Gravitational Waves From Neutron & Strange-quark Stars

Supported by the National Science Foundation
http://www.ligo.caltech.edu

Gregory Mendell

LIGO Hanford Observatory

- A billion tons per teaspoon: the history of neutron stars.
- The discovery of pulsars and identification with NS.
- Are NS really strange-quark stars?
- GWs from NS and SQS.
- What will we learn?

LIGO-G050005-00-W

The Neutron Star Idea

- Chandrasekhar 1931: white dwarf stars will collapse if M > 1.4 solar masses. Then what?

- Baade & Zwicky 1934: suggest SN form NS.

- Oppenheimer & Volkoff 1939: work out NS models.

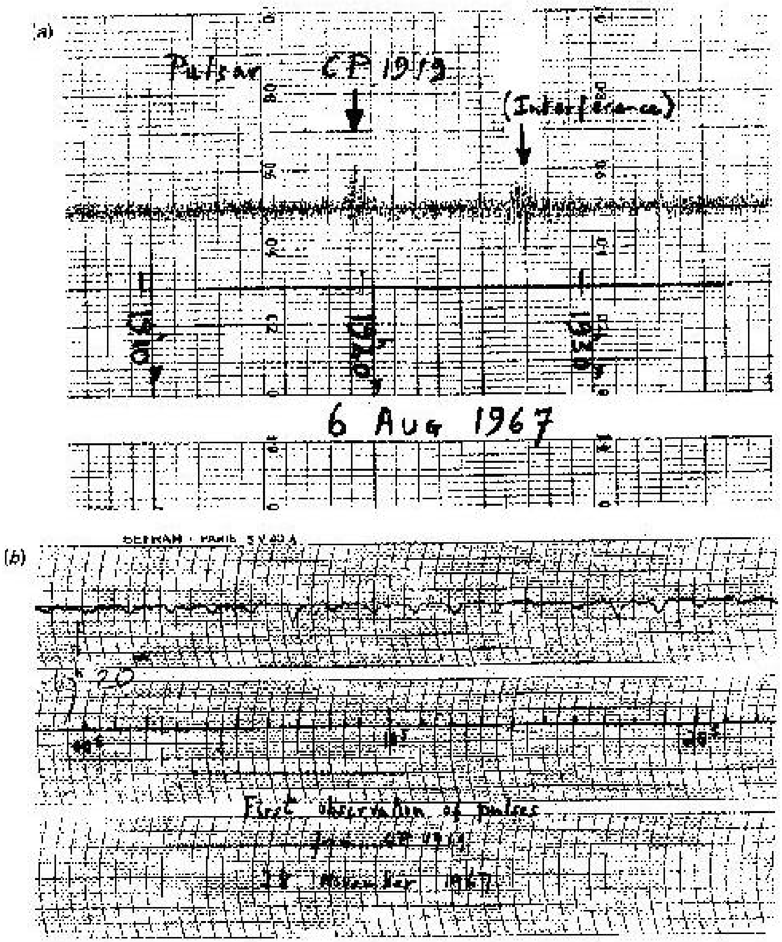
(http://www.jb.man.ac.uk/~pulsar/tutorial/tut/tut.html; Jodrell Bank Tutorial)

Supernova 1987A

http://www.aao.gov.au/images/captions/aat050.html

Anglo-Australian Observatory, photo by David Malin.

Discovery of Pulsars



- Bell notes "scruff" on chart in 1967.
- Close up reveals the first pulsar (pulsating radio source) with P = 1.337 s.
- Rises & sets with the stars: source is extraterrestrial.
- LGM? 
- More pulsars discovered indicating pulsars are natural phenomena.

Figure 2: Discovery observations of the first pulsar. (a) The first recording of PSR 1919+21; the signal resembled the radio interference also seen on this chart. (b) Fast chart recording showing individual pulses as downward deflections of the trace. From Lyne & Graham-Smith 1990 [23].

www.jb.man.ac.uk/~pulsar/tutorial/tut/node3.html#SECTION00012000000000000000
A. G. Lyne and F. G. Smith. Pulsar Astronomy. Cambridge University Press, 1990.

Pulsars = Neutron Stars

- Gold 1968: pulsars are rotating neutron stars.
  - ~~•orbital motion~~
  - ~~•oscillation~~
  - •rotation
- From the Sung-shih

(Chinese Astronomical Treatise): "On the 1st year of the Chi-ho reign period, 5th month, chi-chou (day) [1054 AD], a guest star appeared…south-east of Tian-kuan [Aldebaran].(http://super.colorado.edu/~astr1020/sung.html)

http://antwrp.gsfc.nasa.gov/apod/ap991122.html

Crab Nebula: FORS Team, 8.2-meter VLT, ESO

LIGO

Pulsars Seen and Heard

Play Me

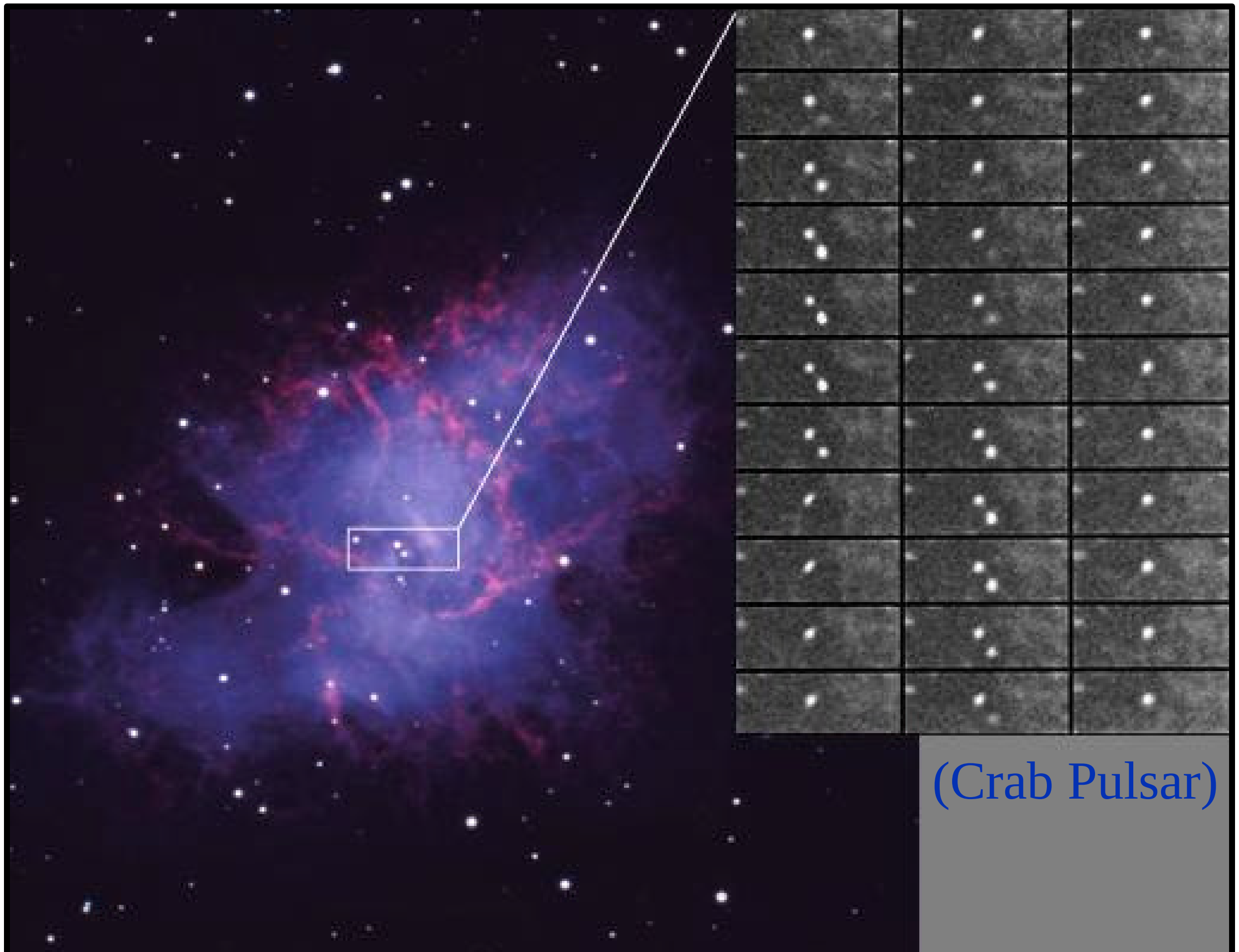
(Vela Pulsar)

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Jodrell Bank Observatory,

Dept. of Physics & Astronomy,

The University of Manchester



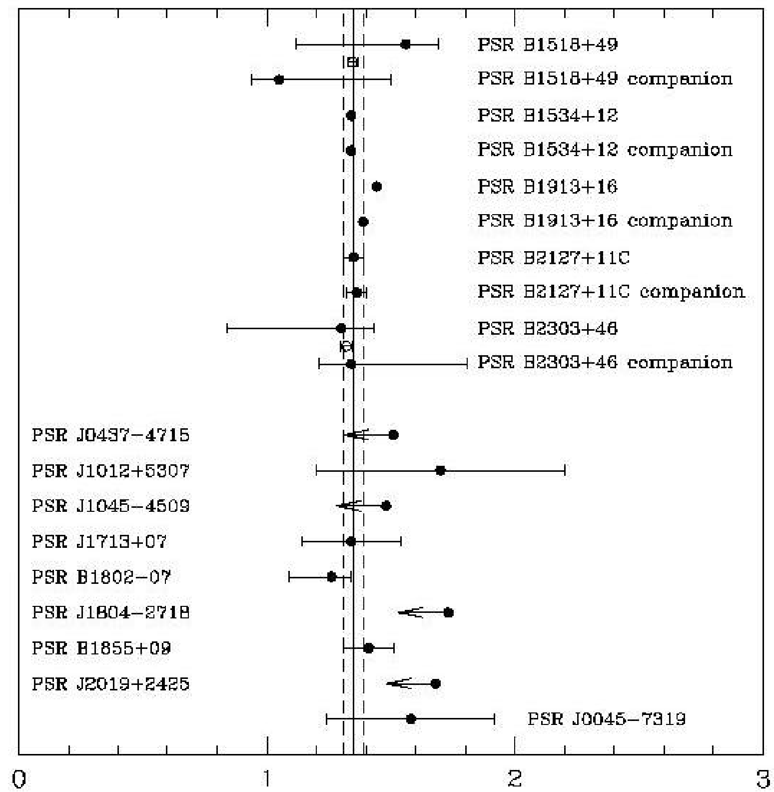
http://www.noao.edu/image_gallery/html/im0565.html

Crab Pulsar: N.A.Sharp/NOAO/AURA/NSF

Why Neutron Stars?

Masses ~ 1.4 Solar Masses

Various Pulsars

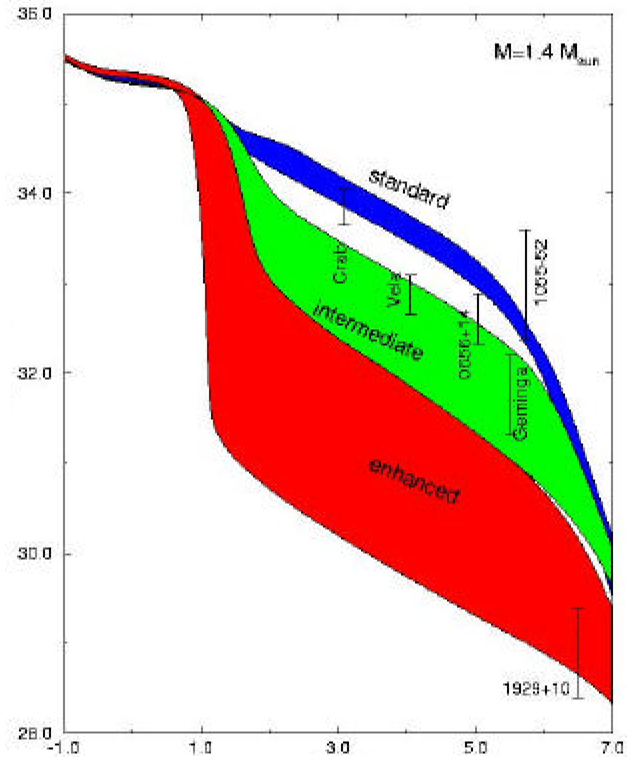


Observed Mass

S. E. Thorsett and D. Chanrabarty, astro-ph/9803260

- Fastest pulsar spins 642 times per seconds; radius < 74 km.
- Brightness and distance suggest radii ~ 5-15 km.

Brightness



Observed Age

www.physik.uni-muenchen.de/sektion/suessmann/astro/cool/

The back of the envelope please…

Don't take this the wrong way…

$$\frac{\text{1.4 Solar Masses}}{\text{10 km Sphere}} = \frac{1.4(1.99 \times 10^{33}\ \text{g})}{4/3\pi(10^{6}\ \text{cm})^{3}}$$

Average density = 6.7×10^{14} g/cm ^{3}

$$\frac{\text{Mass neutron}}{\text{Volume neutron}} = \frac{1.67 \times 10^{-24}\ \text{g}}{4/3\ \pi\ (10^{-13}\ \text{cm})^{3}}$$

= 4.0×10^{14} g/cm ^{3} (billion tons/teaspoon)

… but parts of you are as dense as a neutron star.

$p + e \leftrightarrows n + \nu_e$ (inverse beta and beta decay)

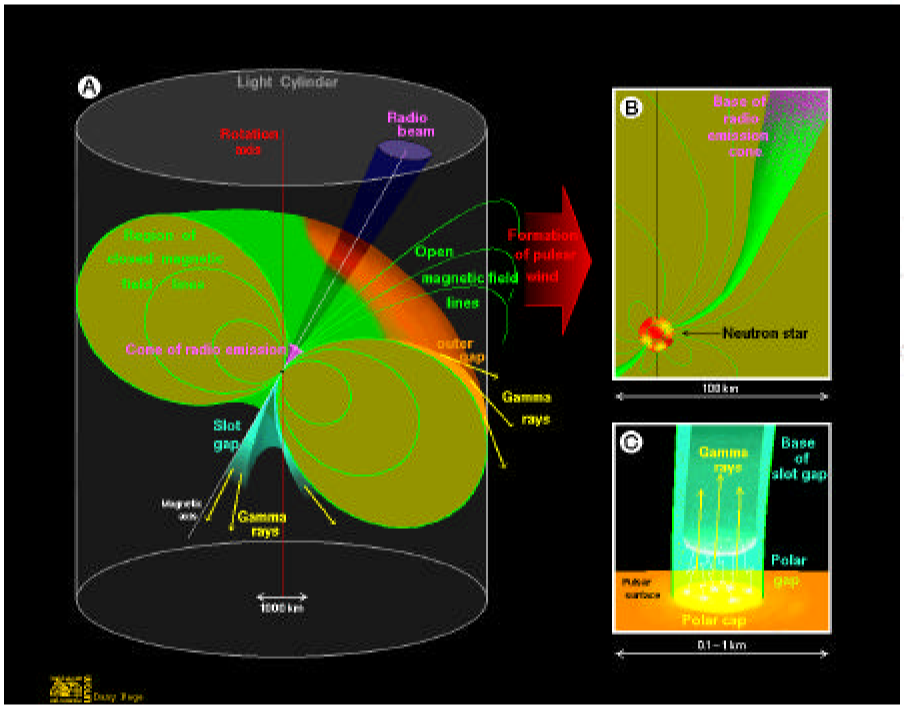
$\mu_p + \mu_e = \mu_n$ (beta equilibrium)

$n_p = n_e$ (charge neutrality)

Seen: SN 1987A!

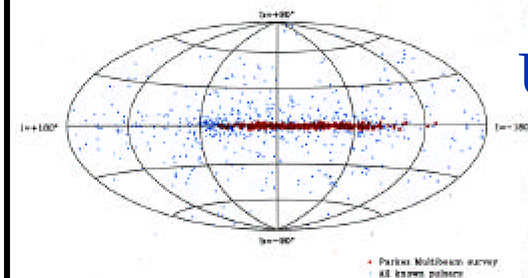
Nuclear density: 95% n, 5% p & e

More on Pulsars



COSMIC LIGHTHOUSES with terra-gauss magnetic fields !

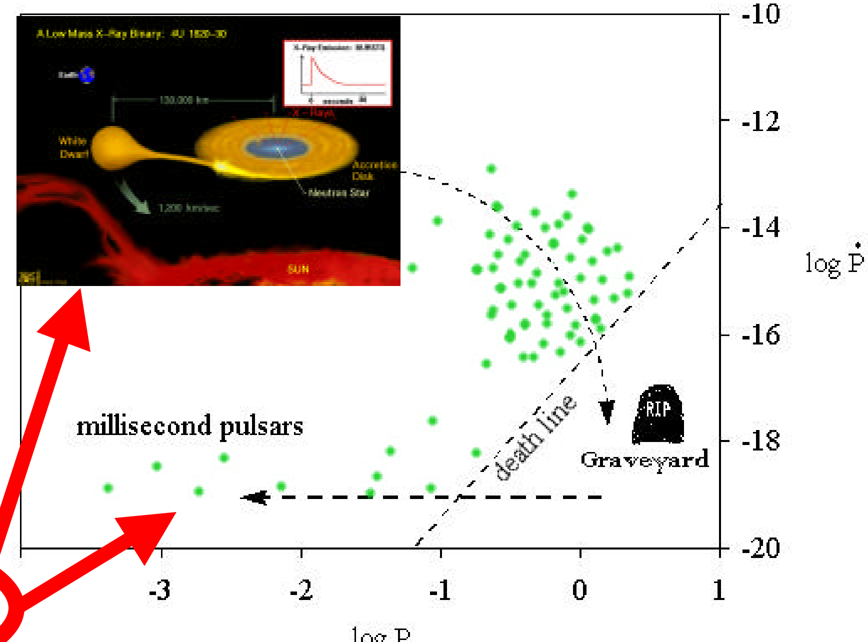
D. Page
http://www.astroscu.unam.mx/neutrones/home.html



Known: 1000+
Unknown: up to 100,000 in the Milkyway.

http://online.itp.ucsb.edu/online/neustars00rmode/kaspi/oh/05.html; Vicky Kaspi McGill University, Montreal Canada

http://www.astroscu.unam.mx/neutrones/home.html



http://astrosun2.astro.cornell.edu/academics/courses/astro201/pulsar_graph.htm

Respun in x-ray binary to 642 Hz! In theory up to 2 kHz.

Getting dense…

- Fermi Temp: 10^{12} K.
- NS born at 10^{11} K, cools below 10^{9} K within a year; form superfluid neutrons, superconducting protons .
- Cools to 10^{6} K after 10^{7} yrs; glows with x-rays.

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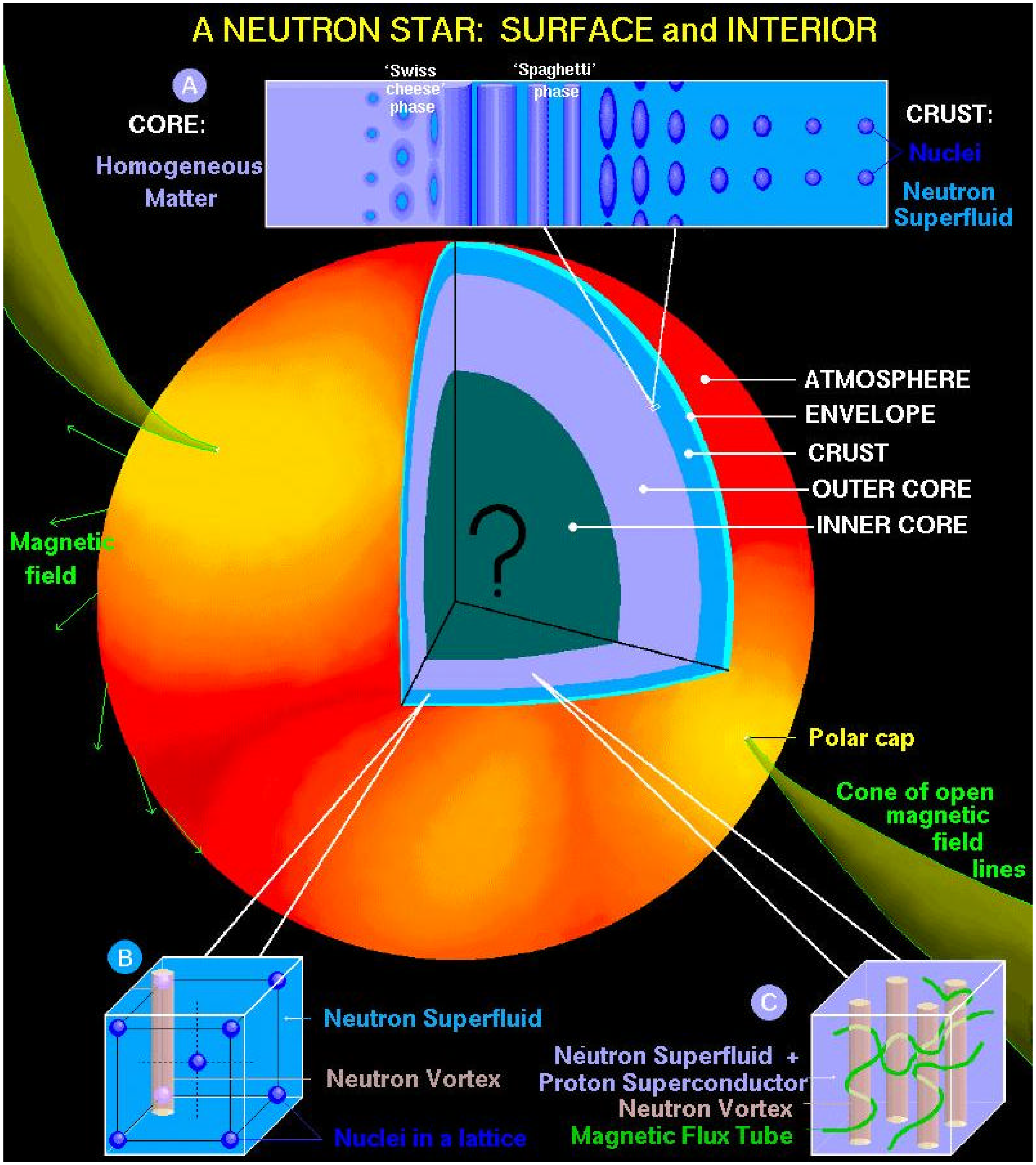
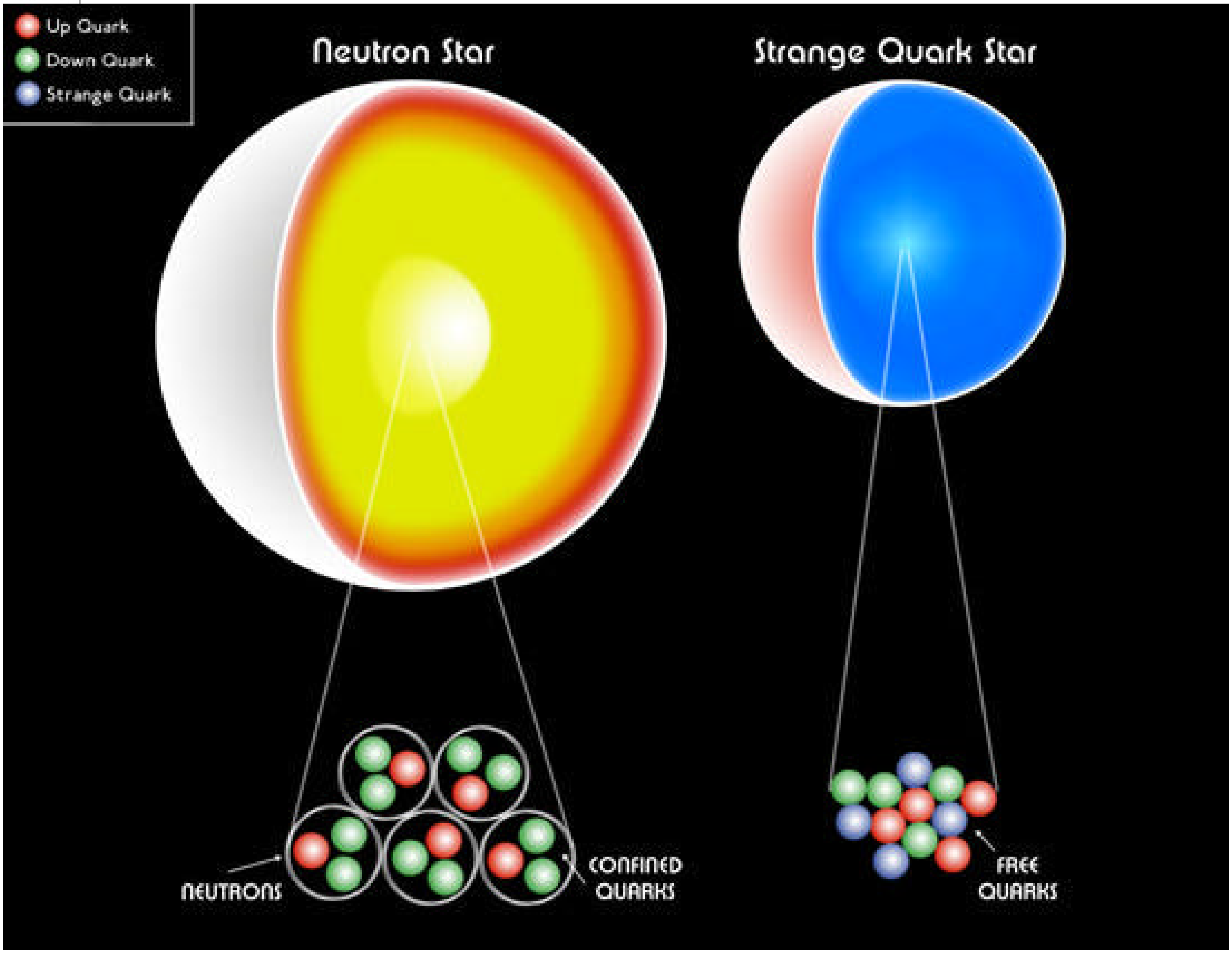


…and strange…



http://chandra.harvard.edu/resources/illustrations/neutronstars_4.html; NASA/CXC/SAO

…and finally, have a slice of neutron-quark layered cake!

arXiv:astro-ph/9706236 v2 23 Jun 97

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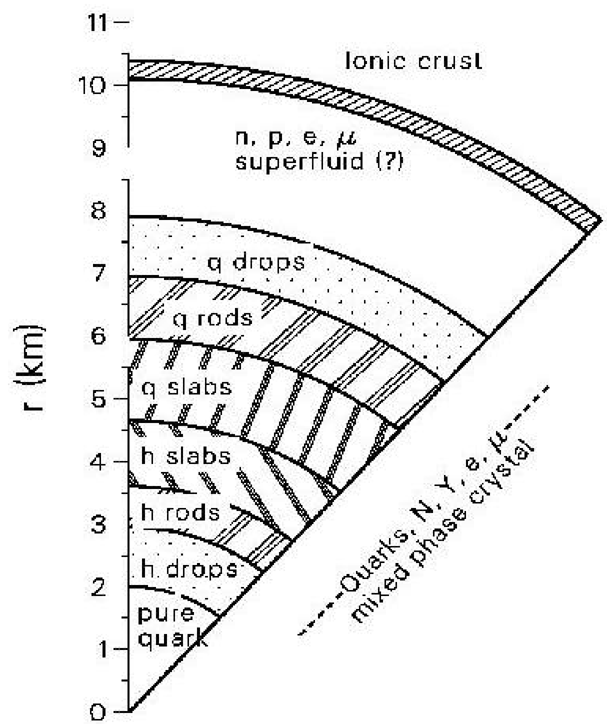

Strange Stars in the News

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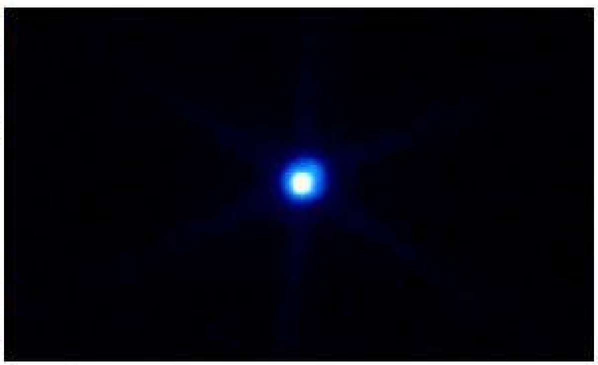
Wednesday, 10 April, 2002, 23:26 GMT 00:26 UK

Quark stars point to new matter



RX J1856.5-3754: Its size, just 11 km across, and temperature profile mean it cannot be a neutron star

By Richard Black
BBC science correspondent

Astronomers believe they have found their first quark stars - super-dense objects that are formed when the remnants of old stars collapse in on themselves.

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Friday, 22 November, 2002, 14:39 GMT

Did quark matter strike Earth?

By Dr David Whitehouse
BBC News Online science editor

A group of researchers have identified two seismic events that they think provide the first evidence of a previously undetected form of matter passing through the Earth.

The so-called strange quark matter is so dense that a piece the size of a human cell would weigh a tonne.

> We can't prove that this was strange quark matter, but that is the only explanation that has been offered so far

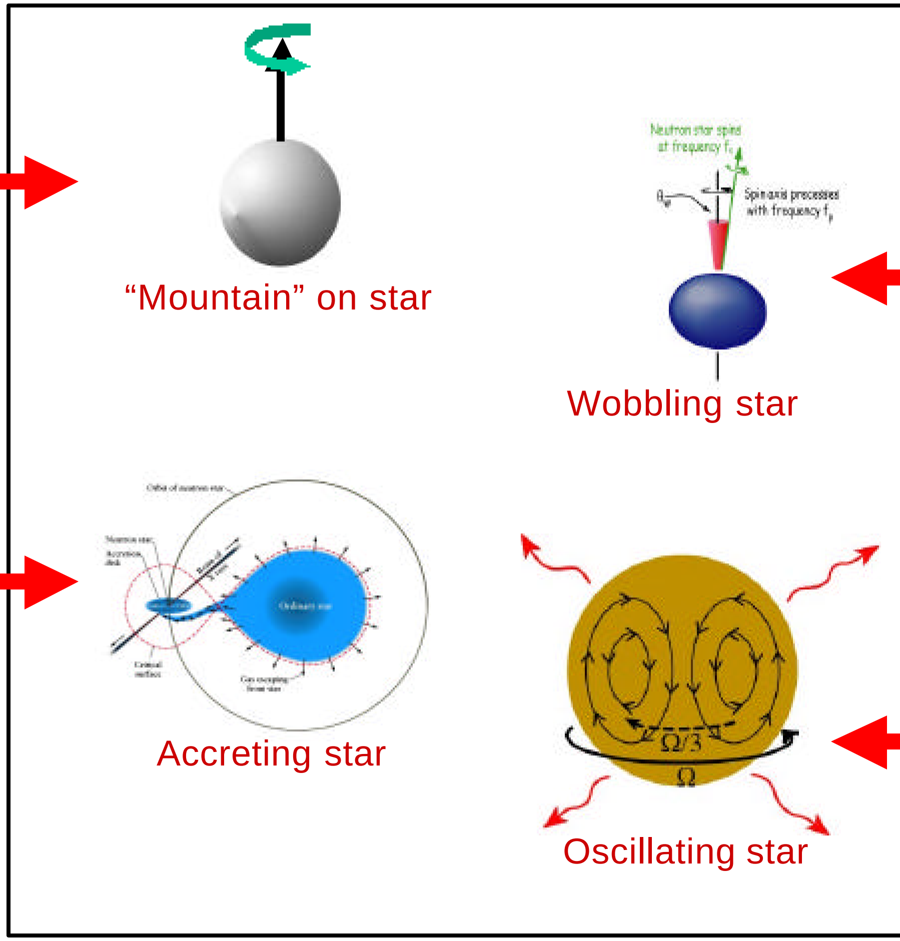
The two events under study both took place in 1993.

Continuous Periodic Gravitational-Wave Sources

$$e = \frac{I_1 - I_2}{I}$$

Mountain mass & height: εMR^2

Low-mass x-ray binary: balance GW torque with accretion torque τ**.**



Free precession wobble angle *q*

Unstable vibrations with amplitude *A*

A. Vecchio on behalf of the LIGO Scientific Collaboration : GR17 – 22nd July, 2004

What might we learn?

• Mountain Heights: is 1 mm typical? If greater than 1 cm then stars that are even “stranger than strange” exist!?

• Wobble Size: are superfluid tornados free to move?

• “Good Vibrations”: apply astro-seismology.

• Torques: GWs may control the spinup, spindown, & spin cycles of these stars.

Summary

- LIGO: a new window on the universe.
- There is good evidence that stars with a density of a billion tons per teaspoon do exist.
- GWs provide new and unique information about neutron & strange-quark stars
- YOU can use Einstein@Home to search LIGO data for GWs from these or even more exotic undiscovered ultra-dense objects!
- Expect the unexpected?!