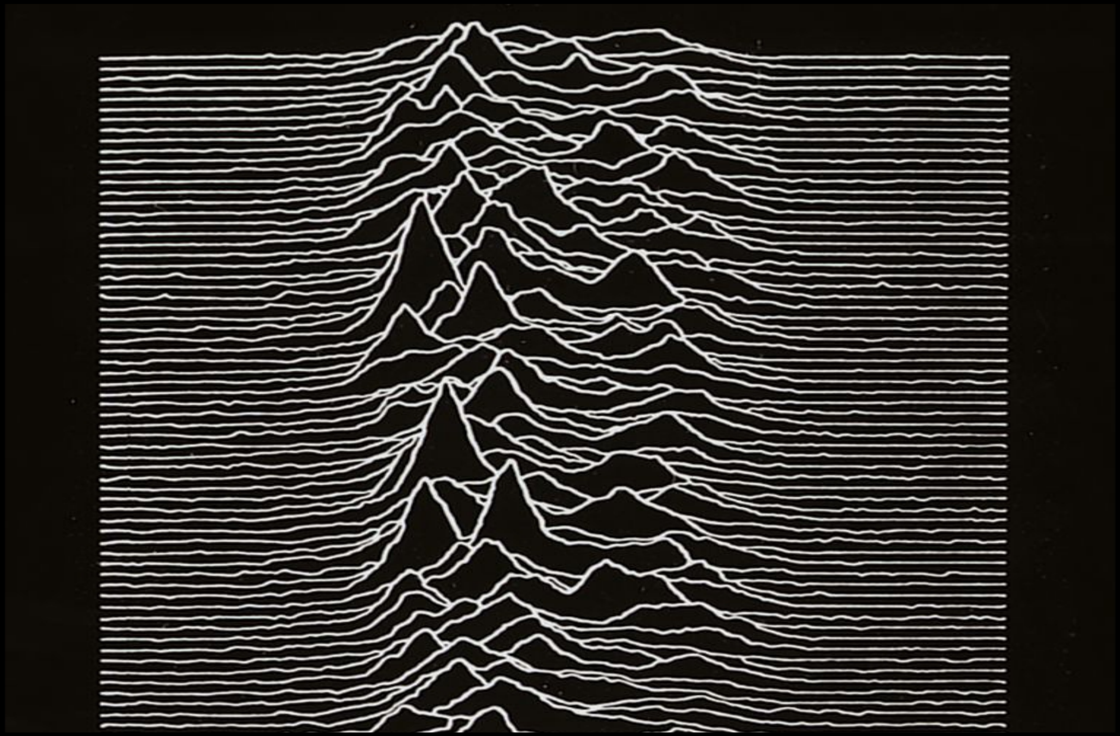
PULSAR GLITCHES



AND NEUTRON STARS STRUCTURE

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Supervisor: Prof. P. M. Pizzochero

PhD School in Physics of Università degli Studi di Milano

First-Year students Workshop , 12 Oct. 2015

What is a **PULSAR** ?

- Astronomical object:

A regular & intermittent radio signal (from a point source inside our Milky Way)...

...pulsation periods from ~ 0.03 s to ~10 s... but can be shorter!

- First observed in 1967 (playful name of LGM-1)

"...a series of pulses lasting 0.3 s with a repetition period of ~1.4 s..."

Observation of a Rapidly Pulsating Radio Source

by

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Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

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In July 1967, a large radio telescope operating at a frequency of 81·5 MHz was brought into use at the Mullard Radio Astronomy Observatory. This instrument was designed to investigate the angular structure of compact radio sources by observing the scintillation caused by the irregular structure of the interplanetary medium[1]. The initial survey includes the whole sky in the declination range $-08° < \delta < 44°$ and this area is scanned once a week. A large fraction of the sky is thus under regular surveillance. Soon after the instrument was brought into of three others having remarkably similar properties which suggests that this type of source may be relatively common at a low flux density. A tentative explanation of these unusual sources in terms of the stable oscillations of white dwarf or neutron stars is proposed.

Position and Flux Density

The aerial consists of a rectangular array containing 2,048 full-wave dipoles arranged in sixteen rows of 128 elements. Each row is 470 m long in an E.–W. direction

J. Bell @ Cambridge, 1966

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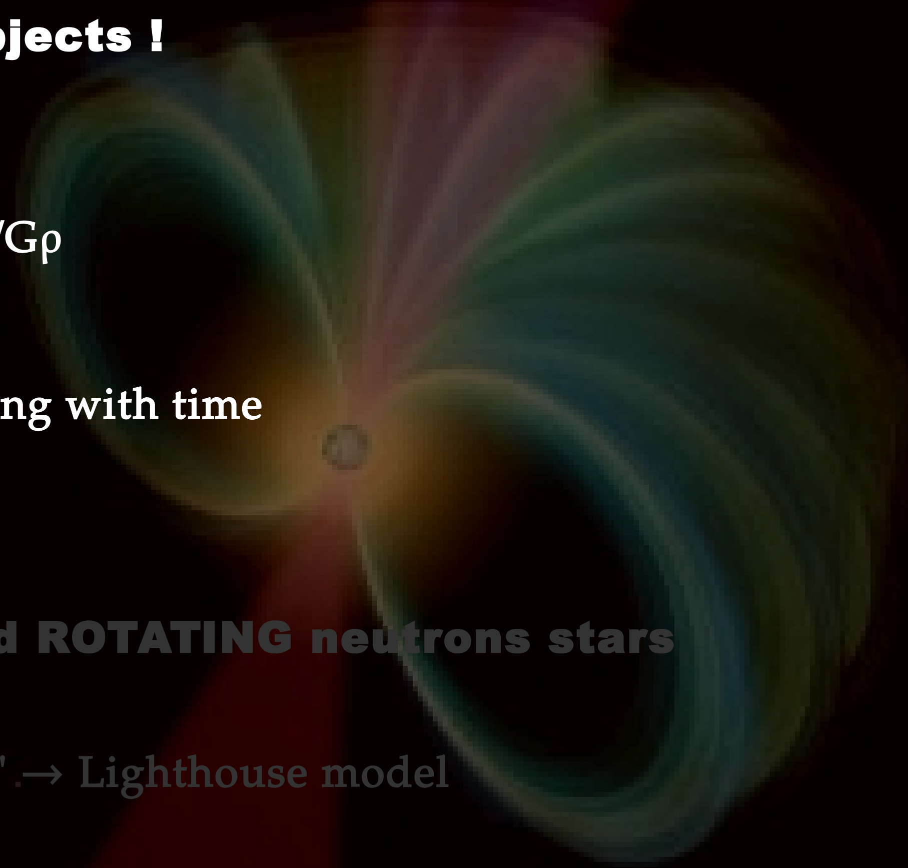
...a cosmic lighthouse!



Coherence + brightness + fast P → small objects !

- **vibrating/rotating WD ?**

  excluded by the very short periods: $P^2 \sim 1/G\rho$

- **vibrating NS ?**

  excluded by pulsar-timing data: P increasing with time

- **BH accretion ?** No regular pulses...

SOLUTION: pulsars are strongly magnetized ROTATING neutrons stars

1969 - Pacini: "Energy Emission from a Neutron Star" → Lighthouse model

Ideas: Very intense dipolar $B \sim 10^{15}$ G

Intense radiation beams from polar caps → detected pulses

Misalignment with the rotation axis

P slightly increases due to EM emission

....but some aspects of the RADIO emission mechanism are still quite mysterious !

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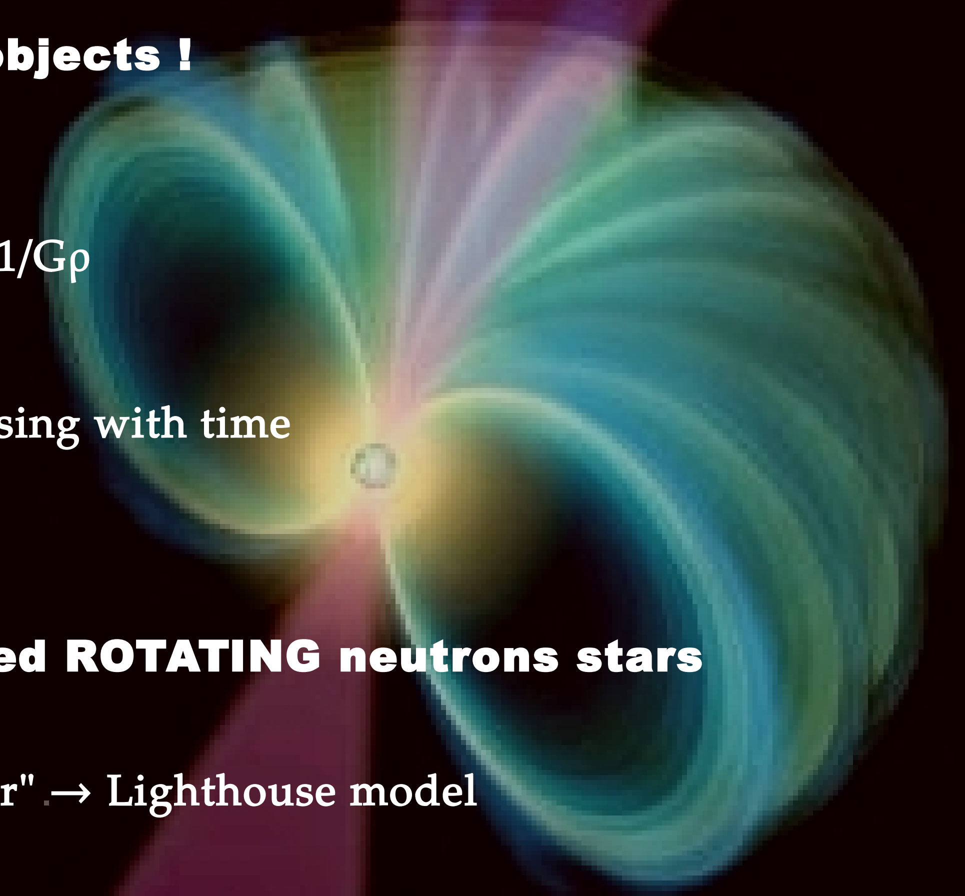

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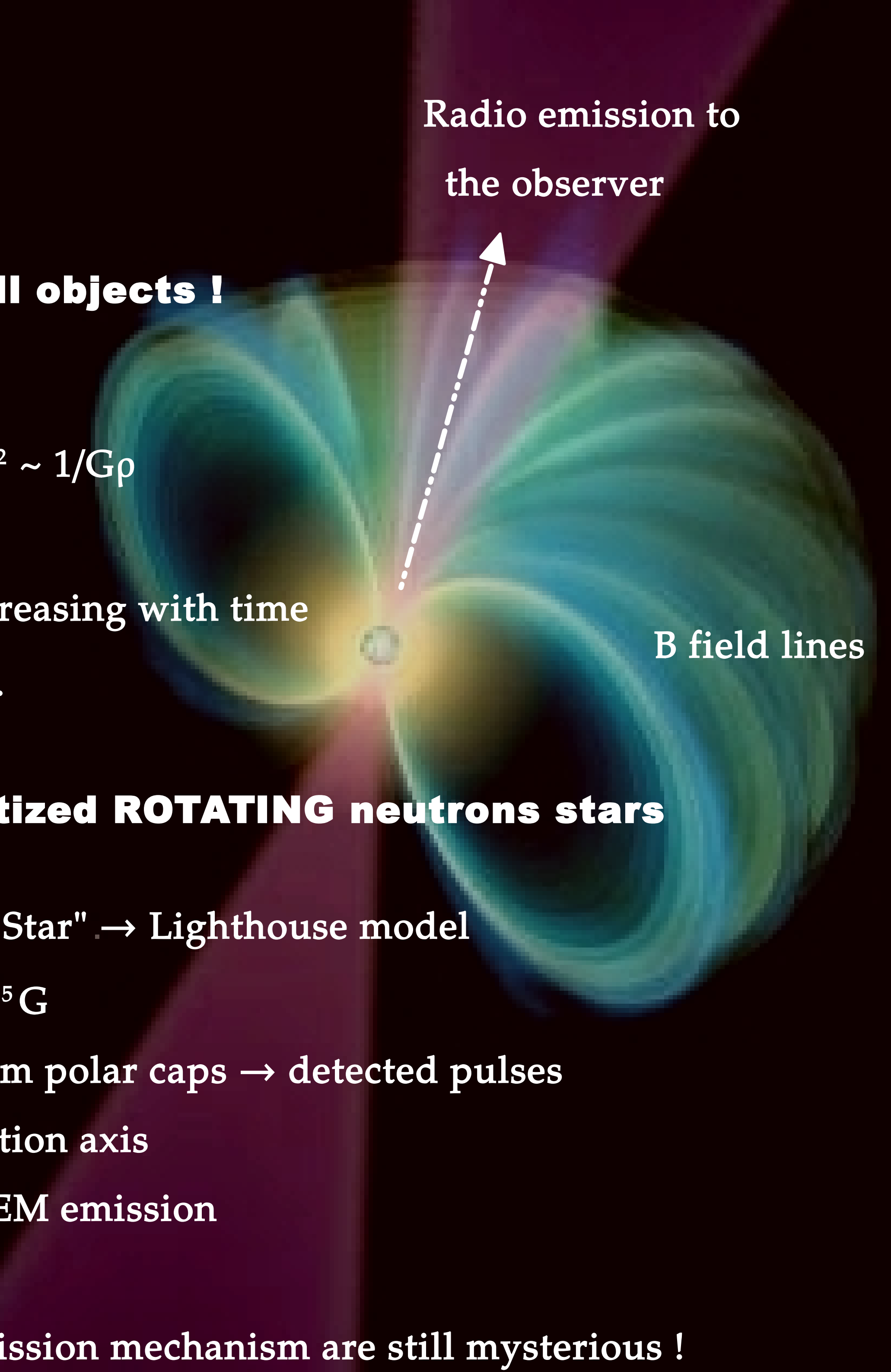

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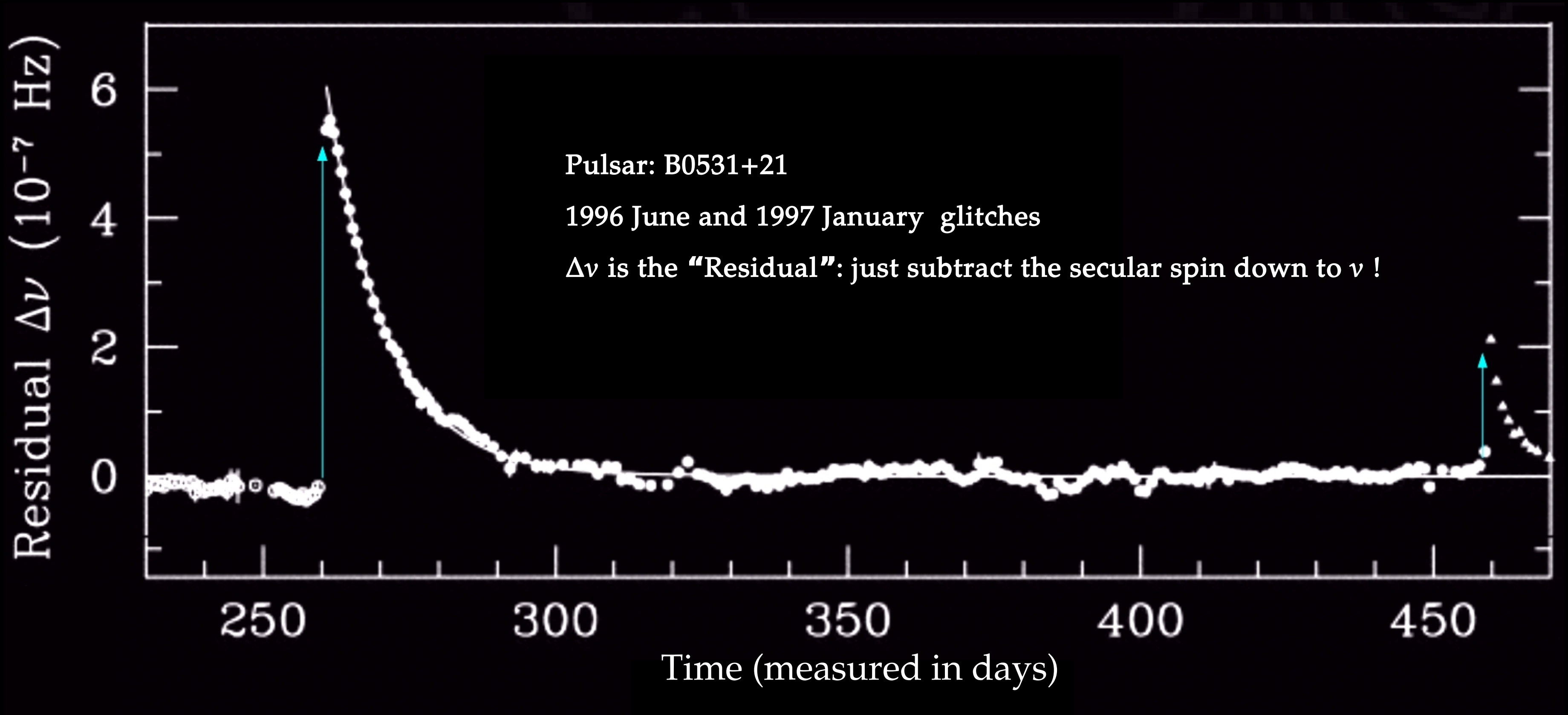
What is a **GLITCH** ?

The pulsar (well, the NS...) rotation is braking...

We expect a regular and (very) slow quasi-linear spin down...

...and we observe it, BUT SOMETIMES...

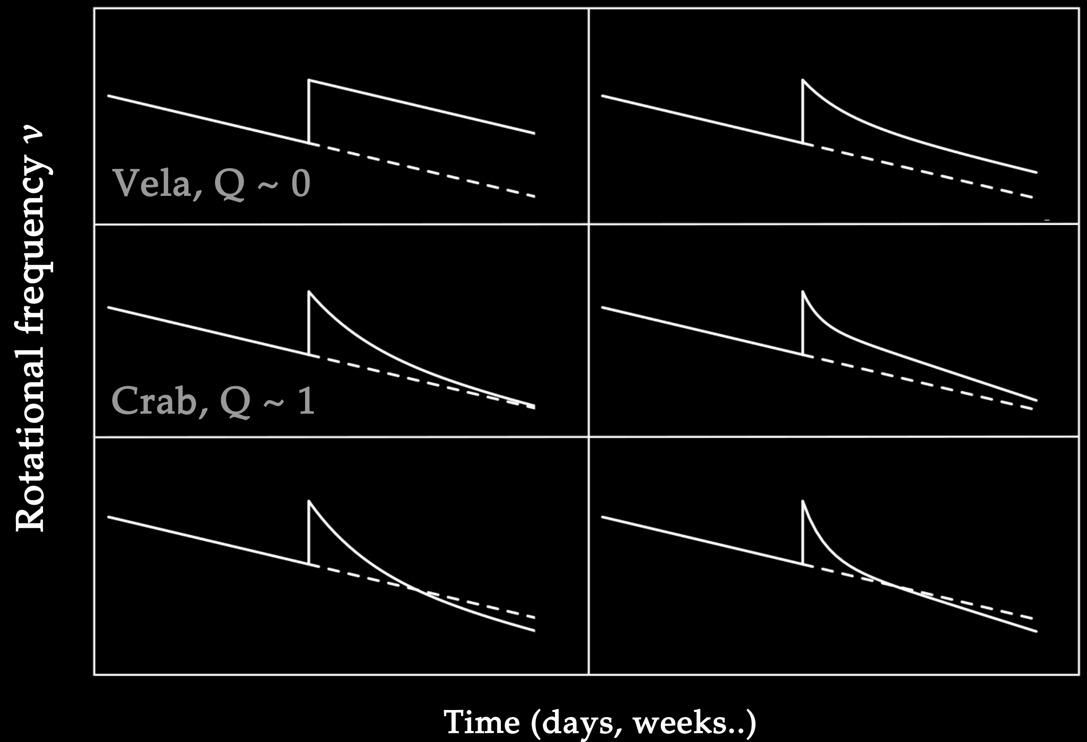


...THE PULSAR IS FOUND TO PULSE (a little bit) MORE RAPIDLY THAN BEFORE !

(i.e. the rotational angular velocity of the underlying NS suddenly increases)

Glitch recoveries

diverse phenomenology and range of timescales



Schematic illustration of observed glitch recoveries:

→ Relaxation time from days to months

→ Healing parameter Q

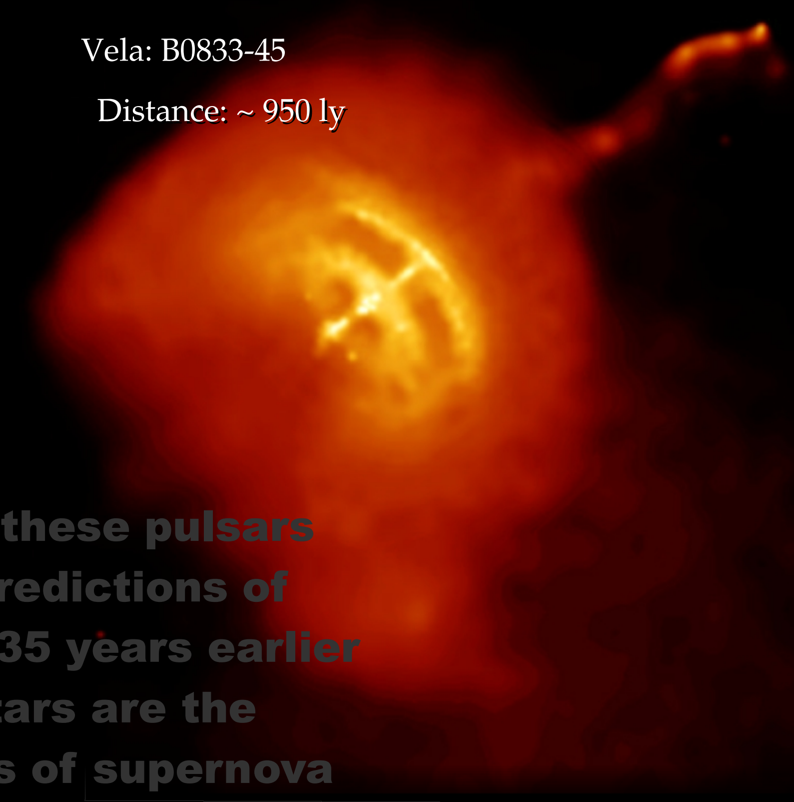
→ Possible permanent change in the spin down rate

→ Best resolution: spin up in less than a minute

Two famous **PULSARS**

Vela: B0833-45

Distance: ~ 950 ly



- VELA:

P ~ 0.09 s ↔ ν ~ 11 Hz

P1 ~ $1.2 \cdot 10^{-13}$ ↔ $\nu 1 \sim -1.5 \cdot 10^{-11}$ Hz/s

#glitches: 17 since 28-02-'69

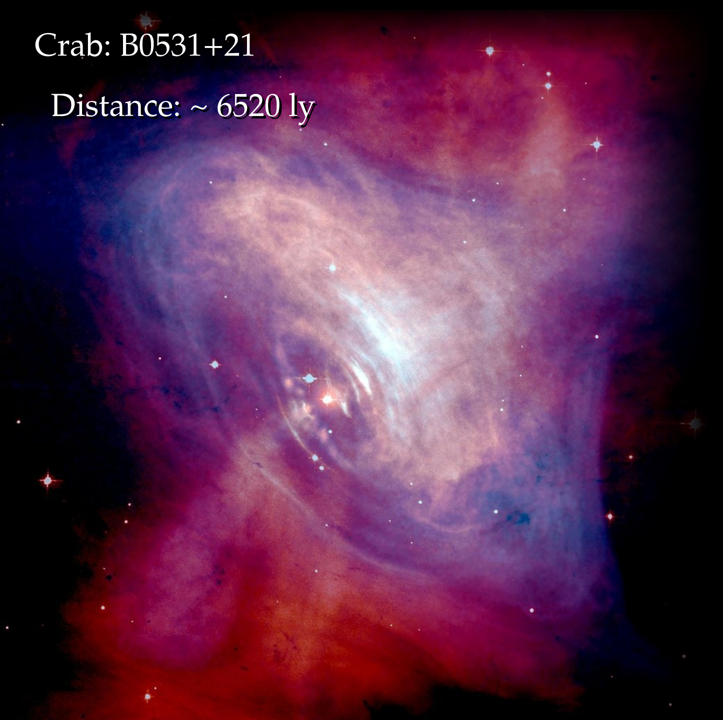
Typical glitch: $\Delta\nu \sim 10^{-6}\,\nu$, $\Delta\nu 1 \sim 10^{-2}\,\nu 1$

Relaxation time ~ months , Q ~ 5%

The discovery of these pulsars confirmed the predictions of Baade and Zwicky 35 years earlier that neutron stars are the compact remnants of supernova explosions.

Crab: B0531+21

Distance: ~ 6520 ly



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Confirmed the link to supernovae

→ First observational clue for "pulsars as rotating NSs" !

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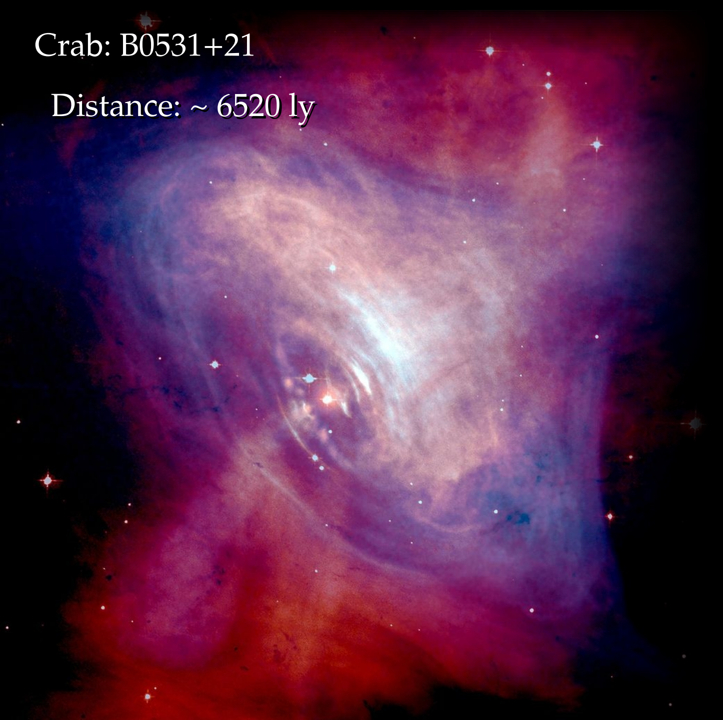

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Glitch amplitude: $\Delta\nu / \nu \sim 10^{-6} \rightarrow \Delta\nu \sim 10^{-5}$ Hz

Moment of inertia: ($M \sim M_\odot$ + $R \sim 10$ km) $\rightarrow$ $I \sim 10^{45}$ g cm^2

$\Delta E_{rot} = 4\pi^2 I \nu \Delta\nu \sim 10^{43}$ erg $\sim L_\odot$ 100 yr

The energy released (as kinetic energy of the rotation) during
a giant glitch is as large as the energy radiated by the Sun in ~ 100 yr!
This rules out the possibility that the spin up follows a change in I.

There must be an angular momentum transfer...

...but "glitchers" are isolated objects $\rightarrow$ INTERNAL MECHANISM !

Key point: to describe glitches we need that a NS is comprised of (at least) two components that exchange angular momentum.

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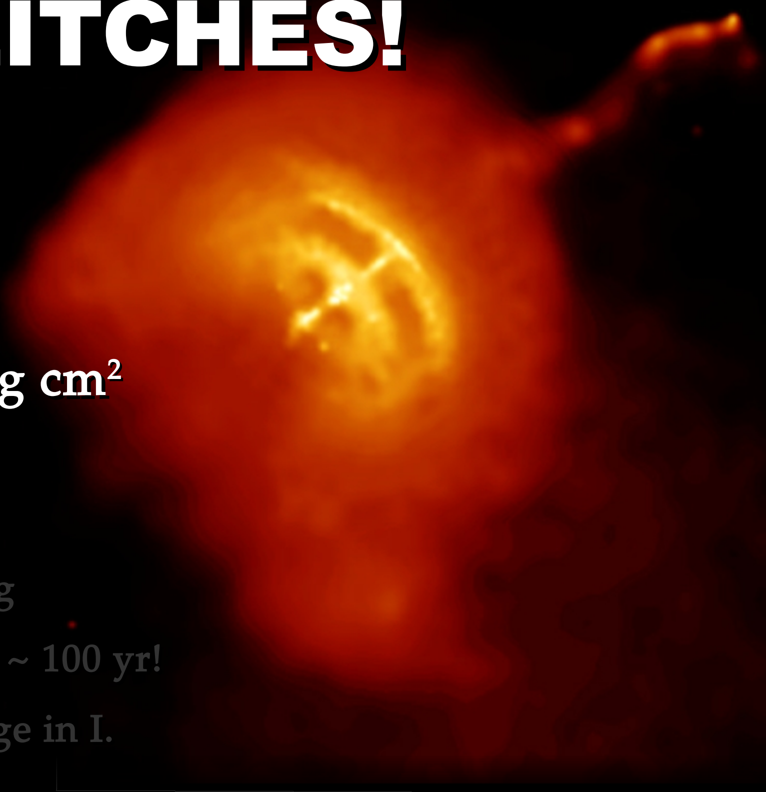

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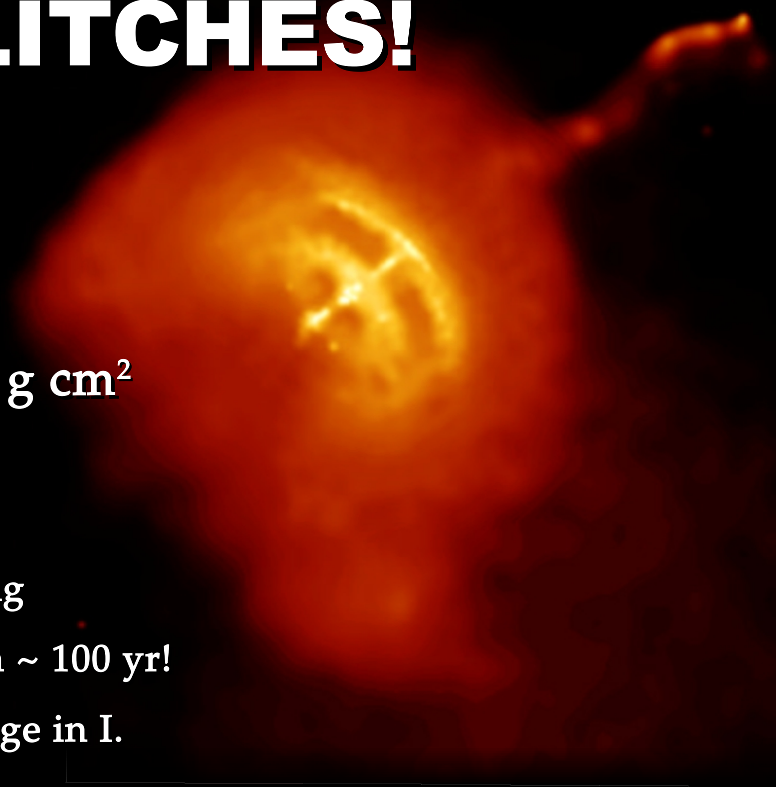

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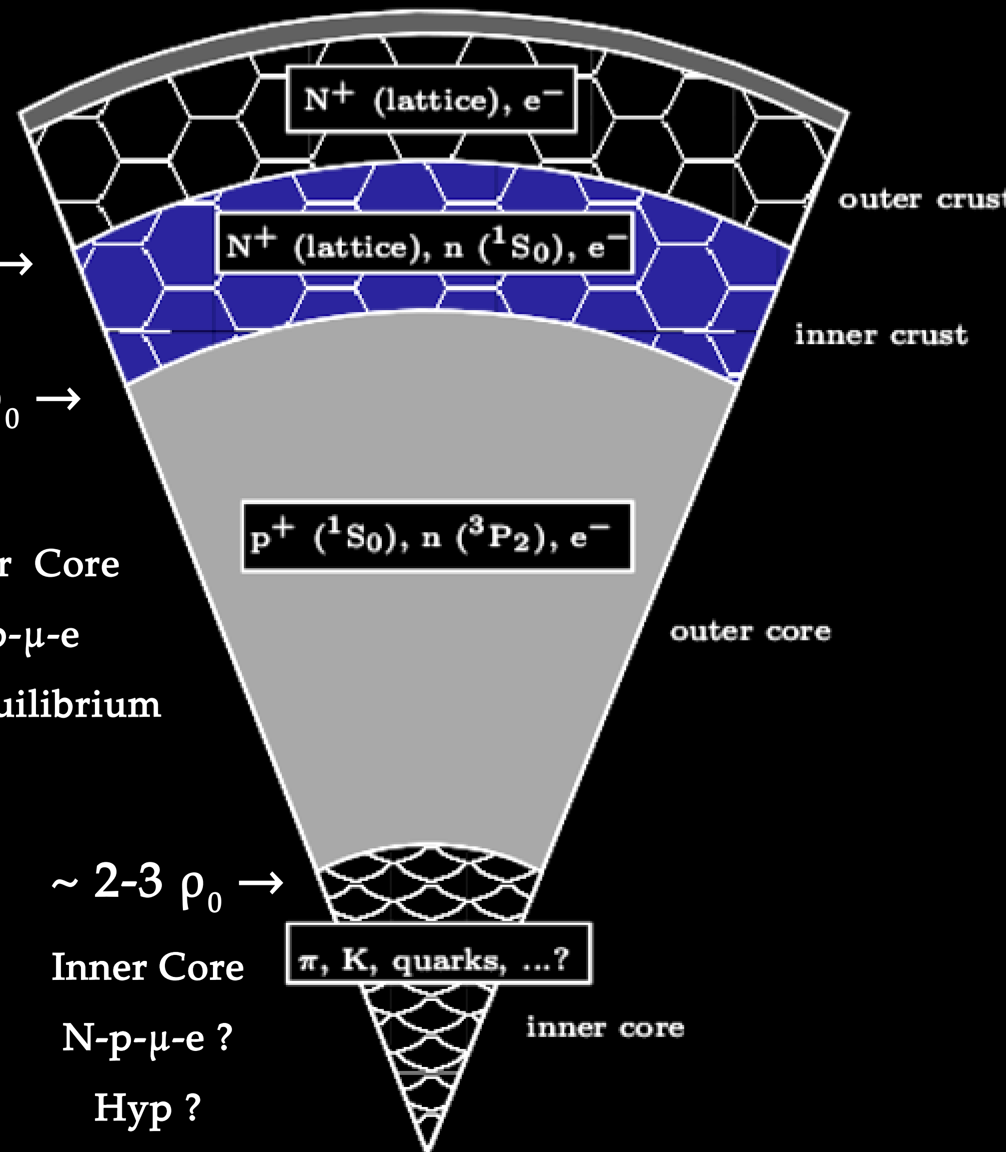
Neutron star's **STRUCTURE** (without details!)

M ~1-2 solar mass compressed inside a radius of about 10 km, a NS represents much extreme physics that cannot be tested in the laboratory.

Neutron drip →

~ 0.5 ρ_0 →



Outer Core
N-p-μ-e
in β-equilibrium

~ 2-3 ρ_0 →

Inner Core
N-p-μ-e ?
Hyp ?
Quarks ?

Relativistic electrons (fluid)
Inner crust: lattice heavy ions + electron and dripped neutron gas (crustal superfluid S-wave)
Pasta phase transition at ~ 0.5 ρ_0
Core: n superfluid and p superconductor (type I or II?)
And relativistic electrons + muons

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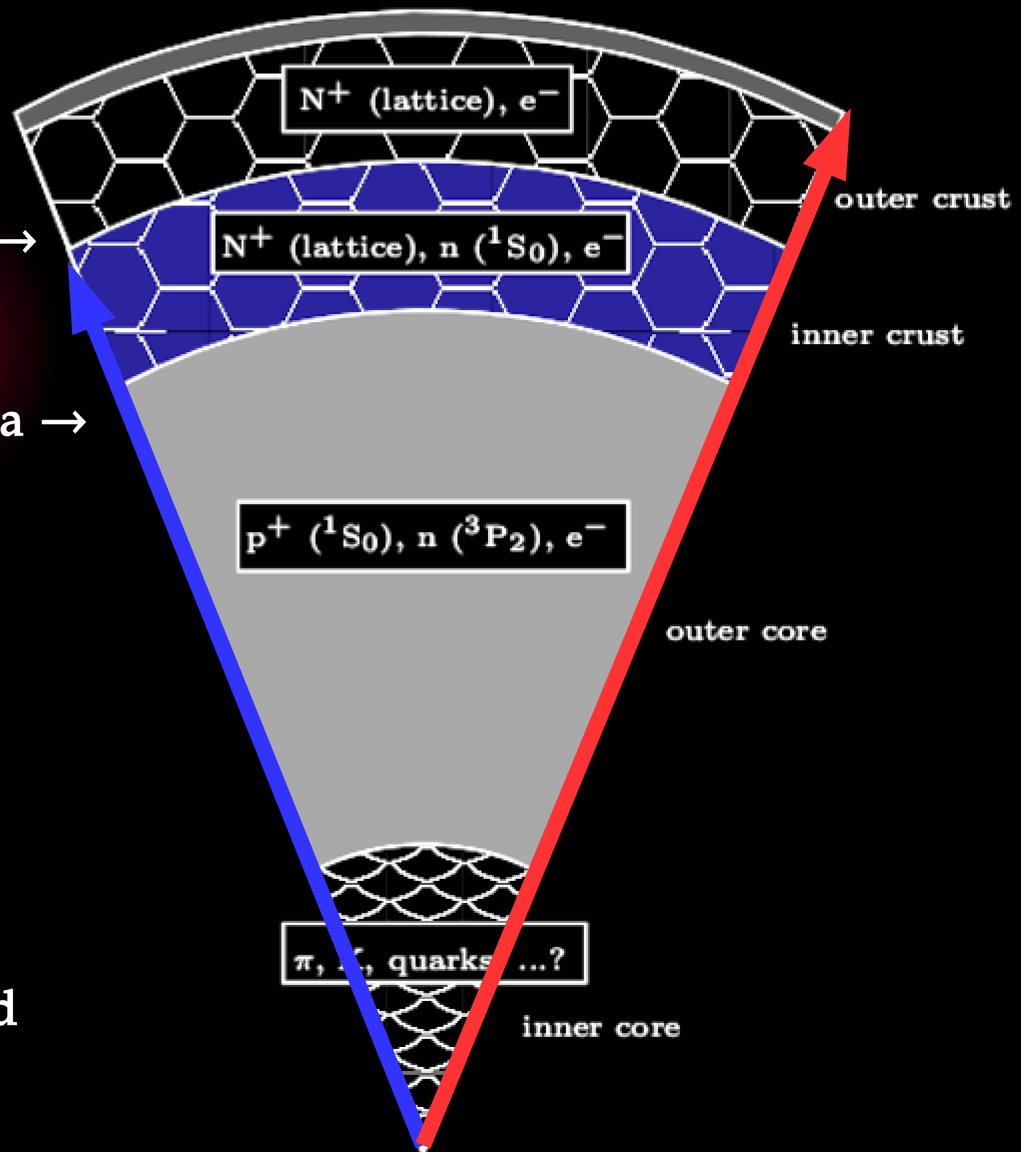
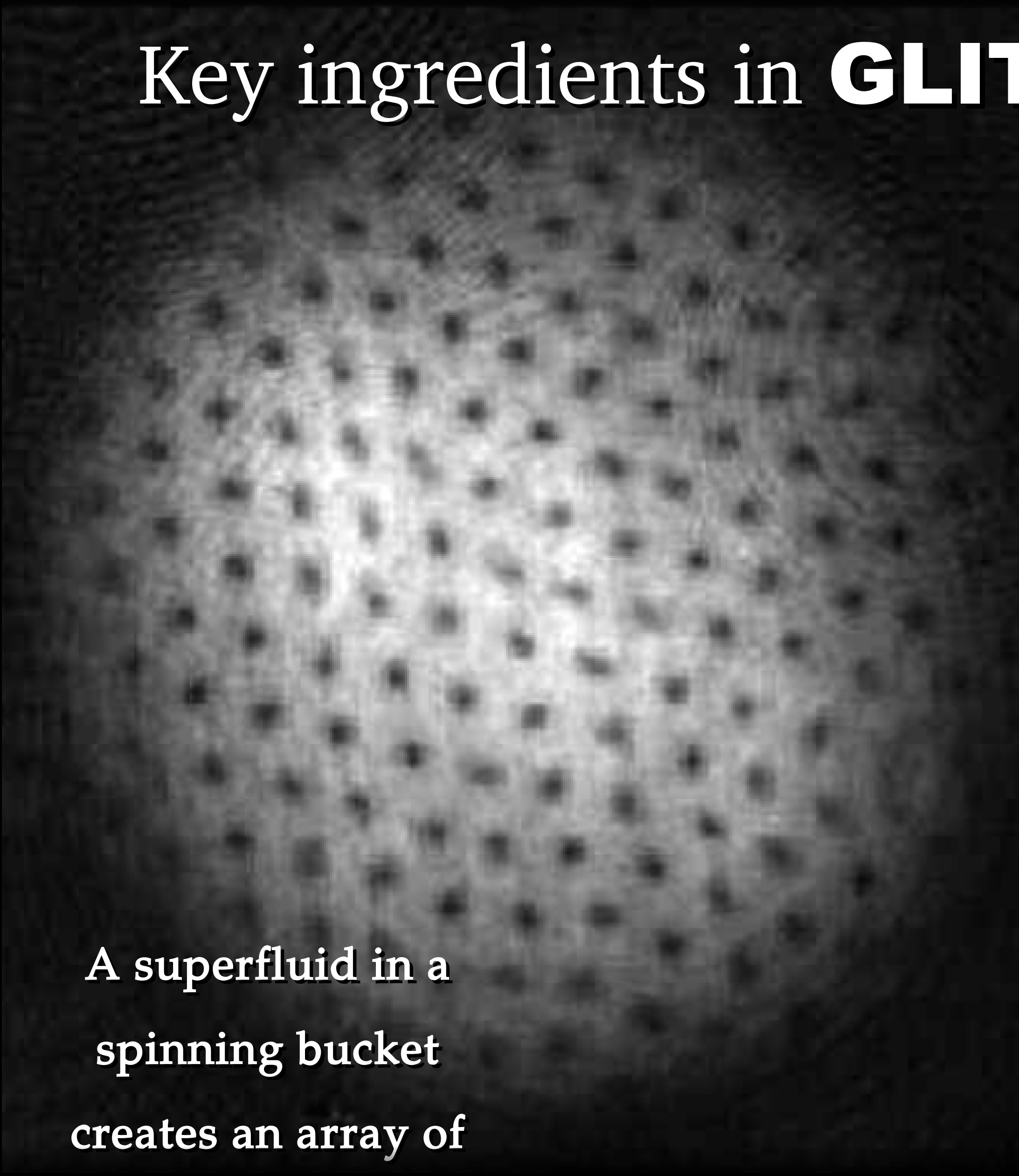


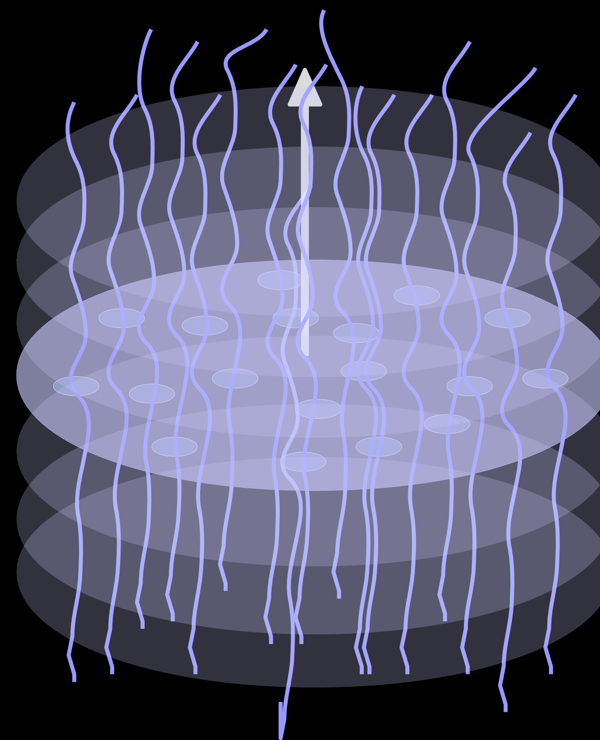
Two component "minimal" model

The inner crust & core contain a neutron superfluid (superfluid n-component)
Everything else (proton superconductor and electron gas) is locked with the solid crust into the magnetic field (rigid p-component)

Key ingredients in **GLITCH MODELS**



A superfluid in a spinning bucket creates an array of vortex lines that are parallel with the rotation axis



Each vortex line produces a microscopic irrotational velocity field…you can have macroscopic rotation but the domain of the velocity field is no more simply connected!

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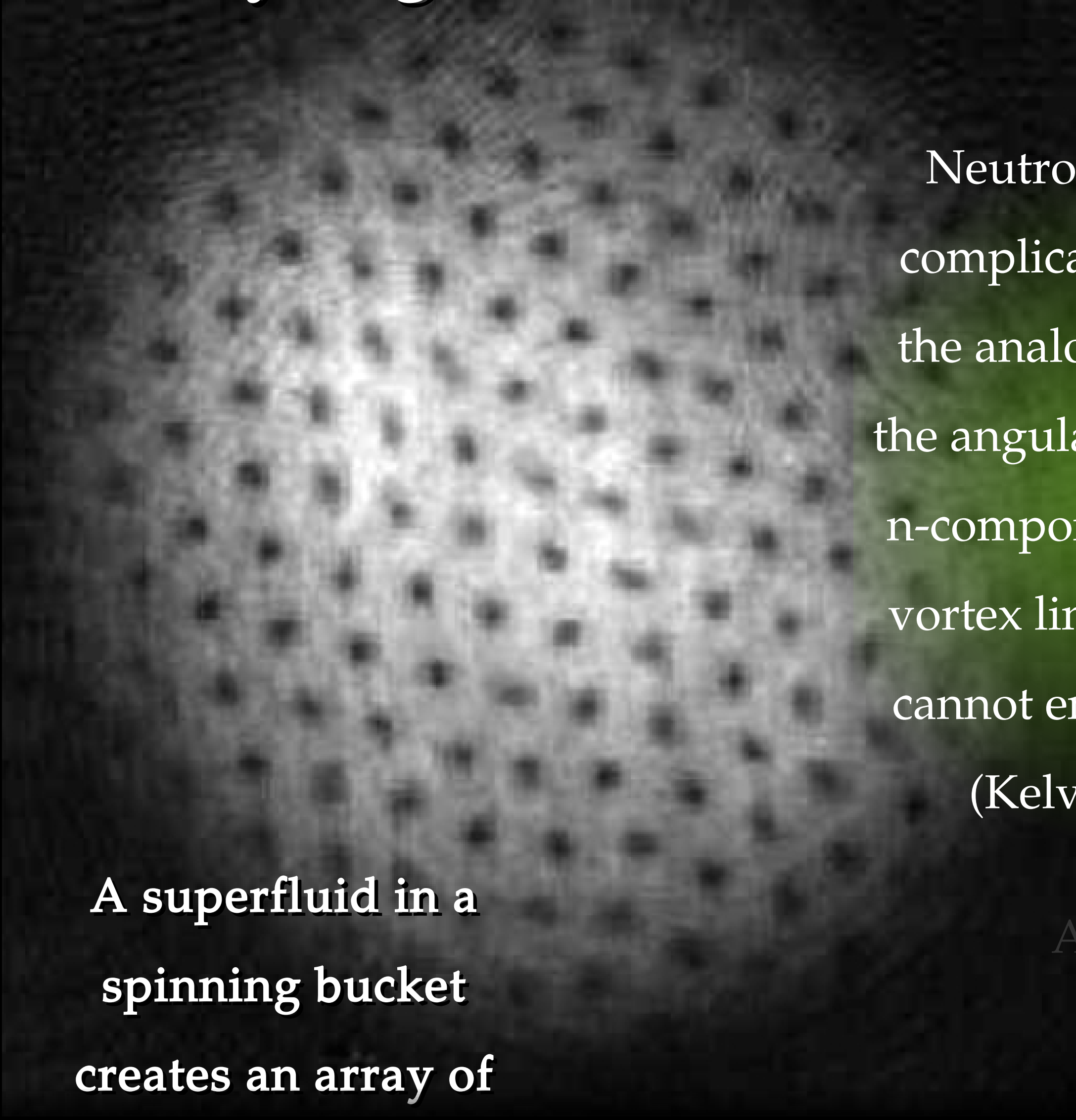
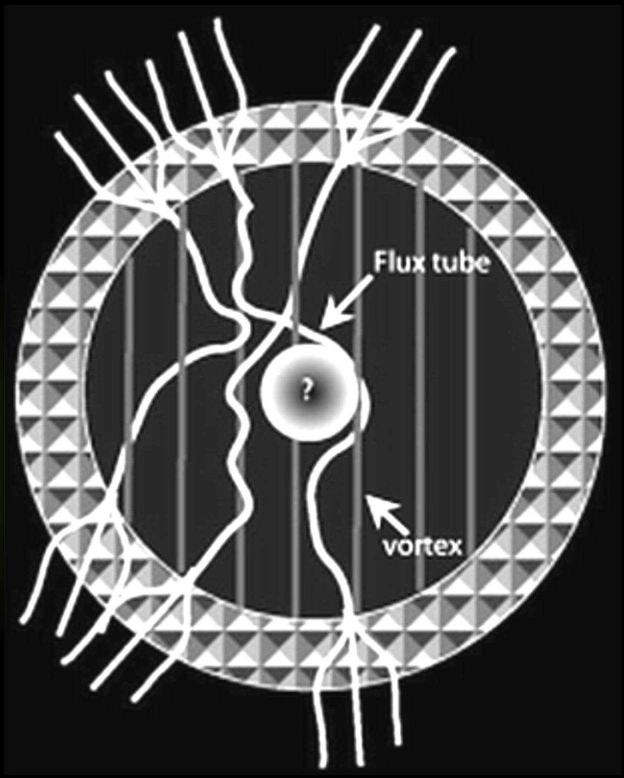
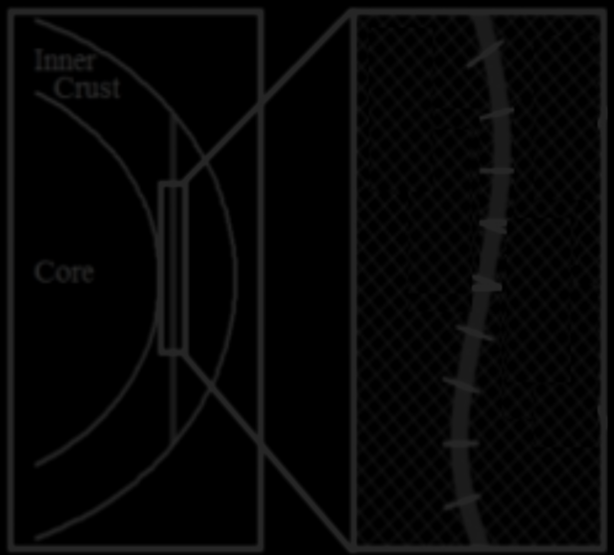


Neutron star → is a complicated system but the analogy is stringent: the angular momentum of n-component is stored in vortex lines. Vortex lines cannot end into the bulk (Kelvin theorem)



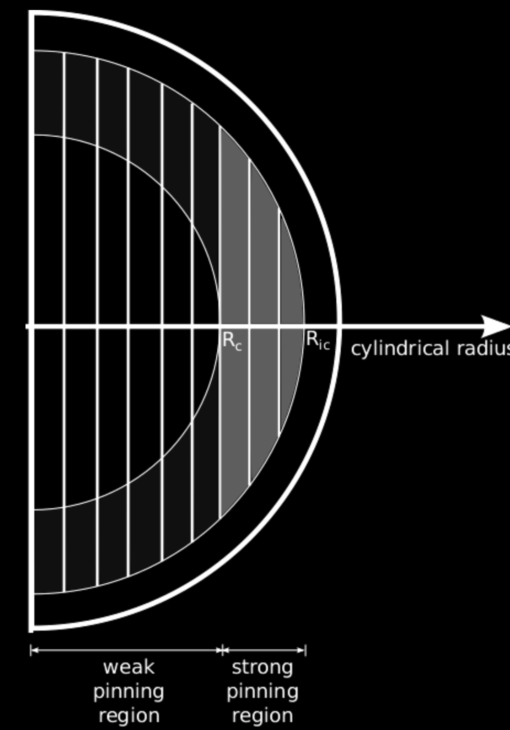
A superfluid in a spinning bucket creates an array of vortex lines that are parallel with the rotation axis

A vortex line can pin to nuclei or defects in the crustal lattice



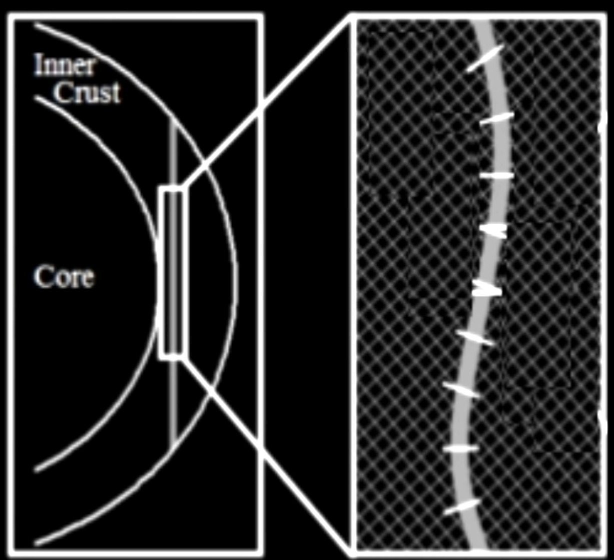
Key ingredients in **GLITCH MODELS**

Vortices pass trough the crustal lattice at their extremities...



Since the vortex core is normal (non-superfluid) it is energetically favorable to include normal matter (nuclei)

...and the line can pin to nuclei or defects (or interstitial vacancies)



Glitch mechanism in the **two component model**

- The p-component follows the observed spin down of the pulsar (the B field!)

- If vortex lines are pinned, the n-component cannot follow p…

  …a velocity lag builds up between n and p

- Hydrodynamical effect: when the Magnus force = pinning force

  the vortex line unpins and due to dissipation processes is expelled

  from the interior → n looses angular momentum, p gains the same amount

  UNPINNING: local → vortex creep | GLOBAL → GLITCH

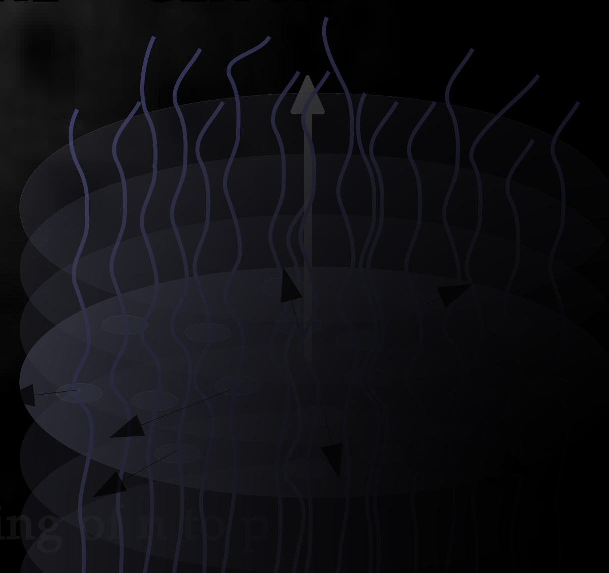
Simple facts: great ratio Ip / In → small glitches

Very efficient dissipation → fast spin-up

Mean inter glitch time ↔ spin-down rate

Post glitch increased spin-down

Long recovery timescale ↔ gradual re-coupling



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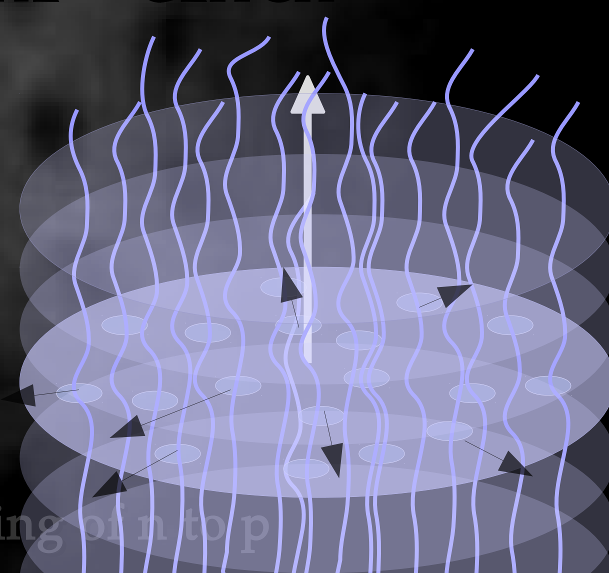

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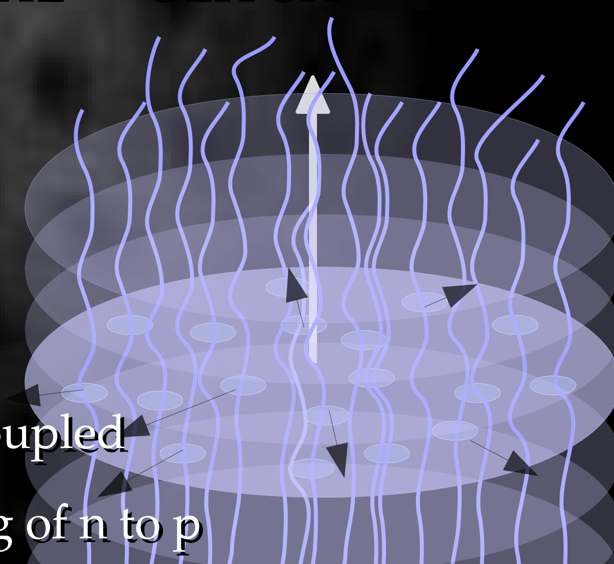
After the glitch: increased spin-down → n decoupled

Long recovery timescale ↔ gradual re-coupling of n to p



Use astrophysics to constrain nuclear physics

Neutron star masses can be deduced from binary dynamics.

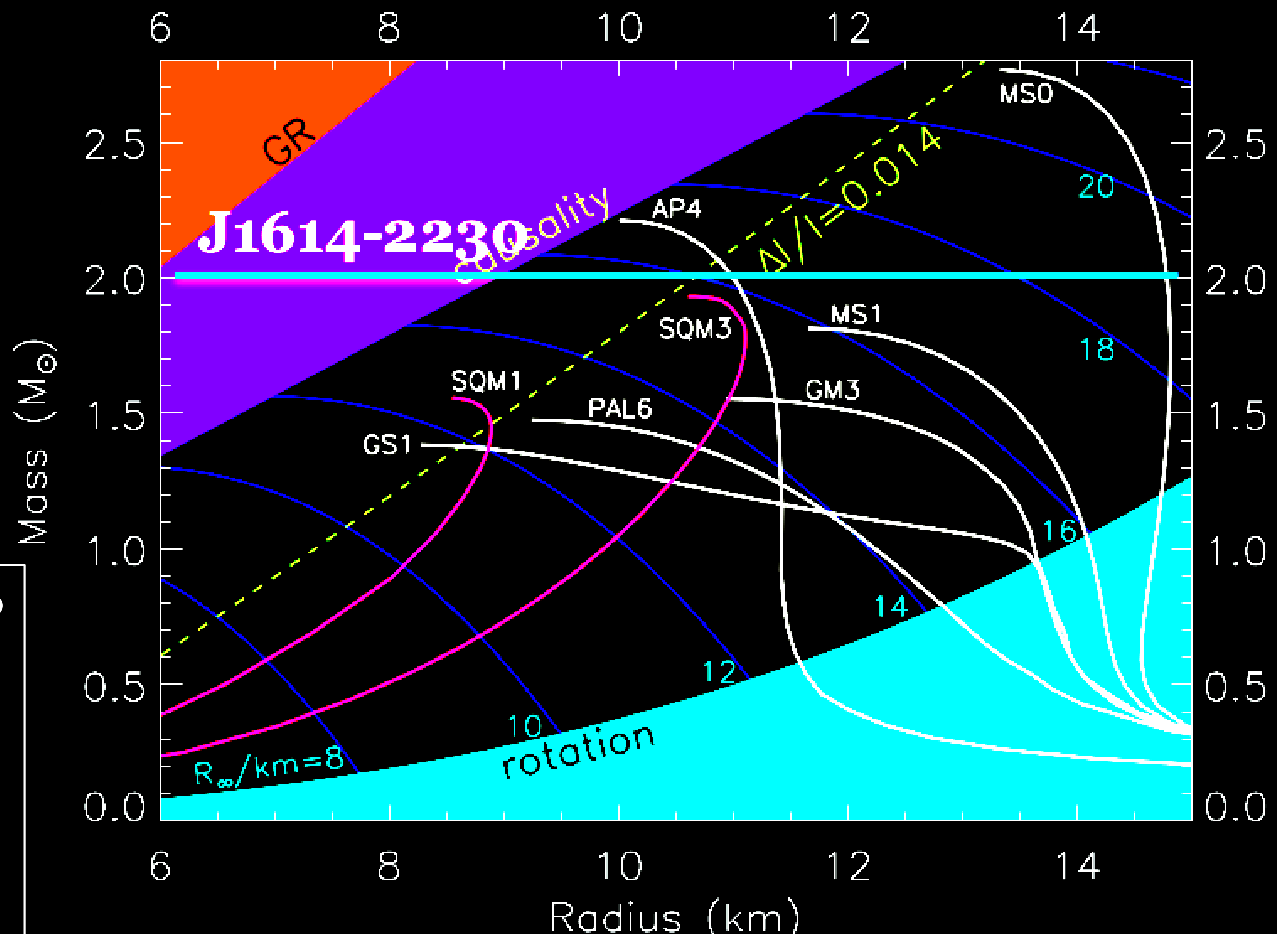
Inferred masses tend to lie in a relatively narrow range, around 1.4 solar masses. Most of these systems do not constrain nuclear physics (much).

The 3.15 ms pulsar J1614-2230 is an exception.

Observed Shapiro time delay yields edge-on inclination.

The inferred pulsar mass is **1.97 ± 0.04 $M_\odot$.**

Constrains the presence of softening components, like hyperons or deconfined quarks.



To date, glitch models and observations do not constrain M(R) relation... but we are fortunate that we have at disposition a steadily increasing set of timing data.

Next spin up resolution ?

PULSAR GLITCHES…
…& NS STRUCTURE

A good macroscopic model for pulsar glitches should explain:

- The great variety of observed behaviors for different pulsars

→ THE INTERNAL STRUCTURE PLAYS A ROLE !

→ try to identify the important quantities: M, B, T…

…that constitute the ID-card of the pulsar

- Glitches in a single pulsar…

…involve two different timescales: (fast) spin-up Vs (slow) recovery

…are not periodic! (Vela ~ QUASI periodic)

…can have different amplitudes and recoveries!

→ DYNAMICAL ASPECT OF THE PROBLEM !

- We cannot predict that a glitch is going to occur…

→ TRIGGER MECHANISM ? Proposals: starquake, fluid instability, SOC ?

PULSAR GLITCHES…
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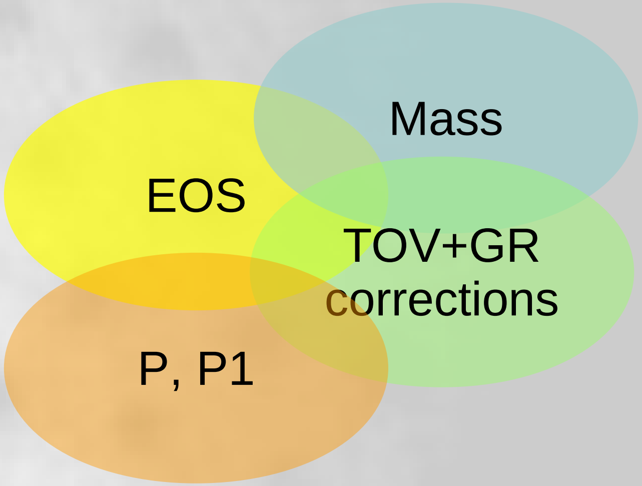

- Glitches in a single pulsar…
  …involve two different timescales: (fast) spin-up Vs (slow) recovery
  …are not periodic! (Vela ~ QUASI periodic)
  …can have different amplitudes and recoveries!
  → DYNAMICAL ASPECT OF THE PROBLEM !

Dynamical simulations

- Glitches are manifestations of a vortex avalanche… SOC?

“Hydro” code cannot handle this!

PULSAR GLITCHES...

...& NS STRUCTURE

A good macroscopic model for pulsar glitches should explain:

- The great variety of observed behaviors for different pulsars

→ THE INTERNAL STRUCTURE PLAYS A ROLE !

→ try to identify the important quantities: M, B, T...

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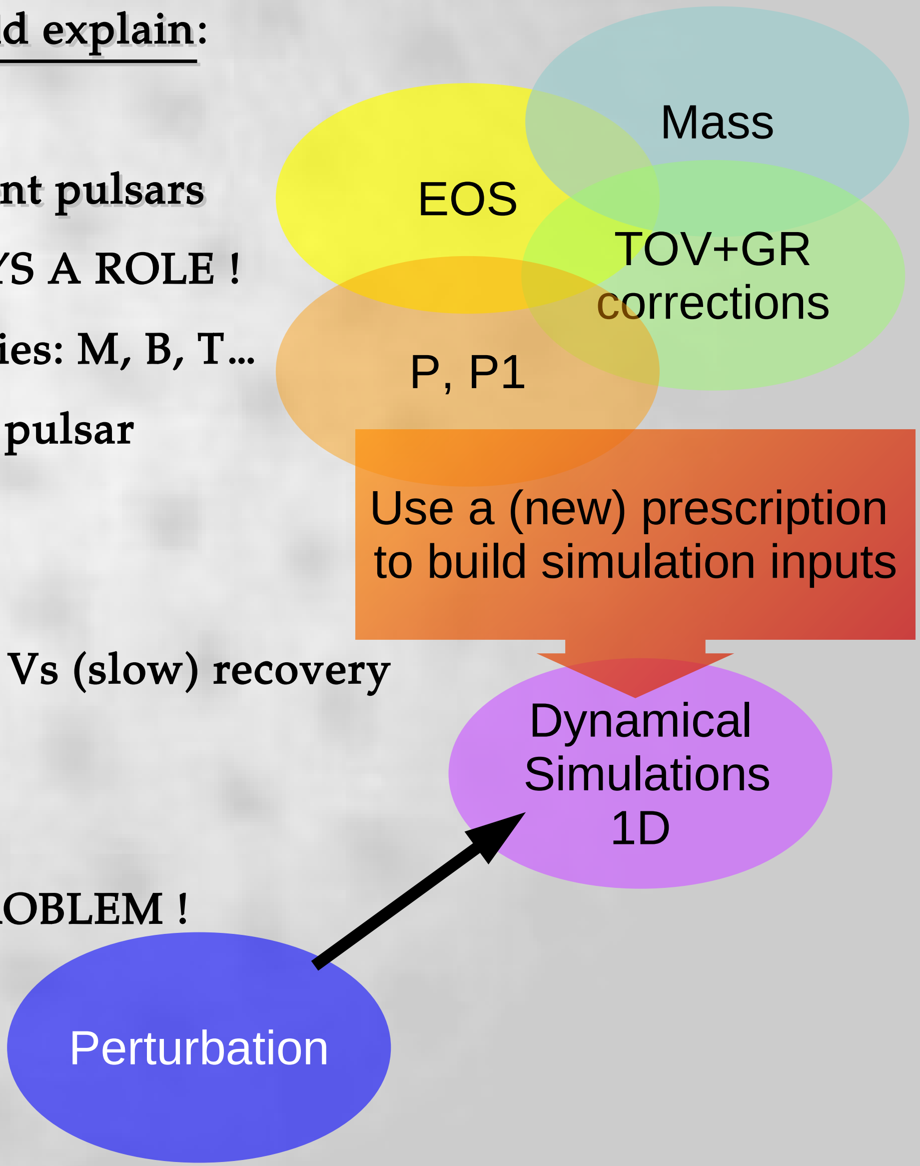

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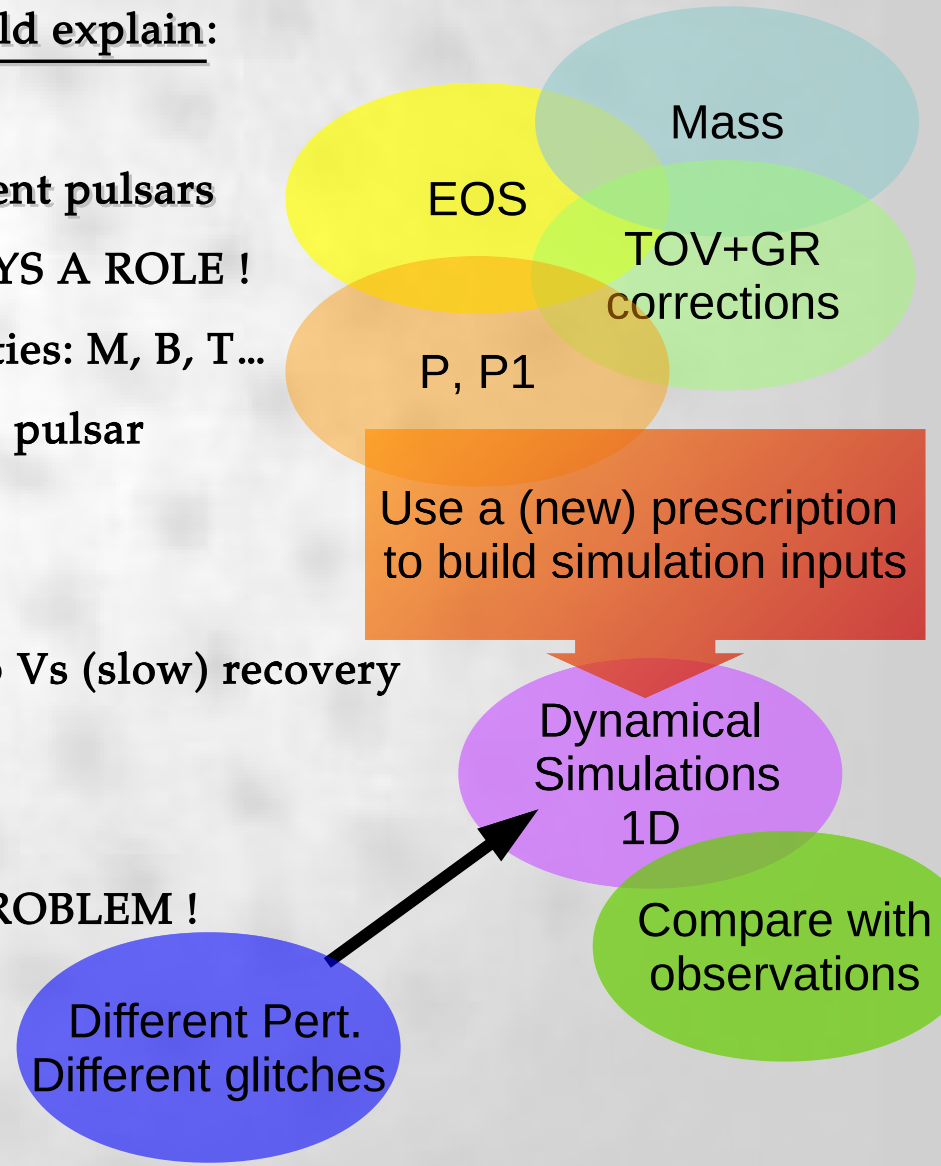

Conclusions & a little summary ;-)

A "neutron star" is the theoretical model that provides the natural scenario for our current understanding of pulsar phenomenology, from the pulse emission to timing irregularities, but also cooling observations :-)

The physical properties of NS are determined by the physics of dense and cold (degenerate) matter → unique possibility to study certain phases of the hadronic matter and the corresponding EOS :-)

Glitches → indirect way to probe NS structure(s)!

Strong clue for neutron superfluidity (this is widely accepted) :-)
Glitch modeling needs quite refined descriptions of the NS crust :-|
Trigger and dynamical aspects of vortex lines :-(

We need global and realistic models for the NS rotational dynamics,

our hope :-(→ :-|

Our model: → it's a simple way to account for many realistic aspects of NS :-)
→ fast spin-up and slow relaxation + glitch amplitude :-)
→ no vortex-vortex interaction :-|
→ axial symmetry of vortex configuration :-|
→ repinning of vortex lines (poorly understood) :-(
→ everything about vortex reconnection & vortex interactions :-(

For details: M. Antonelli, P. Pizzochero "Global equations with entrainment for differential pulsar rotation"

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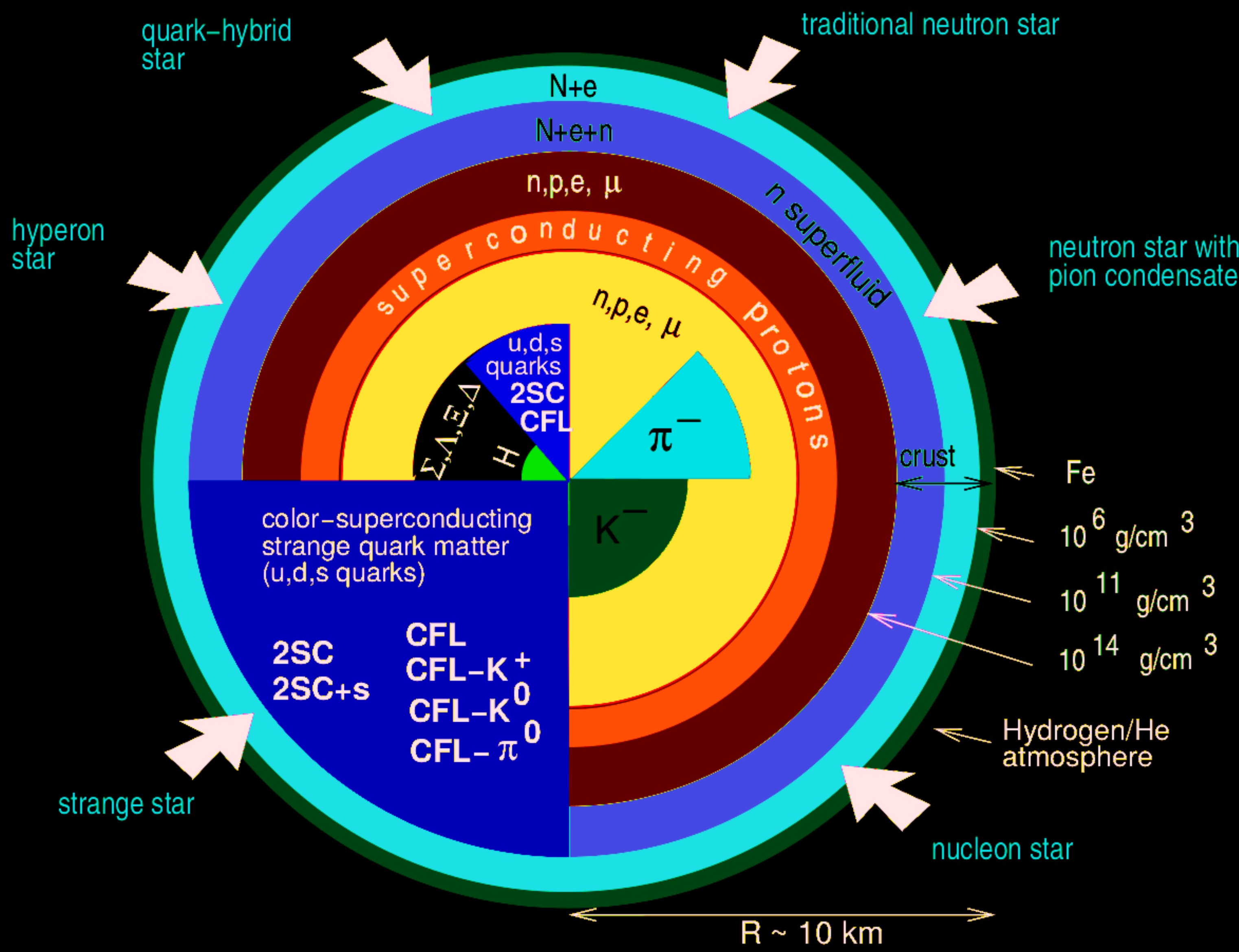
Thanks for your attention!
Questions ?

Neutron star's **PHYSICS:**

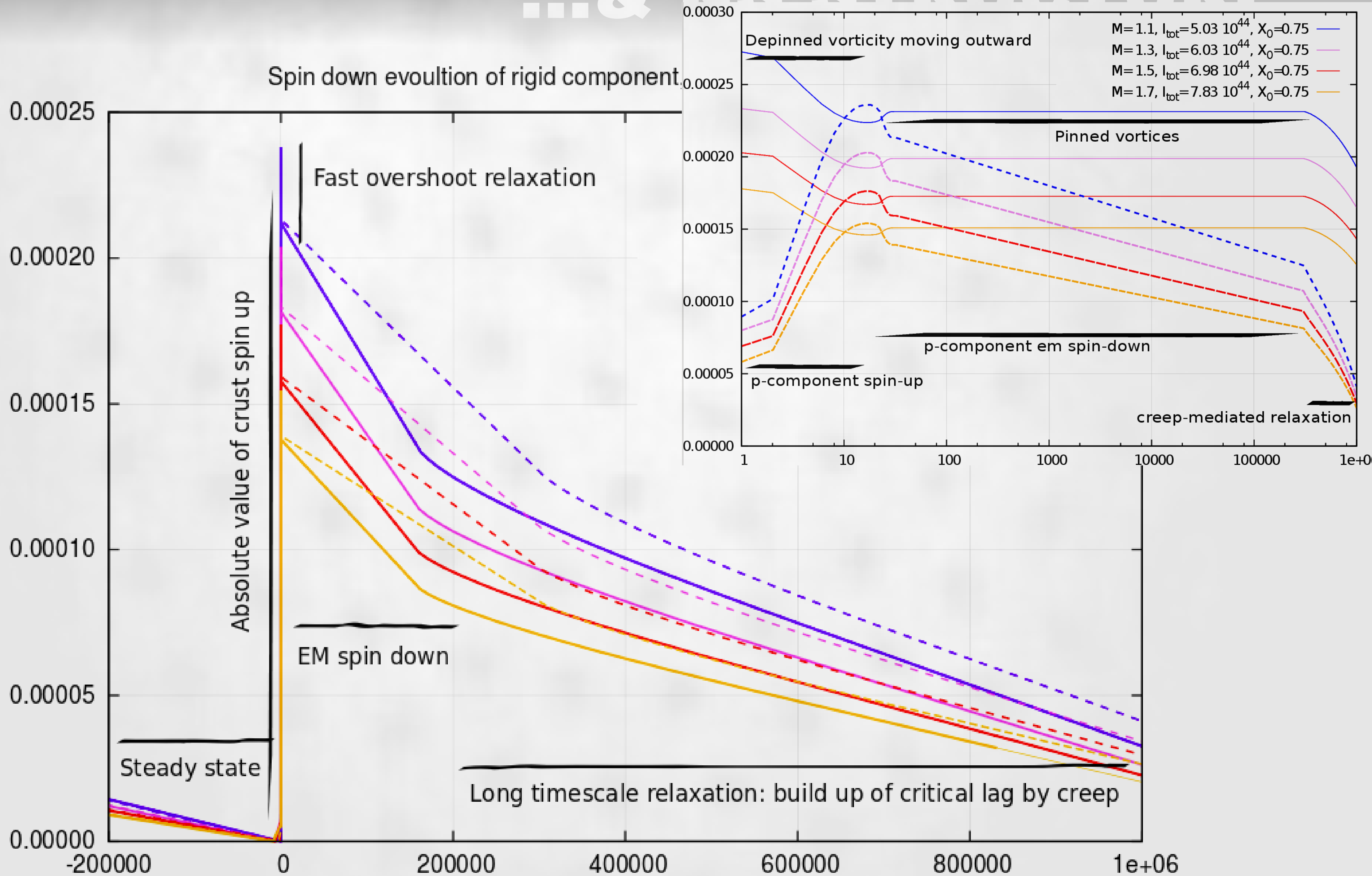
the stellar structure



Neutron star crust ~ 1% mass, 10% radius

PULSAR GLITCHES…

…& NS STRUCTURE



What is a **PULSAR** ?

To date, more than 2300 pulsars have been identified, mostly in the radio band.

Some properties:

The period range: $P \sim 1.4$ ms $\rightarrow$ PSR J1748−2446ad

$P \sim 8.5$ s $\rightarrow$ PSR J2144−3933

P increases gradually with time at a rate given by

$$10^{-19} \lesssim P1 = dP/dt \lesssim 10^{-12}$$

Note: $P1 \sim 10^{-16} \rightarrow$ delay of 1 second every 300 millions years (atomic clocks precision)

Millisecond pulsar $\rightarrow$ pulsar clock

(But not really better than atomic clocks)

Each pulsar has a specific pulse profile $\rightarrow$ "pulsar fingerprint"

Individual pulses vary dramatically. But the average is stable.

We can infer B as (dipole model): $B^2 \sim P\, P1$ (sanity check provided by P2)

GIANT GLITCHES:

The clue for the vortex avalanche

Starquake: the rigid crust has to support stresses during the spin-down.

Suddenly the crust cracks: $I \rightarrow I - dI$ (little change in the moment of inertia)

Conserve angular momentum: $d\nu / \nu = dI / I \sim 2\, dR / R$

We observe $d\nu / \nu \sim 10^{-6}$ $\rightarrow$ for $R \sim 10$ km we have $dR \sim 1$ cm…

In energy terms, analogy with our planet:

– earthquake of 17 on Richter scale

– surface of the Earth moves by 15 m

BUT: modern astroseismology → maximum amplitude for a vibrational mode ~ 0.1 cm

… and for "static" mountains even less! → Giant glitches are hardly explained by starquakes

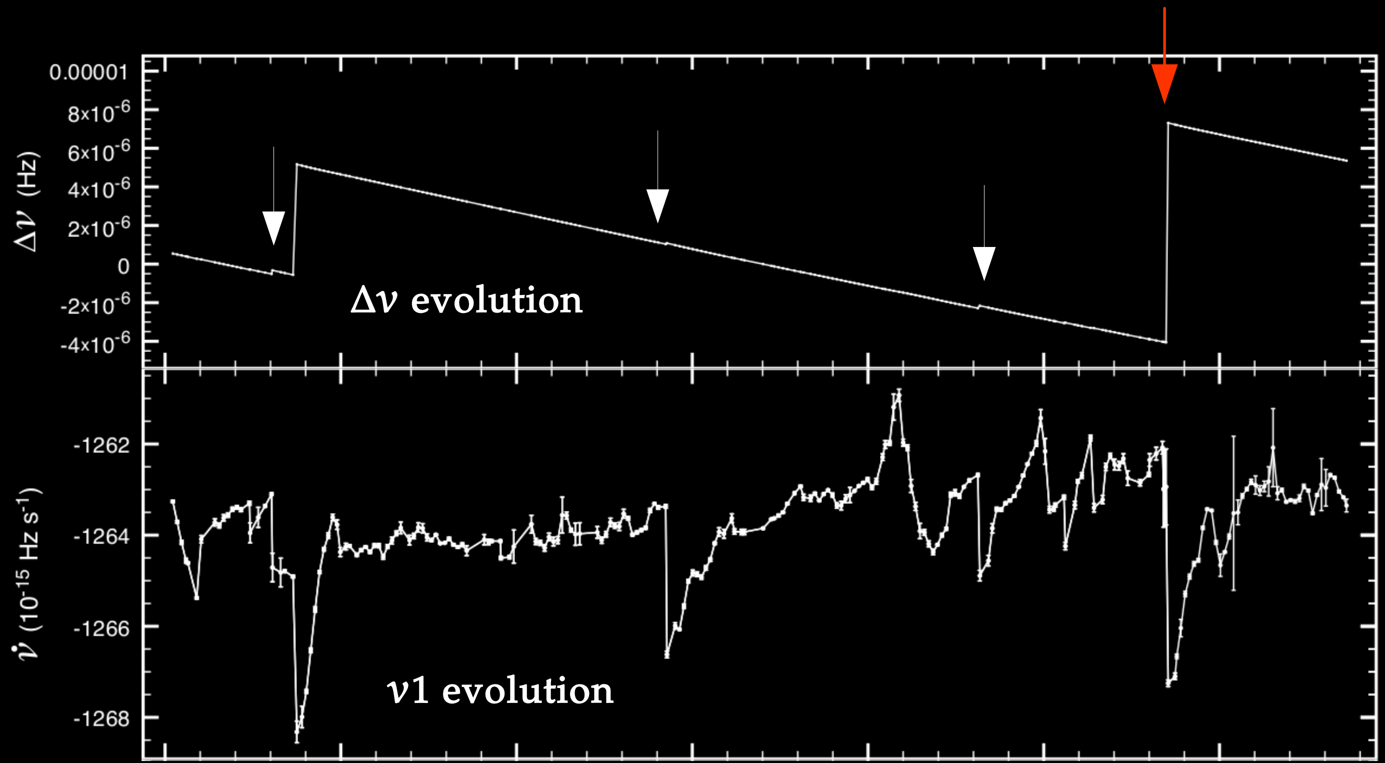
Statistical study:

Distribution of glitch size → power law

Distribution of waiting times → Poissonian

Analysis of the glitch population (~ 285 events from 101 pulsars) demonstrates that the size distribution in individual pulsars is consistent with being scale invariant, as expected for an avalanche process.

Example of a sequence of glitches in the young pulsar **PSR J0631+1036**



Window of observations ~ 20 yrs

Glitches: appear as sharp spin-ups in frequency, superimposed on the long-term spin-down.

← **Frequency residuals $\Delta\nu$**

← **The evolution of the spin-down rate $\nu 1$**

Timing noise is observed in the scattered $\nu 1$ plot, where variations greatly exceed their statistical errors.

(from Espinoza)

$P \sim 0.29$ s ↔ $\nu \sim 3.47$ Hz

$P1 \sim 1.05 \cdot 10^{-13}$ ↔ $\nu 1 \sim -1.26 \cdot 10^{-12}$ Hz/s

$\Delta\nu \sim 10^{-7}$ Hz (small events indicated by arrows)

$\Delta\nu \sim 8 \cdot 10^{-6}$ Hz (red arrow)

Condensed **HISTORY** of **neutron stars**

1931 → Landau, Bohr and Rosenfeld discussed the existence of stars as dense as atomic nuclei

1932 → the neutron was discovered by James Chadwick.

1933 → Baade and Zwicky predicted the existence of neutron stars as supernova remnants:

"With all reserve we advance that supernovae represent the transition from ordinary stars into neutron stars, which in their final states consist of extremely packed neutrons."

1937 → Gamow and Landau: accretion of matter onto a dense neutron core as a possible stellar energy source BUT very soon it was shown that stars are powered by thermonuclear reactions.

1939 → Tolman, Oppenheimer and Volkoff → equations for static spherical stars in GR.

'50s → Wheeler constructed the first realistic EoS of dense matter.

1959 → Migdal predicted NS superfluidity.

1967 → Franco Pacini: a NS can power the Crab nebula and could explain Hewish and Bell observations.

1969 → Radhakrishnan observed beamed radiation and the first glitch (both in Vela).

1971 → Second glitch in Vela ruled out Ruderman's idea of crustquakes.

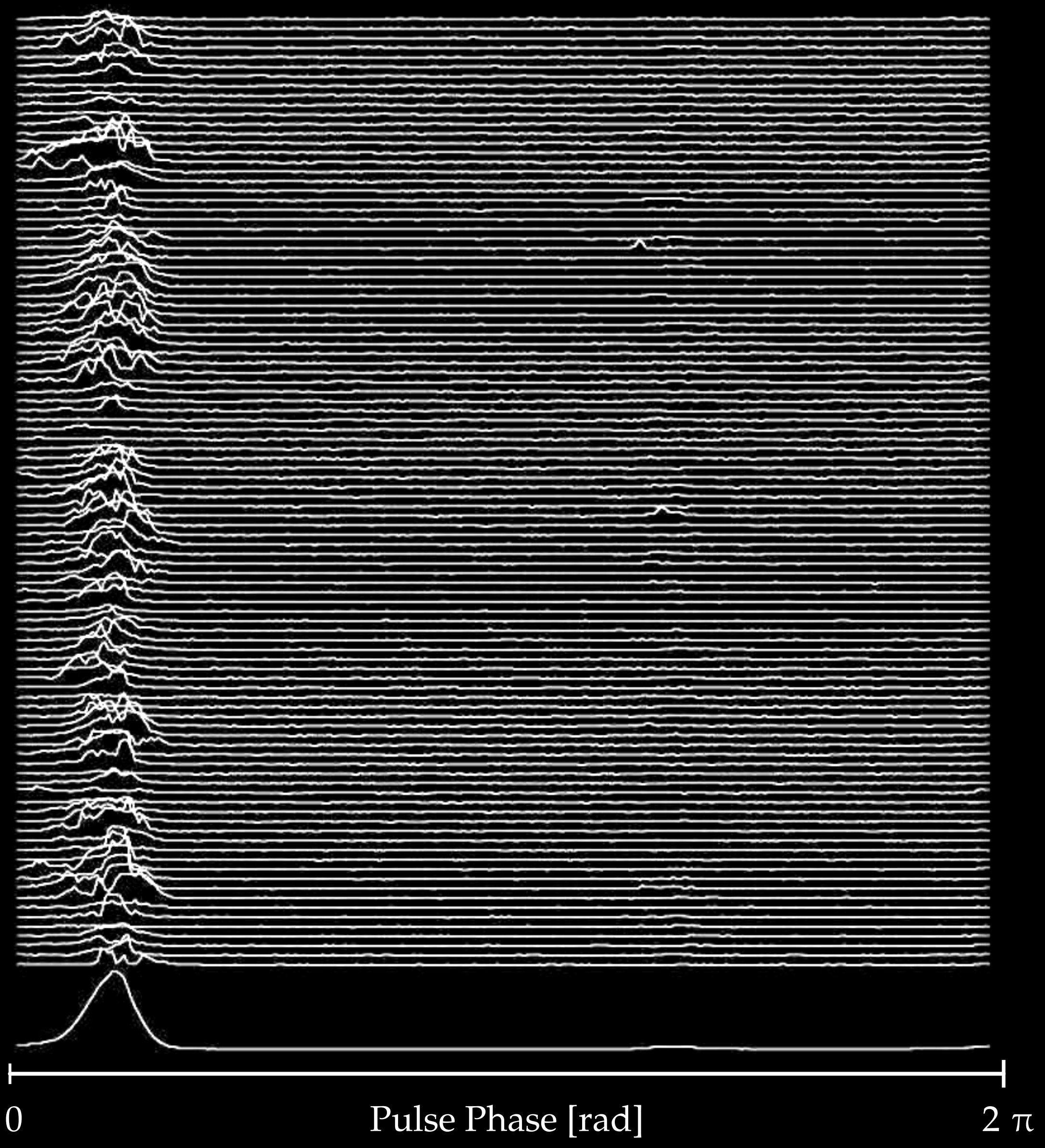
1975 → Anderson & Itoh: seminal idea that glitches are triggered by the sudden unpinning of superfluid vortices in neutron-star crust.

Pacini

Baade

Zwicky

Pulse shape: the pulsar **FINGERPRINT**



This is what you have to know if you like to listen to Joy Division:

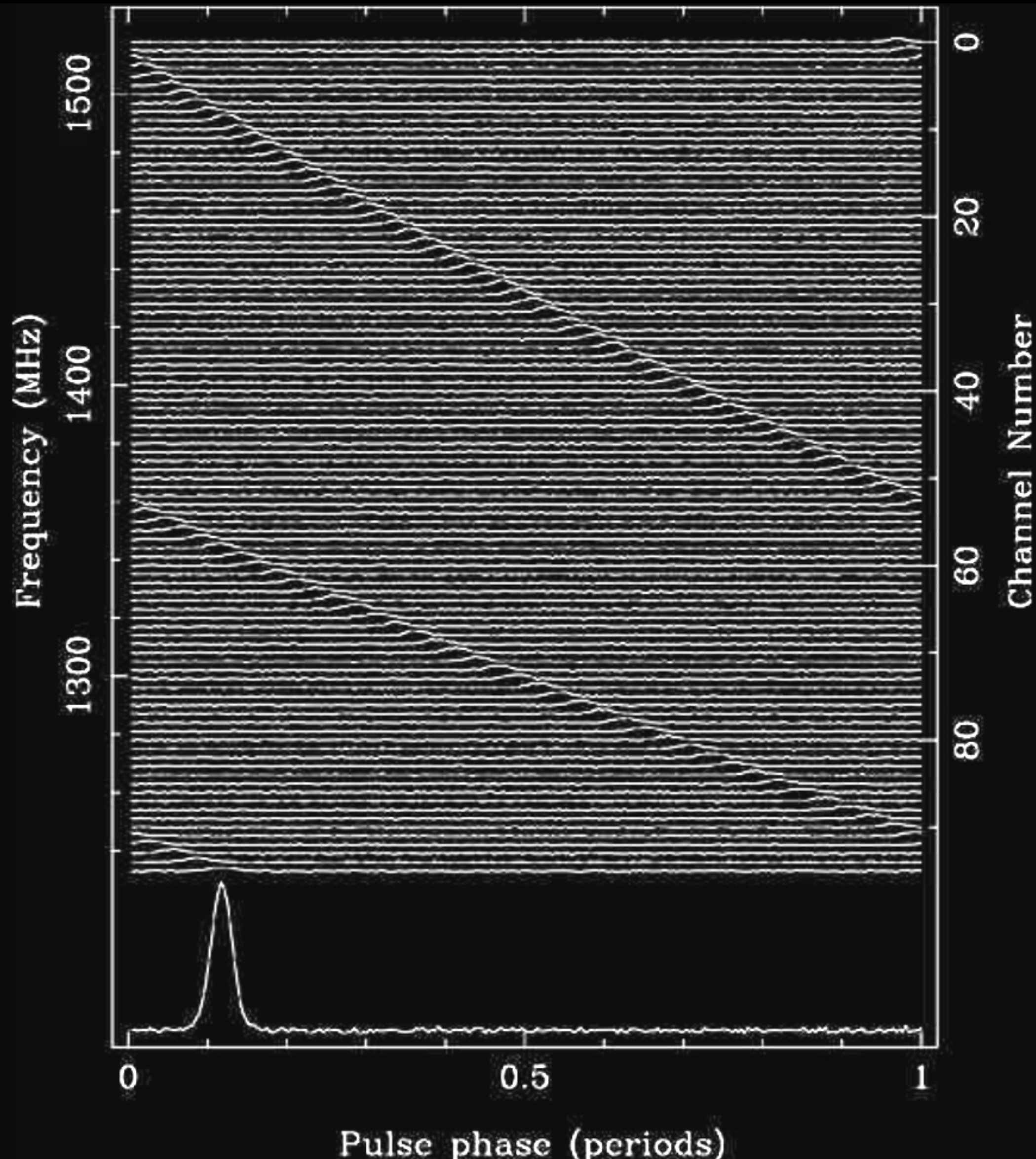
The individual pulses vary dramatically. But the average over many pulses is remarkably stable and is specific to the pulsar.

Here you have 100 single pulses from the pulsar PSRB0950+08

← **The pulse profile averaged over 5 minutes**

(~ 1200 pulses)

Pulse **DISPERSION**

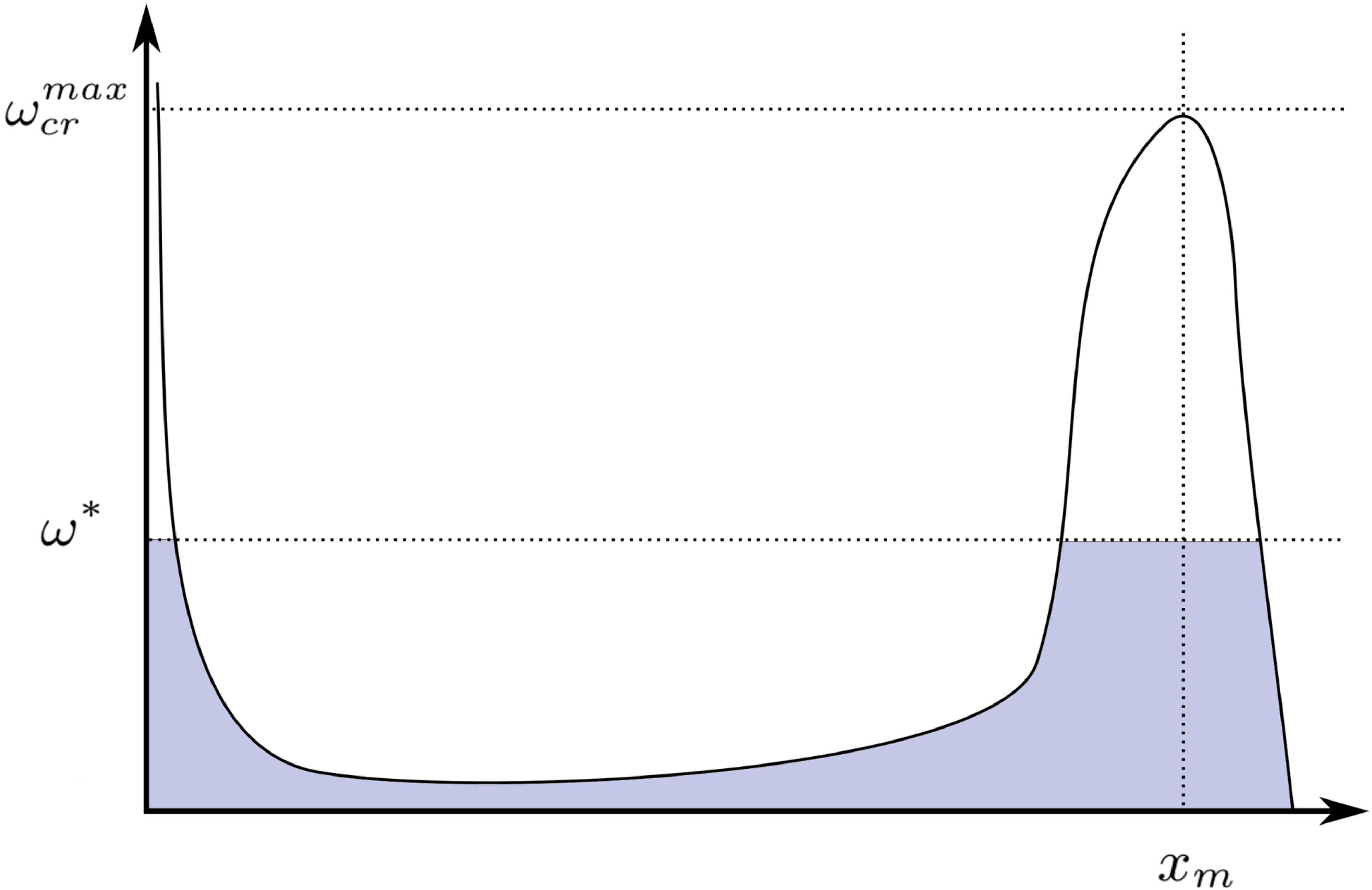


Pulses emitted at **lower EM frequencies** arrive **later** than those emitted at higher EM frequencies due to electrons in the interstellar medium.

→ we can measure the difference in arrival times !

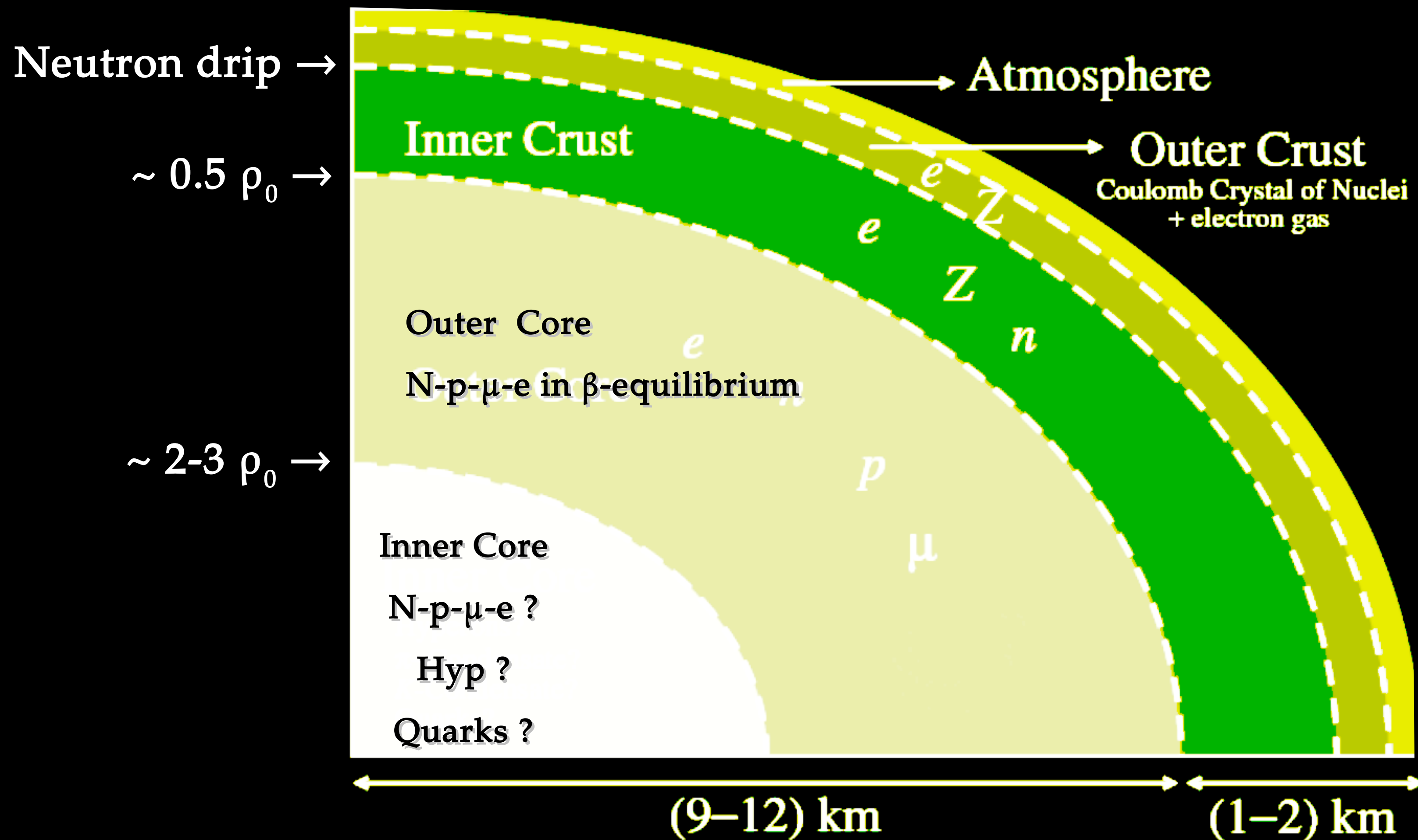
This can be used to infer the distance of the source.

You need to know the density of interstellar electrons integrated along the signal trajectory (the dispersion measure).



ω_{cr}^{max}
ω^*
x_m

Neutron star's **STRUCTURE** (without details!)

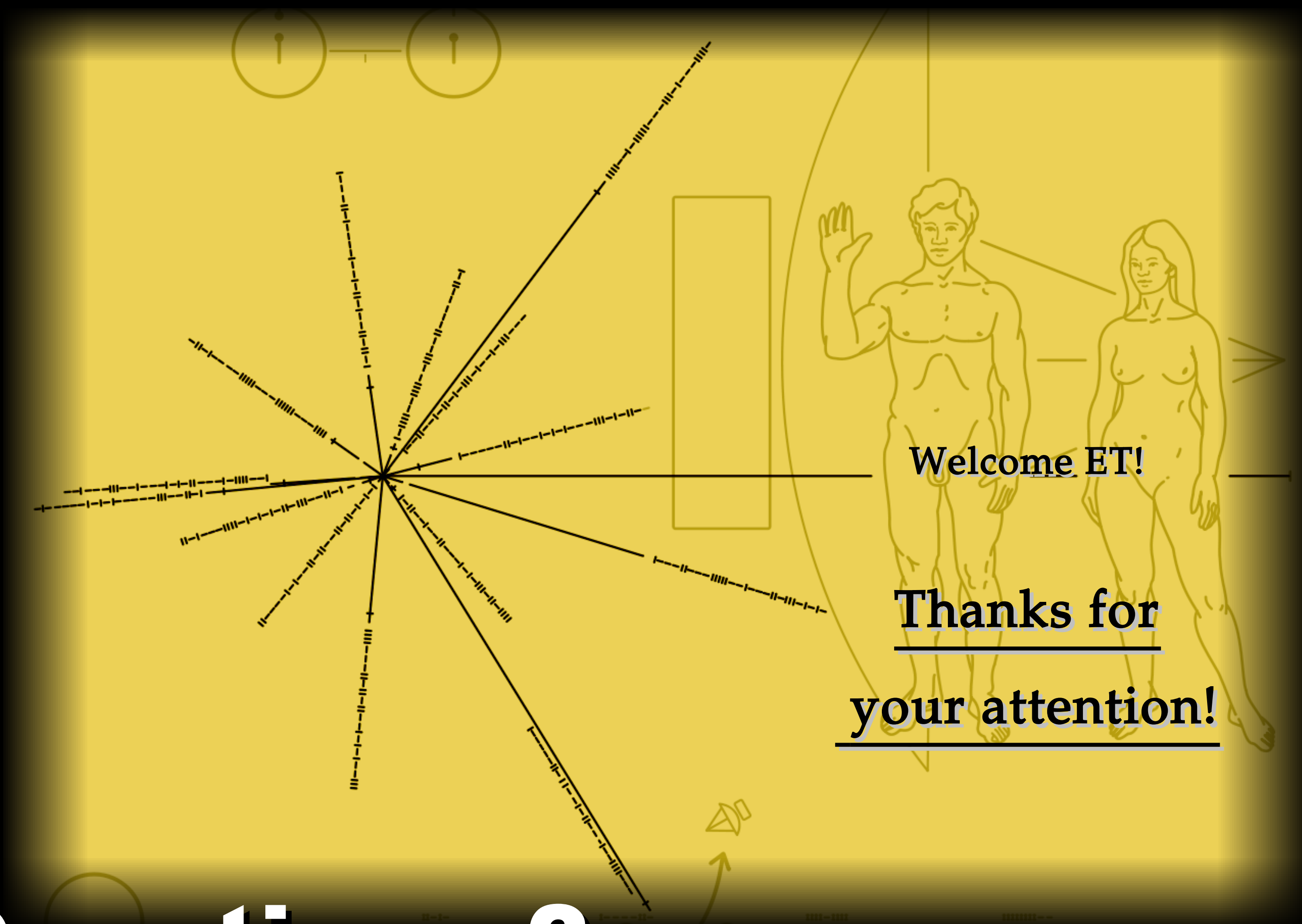


1-2 solar mass compressed inside a radius of about 10 km, a neutron star represents much extreme physics that cannot be tested in the laboratory.

Pulsar maps have been included on the two Pioneer Plaques.

Here we have the position of the Sun, relative to 14 pulsars...

... that are identified by their unique timing.



Welcome ET!

Thanks for your attention!

Questions ?