INTRO TO PULSARS

IPTA Student Workshop 2025

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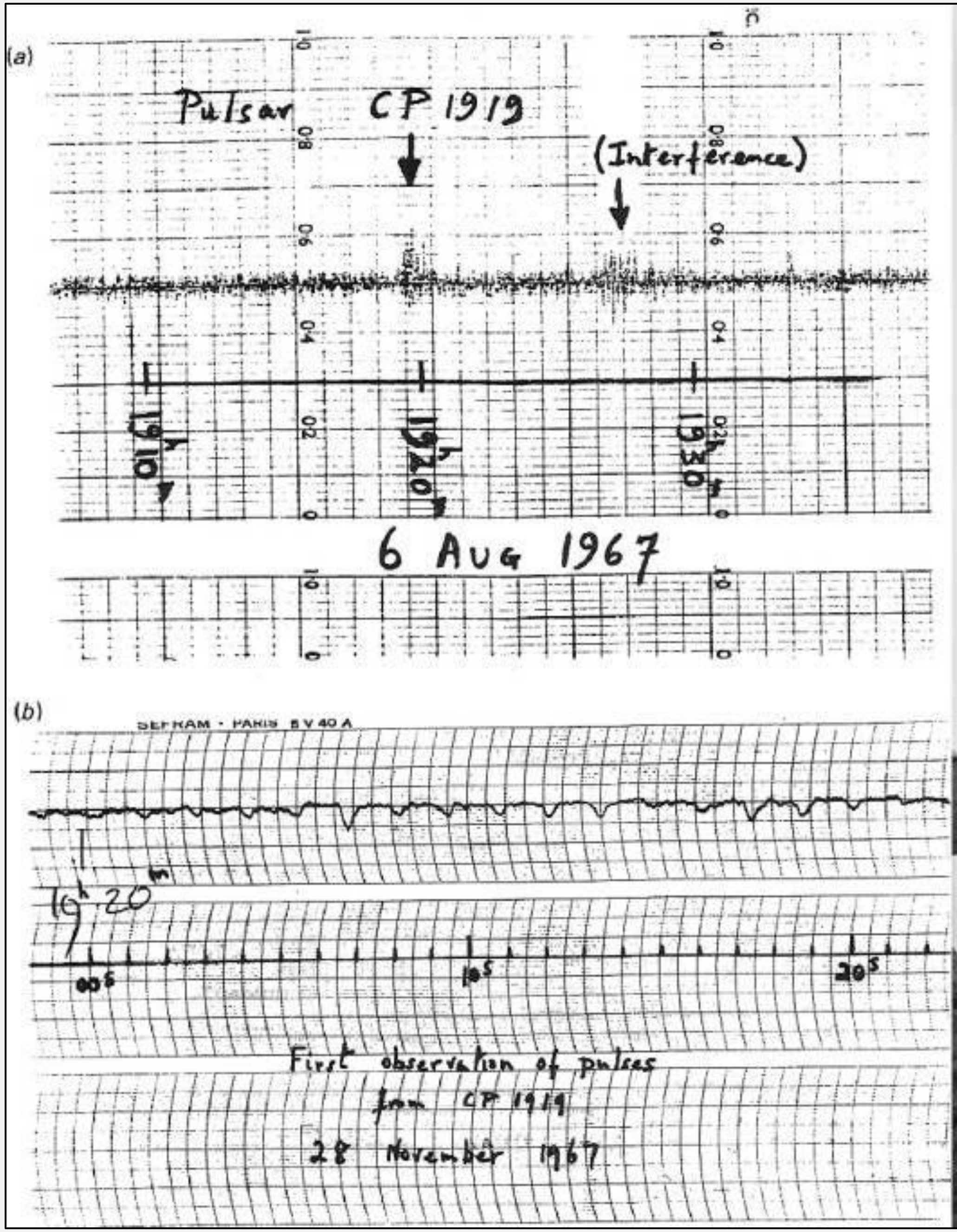
Questions we’ll answer in this half hour

- What is a pulsar?
- What does it do?
- How do we observe pulsars?

Questions we won't answer in this half-hour

- How do we do pulsar timing?
- What software should I use to study pulsars?
- What's going on in the ISM?
- But like, *why* does the pulsar do what it does?
- What will happen if we hurl J1713+0747 into the Sun in a fit of rage?

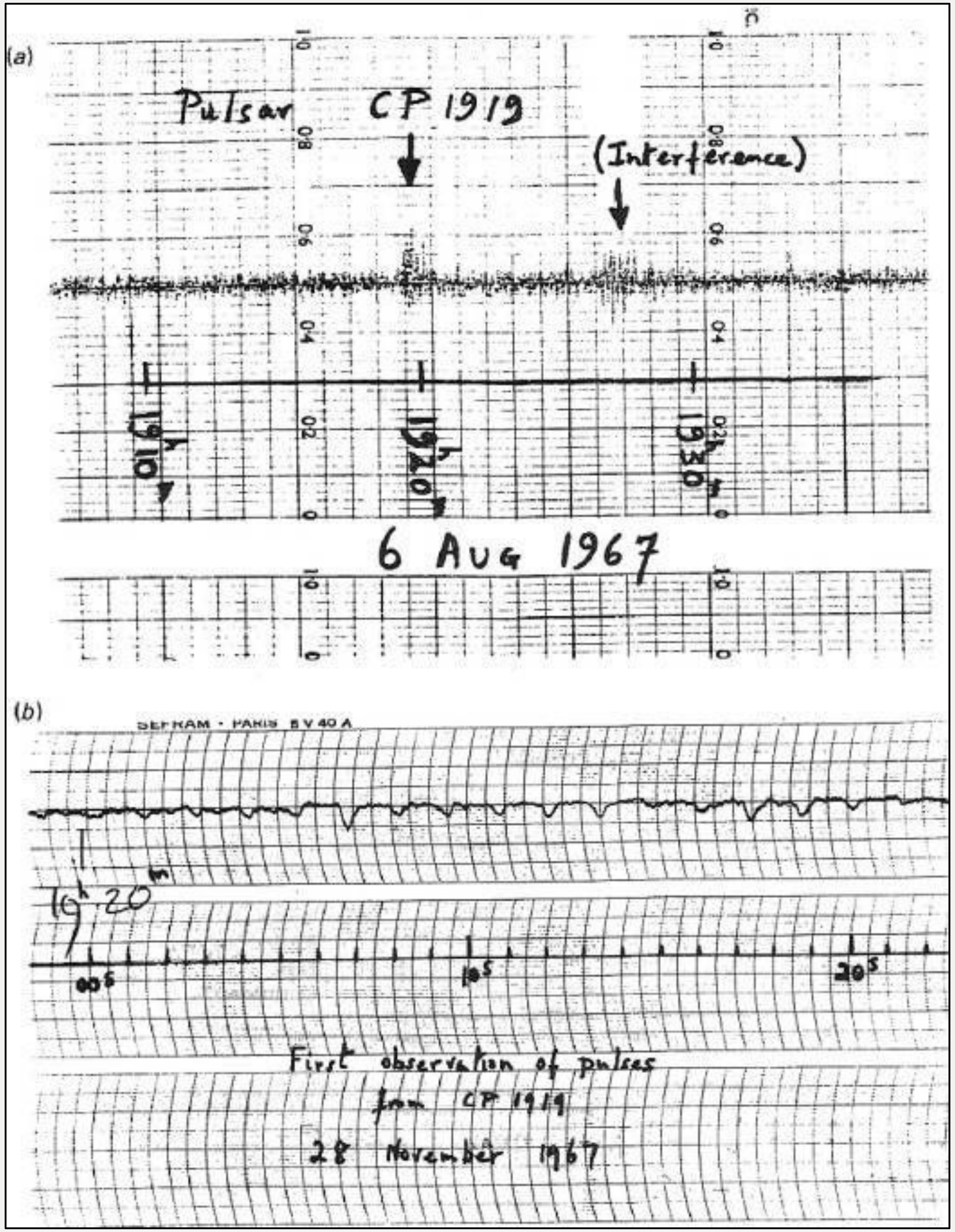
A BRIEF HISTORY OF PULSAR ASTRONOMY


(a)
Pulsar CP 1919
(Interference)
6 AUG 1967
(b)
First observation of pulses
from CP 1919
28 November 1967

Interpreting the "LGM"

- Bell & Hewish's original interpretation: probably a pulsating neutron star or white dwarf?

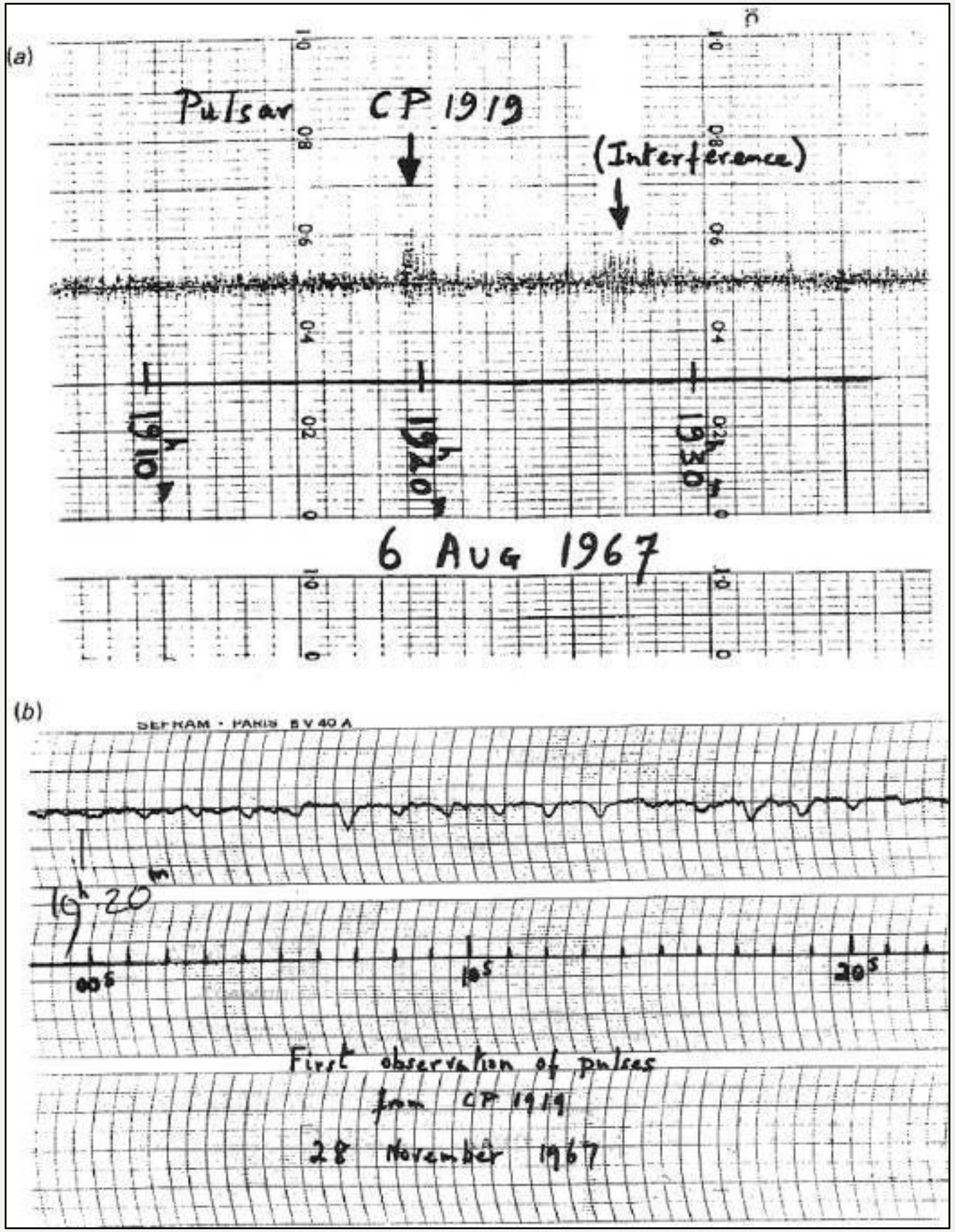
The most significant feature to be accounted for is the extreme regularity of the pulses. This suggests an origin in terms of the pulsation of an entire star, rather than some more localized disturbance in a stellar atmosphere. In this connexion it is interesting to note that it has already been suggested[2,3] that the radial pulsation of neutron stars may play an important part in the history of supernovae and supernova remnants.



Interpreting the “LGM”

- Bell & Hewish’s original interpretation: probably a pulsating WD?
- Better model developed shortly after:

Pulsars are rapidly rotating highly magnetized neutron stars formed during core collapse supernova explosions.



Finding more pulsars

- Two new pulsars in 1968; both in known supernova remnants
- Crab Pulsar
  - *PSR B0531+21*
  - *P ~ 33 ms*
- Vela Pulsar
  - *PSR B0833-45*
  - *P ~89.33 ms*

Optical: NASA/HST/ASU/J. Hester et al.
X-Ray: NASA/CXC/ASU/J. Hester et al.

Finding more pulsars: B1913+16

- Discovered in 1974 by Russell Hulse and Joe Taylor.
  - *Period: $P \sim 59\ ms$*
  - *Spin frequency: 16.940537785677 Hz*
  - *Binary period: 7.75 hrs*
  - *First binary pulsar (neutron star-neutron star)*
- Tool for indirect detection of gravitational radiation
  - *Measure rate of orbital decay*
  - *"Missing" energy was radiated as gravitational waves*

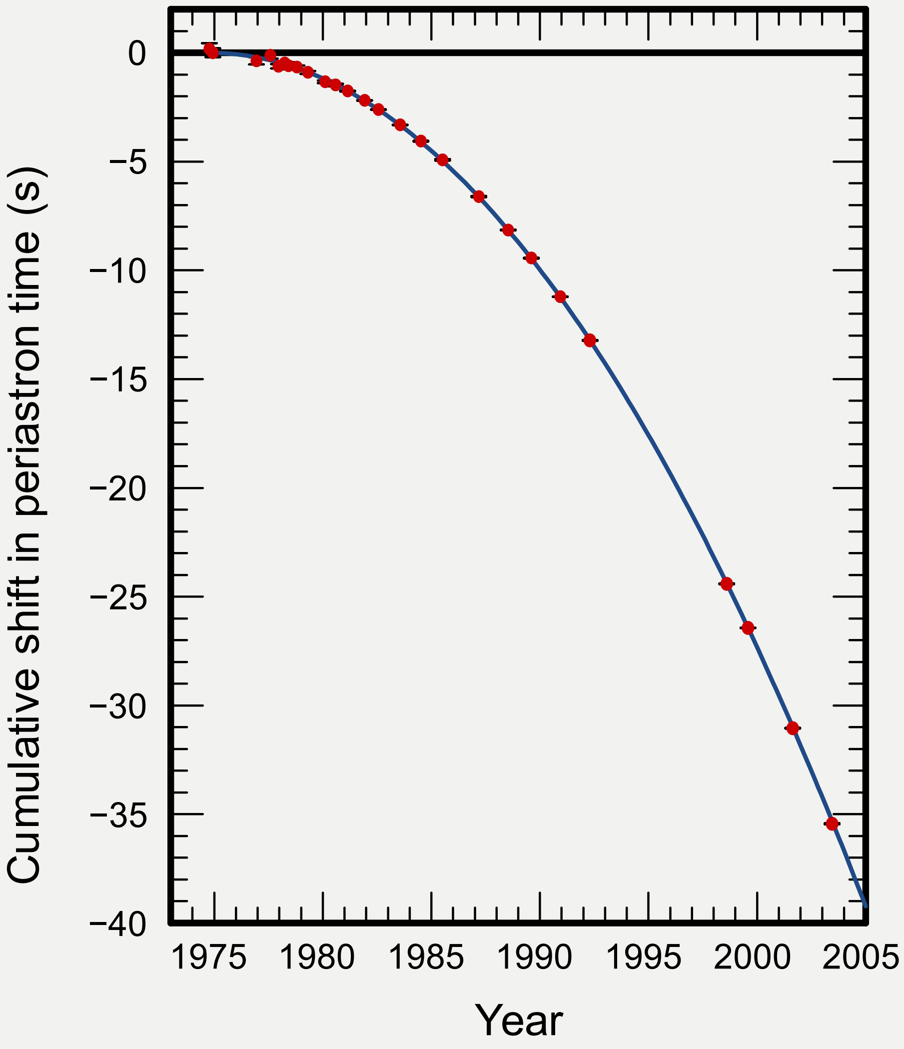


Image credit: Hownottowin (Wikimedia Commons)

Millisecond Pulsars!

- First discovered in 1982 by Shri Kulkarni, Don Backer, et al.
- B1937+21
  - *Discovery period: P = 1.558 ms*
  - *Up-to-date spin frequency: f = 641.928222127829 Hz*

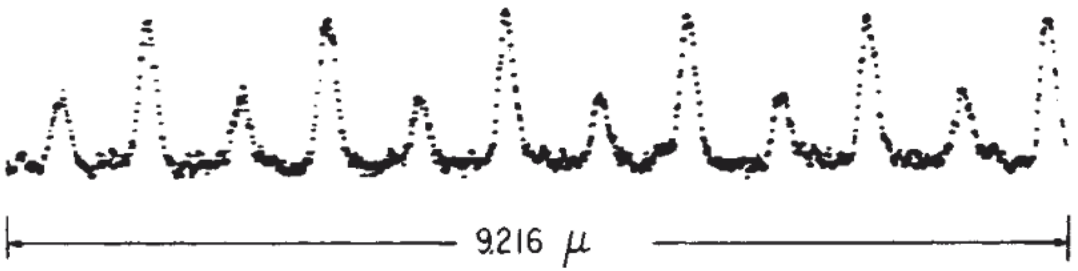
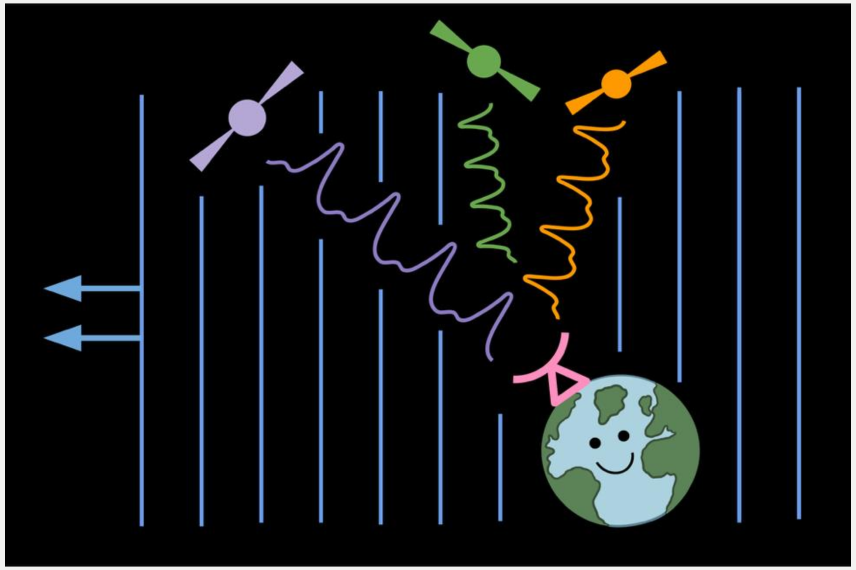


Fig. 4 Waveform of the millisecond pulsar from a signal averager oscilloscope display. Sample spacing is 9 μs. The full trace is roughly six periods, 9,216 μs. The integration lasted ~75 s. The waveform consists of a main pulse and an interpulse separated by nearly 180° of rotational phase. Errors in timing the signal averager and a 20 μs RC time constant are responsible for most of the pulse width.

Image credit: Backer et al. 1982

The coming of PTAs

- First proposed in the 1970s (independently) by Mikhail Sazhin and Steven Detweiler.
- Idea: use the pulsars as a gravitational wave detector
- 1983: Hellings & Downs forecast the stochastic gravitational wave background signal
- 1990: Foster & Backer take a stab (3 pulsars; 2 years of data)
- Late 1990s/early 2000s: modern PTAs take shape



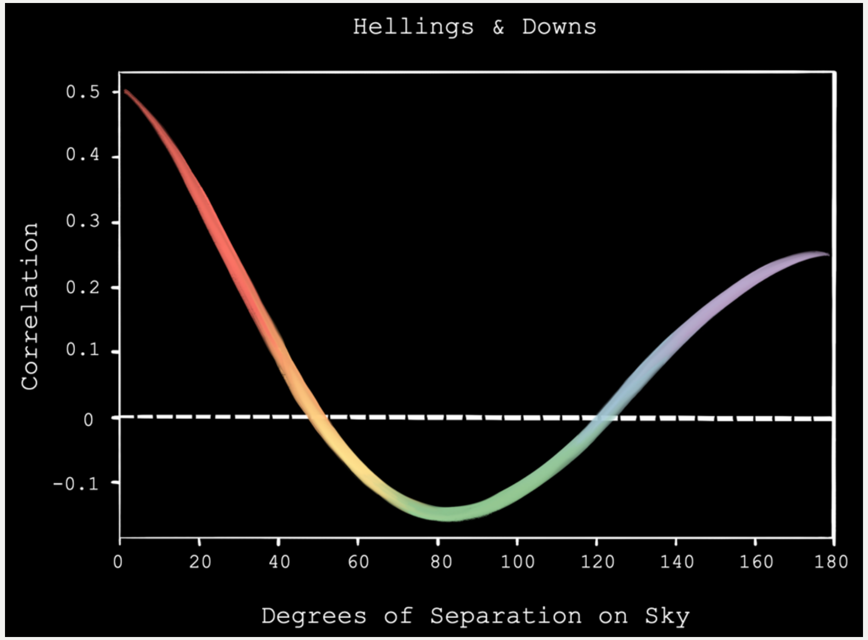


Image credit: H. Thankful Cromartie

WHAT IS A PULSAR?

And what does it do?

Our pulsar model

Pulsars are rapidly rotating highly magnetized neutron stars formed during core collapse supernova explosions.

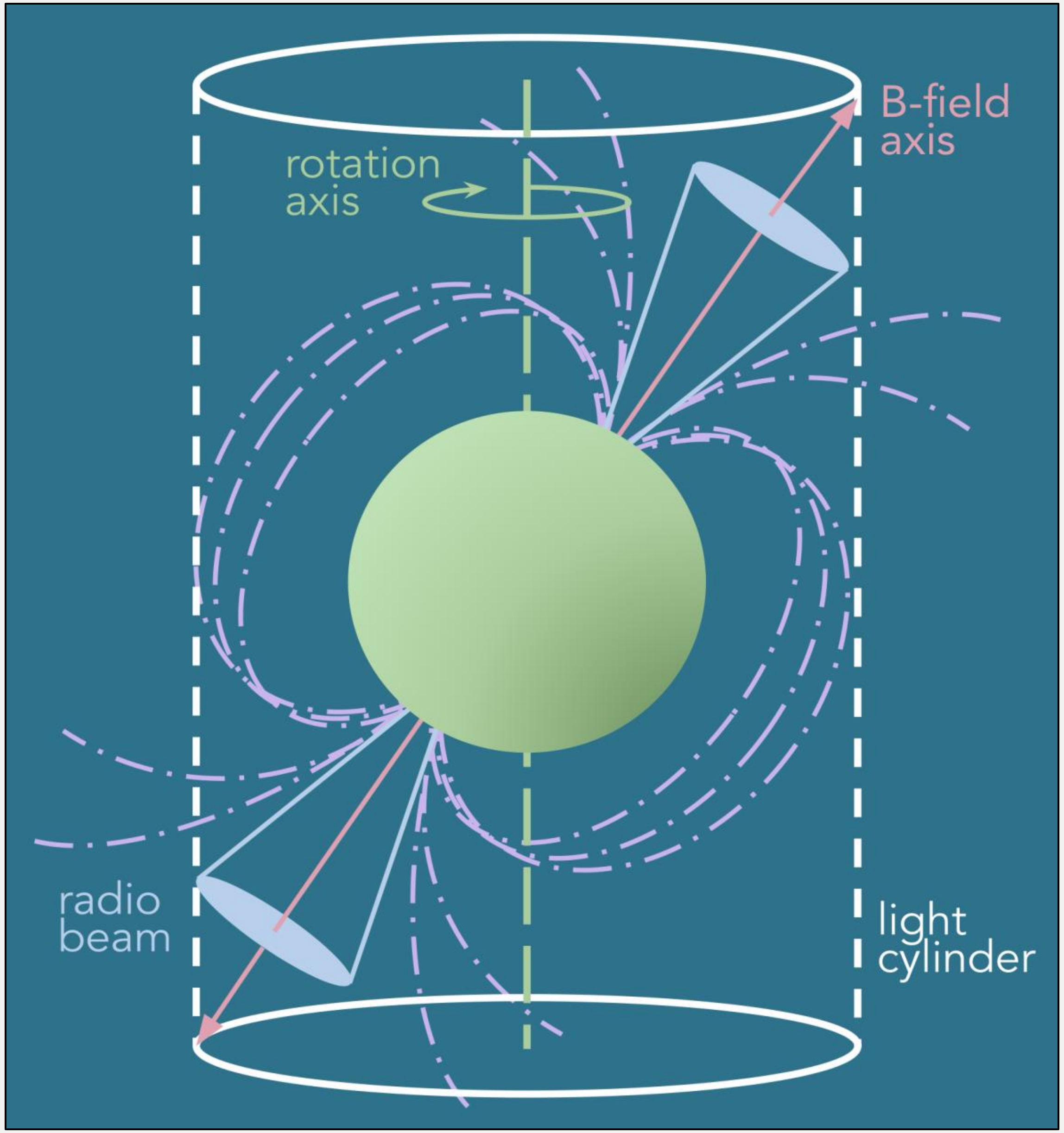
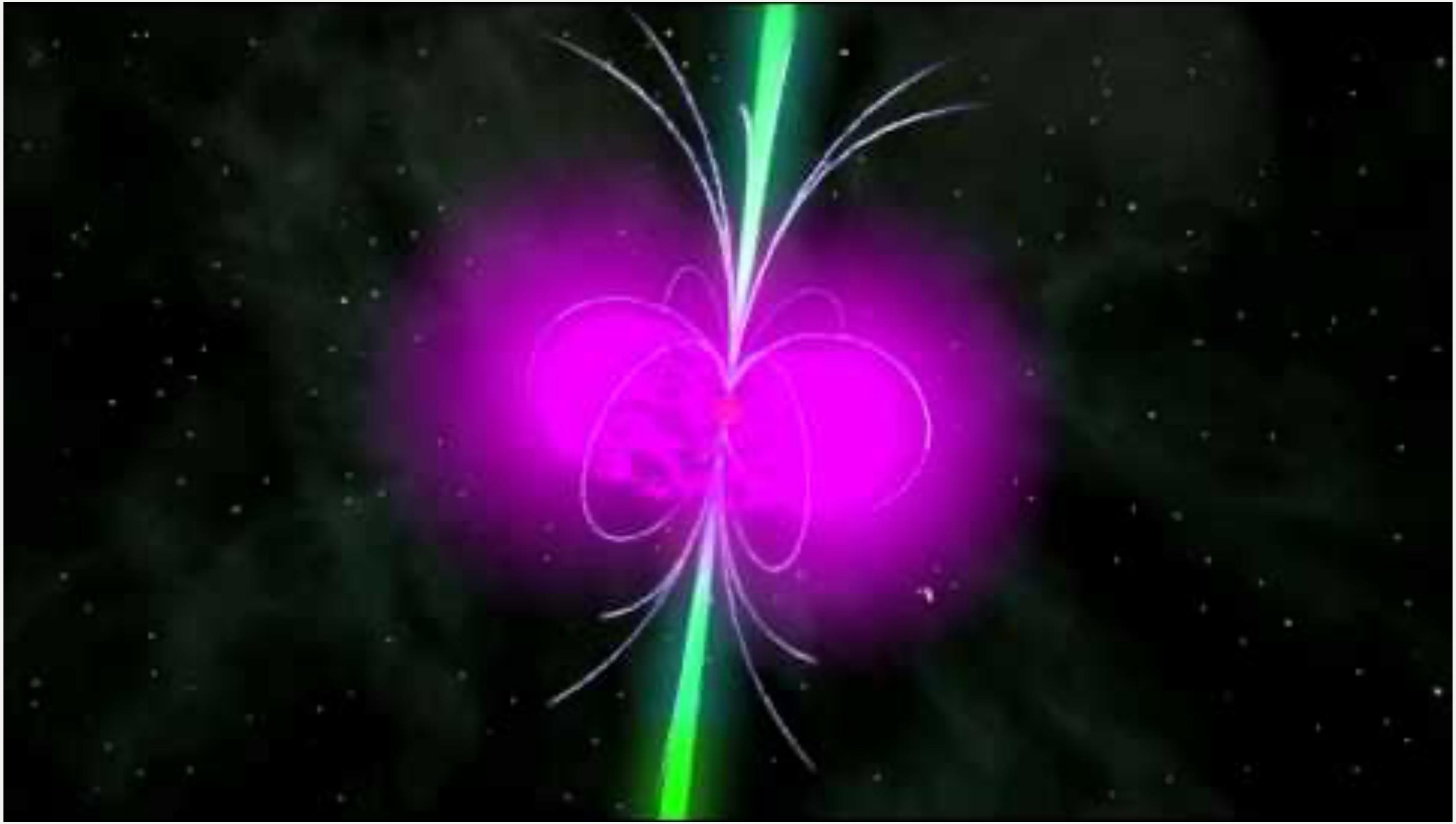


Image credit: H. Thankful Cromartie



Video Credit: NASA

Our pulsar model

How massive can a neutron star be?

- Chandrasekhar mass: 1.4 $M_\odot$ = minimum mass of neutron star.
- Maximum mass of neutron star?
  - *Model dependent, but somewhere between 2 and 3 $M_\odot$.*
  - *Some heavy pulsars: J0952–0607, J0740+6620, J1600-3053*

Our pulsar model

How large can our neutron star radius be?

- Minimum radius
  - *Set by Schwarzschild Radius:* $R_{min} \sim 1.5\, R_s = \frac{3\, G\, M}{c^2} \sim 6.2\, km \left(\frac{M}{1.4\, M_\odot}\right)$
- Maximum radius
  - *Set by the need to not be broken up by centrifugal forces*
  - $R_{max} \sim \left(\frac{G\, M\, P^2}{4\, \pi^2}\right)^{\frac{1}{3}} = 16.8 \left(\frac{M}{1.4\, M_\odot}\right)^{\frac{1}{3}} \left(\frac{P}{ms}\right)^{2/3}$

Taken together, M & R give us $I \sim 10^{38}\, kg\, m^2 = 10^{45}\, g\, cm^2$

Image credit: ultimately, *Inception*

Our pulsar model

Adding spindown rate lets us estimate (characteristic) age and magnetic field

- Characteristic Age:
  - $\tau_c \equiv \frac{P}{2\,\dot{P}} \simeq 15.8\,Myr\,\left(\frac{P}{ms}\right)\left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$
- Magnetic Field:
  - $B_S \equiv B(r = R) = \sqrt{\frac{3\,c^3}{8\,\pi^2}\,\frac{I}{R^6\,\sin^2\alpha}\,P\,\dot{P}}$
  - *For* $I = 10^{45}\ g\ cm^2$, *R = 10 km,* $\alpha = 90°$*:*

$$B_s = 3.2\,\times 10^{19}\,G\,\sqrt{P\dot{P}} \sim 10^{12}\,G\,\left(\frac{\dot{P}}{10^{-15}}\right)\left(\frac{P}{s}\right)^{1/2}$$

The pulsar population

Pulsar Properties	
Mass	1.4 -- 2+ solar masses
Radius	~10-20 km
Magnetic Field	10^{12} -- 10^{14} G
Spin Period	~1.5 ms to ~76 s

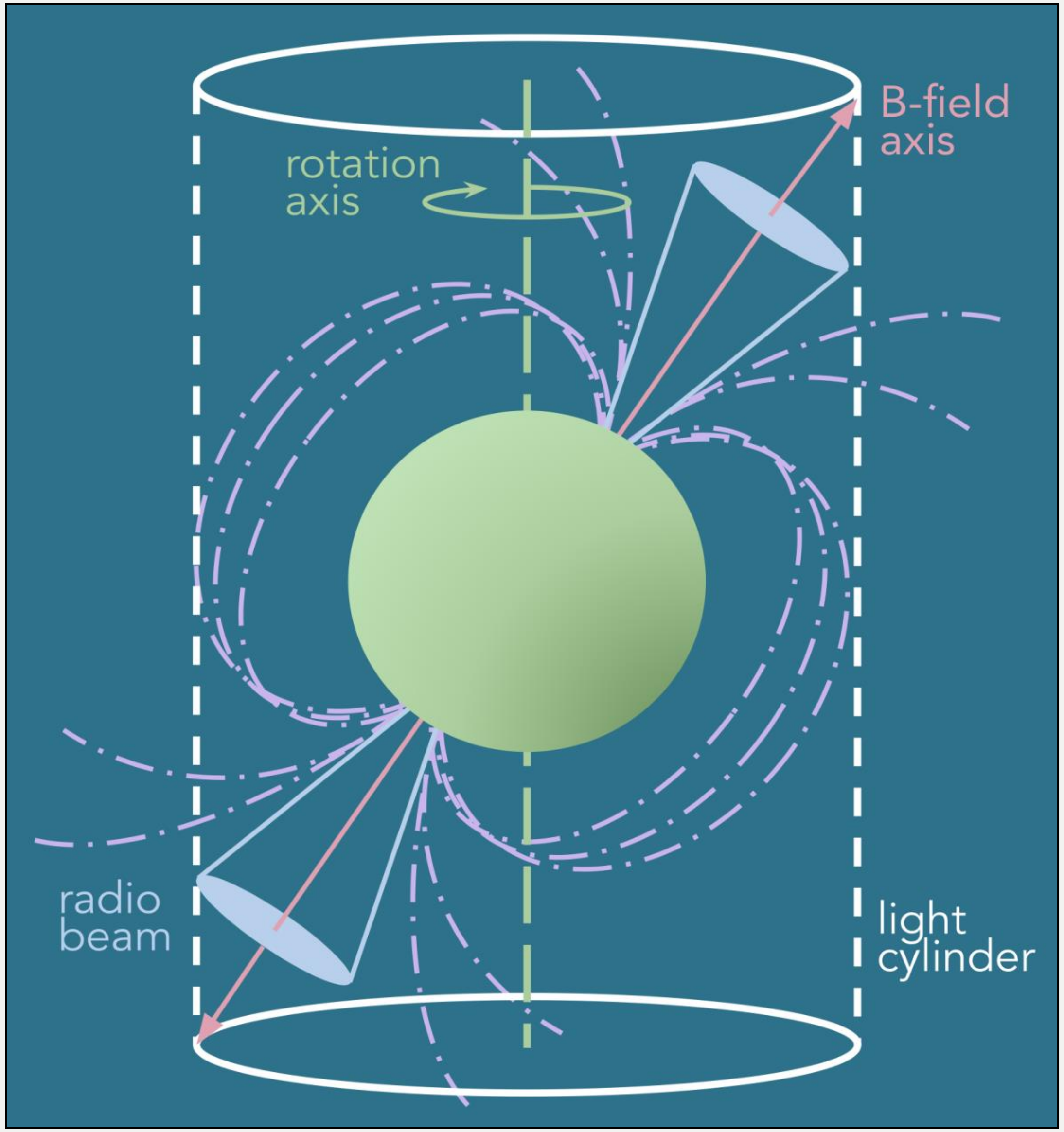
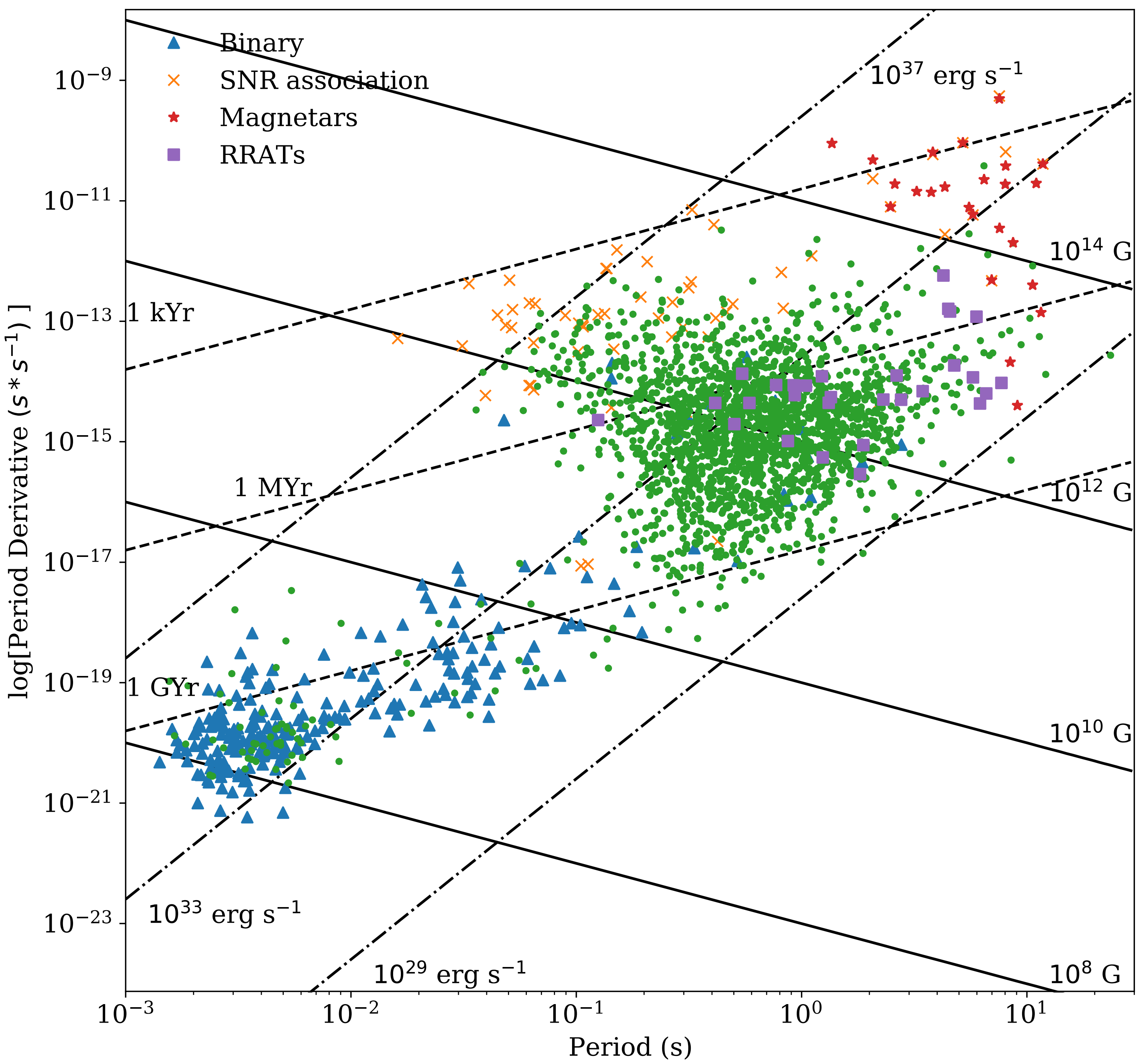
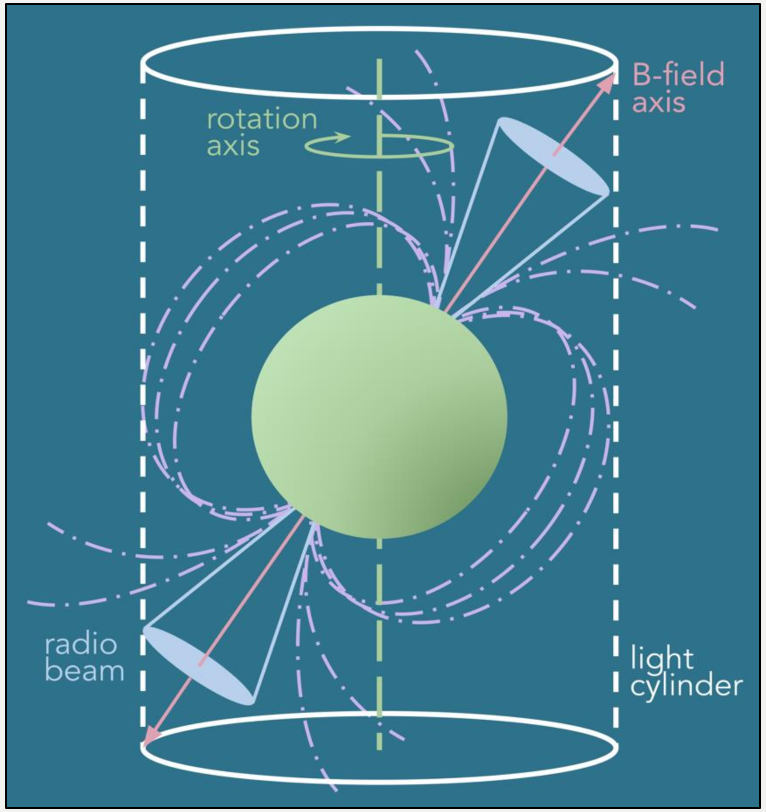


Image credit: H. Thankful Cromartie

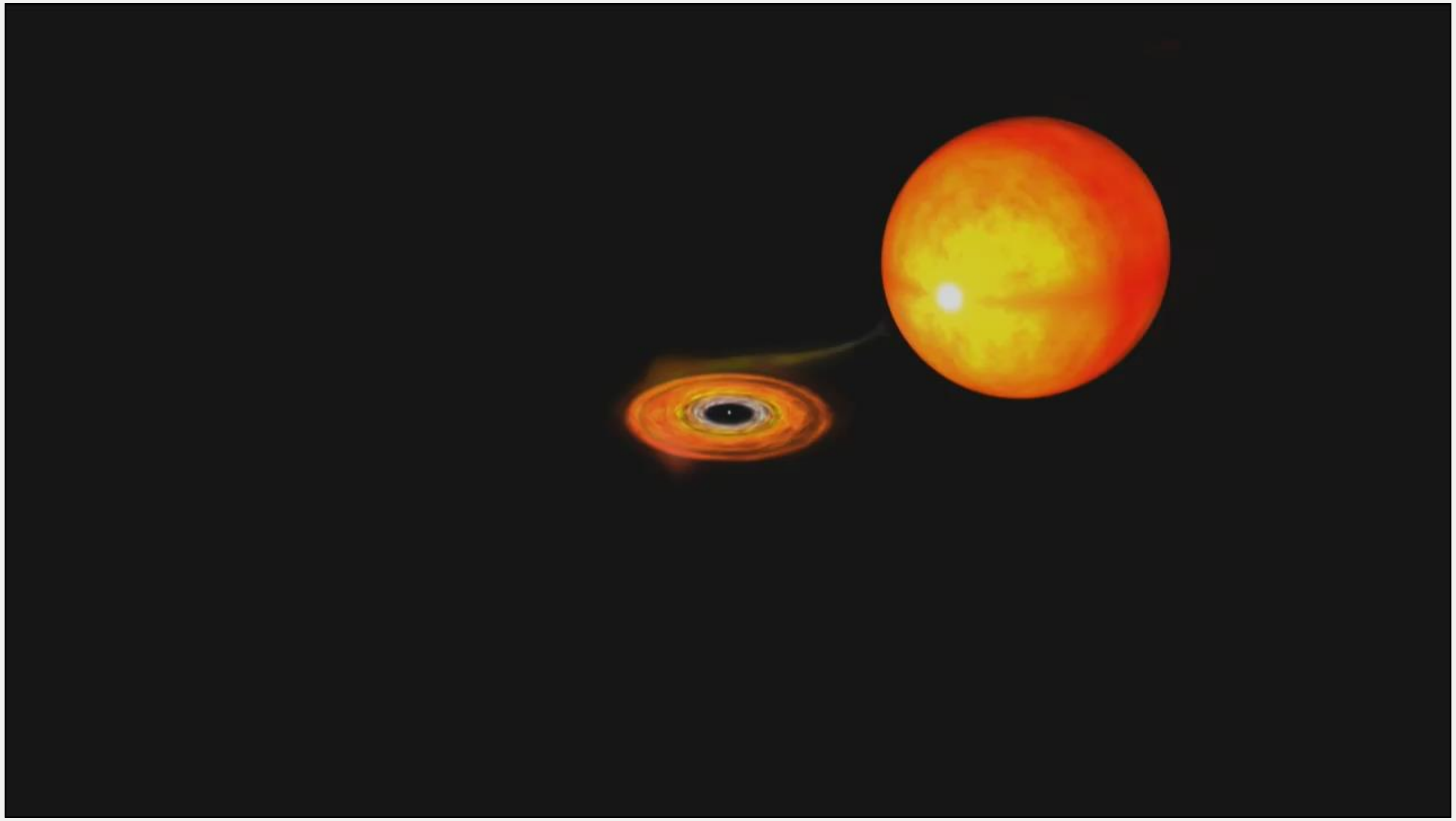
The Pulsar Population

Data represent ATNF pulsar catalog in spring 2021





The Millisecond Pulsar



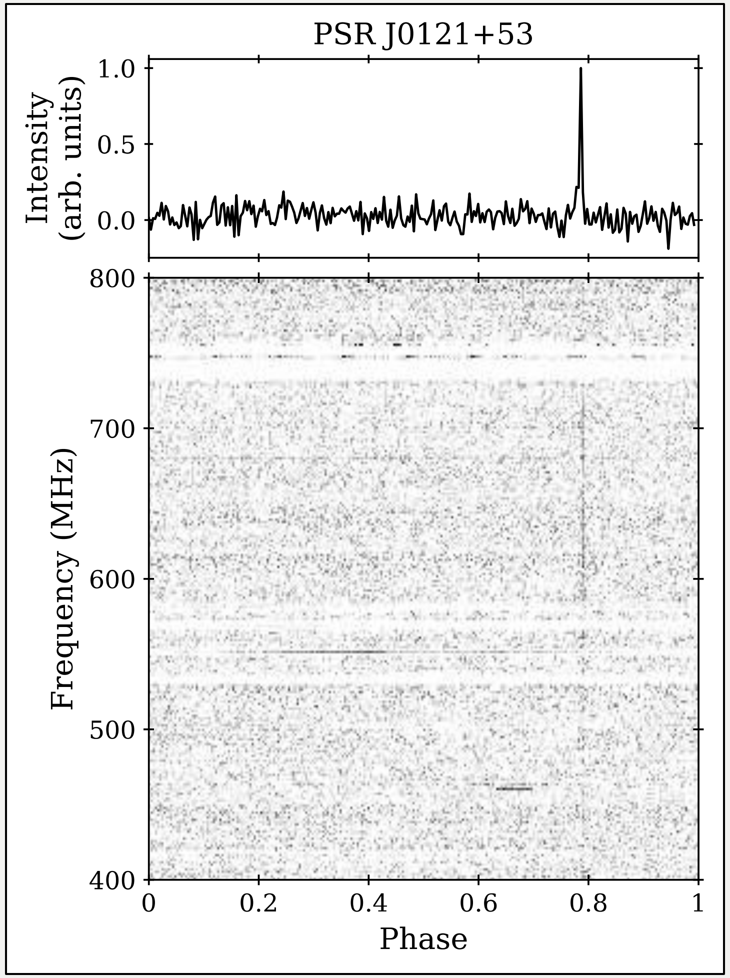
Video Credit: NASA

HOW DO WE OBSERVE PULSARS?

Image credit: H. Thankful Cromartie

Single pulse studies

- In a perfect world, we'd record individual pulses from pulsars.
- Here in the real world, they're mostly too dim for that.
  - *Folding!*



(Good et al. 2021)

Stacking up many pulses

- Each pulse from a pulsar can be very different, but the *integrated pulse profile* is remarkably consistent
- Except that one time with J1713+0747 and we don't talk about that.

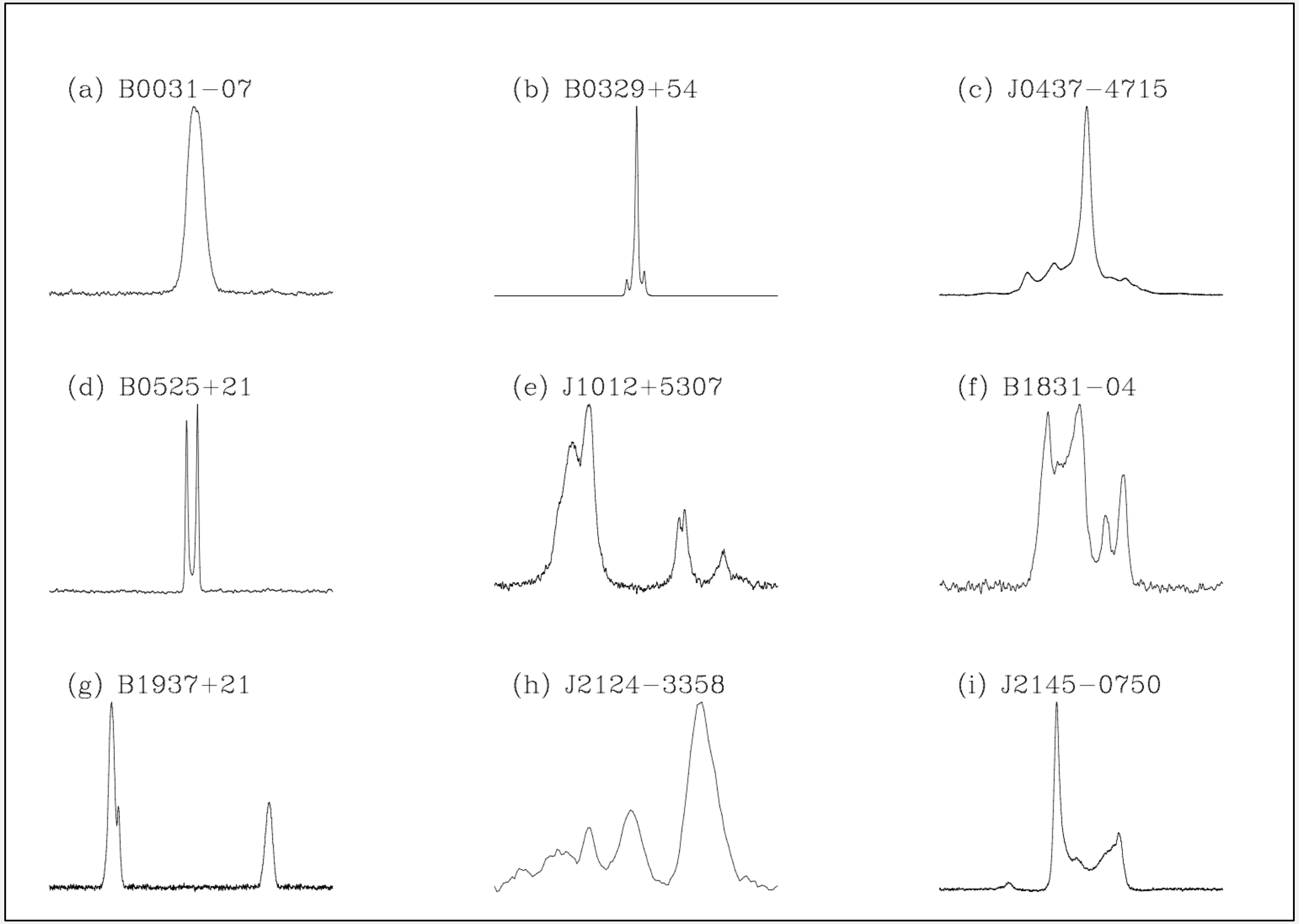


Image credit: Lorimer 2008 (data sources in original caption)

Forming Times of Arrival

- Pulse profiles allow us to record times of arrival (TOAs) via template matching.
- Measure phase shift between observed and predicted profiles
- Subtract model-predicted phase shift from measured phase shift
- Multiply by model-predicted period & add to midpoint time
- Voila: a TOA

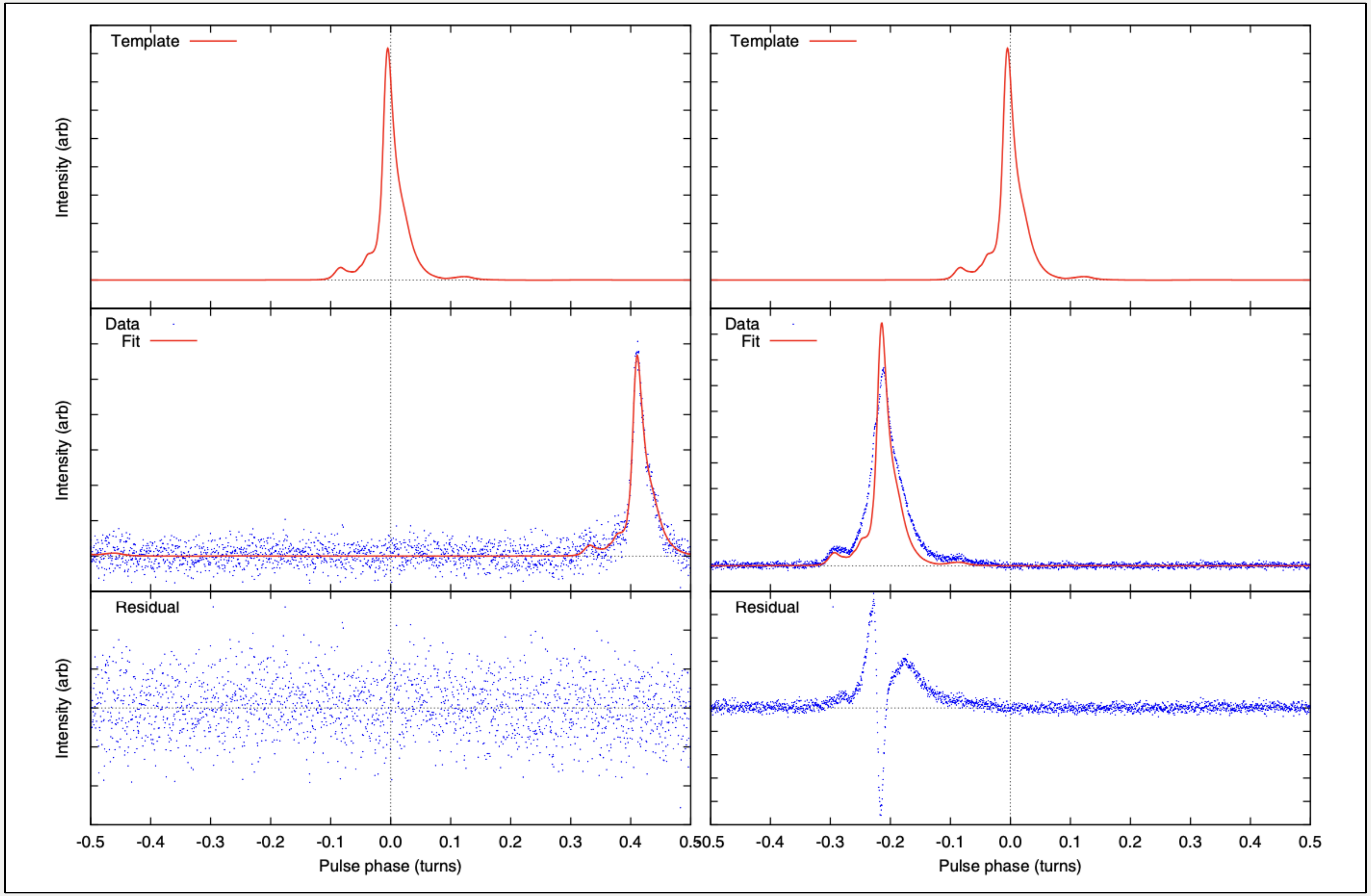
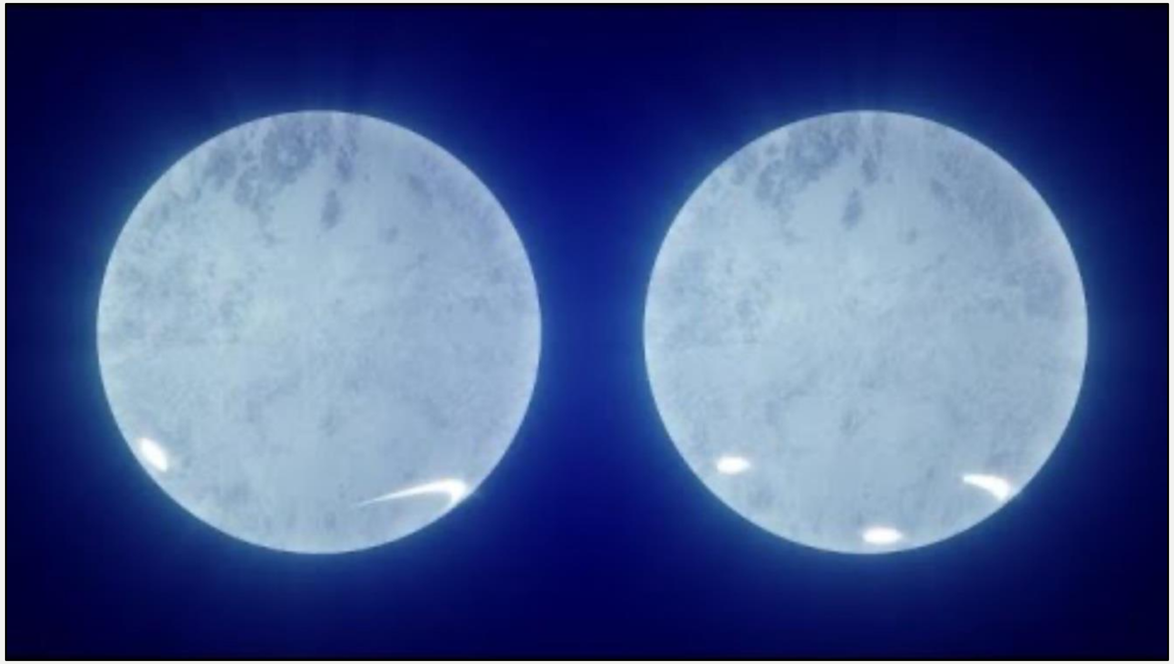


Image Credit: Lommen & Demorest 2013

Observing pulsars in the X-ray and Gamma Ray

- Neutron stars are also visible at very high frequencies – x-ray and gamma-ray.
- Both are increasingly important in pulsar astronomy, but not (yet!) much used in PTA astronomy.
- X-ray astronomy gives us access more of the neutron star than the beam!
- Video: surface map of J0030+0451



Video credit: NASA (NICER)

HOW DO WE FIND NEW PULSARS?

Pulsar Searching
The PRESTO tutorial

- Commonly used "standard" pulsar searching software: https://github.com/scottransom/presto
- Tutorial available here: https://www.cv.nrao.edu/~sransom/PRESTO_search_tutorial.pdf
- We're not formally doing a search tutorial, but this is easy to follow and worth a look if you're interested in pulsar searching.