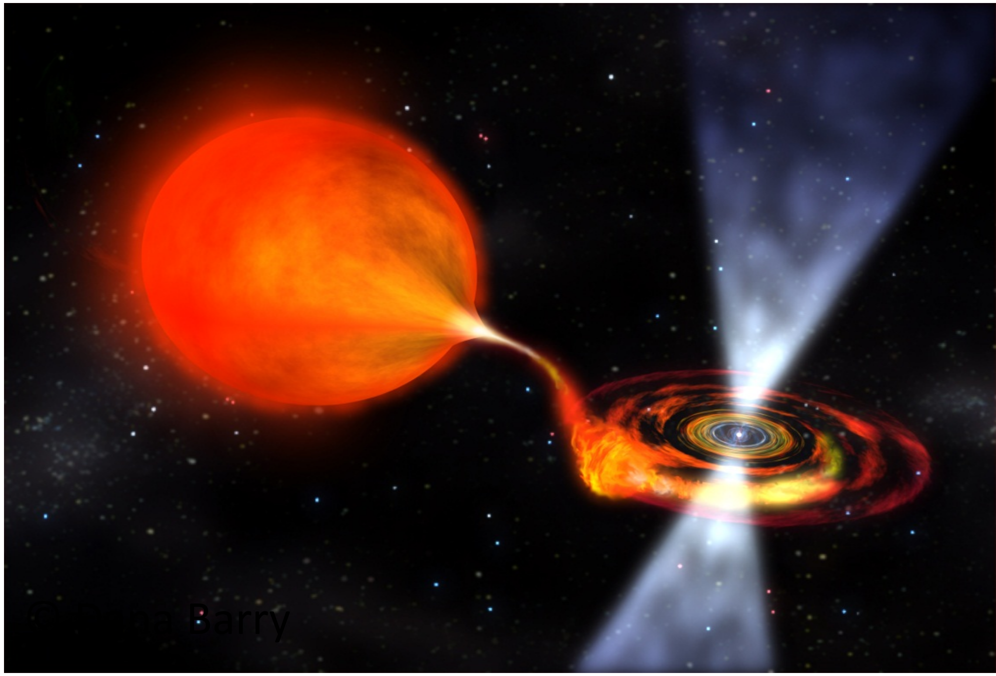


Fig. 2. Mass-radius diagram for neutron stars. Black (green) curves are for normal matter (SQM) equations of state [for definitions of the labels, see (27)]. Regions excluded by general relativity (GR), causality, and rotation constraints are indicated. Contours of radiation radii R_∞ are given by the orange curves. The dashed line labeled $\Delta I/I = 0.014$ is a radius limit estimated from Vela pulsar glitches (27).


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

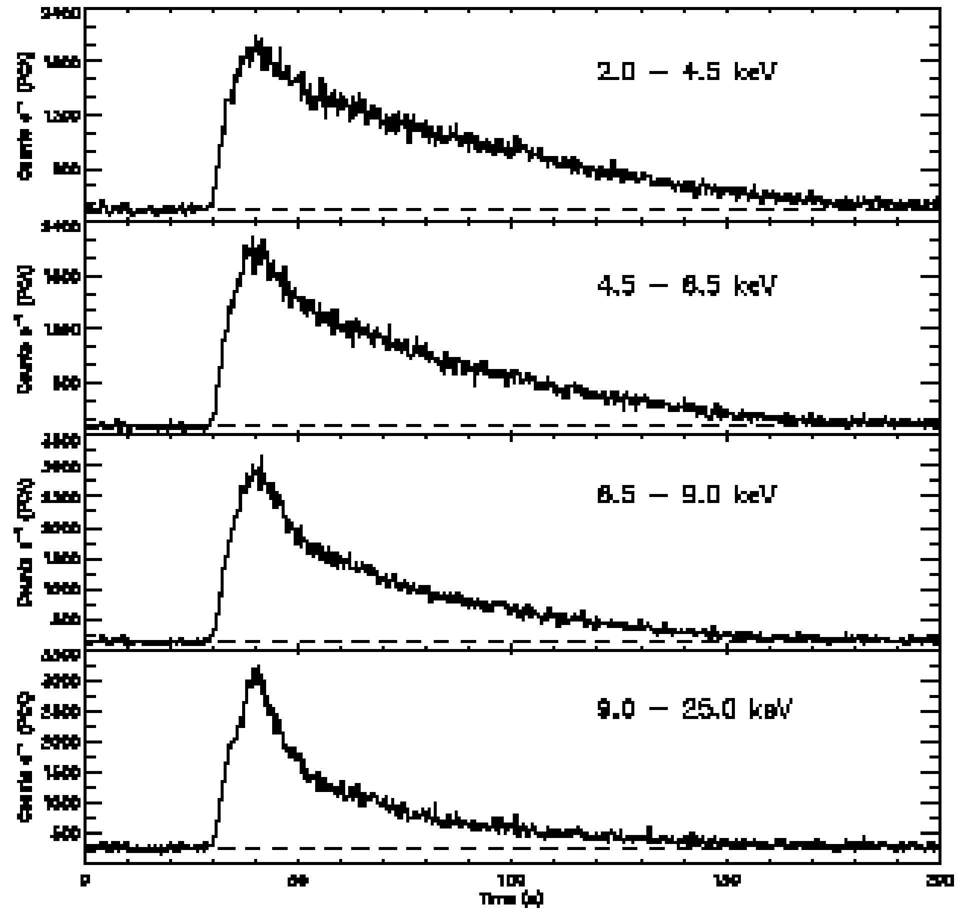
X-ray Bursts on Neutron Stars

- Occur in Low-Mass X-ray Binaries (LMXBs)
- Companions usually old main sequence stars, or (sometimes) C/O or He WDs
- About 70 of the 160 known LMXBs produce bursts
- Accreted H and He builds up on surface of NS
- If the accretion rate is less than Eddington then unstable H or He burning can occur (cf. He flash in AGB stars)
- Generated heat leaks out as X-rays



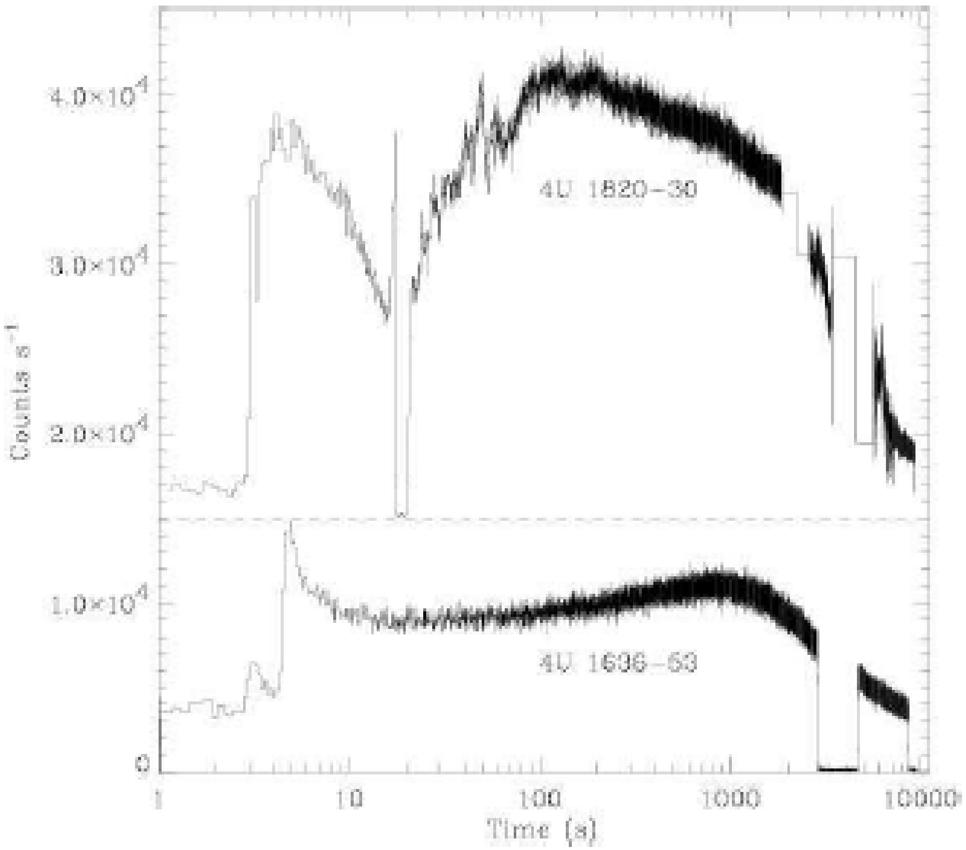
Observational Characteristics – Type I Bursts

- Typical duration: 10s – few minutes
- Can reach the Eddington Luminosity (~10^{38} erg/s)
- Spectra are well described by a blackbody with peak temperature ~3 keV
- Blackbody radii ~10 km
- Recurrence time 2-10 hours (depends on accretion rate)
- Persistent luminosity from accretion and stable burning generally has both a soft thermal blackbody + Comptonized harder component



GS 1826-238; Kong et al. (2000)

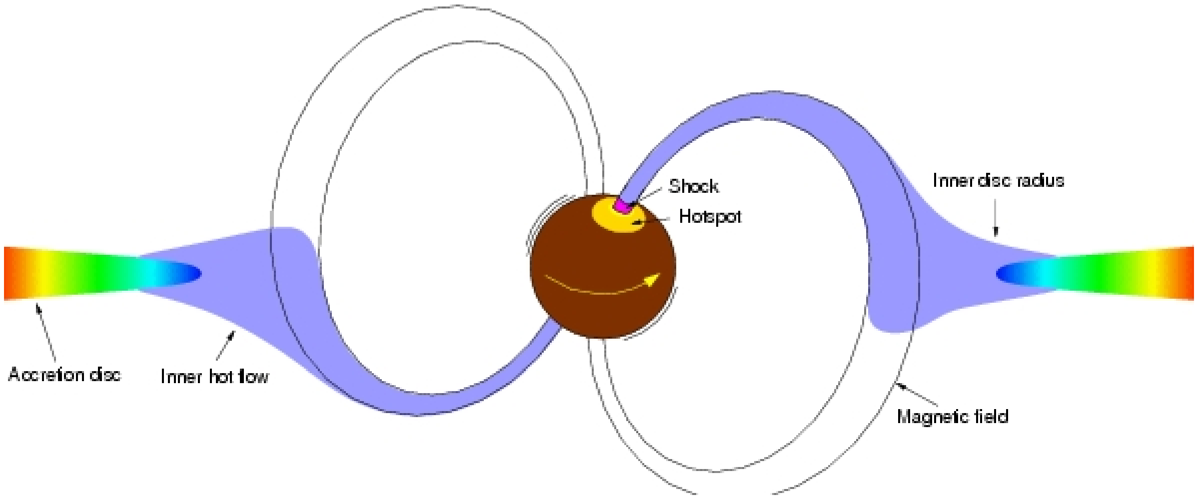
Superbursts – a new regime

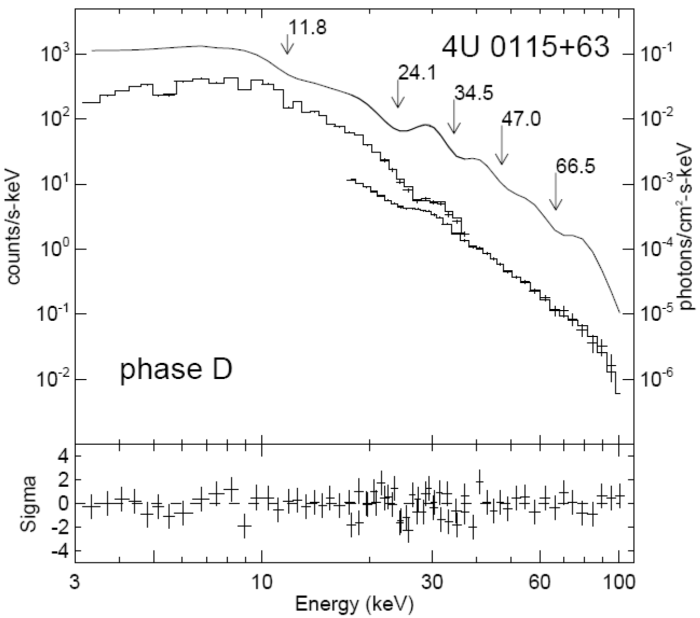


Strohmayer & Bildsten 2003

- 1000x longer and more energetic than Type I bursts
- many show a Type I precursor
- 9 superbursts detected from 7 sources
- also show thermal spectra, but only one (out of 9) reached Eddington L
- possibility that superburst 'quenches' the Type I burst for a number of days
- the total energy released + long timescale → burning in a deep layer
- Thought to be unstable C burning in an ocean of the heavy rp-process ashes from the Type I bursts
- recurrence time unknown (~1 year? 4U 1636)

Accretion Powered Pulsars





The observed (histogram) and model spectrum (solid line) of the accretion-powered
:U 0115+63 showing evidence for cyclotron lines with as many as four overtones
et al. 1999).