Clocking Dead Stars With Radio Telescopes

Joe Swiggum
FYRE (PHYS 194)

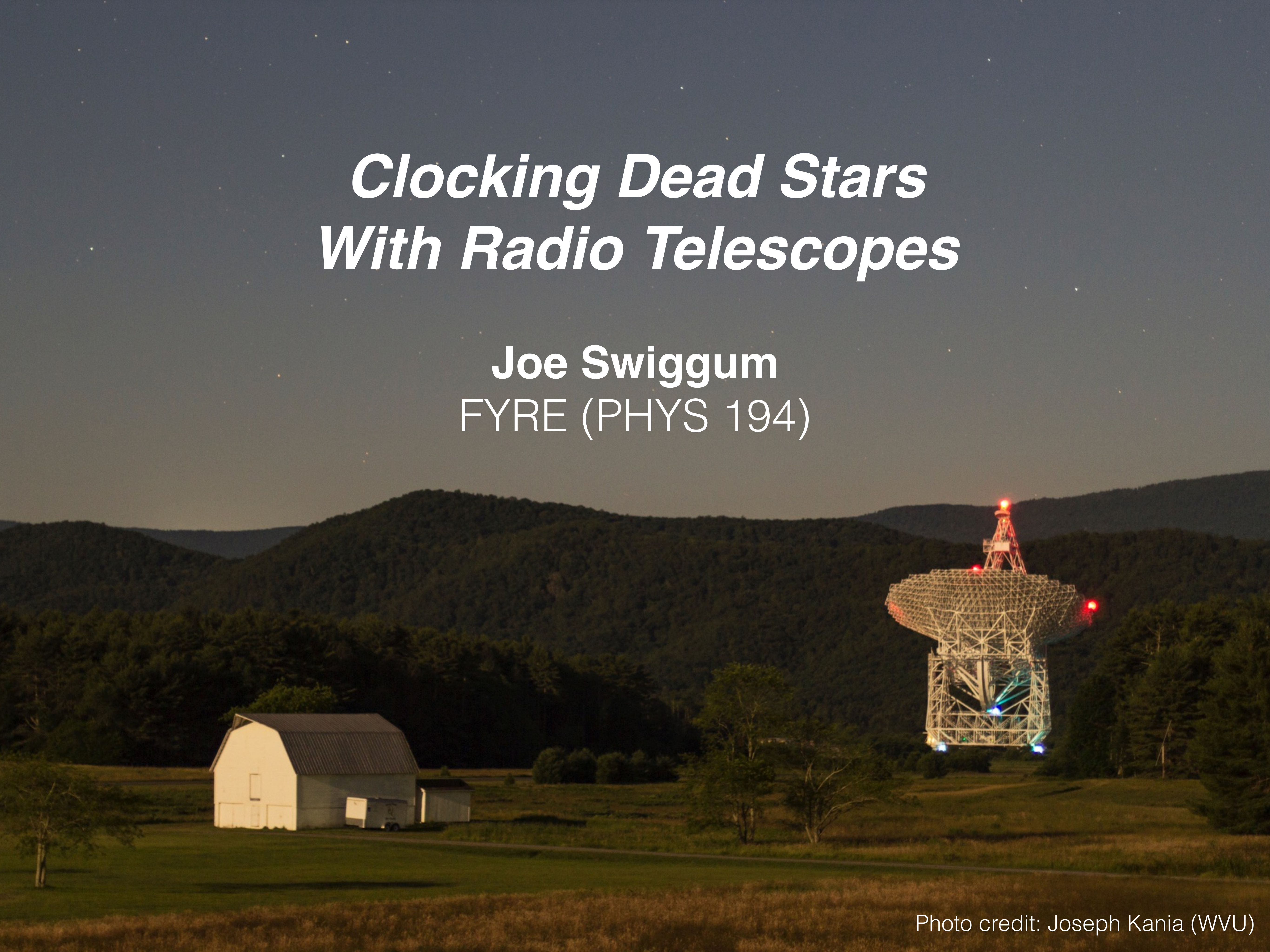
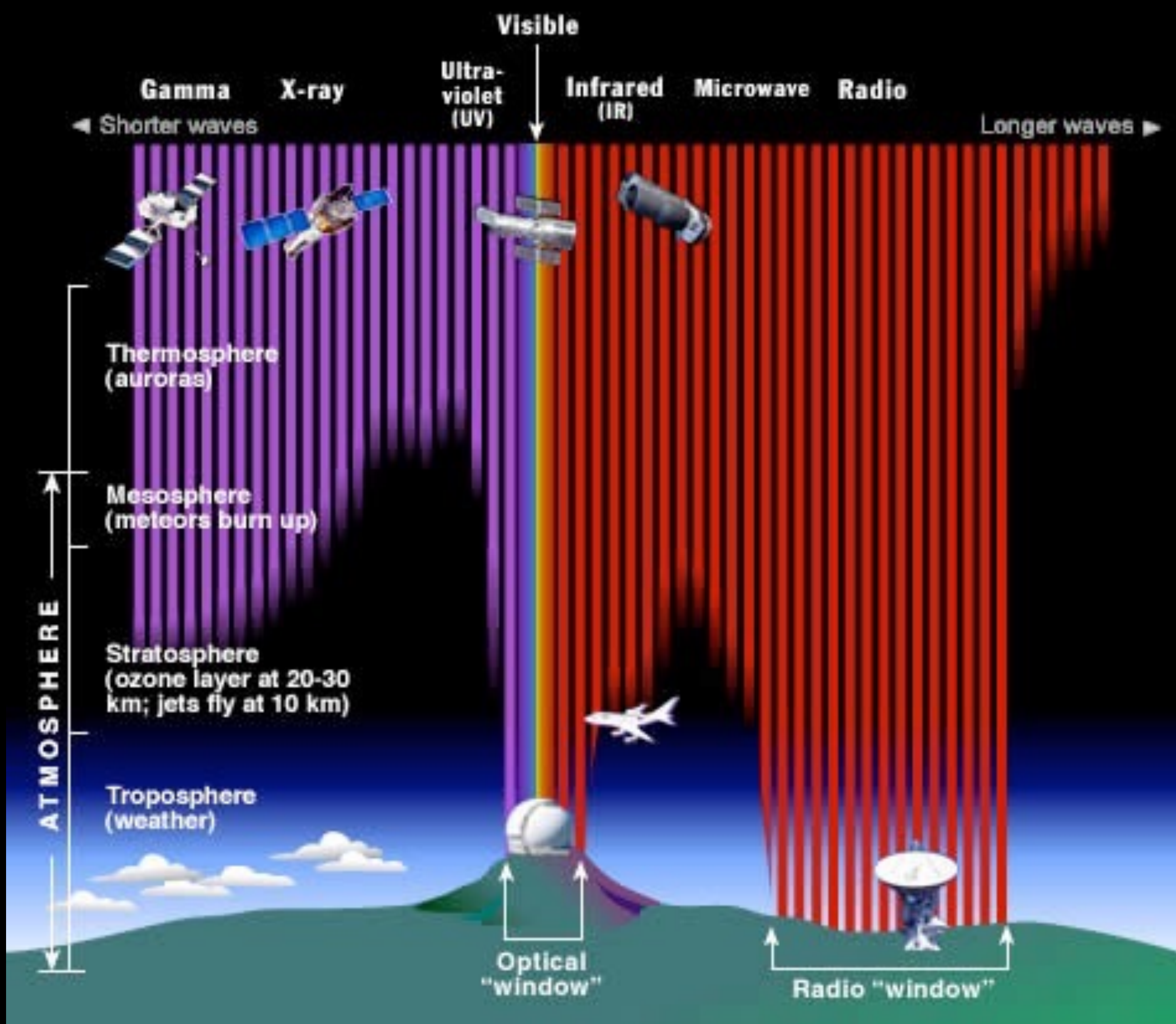


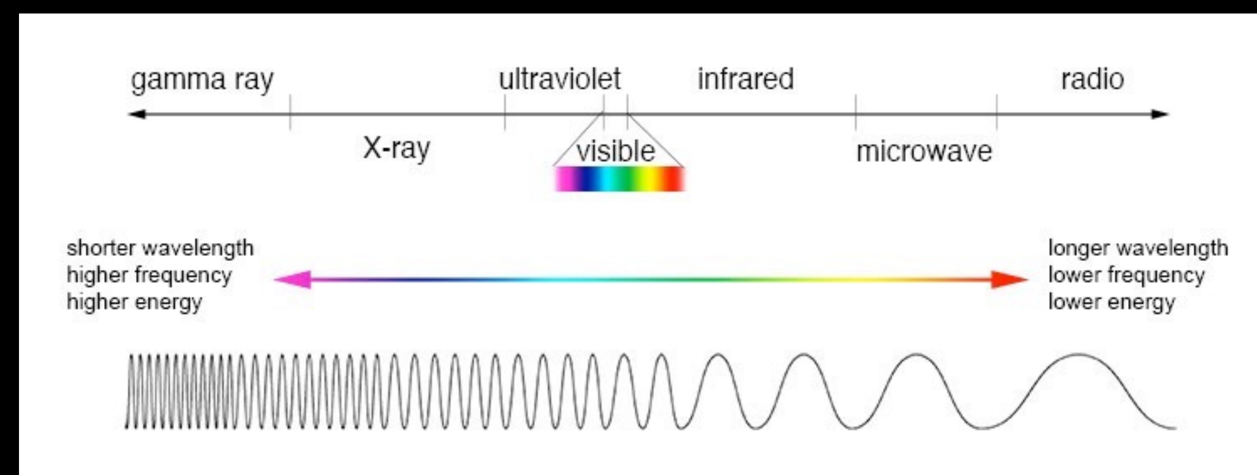
Photo credit: Joseph Kania (WVU)

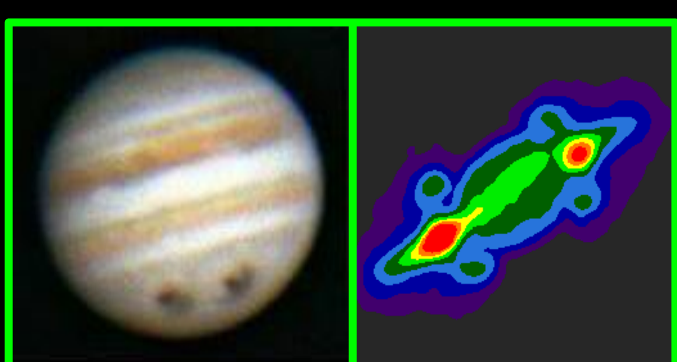
Course Goals

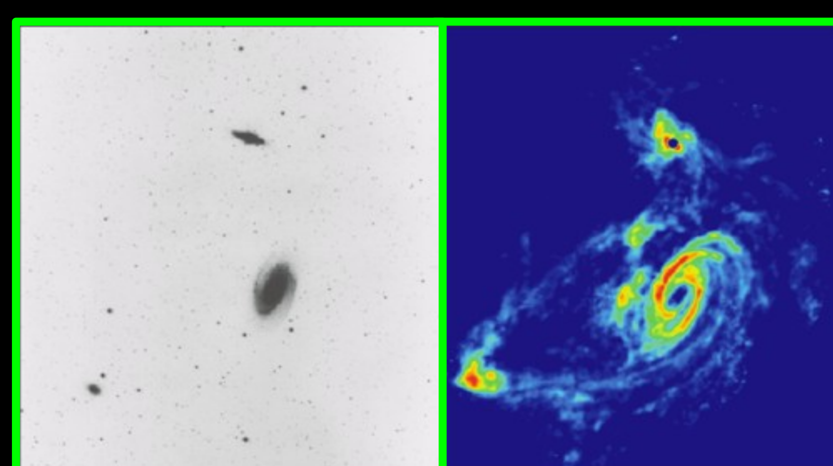
- Learn about pulsars and **radio astronomy**
- Learn basic Unix commands and python **programming**
- Learn to **observe remotely** with the Green Bank Telescope
- With **pulsar timing**, “solve” newly-discovered solitary pulsars in pairs and a binary pulsar as a class
- **Write proposals** for telescope time

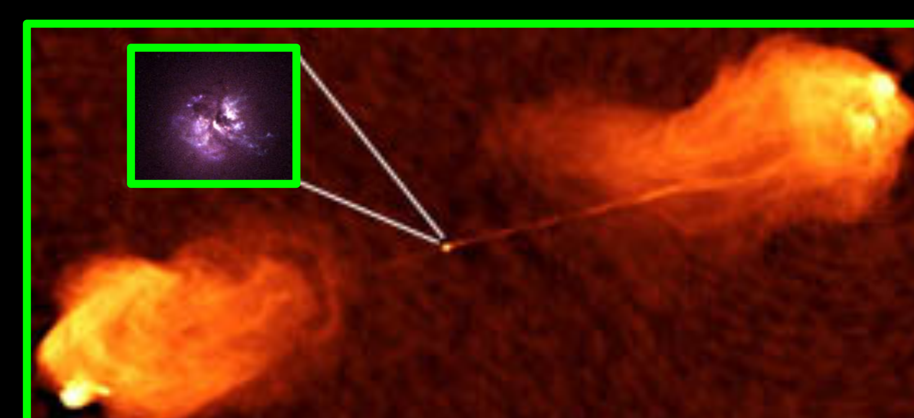
Radio Astronomy



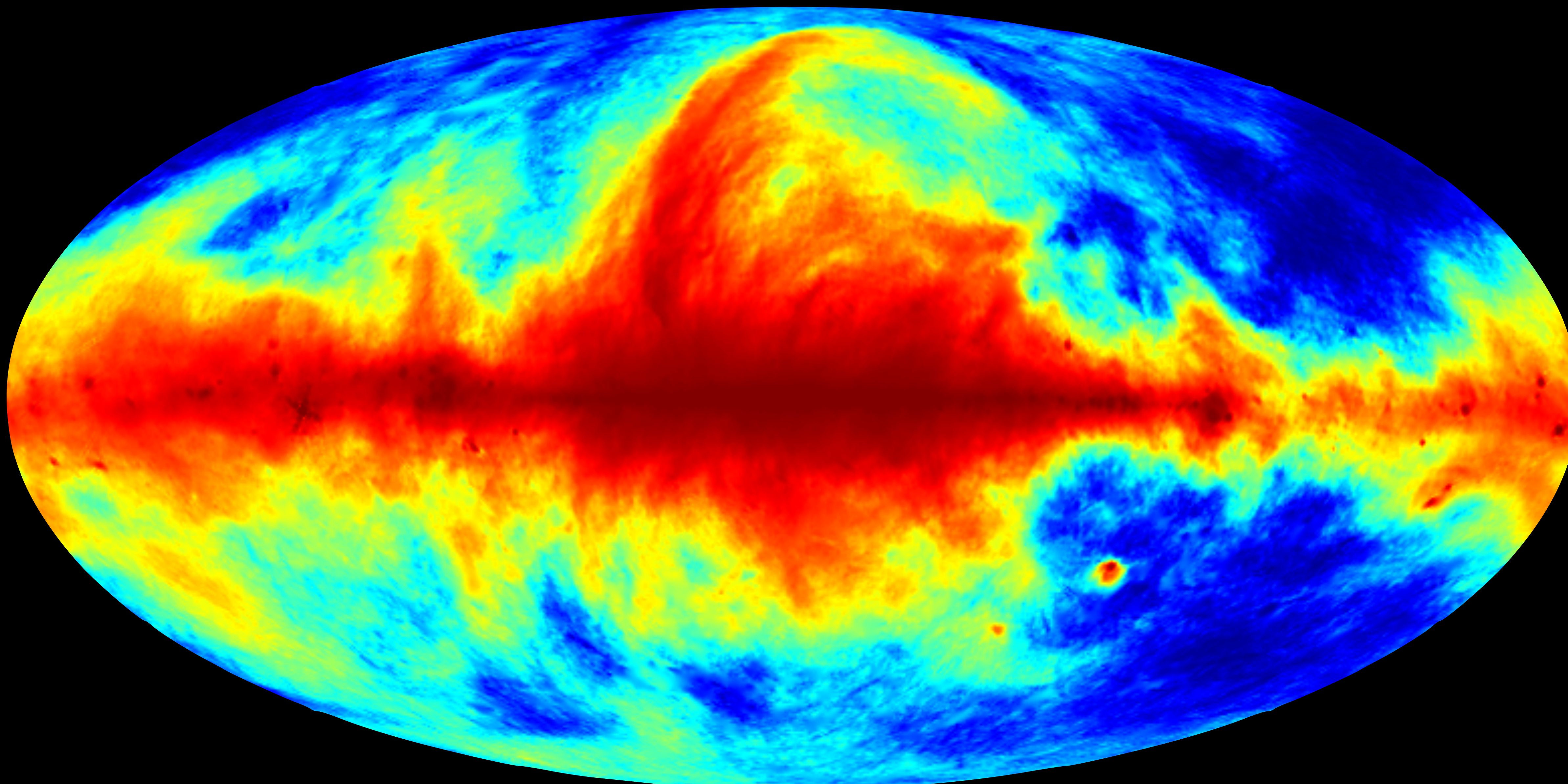








Radio Sky at 408 MHz



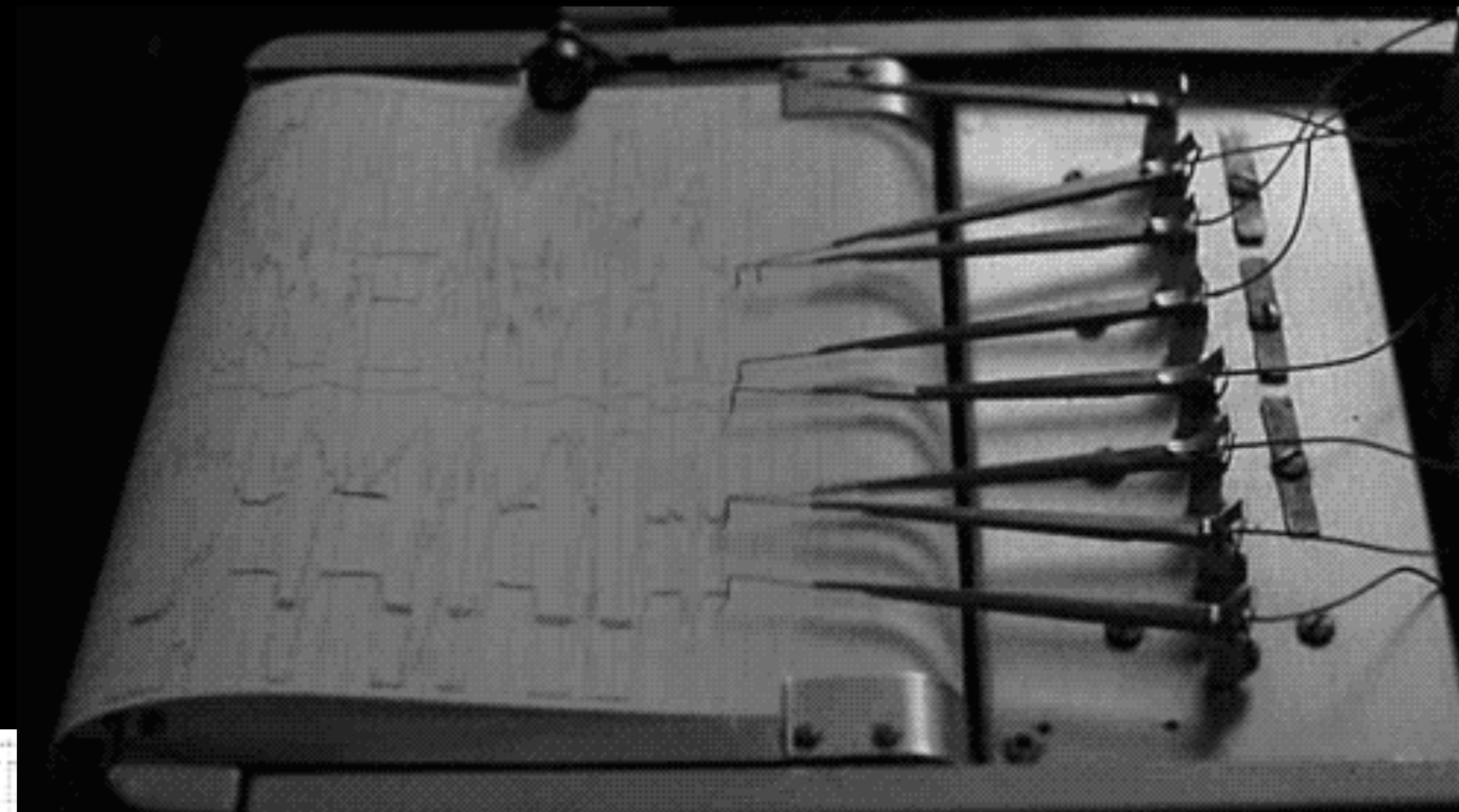
Radio Sky at 4.85 GHz

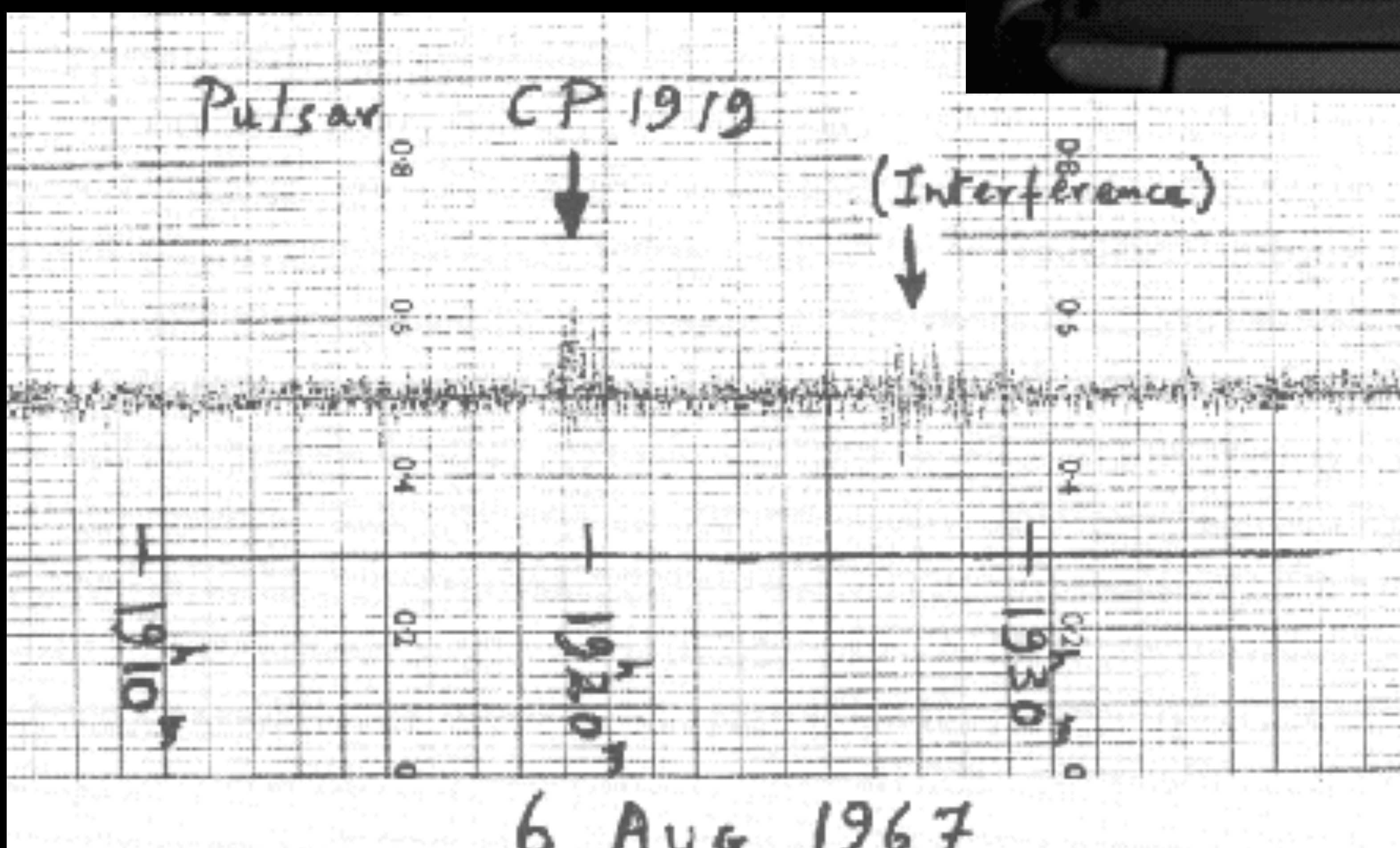
The Discovery of Pulsars

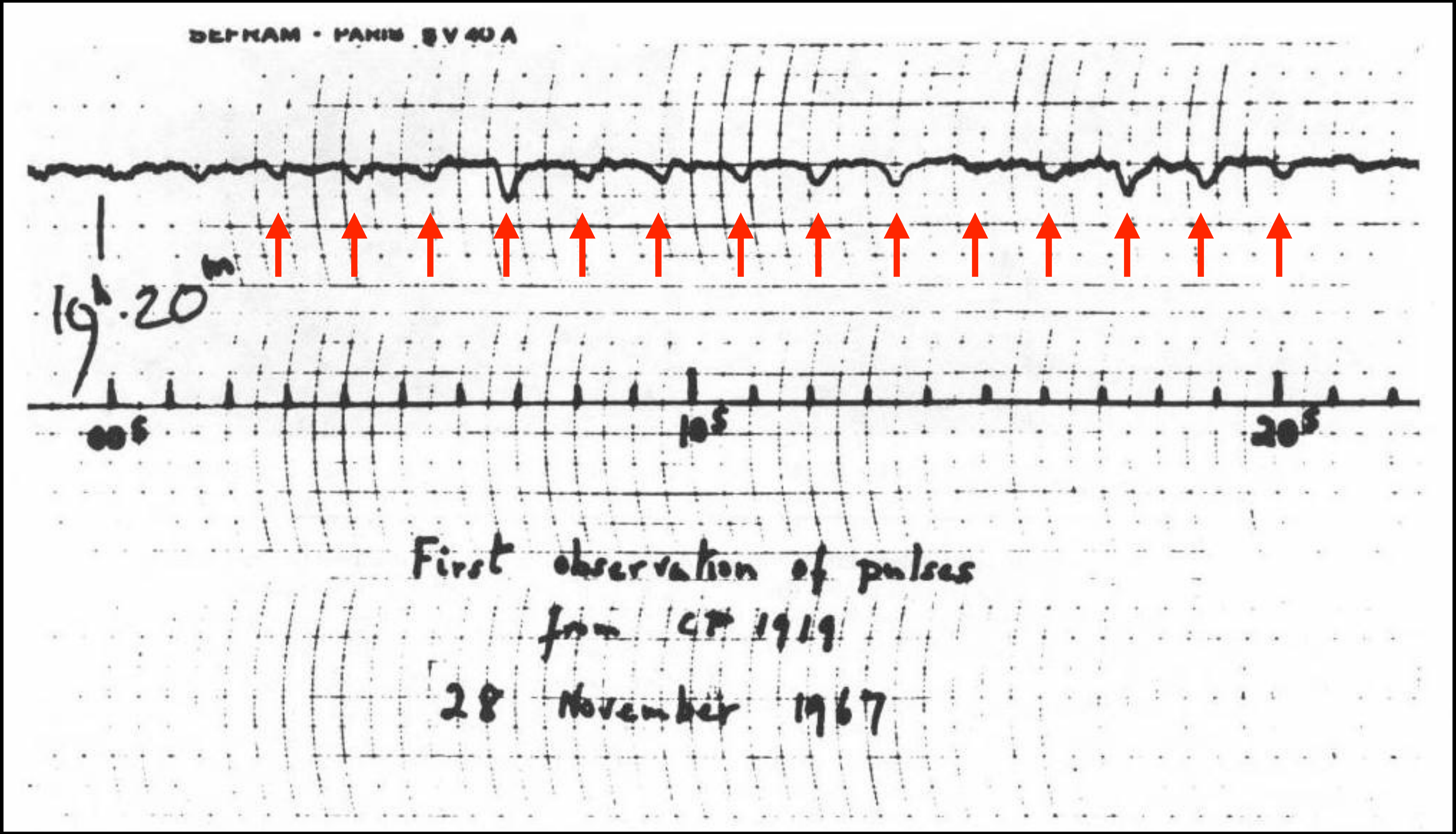
Anthony Hewish

Jocelyn Bell-Burnell

“A Bit of Scruff”



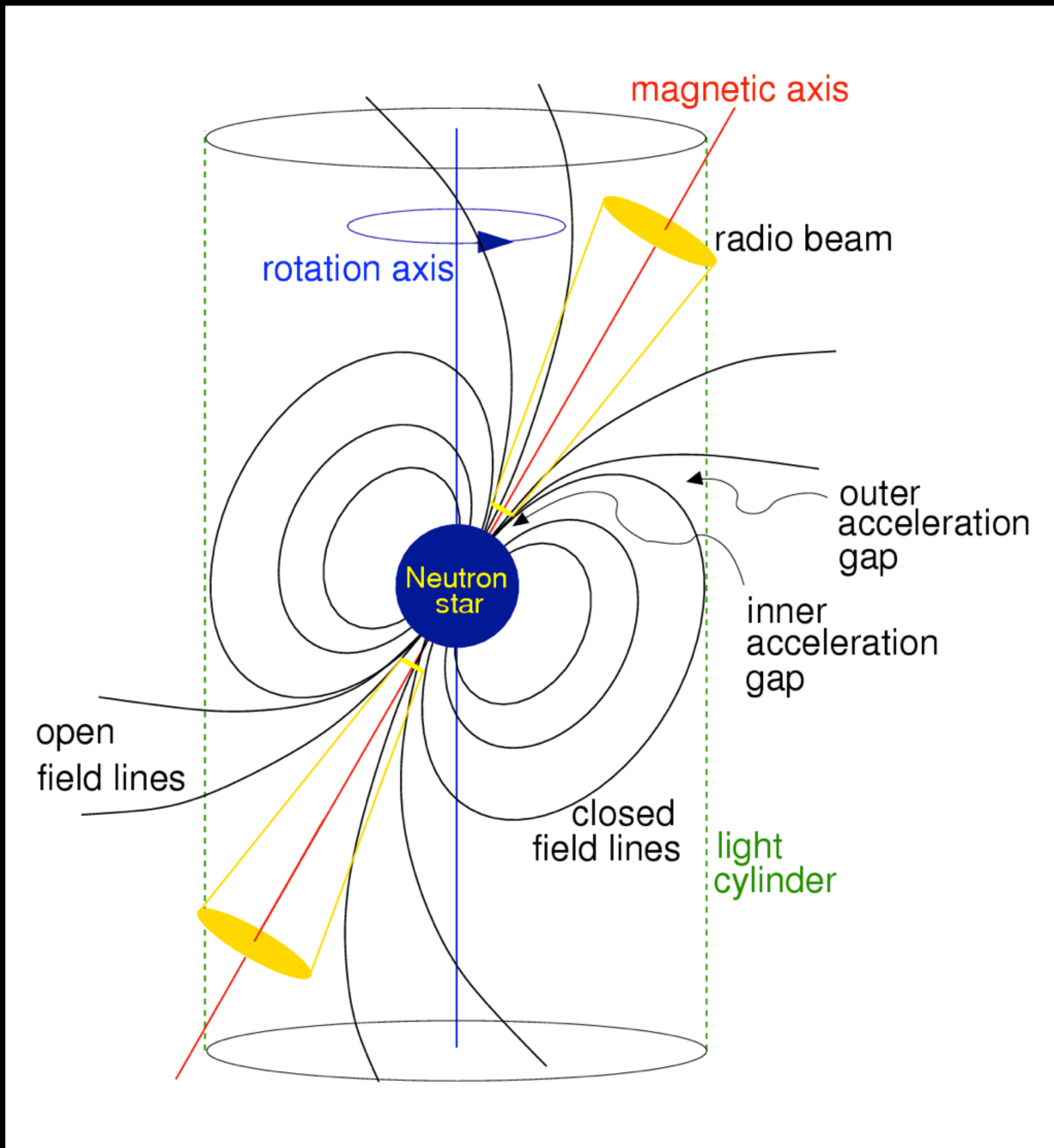


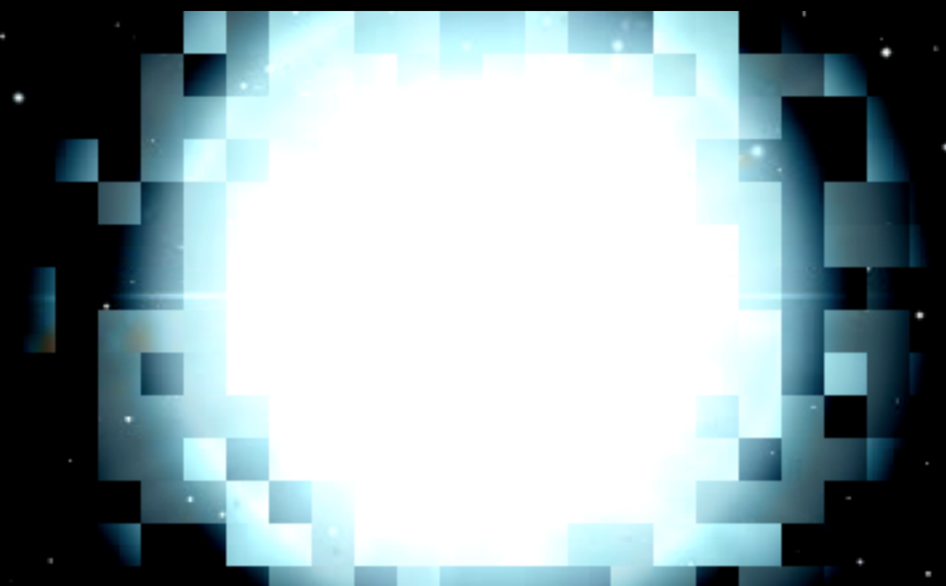


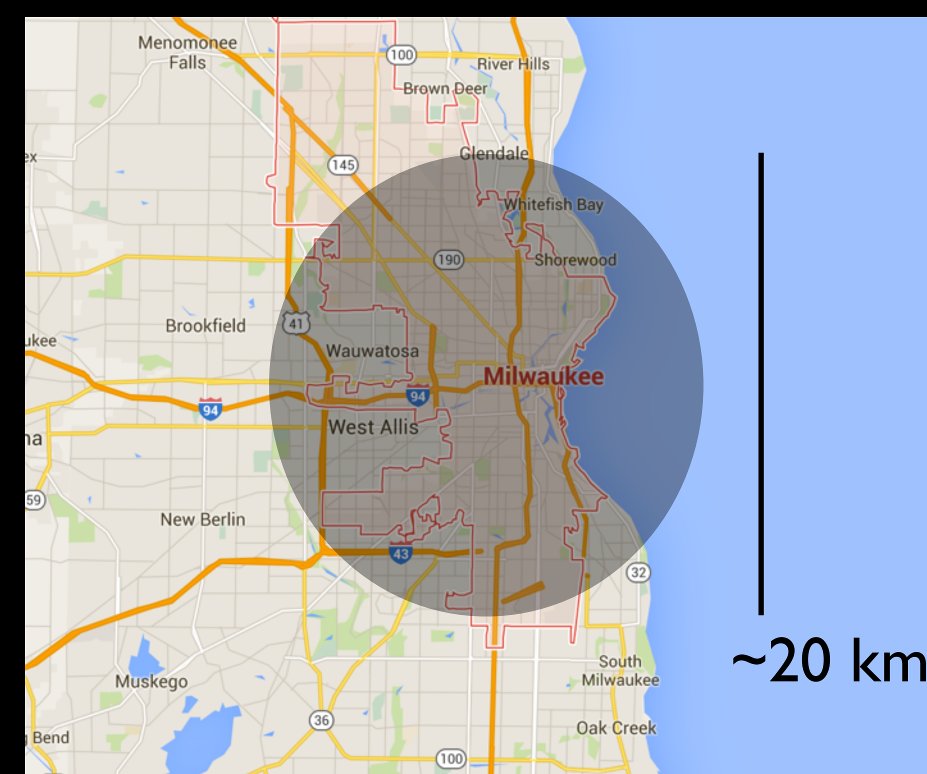
“This is where our problems started.”
- Jocelyn Bell-Burnell

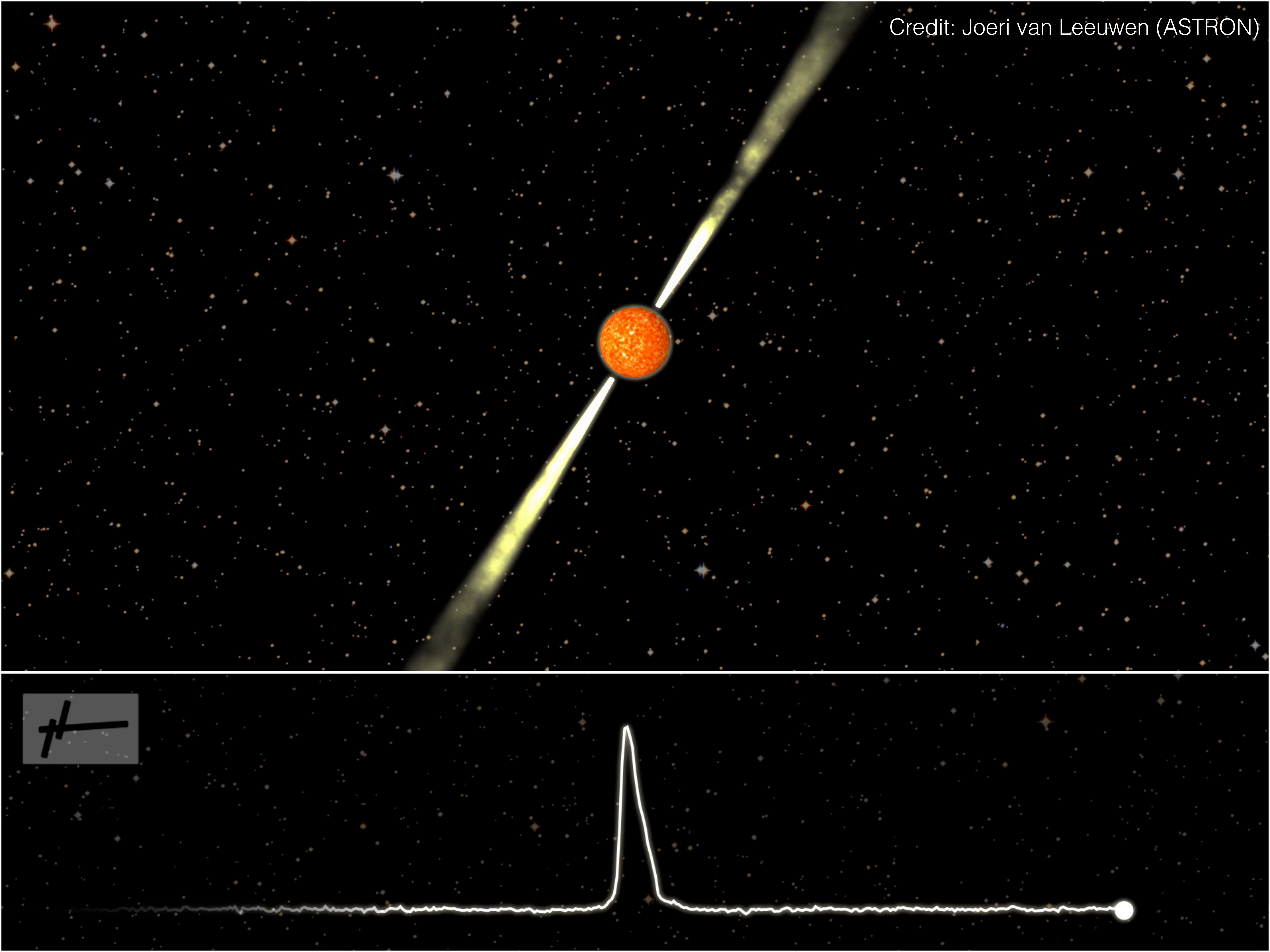
Jocelyn Bell at 50 Years of Pulsars Conference
in Jodrell Bank, Sep. 4-8, 2017

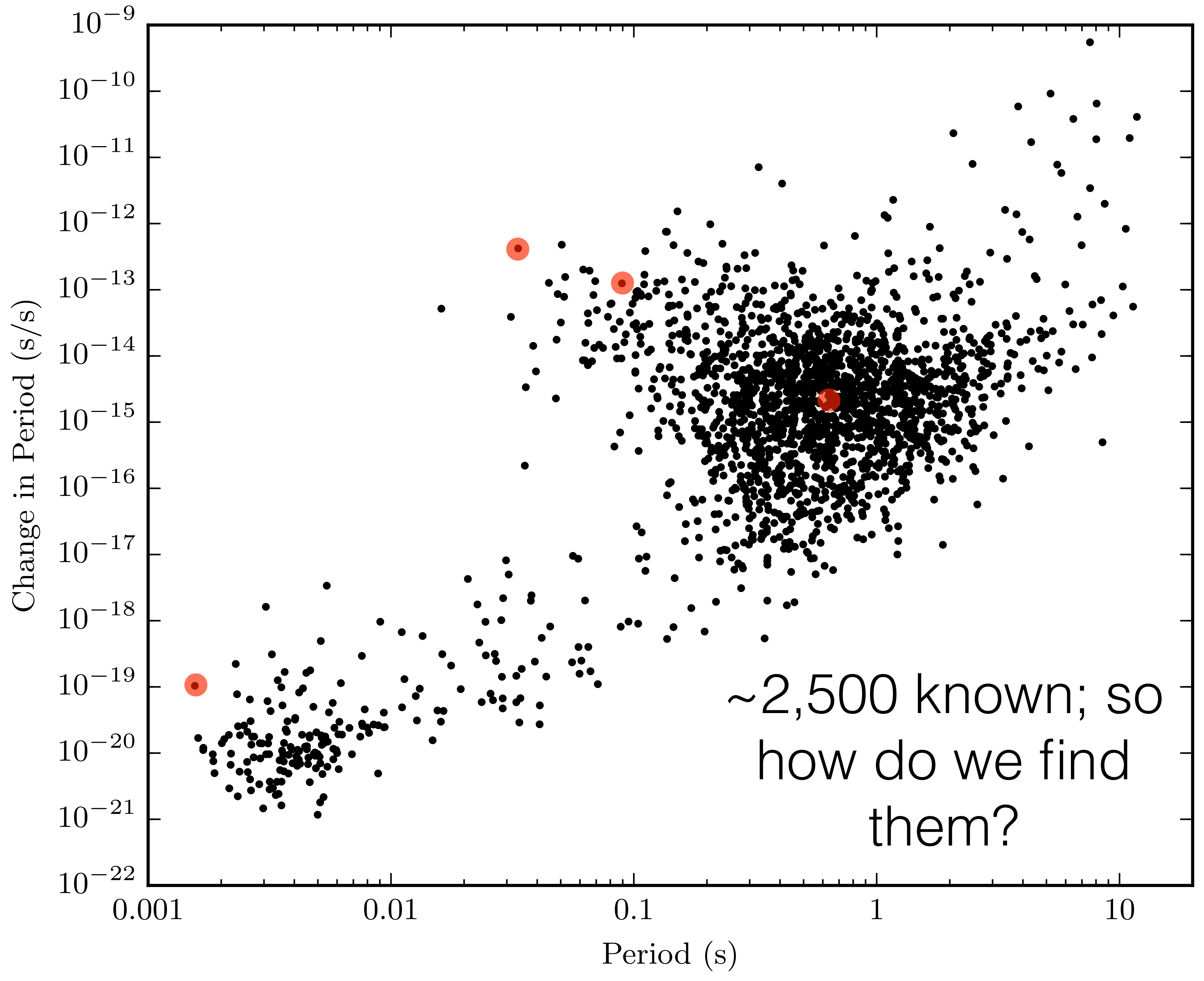
What is a pulsar?








Credit: Joeri van Leeuwen (ASTRON)



~2,500 known; so how do we find them?
Change in Period (s/s)
Period (s)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.01
0.1
1
10

Green Bank North Celestial Cap Survey (GBNCC)

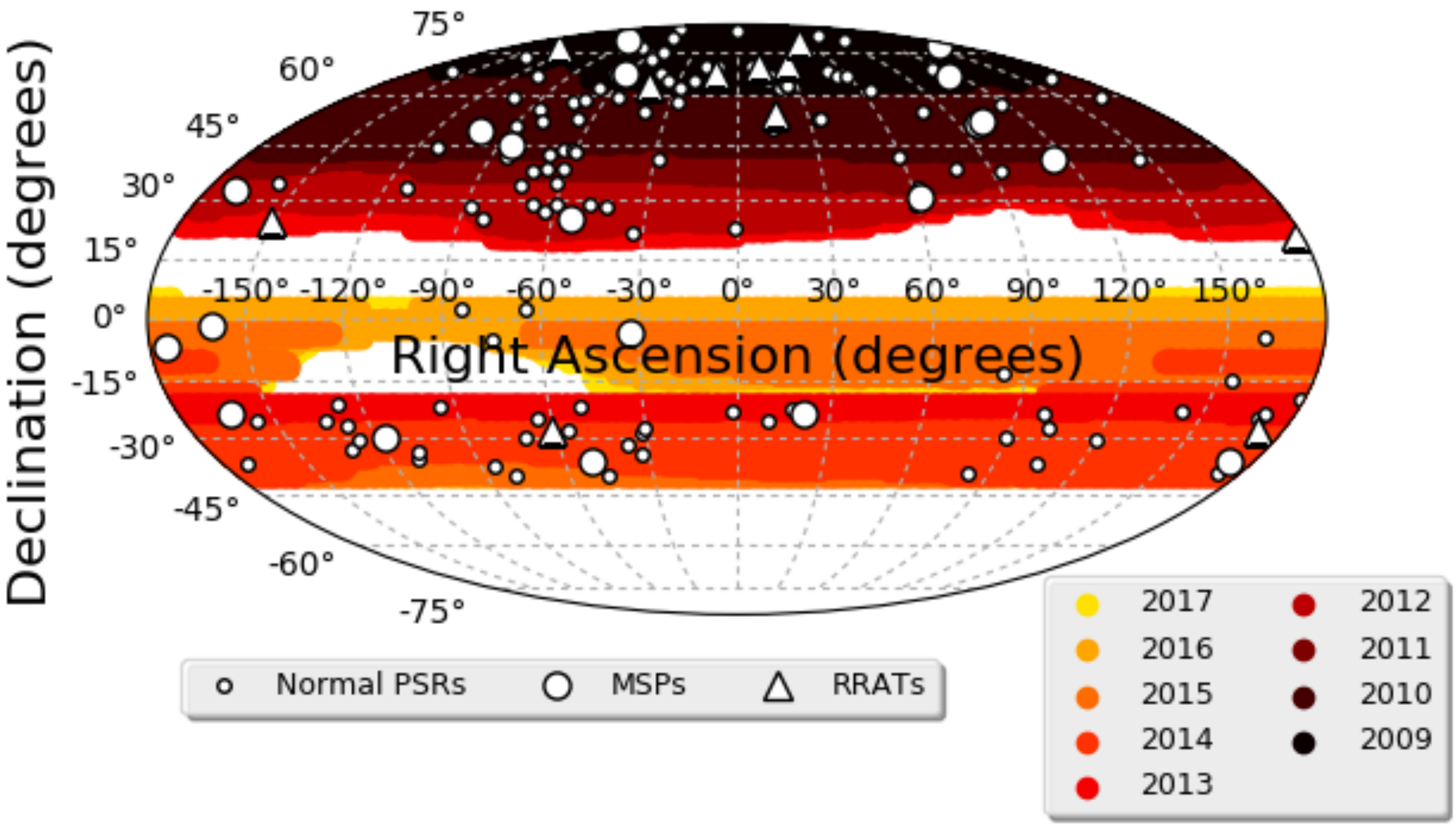
- 350 MHZ pulsar survey commenced in 2009 with the 100-meter Green Bank Telescope.

- 140-second “pointings” on the sky.

- Data collected over 100 MHz of *bandwidth*, with 82-microsecond *time resolution*, and 4096 *frequency channels*.

- Currently about 80% complete.

GBNCC progress: 89636 beams observed



GBNCC ~~is~~ was observing as we ~~speak~~ spoke!

DYNAMIC SCHEDULING SYSTEM

Search | ICAL GBT Schedule

Support Center | My Home | Docs | Logout

GBT Schedule

Wednesday September 06, 2017 10:48 EDT

Start: 09/06/2017 **Days:** 5 **Time Zone:** ET View Schedule

Historical Schedules | **Printer Friendly Schedule**

** The project ID links in the below schedule will bring the user to the appropriate page in the DSS (login required)**

2017-09-06 (ET)	Type	Project ID	Project Title	PI	Friend	Rcvrs	Frequency (GHz)	Backends
+00:00 - 02:00	A	GBT17B-999	Breakthrough Listen Project	Siemion	Maddalena	L, S, X, C	1.15 - 1.73, 1.73 - 2.60, 8.00 - 10.00, 3.85 - 8.00	Other
02:00 - 08:00	A	GBT17B-325	Continuing the GBT All-Sky 350-MHz Pulsar Survey	Stovall	Lynch	342	0.29 - 0.40	GUPPI
08:00 - 12:30	A	GBT17B-374	Mapping HI in Extremely Isolated Early-Type Galaxies	Marcum	Frayer	L	1.15 - 1.73	VEGAS
12:30 - 18:00	A	GBT17B-325	Continuing the GBT All-Sky 350-MHz Pulsar Survey	Stovall	Lynch	342	0.29 - 0.40	GUPPI
18:00 - 23:15	A	GBT17B-173	The GBT Diffuse Ionized Gas Survey (GDIGS)	Anderson	Cunningham	C	3.85 - 8.00	VEGAS
23:15 - 00:00+	A	GBT17B-325	Continuing the GBT All-Sky 350-MHz Pulsar Survey	Stovall	Lynch	800	0.68 - 0.92	GUPPI
2017-09-07 (ET)	**Type**	**Project ID**	**Project Title**	**PI**	**Friend**	**Rcvrs**	**Frequency (GHz)**	**Backends**
+00:00 - 02:00	A	GBT17B-325	Continuing the GBT All-Sky 350-MHz Pulsar Survey	Stovall	Lynch	800	0.68 - 0.92	GUPPI
02:00 - 05:15	A	GBT17B-999	Breakthrough Listen Project	Siemion	Maddalena	L, S, X, C	1.15 - 1.73, 1.73 - 2.60, 8.00 - 10.00, 3.85 - 8.00	Other
05:15 - 08:00	A	GBT17B-325	Continuing the GBT All-Sky 350-MHz Pulsar Survey	Stovall	Lynch	342	0.29 - 0.40	GUPPI
08:00 - 12:00	M	Maintenance	Maintenance day- Add: 800 , Remove: 342	Chestnut	Minter	800, L, S, C, X, Hol, KFPA, ARGUS		
12:00 - 13:30	T	TGBT10A_500	Receiver Checkout - 800	Minter	Minter	800		VEGAS
13:30 - 15:30	T	TGBT10A_500	Receiver Checkout - Holography	Minter	Minter	Hol		VEGAS
15:30 - 18:30	A	GBT17A-012	HI-MaNGA: HI Followup for MaNGA Galaxies	Masters	Cunningham	L	1.15 - 1.73	VEGAS
18:30 - 00:00	A	GBT17B-173	The GBT Diffuse Ionized Gas Survey (GDIGS)	Anderson	Cunningham	C	3.85 - 8.00	VEGAS
2017-09-08 (ET)	**Type**	**Project ID**	**Project Title**	**PI**	**Friend**	**Rcvrs**	**Frequency (GHz)**	**Backends**
00:00 - 07:00	A	GBT17B-155	The Distribution of Optically-Thick Gas in the Halo of Andromeda	Howk	Lockman	L	1.15 - 1.73	VEGAS
07:00 - 08:00	A	GBT17A-421	Confirming HI emission in a gravitationally lensed galaxy. - copy	Hunt	Lewandowska,Perera	800	0.68 - 0.92	VEGAS
08:00 - 16:30	M	Maintenance	Maintenance day- Add: MBA2 ,	Chestnut	Minter	800, L, S, C, X, Hol, KFPA, ARGUS, MBA2		
18:00 - 18:45	A	GBT17A-477	Timing of five faint pulsars	Lorimer	Lynch	800	0.68 - 0.92	GUPPI,VPM
2017-09-09 (ET)	**Type**	**Project ID**	**Project Title**	**PI**	**Friend**	**Rcvrs**	**Frequency (GHz)**	**Backends**
07:45 - 11:00	A	GBT17B-999	Breakthrough Listen Project	Siemion	Maddalena	L, S, X, C	1.15 - 1.73, 1.73 - 2.60, 8.00 - 10.00, 3.85 - 8.00	Other
18:00 - 18:45	A	GBT17A-477	Timing of five faint pulsars	Lorimer	Lynch	800	0.68 - 0.92	GUPPI,VPM
2017-09-10 (ET)	**Type**	**Project ID**	**Project Title**	**PI**	**Friend**	**Rcvrs**	**Frequency (GHz)**	**Backends**
00:30 - 02:00	A	GBT17B-210	Evolution of High Brightness Temperature AGN Cores with RadioAstron	Kovalev	Ghigo	KFPA	17.00 - 27.50	VLBA
00:35 - 01:40		140' C-Band Transmissions						
04:30 - 06:00	A	GBT17B-210	Evolution of High Brightness Temperature AGN Cores with RadioAstron	Kovalev	Ghigo	L	1.15 - 1.73	VLBA
04:35 - 05:40		140' C-Band Transmissions						
11:00 - 13:00	A	GBT17B-999	Breakthrough Listen Project	Siemion	Maddalena	L, S, X, C	1.15 - 1.73, 1.73 - 2.60, 8.00 - 10.00, 3.85 - 8.00	Other
16:15 - 17:00	A	GBT17A-477	Timing of five faint pulsars	Lorimer	Lynch	800	0.68 - 0.92	GUPPI,VPM

https://dss.gb.nrao.edu/schedule/public


(Beam size~0.5 deg
@ 350 MHz)
Question: what is the *wavelength* of 300 MHz radio emission?
The Green Bank Telescope

To date, the GBNCC survey has found 156 new pulsars.

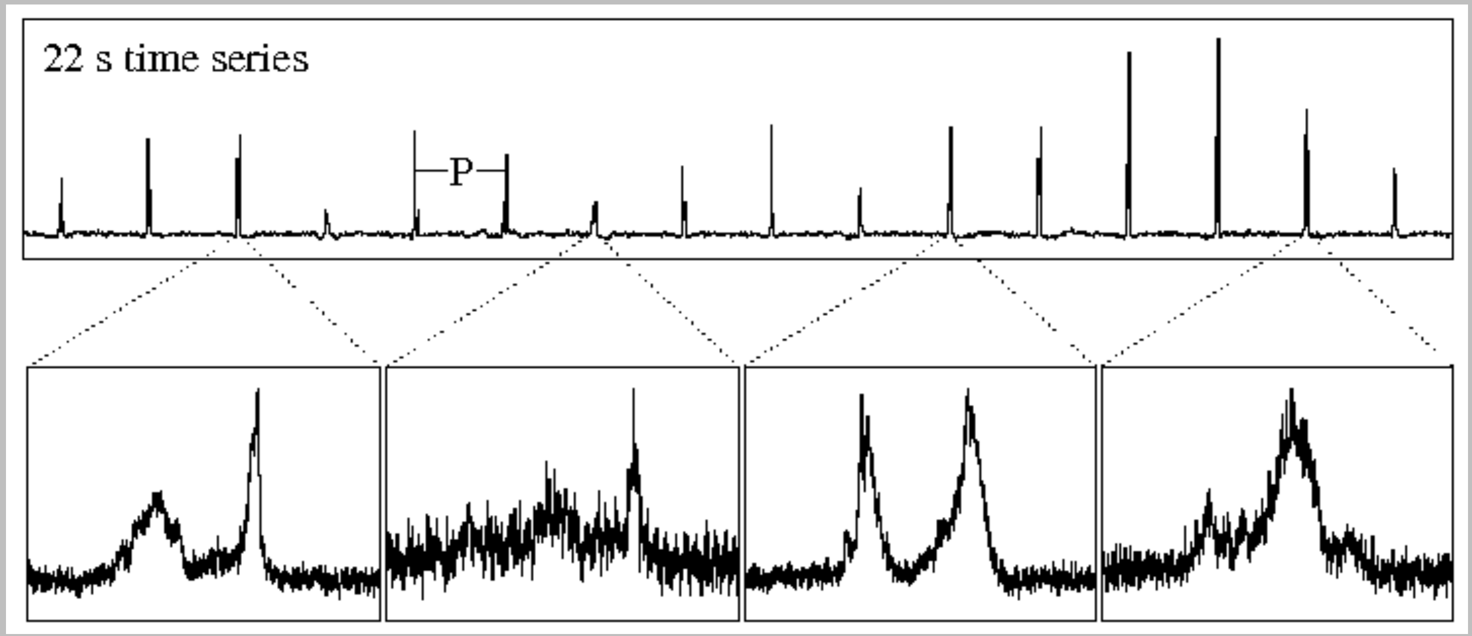
We need to *time* them!

Pulsar Timing: unambiguously accounting for every rotation of the star in order to learn as much as we can about the system.

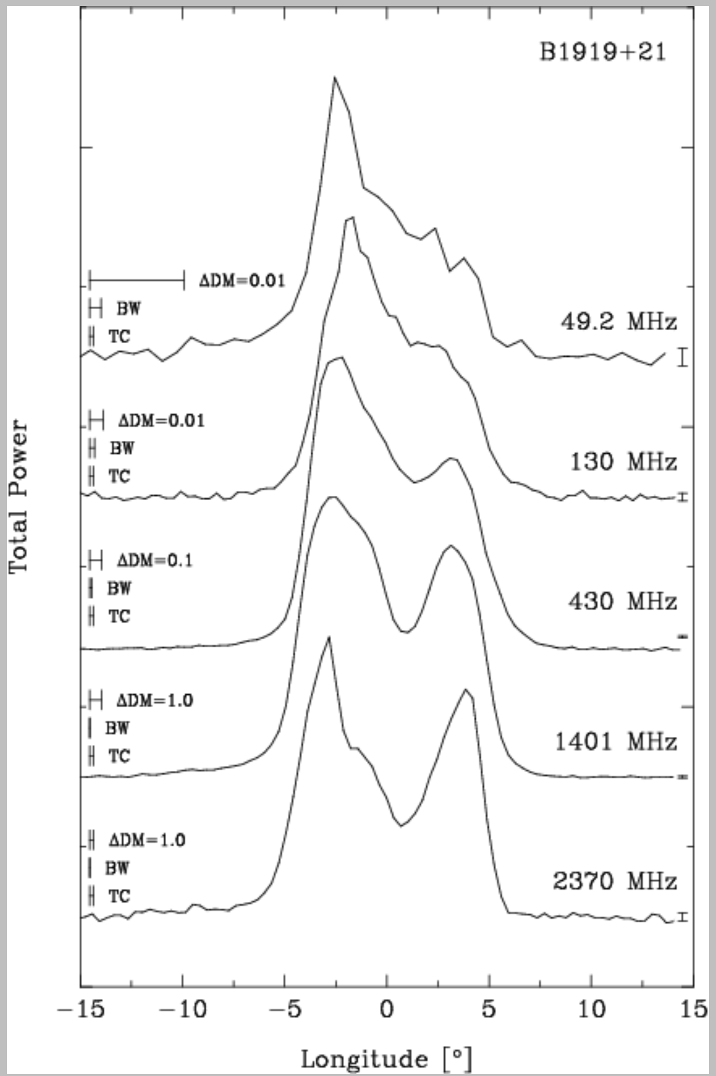
Measuring a Time of Arrival (TOA)

Single Pulses

B1919+21



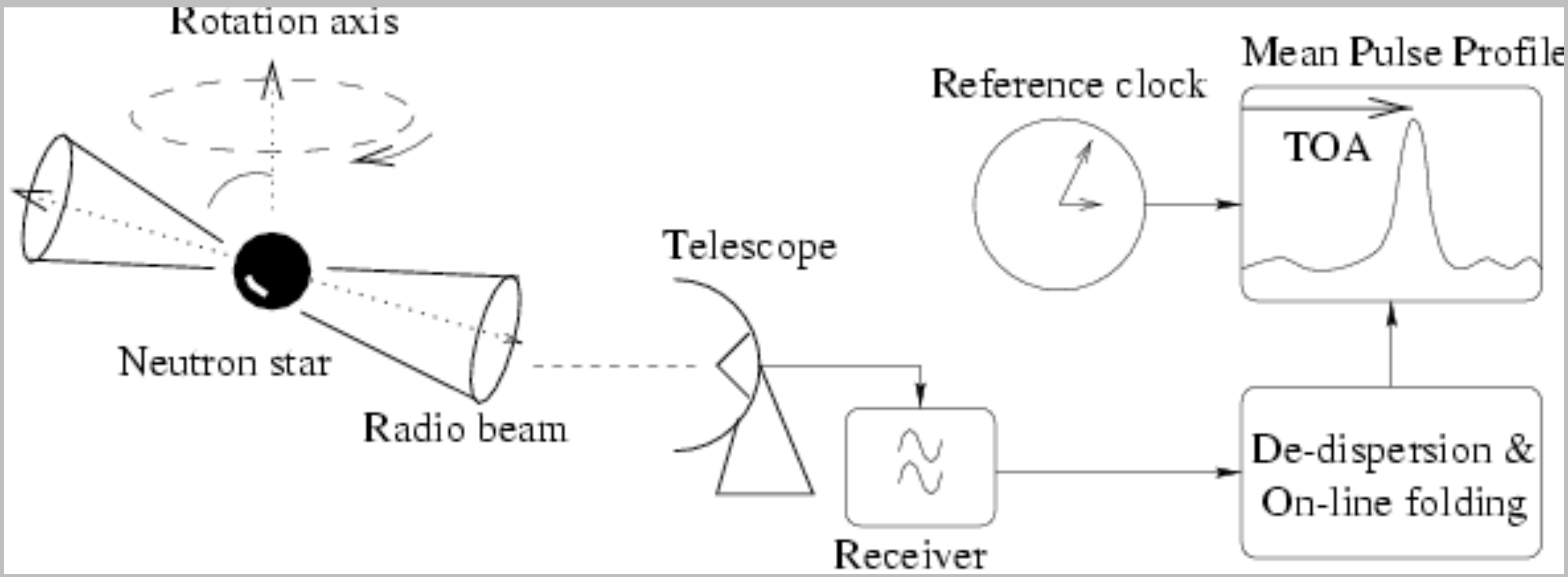
“Folded”
Mean Profile



Mean profiles often made up of 100s-1000s of folded single pulses. High S/N “standard” profiles are generated by fitting gaussians or by averaging profiles from many epochs.

Figures courtesy of *Handbook of Pulsar Astronomy* (Lorimer & Kramer 2004) and Hankins & Rankin (2008)

Measuring a “TOA”



Standard profile cross-correlated with mean pulse profile to generate a TOA.

Figure courtesy of *Handbook of Pulsar Astronomy* (Lorimer & Kramer 2004)

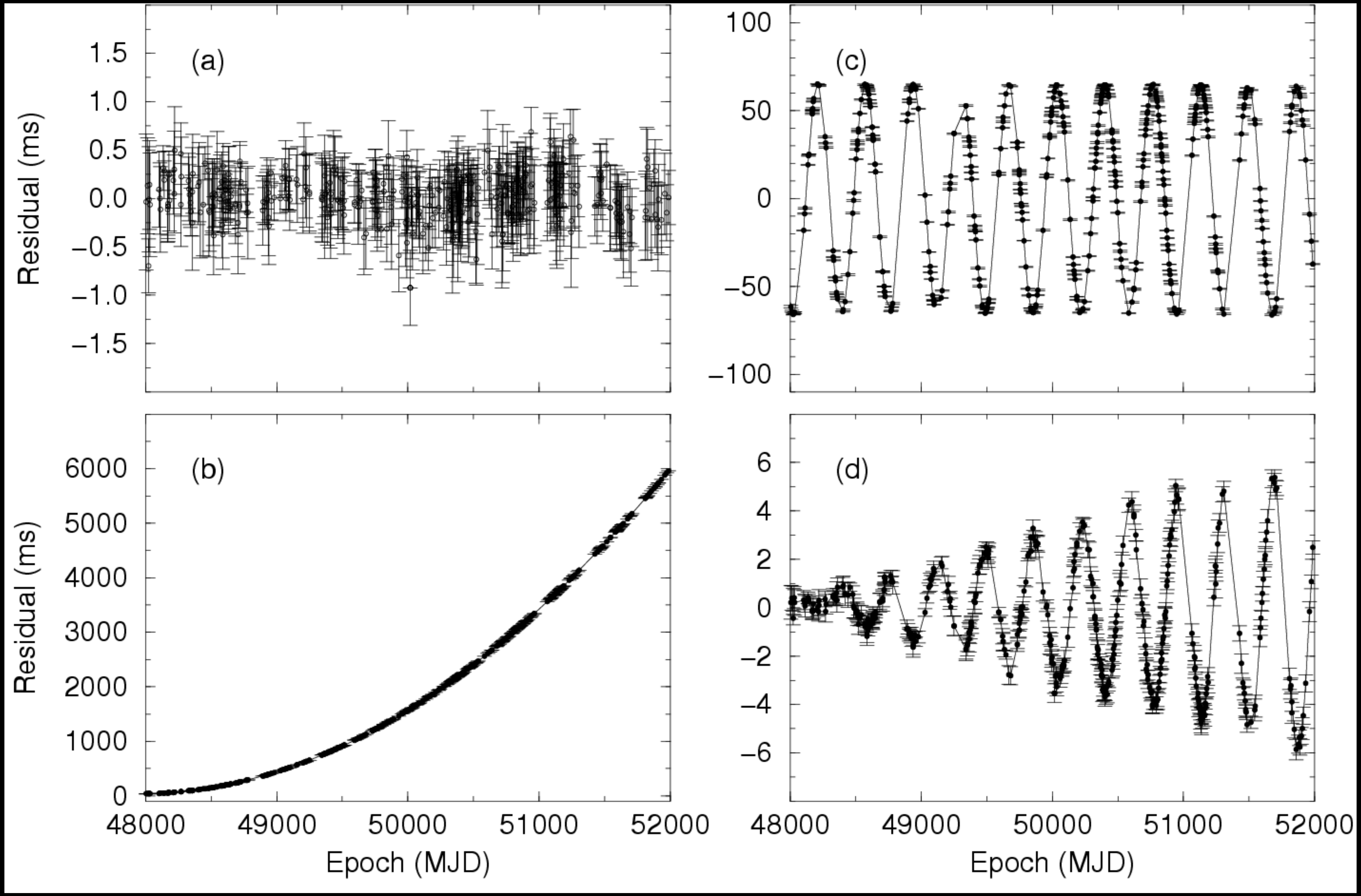
Residuals

Good fit!

Incorrect position.

Incorrect frequency derivative.

Incorrect proper motion



Timing Residual = (Measured - Predicted) TOA

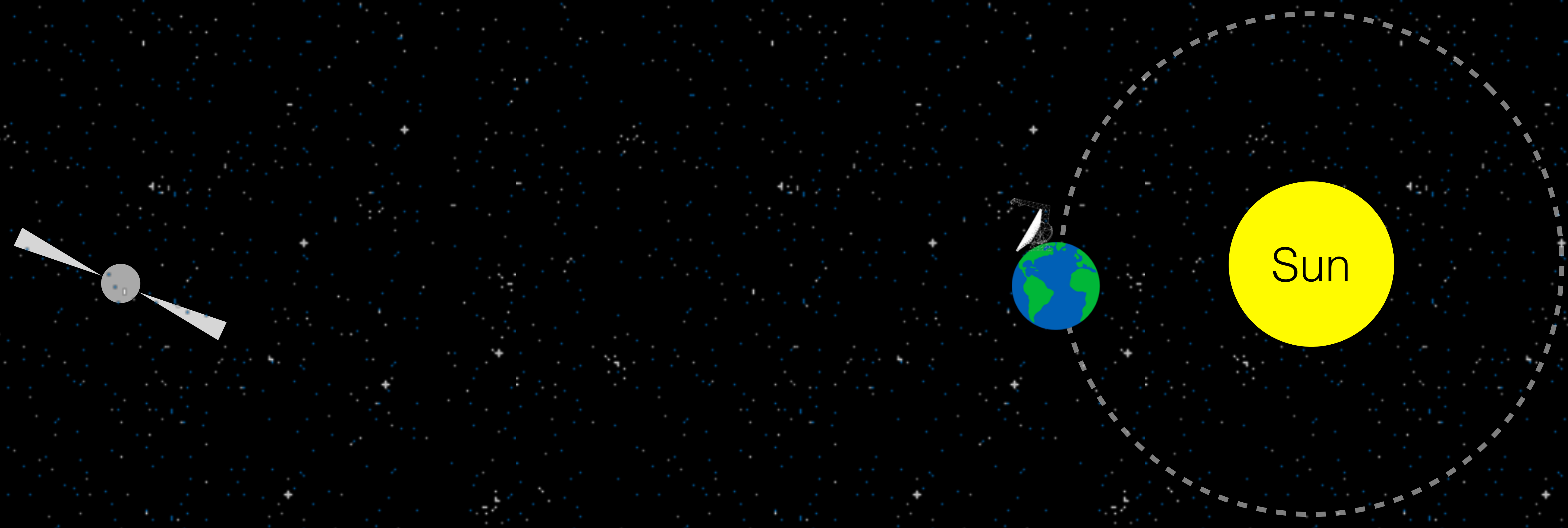
Figure courtesy of *Handbook of Pulsar Astronomy* (Lorimer & Kramer 2004)

Timing a Pulsar from Earth

Observatories on Earth are not in an inertial reference frame. Must correct topocentric TOAs (measured on Earth) to the solar system barycenter.

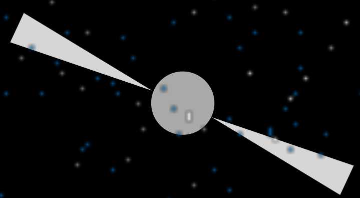
$$t_{\mathrm{bary}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} + t_{\mathrm{disp}} + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot}$$

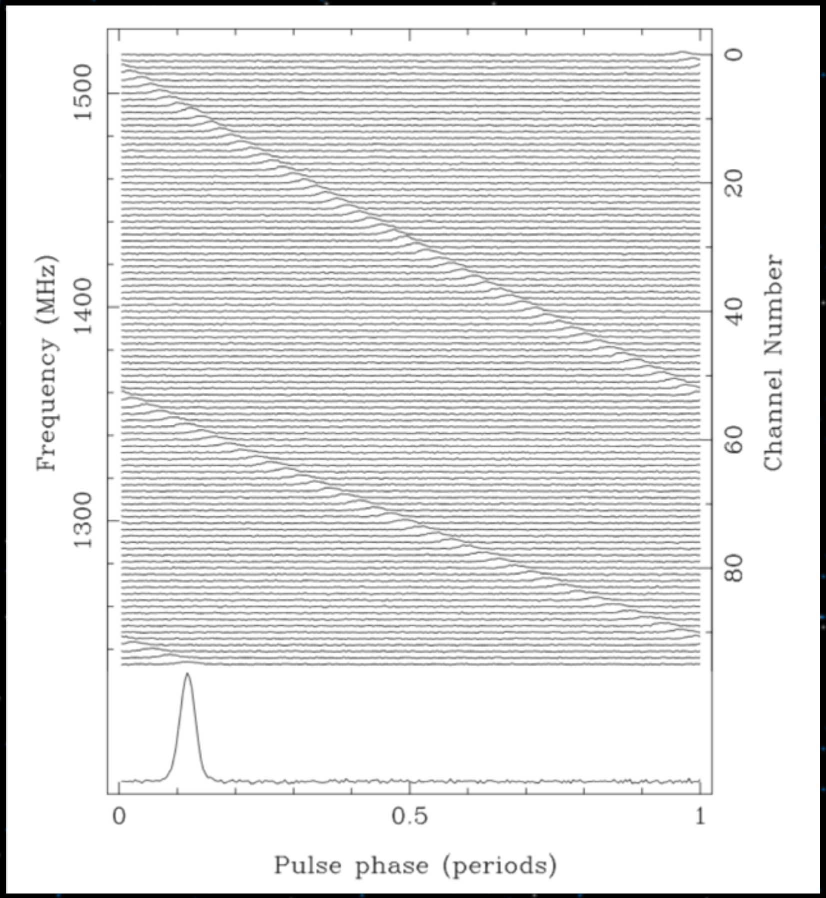
Correcting for delays allows us to measure lots of physical parameters!

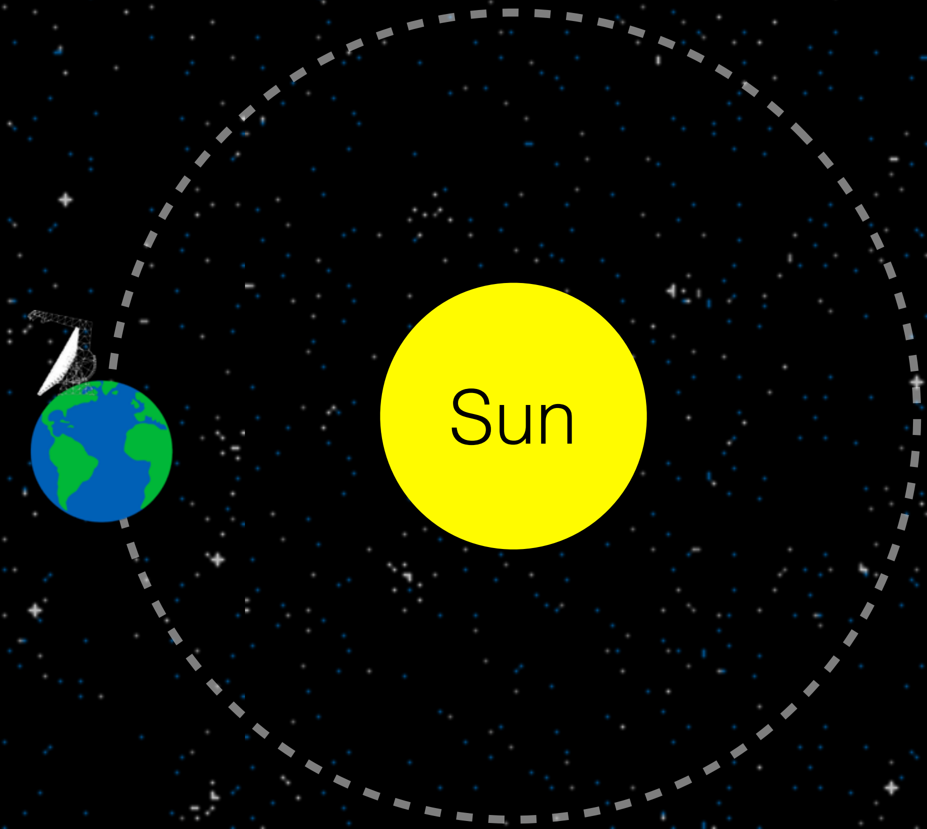


$$t_{\rm bary} = t_{\rm topo} + \boxed{t_{\rm corr}} + t_{\rm disp} + \Delta_{\rm R\odot} + \Delta_{\rm S\odot} + \Delta_{\rm E\odot}$$

Clock correction converts times measured locally to GPS, UT, then Barycentric Dynamical Time (TDB).







$$t_{\text{bary}} = t_{\text{topo}} + t_{\text{corr}} + \boxed{t_{\text{disp}}} + \Delta_{\text{R}\odot} + \Delta_{\text{S}\odot} + \Delta_{\text{E}\odot}$$

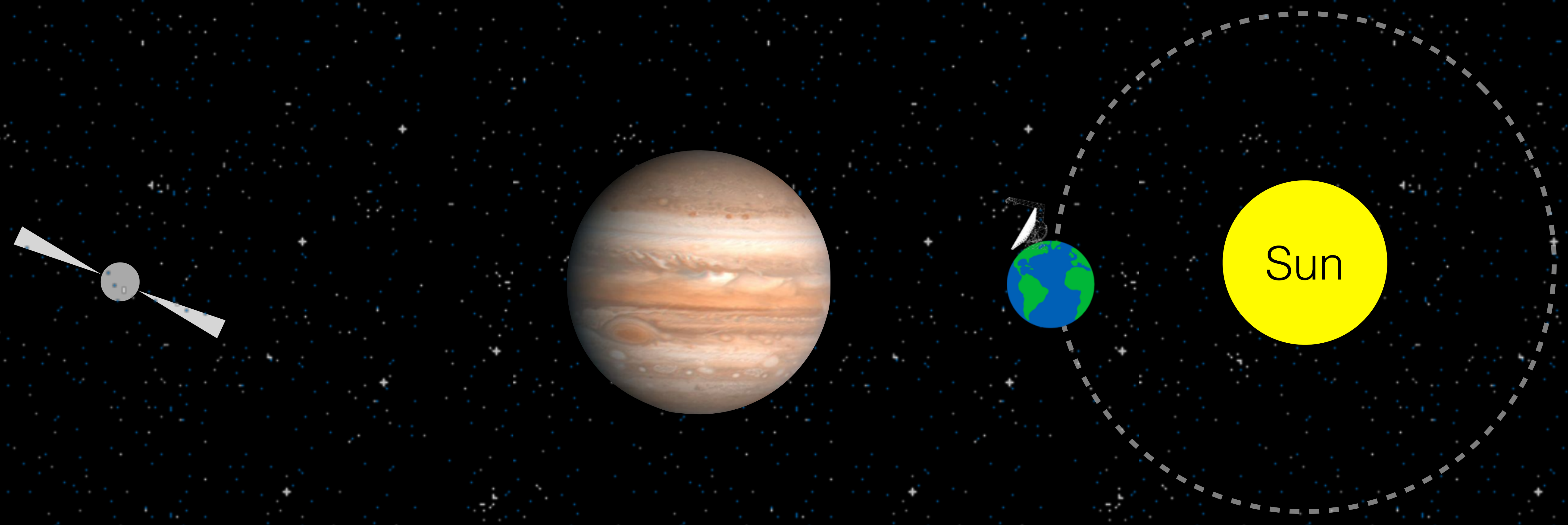
Corrects for frequency-dependent dispersion due to the signal's path through cold, ionized plasma in the ISM.

$$\Delta t \simeq 4.15 \times 10^{6}\ \text{ms}\ \times (f_1^{-2} - f_2^{-2}) \times \text{DM}$$

$$t_c = A\cos(\omega t - \lambda)\cos\beta$$

$$t_{\mathrm{bary}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} + t_{\mathrm{disp}} + \boxed{\Delta_{\mathrm{R}\odot}} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot}$$

Römer delay accounts for the classical light travel time between the phase center of the telescope and SSB.



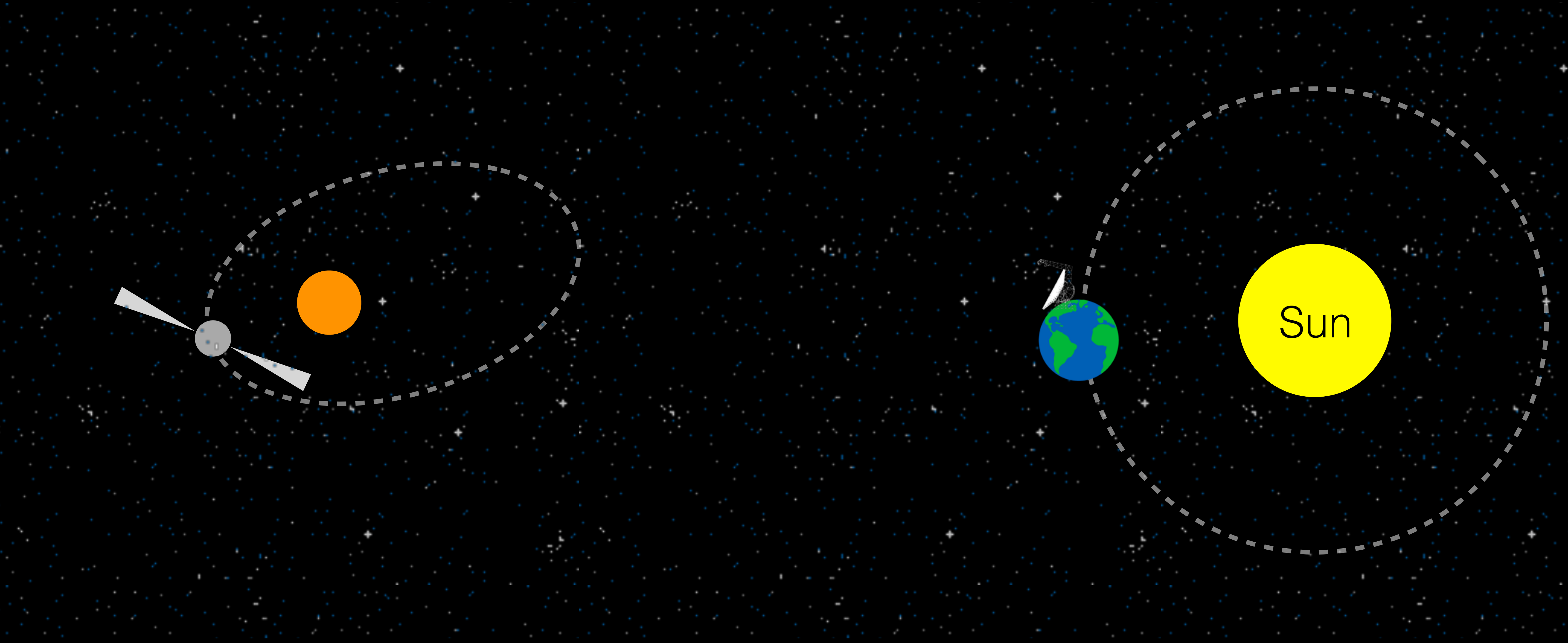
$$t_{\rm bary} = t_{\rm topo} + t_{\rm corr} + t_{\rm disp} + \Delta_{\rm R\odot} + \boxed{\Delta_{\rm S\odot}} + \Delta_{\rm E\odot}$$

Shapiro delay corrects for time delays due to the curvature of spacetime caused by masses in the Solar System (e.g. Jupiter).

$$t_{\mathrm{bary}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} + t_{\mathrm{disp}} + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \boxed{\Delta_{\mathrm{E}\odot}}$$

Einstein delay corrects for time dilation due to the motion of the Earth and gravitational redshift caused by other Solar System bodies.

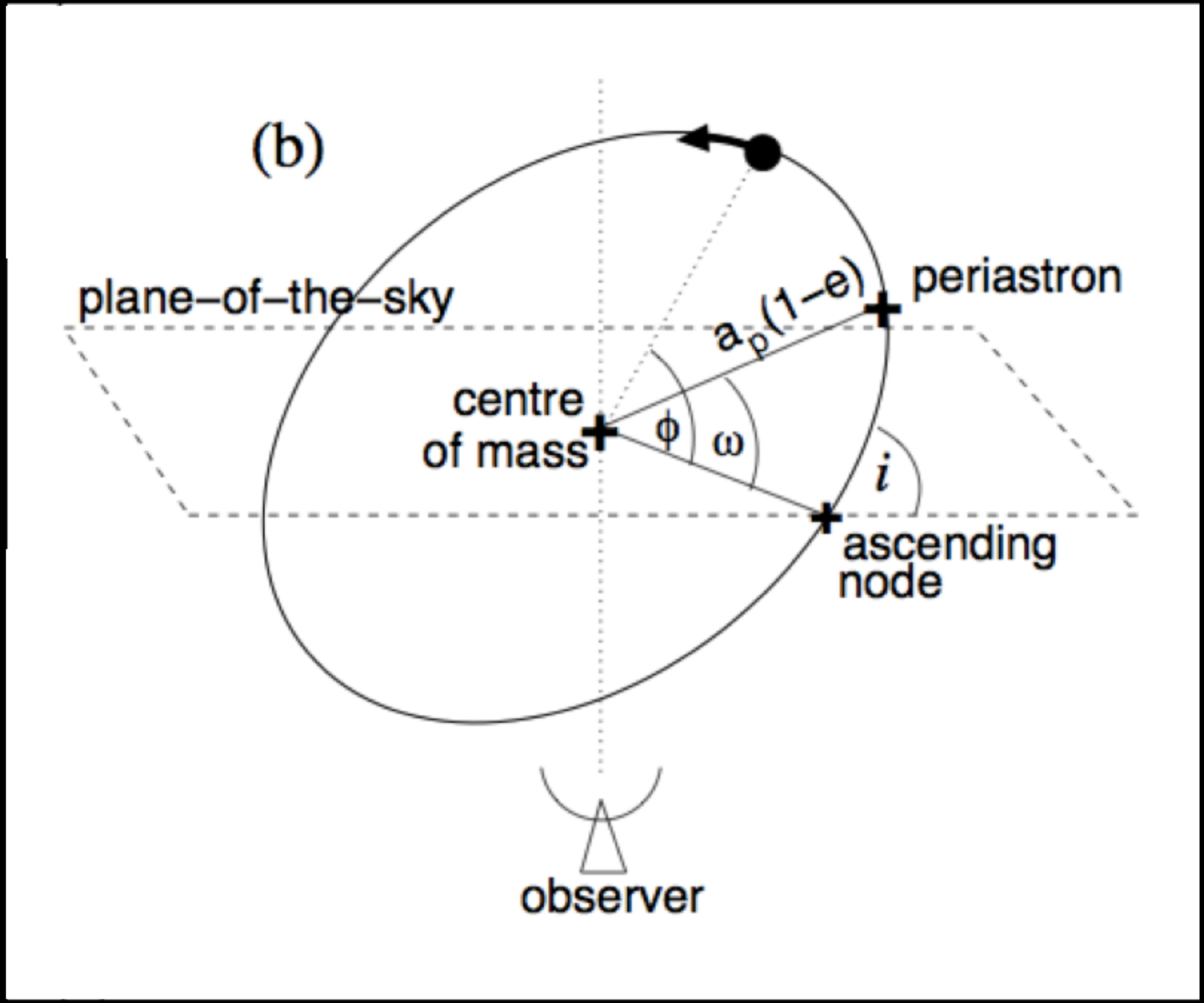
Binary Pulsars

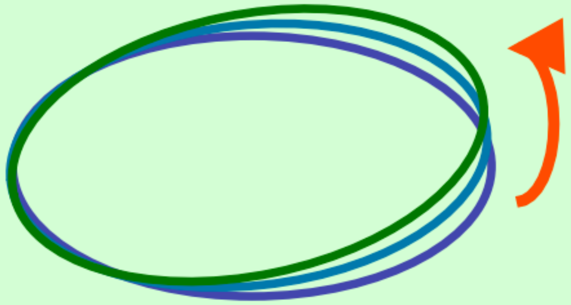


$$t_{\rm bary} = t_{\rm topo} + t_{\rm corr} + t_{\rm disp} + \Delta_{\rm R\odot} + \Delta_{\rm S\odot} + \Delta_{\rm E\odot} + \Delta_{\rm RB} + \Delta_{\rm EB} + \Delta_{\rm SB}$$

Binary Römer Delay

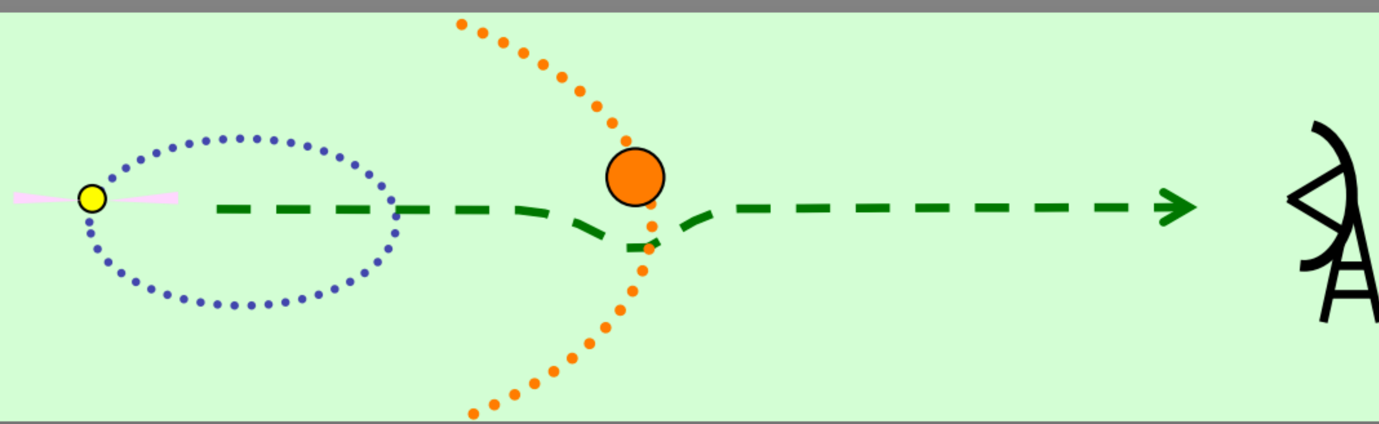
- Projected semi-major axis, $x = a_p \sin i$.
- Orbital period, P_b.
- Eccentricity, *e*.
- Time of periastron passage, T_0.
- Longitude of periastron, ω.





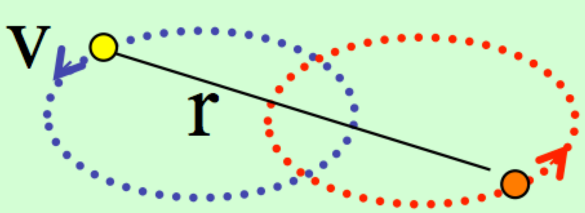
Precession

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} \left[\frac{G}{c^3}(m_1+m_2)\right]^{2/3}$$



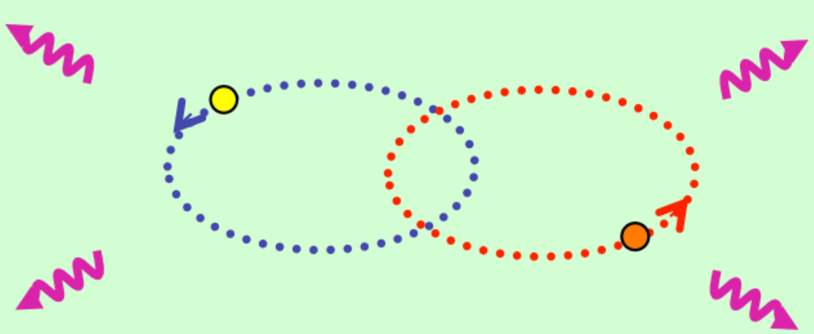
Shapiro Delay

$$\Delta t = 2\frac{G}{c^3} m_2 \ln\left[1 - \sin i \, \sin(\varphi - \varphi_0)\right]$$



Grav Redshift/Time Dilation

$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e \, \frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$



Gravitational Radiation

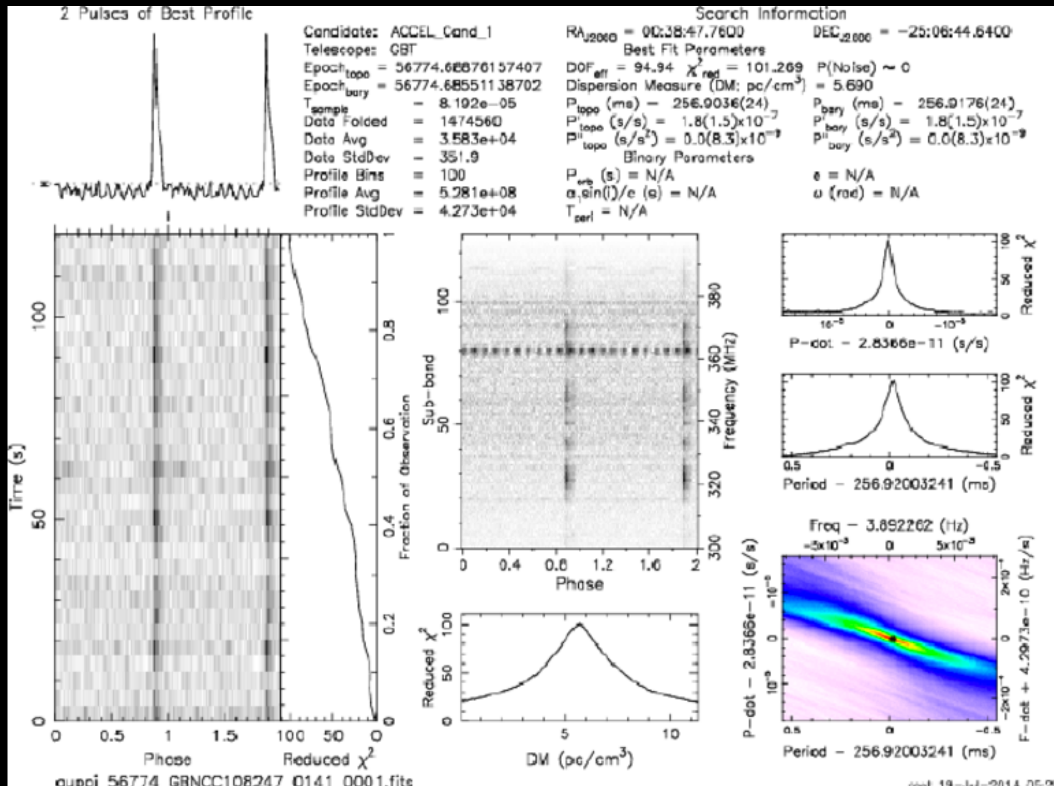
$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\,\frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

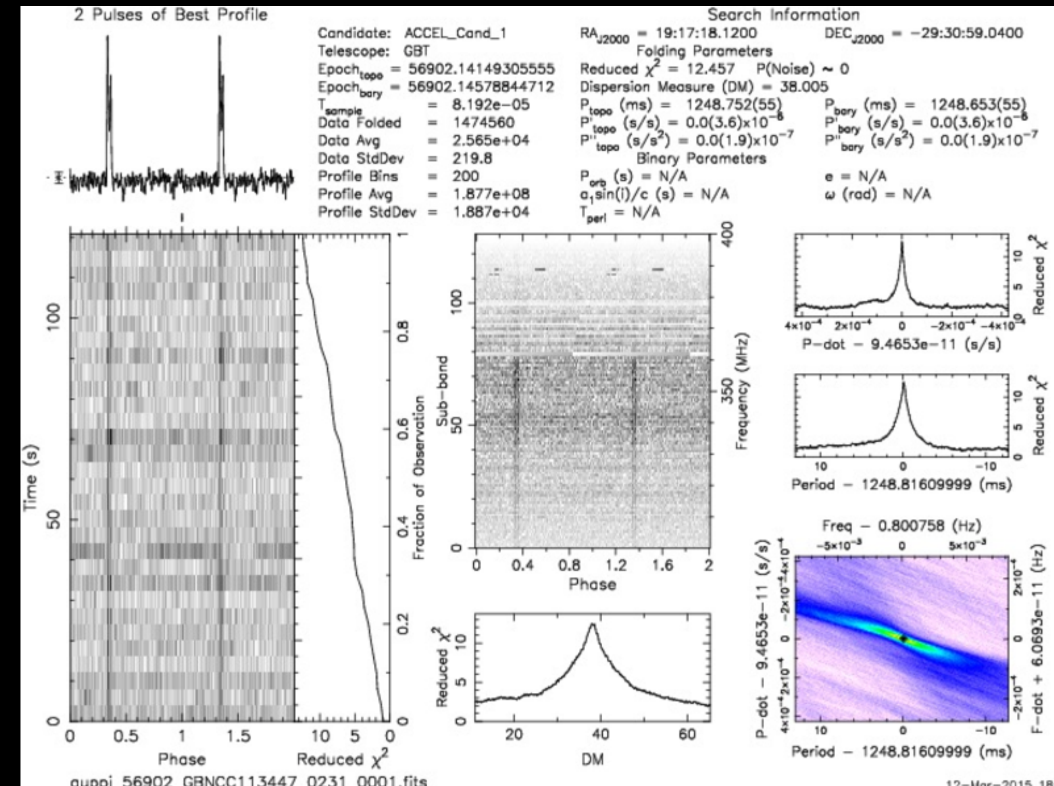
Slide courtesy of David Nice

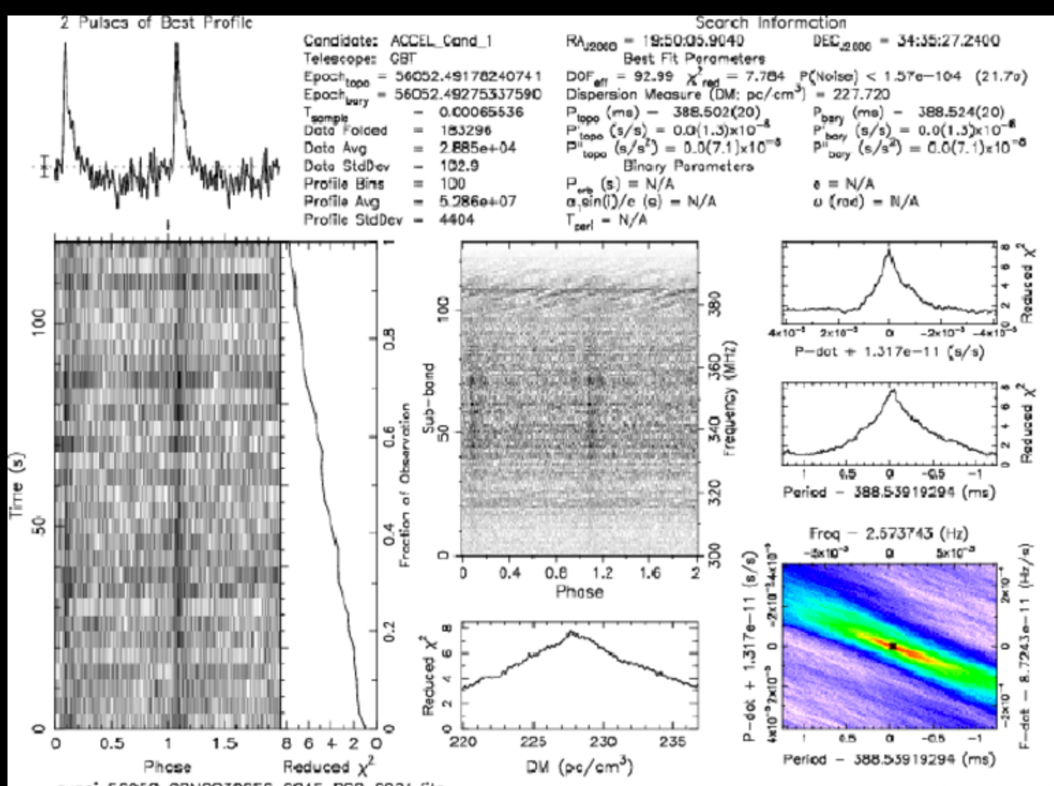
A taste of things to come…

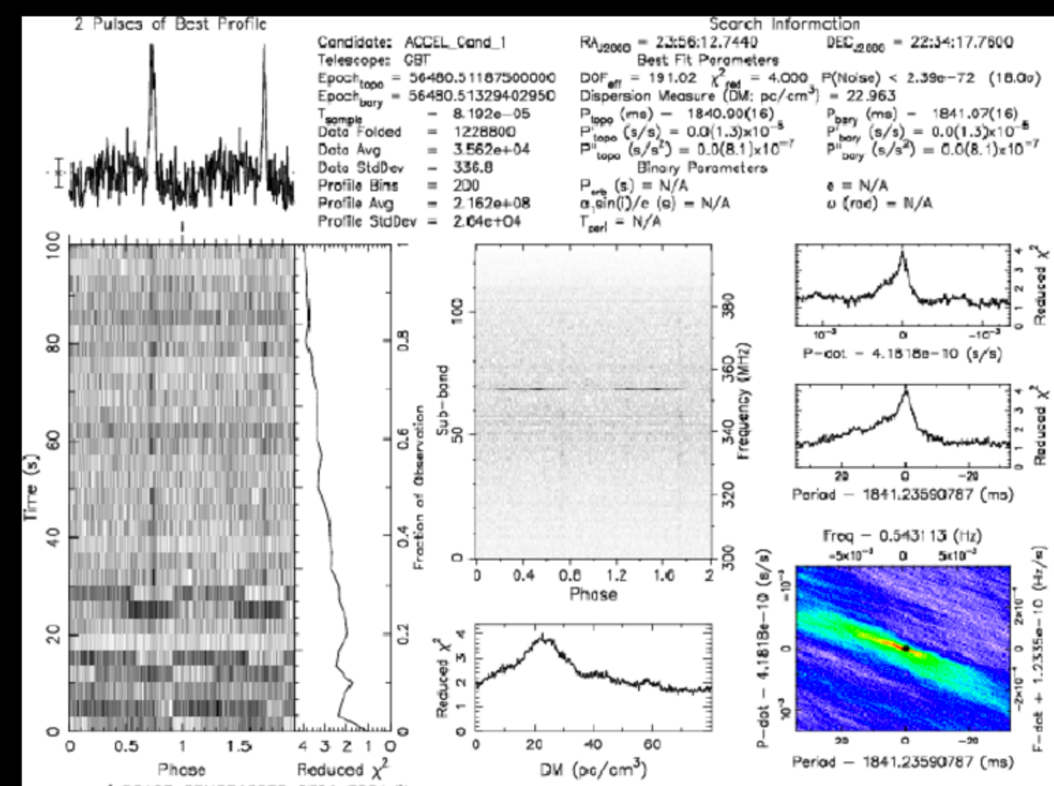
- Use the Fourier Transform to find a pulsar's spin period
- Write a program to determine spin period of a rotating radio transient (RRAT)
- Fit for period derivative using linear least-squares
- Make your own P-Pdot diagram
- Observe a binary pulsar with the NRAO 20-m telescope and solve its orbit

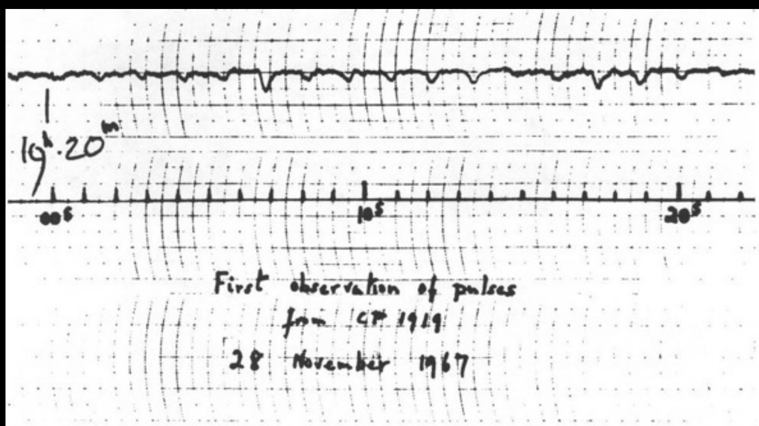
…and "time" a new pulsar of your own!





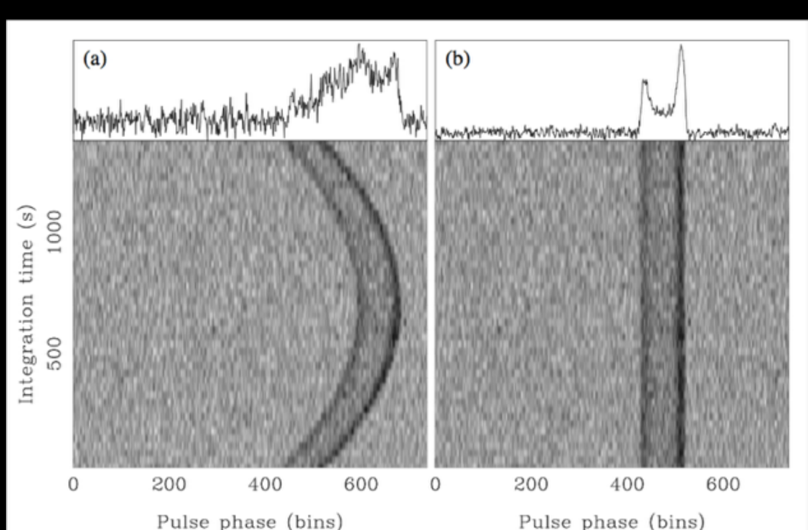


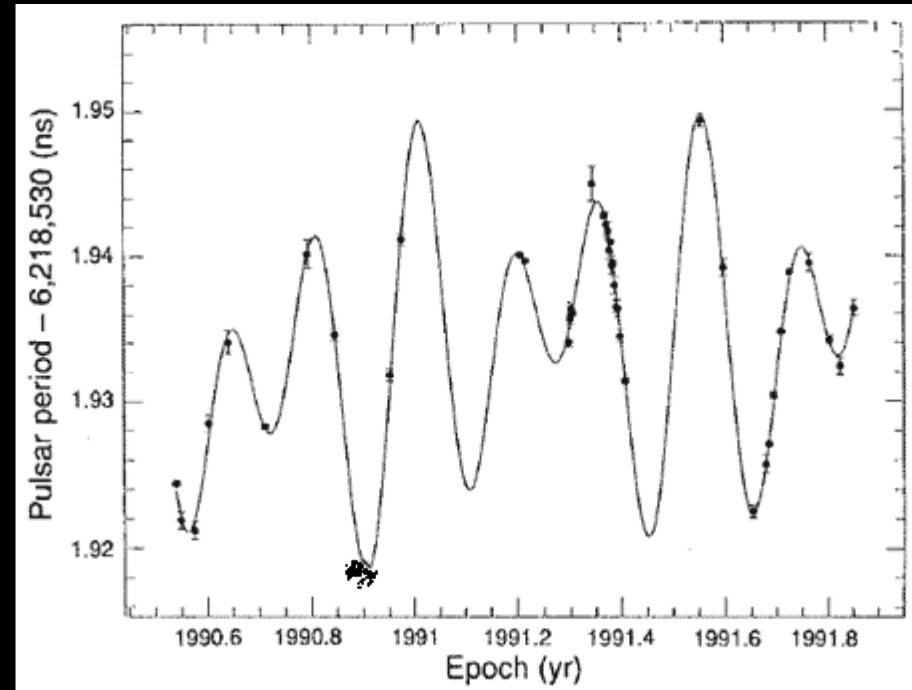




1967-68: pulsar discovery; period, position, dispersion

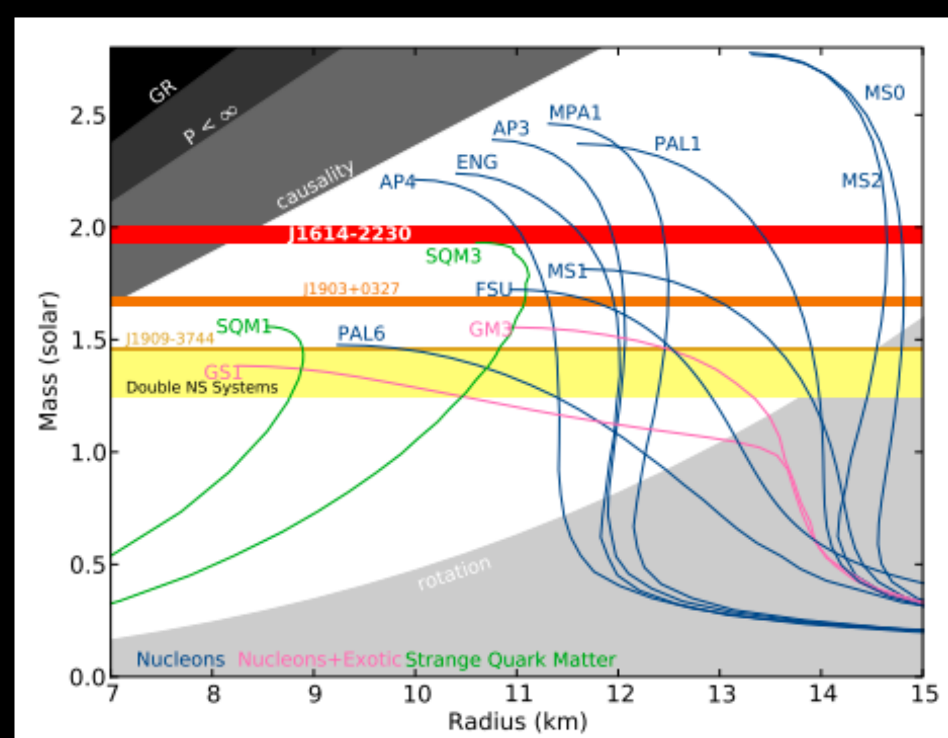
1975: first binary system

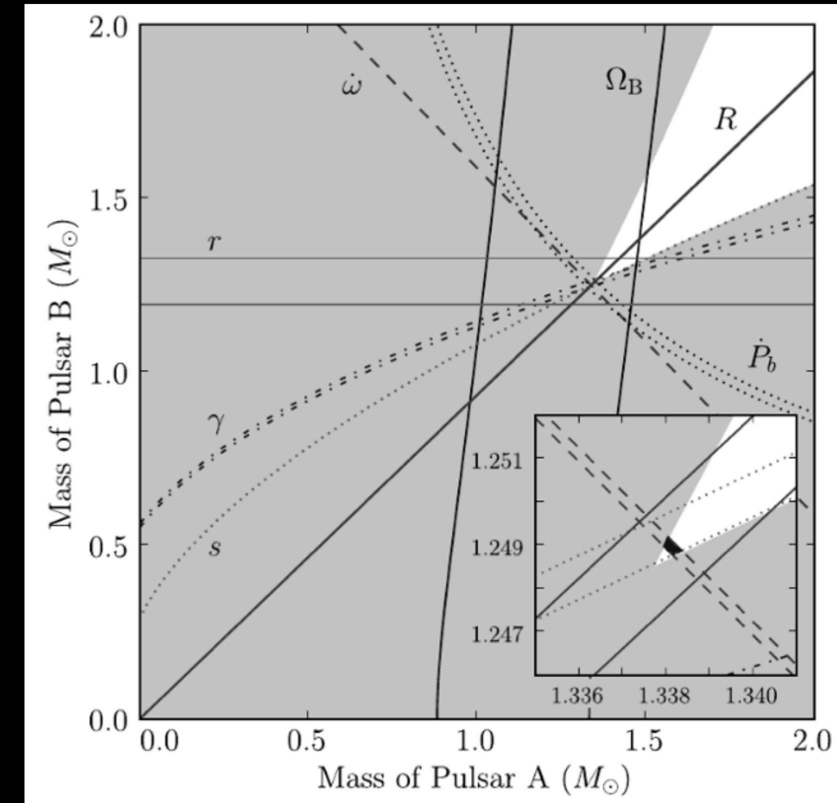




1994: planets discovered orbiting B1257+12

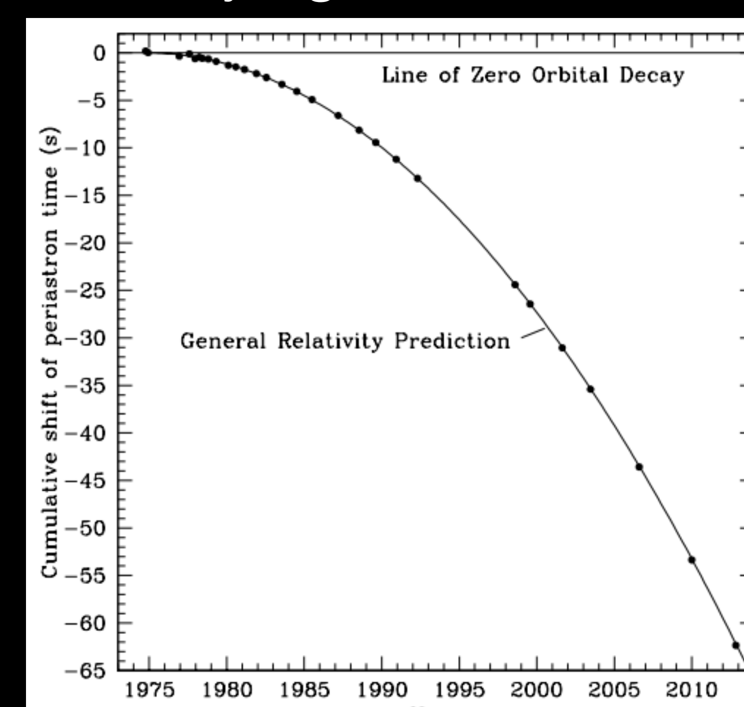
2010: 2-solar-mass pulsar challenges EOS models

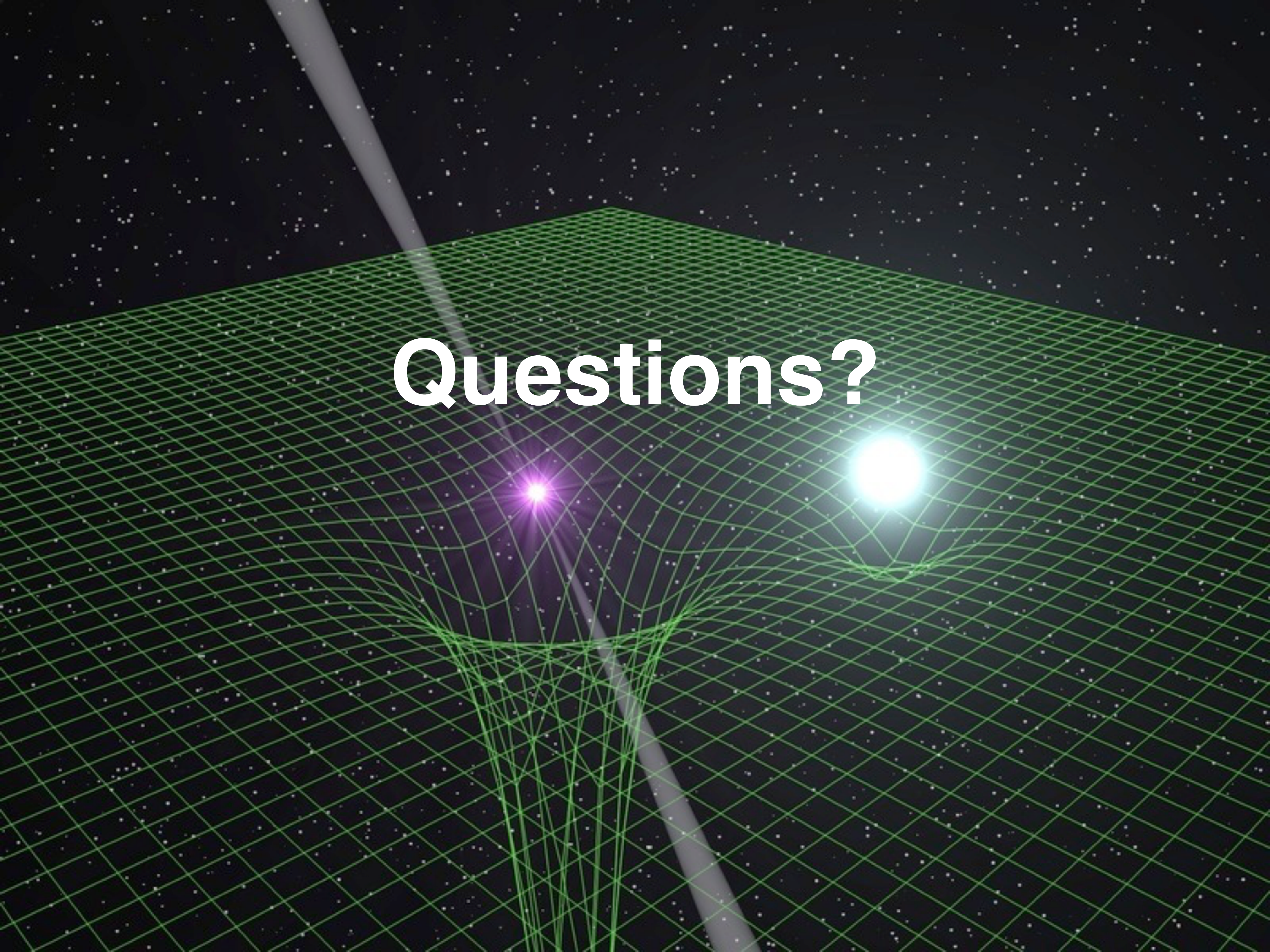




2014: double pulsar agrees with GR to 0.05% precision

2016: B1913+16 orbit still decaying due to GWs




Questions?