Spin Up in Neutron Stars : The Future of the Vela Pulsar

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Nature **224**, 872–874 (1969) | Cite this article

Assuming that the speed up of the Vela pulsar was caused by a “starquake”, a number of predictions can be made, and the event can be taken as evidence that the interior of the pulsar is a superfluid.

Published: 03 July 1975

Pulsar glitches and restlessness as a hard superfluidity phenomenon

P. W. ANDERSON & N. ITOH

Nature **256**, 25–27 (1975) | Cite this article

“the macroglitches, especially those in the Vela pulsar, may be caused by the catastrophic release of pinned vorticity.”

Dynamics of a superfluid in a neutron star crust

Yuri Levin, Columbia (https://yurilevincolumbia.github.io/)
in collaboration with Bennett Link, Montana State

Link & Levin (2022), ApJ, 941, 148
Levin & Link (2023), ApJ, 959, 84

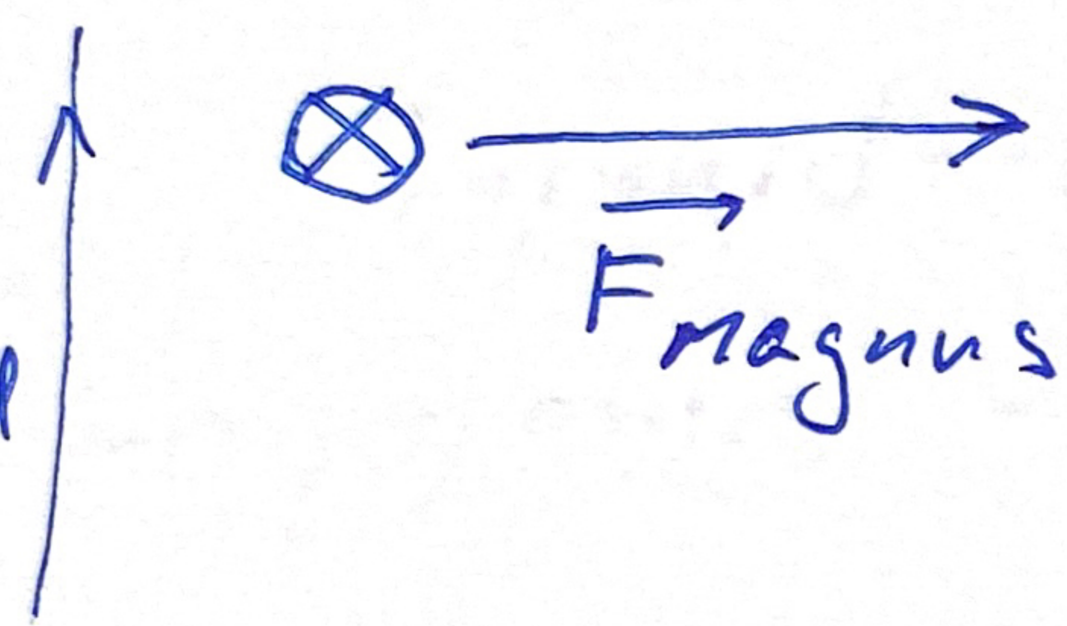
1. Strong hysteresis in pinning/unpinning of a vortex. Bistability of pinned and unpinned states.

2. Non-trivial background configurations with strong localized currents - superfluid rivers.

3. Great observational progress, lots of data. Pushback against observers ("give me the theory of glitches today"). We don't understand basic things.

Vortex motion.

2d – view from above.



$\vec{v}_s - \vec{v}_v$

superfluid velocity relative to the vortex.

$$\vec{F}_{magnus} = \vec{\kappa} \times (\vec{v}_s - \vec{v}_v)$$

$\vec{\kappa}$ ↗ vector along the vortex.

$(\vec{v}_s - \vec{v}_v)$ ↖ relative velocity.

Equation of motion.

$$\vec{F}_{magnus} - \nabla V - \alpha \vec{V}_v = 0$$

∇V ↗ pinning potential.

$\alpha \vec{V}_v$ ↖ friction.

Particular case:

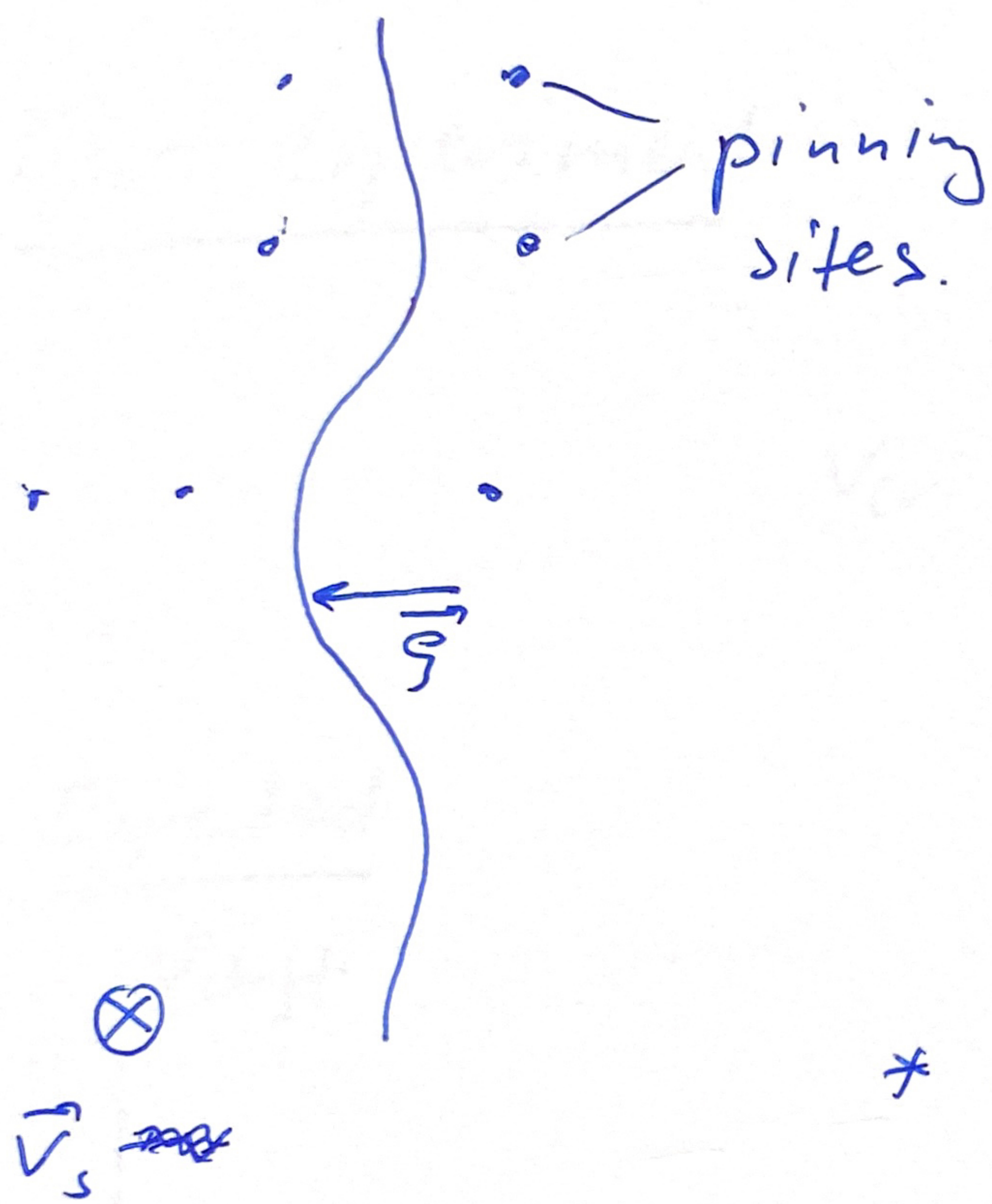
$V_s = 0$

$\alpha = 0$ – no friction.

vortex circles around maxima or minima of $V(\vec{r})$

Vortex motion

3d – view from the side.



Equations of motion:

$$\vec{F}_{Magnus} - \nabla V + T\frac{\partial^2 \xi}{\partial z^2} + \alpha \vec{v}_v = 0$$

Magnus ↗ ; pinning ↗ ; tension ↗ ; friction ↑

* One low-resolution simulation of Link 2009. Saw unpinning.

* Innovation: spectral method, very fast. analytical form of pinning potentials, varied controlled disorder

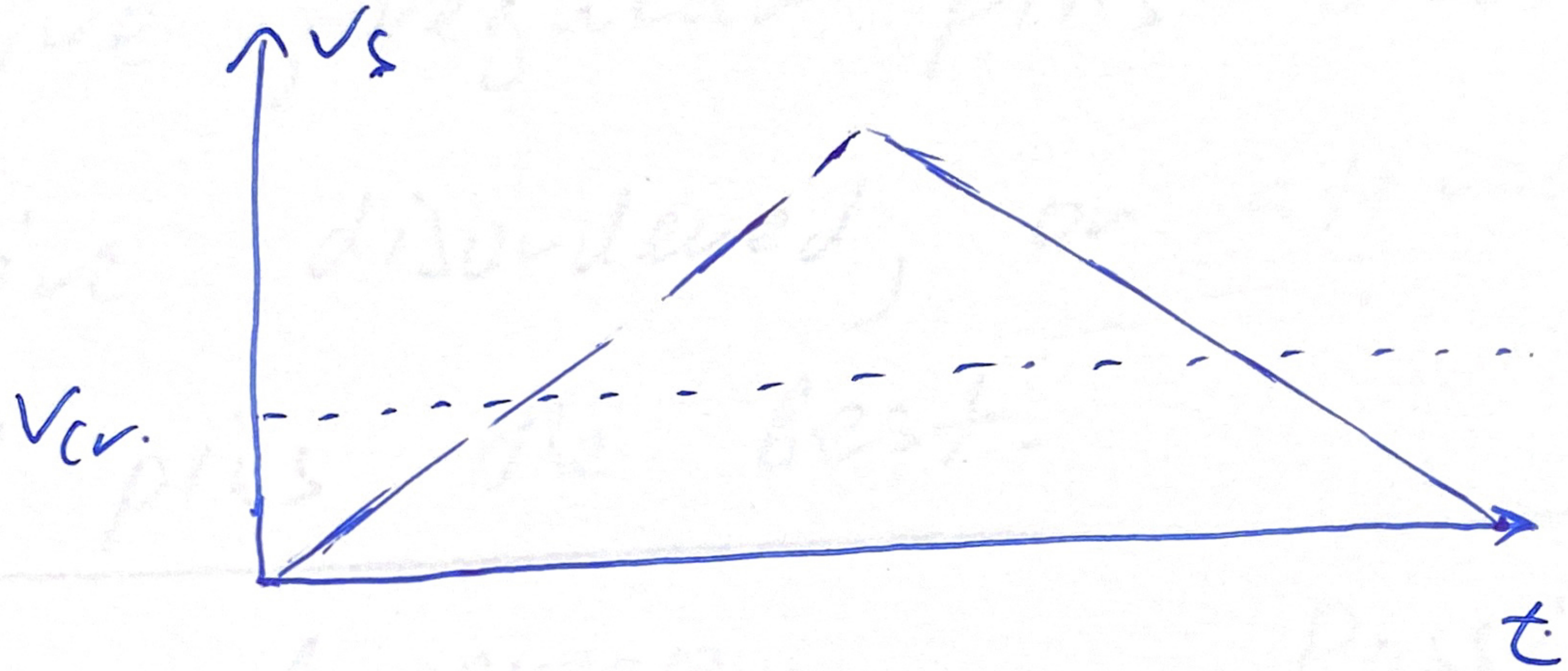
Link & Levin 2012

Standard core.

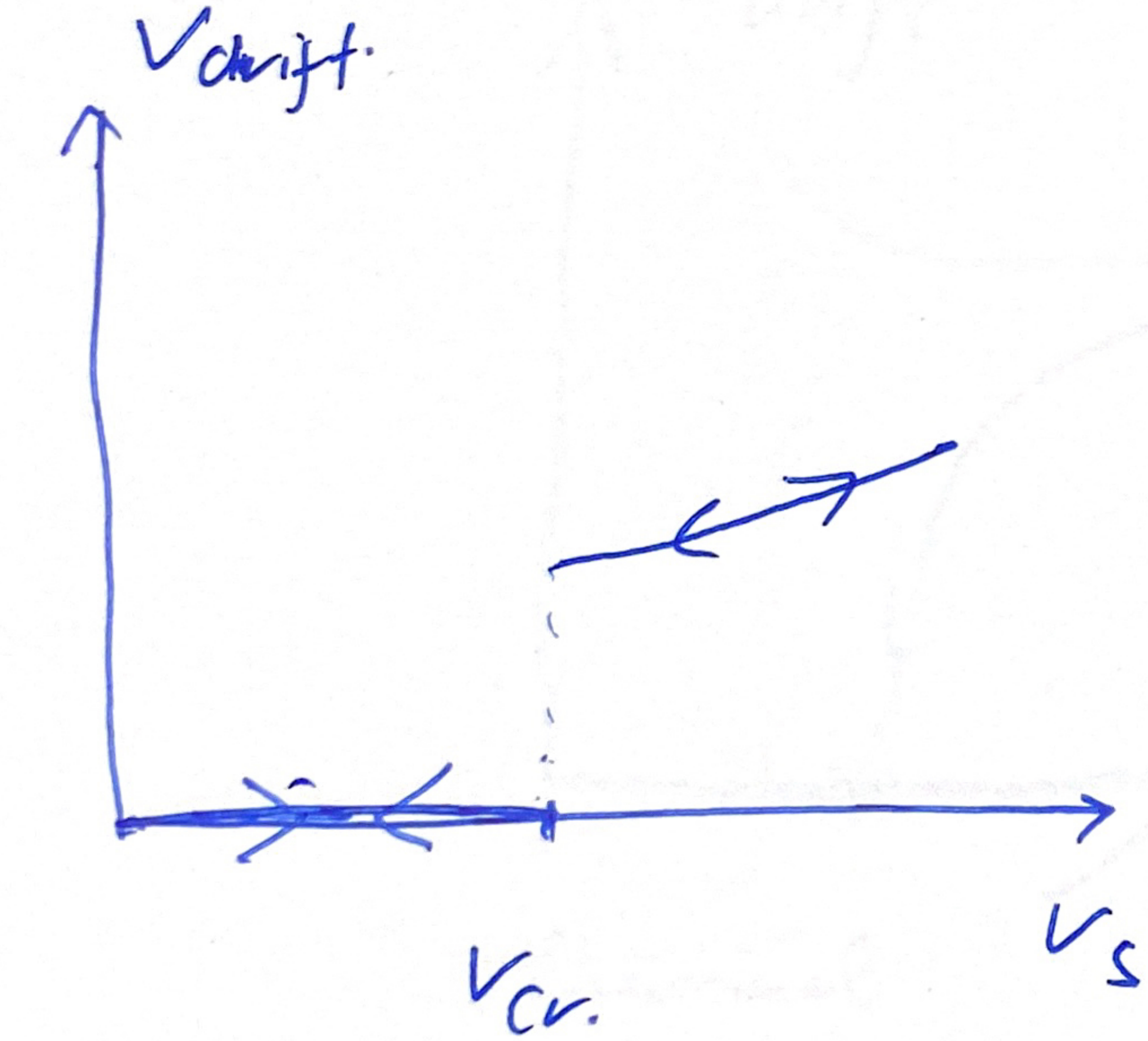
$|\vec{v}_s - \vec{v}_v| < v_{cr.}$ - pinned.

$|\vec{v}_s - v_v| > v_{cr.}$ - unpinned.

Our experiment

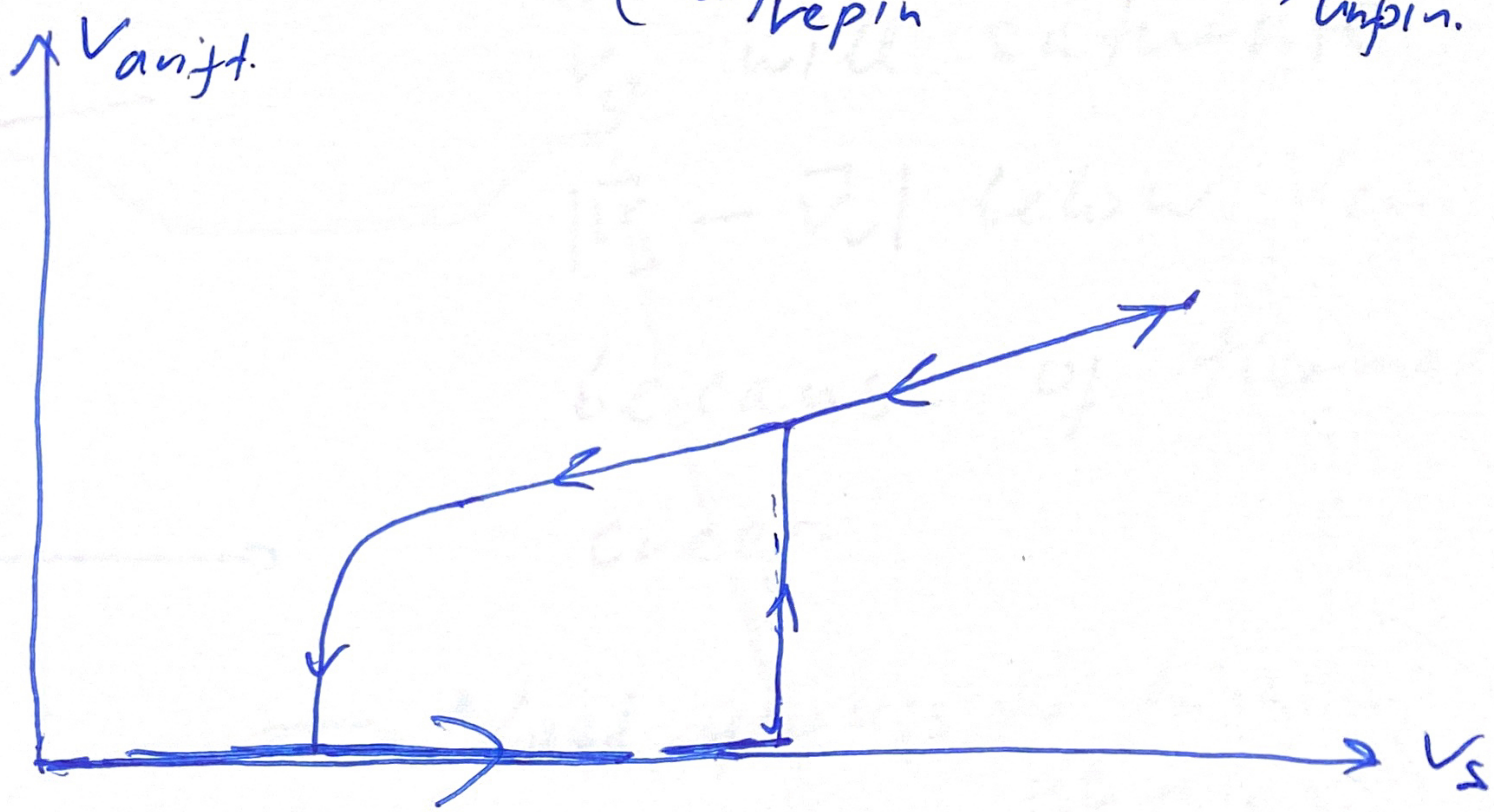


Expected



Results

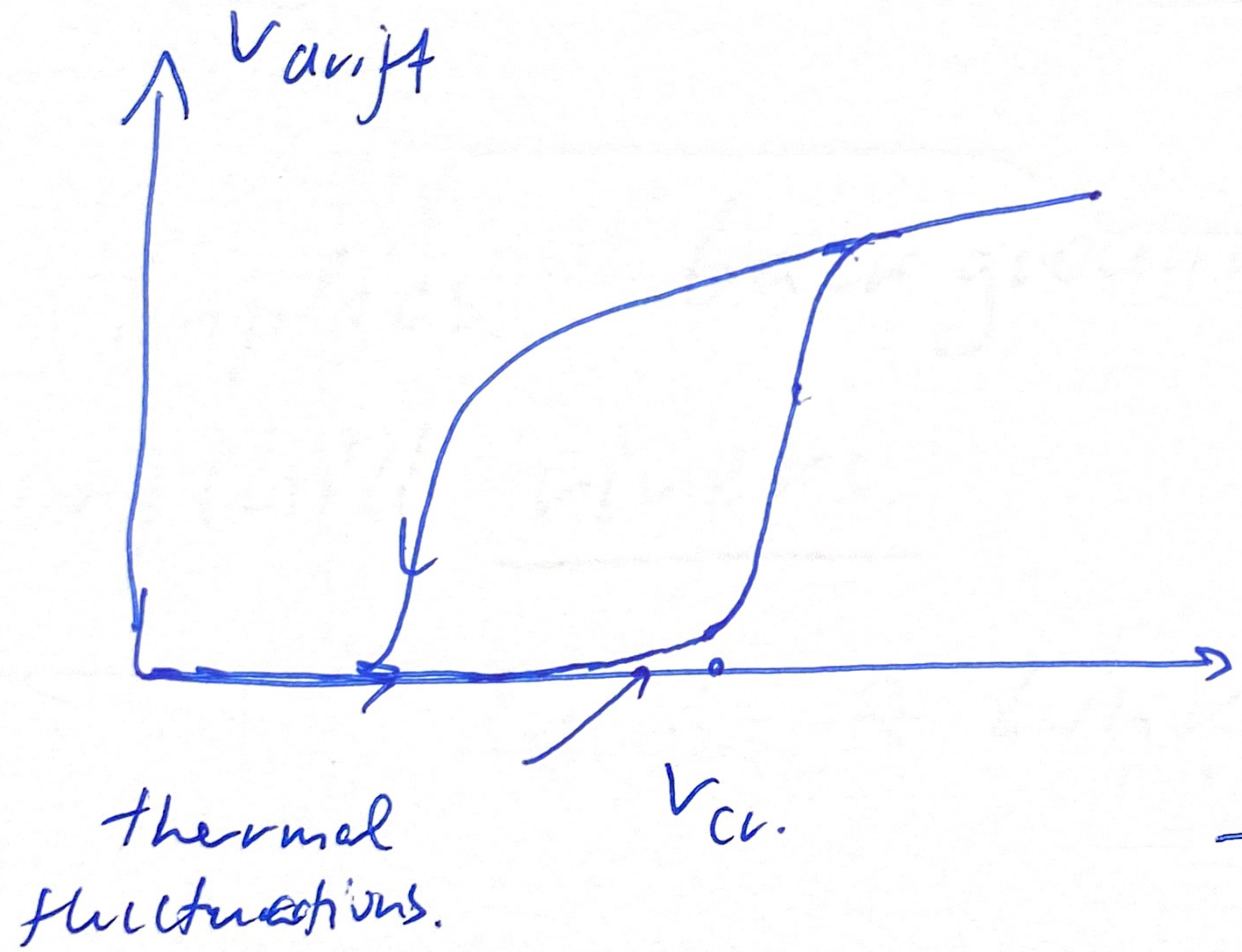
$(v_{cr.})_{repin} < (v_{cr})_{unpin.}$



* Hysteresis, bistability.

* Extreme dependence on lattice structure.
  - repulsive, regular pins badly.
  - attractive disordered, or attractive aligned pins the best.

Caveat: thermal creep.



· Possibility that gradual increase of v_s will saturate $|\vec{v}_s - \vec{v}_L|$ below $v_{cr.}$ because of thermal creep.

— Need quakes to trigger glitches?

Hypothesis

In most of NS

$|\vec{v}_s - \vec{v}_v|$ saturates below

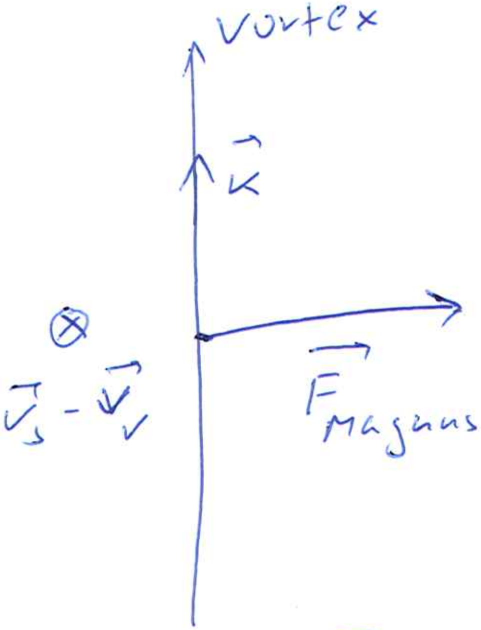
$(v_{cr.})_{unpin}$ as

the NS spins down.

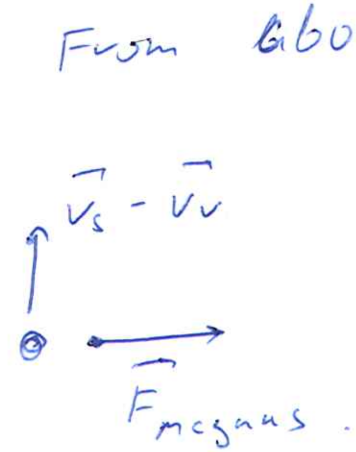
This implies background state with superfluid rivers.

Levin & Link 2023

Magnus force



$$\vec{F}_{Magnus} = \rho_s \vec{\kappa} \times (\vec{v}_s - \vec{v}_v)$$



If a vortex is pinned, as the pulsar is spun down, it feels Magnus force pushing it.

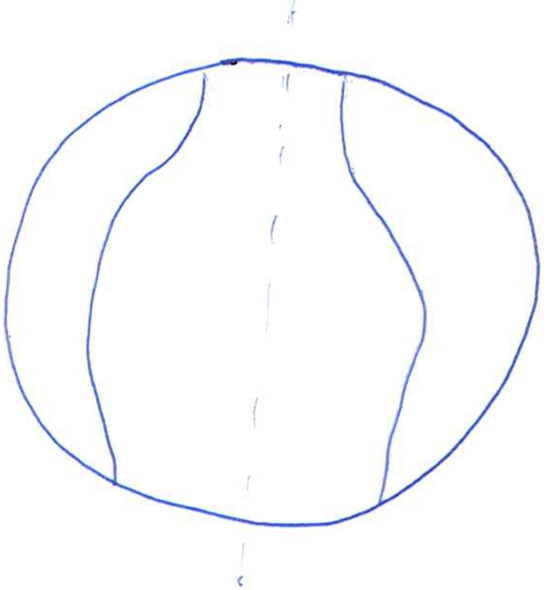
This force builds up.

$$\vec{F}_{magnus} = - \vec{F}_{other}$$

vortex has no inertia.

Evolution in axisymmetry.

Levin & Link 03 accepted.



* Lemma. vortex is a source of circulation.
  $\Rightarrow$ vortex in axisymmetry traces constant circulation surface.

* Corollary Stationary vortex $\Rightarrow$
  $\Rightarrow$ no change in V_s at that location.

* Assumption vortex creeps in the direction of Magnus force.
  when $|\vec{V}_s - \vec{V}_{star}| > V_{cr.}(r)$
  $V_{cr.}(r)$ - critical velocity above which the vortex becomes mobile. $V_{cr.} \sim 10^7$ cm/sec
  ~ 10 rad/sec.

* Theorem vortex motion in the direction of Magnus force leads to local reduction of $|\vec{V}_s - \vec{V}_{star}|$

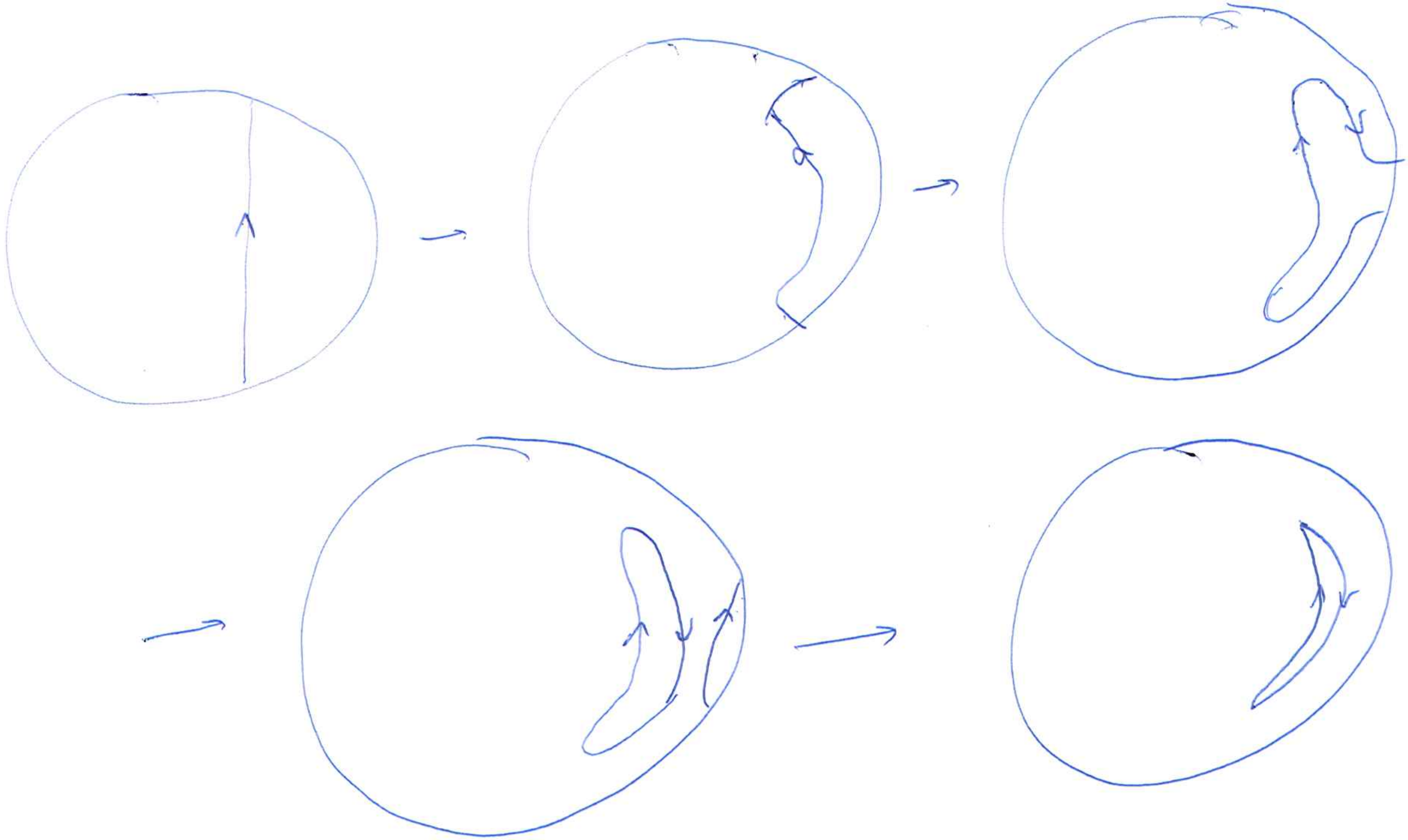
* **Corollary** as $|\vec{v}_s - \vec{v}_{star}|$ increases above v_{cr}, vortex mobility will bring it down to v_{cr} at that location. So once $|\vec{v}_s - \vec{v}_{star}|$ reaches v_{cr}, it stays at that value.

* **Corollary.** fully prescriptive scenario for vortex motion, since each vortex is specified uniquely by the value of $\vec{v}_s$ - circulation.

* **Fact** most models predict large variations in $v_{cr}(r)$: crust-core interface, pasta-normal lattice transition, etc.

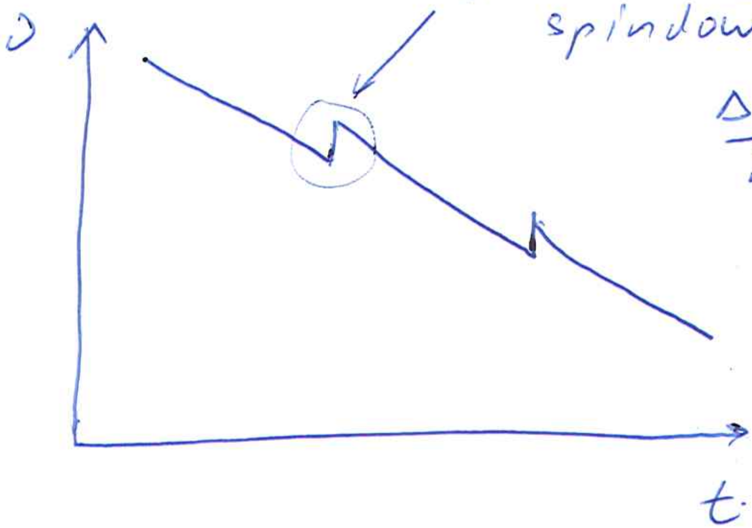
$$\text{Large } \left|\frac{\partial v_{cr}}{\partial r}\right| \Rightarrow \text{strong vortex concentrations}$$

Typical evolution.



Formation of vortex loops around regions of high V_{cr}. Fast flow inside — "river".

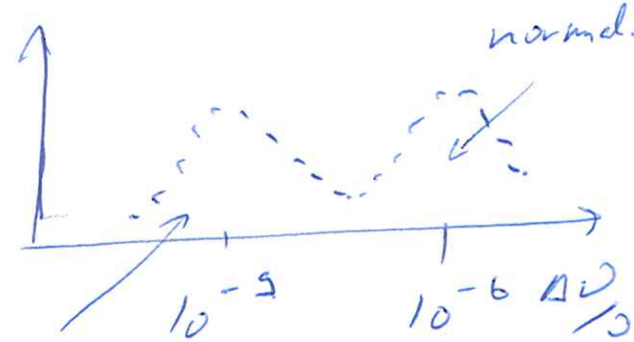
Glitches



Note: huge jumps in spindowns, often $\frac{\Delta\dot{\nu}}{\dot{\nu}} >> \frac{\Delta\nu}{\nu}$

* Only young and middle-aged pulsars

* Distibution bimodal



Espinoza +

* Suspected quake in Vela.

Palfreyman + 2016. Null.

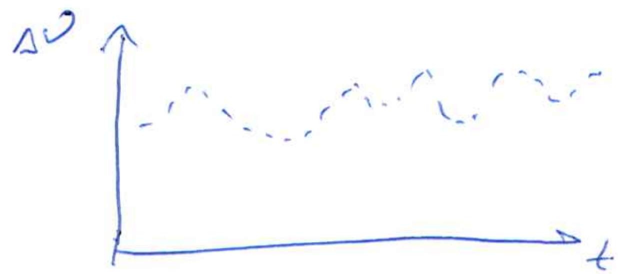
Need more data.

Bransgrove + theory.

- incomplete. Need more detail on discharge & Alfven wave damping.

Timing noise.

Often quasi-periodic.



Magnetars glitles & antiglitches

Radiatie change ⇒ timing features

timing features ⇏ radiative change.

Dib & Kaspi 2014.

Dynamics of a superfluid in a neutron star crust

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Lessons

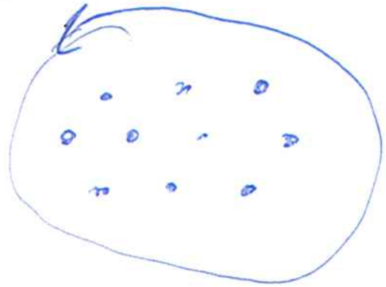
In axisymmetry, with simplest prescriptions for vortex motion.

* Vortices are strongly bent.
* Form loops with rivers inside
* Strongly concentrated in regions of $\left|\frac{\partial v_{cr}}{\partial r}\right|$ that are high, by factors ~100 - 1000 relative to expectations of steady rotation.

Caveats

* Link & Levin (2022) show that unpinning - repinning is complex, stochastic process with large hysteresis.
* Thermal creep can destroy rivers. We are simulating it now.

View from above.



$$\oint \vec{V}_s \cdot d\vec{r} = \frac{2\pi\hbar}{m} N$$

If SF rotates homogeneously, <u>effective</u> angular velocity.

$$\Omega = \frac{\oint \vec{V}_s \cdot dr}{2\,(\text{Area})} = \frac{\pi\hbar}{m} n$$

where $n \equiv \frac{N}{\text{Area}}$ is the density of vortices.

SF vortices are physical objects

* They feel attraction or repulsion to lattice nuclei (people still argue which one)
* They might interact with fluxtubes in the core.
* If vortices are fixed in space by interactions — "pinned" then the circulation pattern of $\vec{V}_s$ is fixed.
* Corollary: pinned superfluid cannot be spun down.
* Important other force:

<u>Magnus force.</u>

Superfluid Rivers.

Yuri Levin
(Columbia, Flatiron)

Normal Fluid

Vorticity: $\vec{\omega} \equiv \nabla \times \vec{v}$

Taylor - Proudman theorem:

unstratified fluid in steady state rotates "on cylinders"

$v_\phi = v_\phi(\tilde{\rho})$ — cylindrical radius

$v_{\tilde{\rho}} = v_\theta = 0$

Superfluid

$\vec{v}_s = \frac{\hbar}{m} \nabla \phi$ $\quad \phi$ - condensate phase.

$\Rightarrow \nabla \times \vec{v}_s = 0$

$\Rightarrow$ circulation $\oint \vec{v}_s \cdot d\vec{r} = 0$

Right?

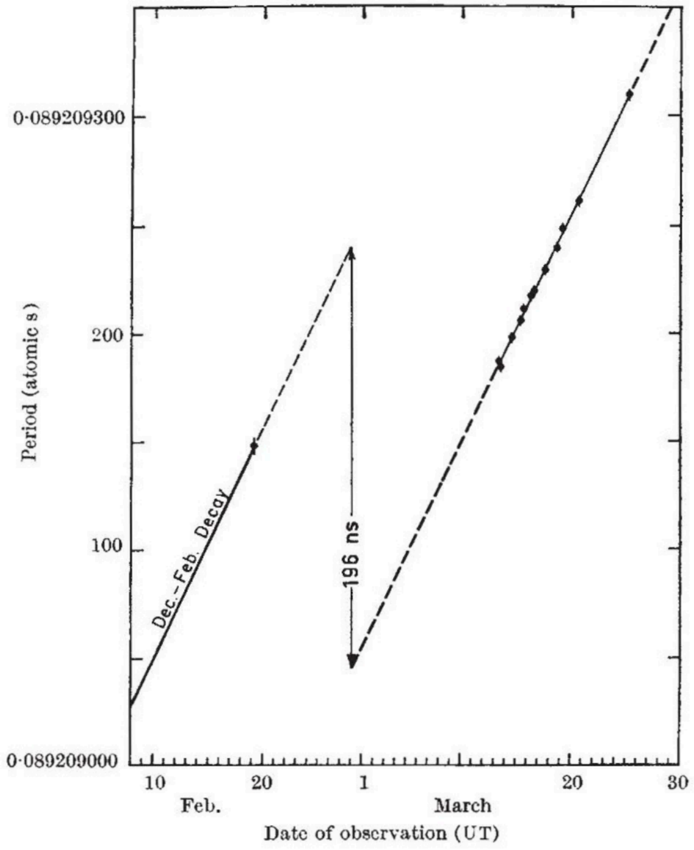
<u>Wrong</u>. Superfluid rotates by forming a dense array of vortices, inside of which superfluidity breaks down.

$\oint_{\text{vortex}} \vec{v}_s \cdot d\vec{r} = \frac{2\pi\hbar}{m}$ around a single vortex

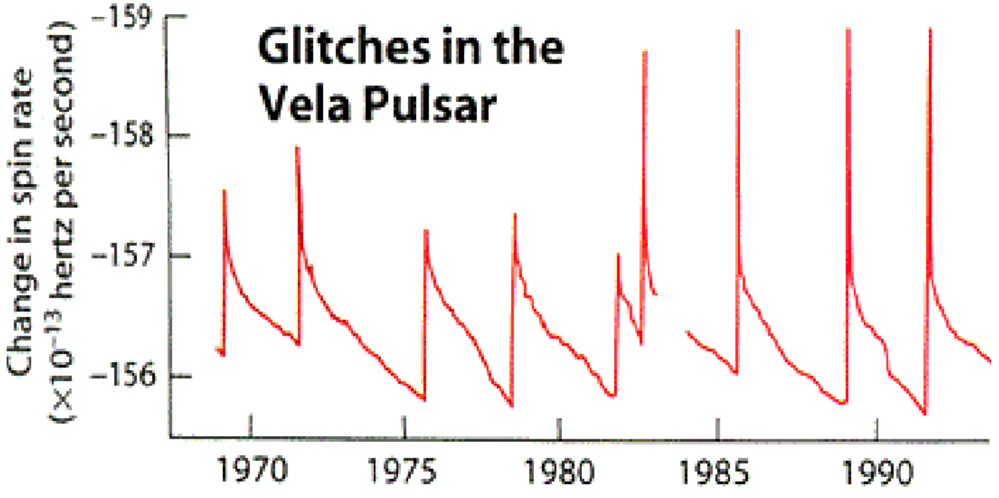
Ensures that phase changes by 2π

2. Unpinning and repinning superfluid vortices in a neutron star crust

The first glitch in Vela



Radhakrishnan & Manchester 1969



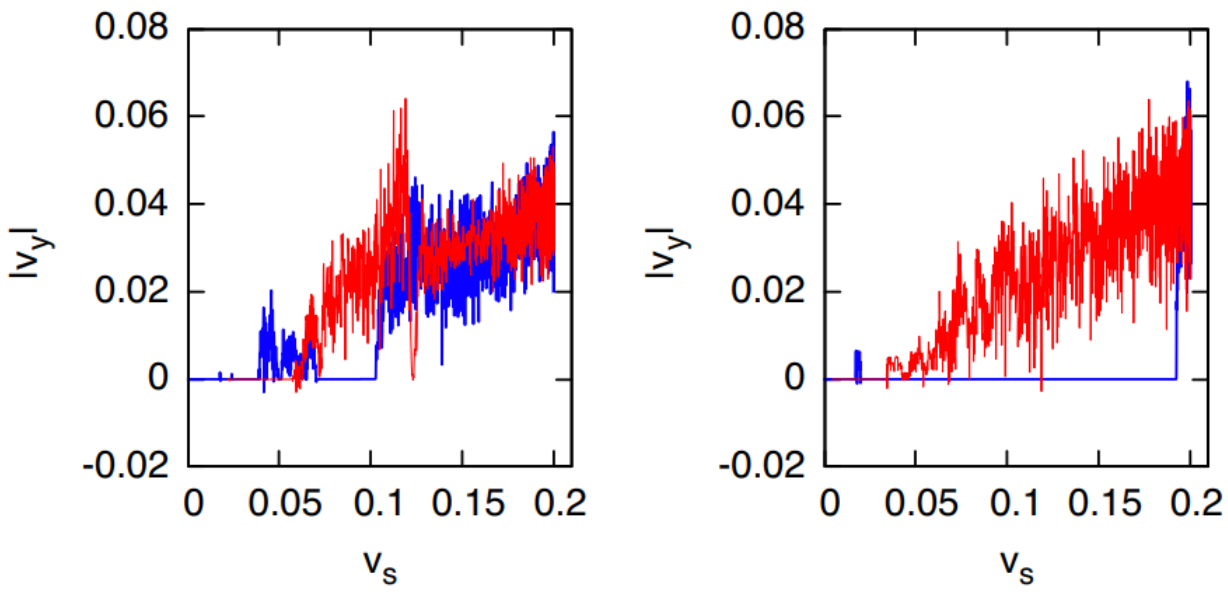
A.G. Lyne, F. Graham-Smith

- Sudden change in spin frequency and/or frequency derivative
- Probably due to the sudden unpinning of many (~1E11) superfluid vortices inside the neutron star

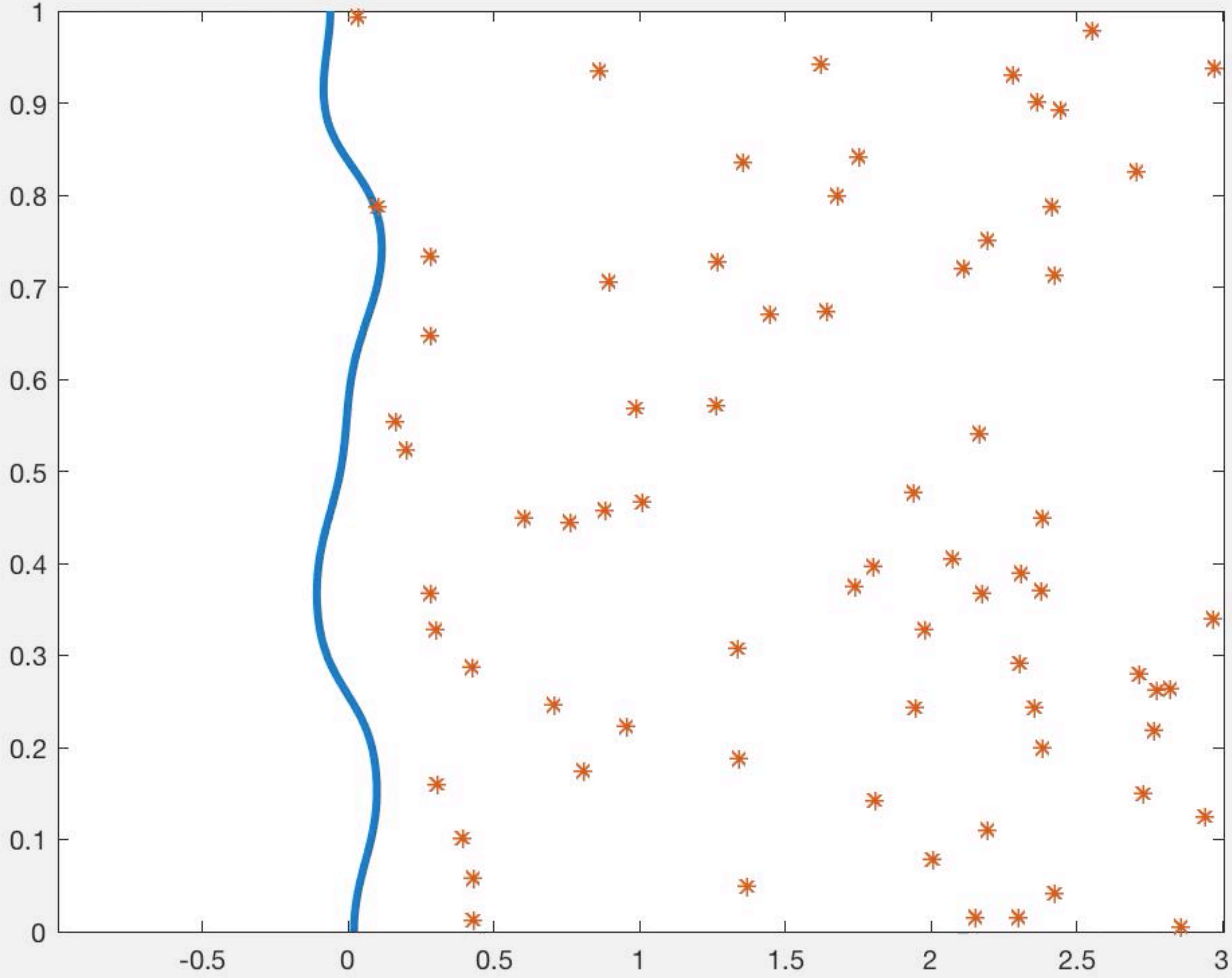
Vortex Pinning in Neutron Stars, Slip-stick Dynamics, and the Origin of Spin Glitches

Bennett Link[1] and Yuri Levin[2,3,4]

Main results



- Hysteresis
- Repulsive regular lattice the worst for pinning
- Attractive irregular or glass the best
- Vortex tangle
- Some ideas for large-scale avalanche of unpinning



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.5
0
0.5
1
1.5
2
2.5
3