Phase Transitions in Neutron Stars: Structure and Signals

- Compact stars are known in the form of:

isolated neutron stars
pulsars
x-ray sources.

- X-ray sources:

accreting black holes
accreting neutron stars.

- Neutron stars with low-mass companion

spun up by conservation of angular momentum during mass transfer from companion
$\Longrightarrow$ the pathway from old canonical neutron stars to millisecond pulsars.

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Pulsars & Compact X-ray sources (= neutron stars)

Densest of stars

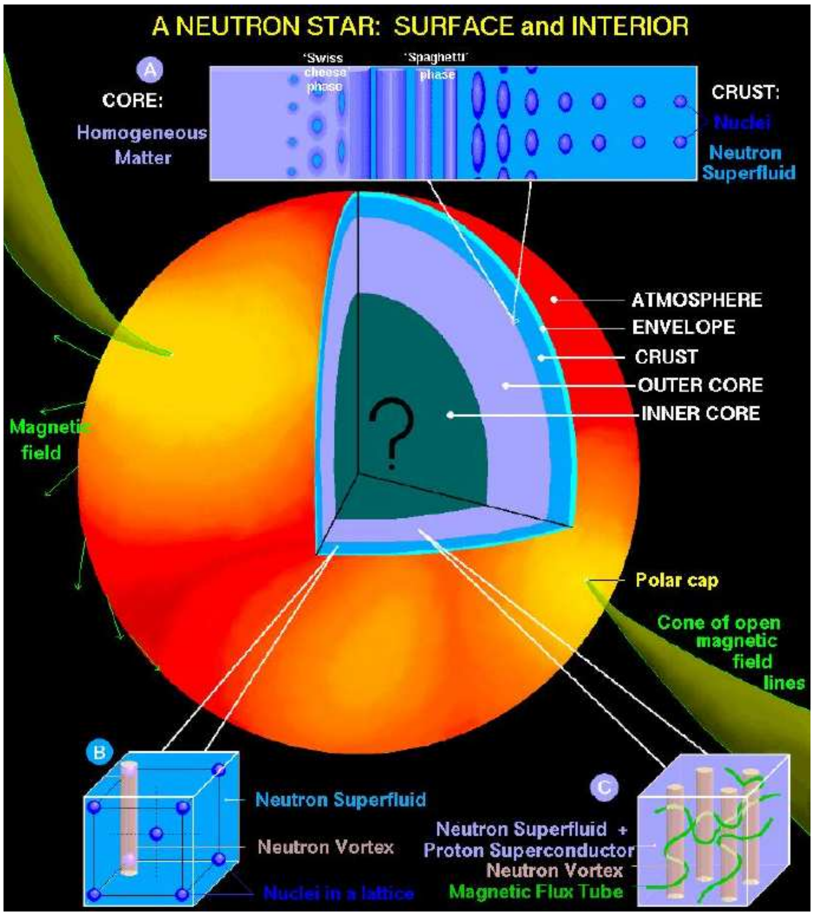
The only General Relativistic Stars

–surface gravity M/R of Black hole =0.5,

Neutron star =0.2,

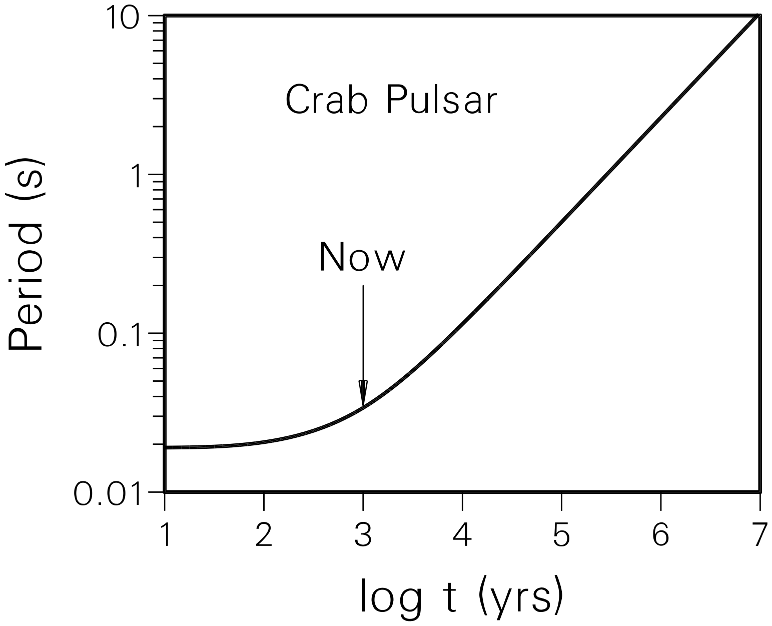
Sun $=10^{-6}$

(Gravitational binding)/(Nuclear binding) ~ 10.



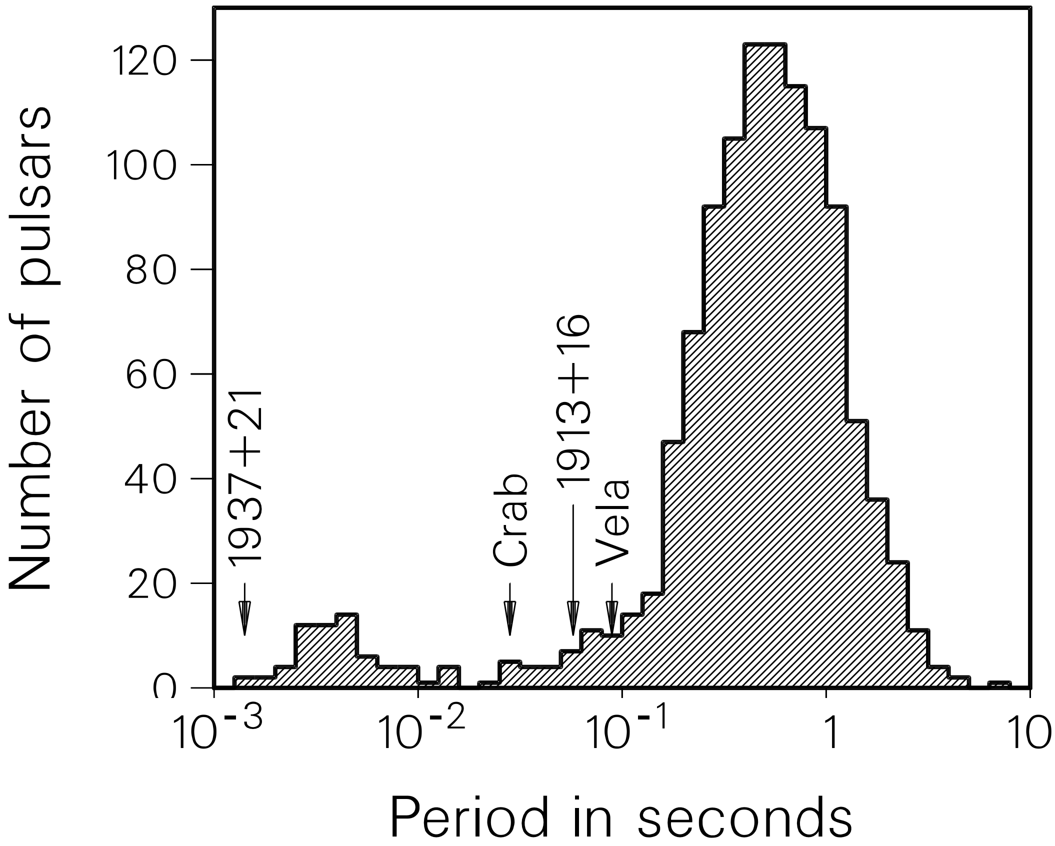
History

- 1054 Chinese astronomer “observed the apparition of a guest star...its color an iridescent yellow”
- 1933 Baade and Zwicky “closely packed neutrons”
- 1939 Oppenheimer, Volkoff and Tolman
- 1967 Pacini predicted magnetic dipole radiation
- 1967 Hewish & Bell’s serendipitous discovery
- 1984 Bacher’s discovery of Millisecond pulsar
- 1992 Wolszczan & Frail, discovery of 3 planets



50 millisecond (mass-accretion) (low magnetic field B)

1000 canonical (SN collapse) (high B)



Ms pulsars have remarkably stable pulses:

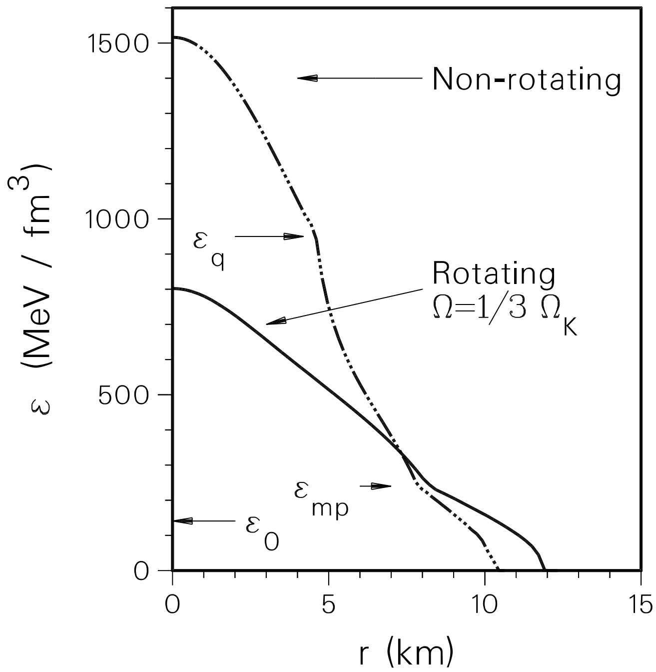
$$P = 1.55780644887275 \pm 0.00000000000003 \text{ ms}$$

(on 29 Nov 1982 at 1903 UT)

Neutron stars:— Stable laboratory for dense matter physics on equilibration timescales.

Central densities change over timescales of Myr caused by—
• spindown by magentic torque
or
• spinup by mass accretion.
• • contrast with relativistic nuclear collision 10^{-23} sec

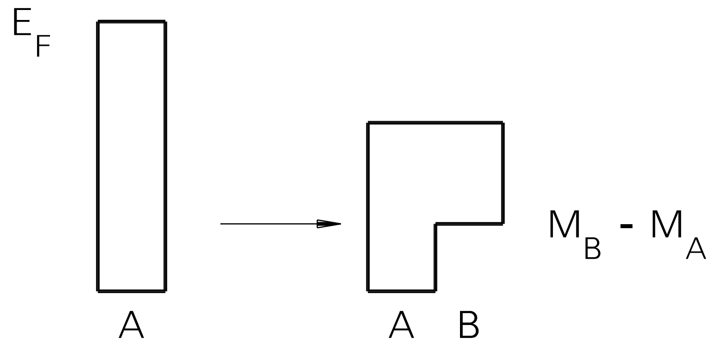
$\Longrightarrow$ Noticable change will not occur on a human lifetime,

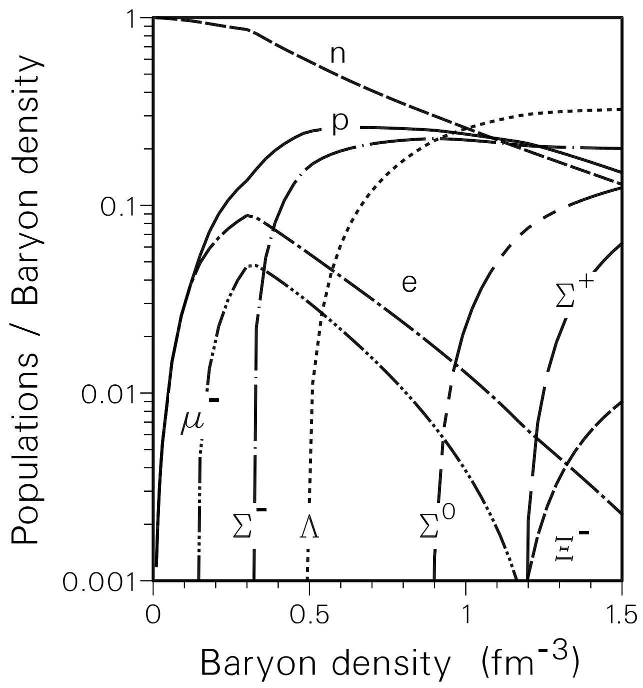


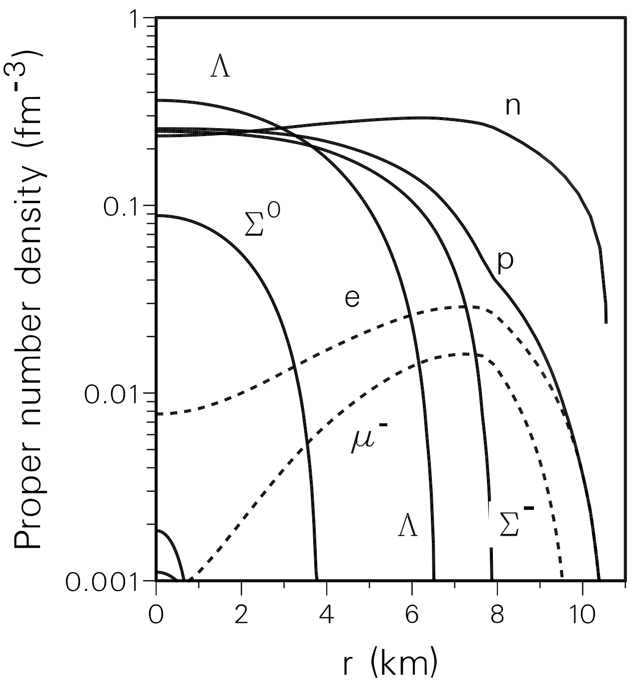
• Neutron stars are <u>degenerate</u> objects ($\mu << T$).
• Stars are electrically <u>neutral</u>. ($Z_{\rm Net}/A \sim (m/e)^2 < 10^{-36}$)
• Baryon number and charge are <u>conserved</u>.
• Strangeness <u>not conserved</u> (beyond 10^{-10} seconds).

Hyperonization

$\Longrightarrow$ Pauli assures baryon number will be distributed over many species, including strange baryons







- Probably 2'nd order

Some possible consequences:

1. The maximum mass is reduced by 1/2 - 3/4 $M_\odot$.
   (60%n, 20%p, 20%Y)
2. Small black hole populations: $1.5 - 2M_\odot$
3. Transport properties
4. charge neutrality achieved among conserved baryons,
   $\Longrightarrow$ electron chem pot. saturates
   $\Longrightarrow$ maybe no kaon condensation,

First order transition in Neutron Stars

(Glendenning, PRD 1992)

for example:
kaon condensation,
quark deconfinement: $\Longrightarrow$

(1) to an uncorrelated phase

(2) to color-flavor locked phase.

IF Color-flavor locked energy-benefit overwhelms the effect of the isospin-symmetry energy of the normal phase

$\Longrightarrow$ mixed phase is absent.

Why a first order phase transition is different in a system with only ONE component rather than in TWO (or more) Concentration of conserved charges

$$Q/B = c$$

is fixed by initial preparation in either <u>pure</u> phase
but:

$$Q_1/B_1 = c_1 \quad \text{and} \quad Q_2/B_1 = c_2$$

may differ from c to minimize energy of <u>mixed</u> phase
so long as:

$$Q_1 + Q_2 = Q, \qquad B_1 + B_2 = B$$

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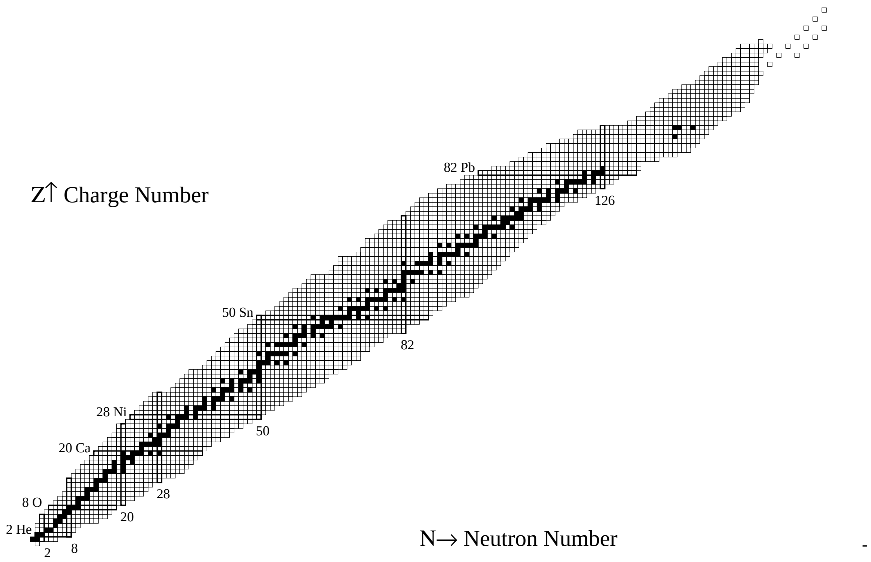
Key Concepts

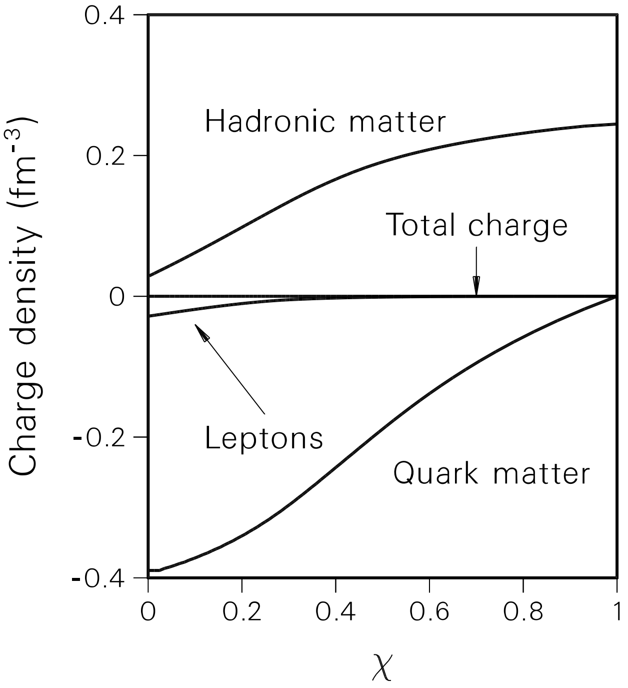
1. **Degree(s) of freedom** to exchange quarks (charge, strangeness) between the phases
which are exploited by
2. **Driving force(s)** such as the symmetry driving term of nuclear matter.



A neutron star matter has many more neutrons than protons $\Longrightarrow$ can reduce the repulsive symmetry driving term by exchanging charge (quarks) with quark matter. Both become charged of opposite sign.

Thus the a neutron star with two phases in equilibrium can achieve charge neutrality more economically globally

$$\int q(r)\, dr = 0 \quad \text{instead of locally} \quad q(r) \equiv 0\,.$$



$$\chi = V_Q/V_N$$

3. **Coulomb force** tends to break up regions of like charge—surface energy resists $\Longrightarrow$ Coulomb lattice of the two phases is formed.

PROOF OF GLOBAL nature of conservation laws

Gibbs condition for phase equilibrium:

1. One Conserved Charge

$p_1(\mu, T) = p_2(\mu, T)$

defines unique solution for μ at given T

2. Two Conserved Charges

$p_1(\mu_n, \mu_e, T) = p_2(\mu_n, \mu_e, T)$

requires **one** additional condition which depends on the proportion of the two phases in equilibrium.

- **global not local** conservation:

$$(1-\chi)q_1(\mu_n, \mu_e, T) + \chi q_2(\mu_n, \mu_e, T) = 0,$$

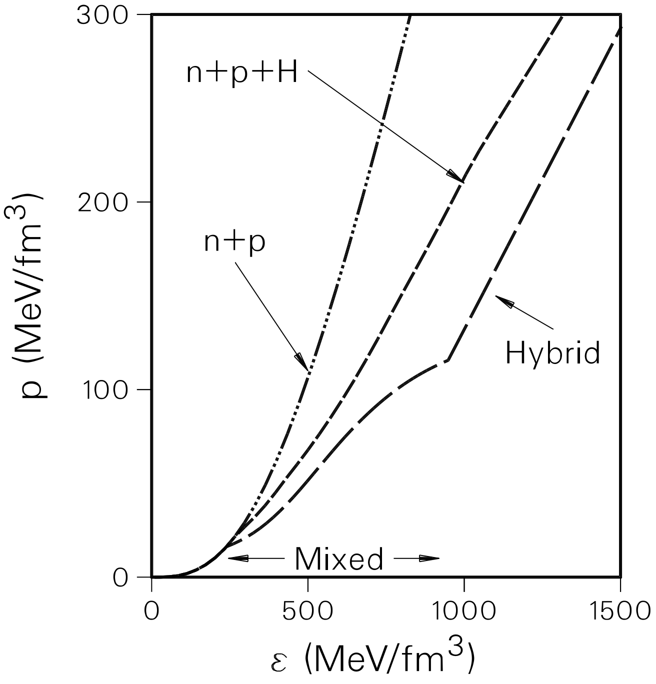
where $\chi = V_2/V, \qquad V = V_1 + V_2.$

Given T and χ solve for $\qquad \mu_n,\ \mu_e$

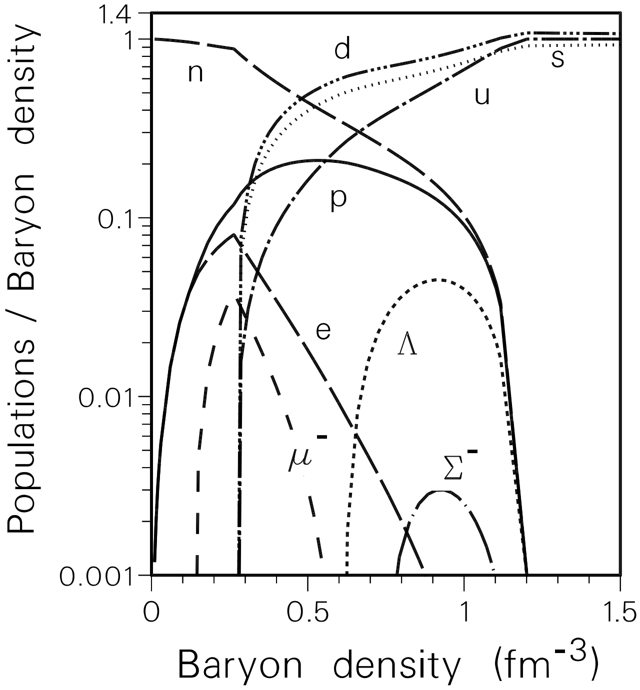
- Thus the solutions are of the form

$$\mu_n = \mu_n(\chi, T), \qquad \mu_e = \mu_e(\chi, T)\,.$$

$\longrightarrow$ all properties of the phases in equilibrium change with proportion.



p (MeV/fm^3)
ε (MeV/fm^3)
n+p+H
n+p
Hybrid
Mixed
0
100
200
300
0
500
1000
1500



Populations / Baryon density
Baryon density (fm^{-3})
n
d
s
u
p
e
Λ
μ^-
Σ^-
1.4
1
0.1
0.01
0.001
0
0.5
1
1.5

STRUCTURES
Wigner-Seitz cells with the rare phase inside.
The Coulomb and surface energy for drops, rods or slabs ($d = 3, 2, 1$).

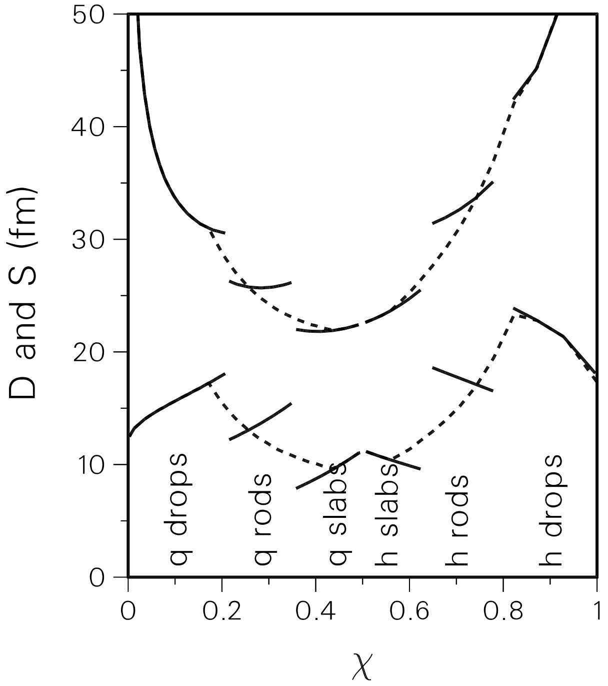
$$\epsilon_C = C_d(\chi) r^2 \,,$$
$$\epsilon_S = S_d(\chi)/r \,,$$

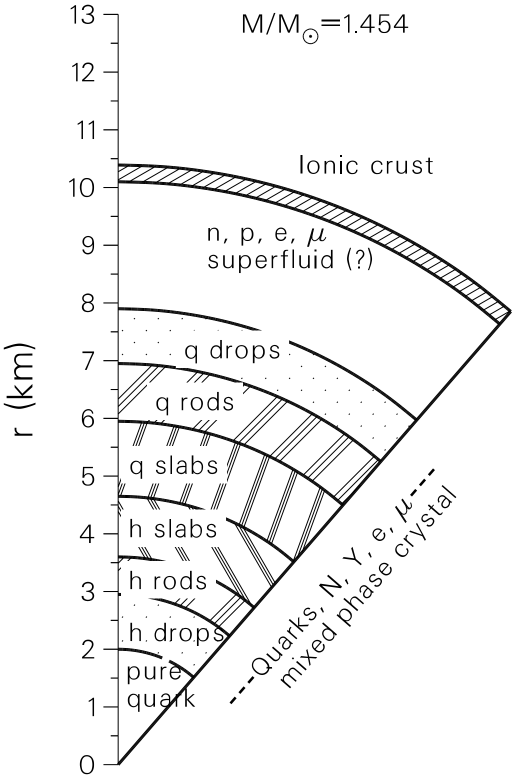
where $\quad \chi = V_2/(V_1 + V_2)$.

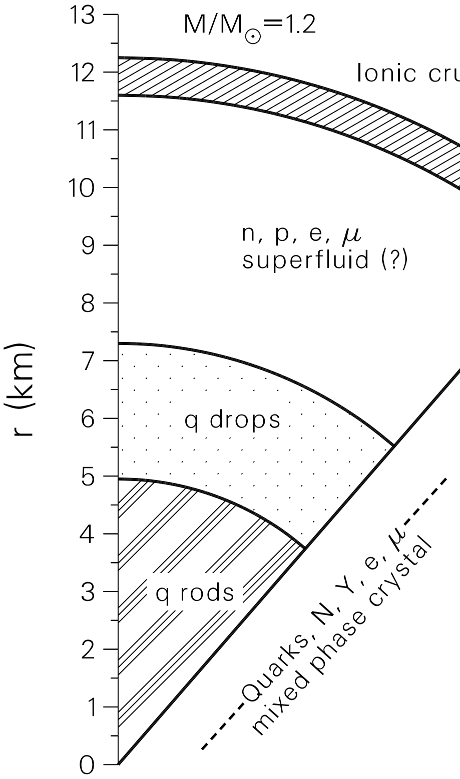
• Minimize the sum to find $\epsilon_S = 2\epsilon_C$. • Hence,

$$r = \left(\frac{S_d(\chi)}{2C_d(\chi)}\right)^{1/3},$$
$$R = \frac{r}{\chi^{1/d}} \quad if\ hadronic\ phase\ is\ background$$
$$R = \frac{r}{(1-\chi)^{1/d}} \quad quark\ phase\ is\ background\,.$$

• Layers of various structures in neighboring mass stars:







Color-Flavor Locked Quark Matter (CFL)

Rajagopal & Wilczek

Fermi surface is unstable to correlations of quarks of opposite momentum and different flavors forming BCS pairs.
Greatest energy benefit if Fermi surfaces of all flavors are equal.
$\Longrightarrow$ color and flavor are linked by an invariance to simultaneous rotations of color and flavor ($\Delta \sim 100$ MeV).

Energy density

$$\epsilon_{\rm CFL} \sim -C(k_F\,\Delta)^2 \sim 50 \cdot C \text{ MeV/fm}^3.$$

$\Longrightarrow$ perhaps
(1) no mixed phase,
(2) equal number of u,d,s quarks, no electrons.

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BUT

Not a question of “either one or the other” BUT “one then the other”

$$\epsilon_{\text{symmetry}} = -35\,[(N-Z)/(N+Z)]^2 \text{ MeV/fm}^3$$

(at density of phase transition, $\rho \sim 1/\text{fm}^3$)
Must compare

$$[V_N/V] \cdot \epsilon_{\text{symmetry}} - [(1-V_N)/V] \cdot \epsilon_{\text{unif.}-\text{quark sym.}}$$

with

$$[(1-V_N)/V] \cdot \epsilon_{\text{CFL}} - [V_N/V] \cdot \epsilon_{\text{nucl. sym.}}$$

at each proportion.

ROTATION INDUCED PHASE TRANSITIONS

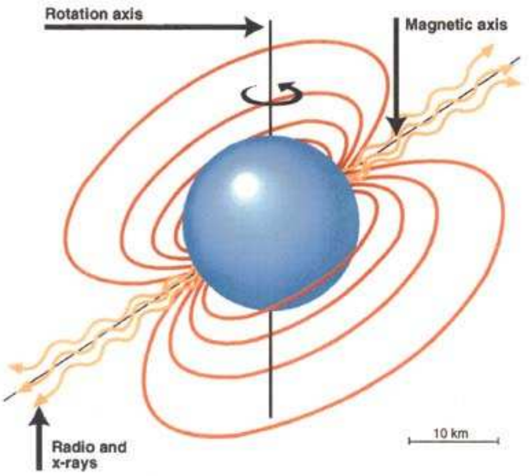
• Pulsars are rotating neutron stars with large magnetic fields and enormous rotational energy ($E_{\rm rot} \sim 10^{55}$ MeV).

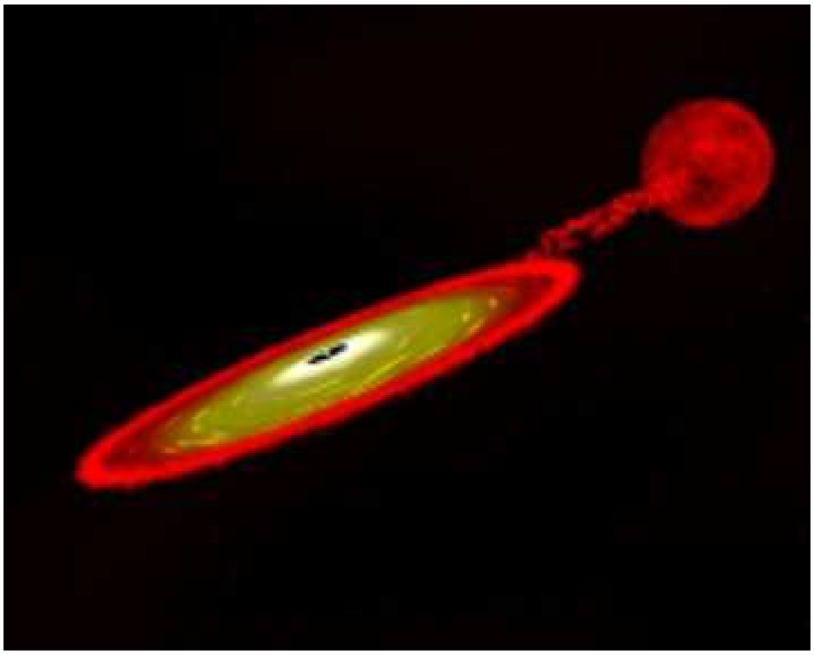
• Angular momentum radiated by <u>weak</u> processes (EM radiation and wind of electron pairs)

• therefore spin down over millions of years;
$(10^{-20} < dP/dt < 10^{-14}$ s/s)

MASS ACCRETION DRIVEN SPINUP

• $\sim 10^{-9} M_\odot$/year





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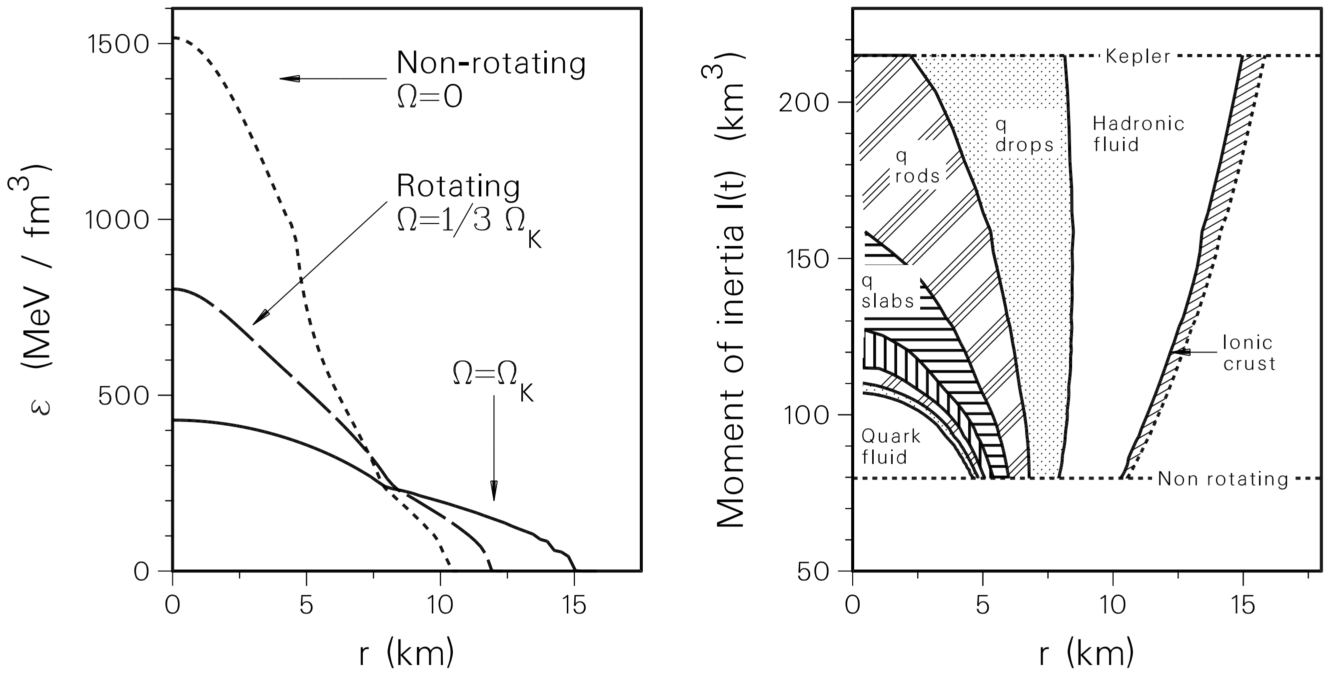
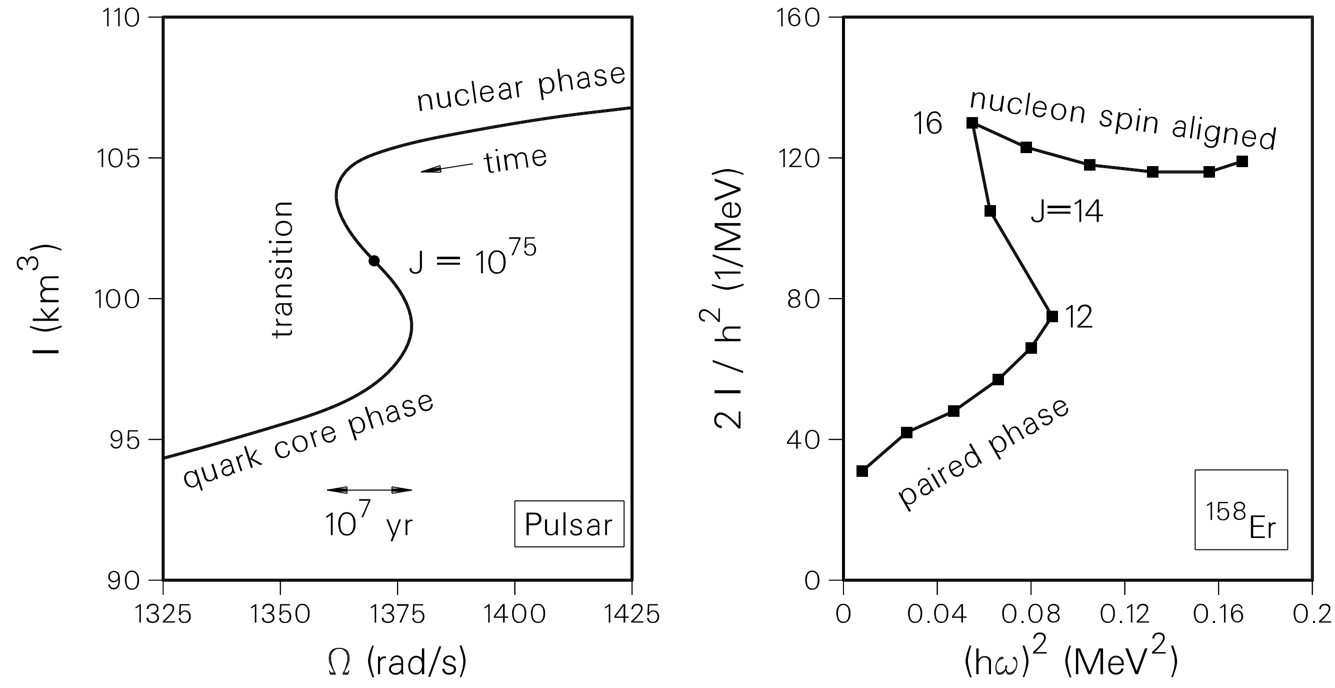
$\Longrightarrow$ pulsar evolves in shape from a spheroid to a sphere.

$\Longrightarrow$ The interior density rises ever so slowly.

$\Longrightarrow$ The star evolves!

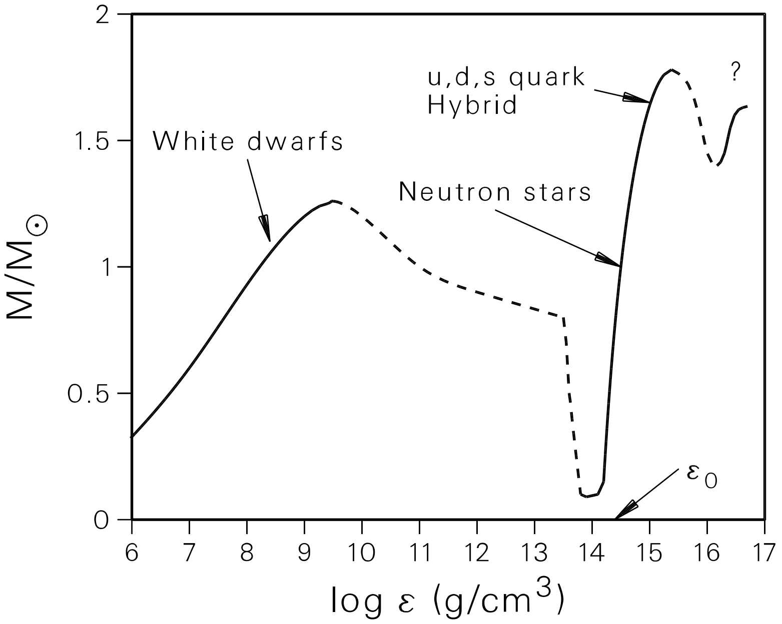


CHANGE IN MOMENT OF INERTIA WITH SPIN AND PHASE CHANGE



Backbending in nuclei predicted in 1960 by Mottelson and Valatin.
(phase transition from spin aligned state at high Ω to pair-correlated superfluid at low Ω)

Non-identical Neutron Star Twins



For smooth EOS $\Longrightarrow$ only **one** family of compact stars (Wheeler, 1964).
In principle second *denser* family could exist if phase transition occurs.

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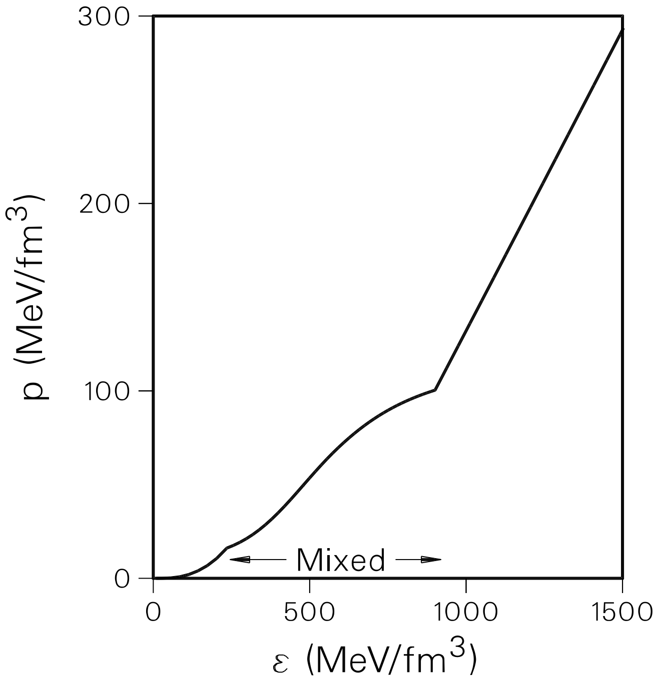
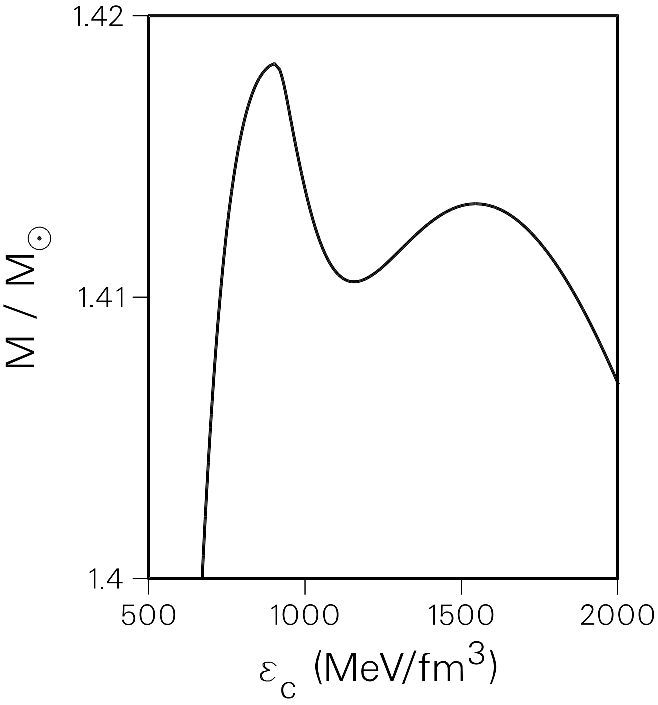
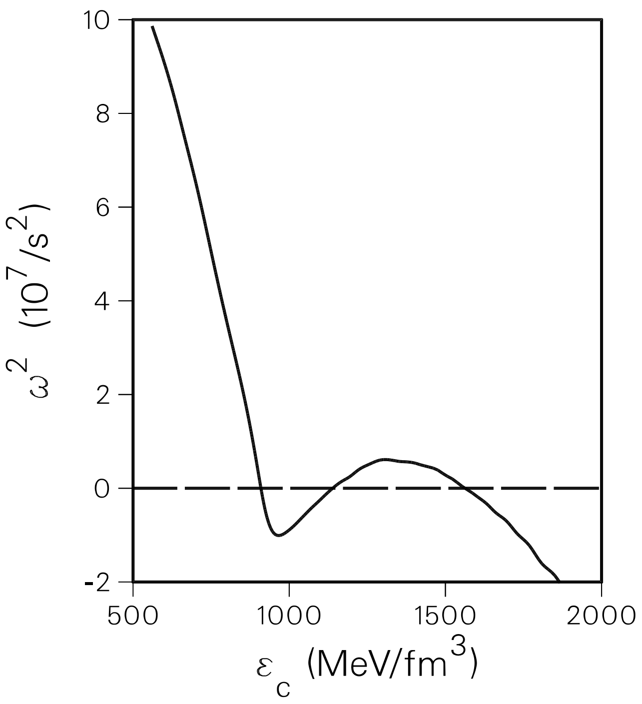
Example !!



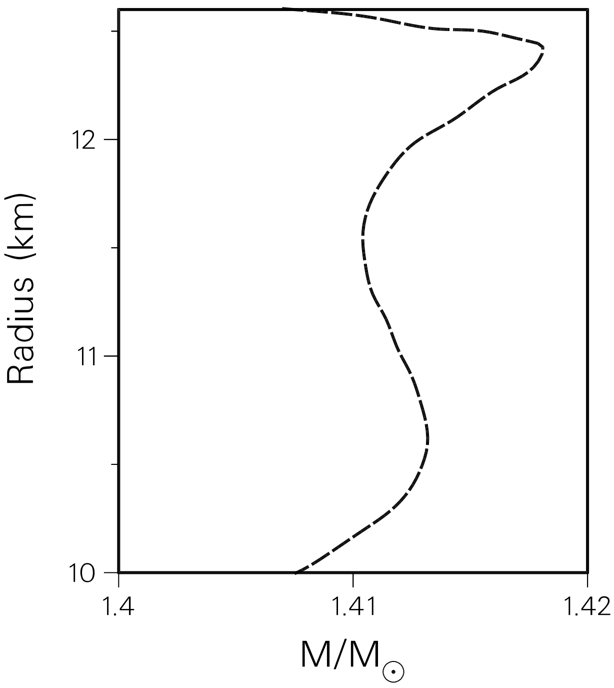
300
200
100
0
0
500
1000
1500
p (MeV/fm3)
ε (MeV/fm3)
Mixed

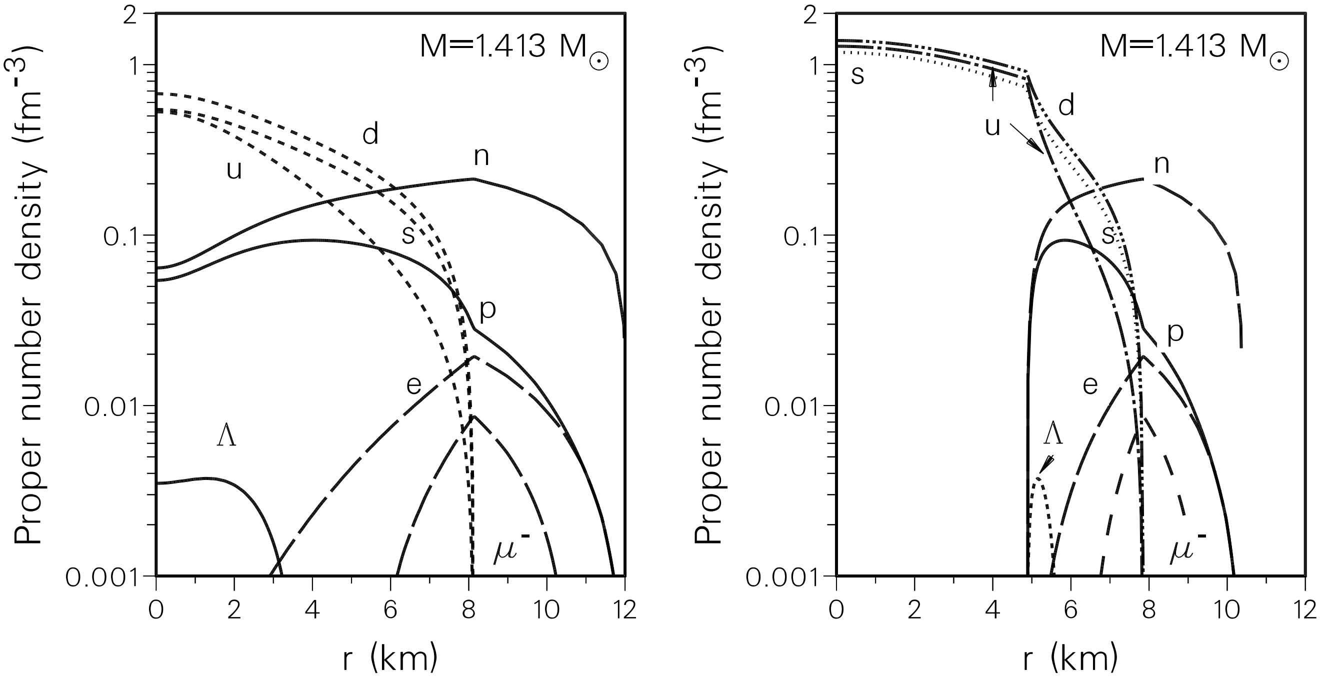


1.42
1.41
1.4
500
1000
1500
2000
M / M⊙
εc (MeV/fm3)



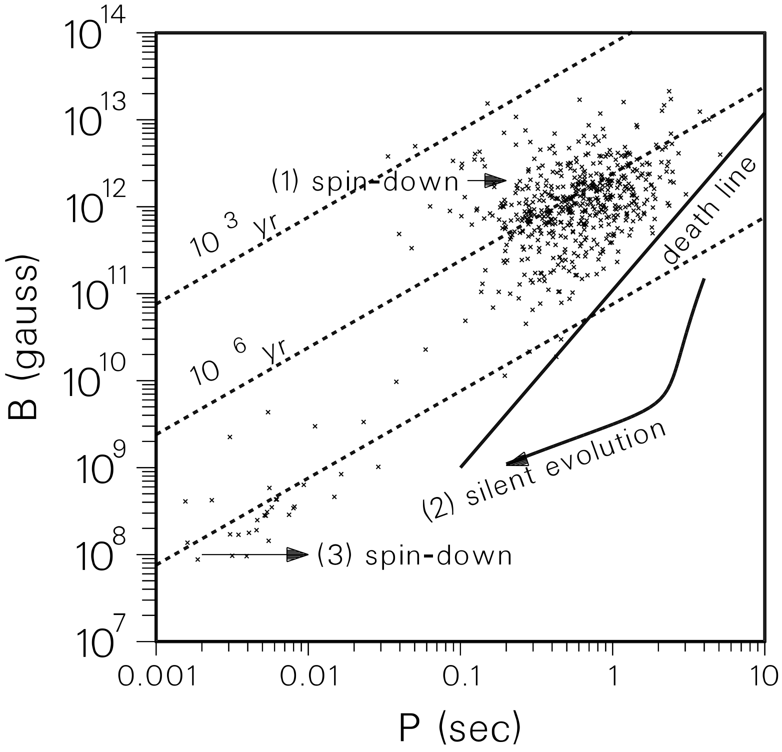
10
8
6
4
2
0
-2
500
1000
1500
2000
ω2 (107/s2)
εc (MeV/fm3)


Radius (km)
12
11
10
1.4
1.41
1.42
M/M$_\odot$


M=1.413 M$_\odot$
Proper number density (fm^{-3})
2
1
0.1
0.01
0.001
d
u
n
s
p
e
Λ
μ^-
0
2
4
6
8
10
12
r (km)
M=1.413 M$_\odot$
Proper number density (fm^{-3})
s
d
u
n
s
p
e
Λ
μ^-
r (km)

X-RAY EMITTING NEUTRON STAR MASS ACCRETERS

pathway (2) from old canonical pulsars to millisecond pulsars (3)



Neutron star has a luminous companion.

Its gravity pulls matter (very slowly) from the companion.

Falling matter heats neutron star surface $\Longrightarrow$ emits x-rays.

Conservation of angular momentum of infalling mass $\Longrightarrow$ spins-up the neutron star.

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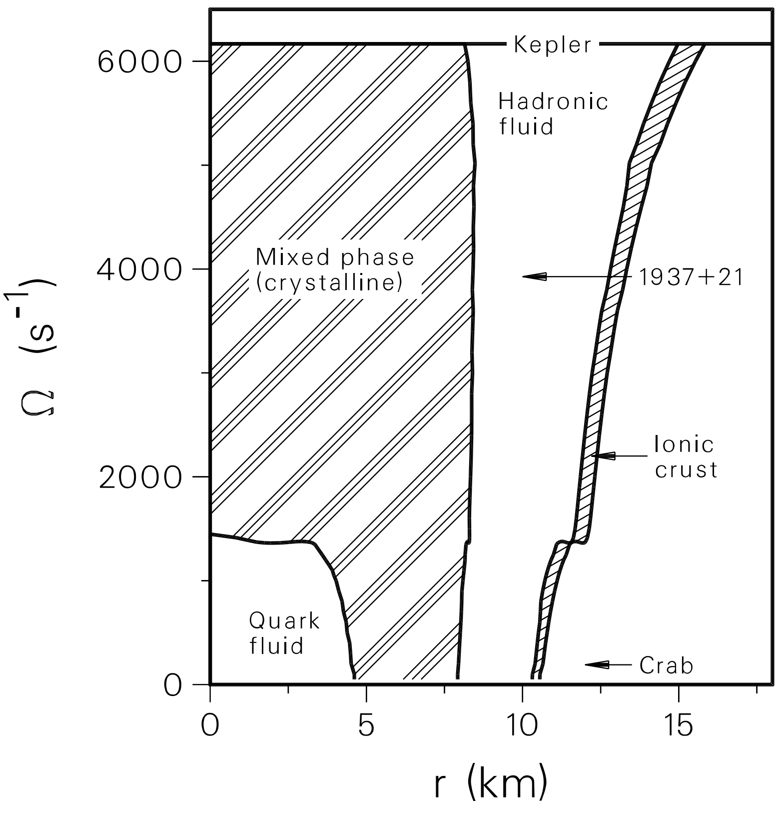
• Changes in rate of rotation, induced either by radiation (i.e. a pulsar)

OR

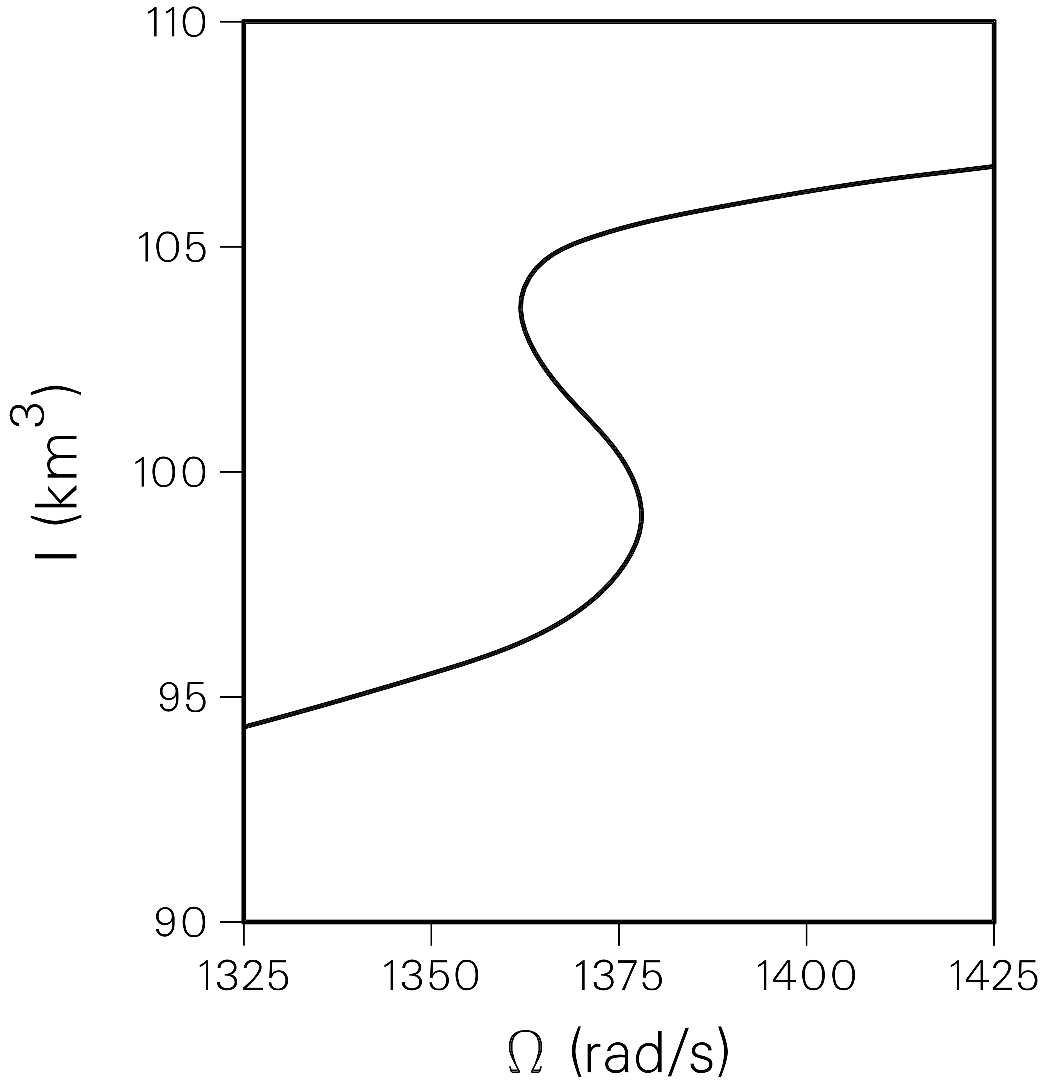
mass accretion driven spinup (i.e. neutron star in binary orbit)

$\Longrightarrow$ cause changes in density profile of the star over time.



• ASSUMPTION: Canonical (slowly rotating) neutron stars have quark matter core from birth.

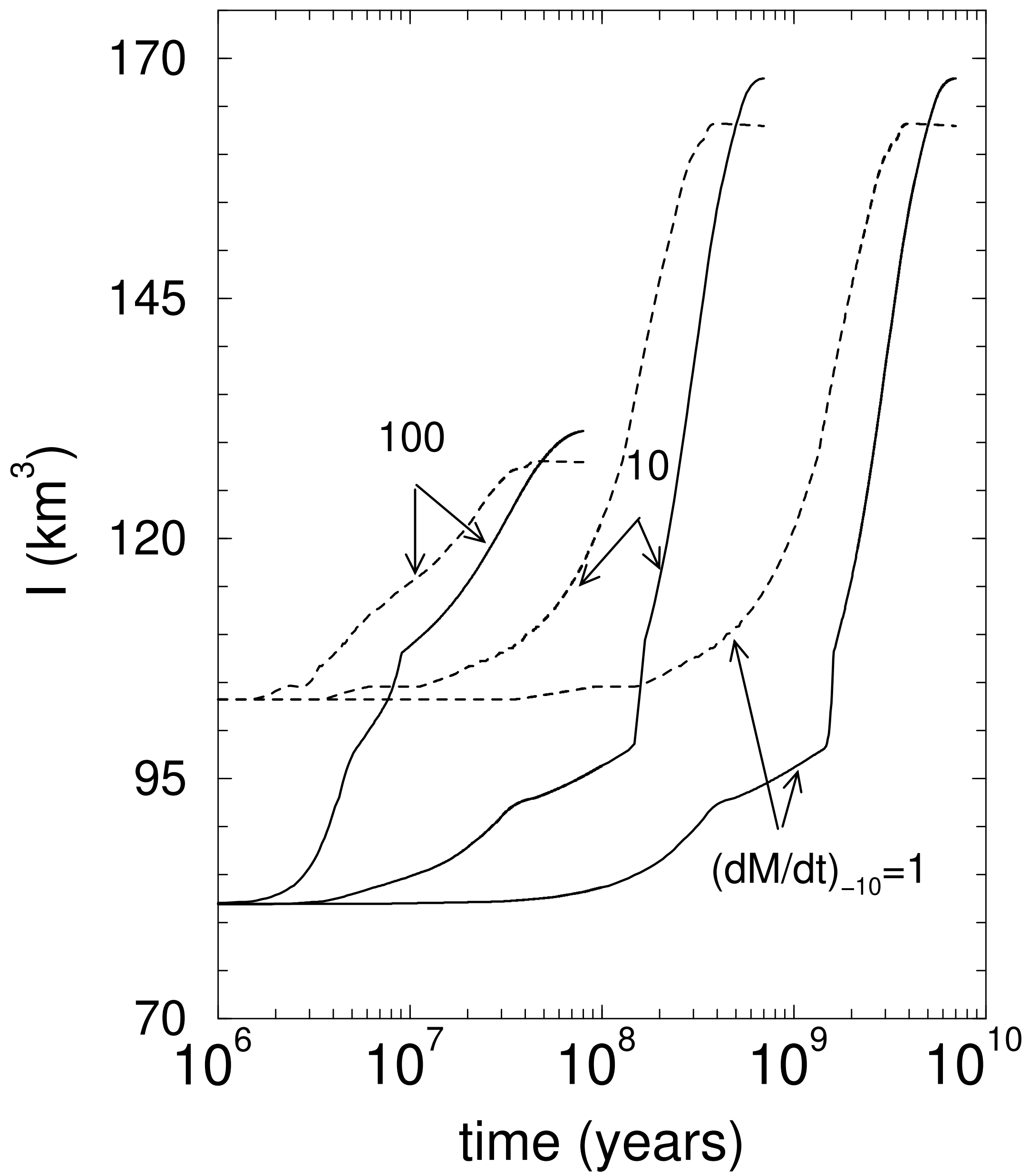
Response of the moment of inertia.



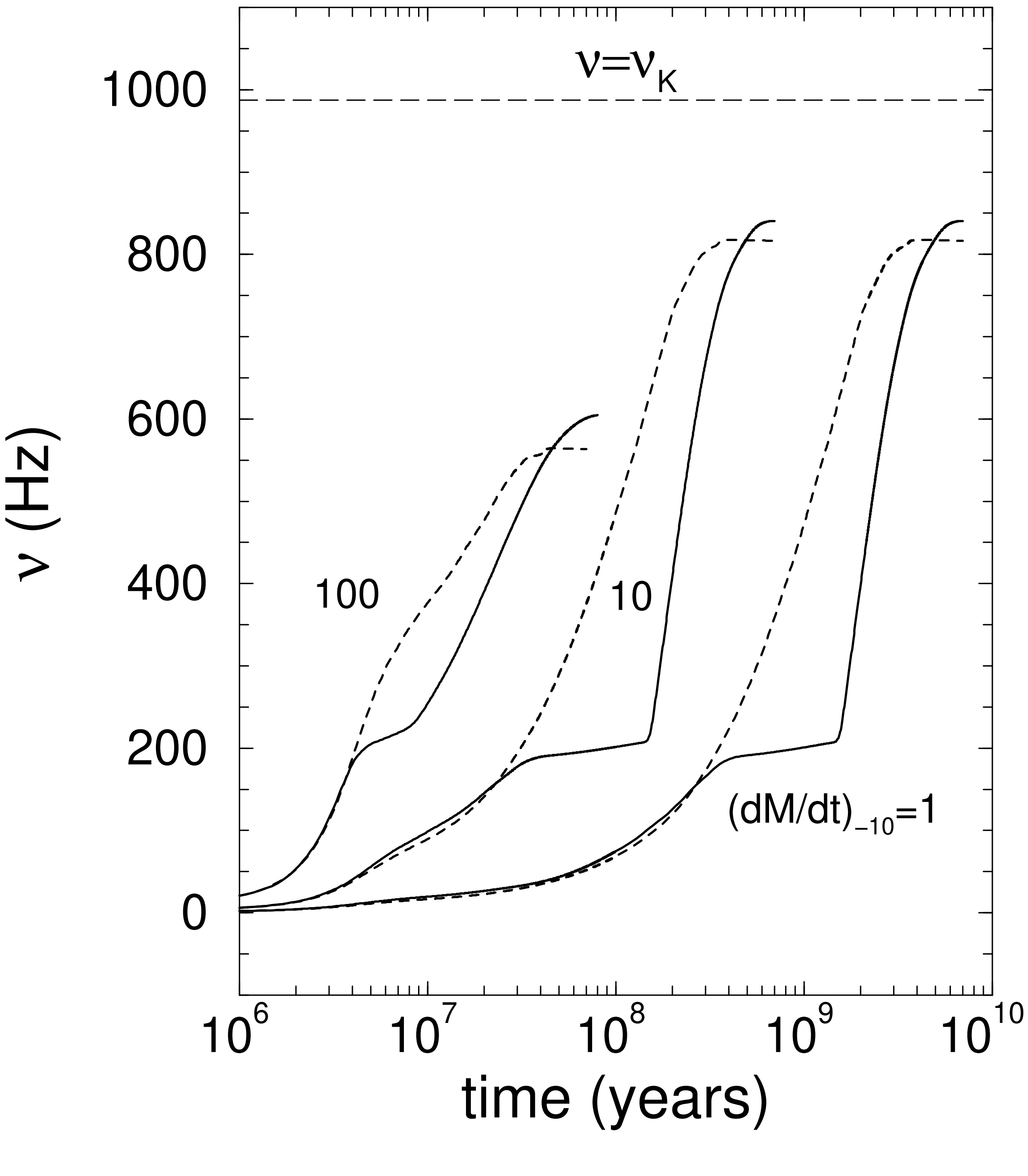
As star spins up **slowly** $\Longrightarrow$ central density reduced $\Longrightarrow$ quark phase is gradually spun out $\Longrightarrow$ moment of inertia annomolously increases as matter converts to stiffer normal phase $\Longrightarrow$ spinup is retarded.

Evolution of moment of inertia:

(dM/dt measured in 10^{-10} solar masses per year)

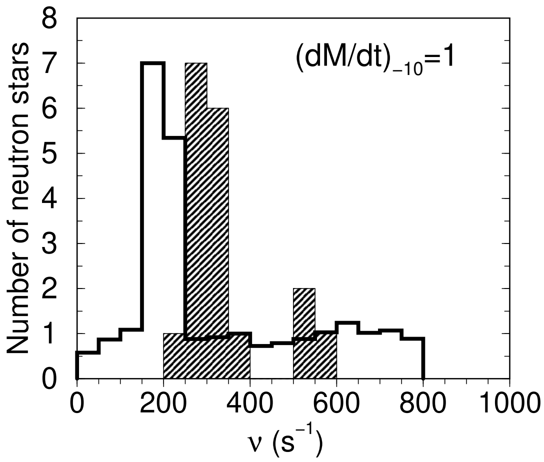


Evolution of rotation frequency of accretors:

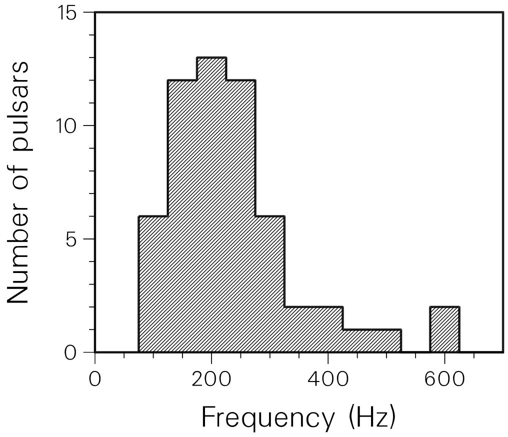


$\Longrightarrow$
There should be a spike in the number of x-ray NS in the corresponding interval of spin.
$\Longrightarrow$ Normal accretion induced spinup **resumes** when quark phase has been spunout.

Shaded histogram is observed in experiments on the Rossi satellite



Measured Spins of millisecond pulsars:



Evolutionary tracks of accretors