PHASES of DENSE MATTER in COMPACT STARS

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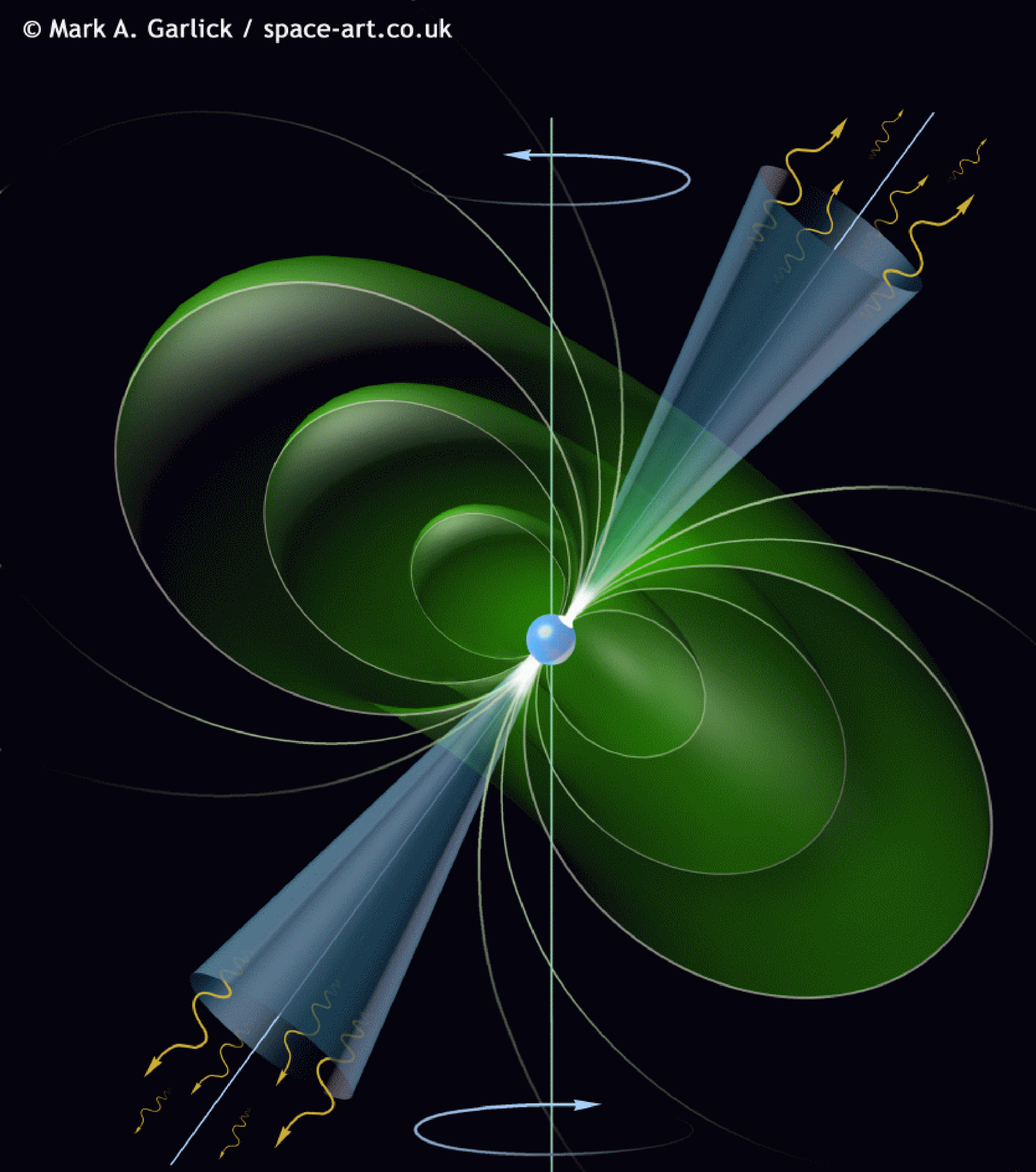
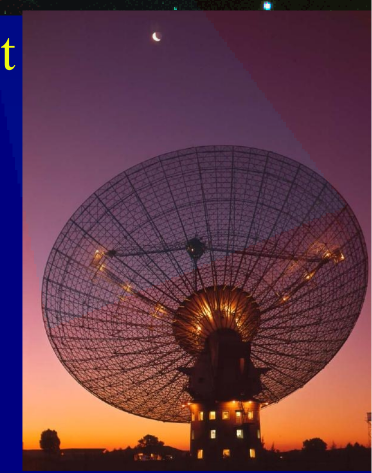
CBM Workshop, GSI, Darmstadt, 15-16 December 2005



Rotating Neutron Star (Pulsar)

Some facts about neutron stars:



$M \sim 1\text{-}2\ M_{sol}$

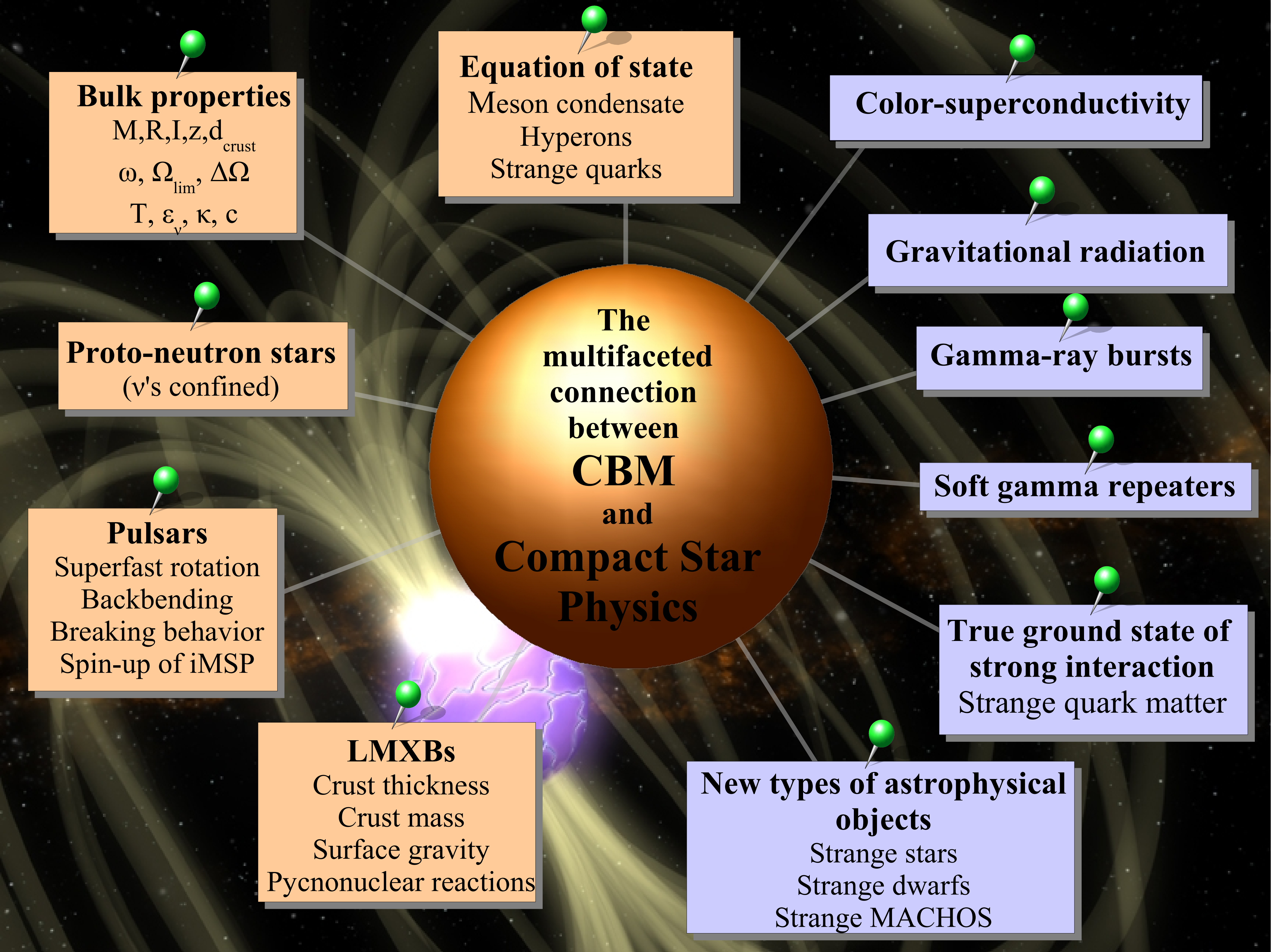
$R \sim 10$ km

$B \sim 10^{12\ \ldots\ 16}$ G

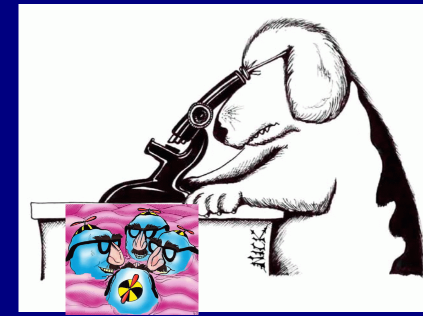
$\# \sim 10^{9} - 10^{10}$

$P_{min} = 1.58$ ms (630 Hz)

Ter5ad pulsar: P=1.39 ms (720 Hz)!


The multifaceted connection between CBM and Compact Star Physics
Bulk properties
M,R,I,z,d_{crust}
ω, Ω_{lim}, $\Delta\Omega$
T, ε_ν, κ, c
Equation of state
Meson condensate
Hyperons
Strange quarks
Color-superconductivity
Gravitational radiation
Gamma-ray bursts
Soft gamma repeaters
Proto-neutron stars
(ν's confined)
Pulsars
Superfast rotation
Backbending
Breaking behavior
Spin-up of iMSP
LMXBs
Crust thickness
Crust mass
Surface gravity
Pycnonuclear reactions
True ground state of strong interaction
Strange quark matter
New types of astrophysical objects
Strange stars
Strange dwarfs
Strange MACHOS

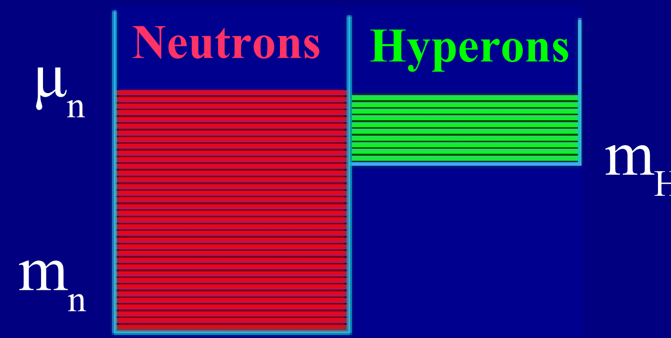
The Suspects



- Baryons (∑, Λ, Ξ, Δ)

$$p_F \geqslant \sqrt{m_H^2 - m_n^2} \simeq 3\, fm^{-1} \Rightarrow \rho > 2\rho_0$$

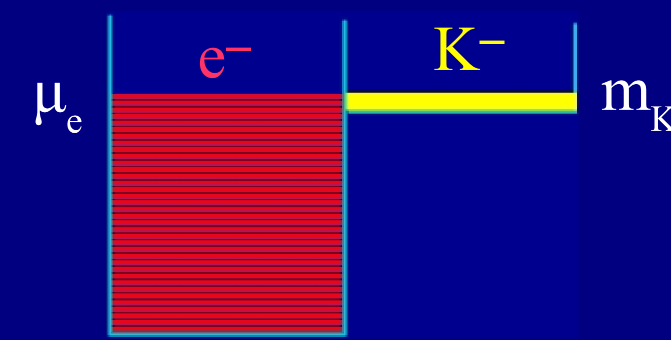
Ambartsumyan & Saakyan, 1960



- Boson condensates (π,K)

$$\rho > 3 - 5\rho_0$$

Brown & Weise, 1976
Kaplan & Nelson, 1986
Politzer & Wise, 1991
Brown et al., 1992
Waas, Rho, Weise 1997
Schaffner-Bielich, 1998
Mao 1999



- Quarks (u,d,s)

$$P_H(\mu^e, \mu^n) = P_Q(\mu^e, \mu^n) \Rightarrow \rho > 2 - 3\rho_0$$

Ivanenko & Kurdgelaidze, 1965
Fritzsch, Gell-Mann & Leutwyler, 1973
Collins & Perry, 1975
Baym & Chin; Keister & Kisslinger, 1976
Chapline & Nauenberg, 1977
Glendenning, 1992

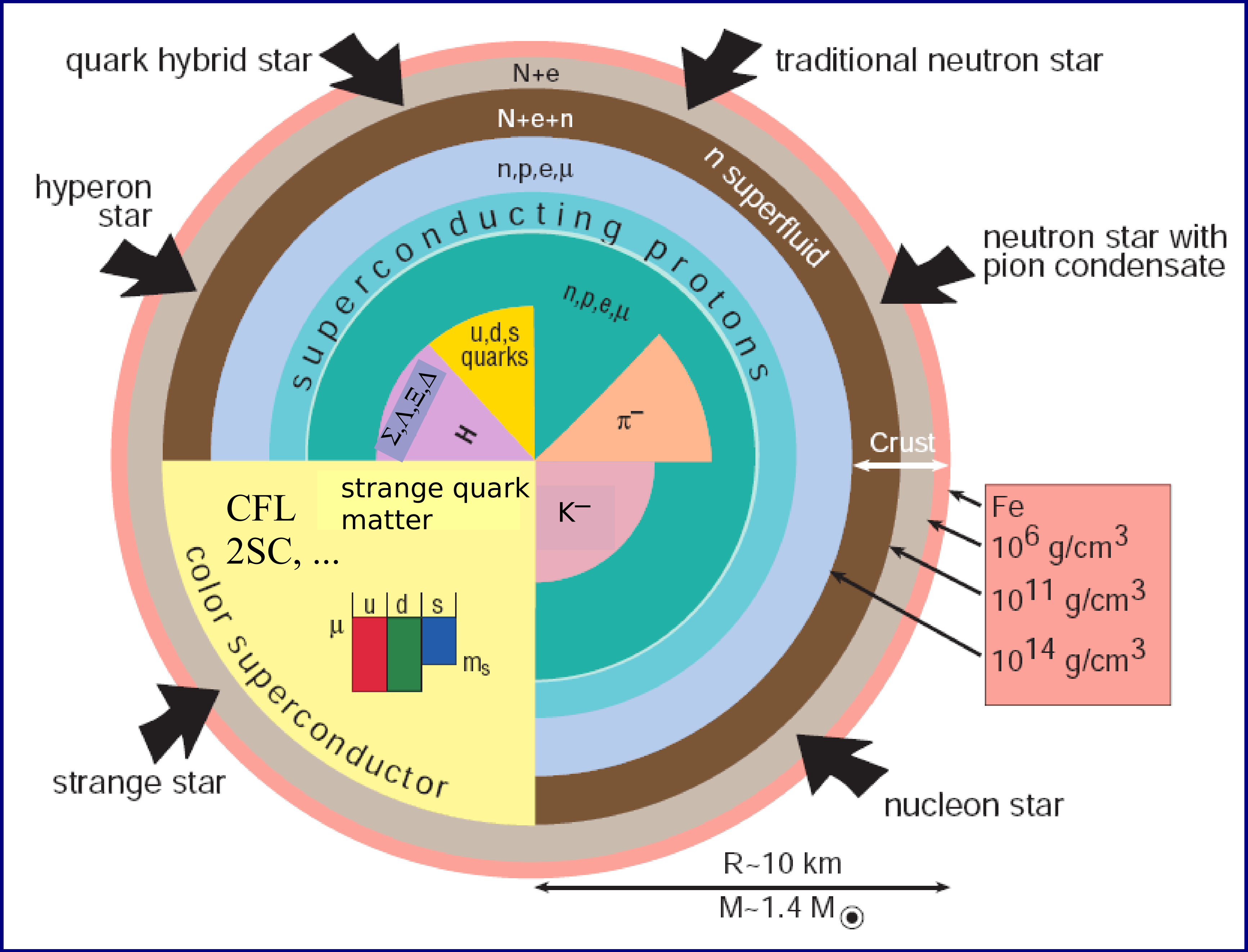
- H dibaryons

$$\rho > 4 - 5\rho_0$$

Glendenning & Schaffner-Bielich, 1998

“Neutron” Star Composition in 2005

(F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193-288)



Pulsar B in J0737-3039

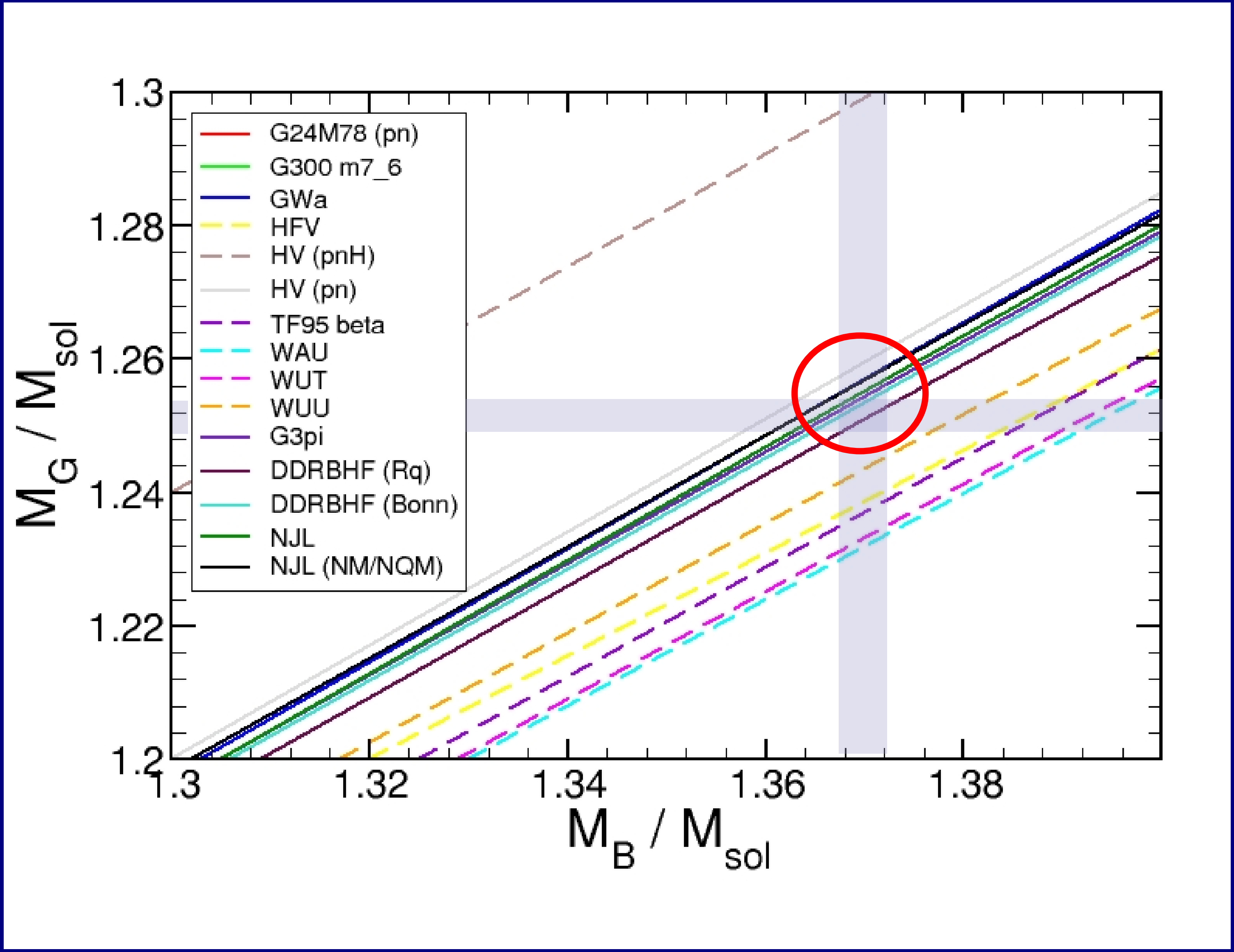
M. Kramer et al. (astro-ph/0503386)

A M_G=1.25 M_{sun} neutron star!

Remnant of a collapsed of ONeMg white dwarf ?
Collapse because of e^- capture onto Mg @ 4.5×10^9 g cm^{-3}
If this interpretation is correct, the star's baryon mass is

$$M_B = 1.37\ M_{sun}$$

Constraints on EoS from Pulsar B in J0737-3039



(Weber & Rosenfield 2005; see also P. Podsiadlowski et al., MNRAS 361 (2005) 1243

Common Feature of the Success Models

1. K≈240 MeV, m*/m≈0.7, a_{sym}≈30 MeV @ saturation

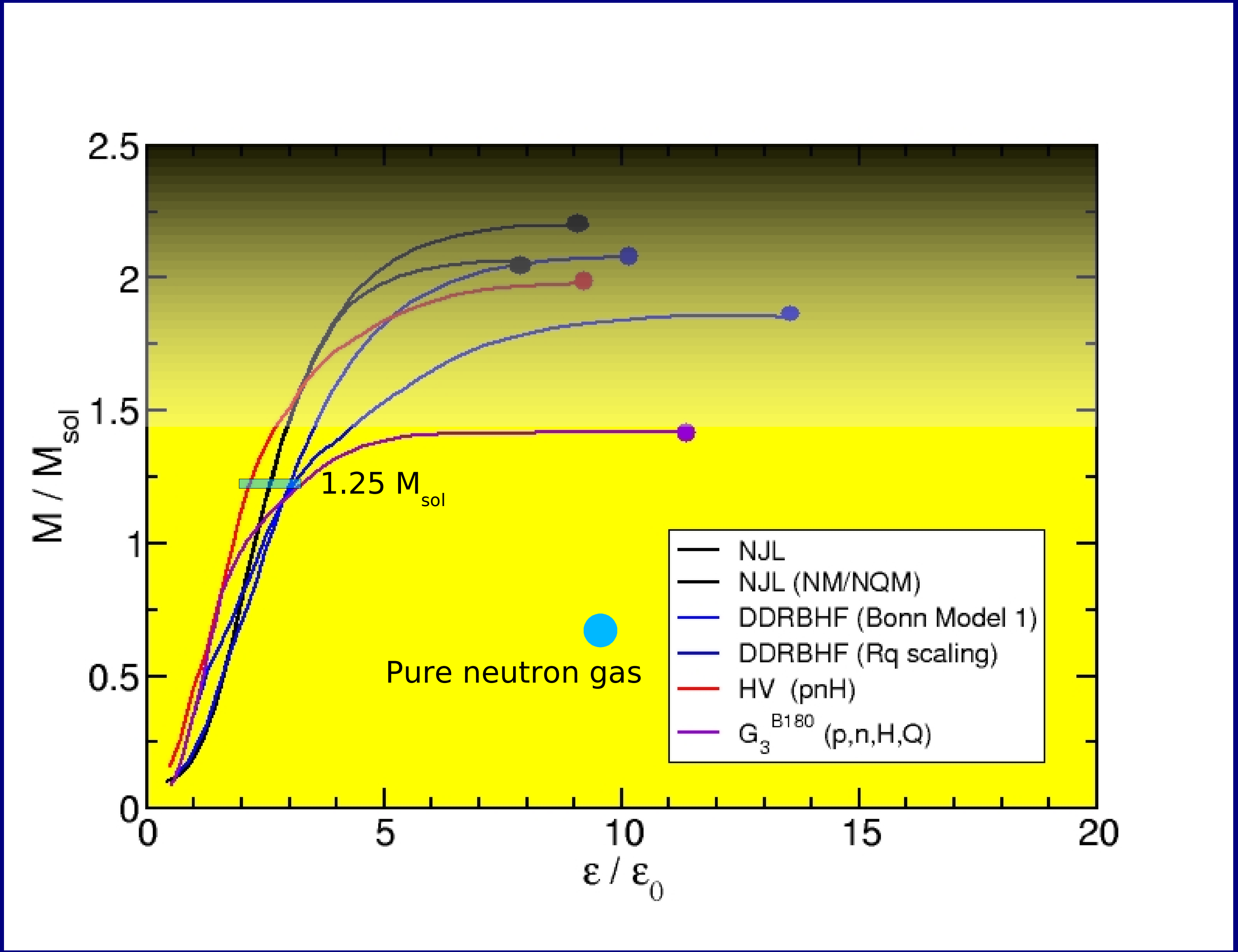
These values agree rather well will the latest values reported at Umesh Garg's workshop on "Nuclear Incompressibility", July 2005, Univ. Notre Dame, IN, USA

2. Protons and neutrons (in chemical equilibrium) only!

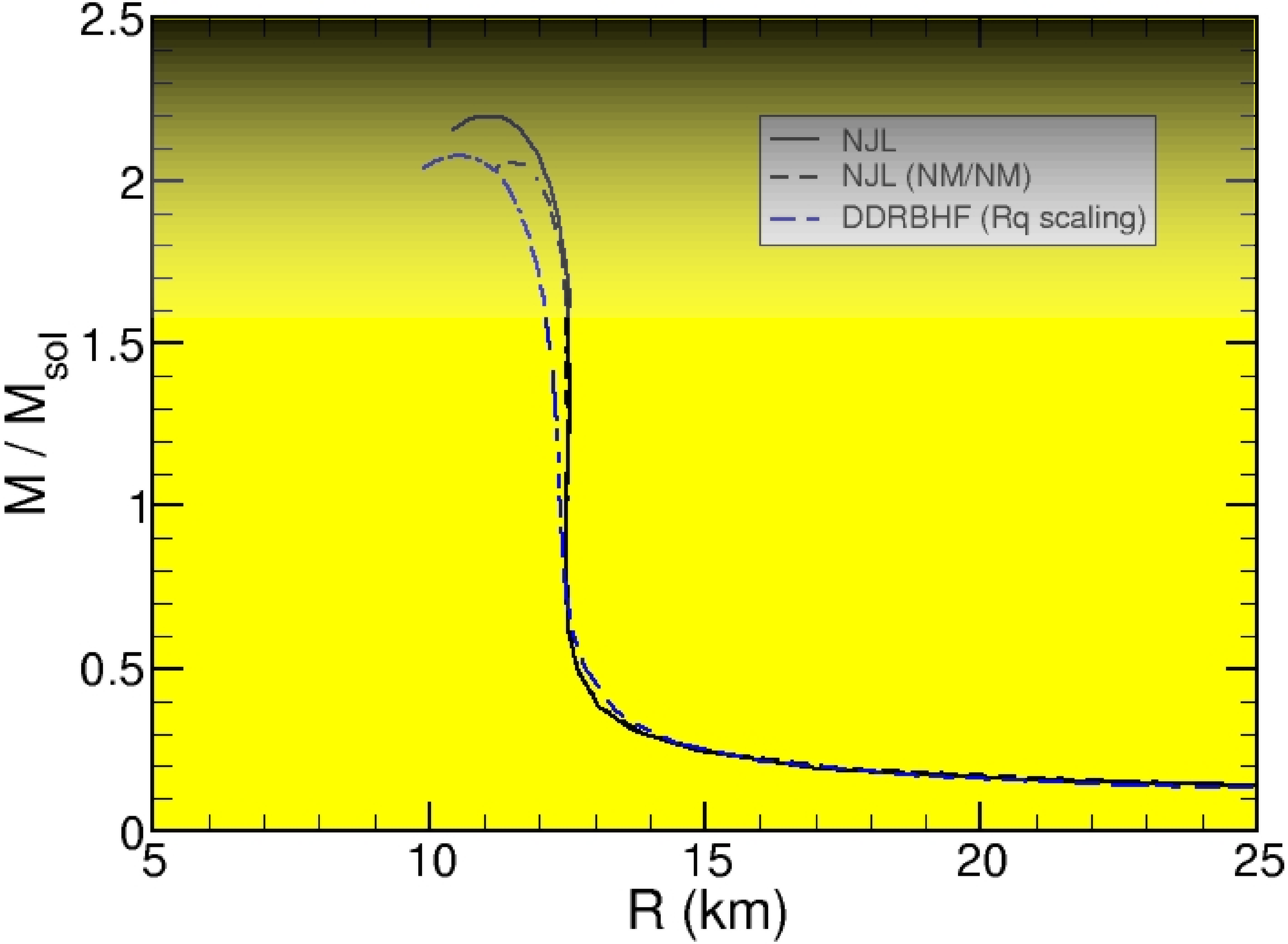
$M/M_{sol=}1.25$ ☞ $\varepsilon_{center}/\varepsilon_0 \sim 2$ to 3

$$M_{J0751+1807} = 2.1^{+0.4}_{-0.5}\ M_{sol}$$ (1.6 < M/M_{sun} < 2.5 at 95% confidence)

(Nice, Splaver, Stuirs, Loehmer, Jessner, Kramer, Cordes, astro-ph/0508050)



NJL: Lawley, Bentz, Thomas, astro-ph/0504020; DDRBHF: Hofman, Keil, Lenske, PRC 64 (2001) 034314



NJL
NJL (NM/NM)
DDRBHF (Rq scaling)
M / M_sol
R (km)
2.5
2
1.5
1
0.5
0
5
10
15
20
25

The stellar composition depends on the star's **mass** but also on the star's **frequency !**

Einstein's Field Equations for Rotating Compact Objects

- Metric: $ds^2 = -\, e^{-2\nu} dt^2 + e^{2(\alpha+\beta)} r^2 \sin^2\theta \, (d\varphi - N^\varphi dt)^2 + e^{2(\alpha-\beta)} (dr^2 + r^2 d\theta^2)$

- Christoffel symbols:
  $\Gamma^\sigma_{\mu\nu} = g^{\sigma\lambda} (\partial_\nu g_{\mu\lambda} + \partial_\mu g_{\nu\lambda} - \partial_\lambda g_{\mu\nu}) / 2$

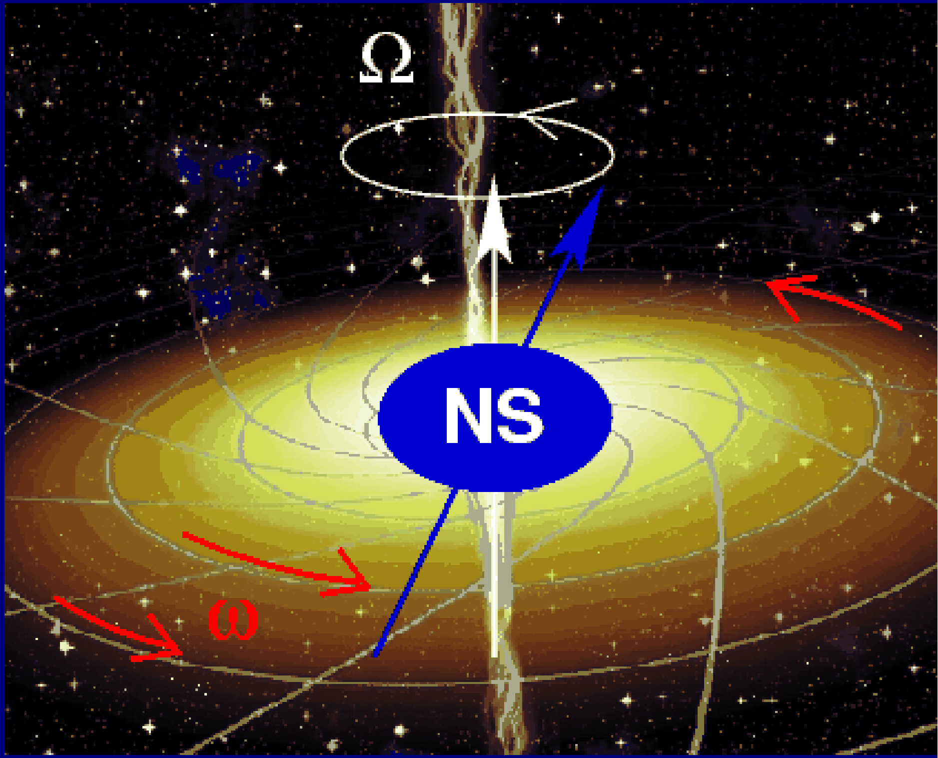
- Riemann tensor:
  $R^\tau_{\mu\nu\sigma} = \partial_\nu \Gamma^\tau_{\mu\sigma} - \partial_\sigma \Gamma^\tau_{\mu\nu} + \Gamma^\kappa_{\mu\sigma} \Gamma^\tau_{\kappa\nu} - \Gamma^\kappa_{\mu\nu} \Gamma^\tau_{\kappa\sigma}$

- Ricci tensor: $R_{\mu\nu} = R^\tau_{\mu\sigma\nu} \, g^\sigma_{\ \tau}$

- Scalar curvature: $R = R_{\mu\nu} \, g^{\mu\nu}$

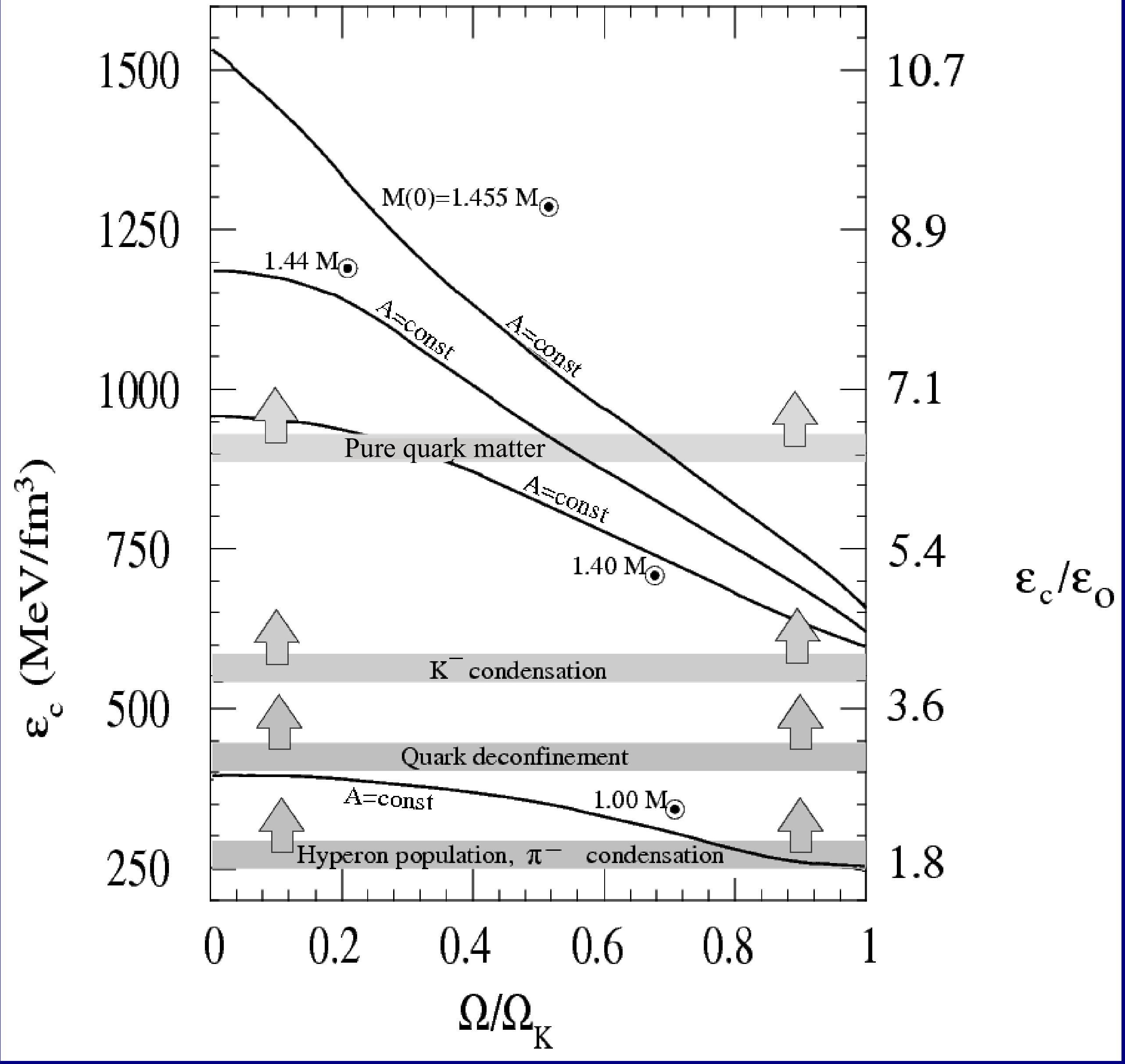
- Kepler frequency: $\Omega_K = r^{-1} e^{\nu-\alpha-\beta} U_K + N^\varphi$

- Differential rotation/uniform rotation



► **Stellar properties: M, R_p, R_{eq}, I, z, Ω_K, ω**

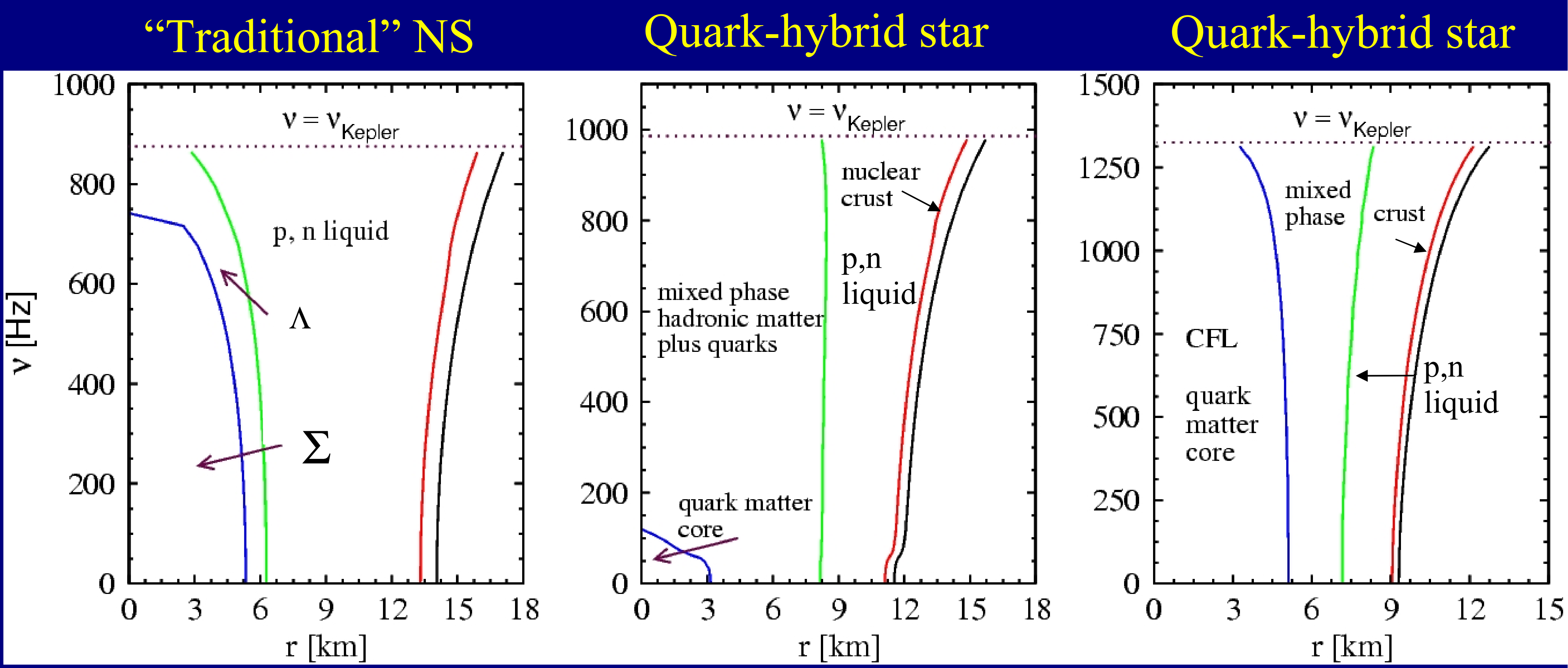
Composition of CBM in Neutron Stars depends on Spin Frequency!



60% change!!

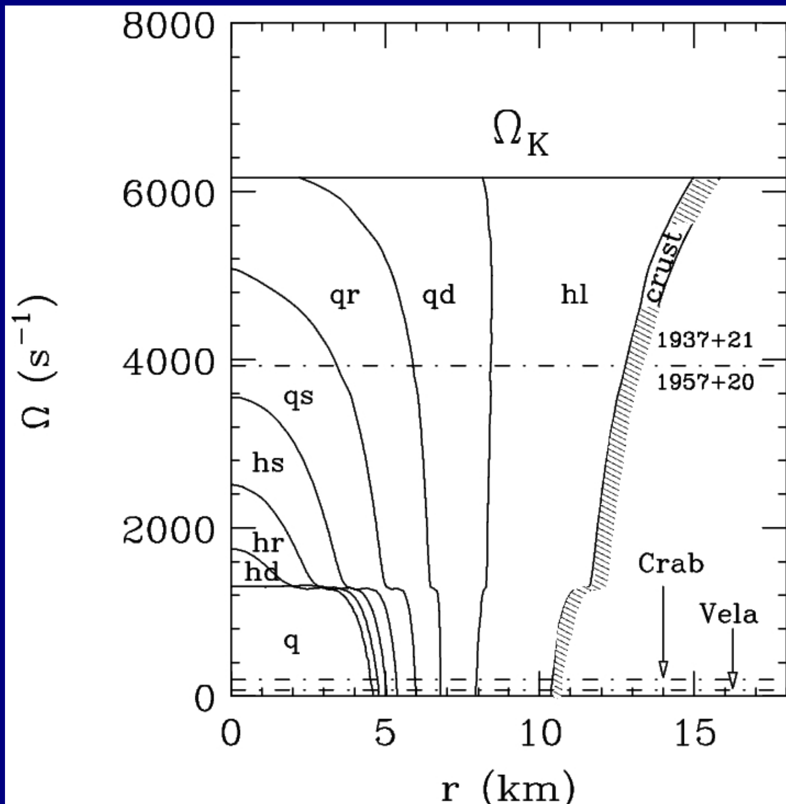
F. Weber, Prog. Nucl. Part. Phys. 54 (2005) 193-288

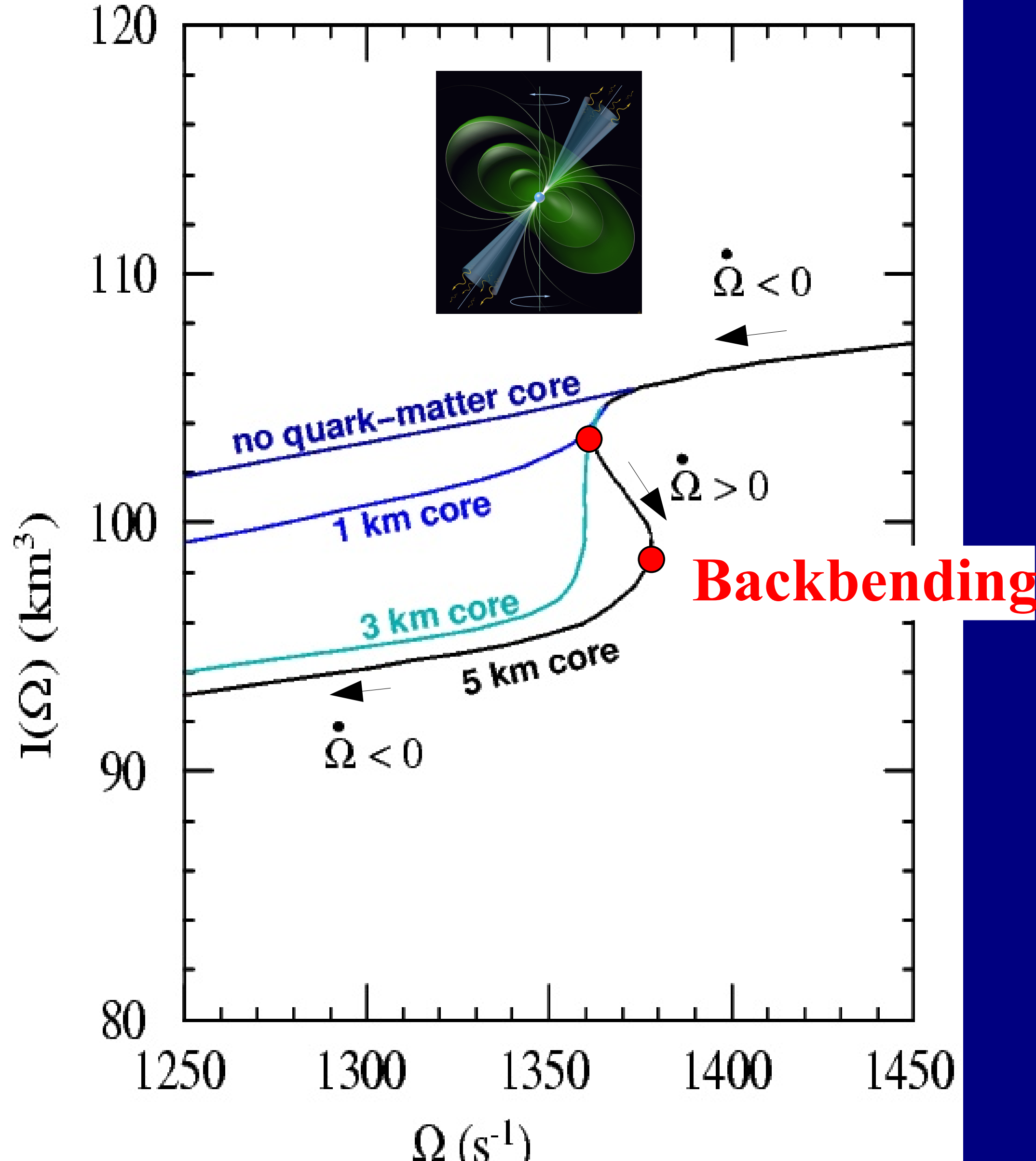
Stellar Compositions ($M \sim 1.4\ M_{sun}$)



Alford&Reddy, PRD 67 (2003) 074024

Moment of Inertia





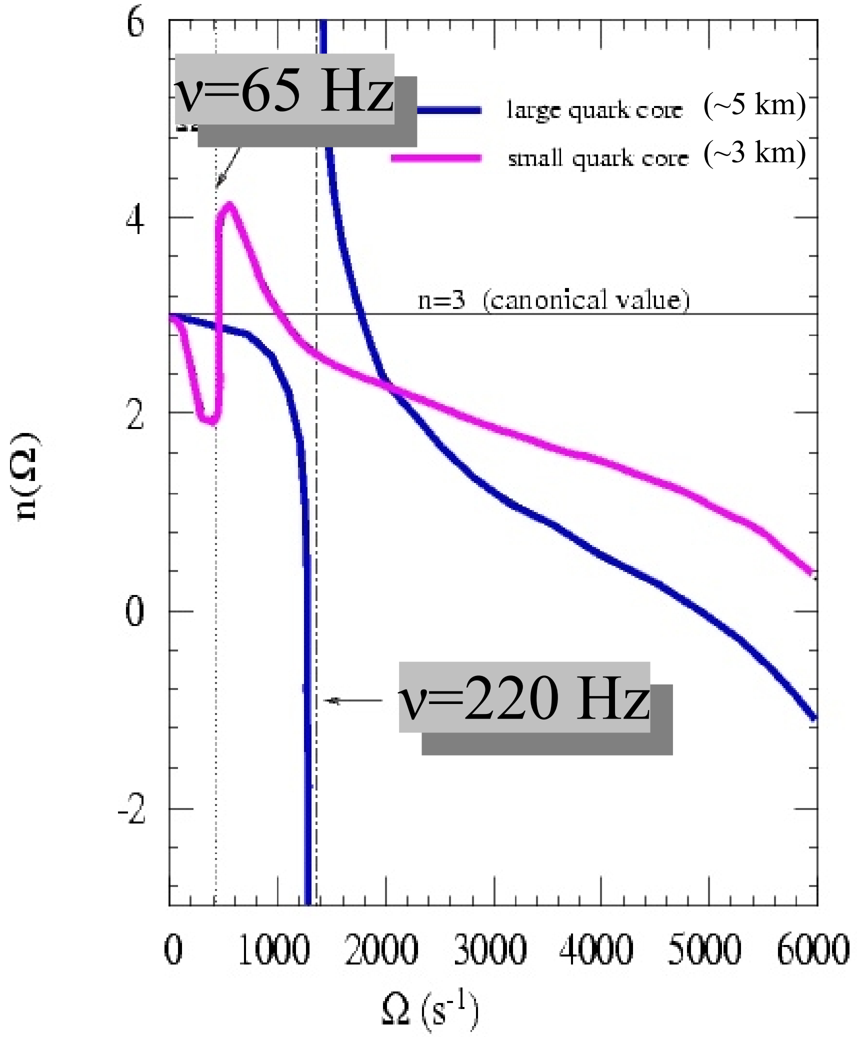
Glendenning & Weber, PRL 79 (1997) 1603;

F. Weber, Prog. Nucl. Part. Phys. 54 (2005) 193-288

Signal of Quark Matter in NSs

Braking index

$$n = \frac{\Omega \ddot{\Omega}}{\dot{\Omega}^2} = 3 - \frac{I'' \Omega^2 + 3 I' \Omega}{I' \Omega + 2 I}$$

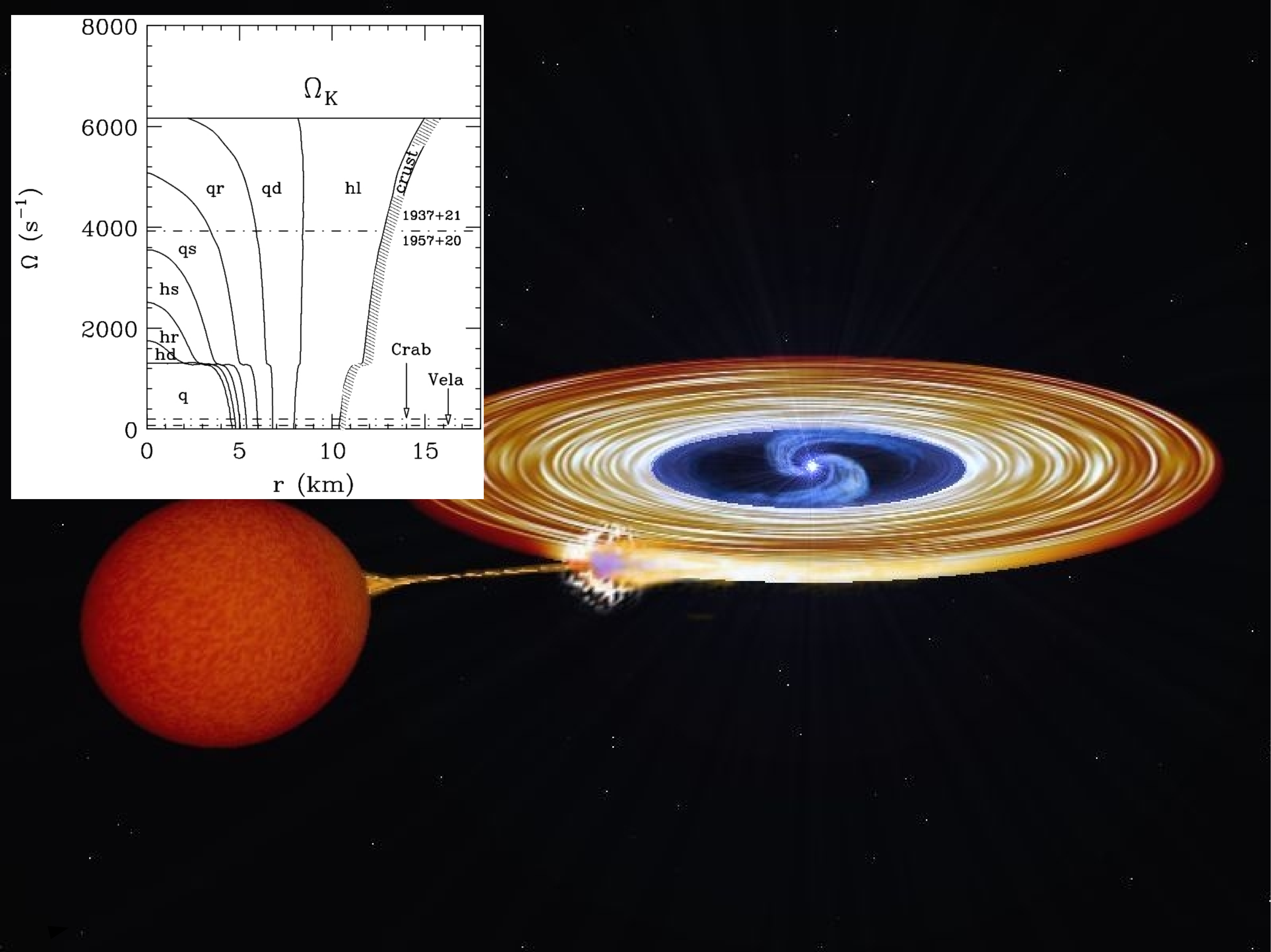


Glendenning, Pei, Weber, PRL 79 (1997) 1603

Weber, J. Phys. G: Nucl. Part. Phys. 25 (1999) R195

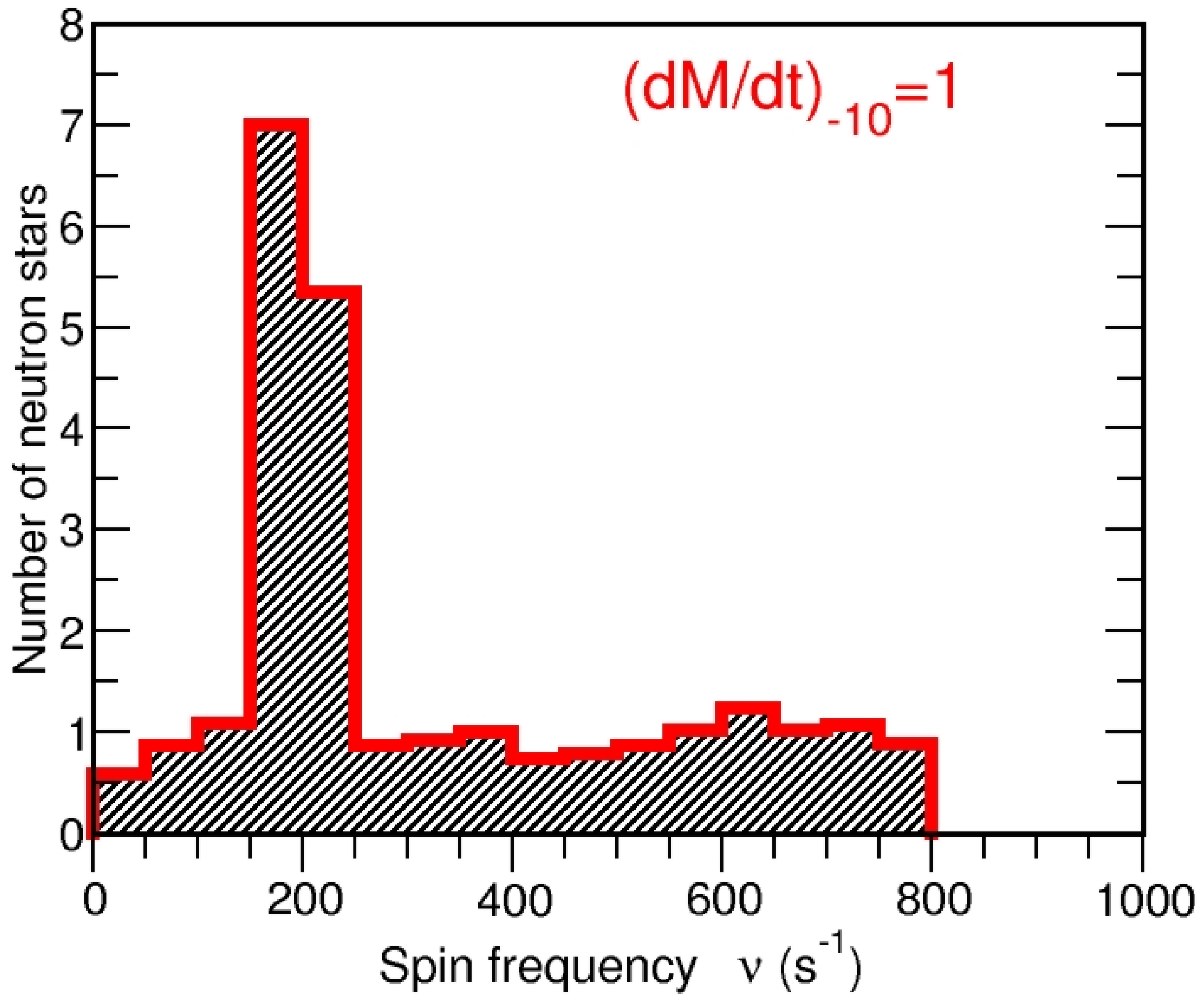
Chubarian, Grigorian, Poghosyan, Blaschke (2000)

Weber, Prog. Part. Nucl. Phys. 54 (2005) 193



Ω_K
8000
6000
4000
2000
0
Ω (s^-1)
qr
qd
hl
crust
1937+21
1957+20
qs
hs
hr
hd
q
Crab
Vela
0
5
10
15
r (km)

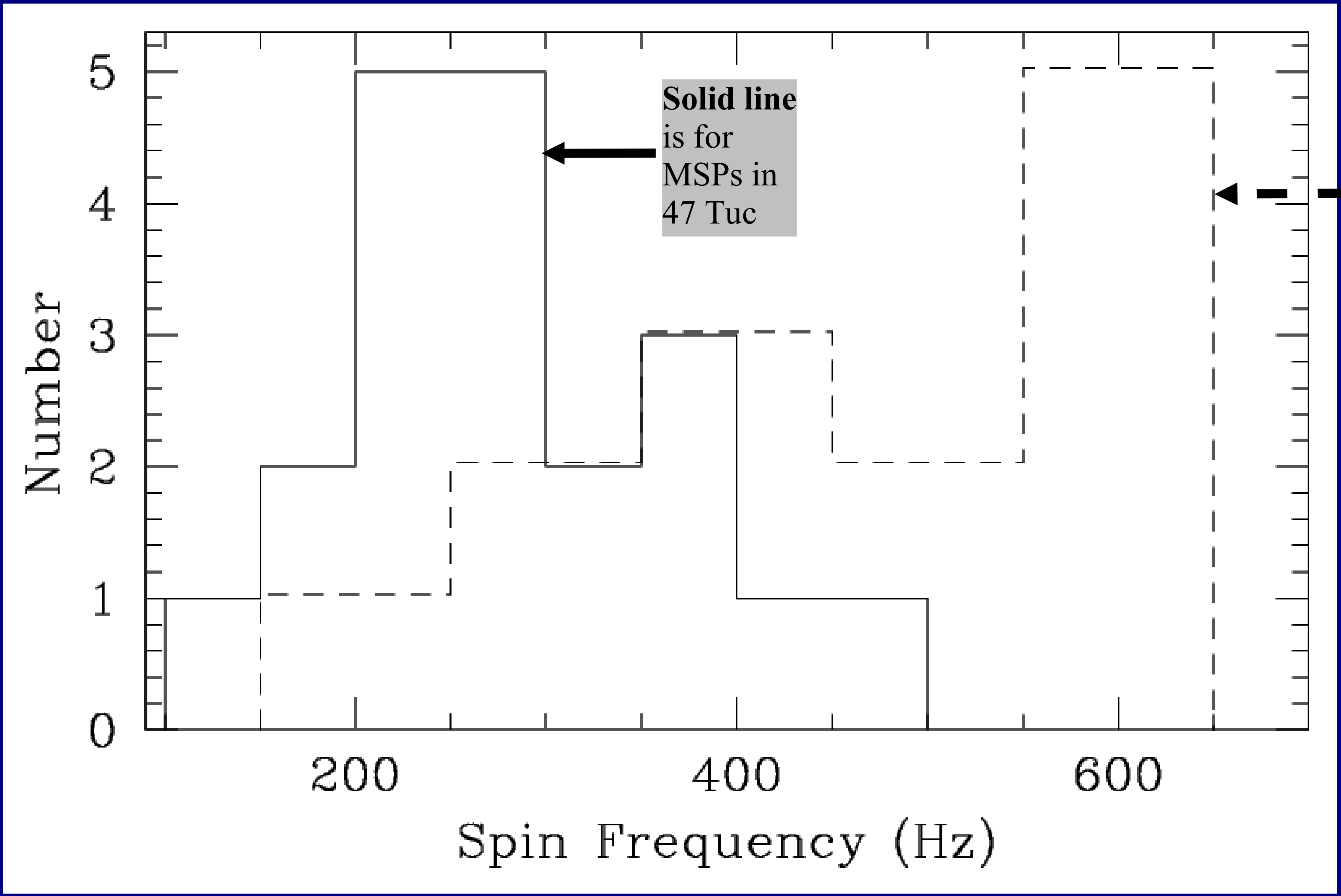
Pile-up of Neutron Stars



Glendenning & Weber, ApJ 559 (2001) L119

Histogram of Neutron Stars Spin Frequencies

(see L. Bildsten, astro-ph/0212004; R. Wijnands, astro-ph/0501264)



Dashed line is for
4U 1916-053
4U 1702-429
4U 1728-34
KS 1731-260
Aql X-1
MXB 1658-298
4U 1636-53
MXB 1743-29
SAX J1750.8-2980
4U 1608-52
Sax J1808.4-3658
XTE J1751-305
XTE J0929-314
XTE 1807-294
XTE J 1814-338
IGR J 00291+5934

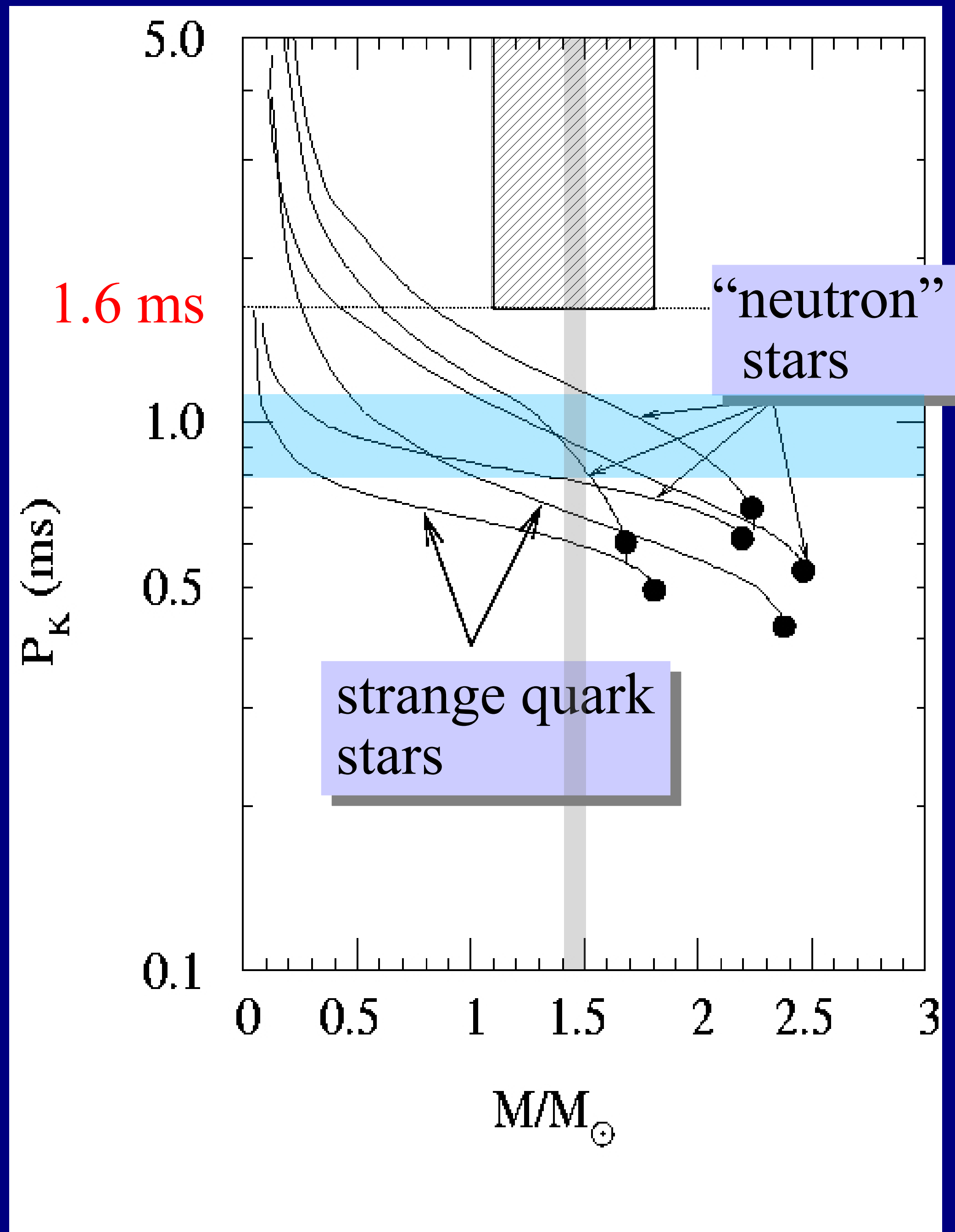
Rotation at Mass Shedding Frequency

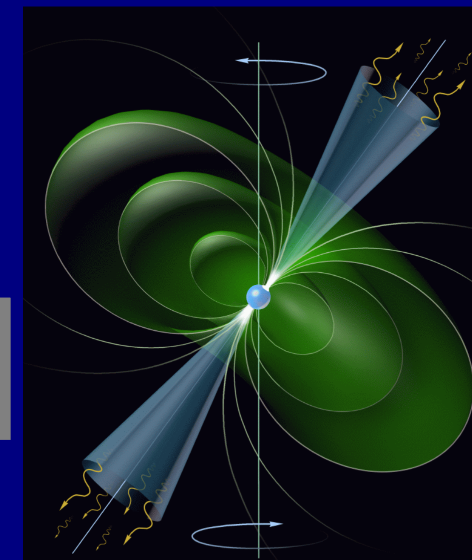
Kepler frequency:

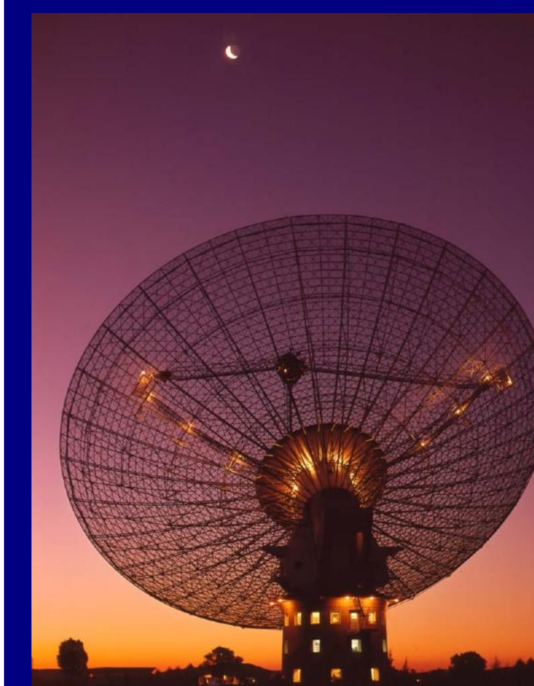
Einstein:
$\Omega_K = r^{-1} e^{\nu-\alpha-\beta} U_K + N^{\varphi}$ at $r=R_{eq}$

► $P_K = 2\pi/\Omega_K$

(Newton:
$P_K = 2\pi\sqrt{(R^3/M)}$)



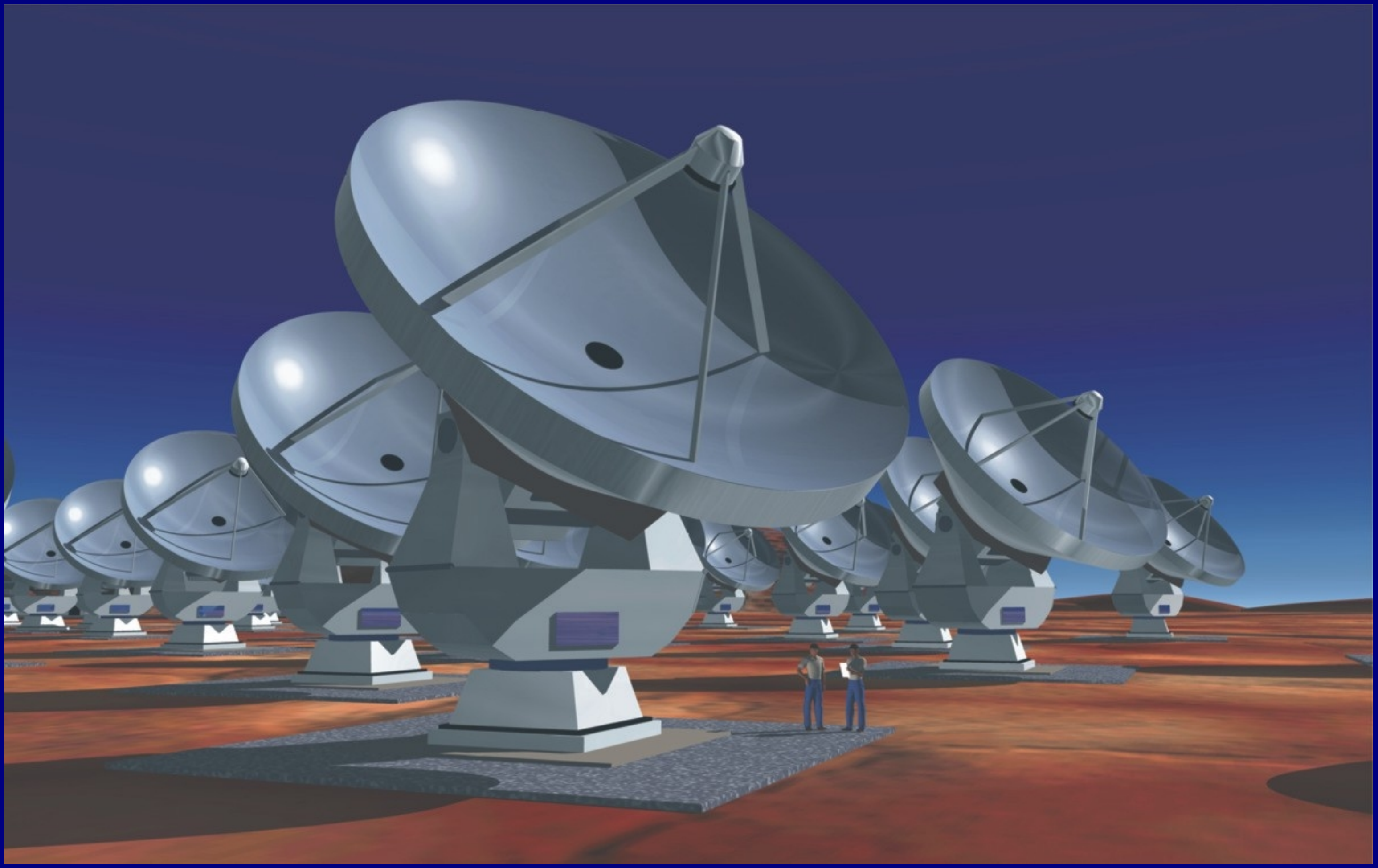




Parkes radio telescope

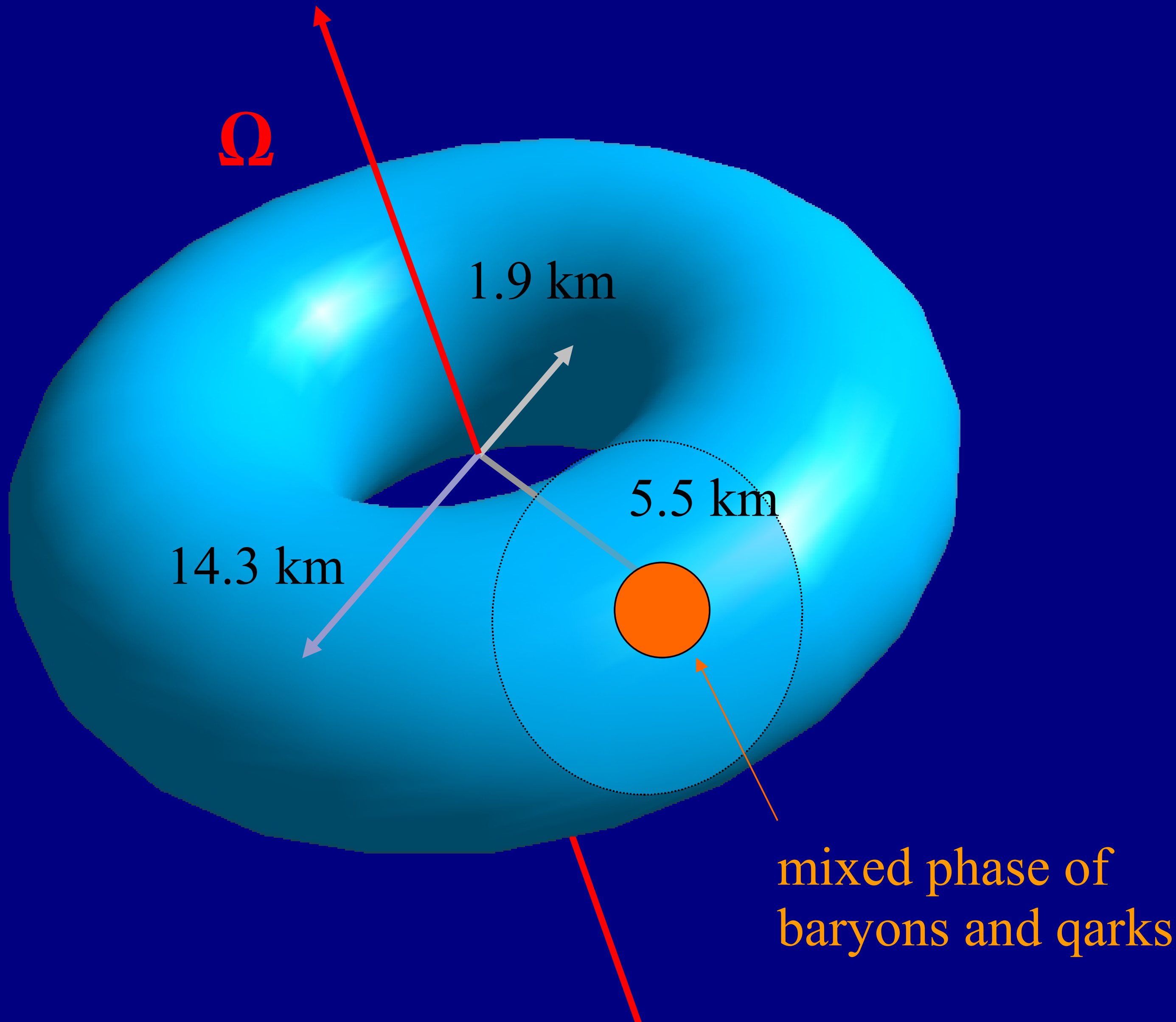
Most exciting future ahead: SKA (Square Kilometer Array)

Sensitivity ~100 times higher than the VLA sensitivity
~ **20,000** pulsars exptected to be discovered
~ 1000 MSPs
Operations start ~2016



ALMA Antennas

Differentially Rotating Stellar Objects

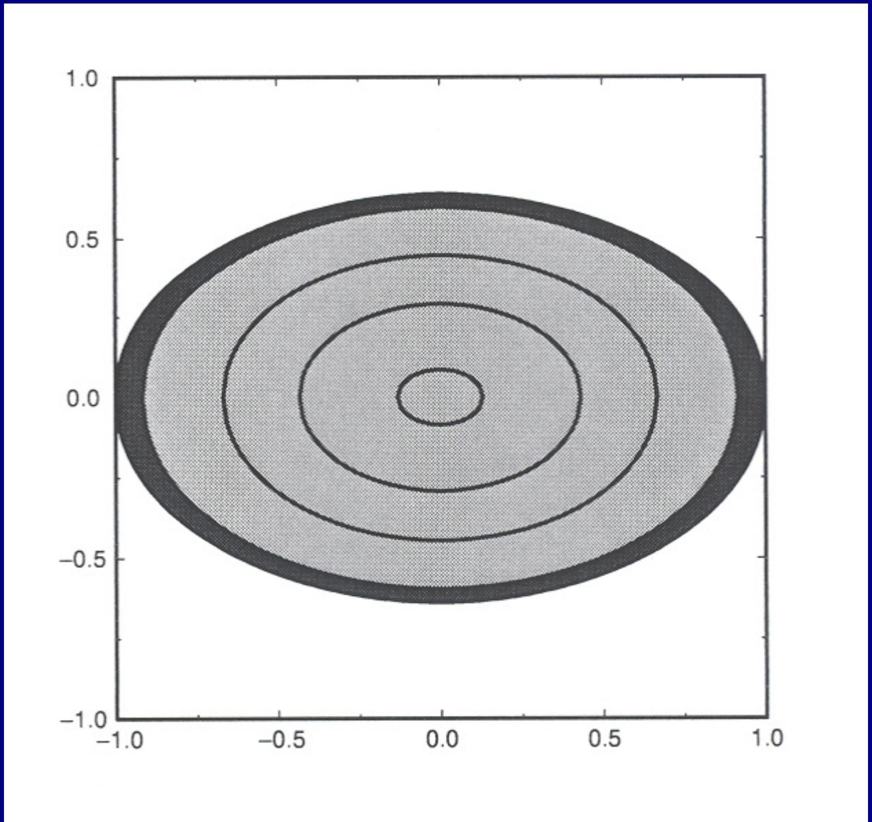


$M = 1.4\ M_{sun}$
$\nu_{eq} = 290$ Hz
$\nu_c = 140\ \nu_{eq}$

Open issue: dynamical stability; secular stability

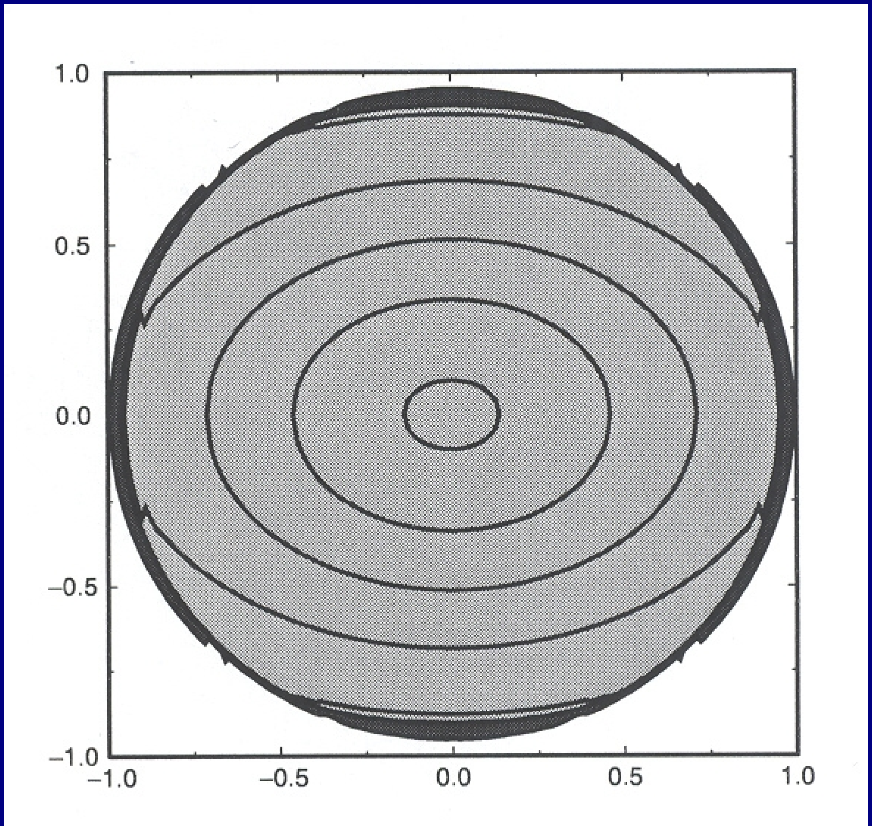
Differentially Rotating Strange Stars

($M=1.40\ M_{sol}$, $B^{1/4}=145$ MeV)



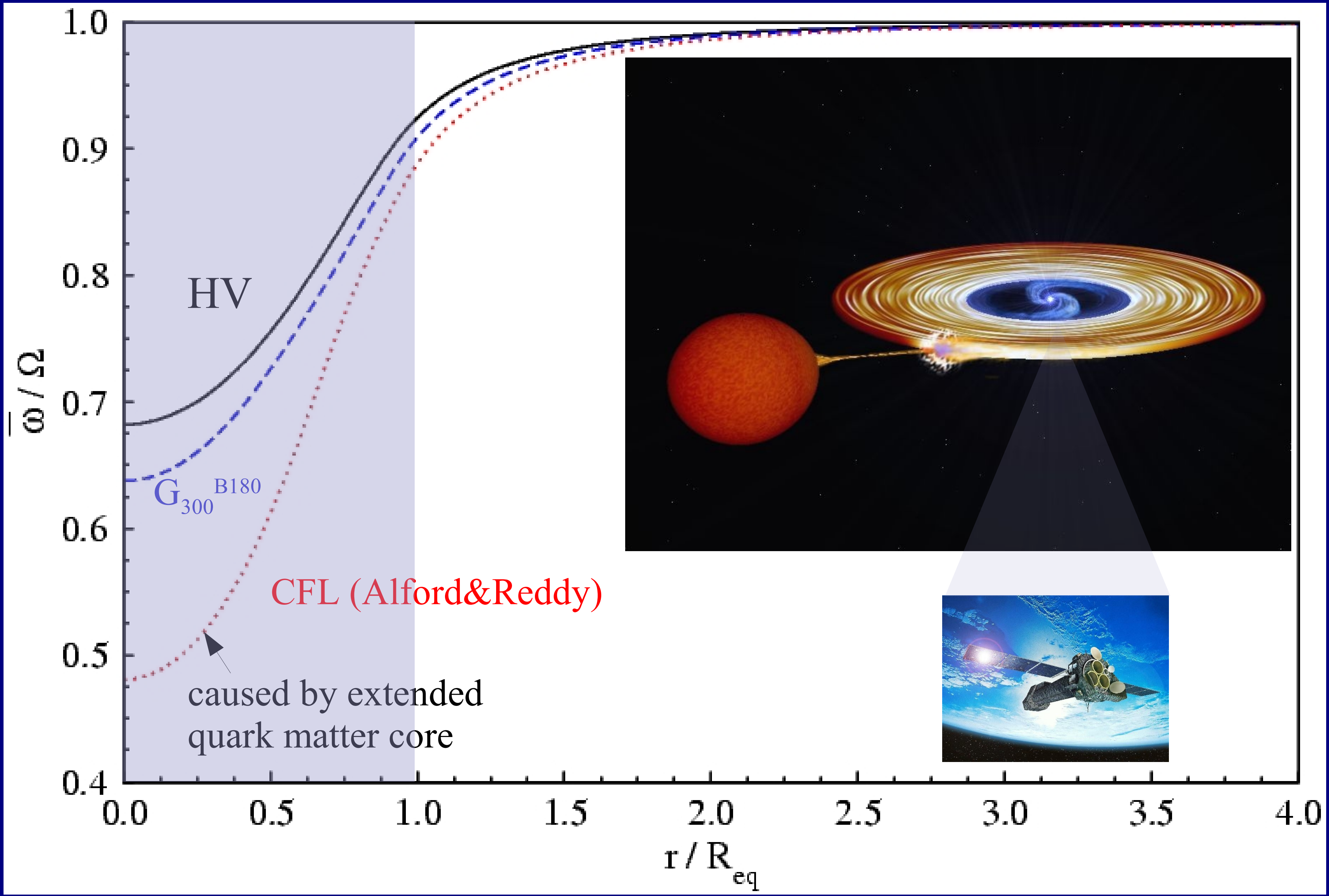
Rigid body rotation

$\Omega_S/\Omega_C = 1$ (1000 Hz)



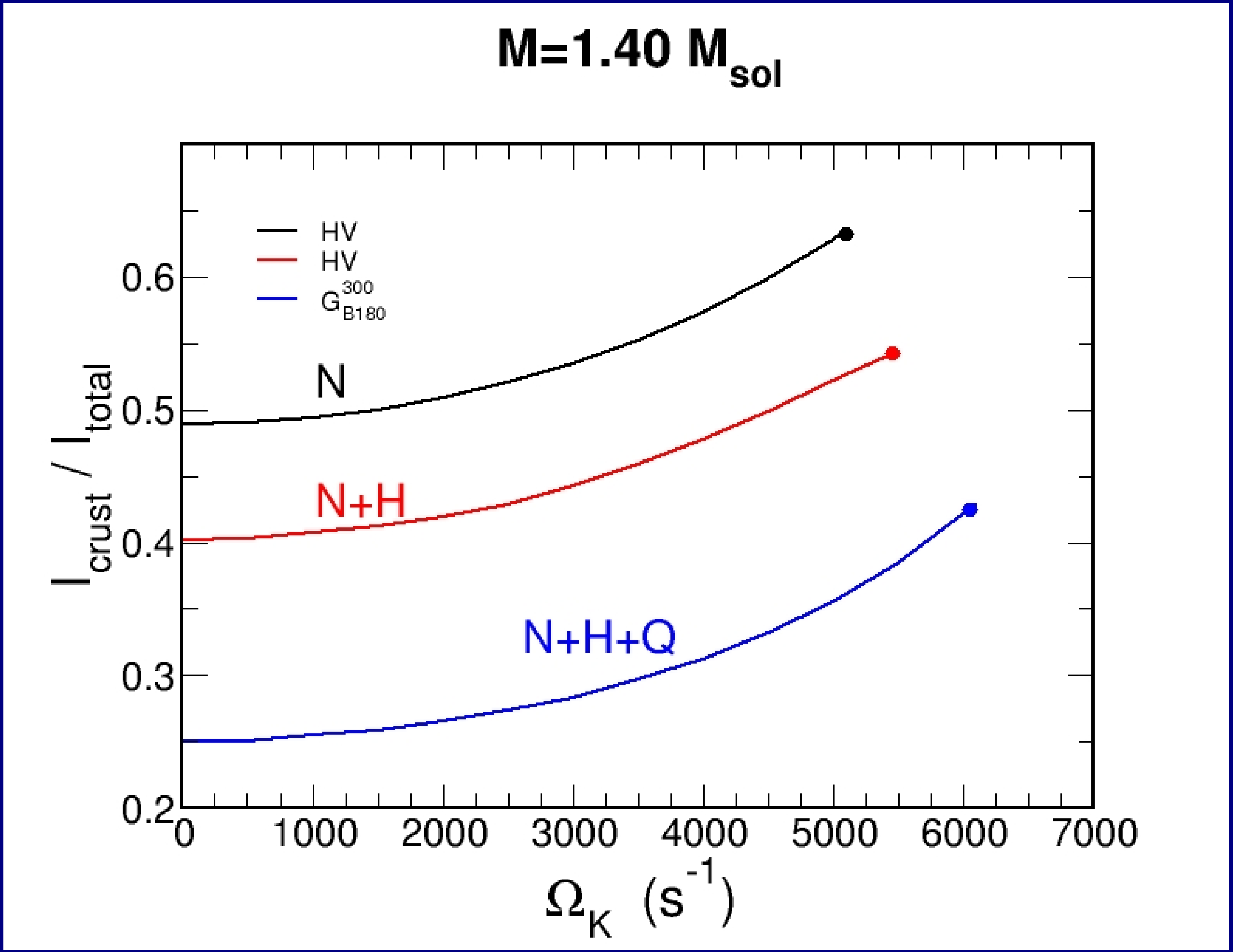
$\Omega_S/\Omega_C = 1/2$

Frame Dragging of the LIFs



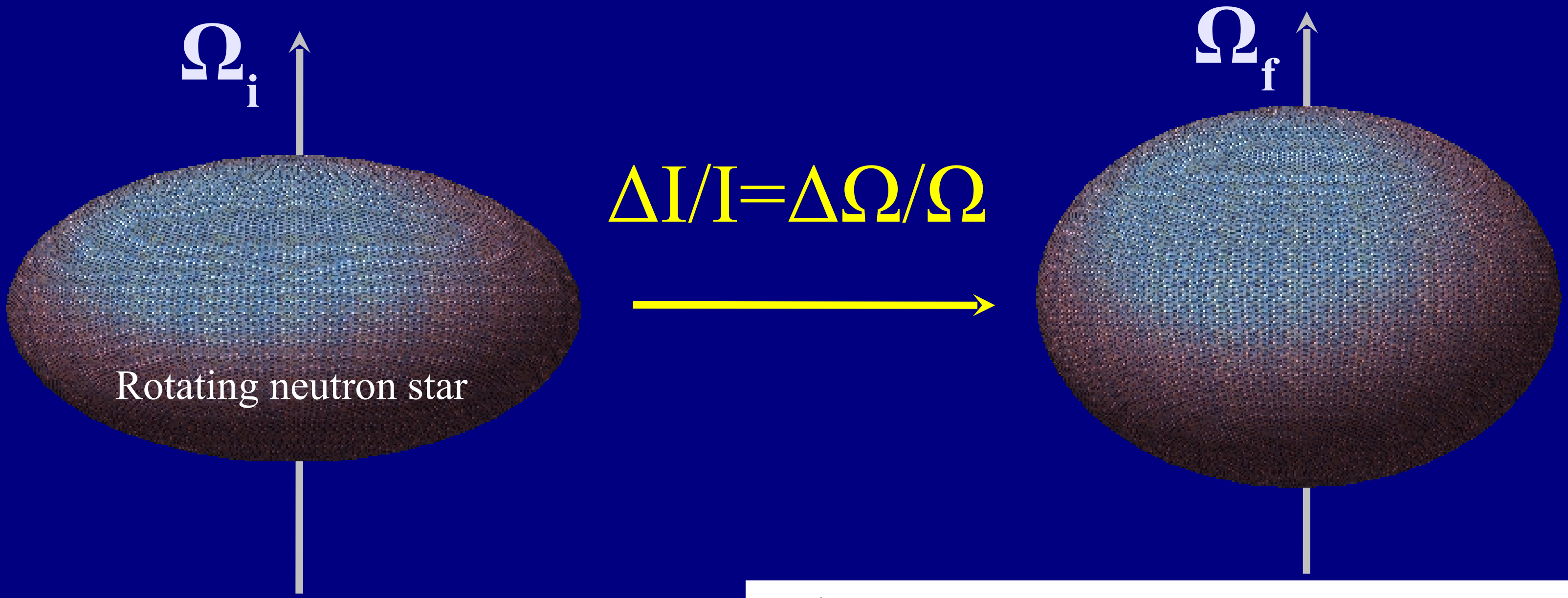
Crustal Moment of Inertia

$$I = \Omega^{-1} \int_V dr\, d\theta\, d\phi\ \sqrt{-g}\ T_\phi^{\ t}$$

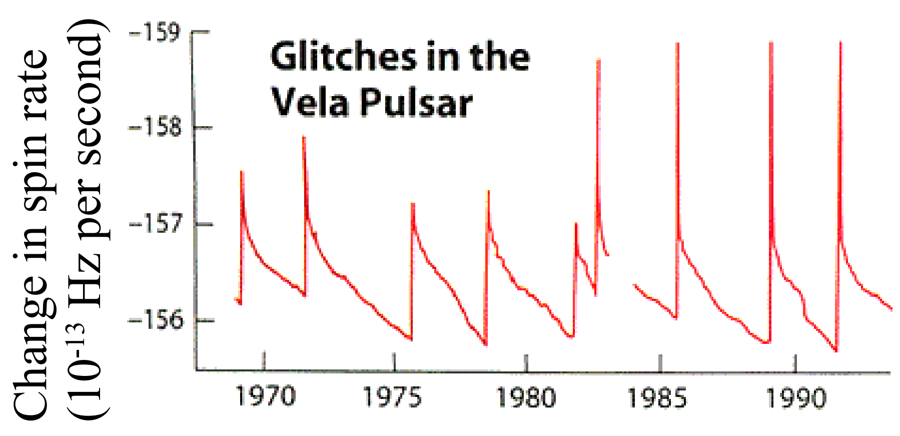


- Pulsar glitches
- Post-glitch behavior
- JINA physics

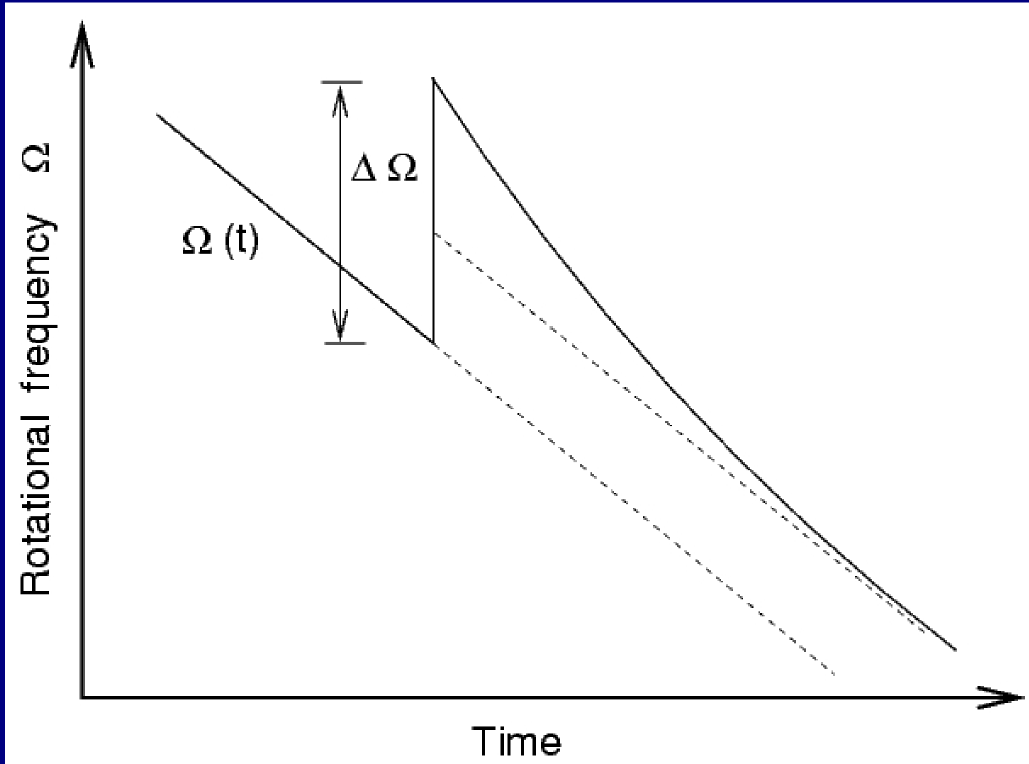
Pulsar Glitches



$$\Delta I/I = \Delta\Omega/\Omega$$

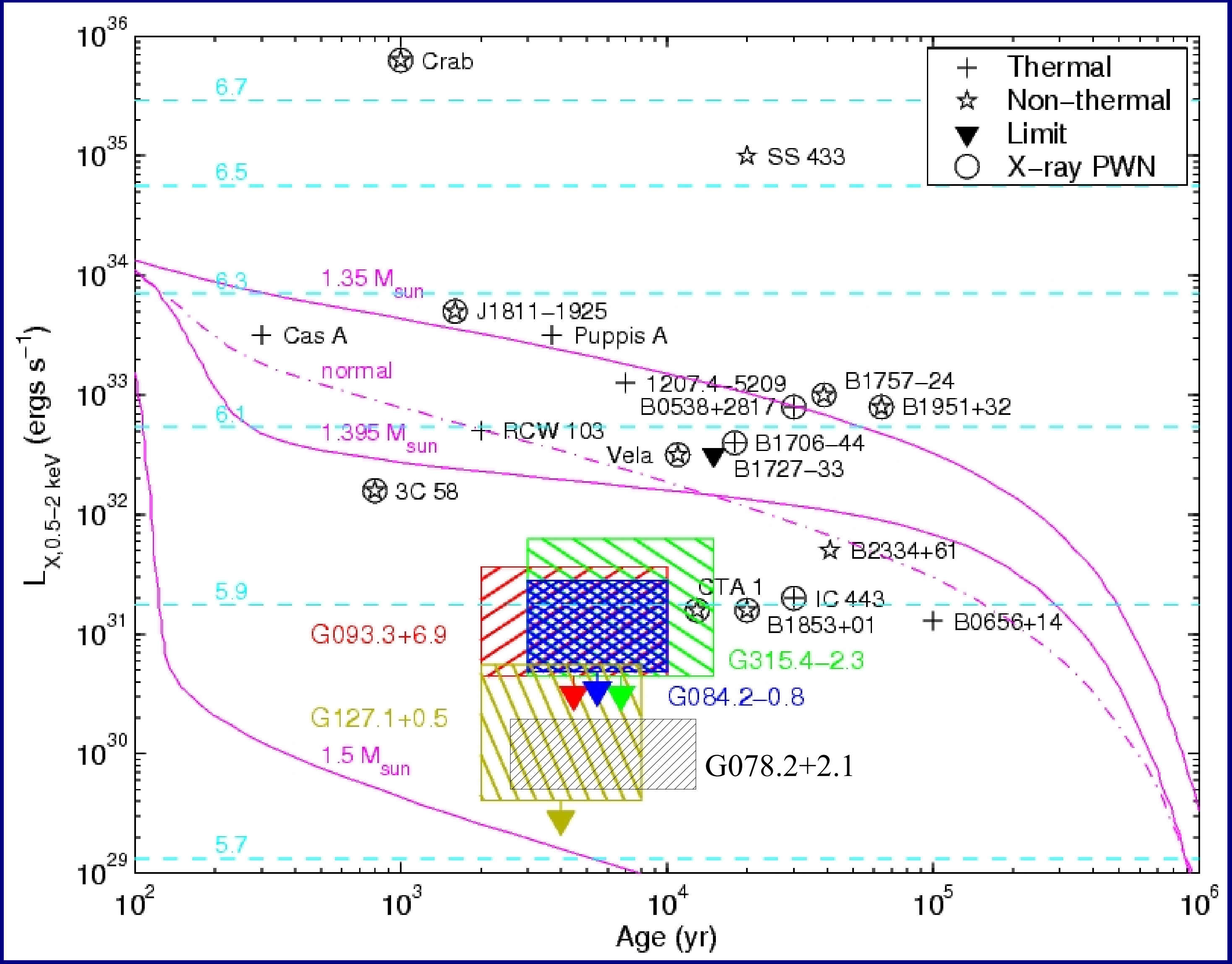


Source: www.kosmologika.net/Stars/



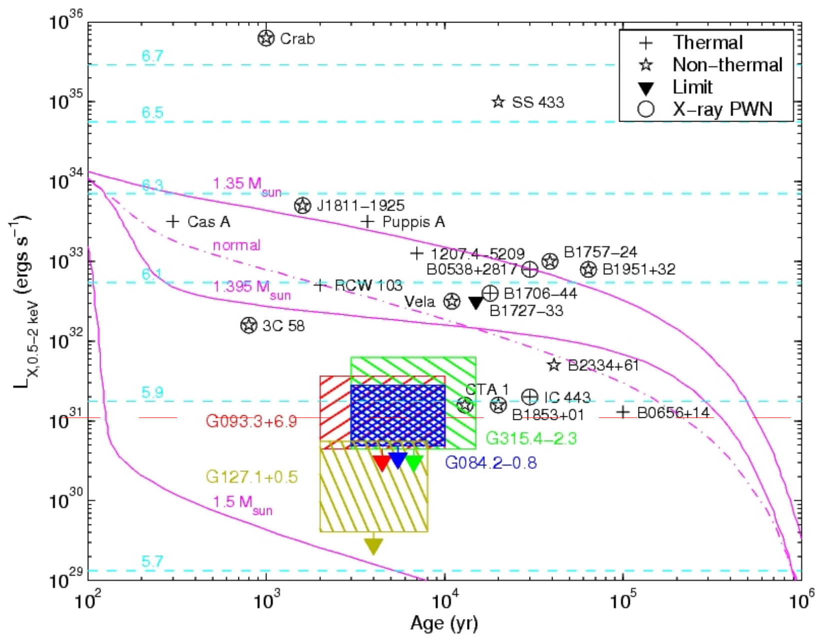
Searching for Young Neutron Stars in SNRs

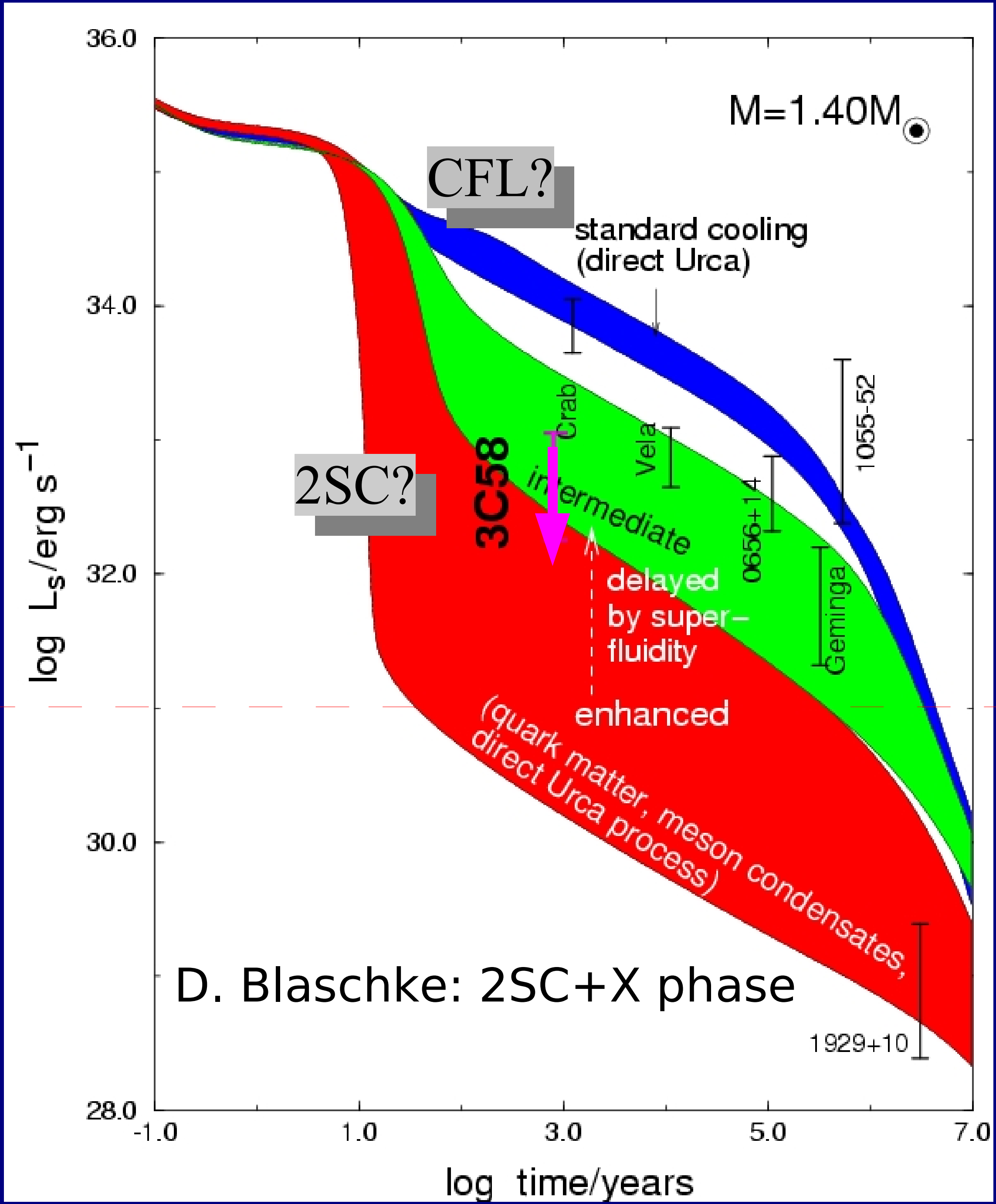
Kaplan et al. (2004)



Non-detection in G084.2-08, G093.3-6.9, G127.1+0.5, G078.2+2.1
→ strong constraints on cooling (?)

“Neutron” Star Cooling





Summary

- Compact stars/Astrophysical settings offer the unique opportunity to explore the properties of CBM, i. e. a portion of the phase diagram of nuclear matter that cannot be probed by RHIC.

- The list of hot research topics includes:

  1. Modern theories of (ultra) dense matter

  2. Fundamental building blocks (true ground state)

  3. Equation of state

  4. Properties of matter subjected to high density radiation fields, magnetic fields, electric fields

  4. Making of the elements, . . .

- We just began to scratch the surface – a most exciting future is ahead driven by unprecedented advaced in observational astronomy!