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Two types of glitches in a solid quark star model

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Outline

Motivation

- Challenges to the theories on pulsar glitches

The model

- Bulk-variable starquake
- Bulk-invariable starquake

The result

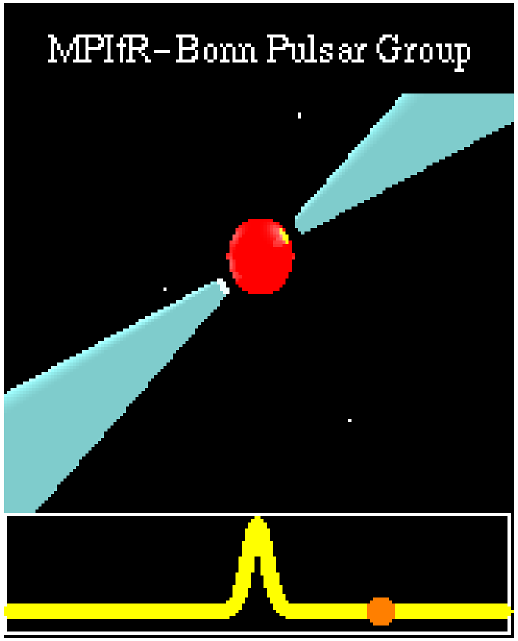
- Two types of starquakes corresponds to two types of glitches in observation

D & C

- Discussion
- Conclusion

Pulsar = Neutron Star??

- Wiki tells us “Pulsar is highly magnetized rotating Neutron star”. But not exactly!



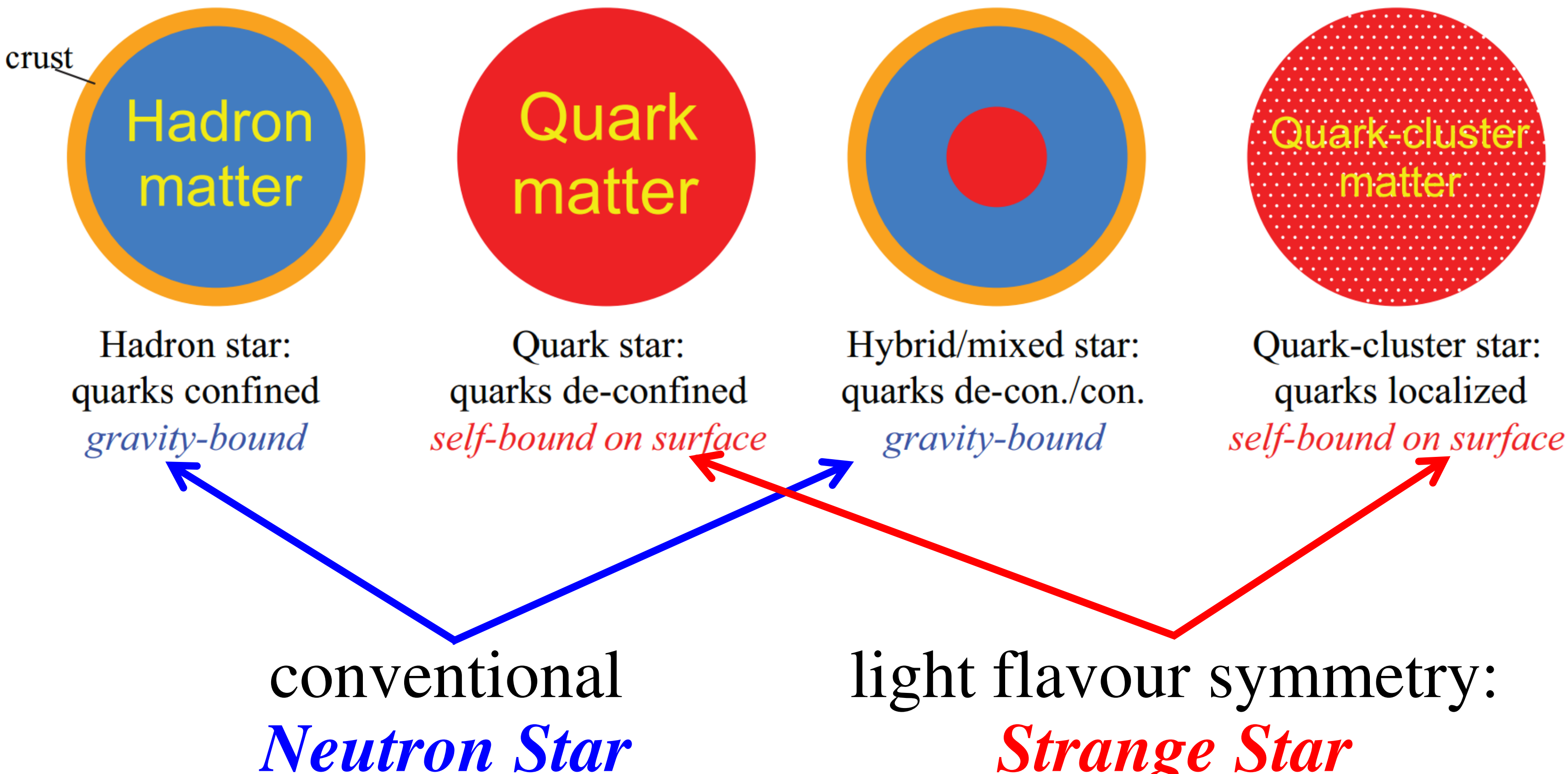
Up: An imaginary model of magnetized rotator model for ‘pulsar’

Twinkle, twinkle, little star
How I wonder what you are

Down: An observed profile in the radio telescope, which is ‘a pulsar’.

Pulsar ≠ Neutron star

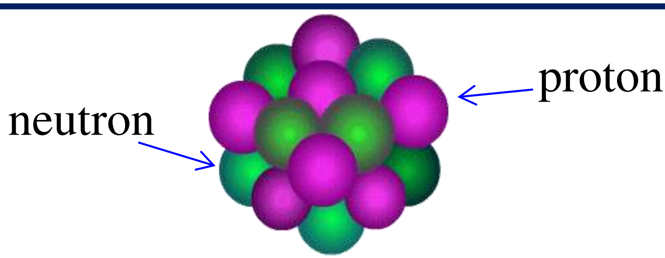
- Different EoS models for pulsars (Xu 2014)



Puzzling Pulsar Inside: EoS...

- Nucleus and Quark-cluster star:

differences and *similarities*

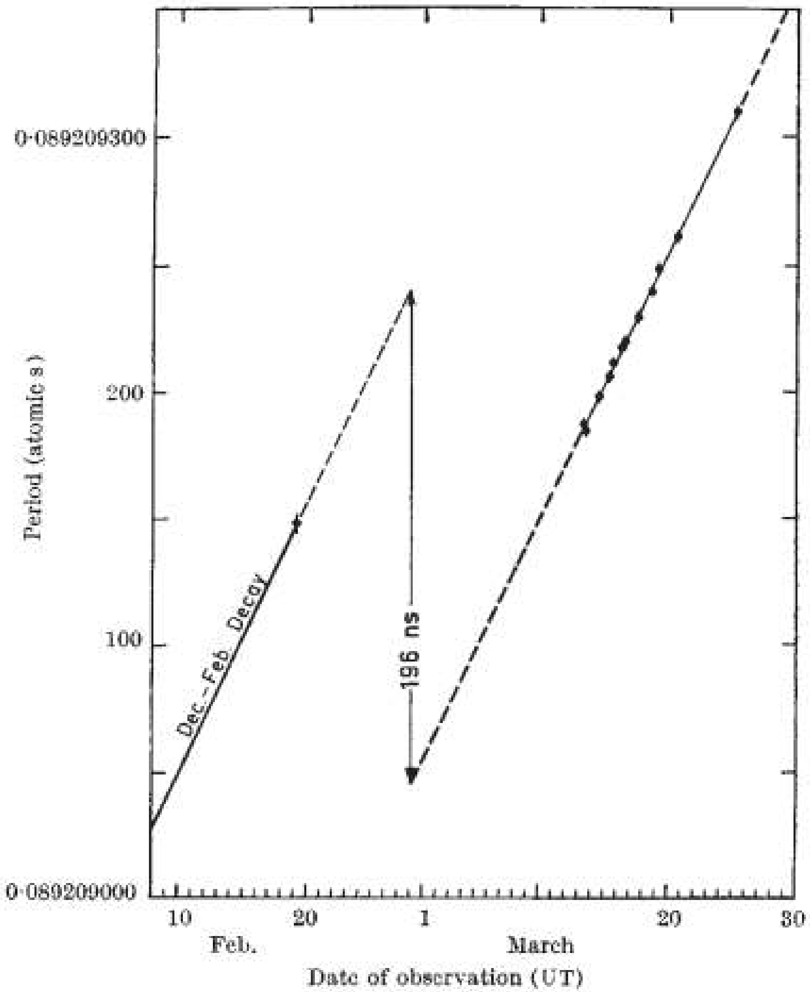


Self-bound: by strong int.	Self-bound: by strong int.
$l \sim$ fm: electrons outside	$l > \lambda_e$: electrons inside
2-flavour symmetry: isospin	3-flavour symmetry: strangeness
light clusters: p(uud), n(udd)	heavy clusters: 6(H), 9, 12, 18
quantum gas/liquid	solid condensed matter at low-T

Xu, 2014 Presentation in CSQCD IV

Neutron Star .vs. Quark Star

- From observational point of views:
  - **The absence of spectrum lines in pulsar spectrums**
    Neutron Star : crust with mostly iron atoms. remark: 1E 1207.4-5209 ☹
    Quark Star: bare, no atomic structure ☺
  - **The binding energy**
    Neutron Star: gravity/em bound on the surface ☹
    Quark Star: self bound on the surface ☺
  - **The iron core collapse model of Type II supernova**
    Neutron Star: optically thick remark: **arXiv:1501.01961** ☹
    Quark Star: optically thin for neutrino ☺
  - **Glitches**
    to be discussed today…

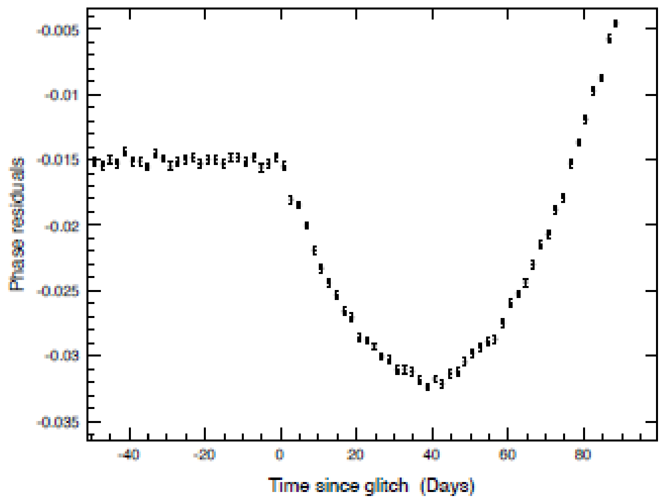


Pulsar glitch

- An important phenomenon to help us understand the EoS of dense matter.
- Normal glitch / Slow glitch / Anti glitch ...
- The mechanism is still a matter of debate.

Glitch: sudden spin up of pulsars.
First observed on Vela pulsar (1969)
A 195ns decrease in the spin period was detected by Radhakrishnan & Manchester

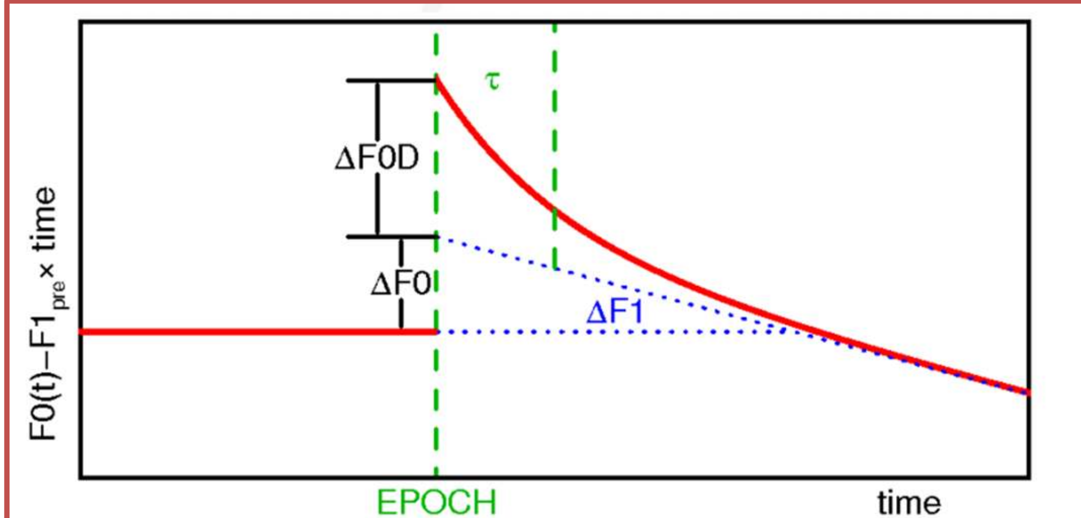
Pulsar Glitch



The quadratic signature of the timing residuals during the glitch (glitch detectors)

Espinoza et al. 2012

Observational parameters of pulsar glitch



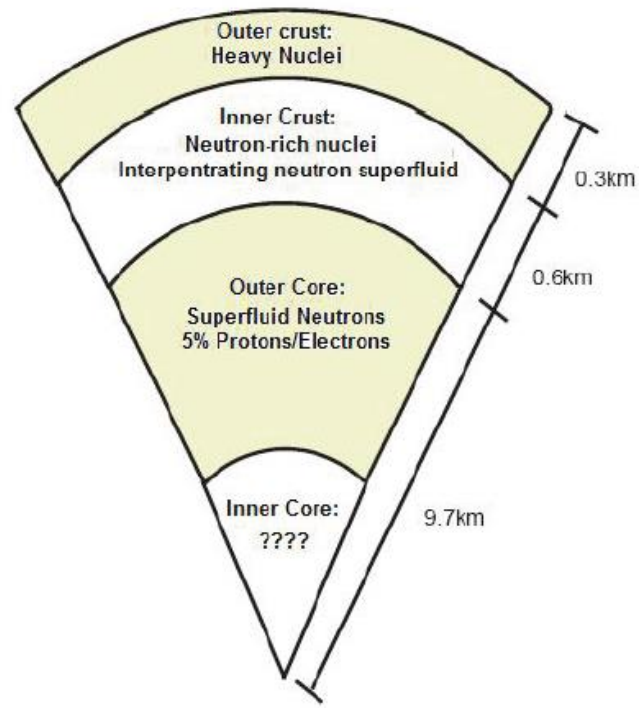
Pulsar glitch

Pin&unpin model

- Coupling and decoupling between the diffrential rotating crusts

Solid crust cracking model

- Starquake induced moment of inertia change



As the development of glitch observations, more and more challenges to the previous theories remain to be solved.

Challenge 1

Radiative quiet glitches of Vela pulsar

$\delta\nu/\nu \sim 10^{-6}$

negligible energy release in observations

(Helfand et al. 2001)

Challenge 2

Radiative loud glitches of AXP/SGRs

~< $\delta\nu/\nu \sim 10^{-6}$

X-ray bursts & radiative anomaly

(Dip & Kaspi 2014)

Starquake models in Solid quark stars

Quakes in solid quark stars

Zhou A Z, et al. 2004 Astro-Particle Journal

Pulsar slow glitches in a solid quark star model

Peng & Xu 2008 MNRAS

Two types of glitches in a solid quark star model

Zhou E P, et al. 2014 MNRAS

The model – bulk variable starquake

The M-R relation for solid quark stars

Physical scenario

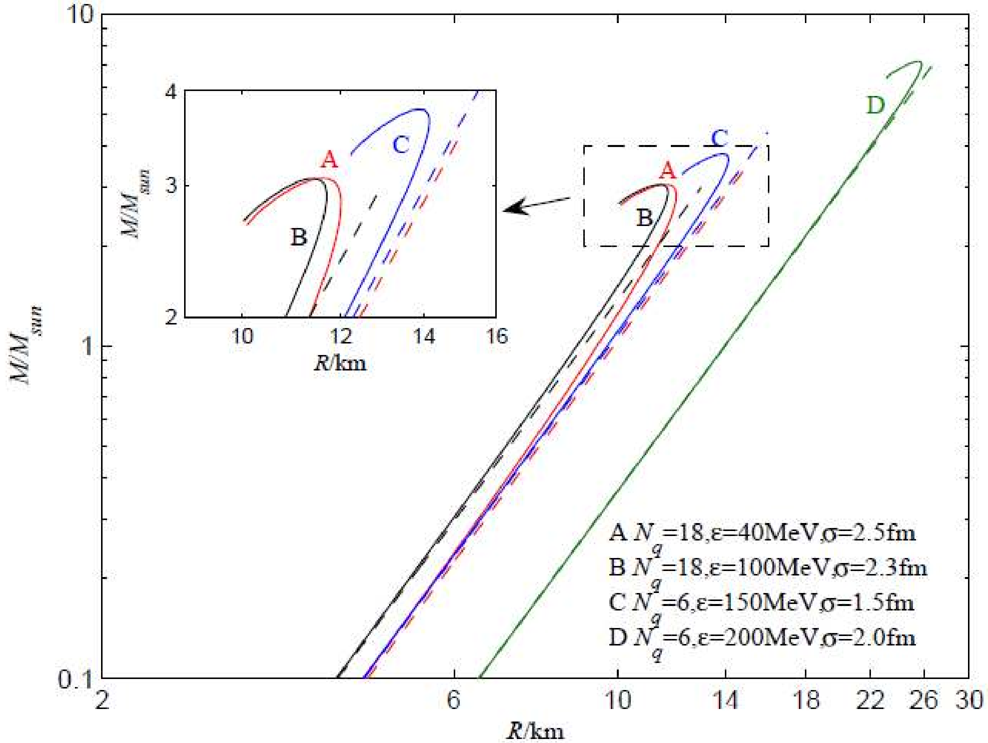
Self-bound (low mass) $M \sim R^3$

↓

Gravity-bound(high mass) $M\nearrow R\searrow$

Exceeding the R_m by accretion will make a solid star accumulate elastic energy and induce a starquake which can be seen as a global reduce of the radius

Simulation

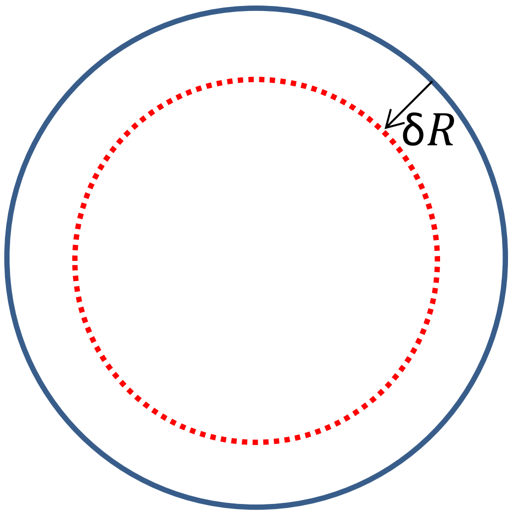


Guo et al. 2014

Bulk variable starquake

Type II starquake can be treated as a global decrease in R.

The main parameter in a Type II starquake: δR



δE w.r.t δR

$$\delta E = (\frac{3GM^2}{5R} - \frac{L^2}{I})\frac{\delta R}{R}$$

- Gravitational energy of a spheroid + kinetic energy
- Conservation of the angular momentum

$\delta \nu/\nu$ w.r.t δR

$$\frac{\delta\omega}{\omega} = -\frac{\delta I}{I} = -\frac{2\delta R}{R}.$$

- The moment of inertia of a spheroid

Result

$$|\delta E| = \frac{3GM^2}{10R}\frac{\delta\nu}{\nu} \sim 10^{47}\,\mathrm{erg}(\frac{M}{1.4\,M_\odot})^2(\frac{R}{10^6\,\mathrm{cm}})^{-1}(\frac{\delta\nu}{\nu}/10^{-6})$$

- The gravitational energy is much larger than the kinetic energy

The model – bulk invariable starquake

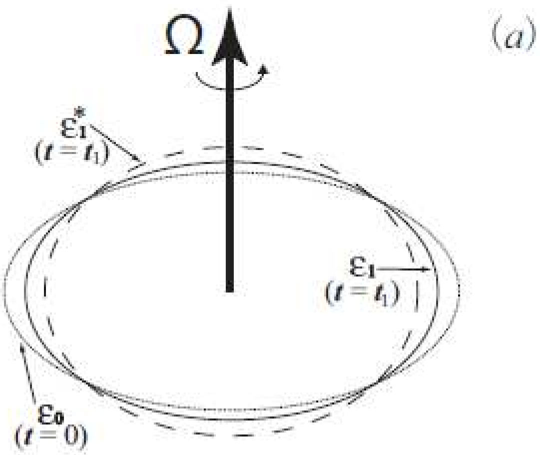
The stable shape of a rotating star will be ellipsoid instead of spheroid.

$$E_{total} = E_k + E_g + E_{el} = E_0 + \frac{L^2}{2I} + A\varepsilon^2 + B(\varepsilon - \varepsilon_0)^2$$

The key parameter in a Type I starquake: $\varepsilon = (I - I_0)/I_0$

For a rotating star with certain density ρ, the relation between ellipticity and angular velocity is

$$\Omega^2 = 2\pi G\rho[\frac{\sqrt{1-e^2}}{e^3}(3-2e^2)\sin^{-1}e - \frac{3(1-e^2)}{e^2}]$$



Remark: Jacobi ellipsoid for extremely fast spinning pulsars

The model – bulk invariable starquake

The evolution between two glitches

t=0 Solidification or the end of previous glitch

- No elastic energy

t=0 ~ t=t_1 Normal spin down phase

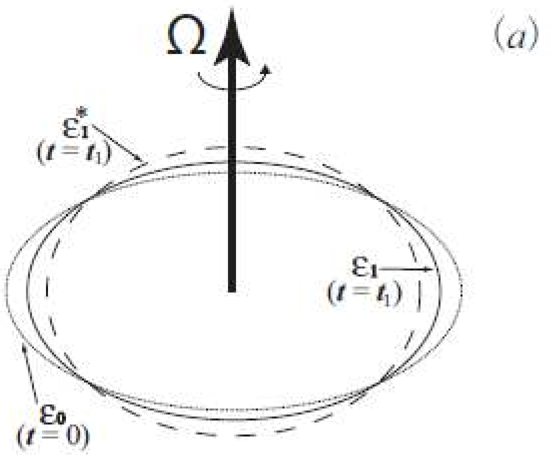
- The difference between ε and ε_{mac}
- Elastic energy accumulated

t=t_1-0 The glitch epoch

- Elastic energy reaches the critical value

t=t_1+0 Glitch

- The elastic energy is released and the pulsar can be treated as fluid
- The shape changes and a new equilibrium is set up at the end of the glitch



The model – bulk invariable starquake

δE w.r.t $\delta\varepsilon$ $E_{\rm ela} < \frac{B}{2(A+B)}|\delta E_{\rm k}|(\varepsilon_0 - \varepsilon_1)$

- The condition of quasi-equilibria during the normal spin down: $\frac{\partial E}{\partial \varepsilon} = 0$

$\delta\nu/\nu$ w.r.t $\delta\varepsilon$ $\frac{\delta\Omega}{\Omega} = -\frac{\delta I}{I} = -\frac{\delta\varepsilon}{1+\varepsilon}$

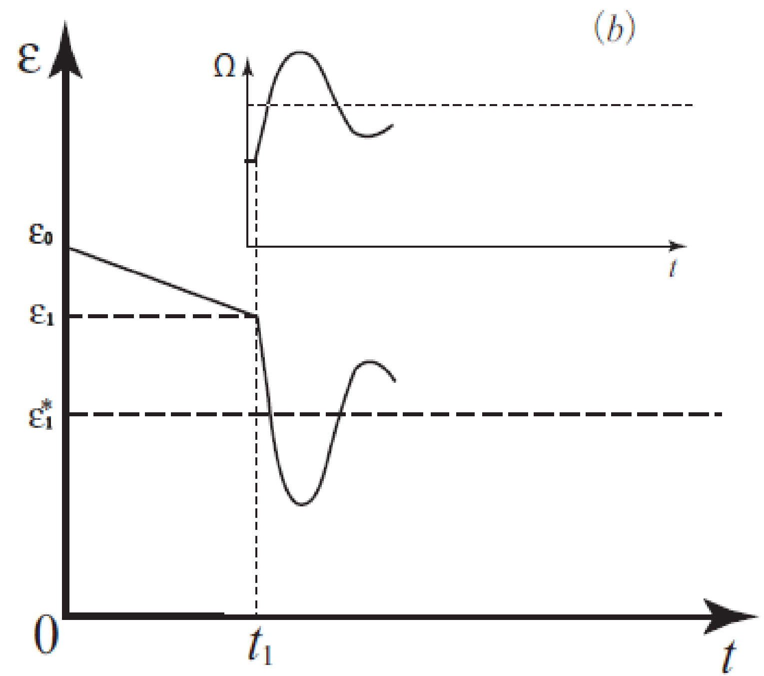
- Conservation of angular momentum

$\delta\varepsilon \ll \varepsilon \ll 1$

- The evolution of ε $\varepsilon_1 - \varepsilon_0 = -\frac{A}{B}\frac{\delta\Omega}{\Omega}$

result $\delta E \sim 4\times 10^{36}\,{\rm erg}(\frac{t}{10^6\,{\rm s}})(\frac{\delta\nu}{\nu}/10^{-6})$

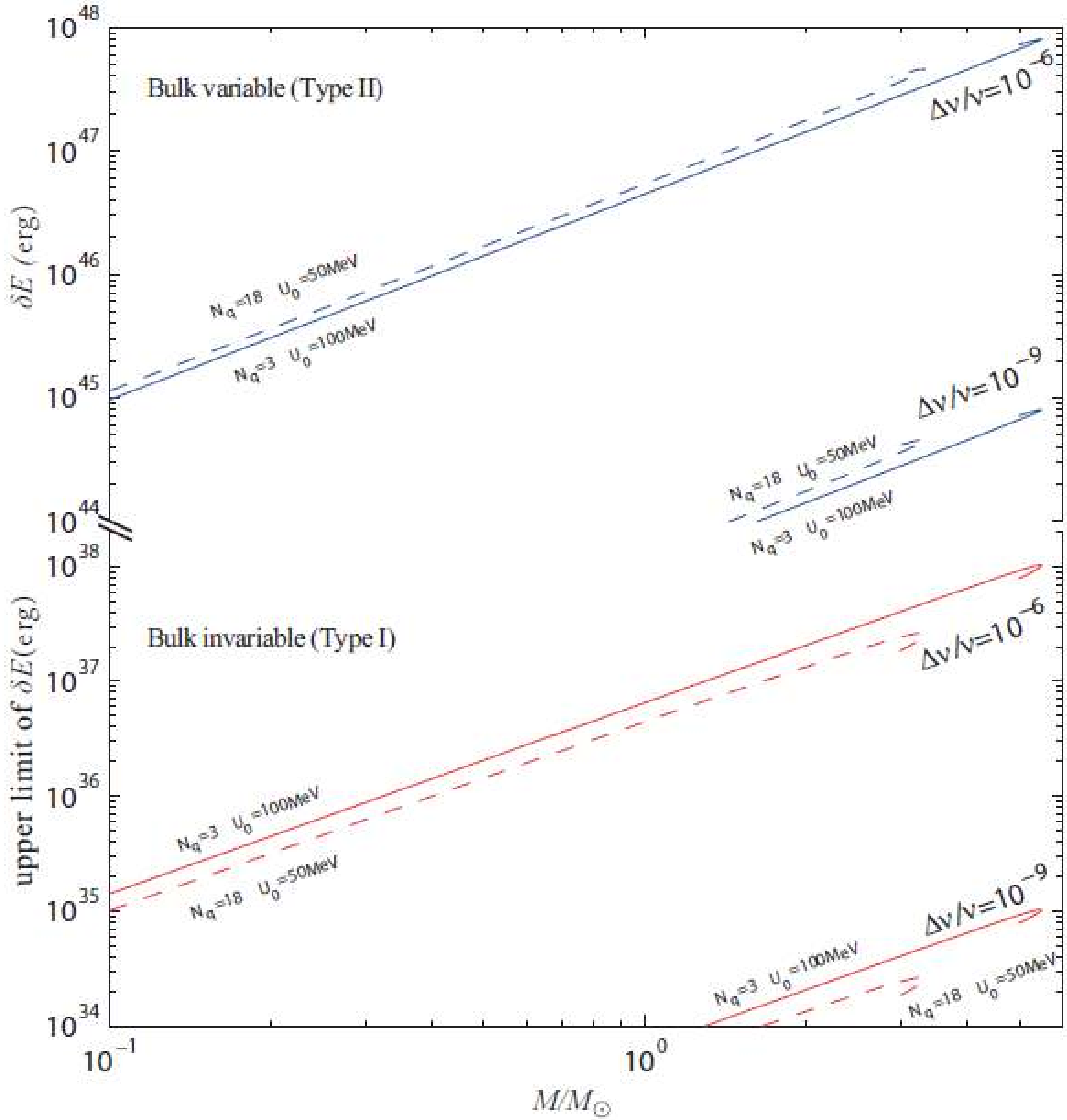
- Note that the spin down power and interval between two glitches also affect the energy released
- The observational data of Vela is applied



The result

EoS by
Lai & Xu 2009

Parameters set to fit the observation of Vela



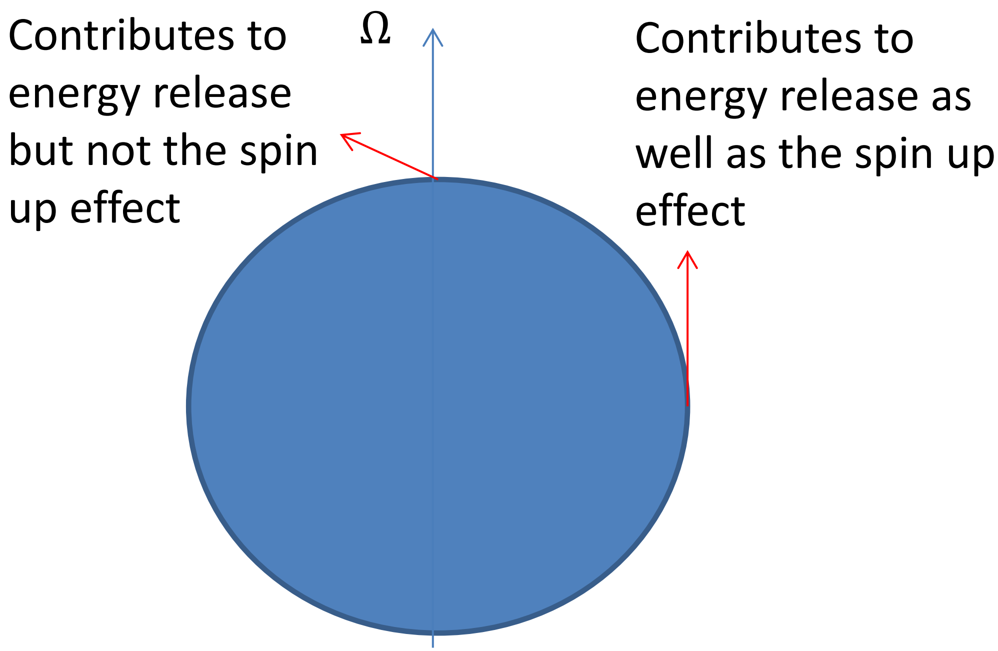
The result

fainter than the first). Thus, the 3 σ limit on any increase in the pulsar luminosity in response to energy input from the glitch is less than 1.2×10^{30} ergs s^{-1} or $\Delta T \sim 0.2\%$, 35 days (3×10^6 s) after the event.[2] The lower half of Figure 5

Helfand et al. 2001

$4 \times 10^{36}/(3\times 10^{6})=1.3\times 10^{30}$erg/s

Zhou et al. 2014



Discussion

- AXP/SGRs: observational hints of accretion (Wang et al. 2006)

  slow rotators (~10s)

  fall back disc + quark star model (Tong & Xu 2011)

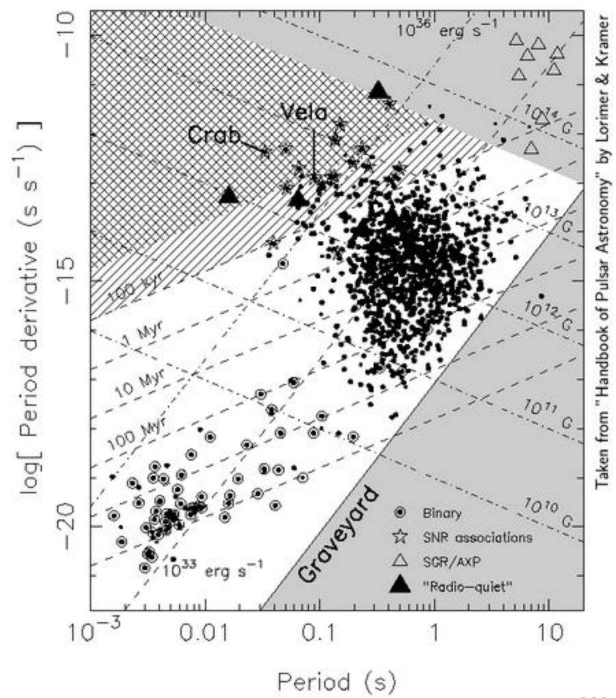
  implies ***Type II***

- Vela like pulsars: no hints for accretion

  fast rotators (~<1s)

  implies ***Type I***

- Possible mechanism for Anti-glitches?



Discussion

- The neutron star crust cracking model (Baym & Pines 1976) failed to explain the glitch on Vela because of the short intervals (~1 month,for largest glitches ~1 year)

$$t_{\mathrm{interval}} = \frac{2(A+B)\left(\frac{A}{B}\right)\left(\frac{\Delta\Omega}{\Omega}\right)}{\mathrm{I}\Omega\dot{\Omega}}.$$

For quark stars it's no longer a problem because the entire star is in solid state, what matters is the initial ellipticity when the pulsar became solid.

Suggesting that the initial ellipticity for Vela is 0.01 (P~4ms), there could be 10^4 glitches with ΔΩ/Ω~10^-6 during the lifetime of Vela, which is coincident with the observation.

Conclusion

- There should be two types of starquakes in a solid quark star model : Type I (bulk invariable) & Type II (bulk variable)
- We figure out the energy release of the two types of starquakes, and find out that Type II starquake is much more energetic than Type I.
- Considering other observational features, we think that the two types of glitches in a solid quark star model can account for the two types of glitches in observation.

- Thanks!