Appearance of a quark matter phase in hybrid stars

Strangeness in Quark Matter
SQM2013, Birmingham

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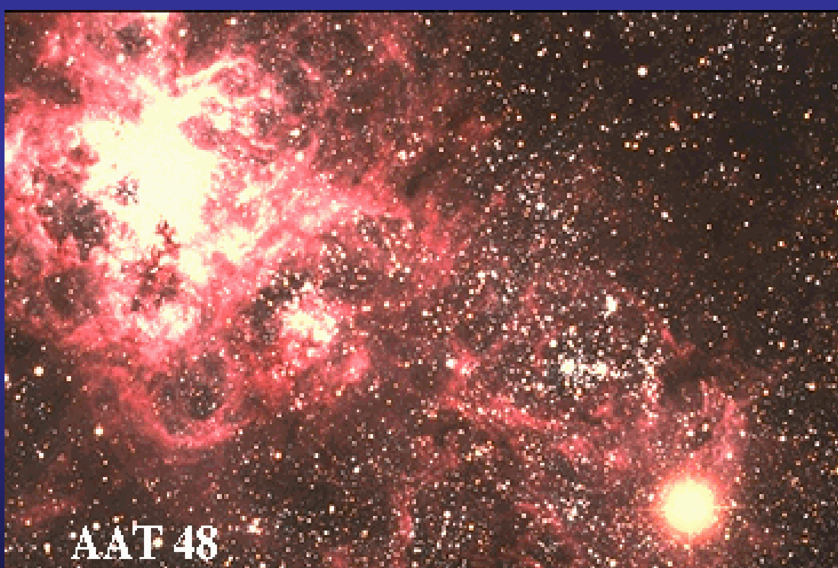
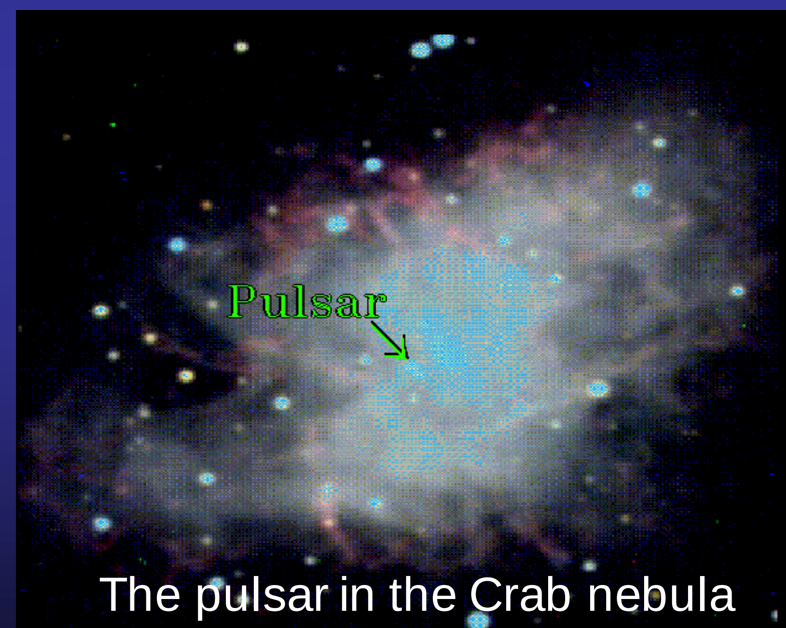
Neutron star : supernova remnant

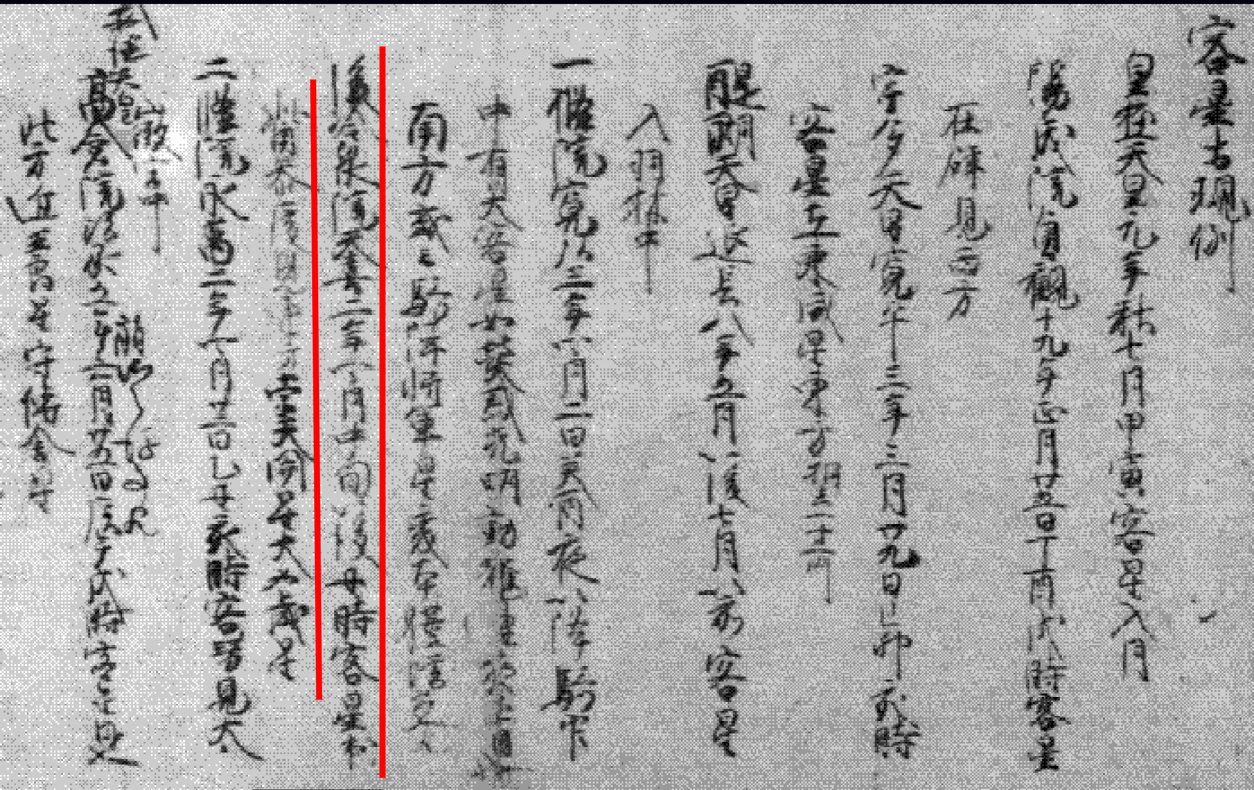


SN 1987A in the Large Magellanic Cloud
But we cannot observe any pulsar



The pulsar in the Crab nebula

This explosion was observed more than 900 years ago…



"Meigetsu-ki(明月記)"

Teika Fujiwara (藤原定家)

"May 1054, a star appeared in the east sky.
The size was as same as Jupiter".

The historical record in China "宋史"
Chinese people also saw this explosion

Quark?
Hyperon?

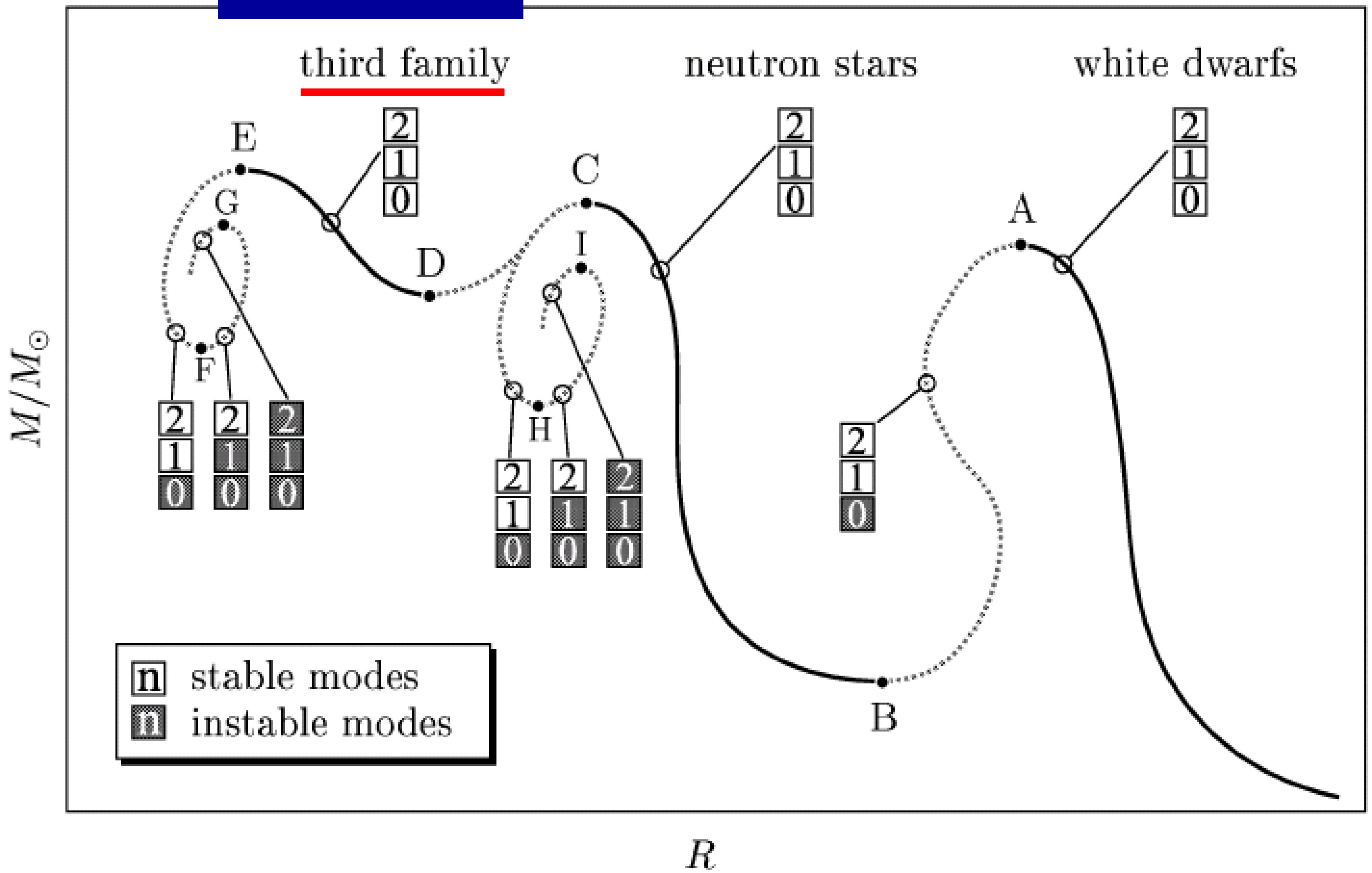
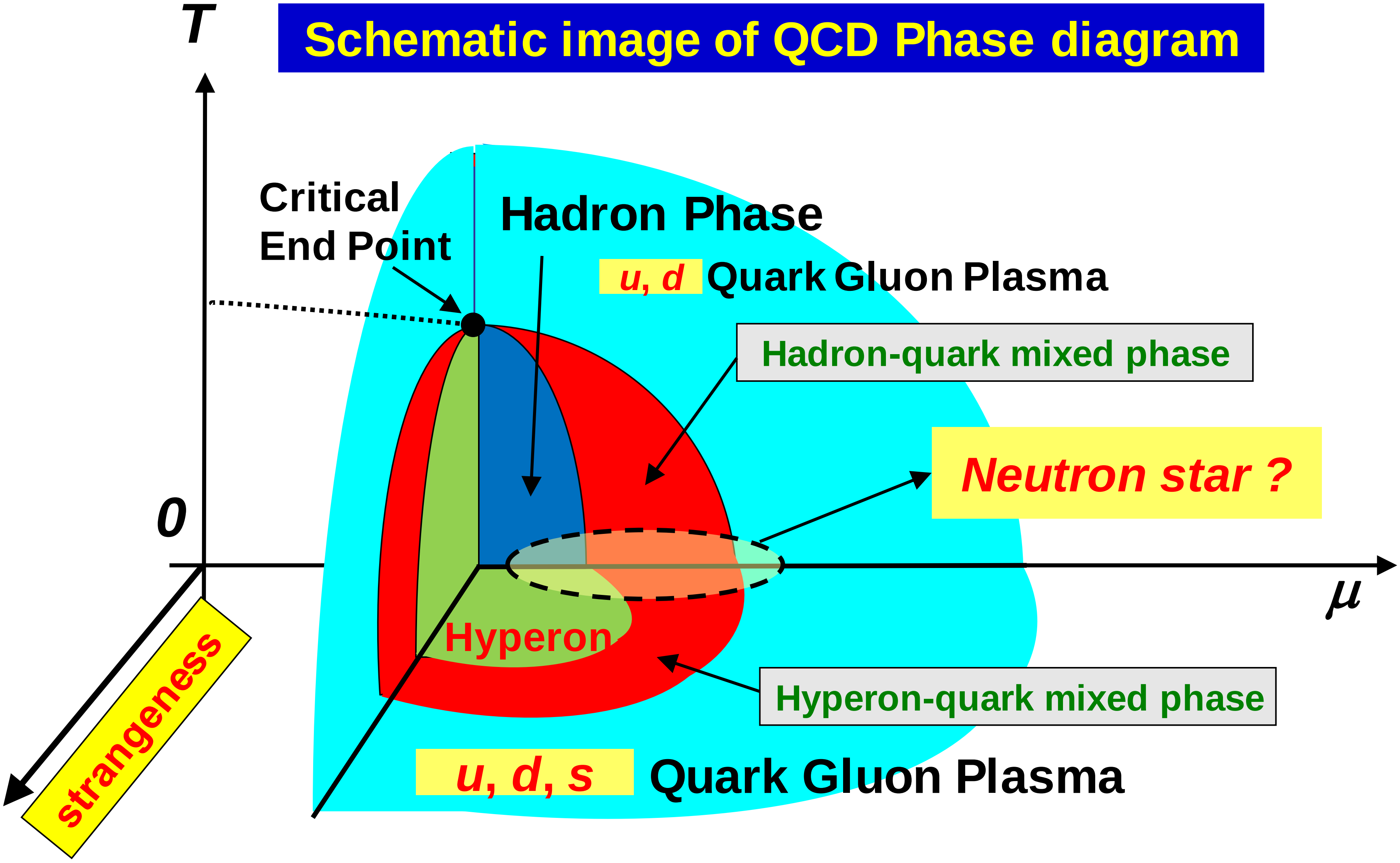


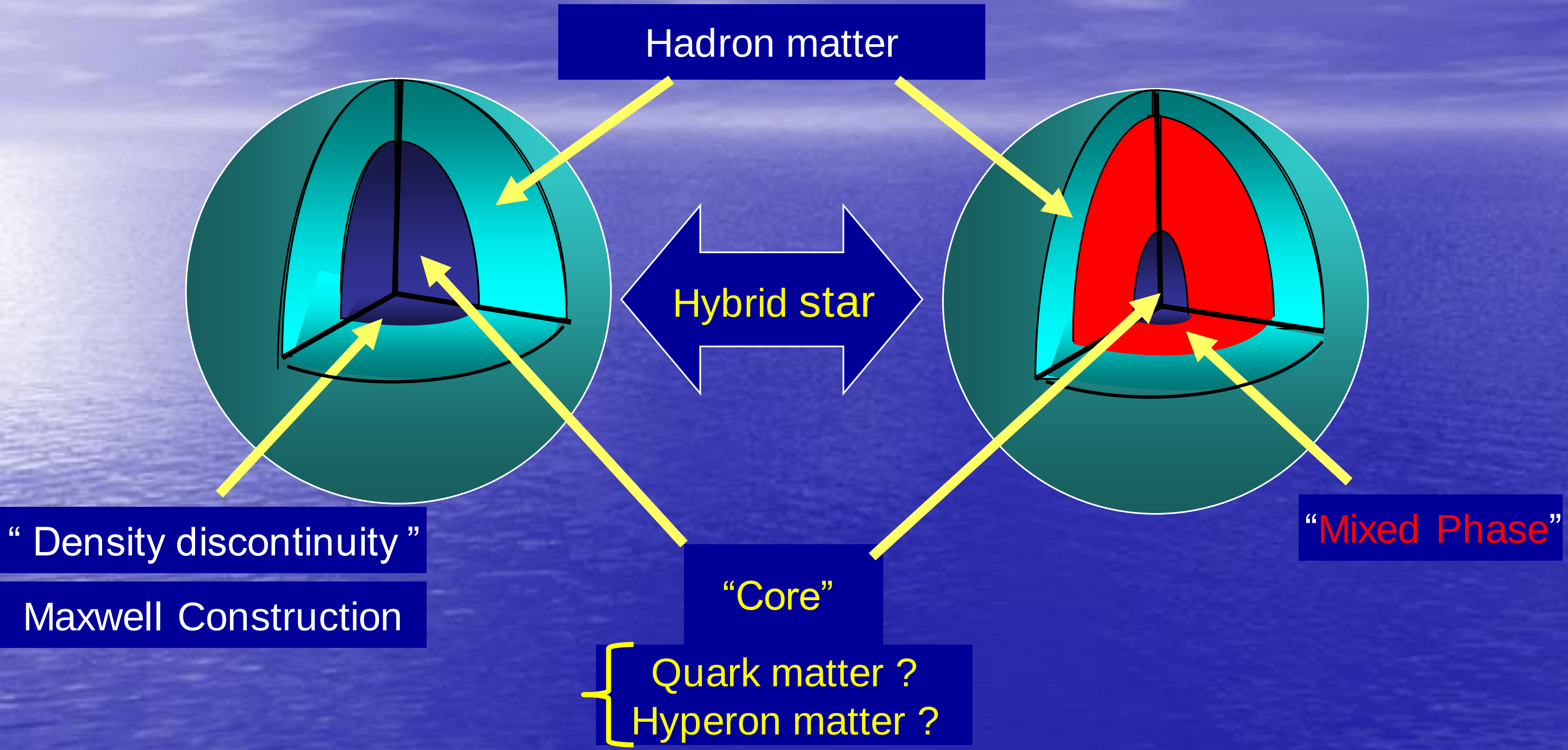
Fig. 14. Schematic mass–radius relation showing three stable families of compact stars. The letters A, B, . . . , I refer to critical points (turning points) where a vibrational mode changes stability [45,69,70]. The stability (solid lines) or instability (dotted lines) of the three lowest-lying modes ($n = 0, 1, 2$) is depicted by the numbers. Higher modes are stable. See text for more details.

K. Schertler et al. NPA**677**(2000)463

Schematic image of QCD Phase diagram



Inner structures of the neutron star…



Inner structures strongly depend on EOS of the matter

Implication to a hybrid star

"Gibbs conditions"

$$P_{\text{quark}} = P_{\text{Hadron}}$$
$$T_{\text{quark}} = T_{\text{Hadron}}$$
$$\mu^{B}_{\text{quark}} = \mu^{B}_{\text{Hadron}}$$
$$\mu^{e}_{\text{Hadron}} = \mu^{e}_{\text{quark}}$$

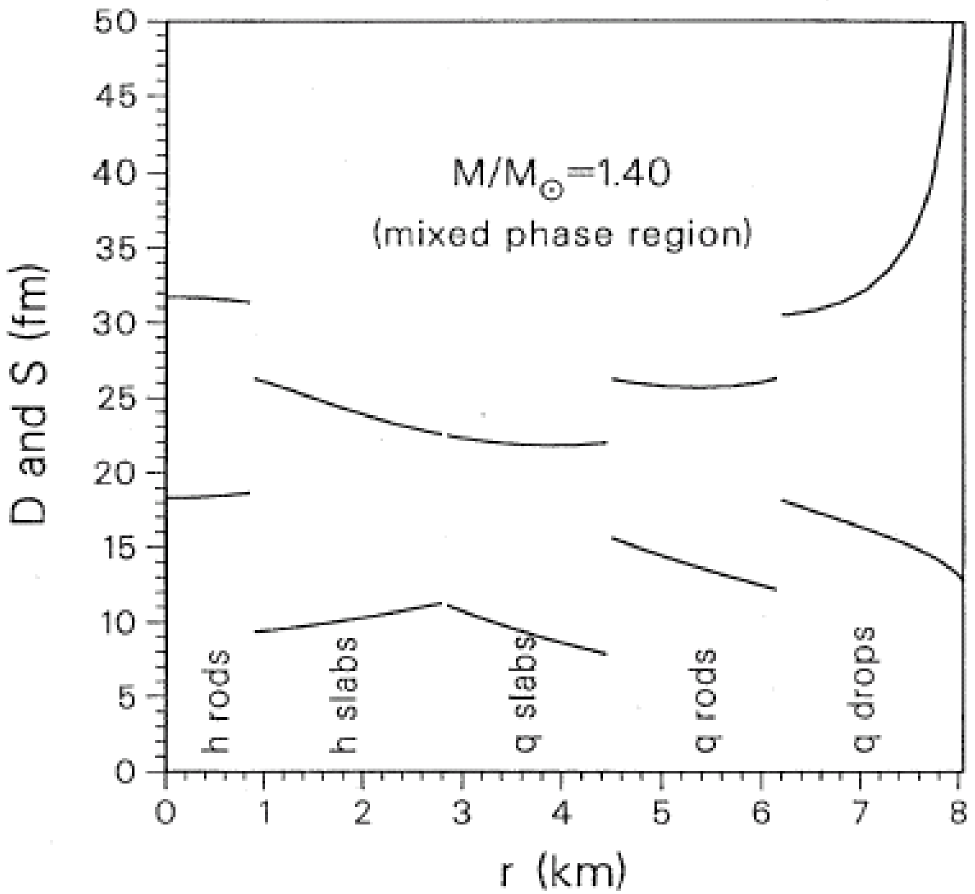
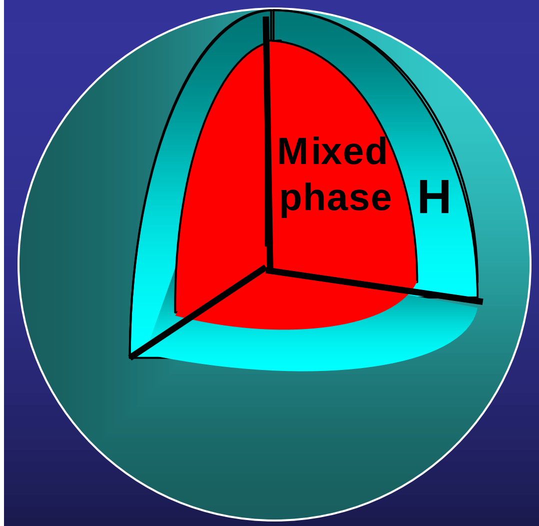


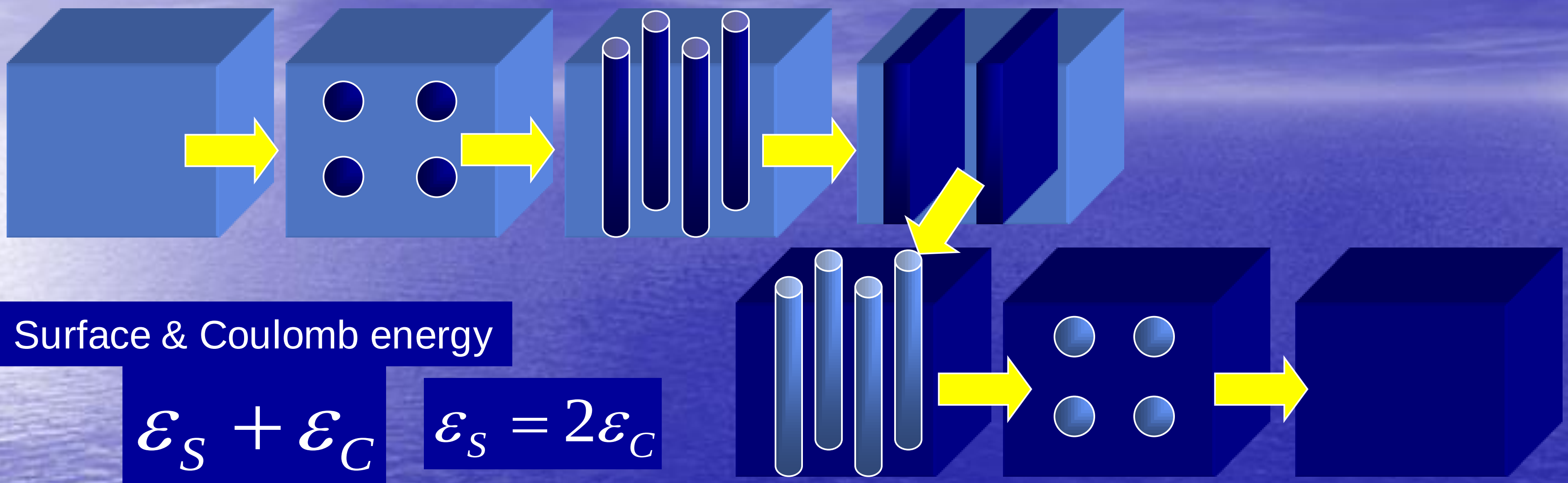
FIG. 2. Similar to Fig. 1 but for slightly less massive star. Mixed crystalline phase now extends to star's center. Radius is 12.3 km.



Glendenning and Pei Phys.Rev.C 52(1995) 2250

“Crystaline structure appear”

Glendenning and Pei Phys.Rev.C 52(1995) 2250



Surface & Coulomb energy

$$\varepsilon_S + \varepsilon_C$$

$$\varepsilon_S = 2\varepsilon_C$$

They didn’t solve the Poisson equation

- Voskresensky ,Yasuhira and Tatsumi, PLB**541**(2002)93 ; NPA**723**(2003)291

with screening effect → “Maxwell construction picture” ・・・○

solve Poisson equation with linear approximation

Density Functional Theory

T.E., T.Maruyama, S.Chiba
and T.Tatsumi PTP115(2006)337

$$\Omega_{\rm tot} = \Omega_{\rm Q} + \Omega_{\rm H} + \Omega_{\rm surface} + \Omega_{\rm e} + E_{\rm V}$$

Quark Phase

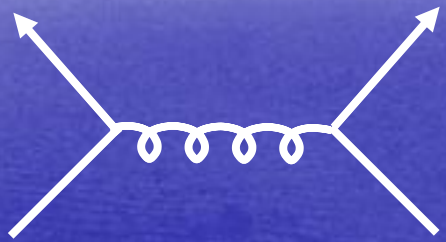
$$\Omega_{\rm u} = \int d^3r \left[\frac{3\pi^{\frac{2}{3}}}{4}\left(1+\frac{2\alpha_c}{3\pi}\right)\rho_{\rm u}^{\frac{4}{3}} - \mu_{\rm u}\rho_{\rm u}\right]$$

$$\Omega_{\rm d} = \int d^3r \left[\frac{3\pi^{\frac{2}{3}}}{4}\left(1+\frac{2\alpha_c}{3\pi}\right)\rho_{\rm d}^{\frac{4}{3}} - \mu_{\rm d}\rho_{\rm d}\right]$$

$$\Omega_{\rm s} = \int d^3r \left[\epsilon_{\rm s}(\rho_{\rm s}) - \mu_{\rm s}\rho_{\rm s} + B\right] \quad B \cdots \text{bag constant}$$

$$\Omega_{\rm I} = \Omega_{\rm u} + \Omega_{\rm d} + \Omega_{\rm s}$$

interaction : One Gluon Exchange



Hadron (Nucleon) Phase

$$\Omega_{\rm n} = \int d^3r \left[\frac{3}{10m}\left(3\pi^2\right)^{\frac{2}{3}}\rho_{\rm n}^{\frac{5}{3}} - \mu_{\rm n}(\rho_{\rm p},\rho_{\rm n})\rho_{\rm n} + \epsilon_{\rm pot}(\rho_{\rm p},\rho_{\rm n})\right]$$

$$\Omega_{\rm p} = \int d^3r \left[\frac{3}{10m}\left(3\pi^2\right)^{\frac{2}{3}}\rho_{\rm p}^{\frac{5}{3}} - \mu_{\rm p}(\rho_{\rm p},\rho_{\rm n}) - V\rho_{\rm p}\right]$$

$$\Omega_{\rm II} = \Omega_{\rm n} + \Omega_{\rm p}$$

interaction :effective potential to reproduce the nuclear matter saturation property

Electron : Phase Ⅰ &Phase Ⅱ

$$\Omega_{\rm em} = \int d^3r \left[-\frac{1}{8\pi e^2}(\nabla V)^2 - \frac{(V-\mu_e)^4}{12\pi^2}\right]$$

$$V(r) = -\int d^3r' \frac{Q_i\rho_i(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}$$

$$E_{\rm V} = \frac{1}{2}\int d^3r d^3r' \frac{Q_i\rho_i(\boldsymbol{r})Q_j\rho_j(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}$$

We can get “equation of motion” from

$$\frac{\delta\Omega_{tot}}{\delta\rho_i} = 0 \quad \Rightarrow \quad \mu_i = \frac{\delta\varepsilon}{\delta\rho_i} - Q_i V$$

gauge invariant form

Equations of motion

T.E., T.Maruyama, S.Chiba and T.Tatsumi PTP115(2006)337

● quark phase

$$\mu_{\rm u} = \left(1 + \frac{2\alpha_c}{3\pi}\right)\pi^{\frac{2}{3}}\rho_{\rm u}^{\frac{1}{3}} - \frac{2}{3}V$$

$$\mu_{\rm d} = \left(1 + \frac{2\alpha_c}{3\pi}\right)\pi^{\frac{2}{3}}\rho_{\rm d}^{\frac{1}{3}} + \frac{1}{3}V$$

$$\mu_{\rm s} = \epsilon_{\rm s} + \frac{2\alpha_c}{3\pi}\left[p_{\rm Fs} - 3\frac{m_{\rm Fs}^2}{\epsilon_{\rm Fs}}\ln\left(\frac{\epsilon_{\rm Fs}+p_{\rm Fs}}{m_{\rm s}}\right)\right] + \frac{1}{3}V$$

● nucleon phase

$$\mu_{\rm n} = \frac{p_{\rm Fn}^2}{2m} + \frac{2S_0(\rho_n - \rho_{\rm p})}{\rho_0} + \epsilon_{\rm bind} + \frac{K_0}{6}\left(\frac{\rho_{\rm n}+\rho_{\rm p}}{\rho_0} - 1\right)^2 + \frac{K_0}{9}\left(\frac{\rho_{\rm n}+\rho_{\rm p}}{\rho_0} - 1\right) + 2C_{\rm sat}\frac{\rho_{\rm n}+\rho_{\rm p}}{\rho_0} - C_{\rm sat}$$

$$\mu_{\rm p} = \mu_{\rm n} - \frac{p_{\rm Fn}^2}{2m} + \frac{p_{\rm Fp}^2}{2m} - \frac{4S_0(\rho_{\rm B} - 2\rho_{\rm p})}{\rho_0} + V$$

$$\mu_e = (3\pi^2\rho_e)^{\frac{1}{3}} + V$$

Poisson equation

$$\nabla^2 V = 4\pi e^2\left[\left(\frac{2}{3}\rho_u - \frac{1}{3}\rho_d - \frac{1}{3}\rho_s\right)\theta(R-r) + \rho_{\rm p}\theta(r-R) - \rho_e\right]$$

Chemical equilibrium

$$\mu_{\rm u} - \mu_{\rm s} + \mu_{\rm e} = 0$$

$$\mu_{\rm d} = \mu_{\rm s}$$

Quark phase

$$\mu_{\rm n}\,(\equiv \mu_{\rm B}) = \mu_{\rm p} + \mu_{\rm e}$$

Nucleon phase

$$\mu_n = \mu_u + 2\mu_d$$

$$\mu_p = 2\mu_u + \mu_d$$

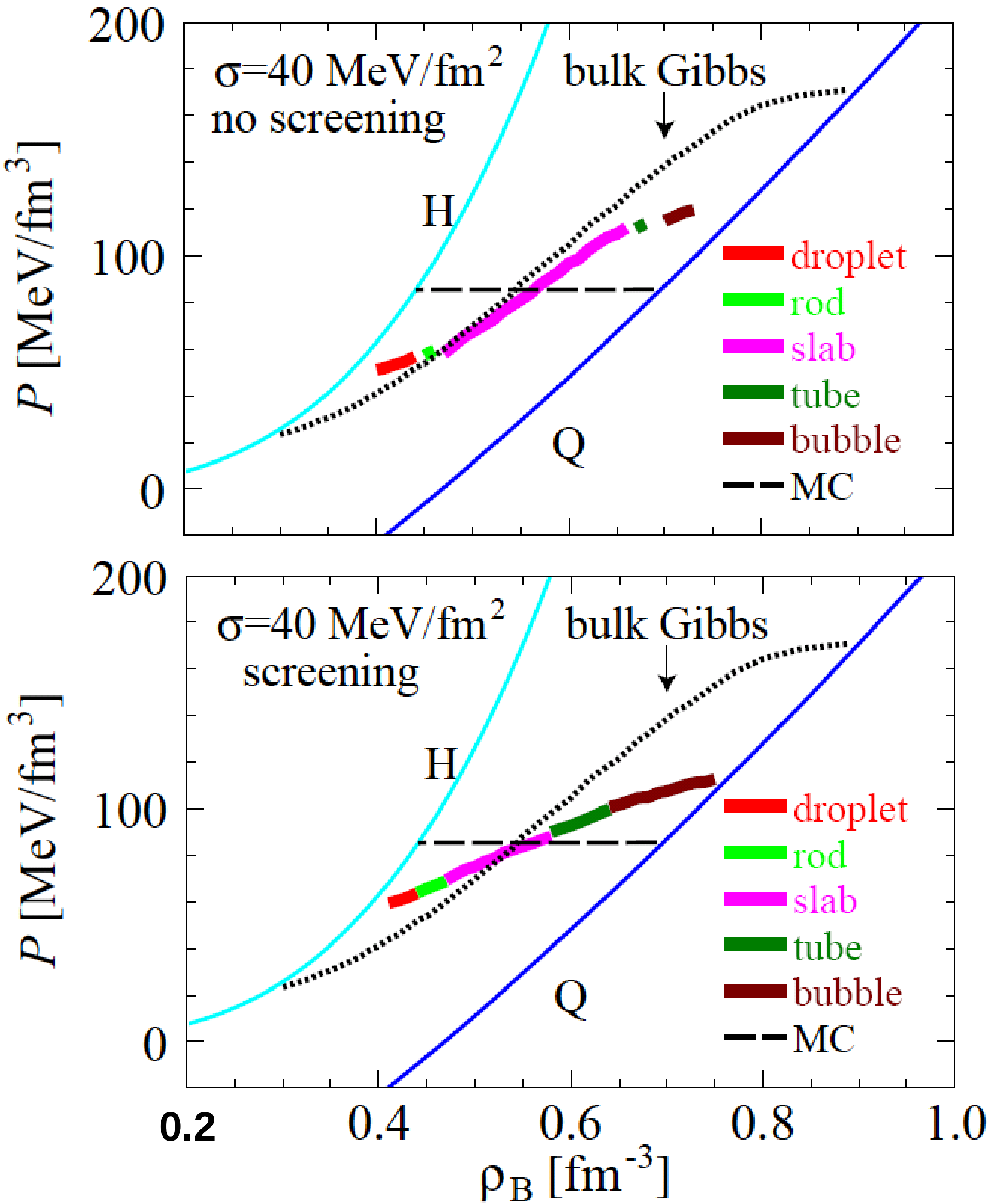
Quark & nucleon boundary

With Gibbs conditions

ρ_i is the function of V

V is the function of ρ_i

Poisson equation become highly nonlinear equation. With screening effect, it asks for rearrangement of ρ_i.



T.E., T.Maruyama, S.Chiba and T.Tatsumi PTP**115**(2006)337

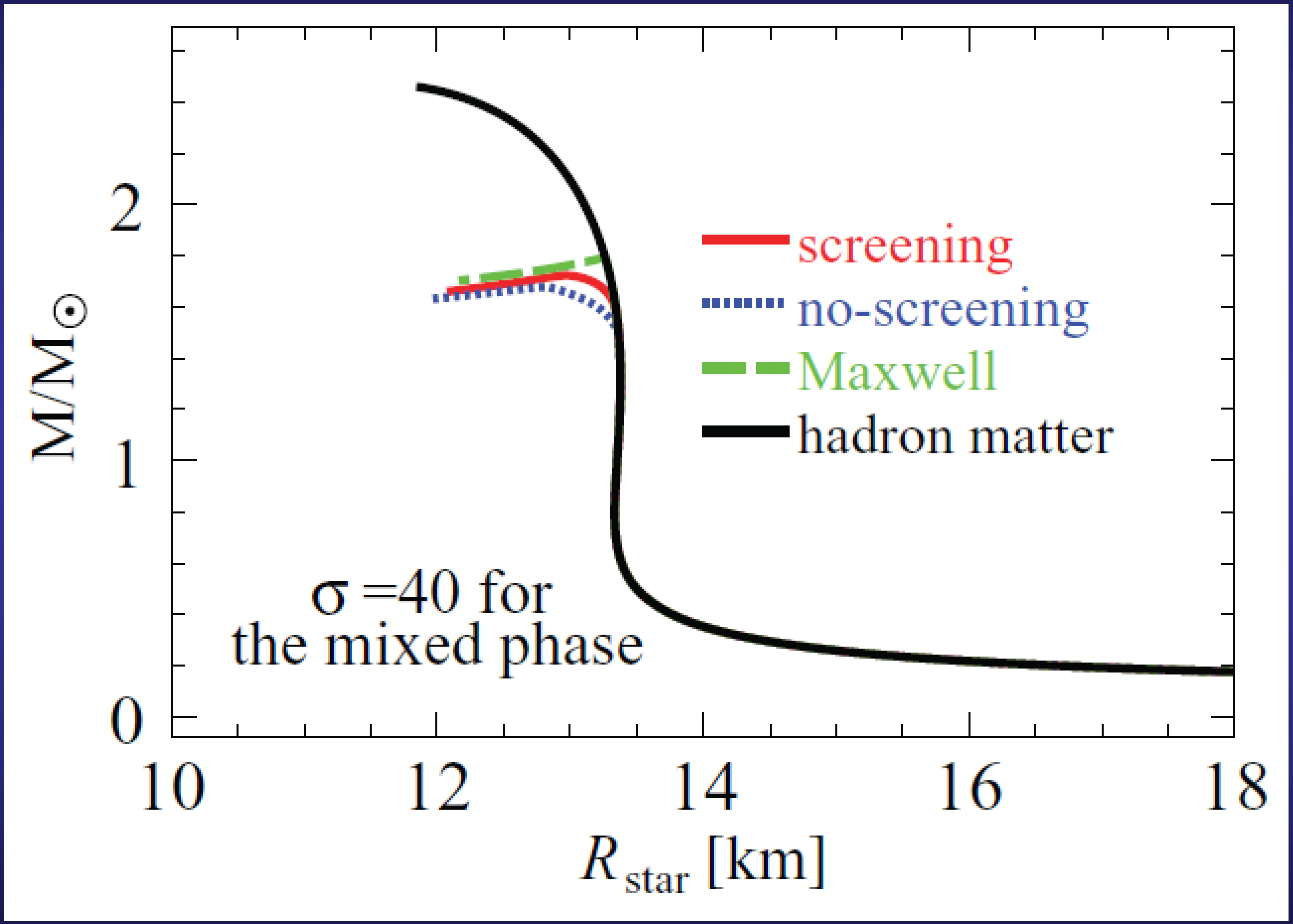
“Finite size effects”

- Screening effect
- Surface tension

Lattice QCD (finite temperature)
10 ~ 100 [Mev/fm^2]
Kajantie et al NPB**357** (1991)693
Huang et al PRD**42**(1990)2864

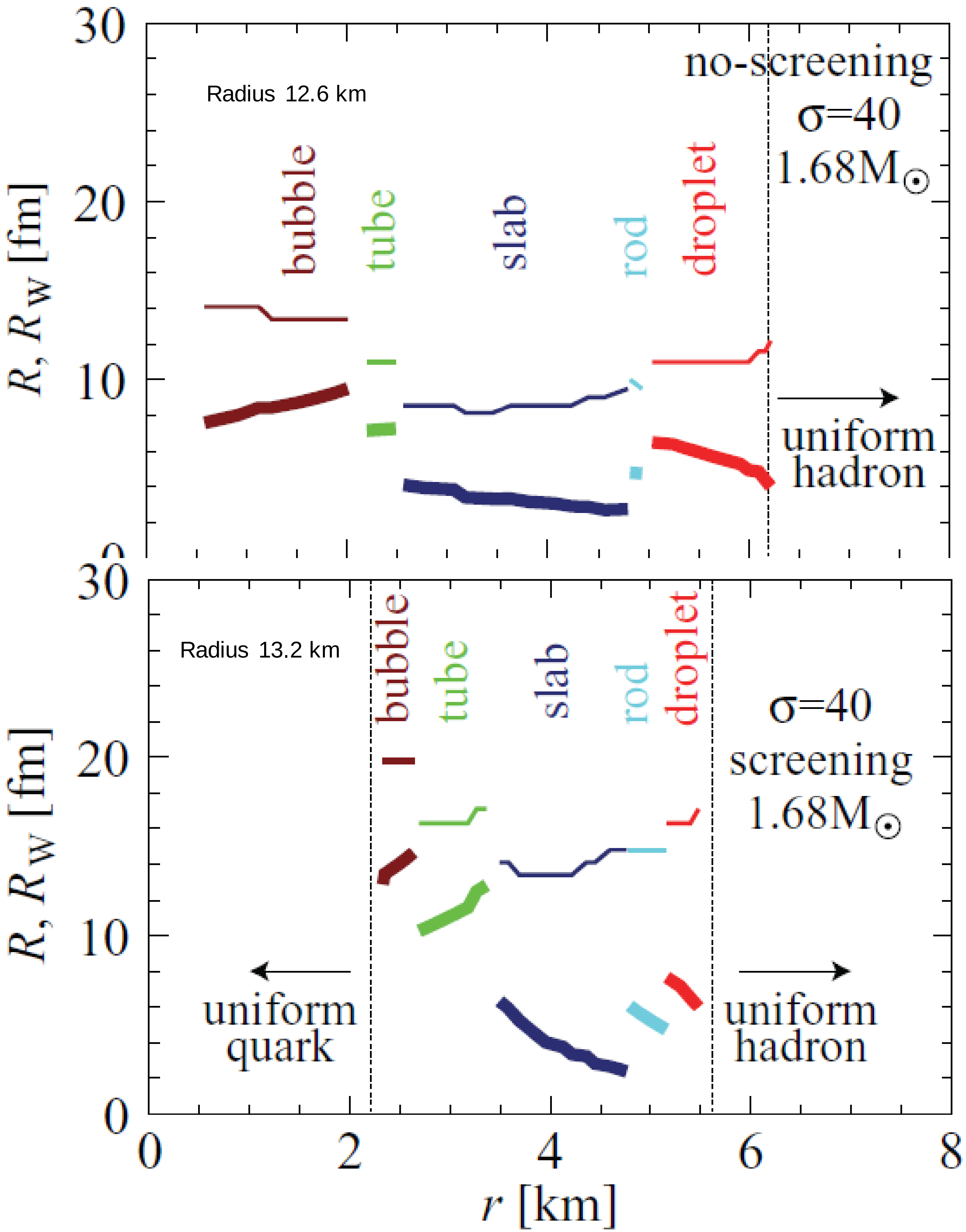
Implication to hybrid stars

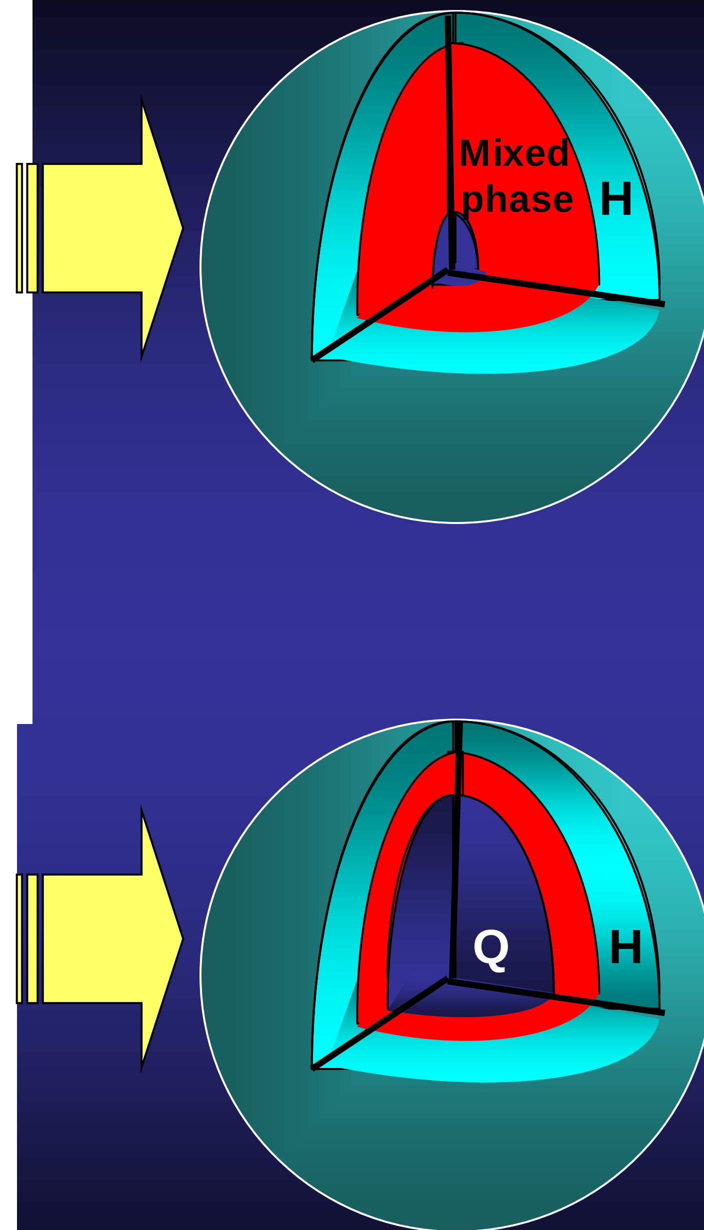
Our EOS ⇒ Tolman-Oppenheimer-Volkoff (TOV) equation



T.E., PRC83, 068801 (2011)

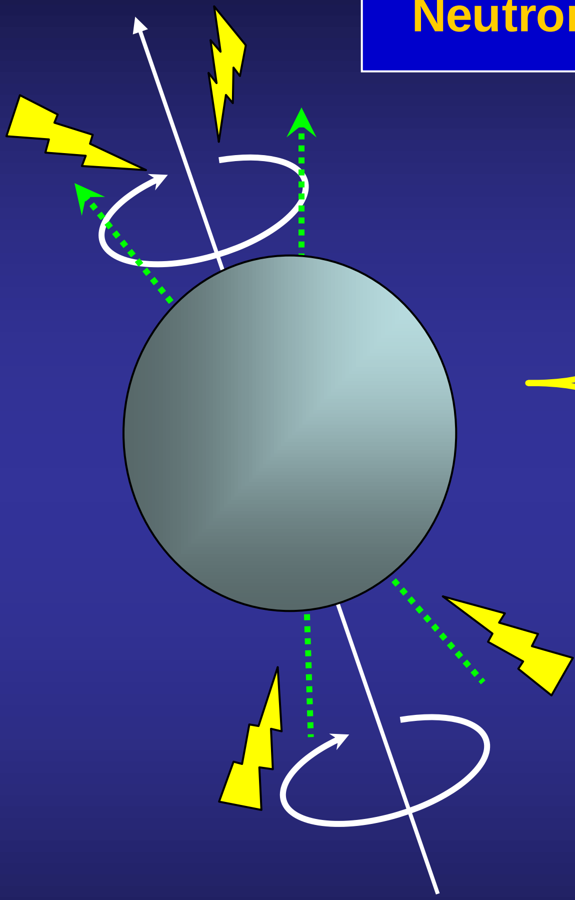
T.E. Phys.Rev.C83, 068801 (2011)





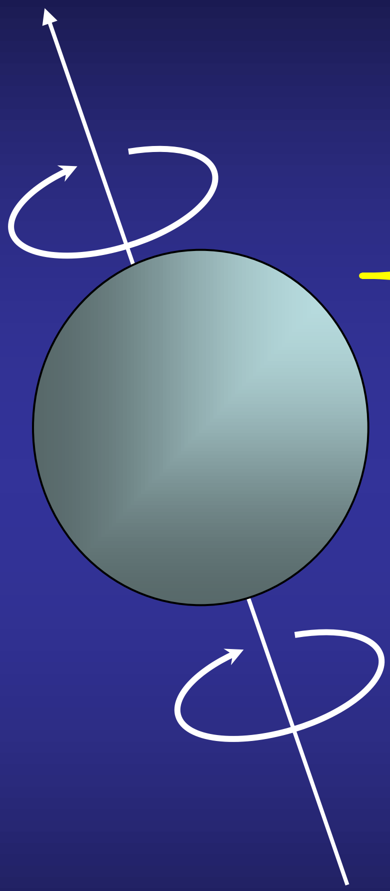
About 1000 pulsars are observed…

Neutron stars (hybrid stars) have many physical phenomena



- **Glitch phenomena**
- **Cooling problem**
- **Strong magnetic field** — 10^{12} G～10^{15} G(magneters)
- **Maximum mass** — $\sim 2.1 M_{\odot}$
- **Othres…**
- **Rotation**

Including the rotation effect



Approximation

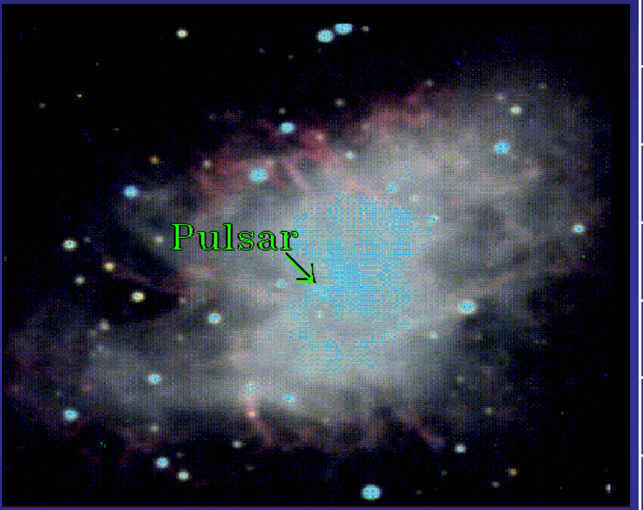
- Stationary rigid rotation (Uniform rotation)
- Axially symmetric with respect to the spin axis
- Perfect fluid

Review of stationary rotation in General Relativity
: Stergioulas, (2003)

A. Kurkela et al. arXiv:1006.4062[astro-ph.HE]

Our EOS ⇒ Rotating Neutron Star (RNS)

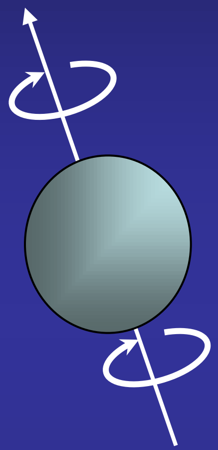
Observations

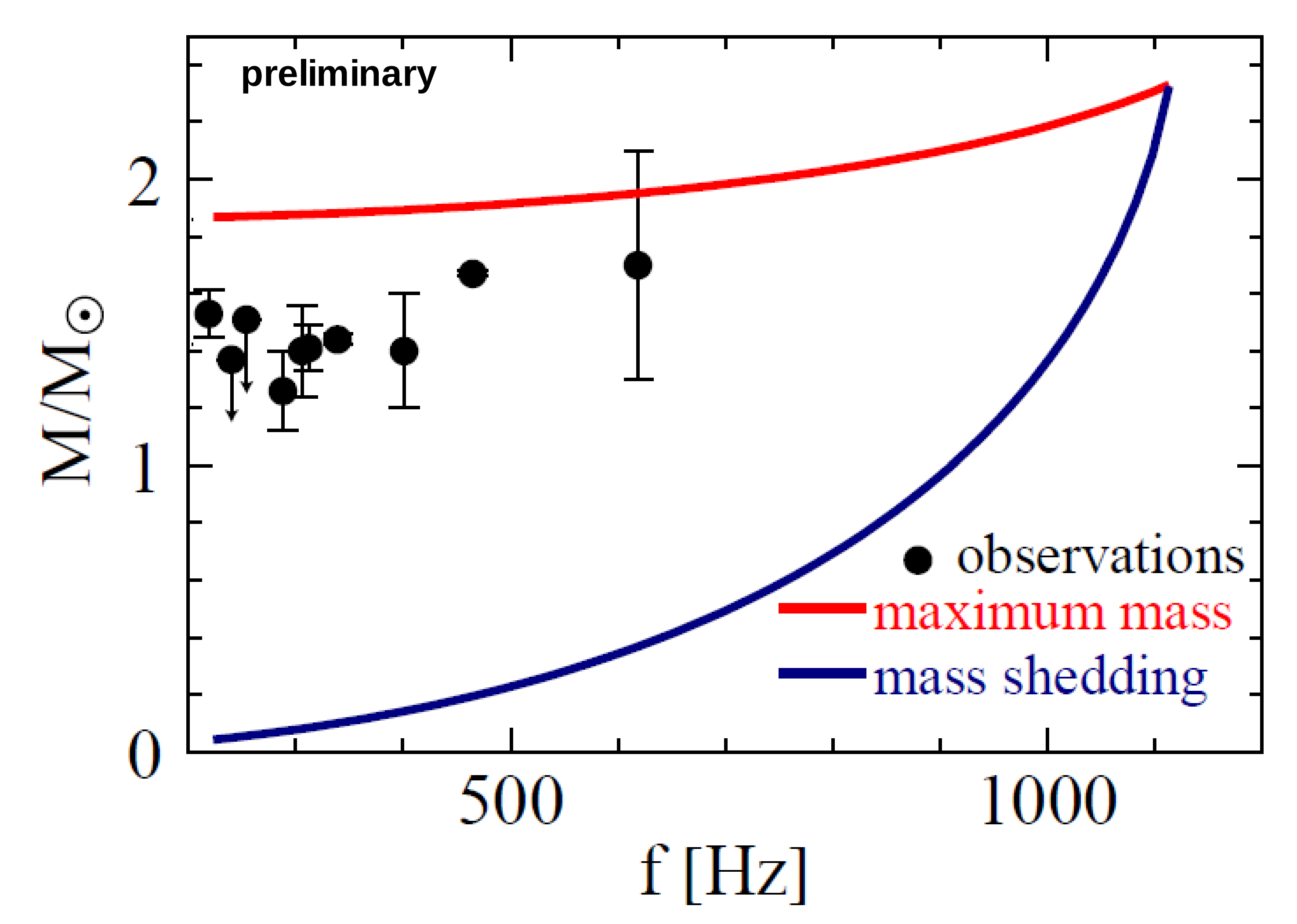


Name	Spin [Hz]	Mass/M⊙
J0024-7204H	312	1.41±0.08
J0437-4715	174	1.76±0.20
J0514-4002A	126	< 1.52
J0751+1807	288	1.26±0.14
J1012+5307	190	1.64±0.22
J1713+0747	219	1.53±0.08
4U1608-52	619	1.70±0.40
J1748-2446I	105	1.85±0.05
SAXJ1808.4-3658	401	1.40±0.20
J1824-2452C	240	< 1.37
B1855+09	187	1.58±0.13
J1903+0327	465	1.67±0.01
J1909-3744	339	1.44±0.02
J1911-5958A	306	1.40±0.16
J2019+2425	254	< 1.51

Masses of neutron stars with millisecond periods

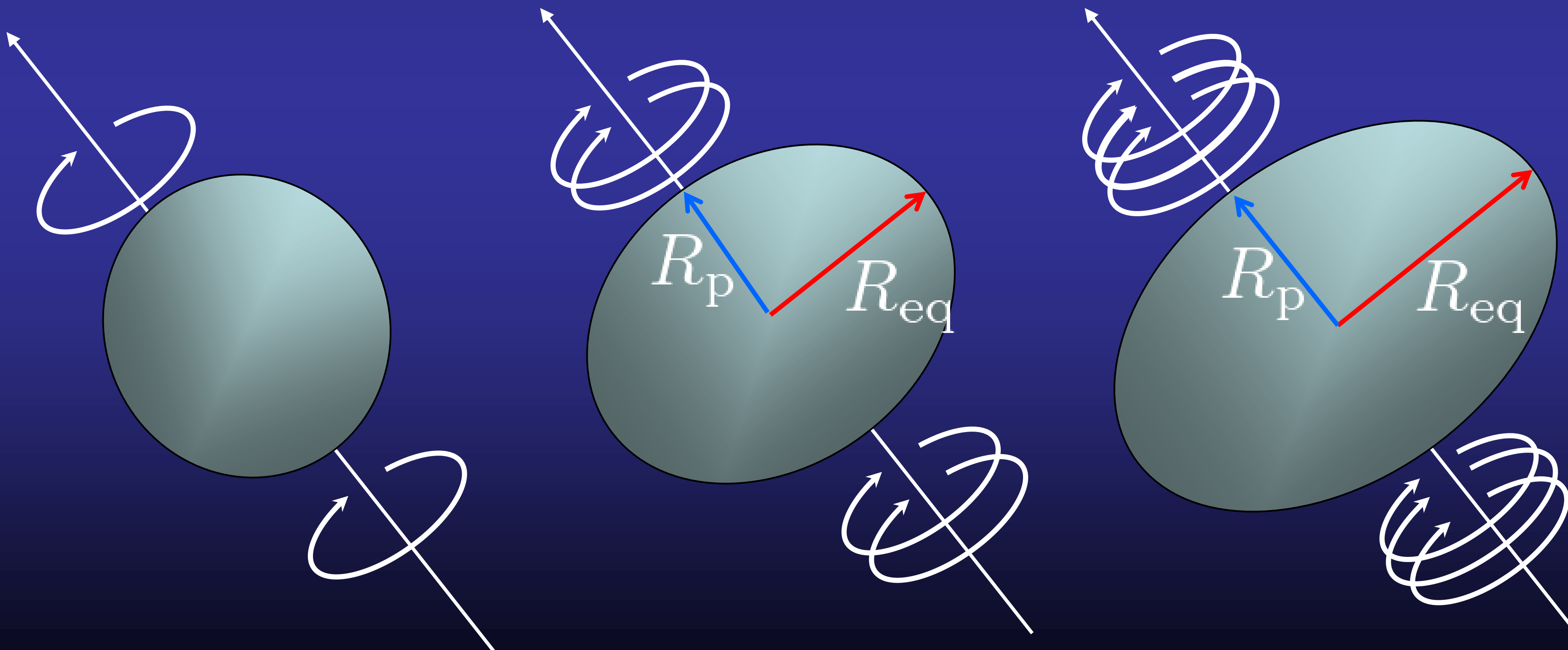
Including rotation: EOS(with screening)

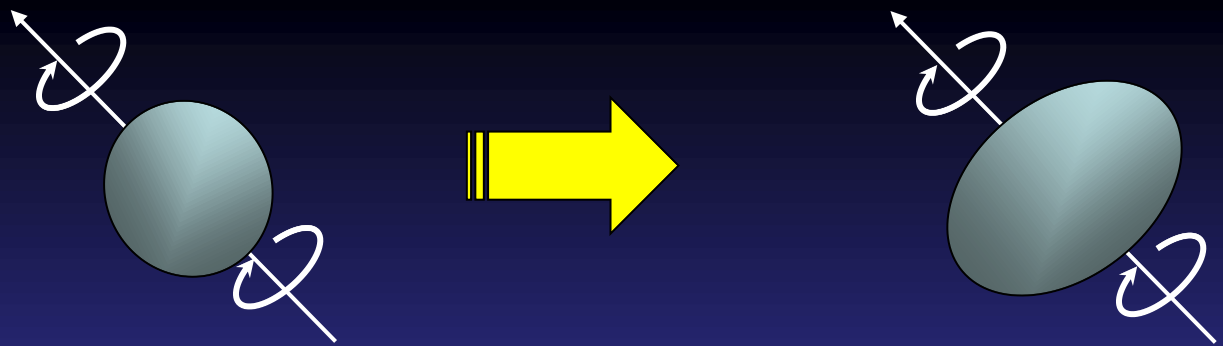


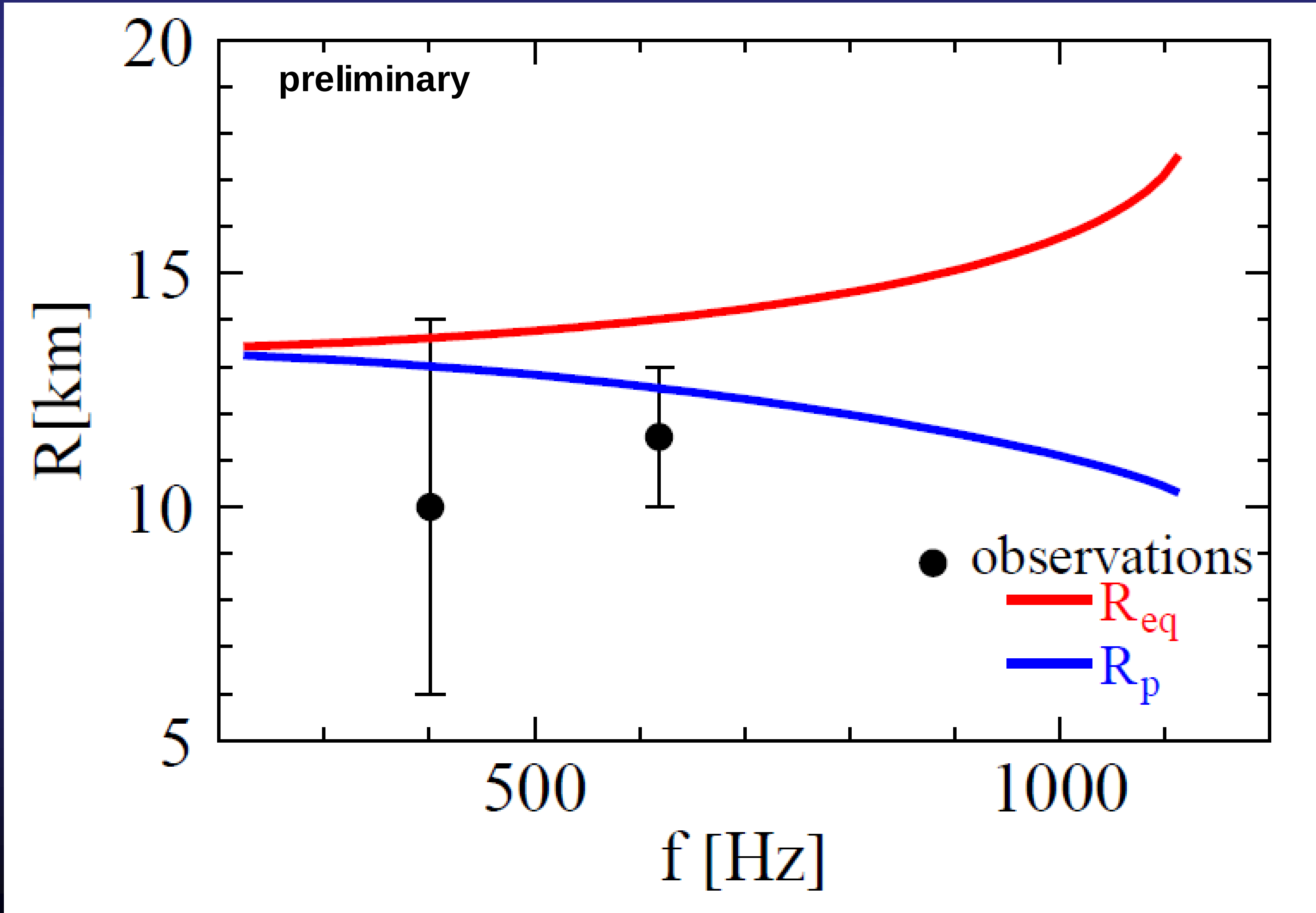


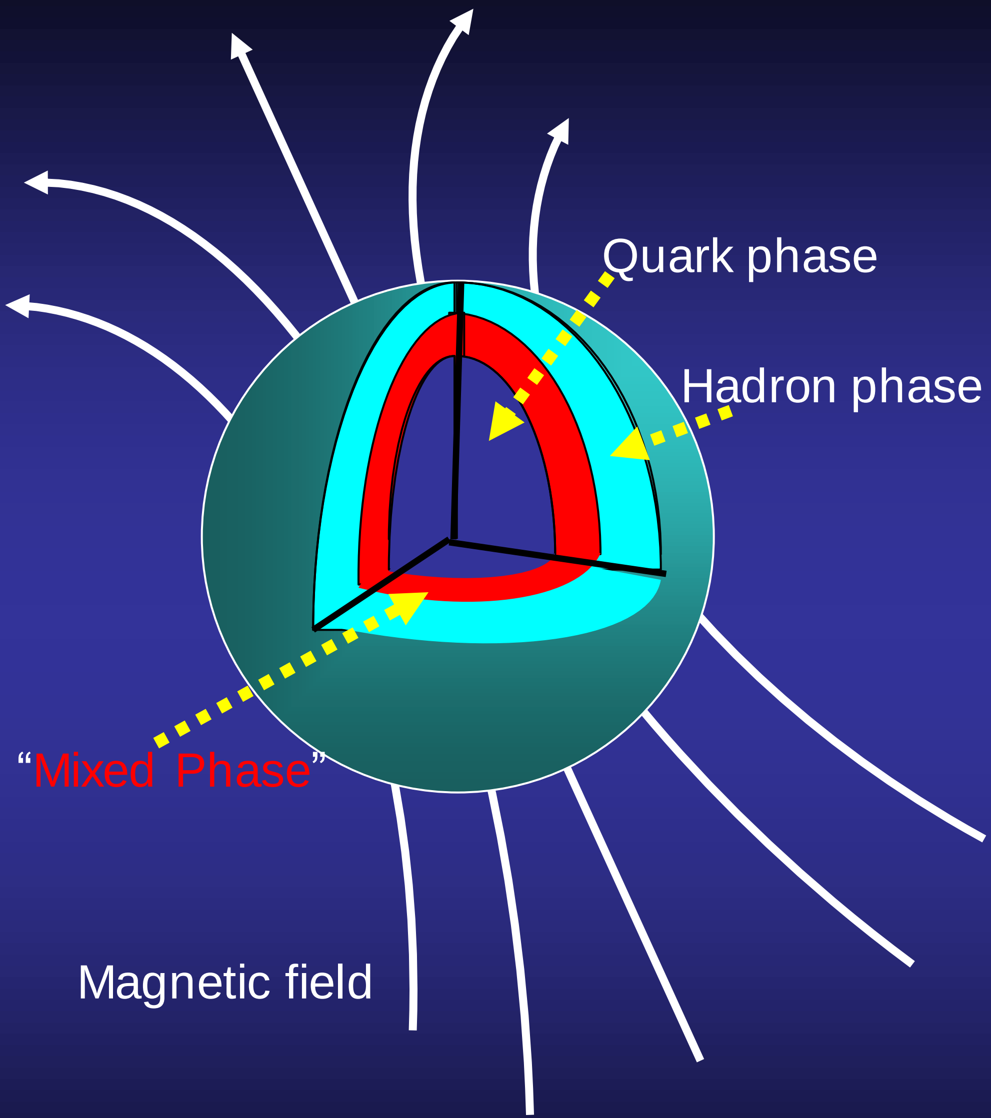
Name	Spin [Hz]	Radius
4U1608-52	619	11.5±2.0
SAXJ1808.4-3658	401	10.0±4.0

Neutron star periods and radii






20
15
10
5
R[km]
preliminary
500
1000
f [Hz]
observations
R_{eq}
R_p



Strong magnetic field～10^{12} G

Magnetars～10^{15} G

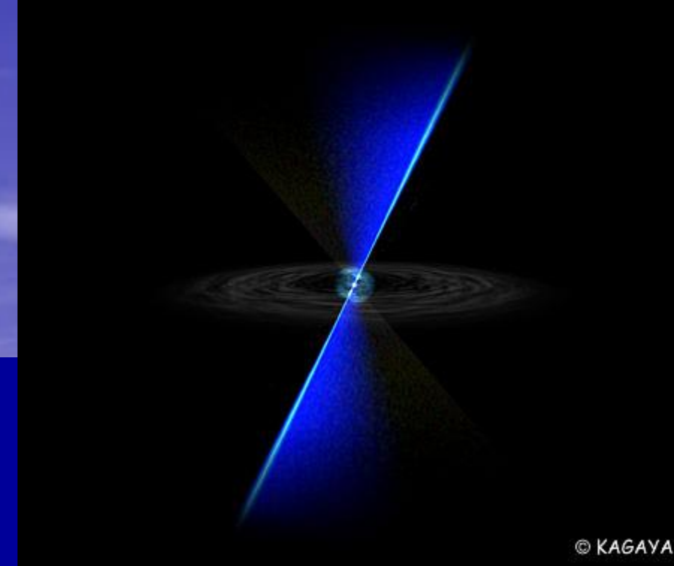
The origin of magnetic field unknown…

spin-polarization of nuclear matter
⇒many calculations in 1970s,
But negative results…
cf. J.M. Pearson et al. PRL**24**(1970)325
J. Dabrowski et al. PRC**17**(1978)1516

⇒**spin-polarization** of liquid ^{3}He "favorable"
M. Takano, **T. E.**, R. Kimura and M. Yamada, PTP**109**(2003)213

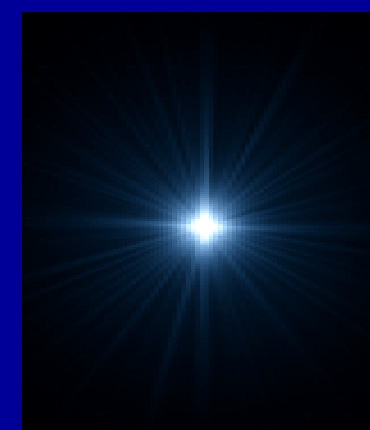
How about quark matter?
spin-polarization⇒may be possible
T. Tatsumi PLB**489**(2000)280
Quark matter would exist or not?

cf. Dynamo effect



Summary

- Inner structures of the star strongly depend on EOSs
- EOSs confront observations.
- “Rotation” restricts EOSs of the matter.



Future plans ;

- Rotation effects on inner structures of the star
- Magnetic fields are needed for our EOS
- Strong magnetic fields – what is the origin ?

Thank you for your attention.