Dense matter physics from observations of neutron star cooling and dynamics

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ACFI workshop – 2022 October 13–15

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Outline

- Neutron star in Cassiopeia A supernova remnant
  - from X-ray spectra:
    - mass–radius *M*–*R*
    - temperature *T*
  - cooling constraints on *core* superfluid and superconductor

- Fastest young pulsar PSR J0537–6910
  - spin-down interrupted by spin-up glitches
    - from only glitch data: mild constraints on *crust* superfluid and nuclear EOS
    - with X-ray or age data: strong constraints on *crust* superfluid and mass *M*
  - multi-messenger: EM spin-down suggests GWs from r-mode

- Summary and a few other examples of physics from pulsar dynamics

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Cassiopeia A supernova remnant and neutron star

Chandra graded
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov

- ≈1680: supernova (age ≈ **340 yr**; Fesen+2006) at distance ≈ 3.3 kpc (Alarie+2014)
- 1999: **non-pulsed** X-ray source discovered in *Chandra* first light (Tananbaum)
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- 2011: rapid cooling due to **superfluid+superconductor** (Shternin,WH+; Page+)

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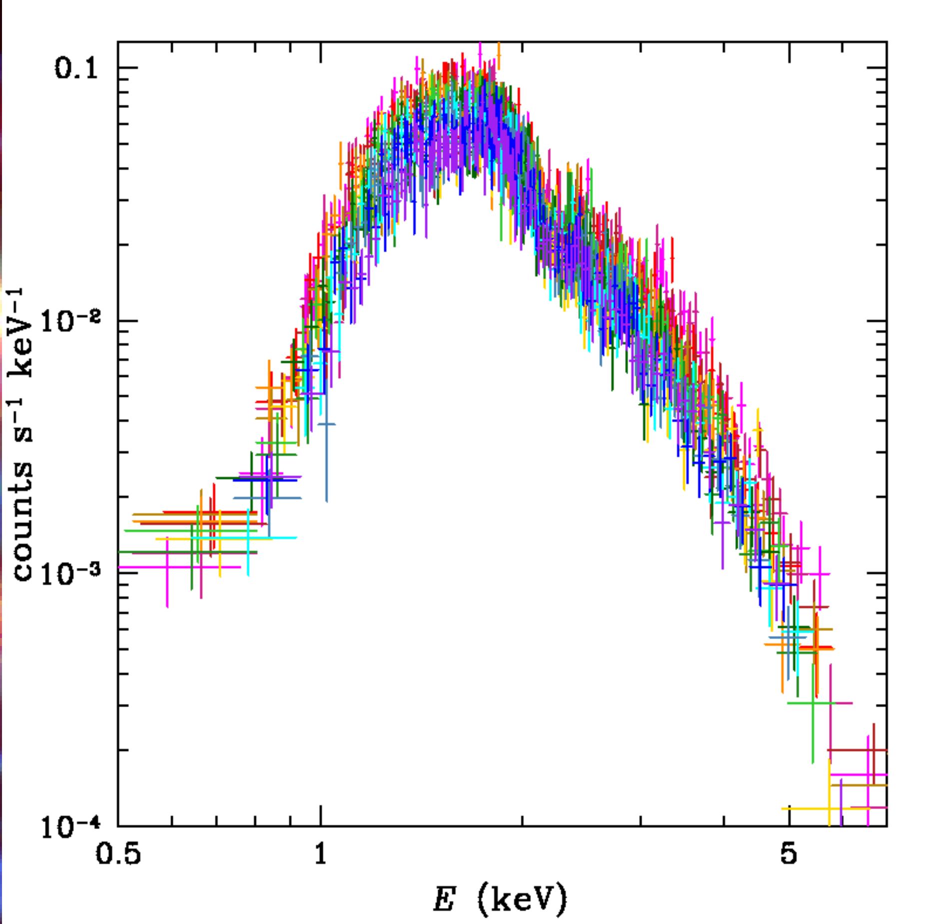
Chandra subarray

- 2006 Oct
- 2012 May
- 2015 Apr
- 2020 May



Fit X-ray spectra with model spectrum:

- interstellar absorption N_H
- neutron star atmosphere d, M, R, T

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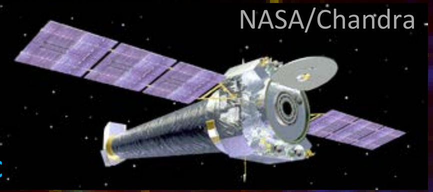
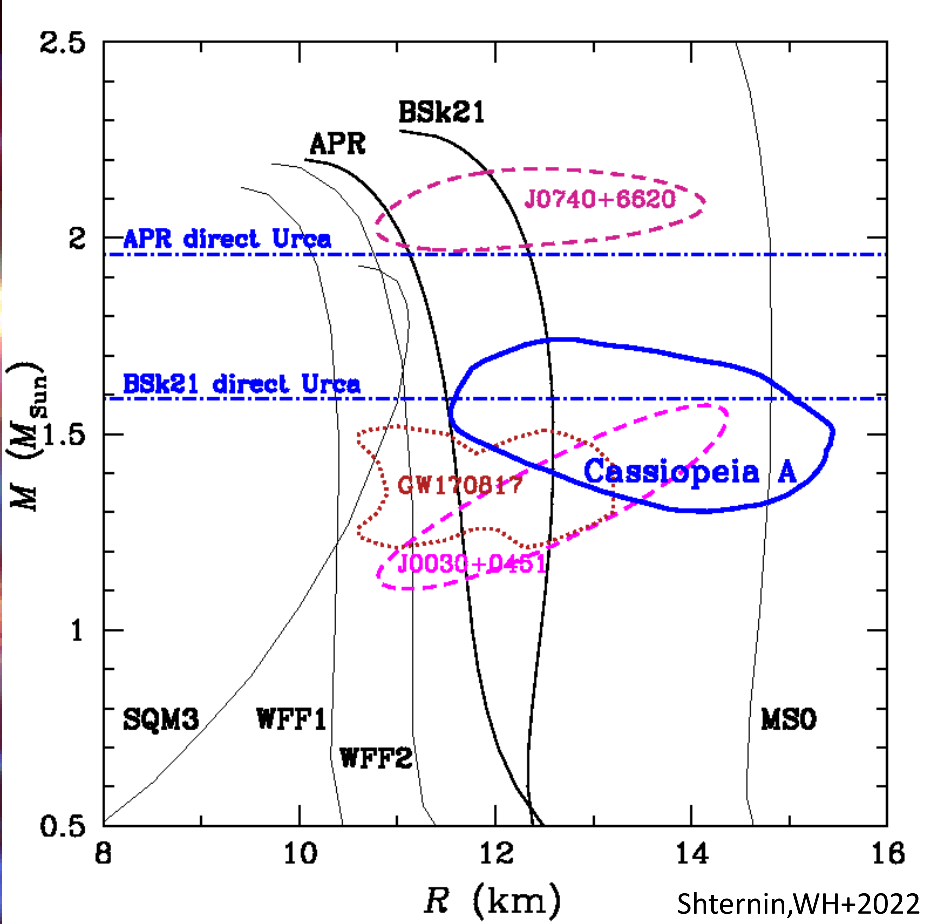

NASA/Chandra



Shternin,WH+2022

Fit X-ray spectra with model spectrum:
- interstellar absorption N_H
- neutron star atmosphere *d*, ***M***, ***R***, *T*

Mass upper limit due to measured flux
- EOS-dependent fast cooling (direct Urca)

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Cooling of Cassiopeia A neutron star

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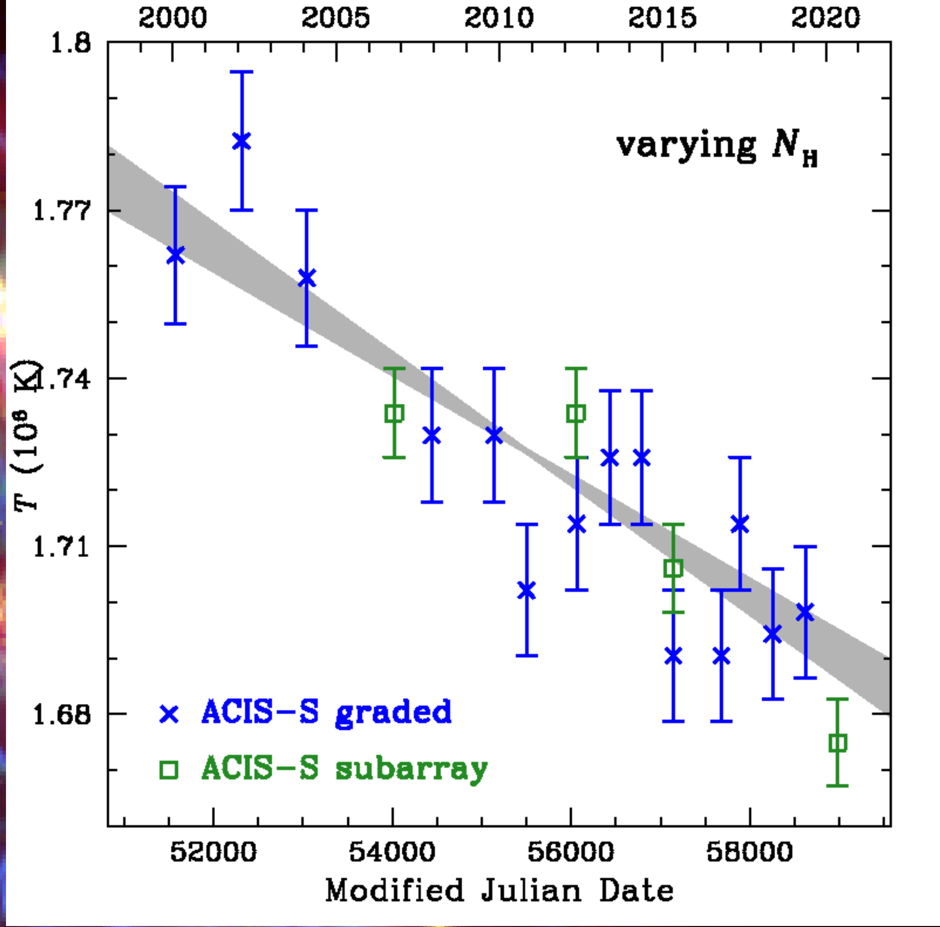
NASA/Chandra



Fit X-ray spectra with model spectrum:
- interstellar absorption **N_H = variable**
- neutron star atmosphere *d*, *M*, *R*, ***T***

- 18 *T* over 20 years: cooling rate 1.6 ± 0.2% or **2.2 ± 0.3%** per decade [Shternin,WH+2022]
  - 14 *T* over 19 years: cooling rate 2.2 ± 0.2% or 2.8 ± 0.3% per decade [WH+2021]
  - 4 *T* over 14 years: 1.5 ± 0.3% or 2.3 ± 0.4% [Posselt+Pavlov 2022]

Cassiopeia A on superfluidity and superconductivity

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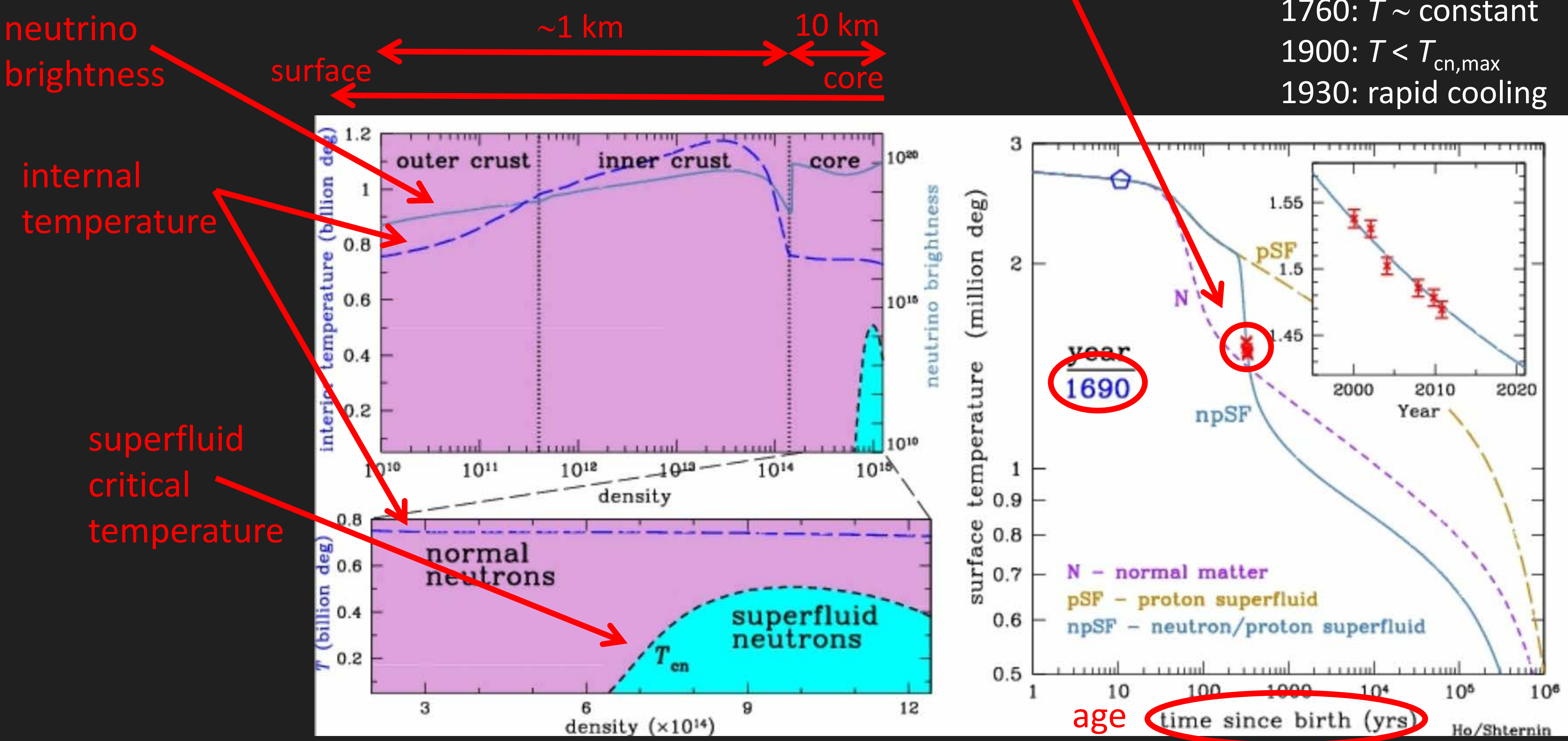
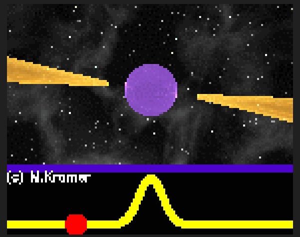
<ins>Milestones</ins>:
1680: supernova
1690: $T_{core} < T_{crust}$
1760: $T \sim$ constant
1900: $T < T_{cn,max}$
1930: rapid cooling



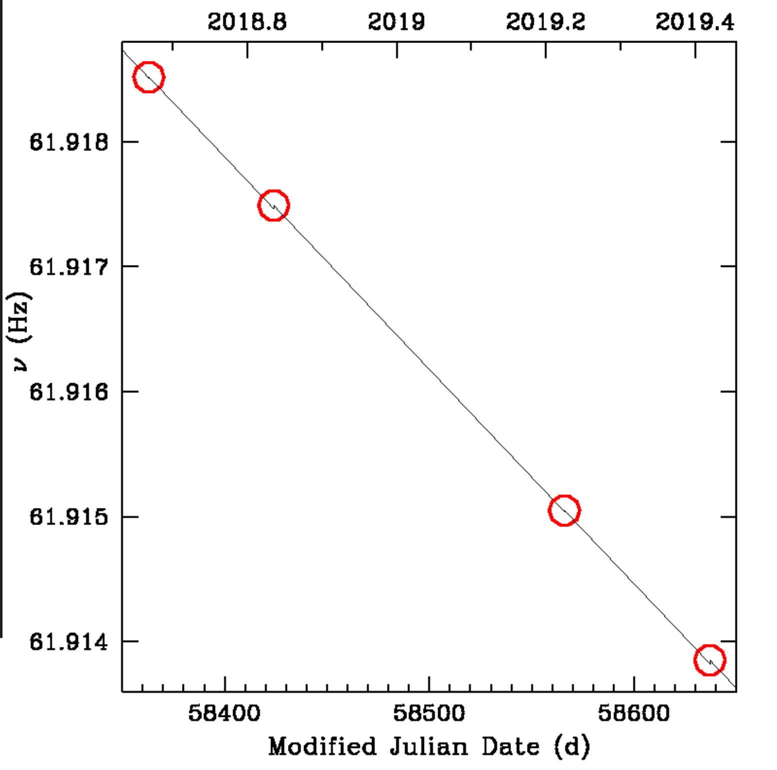
PSR J0537–6910

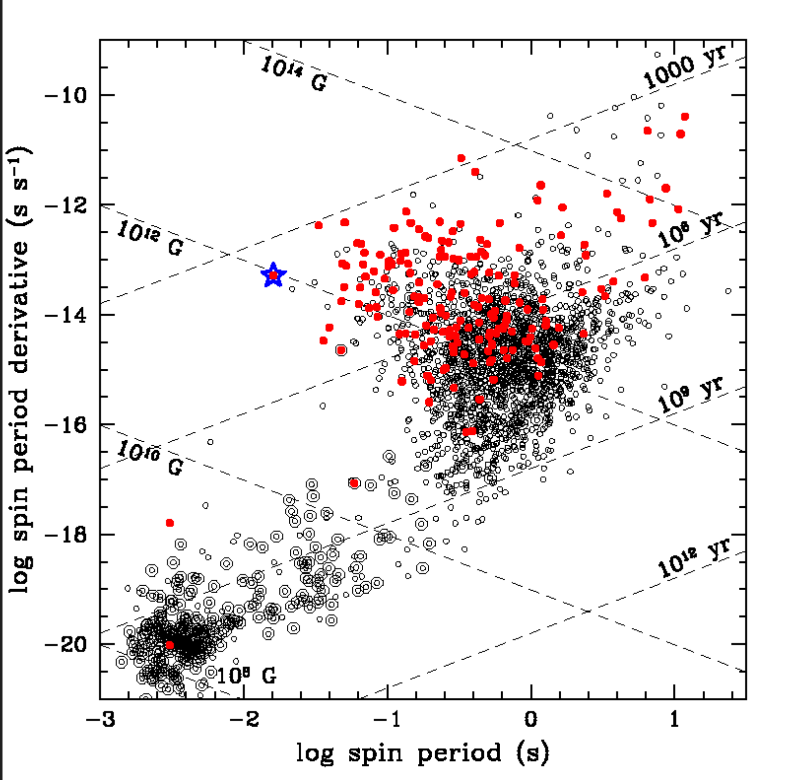
- Spin period $P = 16$ ms ($\nu = 62$ Hz) only in X-ray
- 1–5 kyr supernova remnant N157B in Large Magellanic Cloud
  $\Rightarrow$ fastest-spinning young pulsar



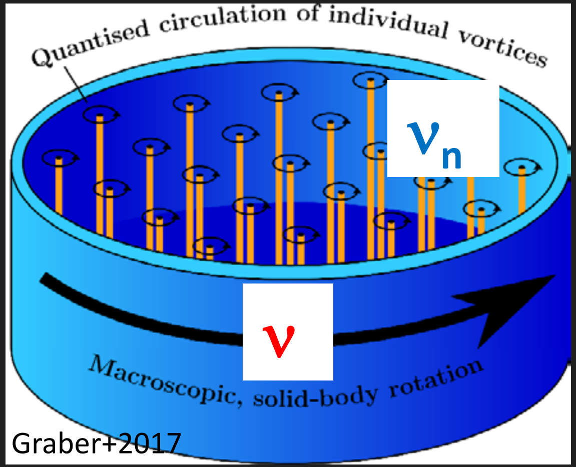
- also known as the Big Glitcher
  - 45 glitches in 13 years with *RXTE* (1999–2011)
  - 17 glitches in 5.2 years with *NICER* (2017–2022)
  - glitch rate > 3/yr

- Braking index $n = \ddot{\nu}\nu / \dot{\nu}^2$
  - $n = -1.234 \pm 0.009$ for long-term spin-down (≈23 yr)
  - $n \rightarrow 7$ or lower between glitches (~100 day)

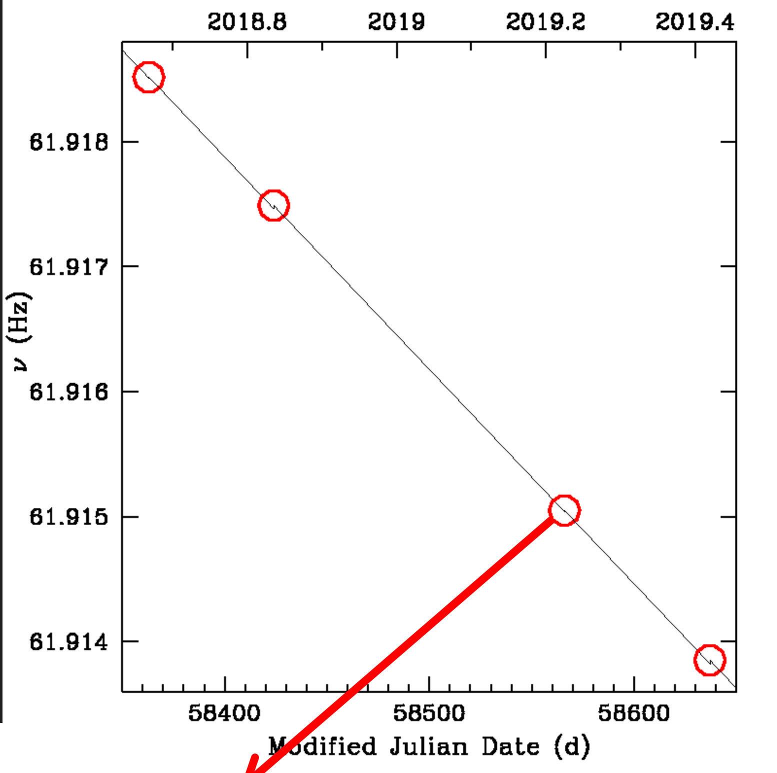




Superfluid model of pulsar glitches

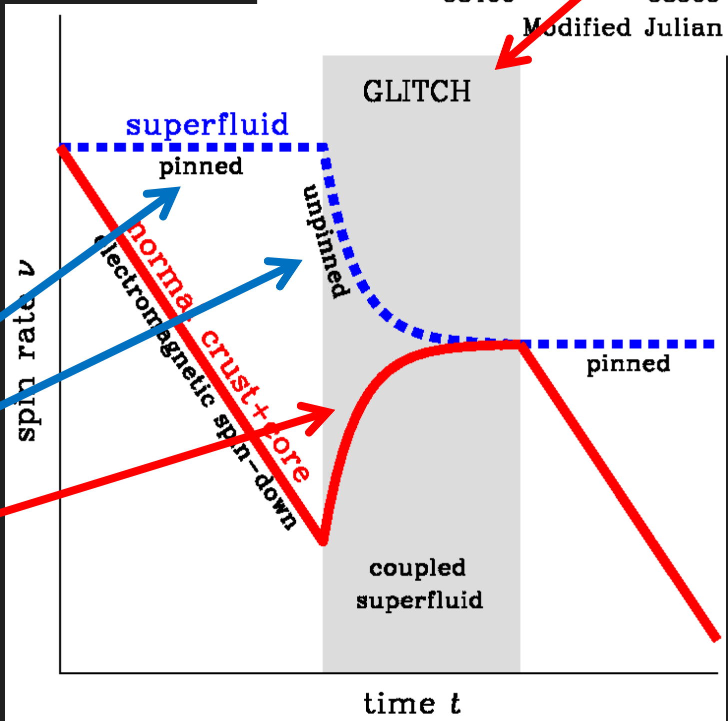


$\Delta\nu \propto \nu_n - \nu$



- Spin rate ν decrease (spin-down) due to EM radiation loss
- Regular spin-down interrupted by spin-up glitches

- Angular momentum transfer from superfluid (Anderson+Itoh 1975)
  - superfluid rotation ν_n by vortex formation but pinned so NO spin-down
  - glitch event
    - Δν exceeds critical value
    - vortices unpin – coupling of superfluid with rest of star
    - angular momentum transfer



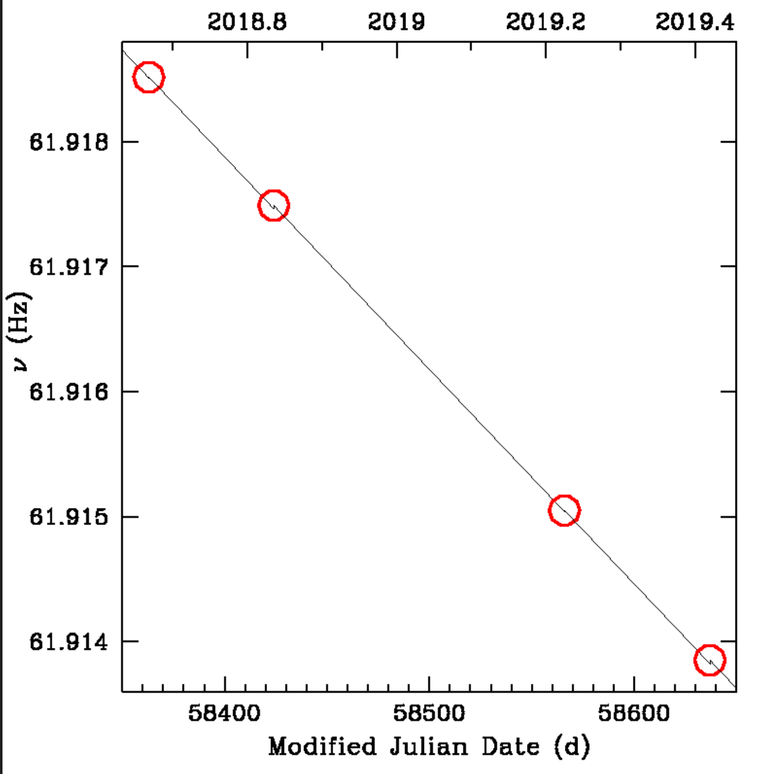
Neutron star mass from glitches

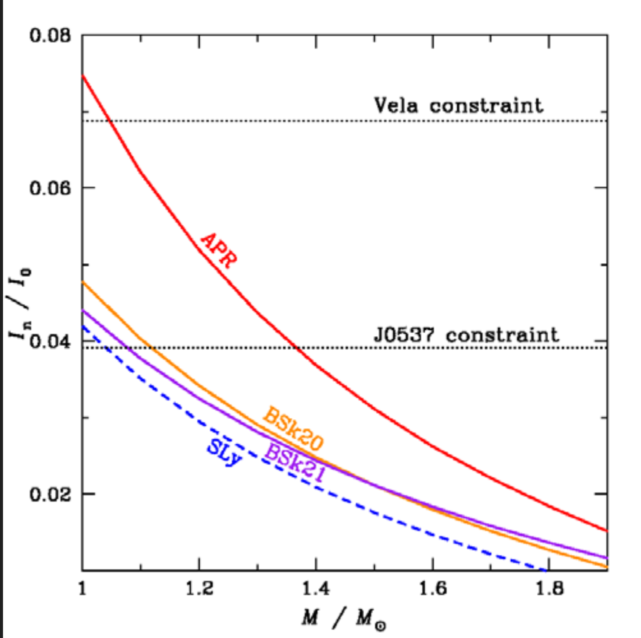
- Young pulsar spin-down interrupted by spin-up glitches
- Extra angular momentum from superfluid [Anderson+Itoh 1975]

- Consider moment of inertia for glitches:
  - how much does observed glitch require?

    EOS models [Link+1999; Andersson,WH+2012; Chamel 2013; Piekarewicz,Fattoyev,Horowitz 2014; Steiner,Gandolfi+2015; Pizzochero+2017]

    $I_{glitch} \sim I_{crust} \equiv I_{sf} \Rightarrow$ **confirmation of crust superfluid**





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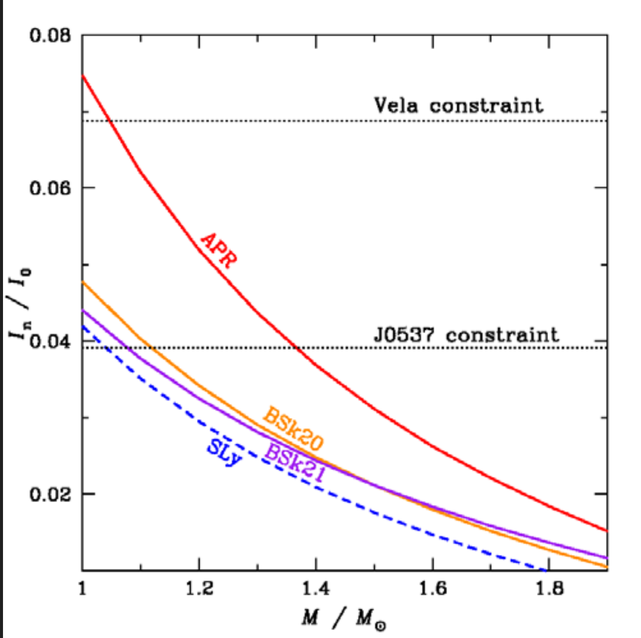

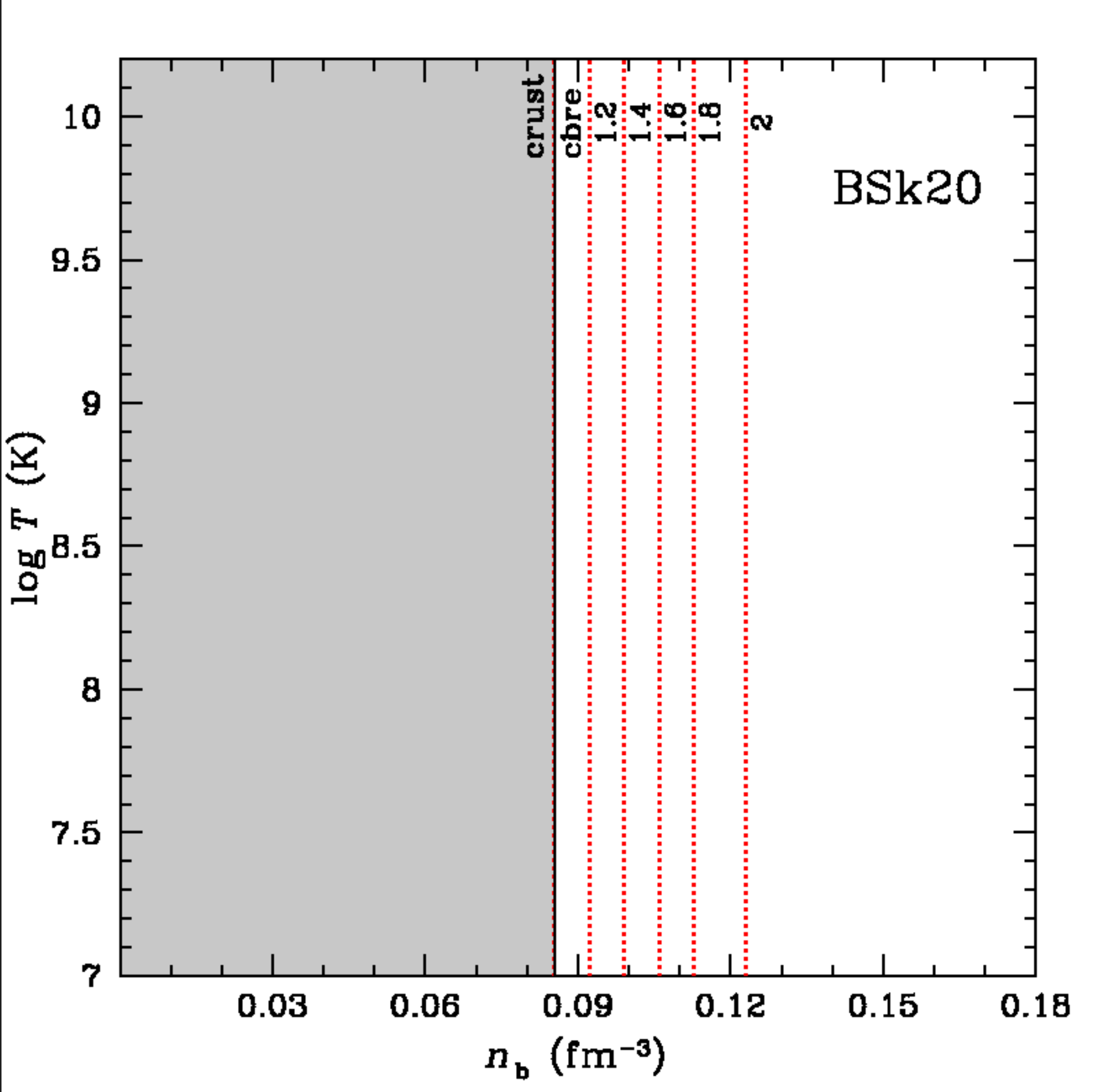

Going beyond glitch data

- Young pulsar spin-down interrupted by spin-up glitches
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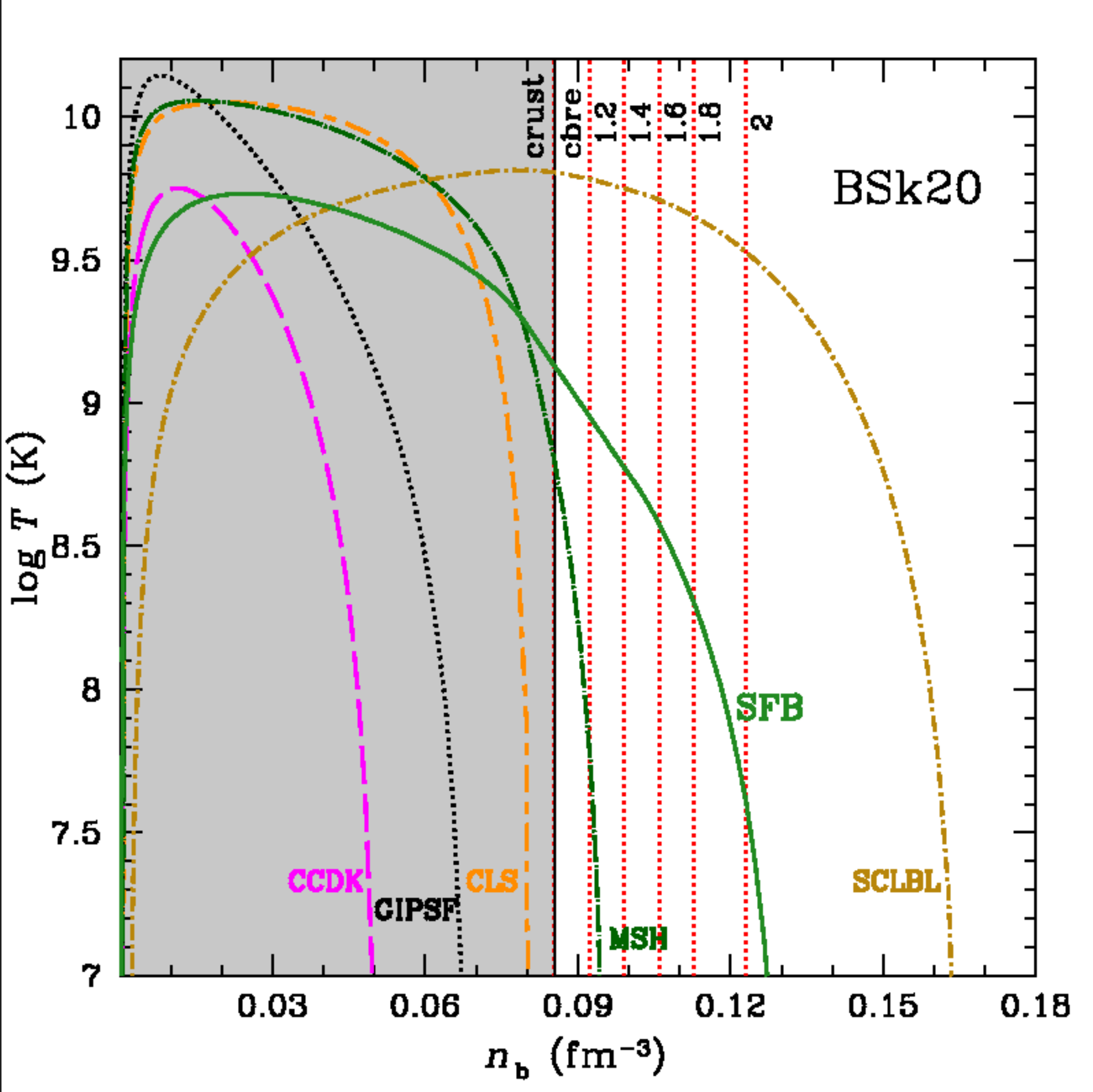
    EOS models
  - how much superfluid is available?
    superfluid models: $T_c(n_b)$
  - how much does pulsar have now?
    temperature from age/X-ray: $T < T_c(n_b)$



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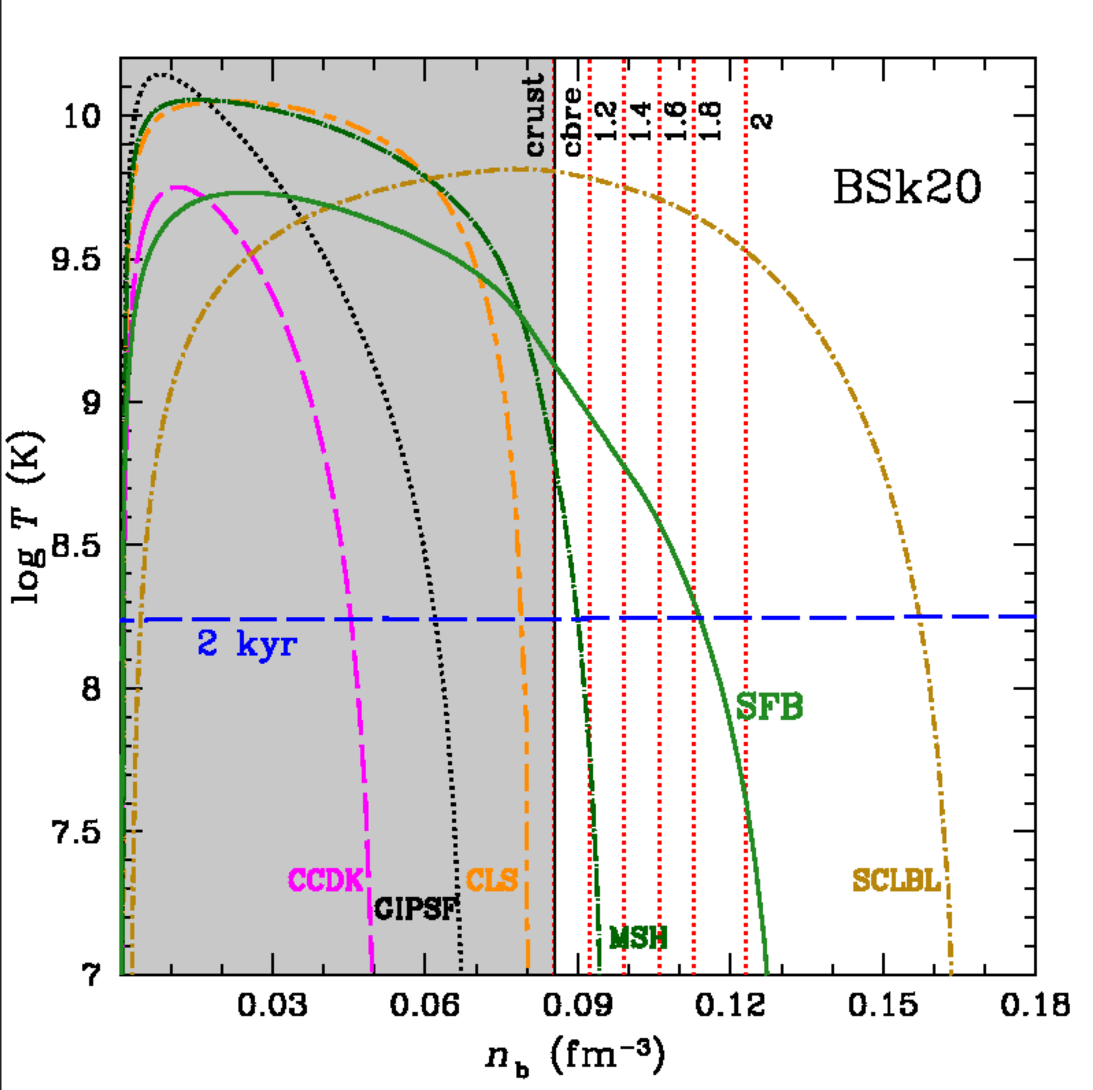

Measuring mass and testing EOS/superfluid models

- Young pulsar spin-down interrupted by spin-up glitches
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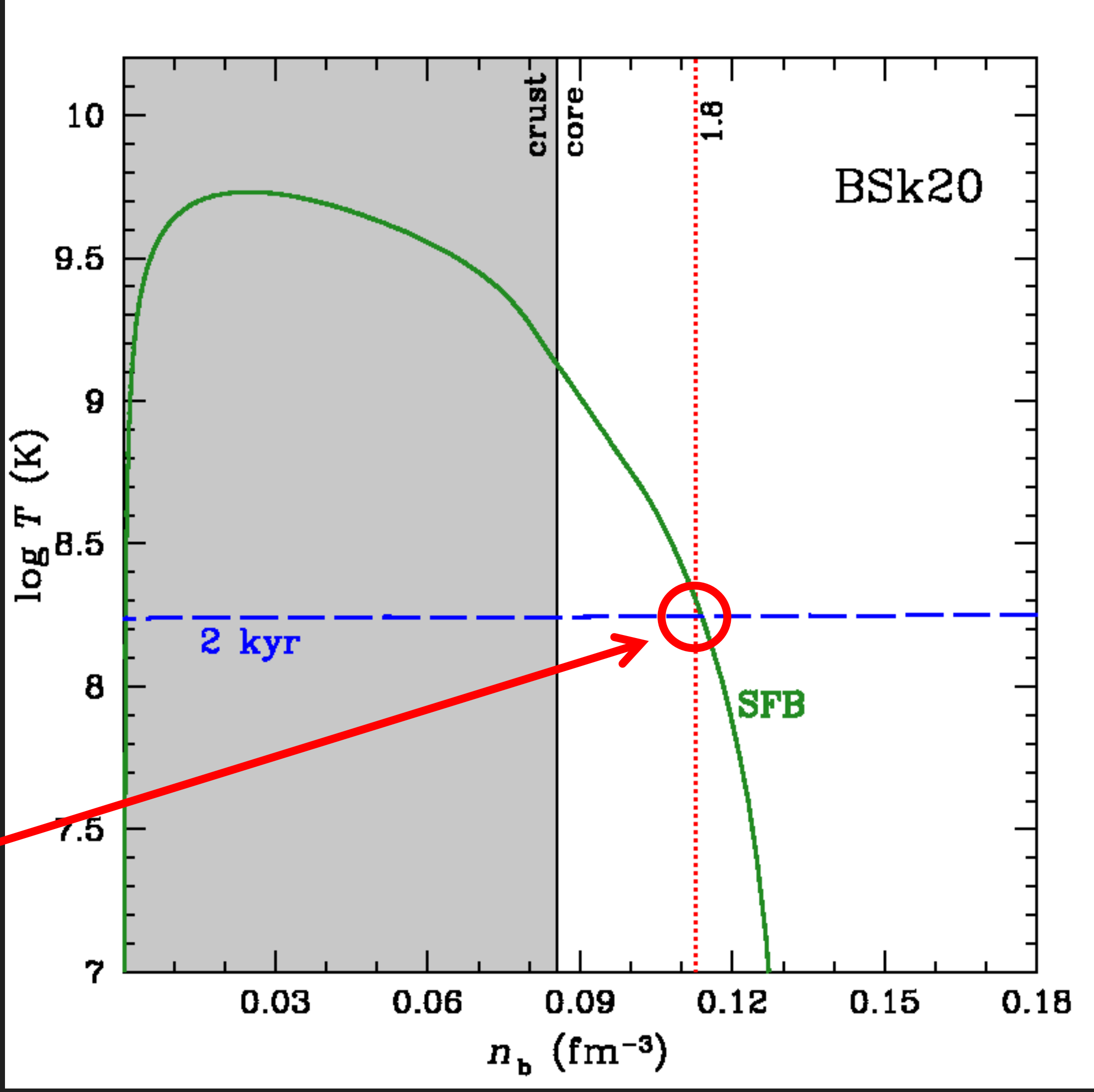
J0537–6910 is ≈ 1.8M_{Sun} neutron star and glitch size and frequency due to available superfluid moment of inertia at age 2 kyr



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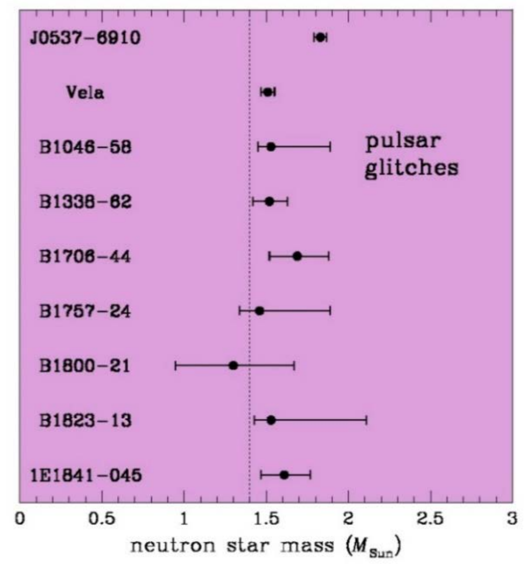

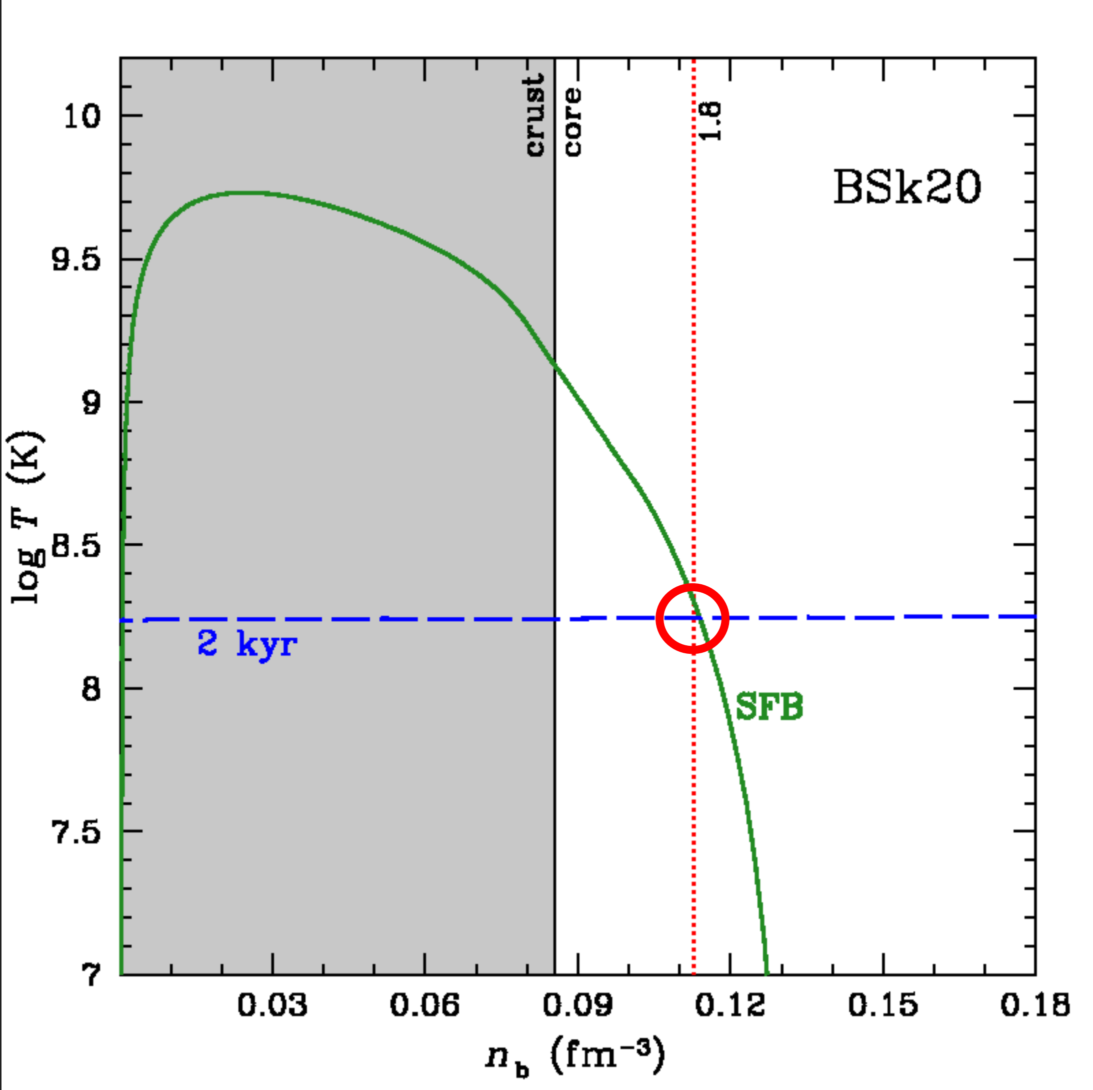

Spin evolution of PSR J0537–6910

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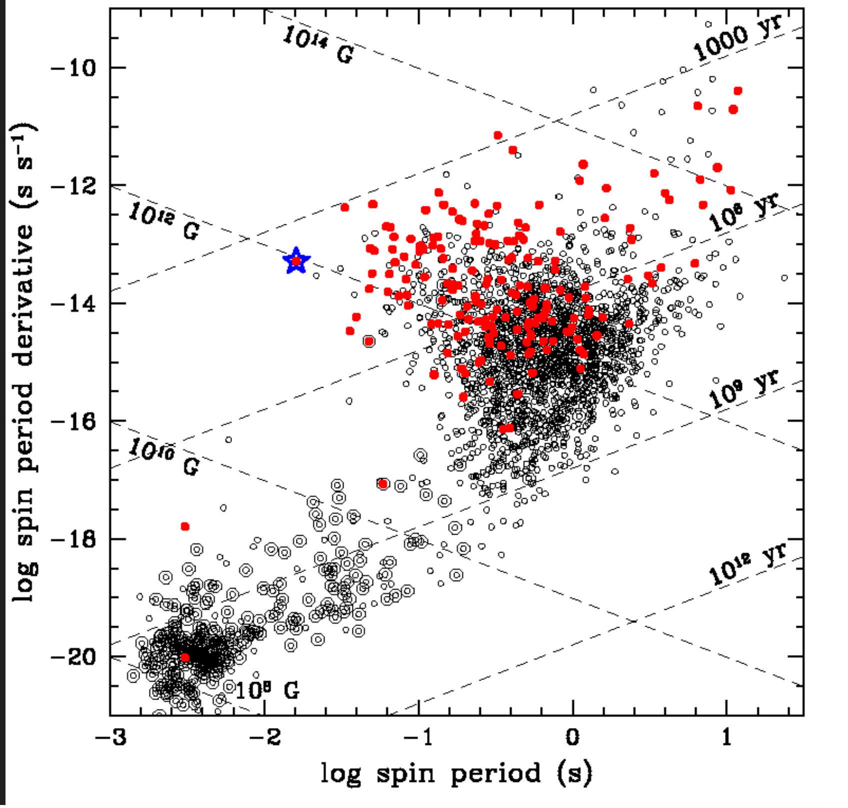
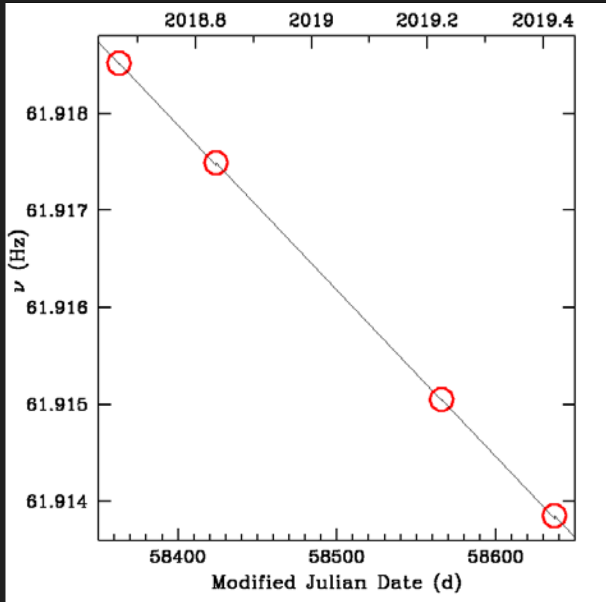
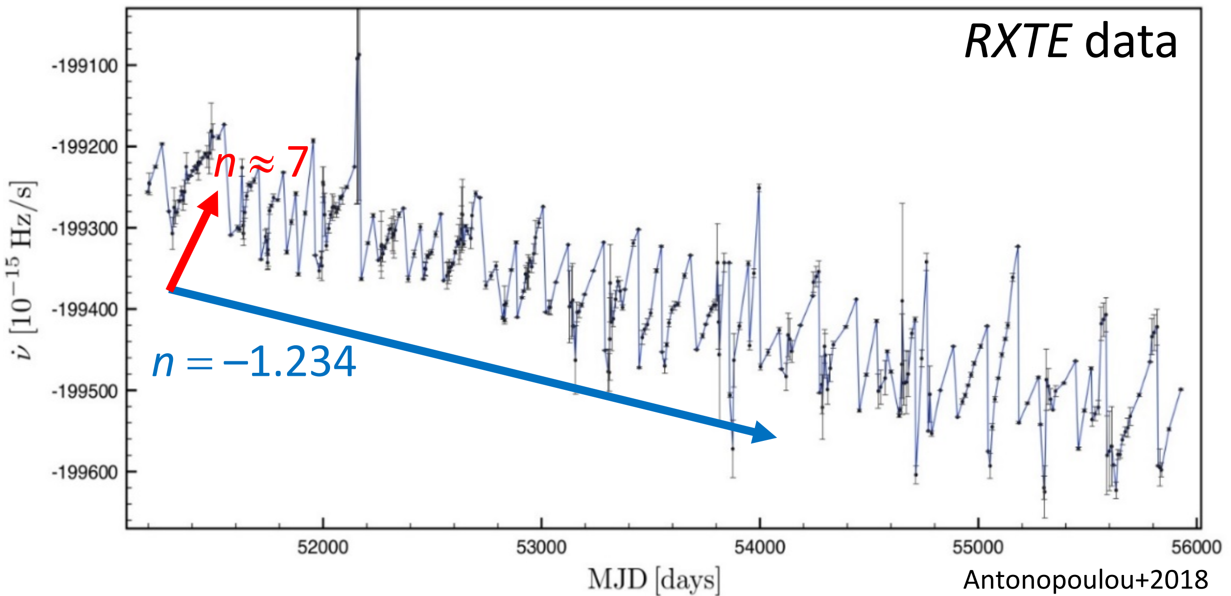
  - $n = 3$: magnetic dipole
  - $n = 5$: GW mountain
  - $n = 7$: GW r-mode







Antonopoulou+2018

Inter-glitch braking index

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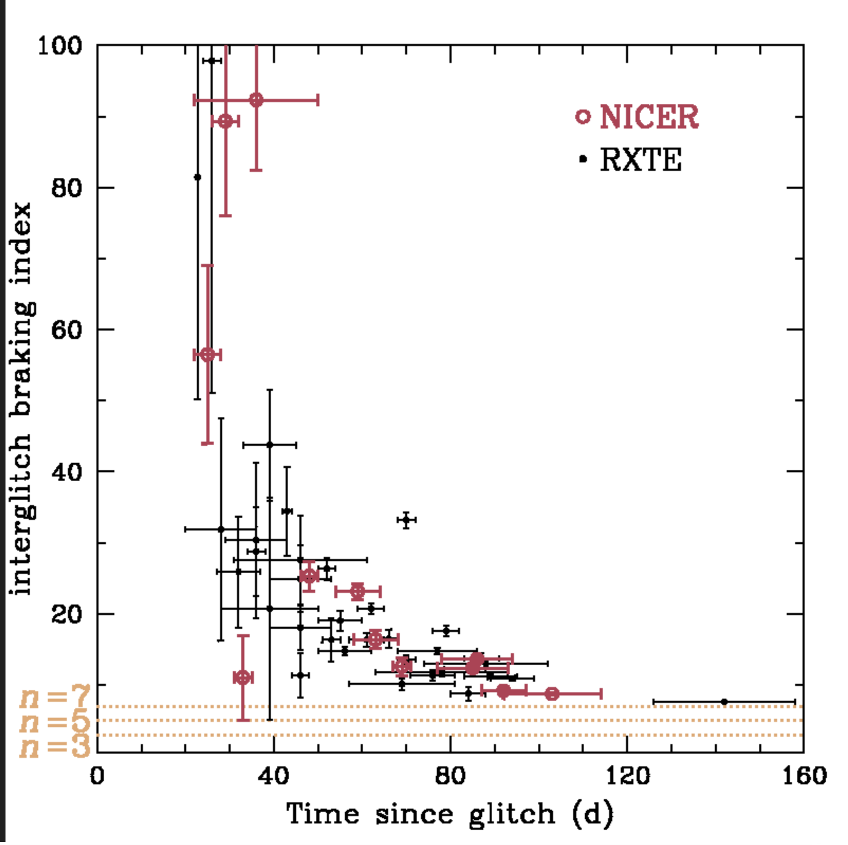

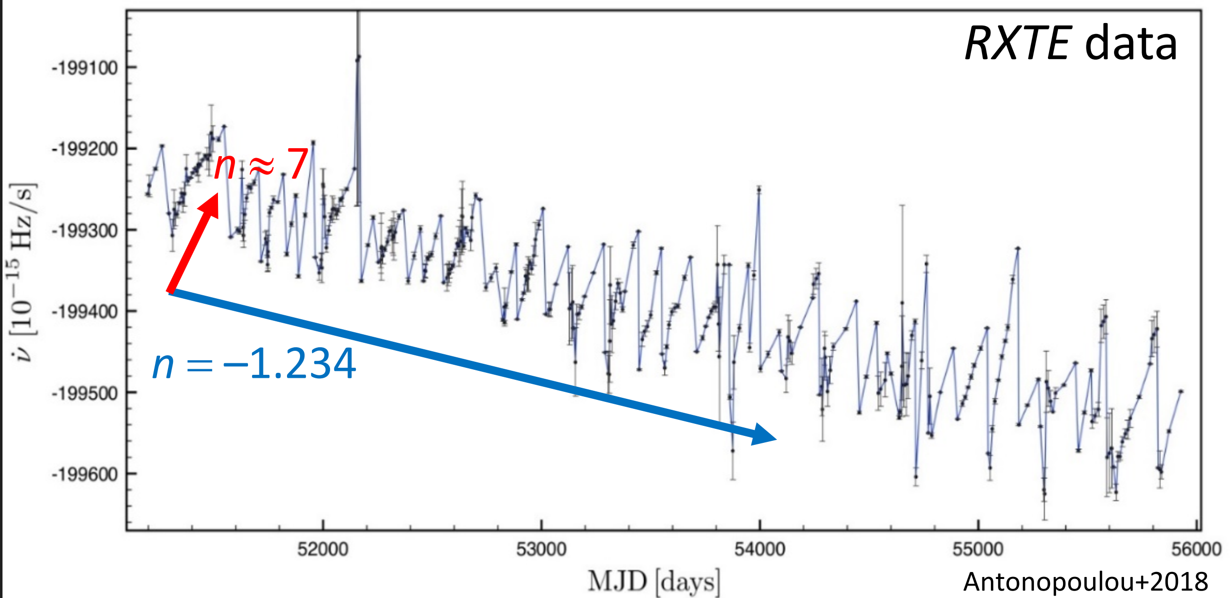

Antonopoulou+2018

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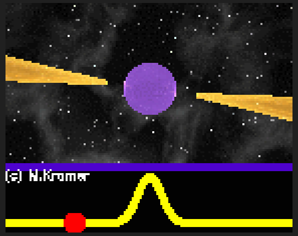
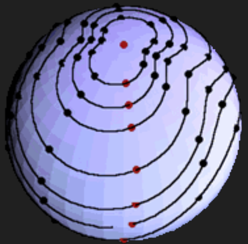
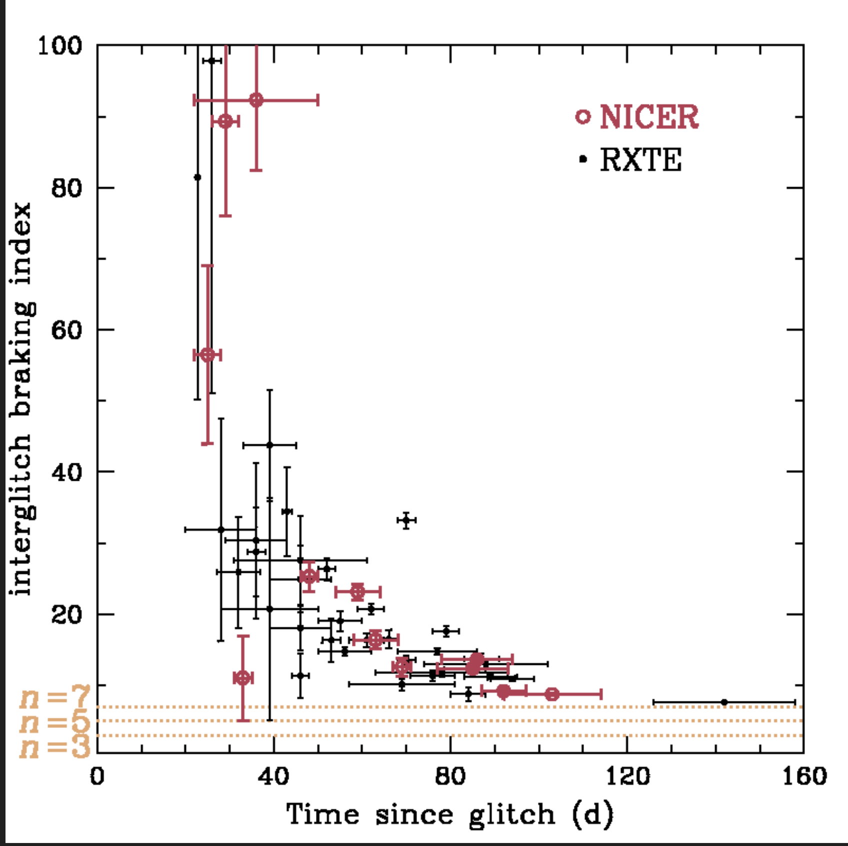
see talks by Horowitz

- Physics of mountain/r-mode: crust EOS and elasticity, superfluid mutual friction or hyperons, etc







PSR J0537–6910 as a GW source

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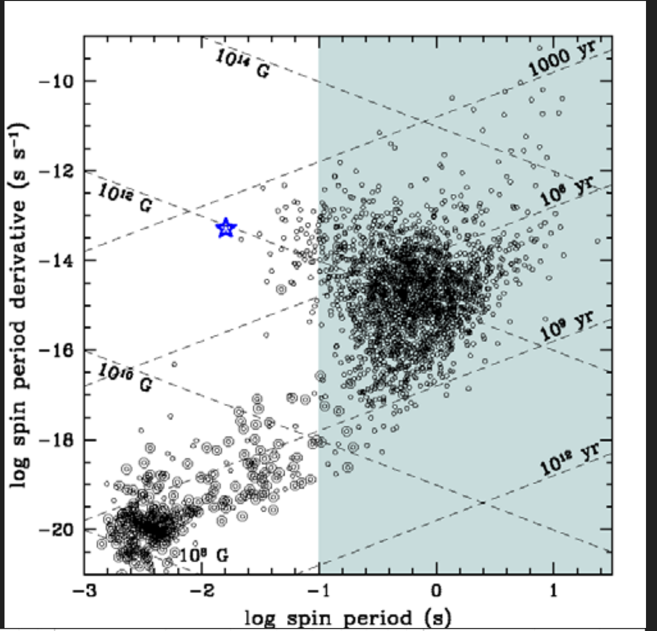
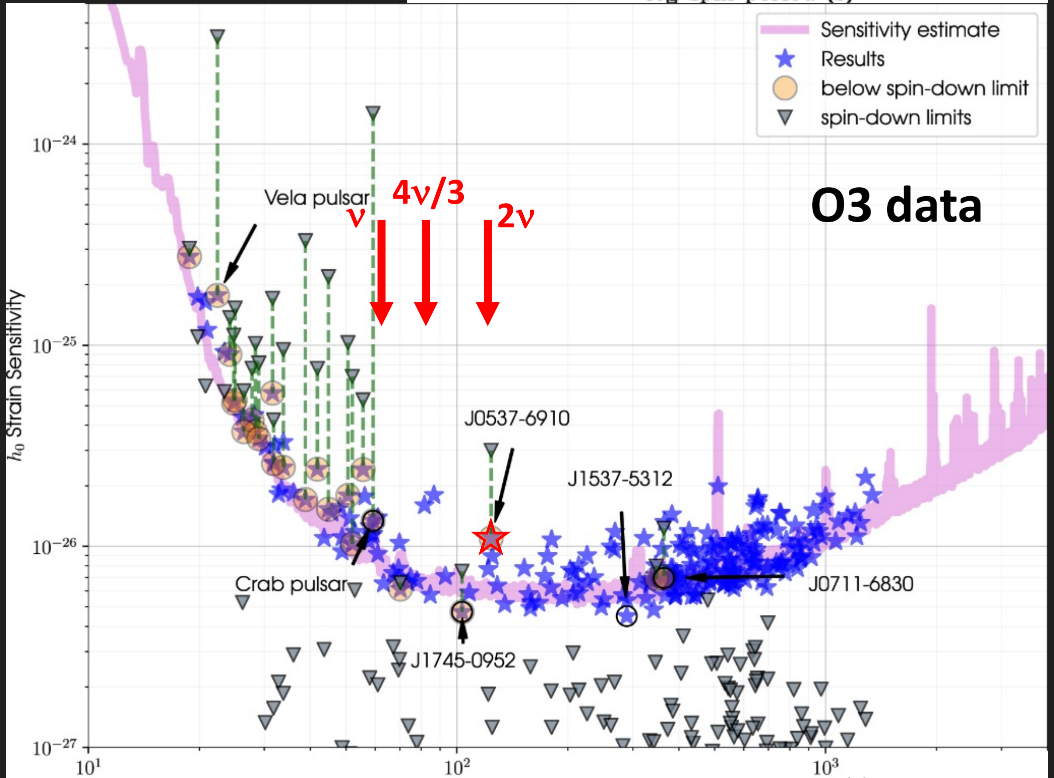
- LIGO/Virgo/KAGRA sensitive at $\nu_{gw} > 20$ Hz
  - ~ 500 pulsars with $\nu_{spin} > 10$ Hz
  - Most sensitive GW searches use contemporaneous EM observations (track pulsar spin)

see talks by Hinderer and Millhouse





Abbott,WH+2022

Summary

Comparison of **cooling and dynamics** reveals dense matter physics beyond just mass–radius

- Cassiopeia A cooling at ≈ **2% per decade**
- Glitches in young pulsars imply ~ $\mathbf{1.4}M_{\mathrm{Sun}}$
- Spin evolution of PSR J0537–6910 due to **GWs**
- Unique insights into superfluids and superconductors

- Dense matter impact on other dynamics
  - o cooling in low-mass X-ray binaries [eg Brown,Horowitz,Reddy+2018]
  - o millisecond magnetars in gamma-ray bursts and superluminous supernovae
  - o transient f-modes in pulsars

- Astrophysics need: Consistent EOS and sf/sc models