Neutron Star Seismology

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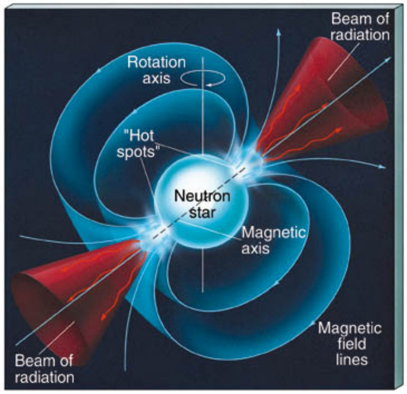
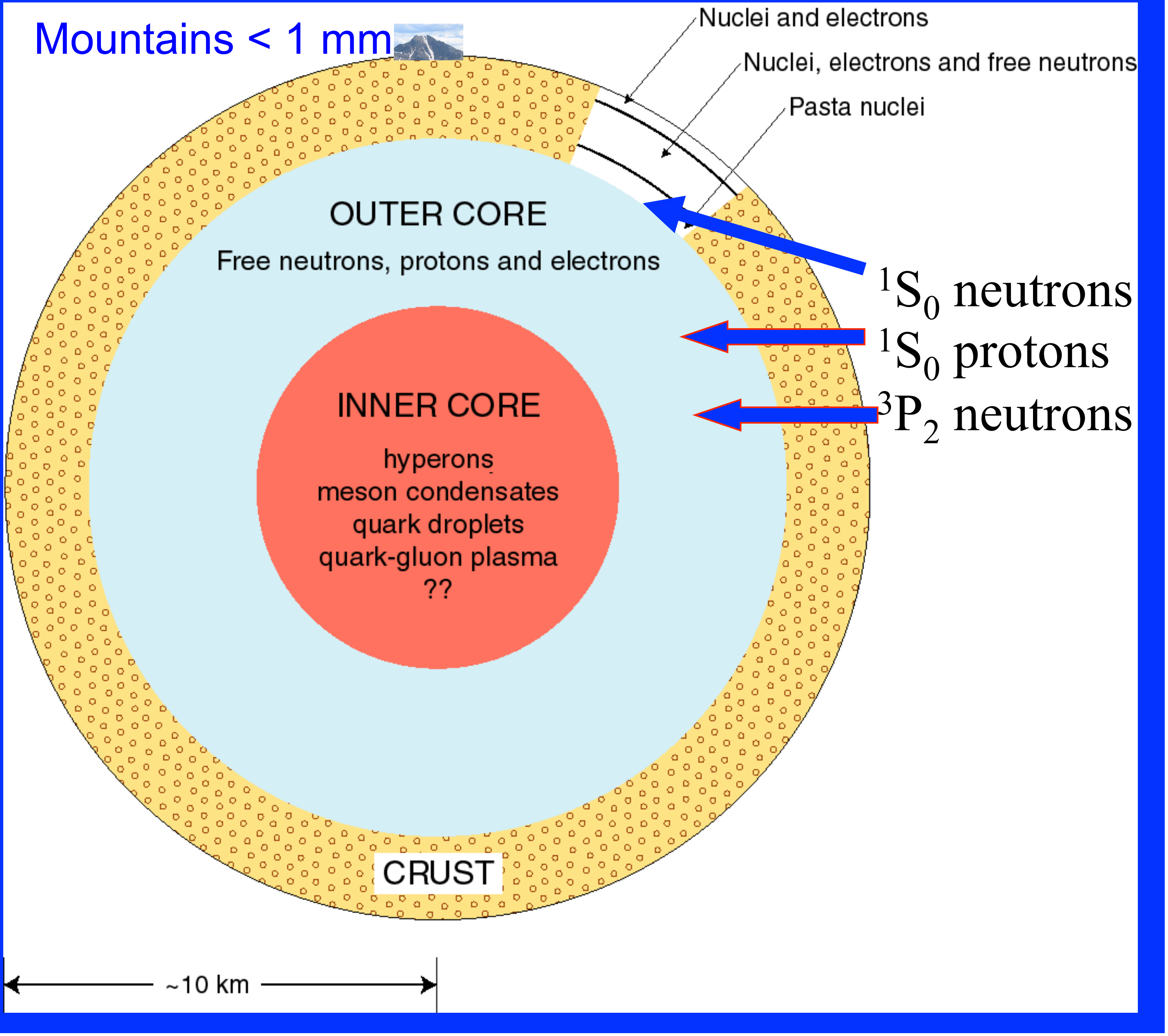
Large Fluctuations and Collective Phenomena in Disordered Materials
ICMT May 18, 2011

Neutron star – full of superfluids

Mass ~ 1.4-2 M_{sun}
Radius ~ 10-12 km
Temperature
~ 10^6-10^9 K

Surface gravity
~10^{14} that of Earth
Surface binding
~ 1/10 mc^2



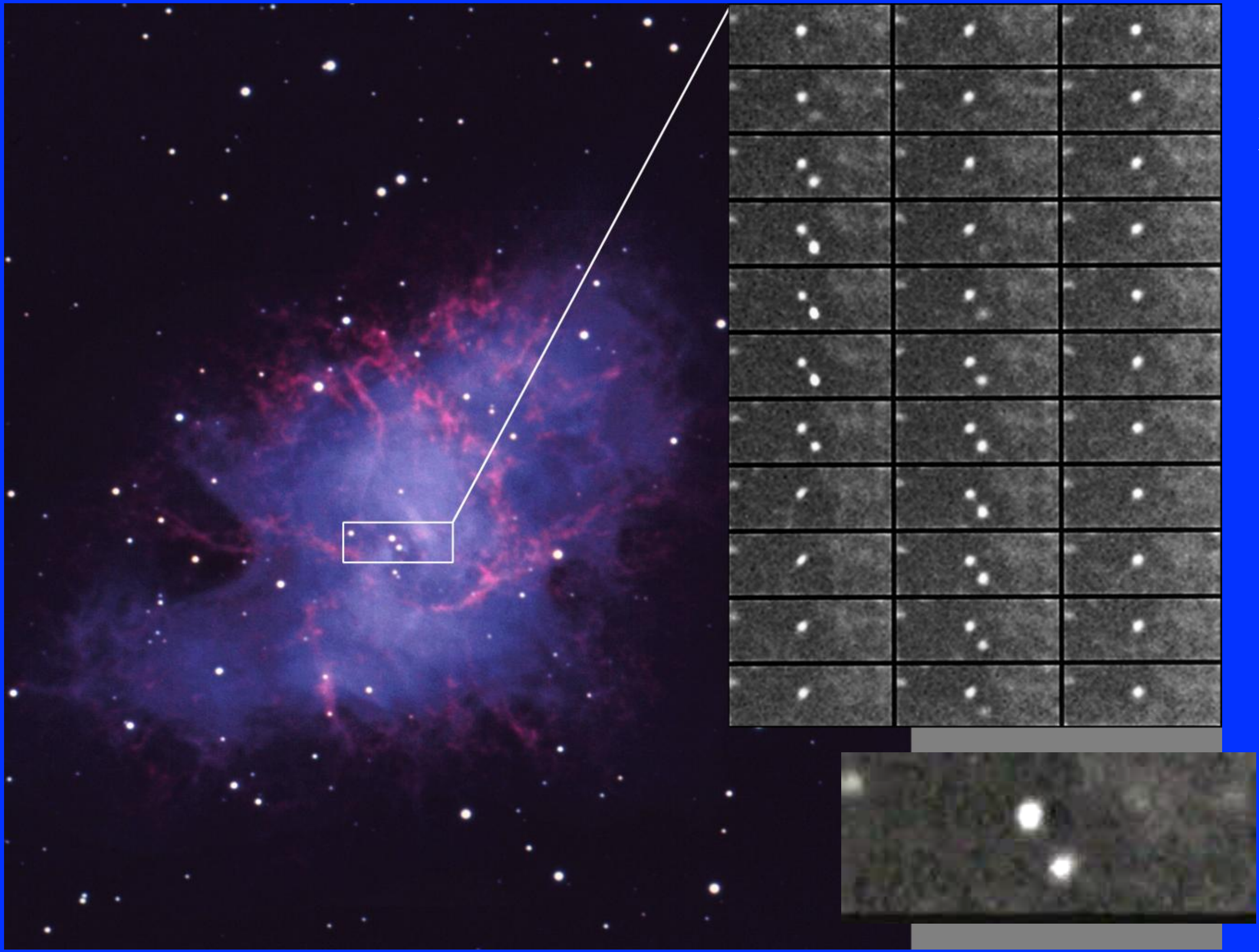


Mountains < 1 mm

$^1S_0$ neutrons
$^1S_0$ protons
$^3P_2$ neutrons

Crab Pulsar (period = 33 msec)

Supernova July 4, 1054



1 msec
per frame

Fluctuations in pulsar timing

Glitches:

Sudden speedups in rotation period,
relaxing back in days to years,
with no significant change in pulsed
electromagnetic emission

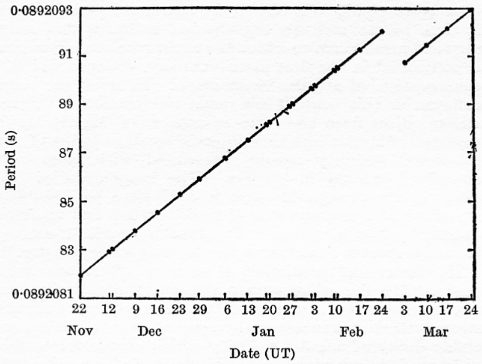


Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Rotational energy= $I\Omega^2/2$ $\quad$ I = moment of inertia ~ 10^{45}g cm^2
Ω = rotational rate ~ 0.0014 – 8 /sec.

To date 315 glitches detected in 102 pulsars (*Espinoza et al. 1102-1743*)

$\Delta\Omega/\Omega$: 10^{-5} -10^{-11}

Timing noise:

Long term continuous unpredictable phase wandering

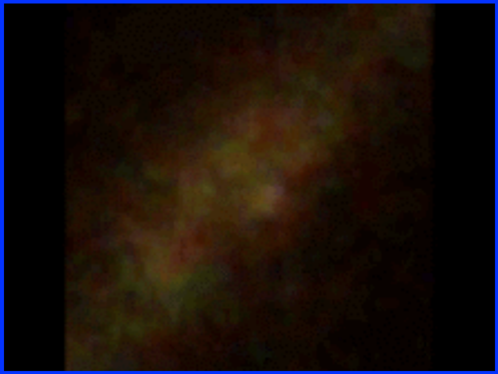
Vela (PSR0833-45)

Period=1/Ω=0.089 sec

16 glitches since discovery in 1969

$\Delta\Omega/\Omega \sim 10^{-6}$ $\Delta E_{rot} \sim 10^{43}$ erg

Largest = 3.14×10^{-6} on 16/01/2000



24/12/1988: $\Delta T_{spinup} < 2$ min. (“Christmas glitch”)

Feb. 28, 1969

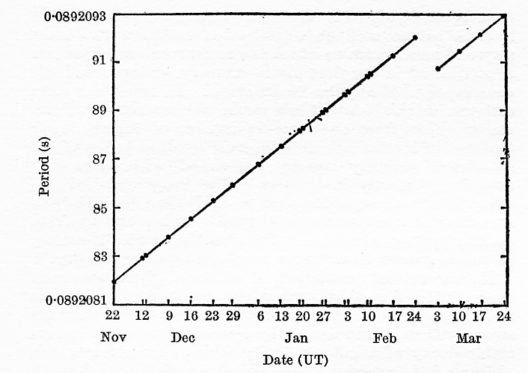


Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Reichley and Downs, Nature 1969

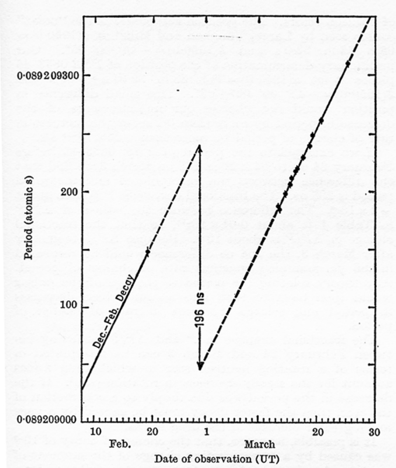
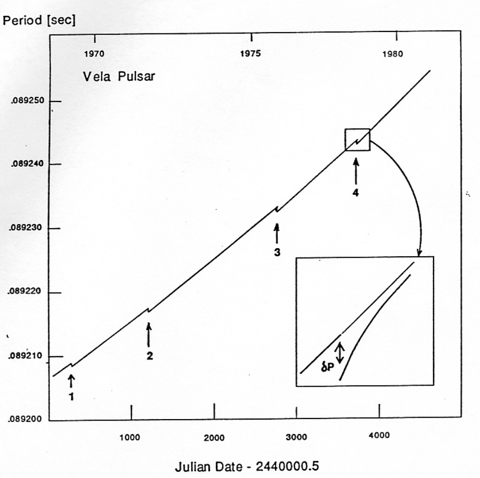
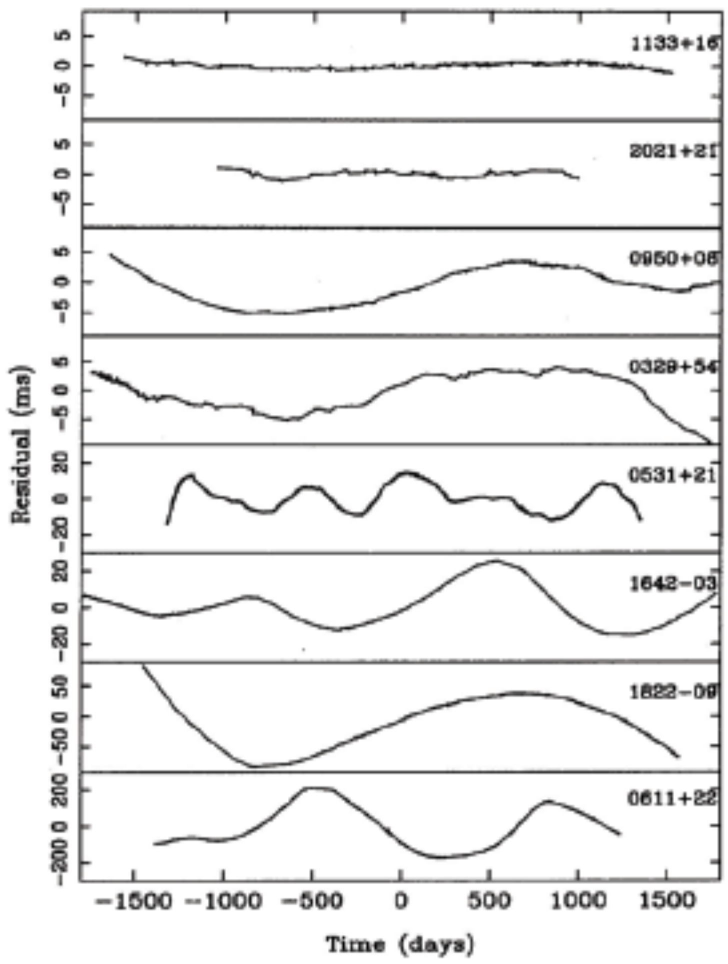


Fig. 1. Heliocentric period of *PSR* 0833–45 observed in February and March 1969, based on position α 08 h 33 m 39·0 s, δ −45° 00′ 05·0″ (epoch 1950·0) (ref. 3). The rate of increase of the period was 10·69 ± 0·20 ns day⁻¹ between December 8, 1968, and February 19, 1969. Since March 13, 1969, the rate of decay has been 10·64 ± 0·20 ns day⁻¹. At some time between February 19 and March 13 the period decreased by 196 ns.



Radhakrishnan and Manchester, Nature 1969

Pulsar timing noise (phase residuals):



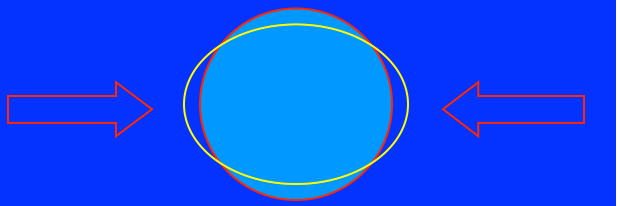
Over about 10 years

Noise amplitude ~
rate of slowing down dP/dt

Lyne et al., J. Astrophys. Astr. 1995.
Shannon & Cordes, Ap.J. 2010

Sources:
microglitches
fluctuations in radiative loss
magnetospheric noise
accretion fluctuations in binaries
???

Starquake?



As star slows down, mechanical stresses increase in crust -- possibly past the breaking point of matter. Cracking = starquake tends to make crust more spherical (*Ruderman 1968, GB et al. 1969, GB & Pines 1971*).

Conservation of angular momentum => $\Delta\Omega/\Omega = -\Delta I / I$

Surface motion of ~ 1 cm would give $\Delta\Omega/\Omega \sim 10^{-6}$

BUT

$\Delta E \sim 10^{43}$ erg/glitch too much energy to store in crust to enable ~ 4-5 glitches per decade.

Physical picture of glitches

Since pulse structure not notably affected by glitch, must be internal phenomenon in the neutron star. Long time scales for response indicate well-oiled machinery -- superfluidity! [Metastable superfluid flow (Packard 1972).]

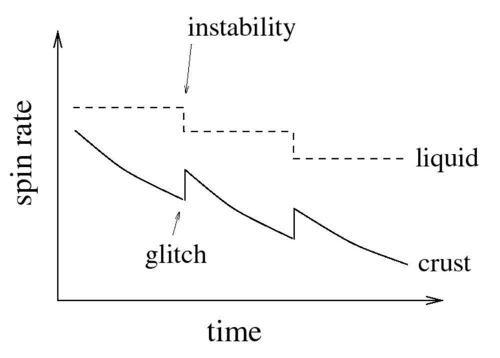
Pulses connected - via magnetic field - to the crust.

Neutron superfluids in interior act as a reservoir of angular momentum. Transfer of angular momentum to crust speeds it up => glitch

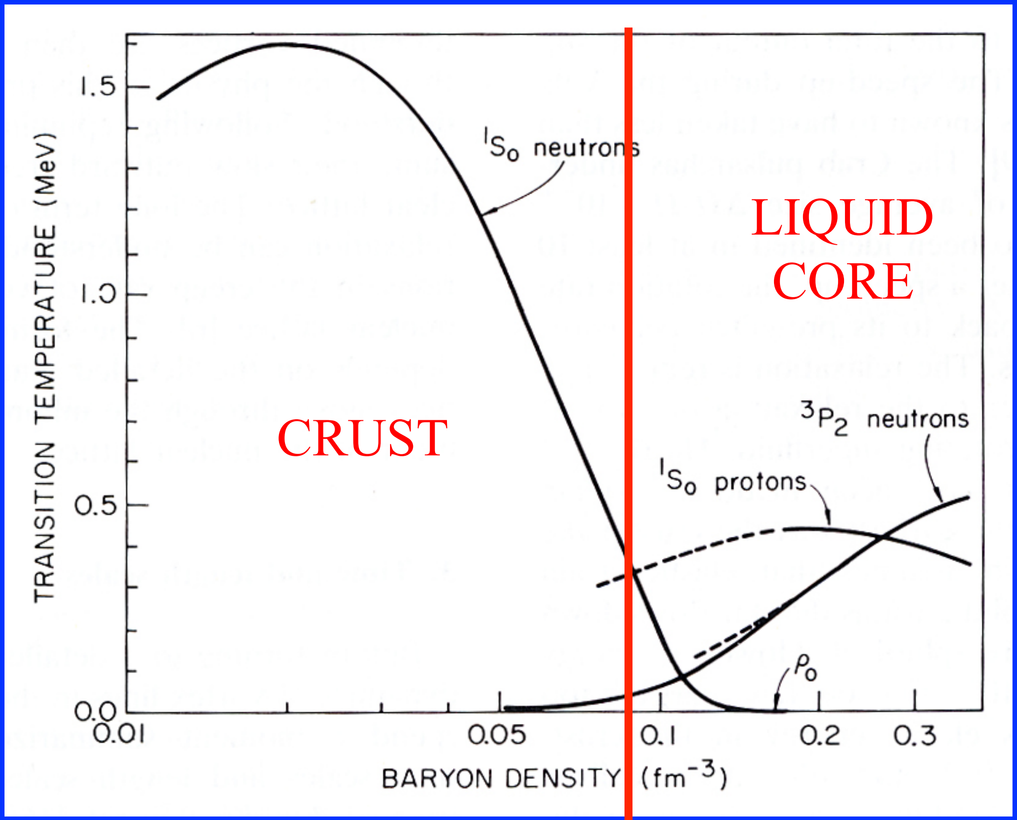
Where in neutron star is the reservoir?

How is the differential velocity between the crust and liquid maintained?

How is the reservoir tapped?



First estimates of pairing gaps in neutron and proton liquids based on scattering phase shifts



Neutron fluid in crust BCS-paired in relative $^1S_0$ states

Neutron fluid in core 3^P2 paired
Proton fluid $^1S_0$ paired

n=Hoffberg et al. 1970, p=Chao et al. 1972

Quantum Monte Carlo $^1S_0$ nn gap in crust

Alex Gezerlis, UI 2009

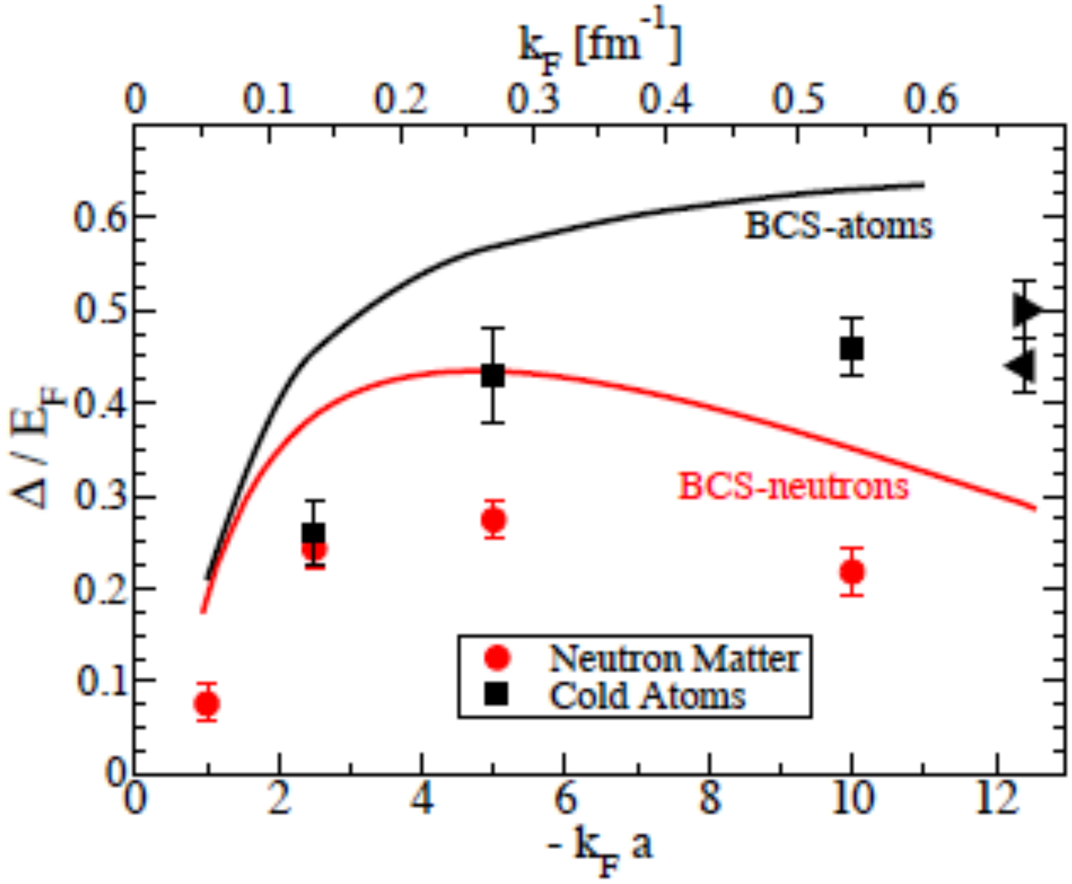
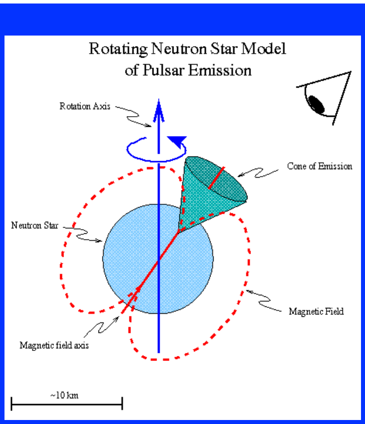
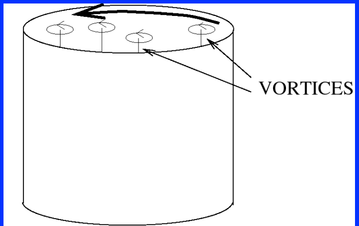


Figure 6.3: Superfluid pairing gap versus $k_F a$ for cold atoms ($r_e \approx 0$) and neutron matter ($|r_e/a| \approx 0.15$). BCS (solid lines) and QMC results (points) are shown. Also shown are QMC (right arrow) and experimental (left arrow) results at unitarity.

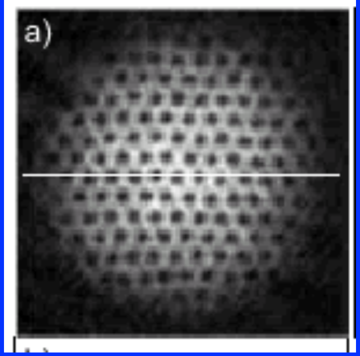
Rotating superfluid neutrons



Rotating superfluid threaded by triangular lattice of vortices parallel to stellar rotation axis



Bose-condensed ^{87}Rb atoms
Schweikhard et al., PRL92 040404 (2004)



Circulation of superfluid velocity about a vortex is quantized:

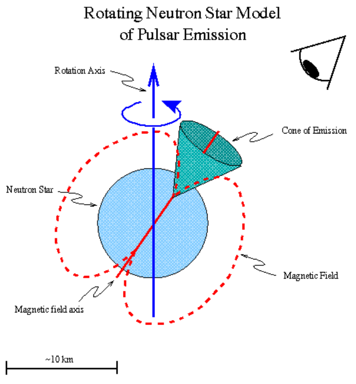
$$\oint_C \mathbf{v_s} \cdot d\ell = \frac{2\pi\hbar}{2m_n}$$

Vortex core ~ 10 fm
Vortex separation ~ 0.01P(s)$^{1/2}$cm; Vela contains ~ 10^{17} vortices

Angular momentum of vortex =N~ (1-r^2/R^2) decreases as vortex moves outwards => to spin down must move vortices outwards

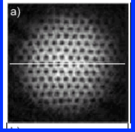
Superfluid spindown controlled by rate at which vortices can move against barriers, under dissipation

Superconducting protons in magnetic field



Even though superconductors expel magnetic flux, for magnetic field below critical value, flux diffusion times in neutron stars are >> age of universe. Proton superconductivity forms with field present.

Proton fluid threaded by triangular (Abrikosov) lattice of vortices parallel to magnetic field (for Type II superconductor)



Magnetic flux associated with each vortex is quantized:

$$\oint_C \mathbf{B} \cdot d\ell = \frac{2\pi\hbar c}{2e} = \phi_0 = 2\text{X } 10^{-7}\text{G.}$$

Vortex core ~ 10 fm,

$n_{vort} = B/\phi_0$ => spacing ~ 5×10^{-10} cm $(B/10^{12}\text{G})^{-1/2}$

Time scales

Need intermediate time scale (~ months) to understand glitches.

Slowing down: $P/(dP/dt) \sim$ age of pulsar $\sim 10^3$-10^6 y

Spin down of charged particles: $\tau \sim \tau_{\mathrm{Alfven}} \sim R(4\pi\rho)^{1/2}/B \sim 10$ s

Normal quasiparticle scattering: $\tau_{np} \sim E_f/T^2 \sim 10^{-11}$s

Superfluid q.p. scattering: $\tau_{np} \sim e^{\Delta/T}/E_f$ $(\Delta/T \sim 10^2 - 10^3)$

Vortex dynamics only promising way to get required time scales

Neutron vortex-charged particle scatterings:

$\tau_{e^- \text{- vortex core exc.}} \sim \tau_{em} e^{\Delta_n^2/E_f T} \sim 10^{20}$ s $({}^1S_0$ vortices)
$\tau_{e^- \text{-} {}^3P_2} \sim 10^8 P(\mathrm{sec})/\Delta_n(\mathrm{MeV}) \sim 2$ mos. (magnetized ${}^3P_2$ vortices)
(*Sauls, Stein, & Serene, Muzikar, Sauls, & Serene*)

Length scales

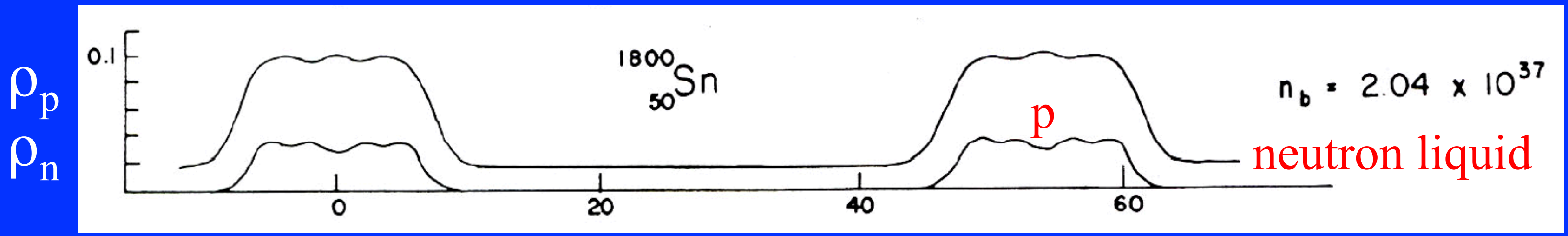
Spacing of n vortices ~ 10^{-2} cm

Spacing of p vortices ~ 5×10^{-10} cm

Spacing of nuclei ~ $2 \times 10^{-12} (\rho/\rho_{nm})^{1/3}$ cm

Nuclear size, $R_A \sim 10^{-12}$ cm

Neutron superfluid coherence length, $\xi_n \sim 10^{-12}$ cm ~ R_A



Models of glitches

Pin vortices to (or between) nuclei in inner crust (*Anderson & Itoh 1975*).

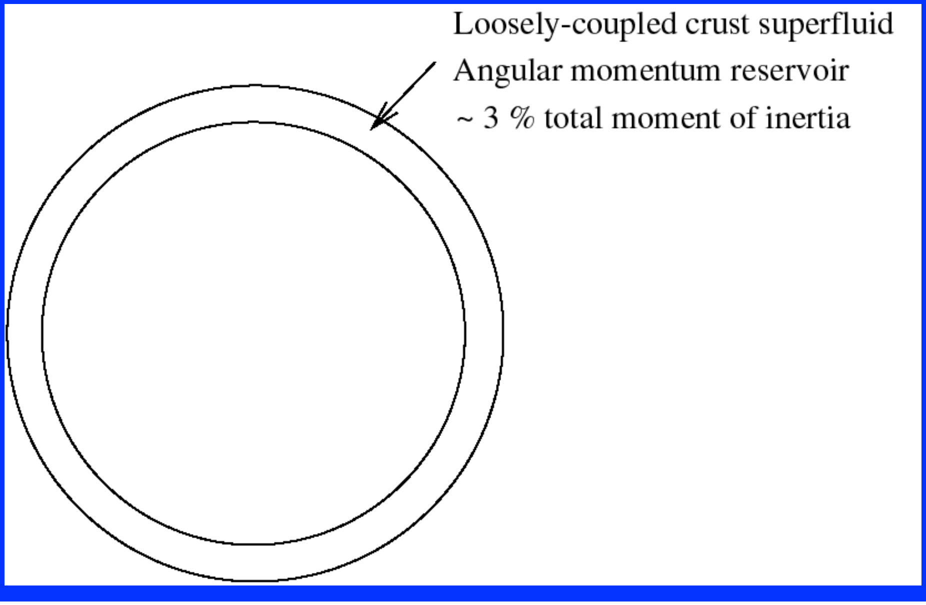
n_{vortices} fixed => $\Omega_{\mathrm{superfluid}}$ fixed; Ω_{normal} decreases as star radiates.

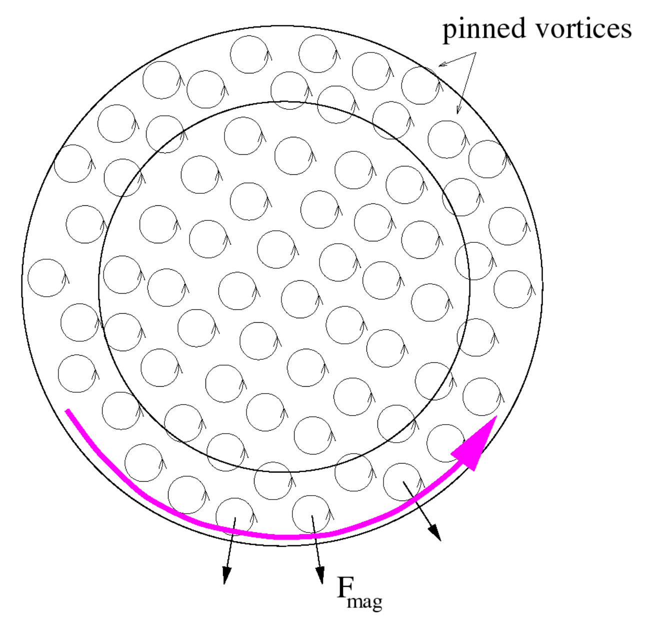
$$\oint_C \mathbf{v_s} \cdot d\ell = 2\pi\Omega_s r^2 = \frac{2\pi\hbar}{2m_n} n_v \pi r^2$$

$$\Omega_s = \frac{\pi\hbar}{2m_n} n_v$$

As $\Omega_{\mathrm{sf}} - \Omega_{\mathrm{n}}$ grows get unpinning (glitch) and outward relaxation.

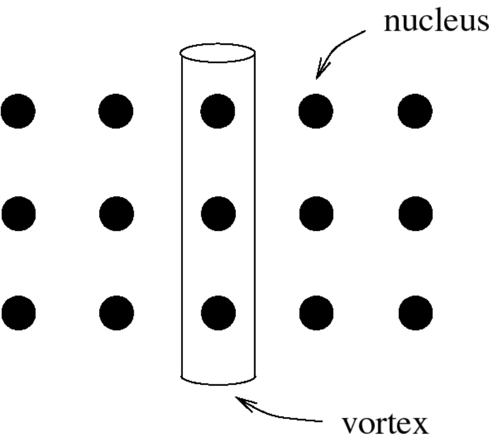
Collective outward motion of many (~ 10^{14}) vortices would produce large glitch





Pinning of neutron vortices to crust lattice

Energetically favorable for vortices
to pin to nuclei with energies
up to ~ 3 MeV per nucleus.



Epstein & GB 1988
Alpar, Cheng, & Pines 1989
Avogadro, Barranco, Broglia, & Vigezzi 2007

Do vortices pin on nuclei or in-between nuclei? BCS coherence lengths comparable to nuclear radii.

Consequences:

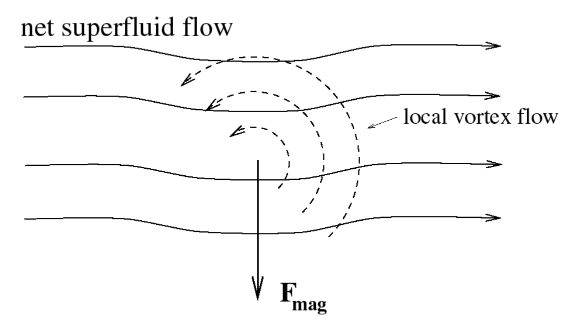
Crust and superfluid rotations are largely decoupled

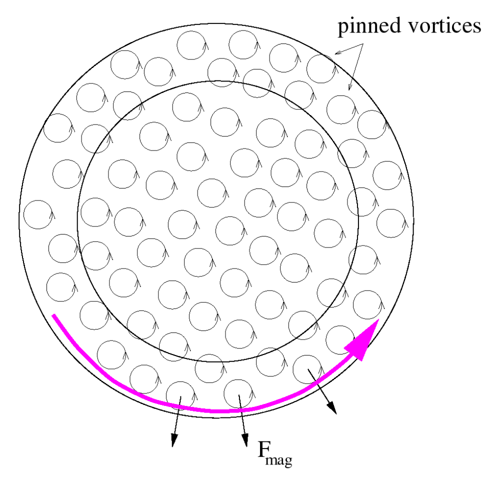
As crust spins down, velocity difference between nuclei and neutron superfluid in crust grows. Stress on vortices grows.

Magnus force on vortex from fluid flow

Differential rotation of nuclei and neutron superfluid in crust produces outwards force on vortices, trying to unpin them

$$\mathbf{F}_{\text{Magnus}}=\rho_s\,\boldsymbol{\kappa}\times(\mathbf{v}_{\text{vortex}}-\mathbf{v}_{\text{superfl}})$$





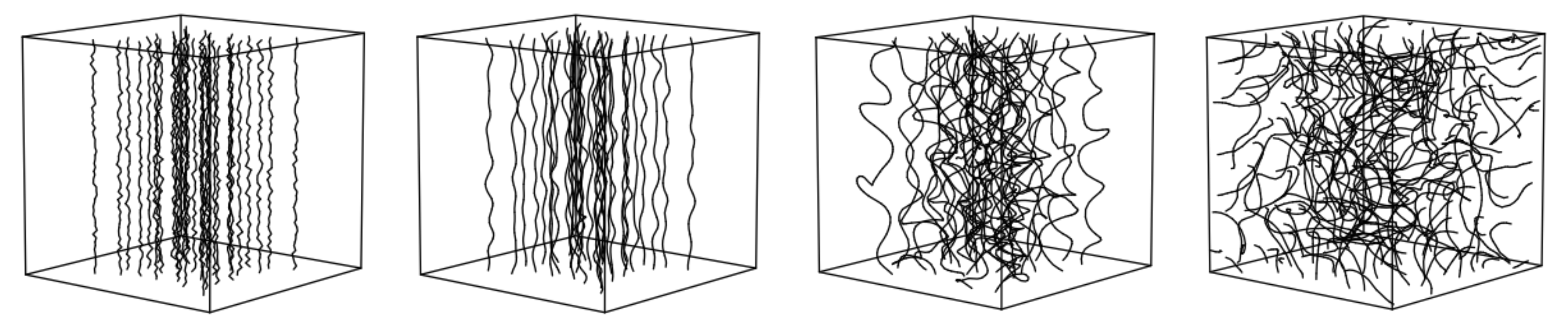
Pinning can sustain differential velocity up to ~ 10 rad / s
=> large angular momentum reservoir!

Capable of producing spin jump $\boxed{\Delta\,\Omega_c/\Omega_c \sim 10^{-3}}$

Expect slow outward vortex creep under Magnus force by thermal activation or quantum tunneling of vortices past pinning barrier

Evolution to superfluid turbulence?

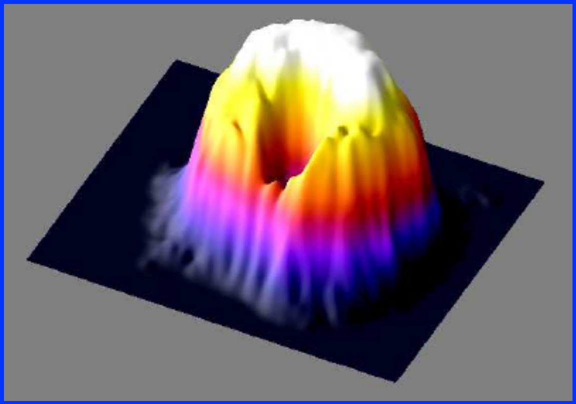
Differential rotation => superfluid flow unstable over length scales < 10 m. Timescales days to minutes. *B. Link 2011, in press*



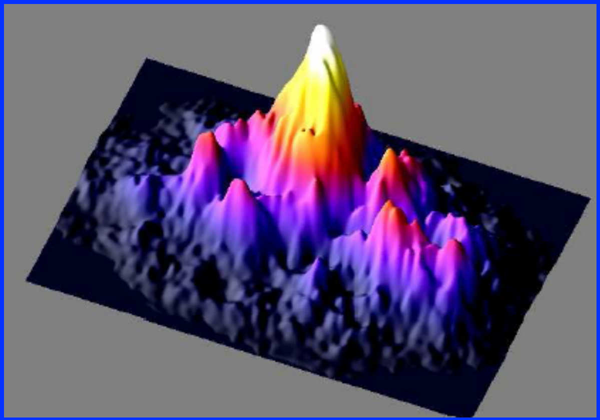
Tsubota et al. 2003

Density images
^{87}Rb BEC

Caracanhas et al.
1103.2039

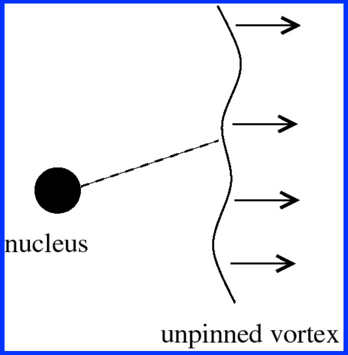


single vortex



turbulent condensate

Initiation of glitch (fast)



Catastrophic vortex unpinning via:

-- Thermal pulse, e.g., via starquakes

-- Crust cracking induced by magnetic stresses
from neutron vortex – proton vortex (flux tube)
interactions in core

--

Possible triggering of glitch by starquake

Increase of mechanical stresses on crust:
- Slowing down <=> less centrifugal force
- Magnetic stress.

Starquake can deposit considerable heat ~ $\boxed{E_b\ \theta_c^2 \lesssim 10^{42}\ \text{erg}}$
E_b = solid state binding energy of crust, θ_c = yield strain ~ 10^{-2}

Starquake can produce small spin jump, but can also trigger much larger event, since large heat pulse due to starquake can cause transition from vortex creep to highly dissipative flow (*Link & Epstein 1996*)

Vortex creep very temperature sensitive: $v_{\text{creep}} \sim e^{-A/kT}$
A = activation energy >> T

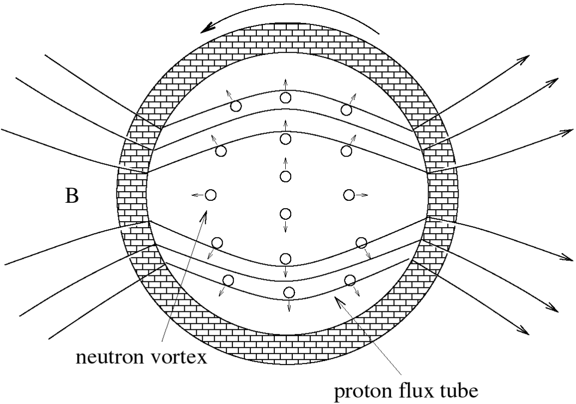
Physics in the core

Neutron vortices in core become coupled to magnetic field.
Vortex-electron drag => co-rotation of e,p,n

Proton vortices (magnetic flux tubes) and neutron vortices interact:

$$E_{\text{intersection}} \sim (B_p B_n / 4\pi) V_{\text{overlap}} \sim 100\ \text{keV}$$

Impedes independent motion of n vortices



Core fluid coupled to crust via magnetic stresses.
Core vortices move out as crust spins down,
forcing magnetic field against crust, cracking
it, allowing large outward vortex motion
=> glitch

Glitches vs. earthquakes?

Distribution of earthquakes of amplitude A ~ 10^M

$$\frac{dN}{d\ln A} \sim \frac{1}{A^b}$$

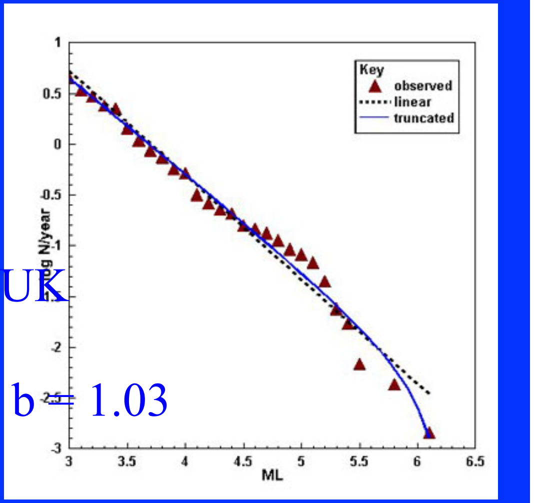
b ~ 1

(M=Richter mag.)

$$\boxed{\frac{dN}{d\log E} \sim \frac{1}{E^{2/3}}}$$

Energy release E ~ $A^{3/2}$

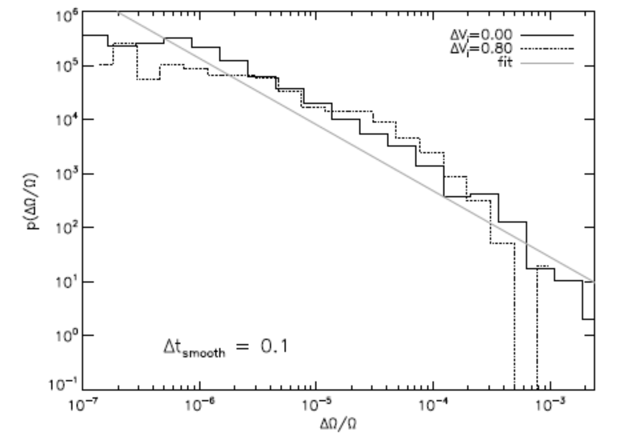
(Sendai, M = 9.0, E ~ 480 Megatons TNT)



UK

b = 1.03

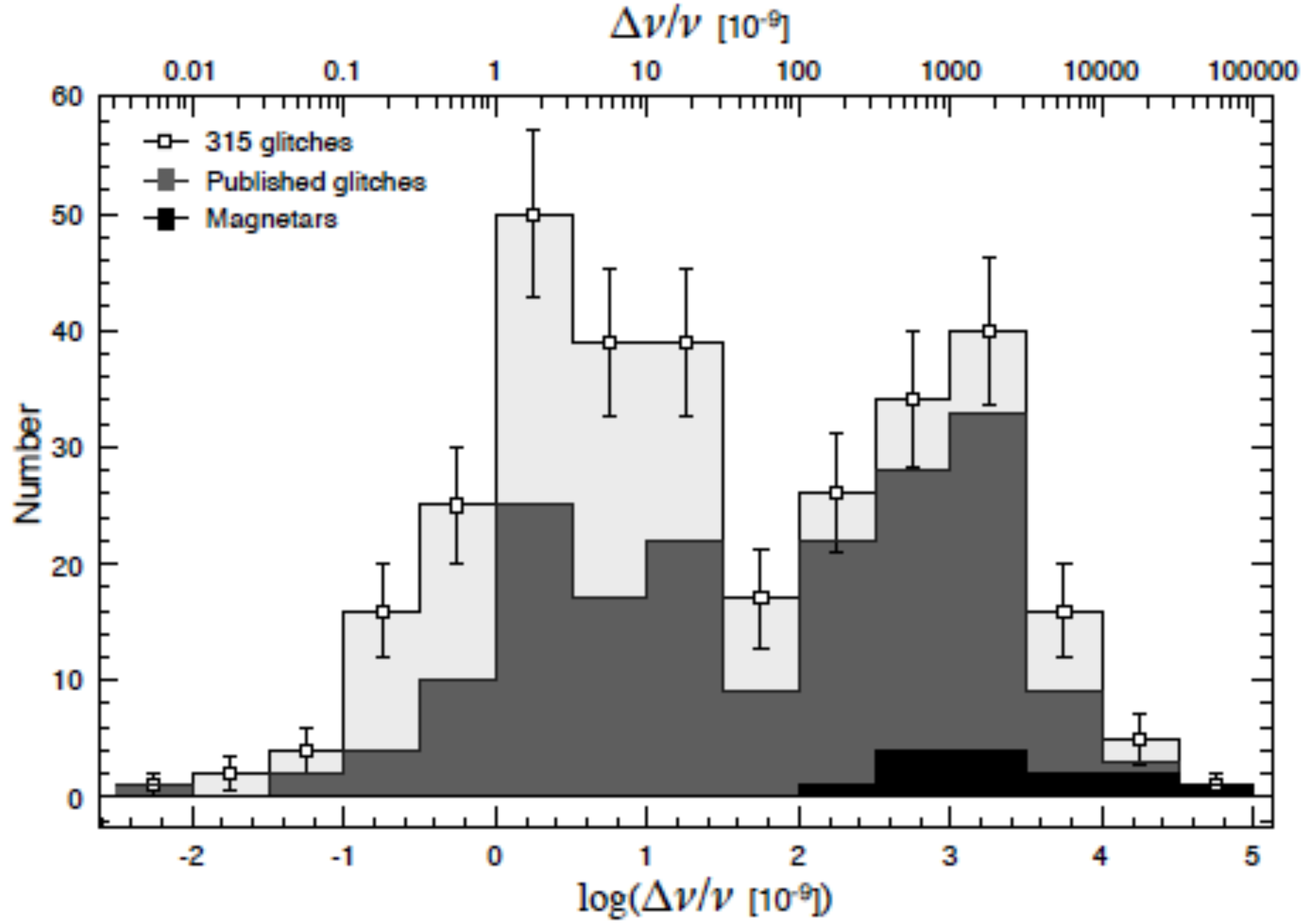
Simulation of neutron star glitches via Gross-Pitaevskii eqn., with pinning sites (*Warszawski and Melatos, 1103.6090*):



similar power law falloff
vs. amplitude Δ Ω/Ω

Glitch distribution vs. relative amplitude is bimodal

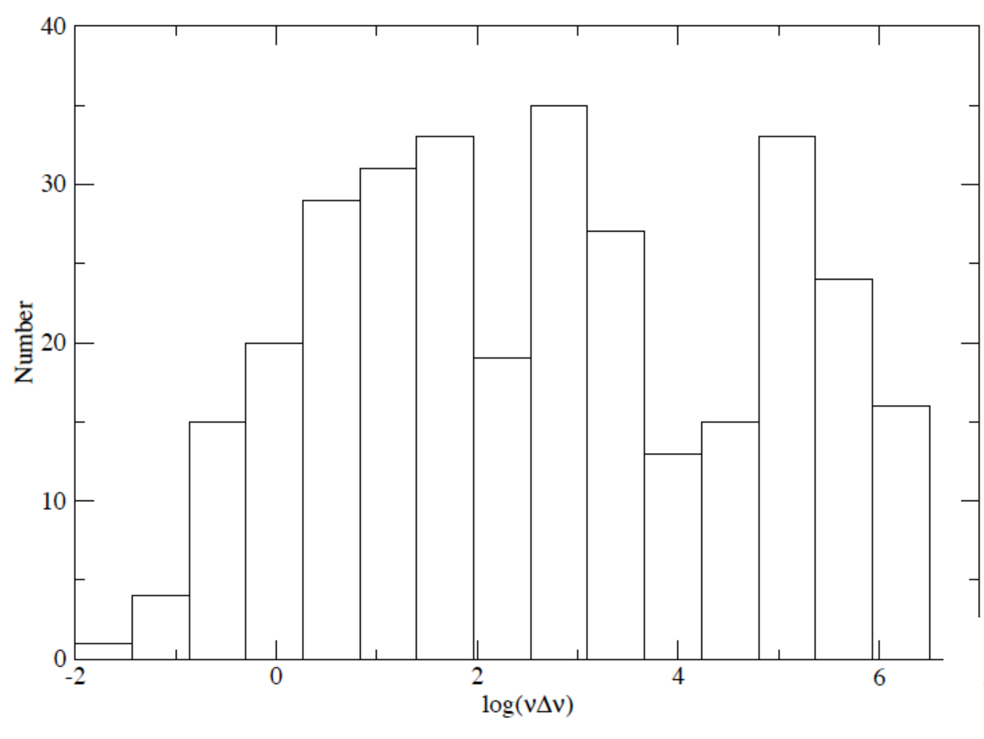
Espinoza et al. arXiv 1102.1743

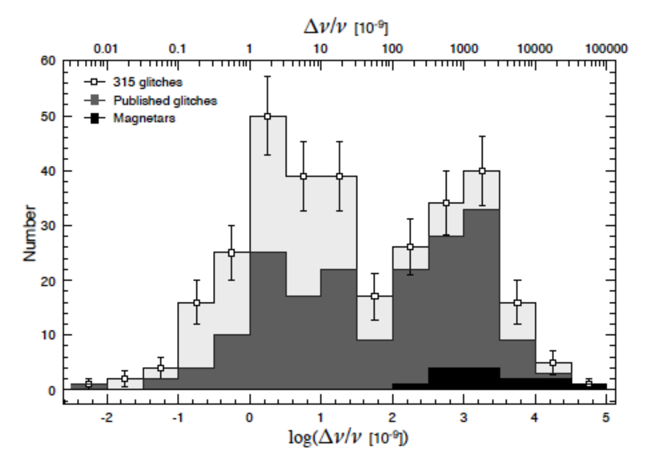


Glitch distribution vs. energy release $\Delta E = I\Omega\Delta\Omega$

Graph from B. Link, with data from C. Espinoza

$$\frac{dN}{d\log\Delta E}$$





Less bimodal, but not a power law falloff

THE END