

Ben Stappers, University of Manchester

Pulsars and Fast Transients:

Find them, study them, understand them (and use them)!

- ❖ Lecture 1: **Find them, study them, understand them (and use them)!**
- ❖ Lecture 2: **Find them, study them, understand them (and use them)!**
- ❖ Lecture 3: **Find them, study them, understand them (and use them)!**
- ❖ Lecture 4: **Find them, study them, understand them (and use them)!**

mentimeter: 72286931

TIMELINE OF THE CONCEPT OF NEUTRON STARS

★ 1932 neutron discovered

★ 1934 suggestion that supernovae form NSs?

"...with all reserve we advance the view that a supernova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density." *Baade & Zwicky*

★ 1939 Structure of a neutron star first estimated.

★ 1964 magnetic field of a neutron star is a billion times stronger than that of the Earth

★ 1966 Crab nebula lit up by a neutron star?

★ 1967 NS can radiate.

TIMELINE TO CONNECTING PULSARS TO NEUTRON STARS

★ 1967 Discovery of Pulsars

Observation of a Rapidly Pulsating Radio Source

by

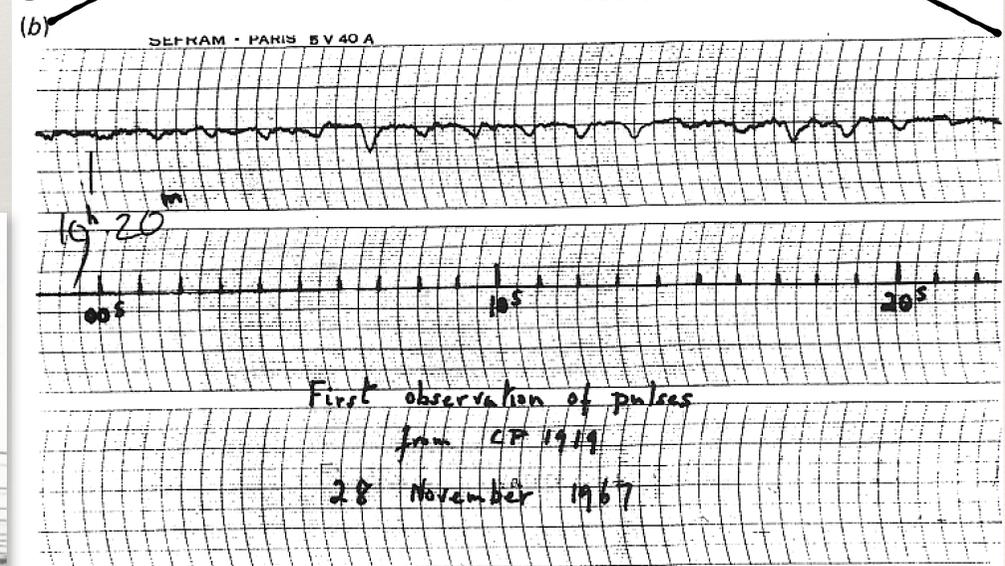
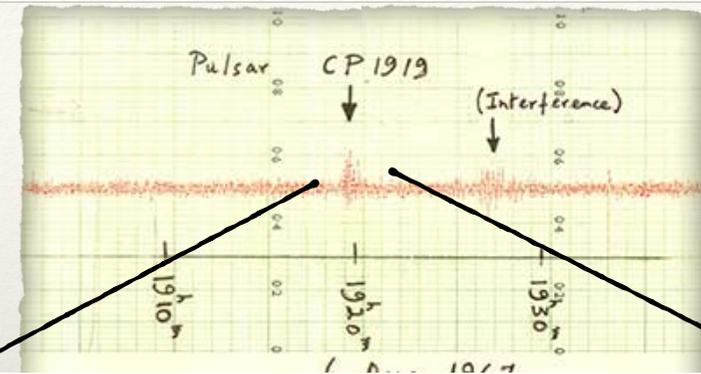
A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

Discovery of Pulsars

- Found by Dame Jocelyn Bell Burnell when she was a PhD student
- Trying to find new types of powerful galaxies called quasars
- Compact sources so they should show scintillation
- Studies demanded observations with high time resolution \Rightarrow new dimension in measurement space.
- They performed an untargetted survey at a long wavelength (3.75 m) ...
- She was not happy with unexplained signals
- Understood the instrument extremely well
- Persistence!



Discovery of Pulsars



Man made or LGMs?

- Source appeared 4 minutes earlier every day — not terrestrial.
- Parallax < 2 arcminutes — outside the solar system
- Pulses last < 20 milliseconds — means source is smaller than the Earth
- No Doppler effect — means outside of the solar system
- A month later, a second source was found!
- Pulse period was very stable ($< 10^{-7}$) — large moment of inertia
- White Dwarf (known) or neutron stars (theoretical)

TIMELINE TO CONNECTING PULSARS TO NEUTRON STARS

- ★ 1967 Discovery of Pulsars
- ★ 1968 Pulsar is a neutron star?
- ★ 1968 Crab and Vela pulsar discovered ($P \sim 0.033\text{s}$ & 0.089s)
- ★ 1969 Crab pulsar observed optically*
- ★ 1969 Crab pulsar period seen to lengthen

Observation of a Rapidly Pulsating Radio Source

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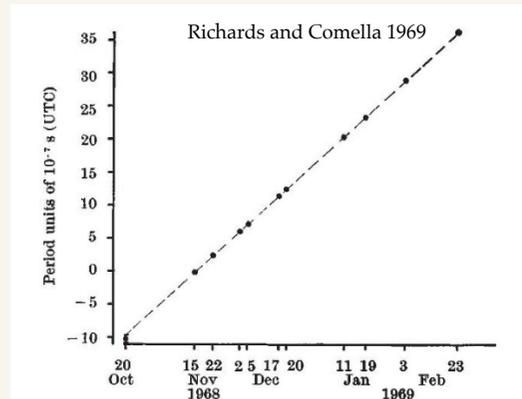
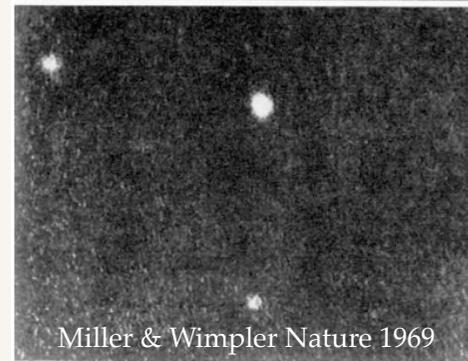
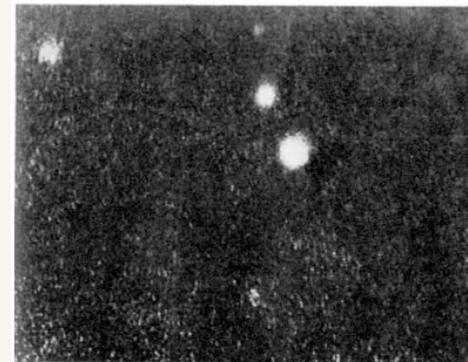


Fig. 1. Pulsar NP 0532, Arecibo barycentric periods. Points plotted are period of date minus the November 15, 1968, period of 0.033 s 091 121.



Miller & Wimpler Nature 1969

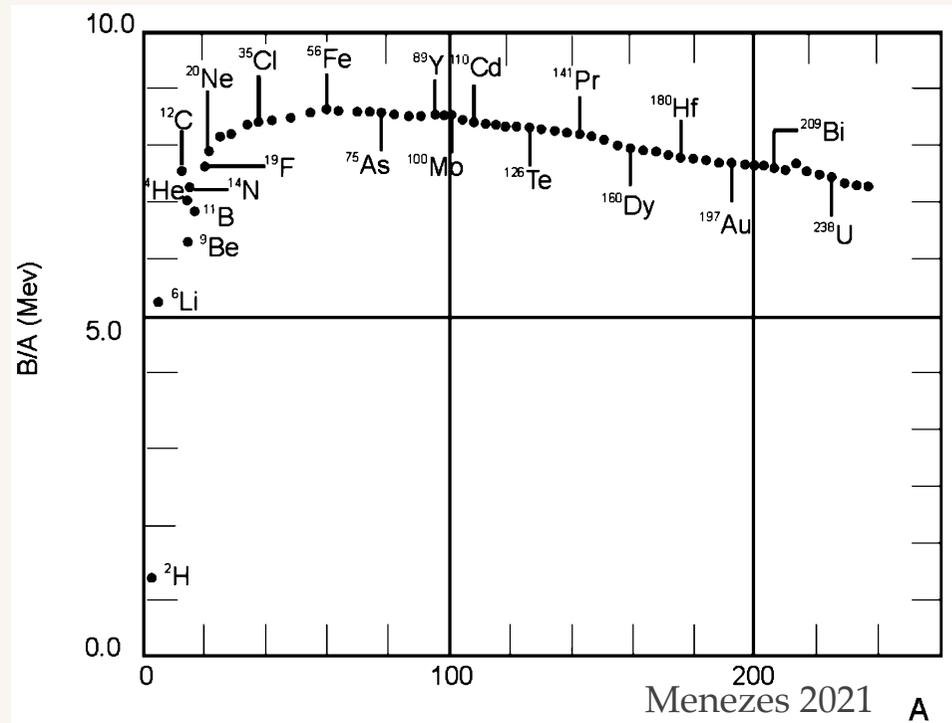
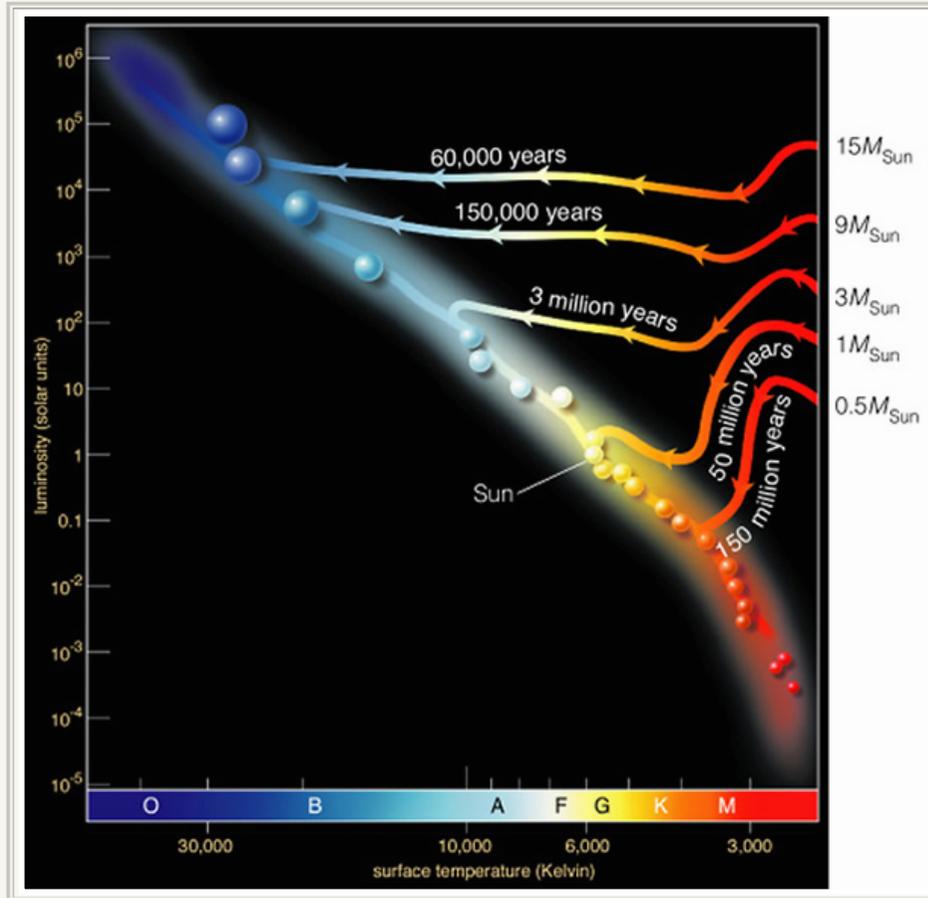


NASA

* Two papers in Nature in 1969: Cooke et al. and Nather et al.

AT THE END OF ITS LIFE A STAR 8-20 TIMES HEAVIER THAN THE SUN GOES SUPERNOVA!

NEUTRON STARS



Binding energy per nucleon.

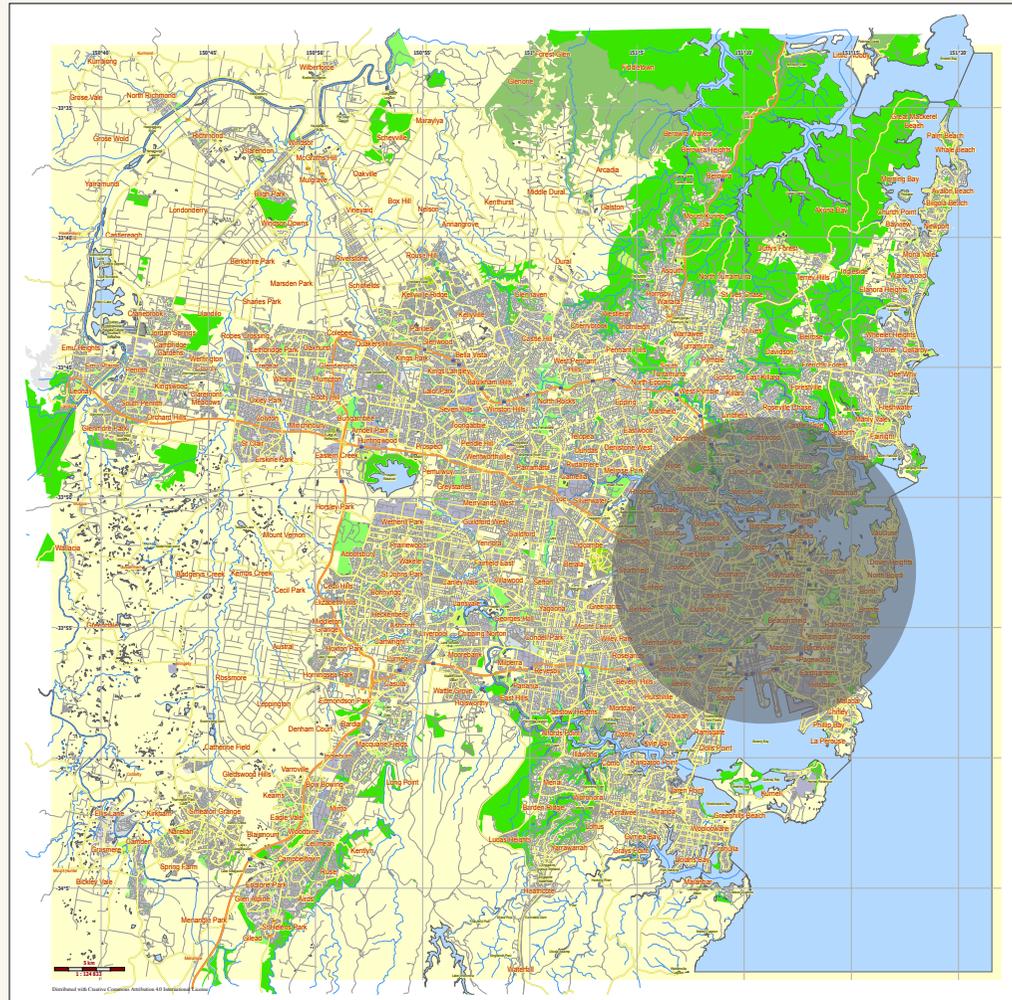
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NEUTRON STARS



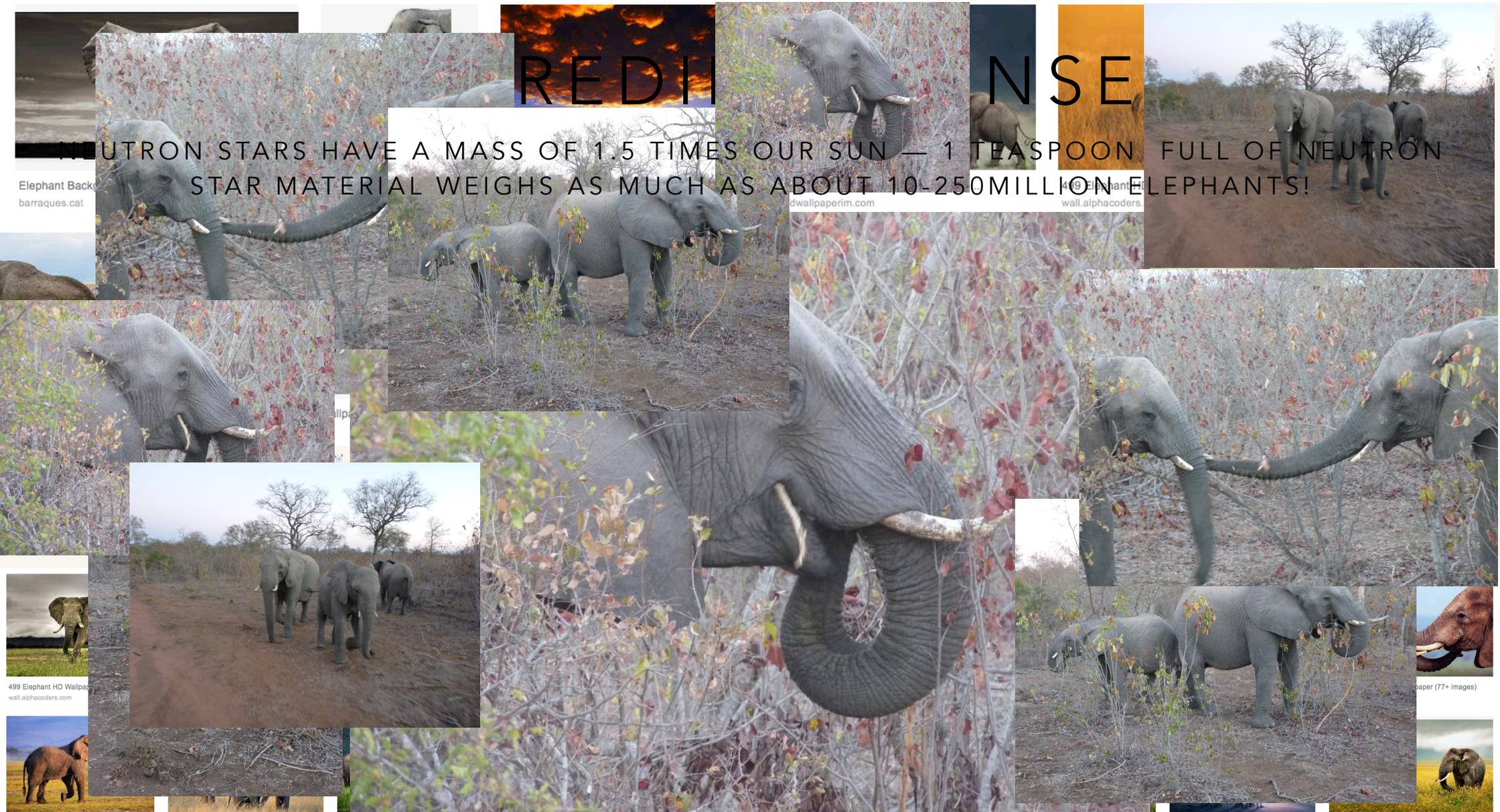
NEUTRON STARS HAVE A RADIUS OF ABOUT 10 KM

THE SIZE OF A CITY



REDI NSE

NEUTRON STARS HAVE A MASS OF 1.5 TIMES OUR SUN — 1 TEASPOON FULL OF NEUTRON STAR MATERIAL WEIGHS AS MUCH AS ABOUT 10-250MILLION ELEPHANTS!



Elephant Back
barraques.cat

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wall.alphacoders.com

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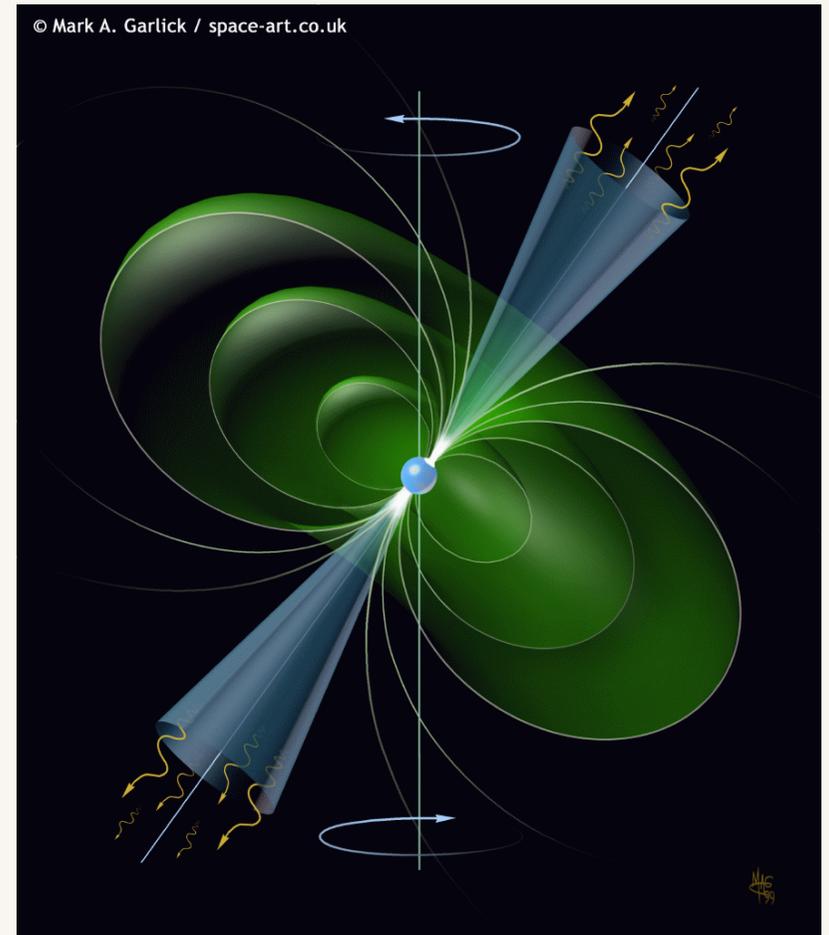
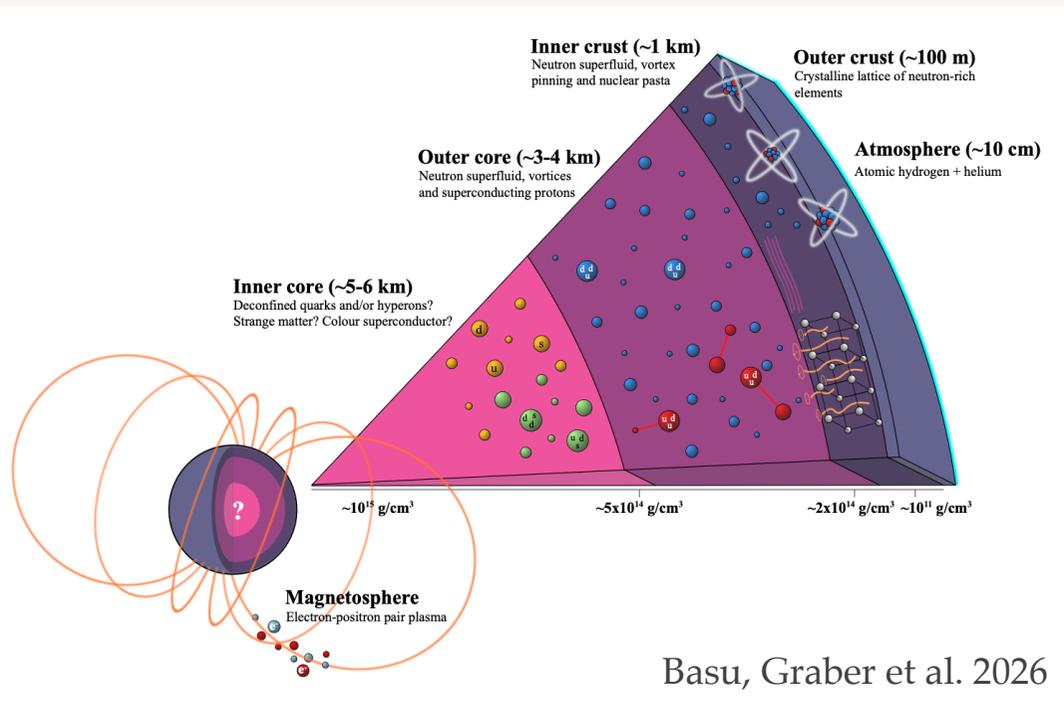
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wall.alphacoders.com

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wallpapersafari.com

fantasy Art, Elephants, Men Wallpapers ...
wallup.net

Elephant Desktop Wallpapers ...
pixelstalk.net

PULSARS



PULSARS ARE BORN SPINNING AT LEAST ONCE EVERY 30 MILLISECONDS

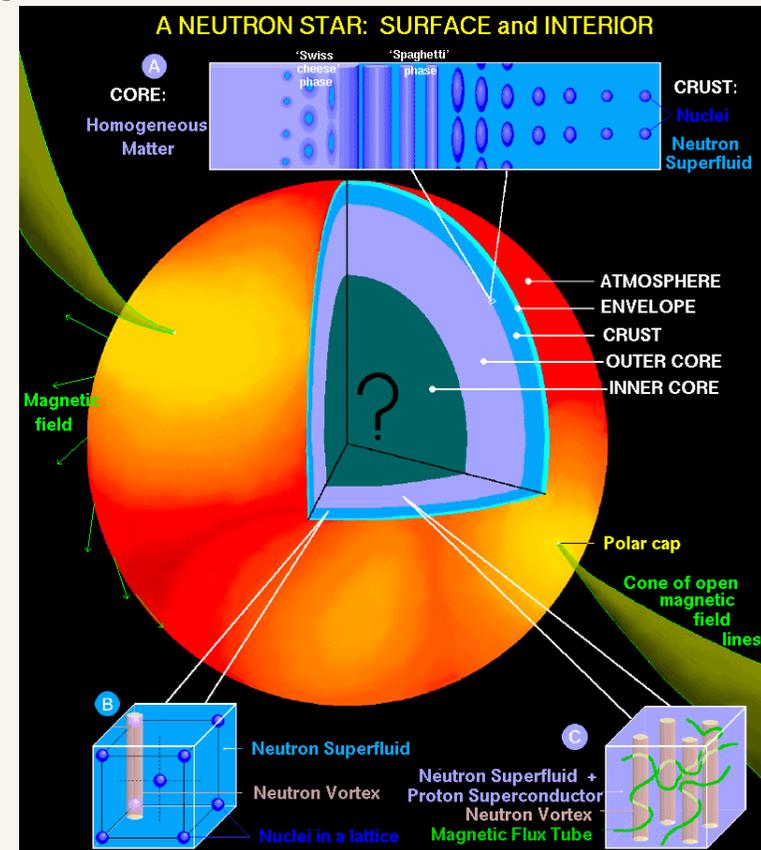
RAPID SPIN



CONSERVE THAT ANGULAR MOMENTUM.

PROPERTIES OF PULSARS

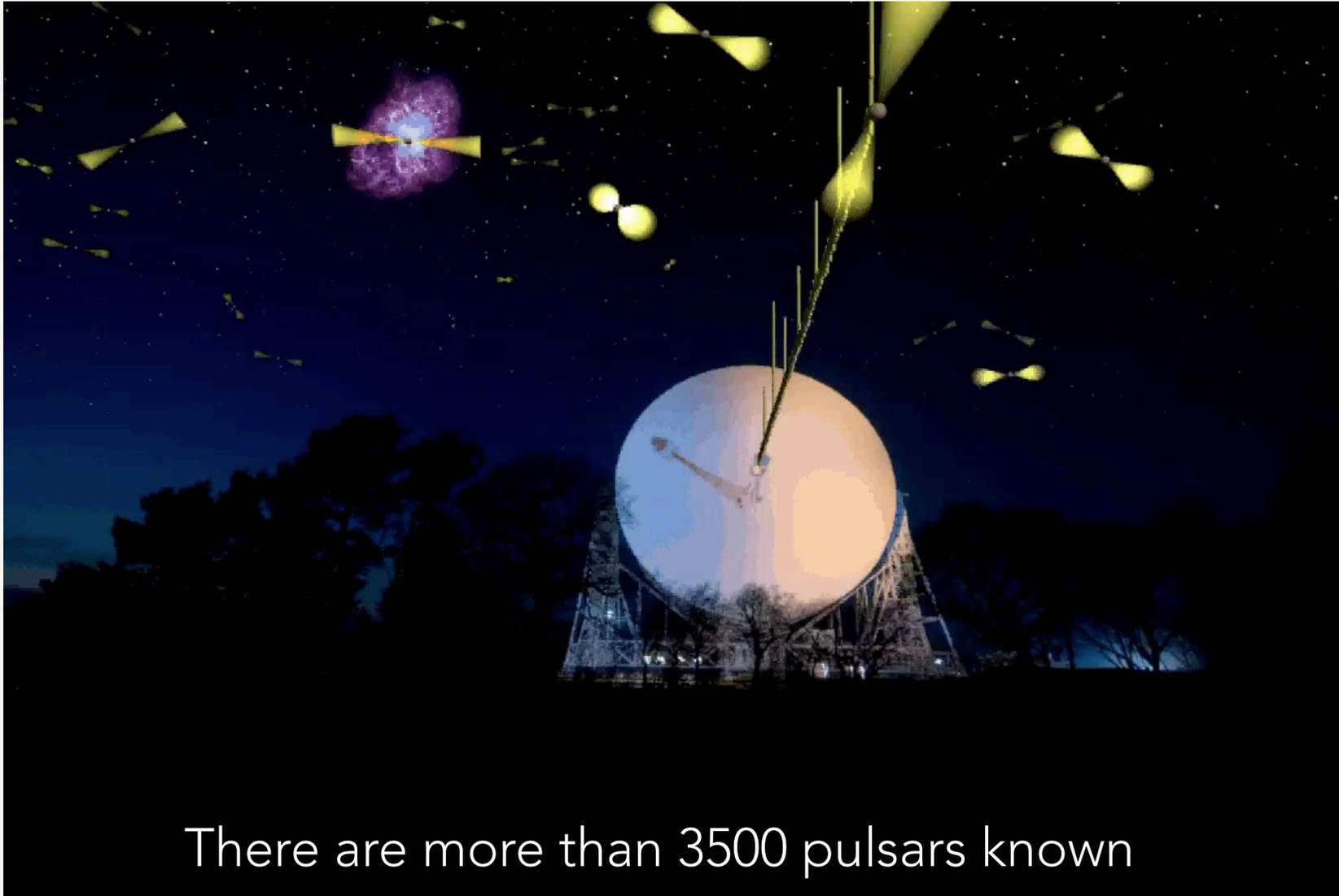
- * Remnant of Supernova
- * Rotating Neutron Stars
- * Mass = $1.4M_{\odot}$, Radius = 10km
- * Periods = 0.0013 - 76 s (plus?)
- * Density in range $10^6 - 10^{15}$ g/cm³
- * Magnetic field strength = $10^8 - 10^{14}$ G
- * Mainly Radio emitters
- * Many also emit Optical, X-ray, Gamma-ray.
- * Emit radio in narrow beam
- * Clock like stability



Credit: Danny Page

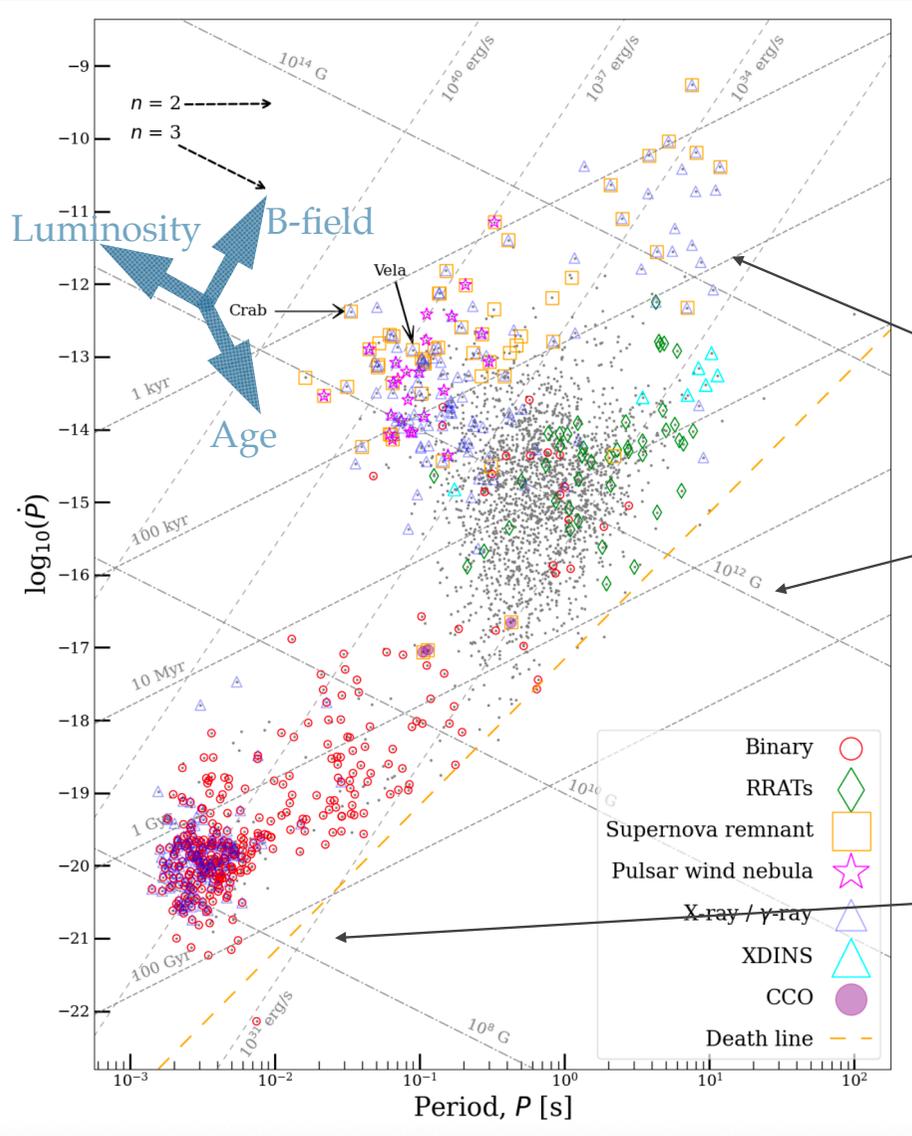
Most extreme states of matter known and the strongest magnetic fields.

Magnetic field of the Earth is just 0.5 G and a bar magnet 100 G



There are more than 3500 pulsars known

P-PDOT DIAGRAM



Characteristic Age

$$\tau_c \equiv \frac{P}{2\dot{P}} \approx 15.8 \text{ Myr} \left(\frac{P}{\text{s}}\right) \left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$$

Surface magnetic field strength

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

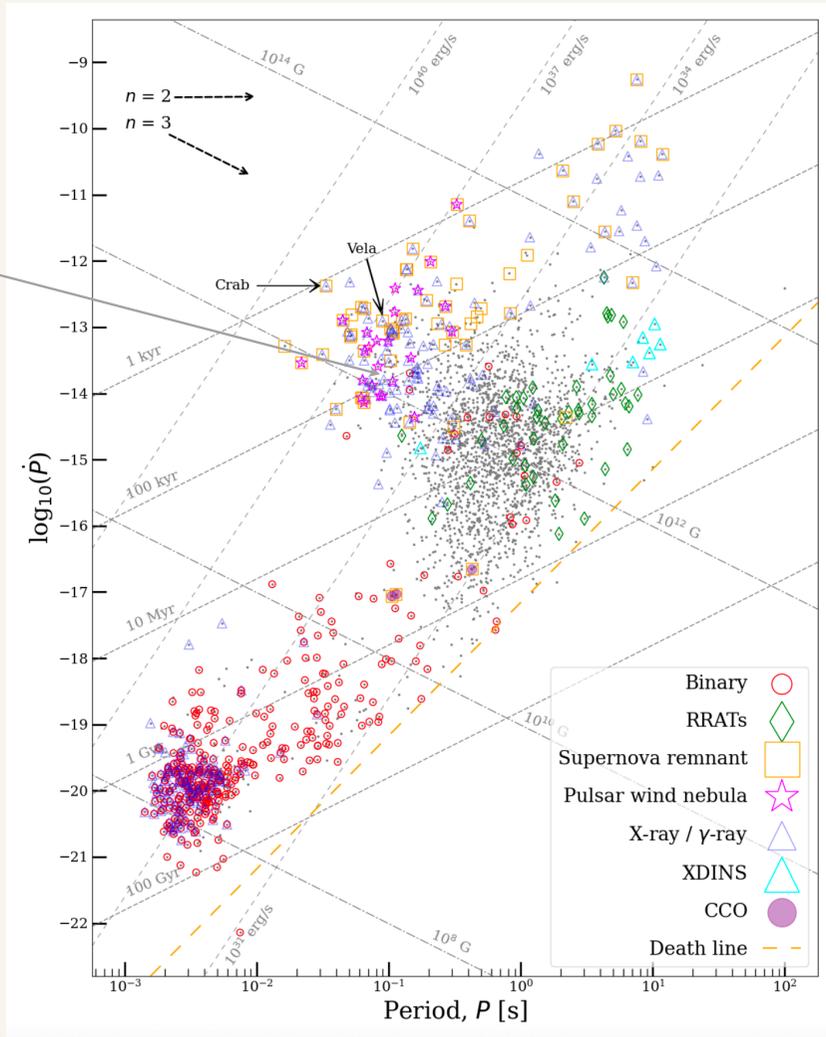
Spin down Luminosity

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3} \approx 3.95 \times 10^{31} \left(\frac{\dot{P}}{10^{-15}}\right) \left(\frac{P}{\text{s}}\right)^{-3} \text{ erg s}^{-1}$$

P-PDOT DIAGRAM

YOUNG PULSARS

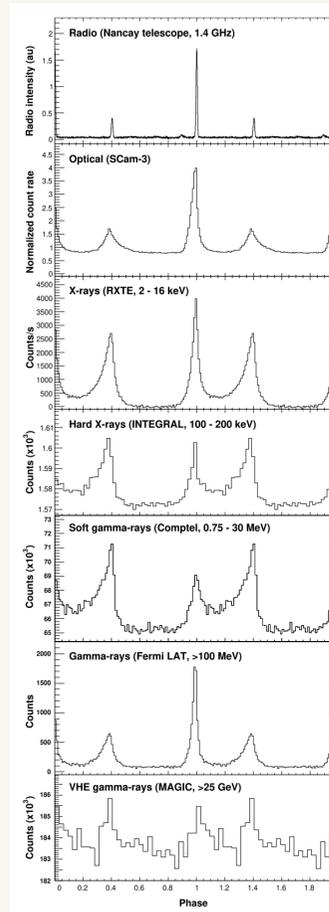
- SPIN FAST
- ASSOCIATED SNRS
- ENERGETIC
- GLITCH



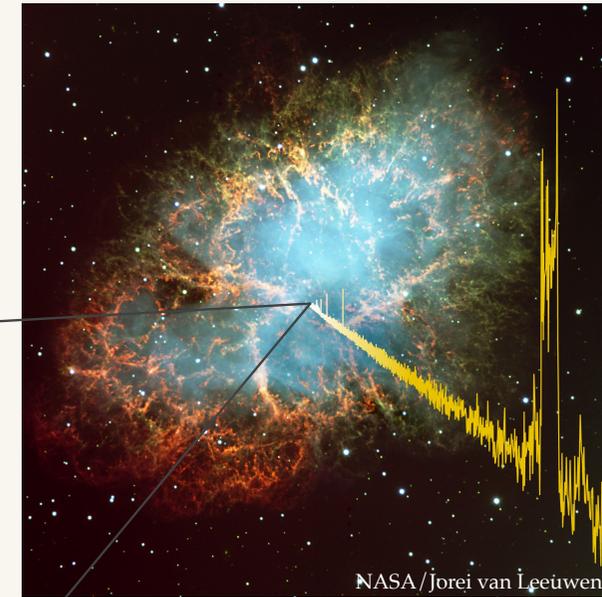
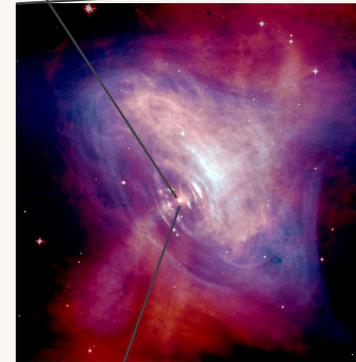
FINDING THEM WHERE THEY ARE BORN

YOUNG PULSARS

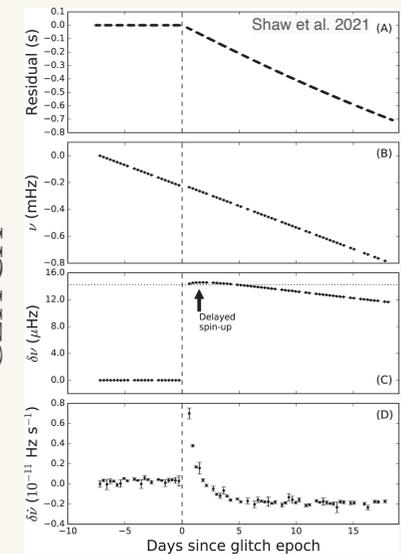
- Spin FAST
- Associated SNRs
 - Some are located in their birth remnants, e.g. Crab, Vela, but some outside
 - Physics of the explosion
 - Evolution and physics of the spin evolution
 - Physics of the NS formation
- Energetic
 - Some are seen across the entire electromagnetic spectrum from Radio to TeV
 - Some give off giant pulses which can be many orders of magnitude brighter than the normal pulses
 - Probe a wide range of different physics regarding both the pulses and unpulsed/nebula emission.
- GLITCH
 - Rapid changes in the rate of spin and slow down
 - Thought to be associated with properties of the interior of the NS, e.g. superfluid interior, crust and interactions between them.
 - Physics of the interior and equation of state.



Abdo et al. 2010



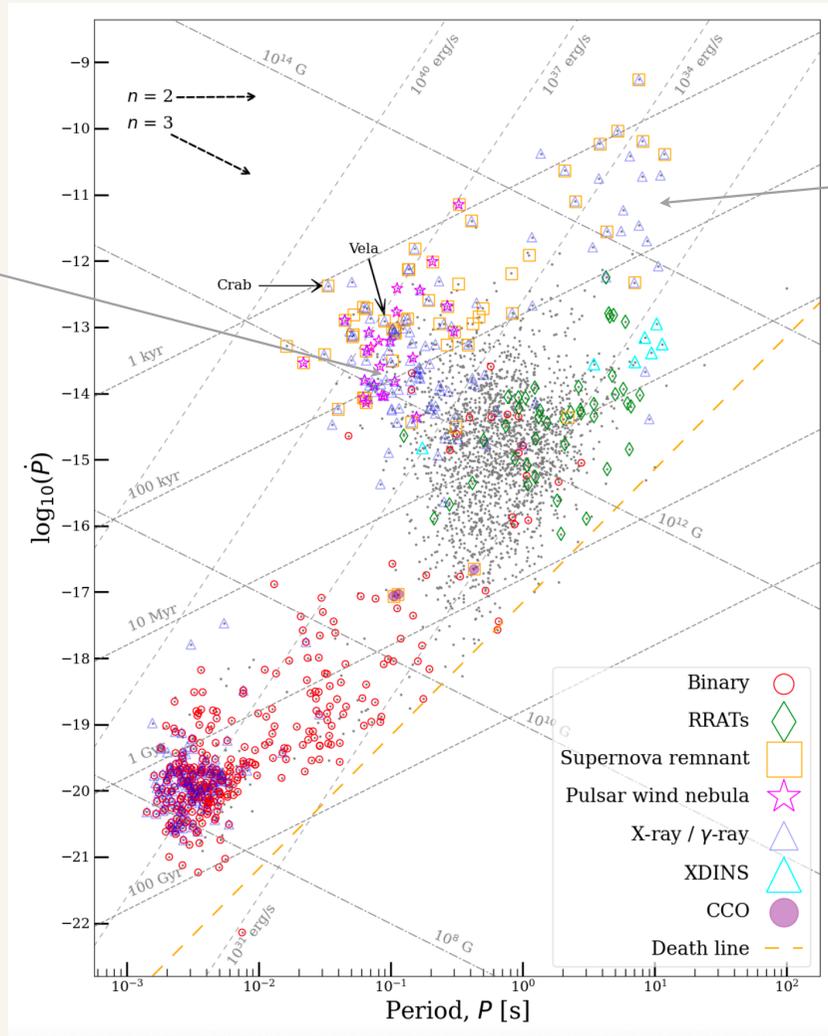
GLITCH



P-PDOT DIAGRAM

YOUNG PULSARS

- SPIN FAST
- ASSOCIATED SNRS
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- GLITCH



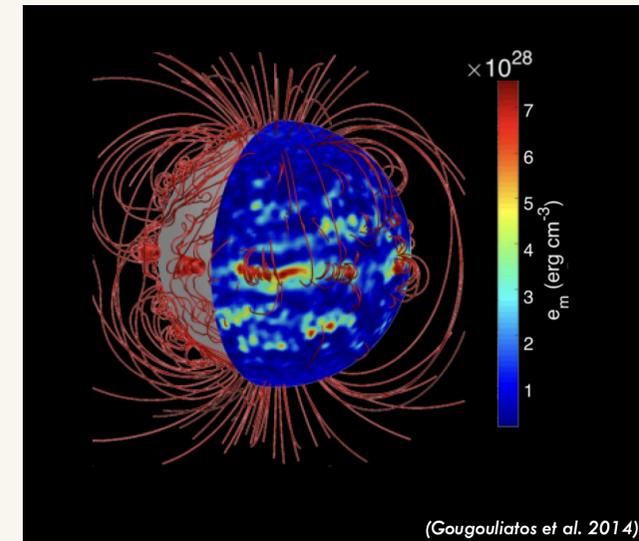
MAGNETARS

- SPIN SLOWLY
- VERY HIGH B
- NOT ROT^N POWERED
- FEW RADIO
- FRBS?
- ABOUT 30 KNOWN

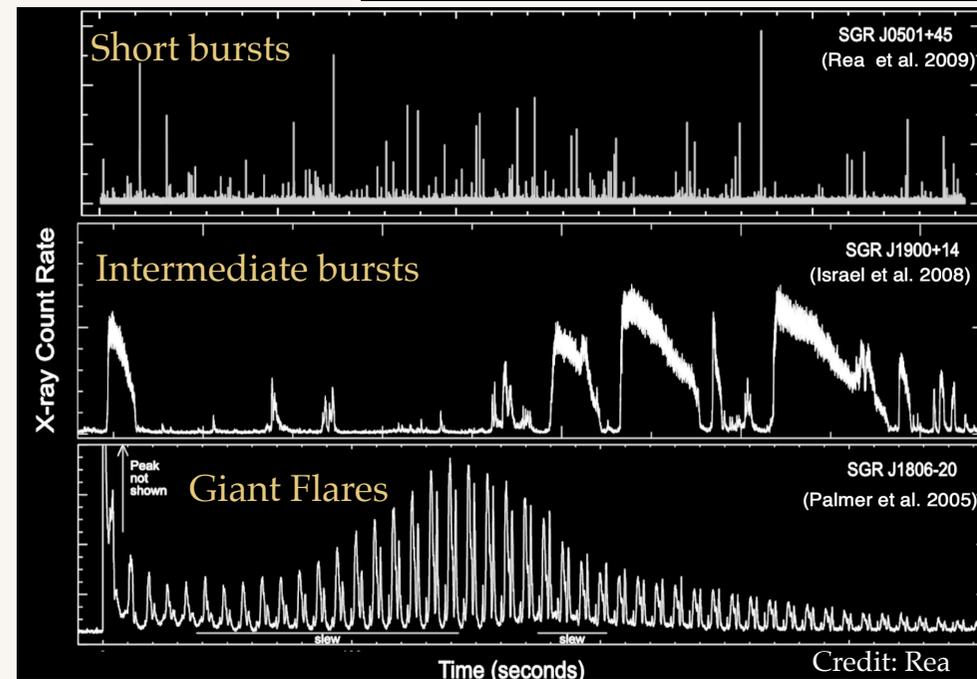
THE HIGHLY MAGNETISED VERSION...

MAGNETARS

- Highly Magnetised
 - Spin slowly 0.3-12 seconds
 - Magnetic fields of 10^{13} — 10^{15} Gauss
 - They were originally thought to be two different classes:
 - Soft gamma-ray repeaters
 - Anomalous X-ray pulsars
 - Now thought to be different manifestations of the same thing and some high-B pulsars show some similar properties.
 - Only about 1/4 are seen to emit in the radio — Transient.
 - One in the LMC and candidate Giant Flares/Magnetars in other galaxies
- Energetics of the emission (steady 10^{31} — 10^{36} erg/s) says they are NOT rotation powered but probably powered by the strong magnetic field.
- Giant Flares can be up to 10^{47} erg/s
- Likely young as about 1/3rd associated with SNRs
 - Physics of the NS formation
- A strong candidate for being the origin of at least some FRBs.



(Gougiolatos et al. 2014)



Credit: Rea

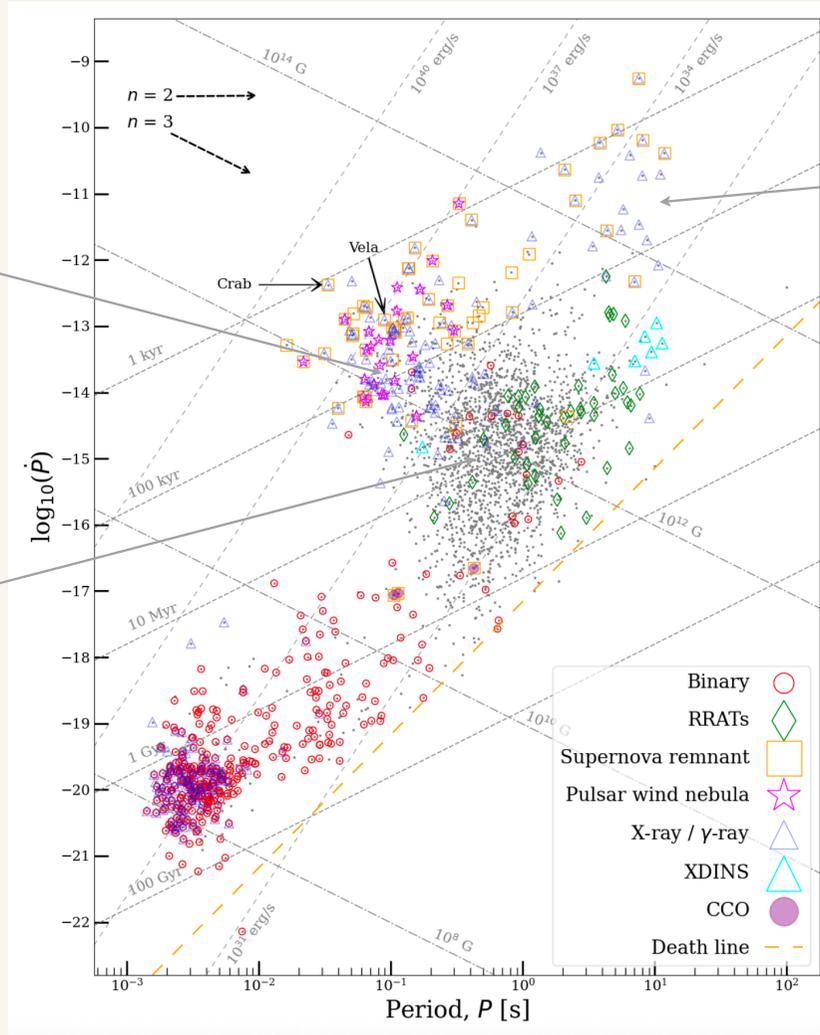
P-PDOT DIAGRAM

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- GLITCH

“NORMAL” PULSARS

- BULK OF PSRS
- GREAT PSR STUDIES
- LOTS GOING ON
- NOBEL PRIZE



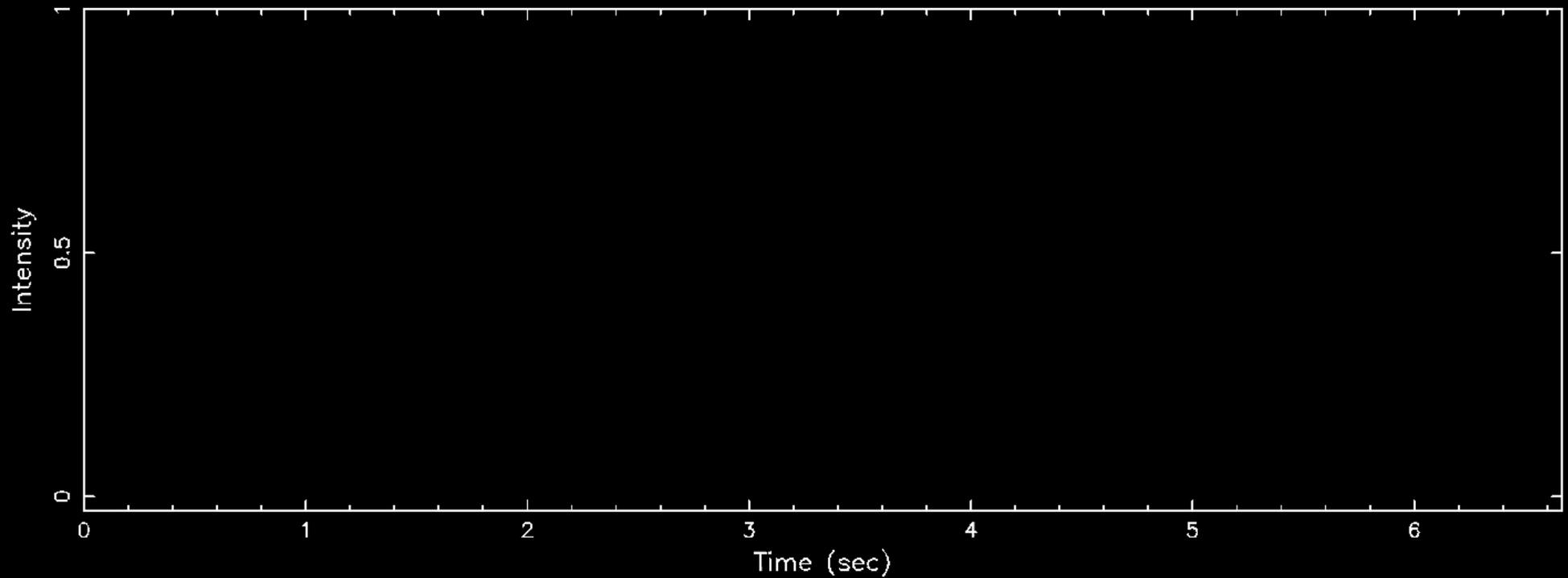
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EVERY TIME THE PULSAR ROTATES WE RECEIVE A PULSE OF RADIO EMISSION LIKE THE TICK OF A CLOCK

PULSARS ARE COSMIC CLOCKS

Pulsar B0329+54 observed with the Lovell telescope at Jodrell Bank



© Jodrell Bank Centre for Astrophysics pulsar group

P-PDOT DIAGRAM

YOUNG PULSARS

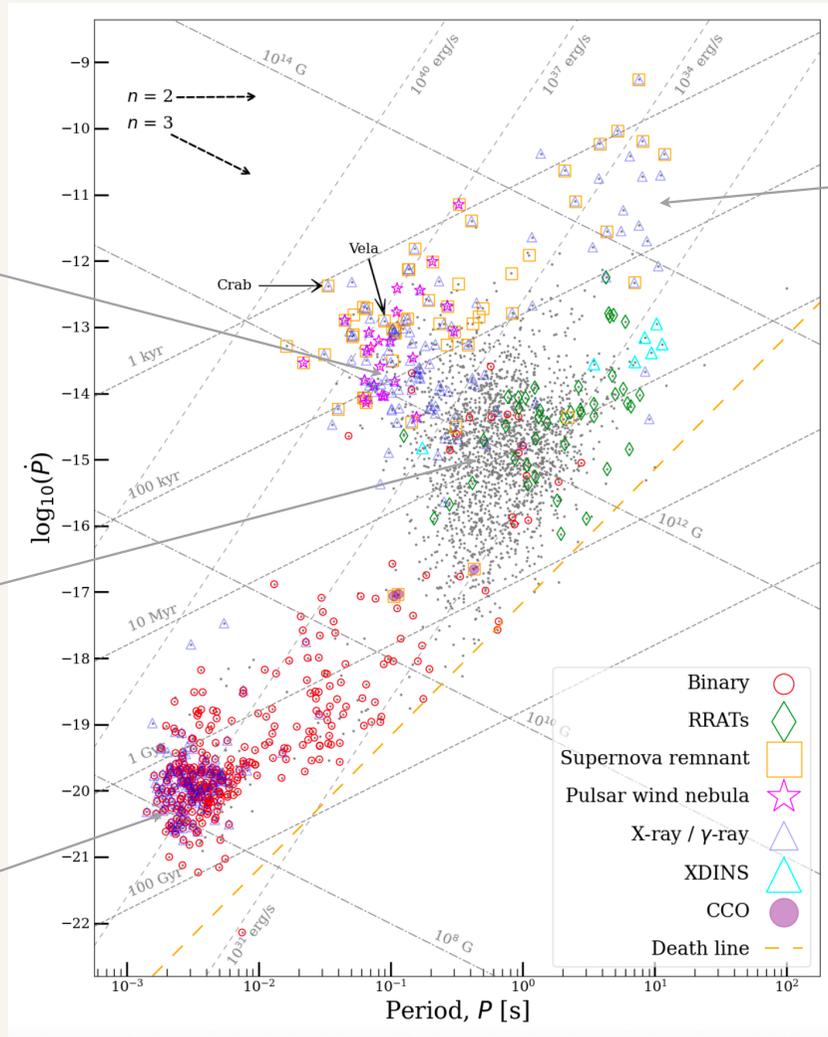
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MILLISECOND PULSARS

- SPIN VERY FAST
- USUALLY BINARY
- VERY STABLE
- BEST CLOCKS

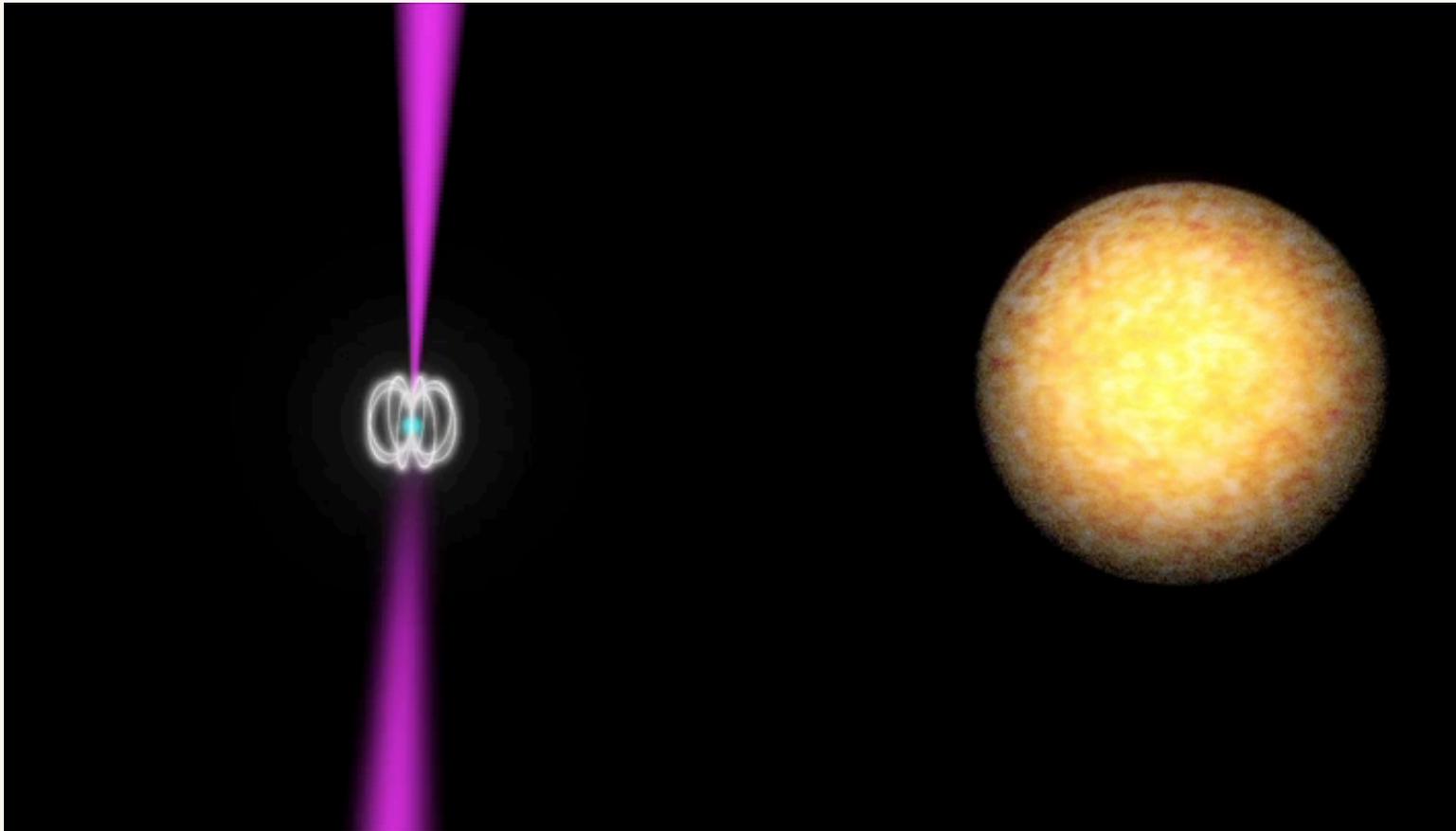


MAGNETARS

- SPIN SLOWLY
- VERY HIGH B
- NOT ROT^N POWERED
- FEW RADIO
- FRBS?

SOME PULSARS ARE "REBORN" WHEN THEY ACCRETE MATERIAL FROM THEIR COMPANION STAR

SPIN EVEN FASTER.....



EXTREMELY PRECISE

IF THE MOST PRECISE PULSARS WERE WATCHES THEY WOULD LOSE JUST 1 SECOND IN 30 MILLION YEARS!

The spin period of one of the most precisely measured pulsars known, can be written as:

$$P = 0.002947108069160717 \pm 0.00000000000000000003 \text{ seconds}$$

Reardon et al. 2015

We can measure the arrival time of the most stable pulsars to:

<50 nanoseconds (10^{-9} seconds)

ANY SMALL CHANGE WILL CHANGE THE TIME WHEN THE PULSES ARRIVE

THE ULTIMATE COSMIC CLOCKS

MILLISECOND PULSARS

Gravitational Waves



NASA

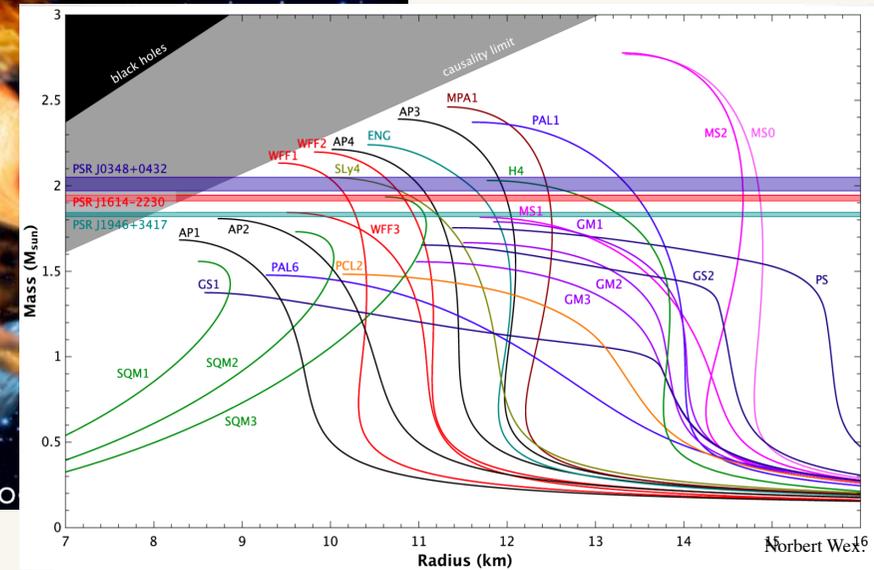
NS/BH BINARIES?



Fig. 1: An artist's impression of the system assuming that is its orbital companion, the radio pulsar PSR J0514-40028 days.
[less]
© MPIfR; Daniëlle Futselaar (artsource.nl)

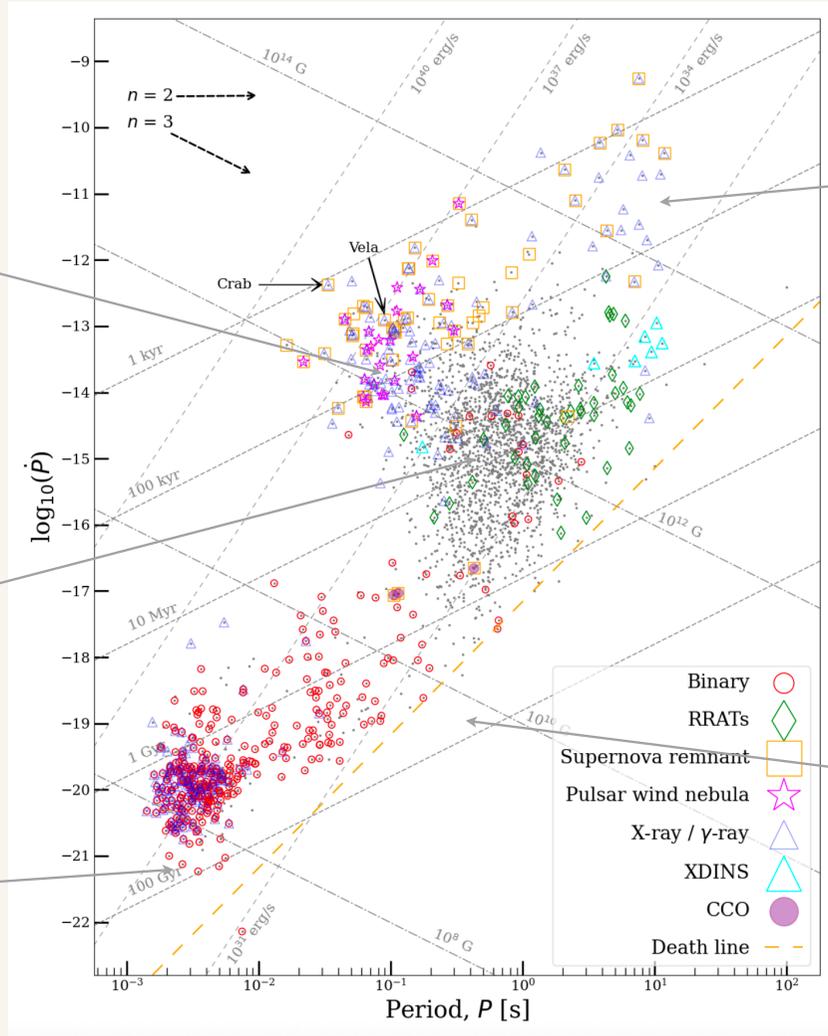
SPIDER BINARIES

NS equation of state



Robert Weh

P-PDOT DIAGRAM



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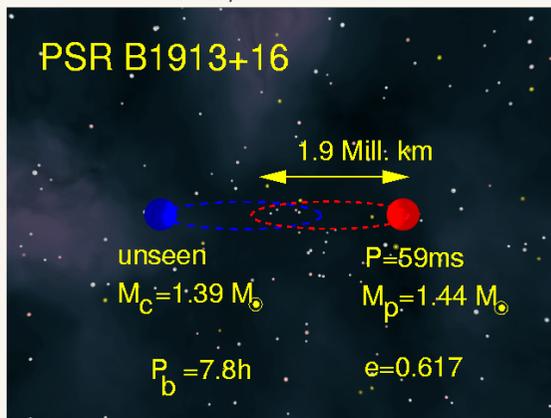
DOUBLE NEUTRON STARS

- SPIN QUITE FAST
- GREAT FOR GR TESTS
- INCL. DOUBLE PSR
- NOBEL PRIZE

ALMOST THE ULTIMATE PHYSICAL LABORATORY TO TEST GRAVITY

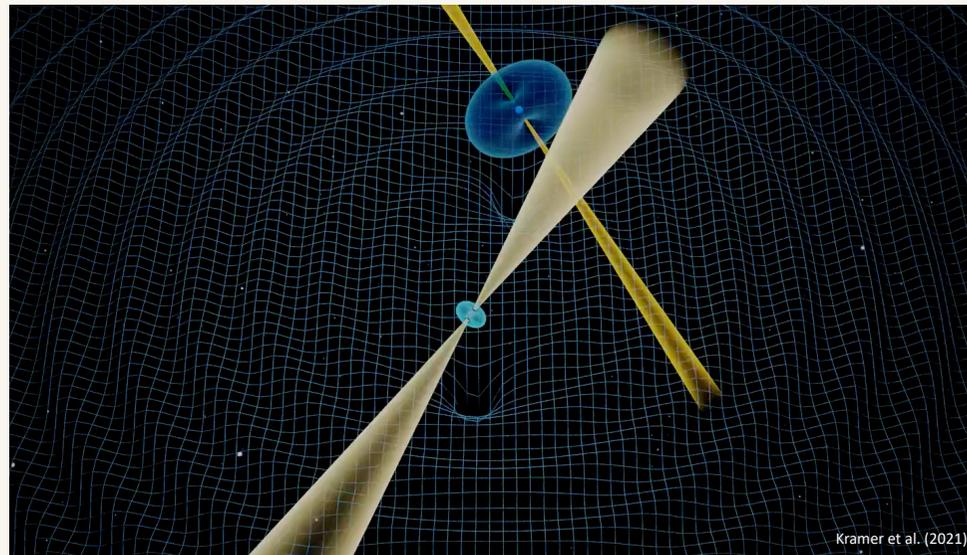
DOUBLE NEUTRON STARS

The OG/Nobel One



The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Discovered using the Murrumbidgee telescope at Parkes in Australia
- 22.7-ms pulsar and a 2.77-s pulsar
- In a 2.4-hr eccentric ($e=0.088$), compact orbit
- Orbit shrinks due to GW emission: $\Delta P_b = 107,820 \pm 7$ ps/day!

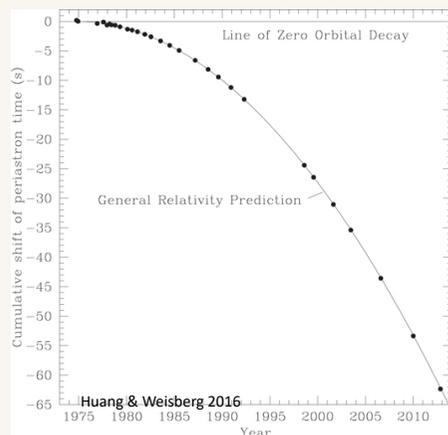


Relativistic effects measured:

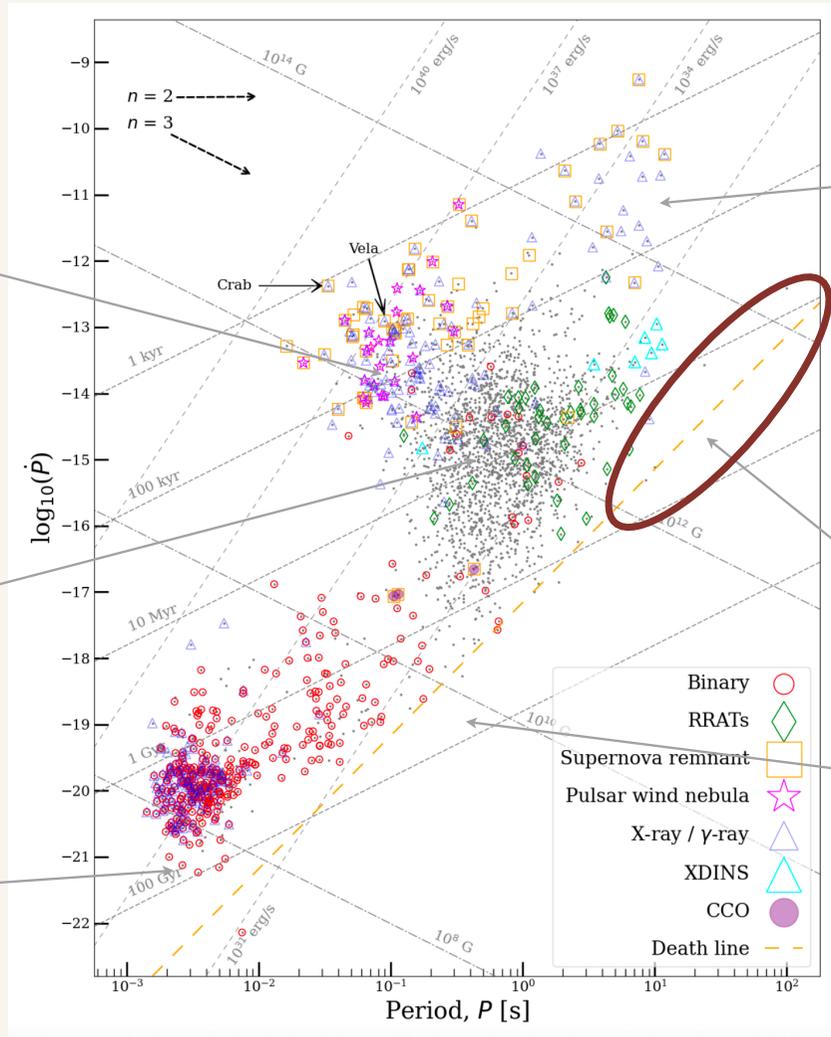
- Orbital precession
- Time dilation
- Shapiro delay (incl. next-to-leading order)
- Aberrational light bending
- Spin precession
- Relativistic deformation of orbit
- GW emission

Plus theory-independent mass-ratio

Kramer et al. (2021)



P-PDOT DIAGRAM



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LONG PERIOD PULSARS

- BEYOND THE DEATH LINE
- HOW ARE THEY STILL RADIO EMITTING?
- LINK TO EVEN LONGER PERIODS?
- HOW MANY TYPES OF NS?

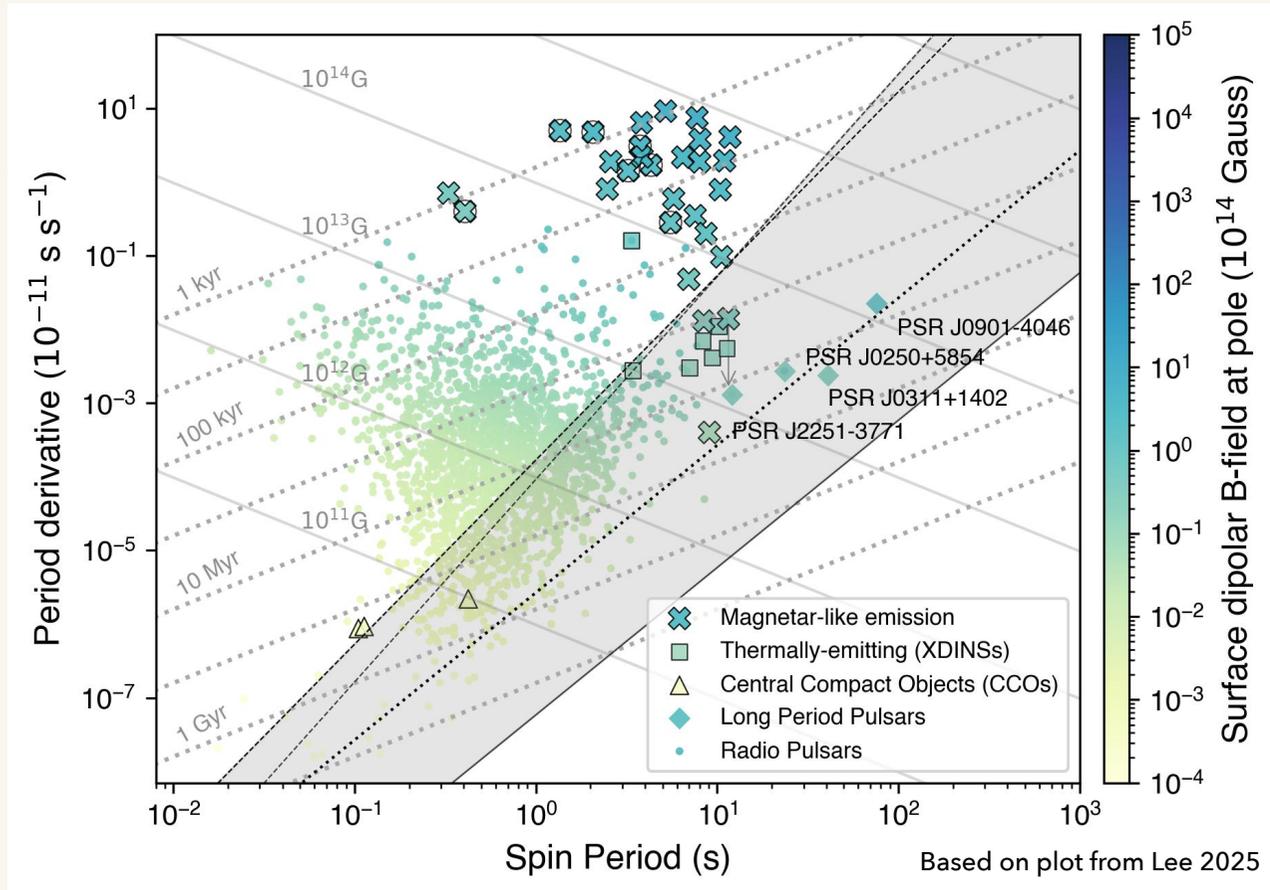
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STAYING ALIVE

LONG PERIOD PULSARS

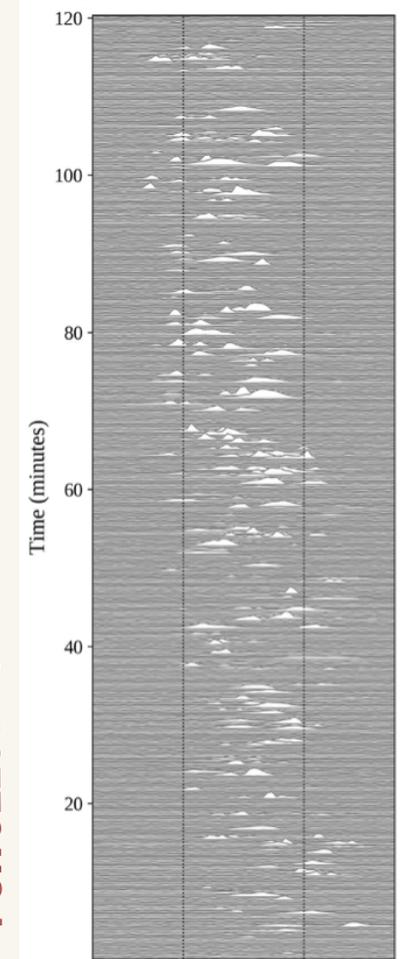
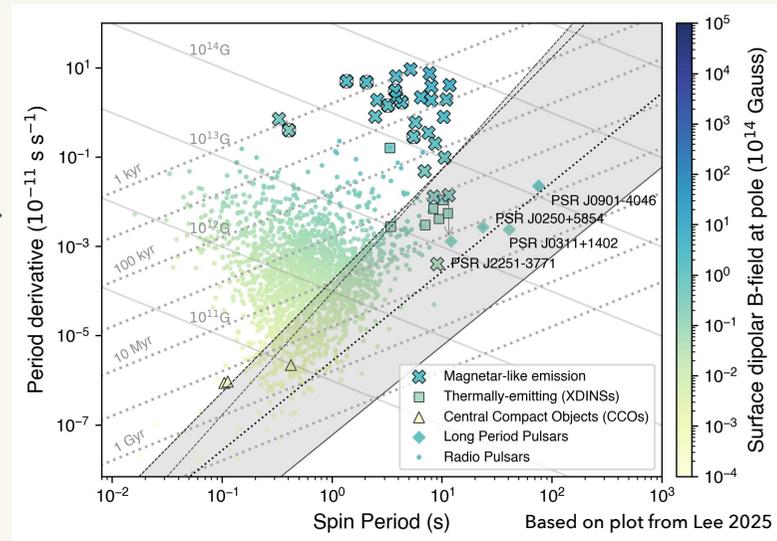
- It is expected that pulsars will move through the P-Pdot diagram and eventually cross the death line.
- Depending on the exact nature of the emission process exhibit radio emission to cease — Death Valley / Death Line.
- Perhaps connection to even longer period sources we will discuss later in the transients section.
- Emission does start to get a bit weird out here...
- What does it say about how many Neutron Stars there are?



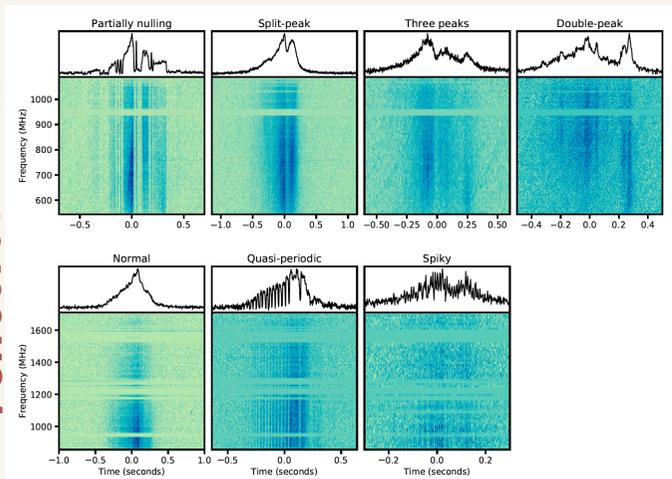
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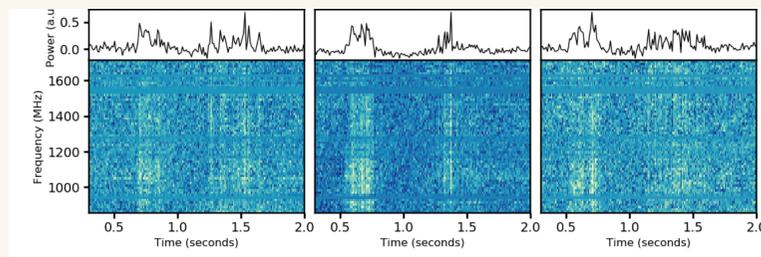


Morello et al. 2023



Caleb et al. 2022

PSR J1710-3542



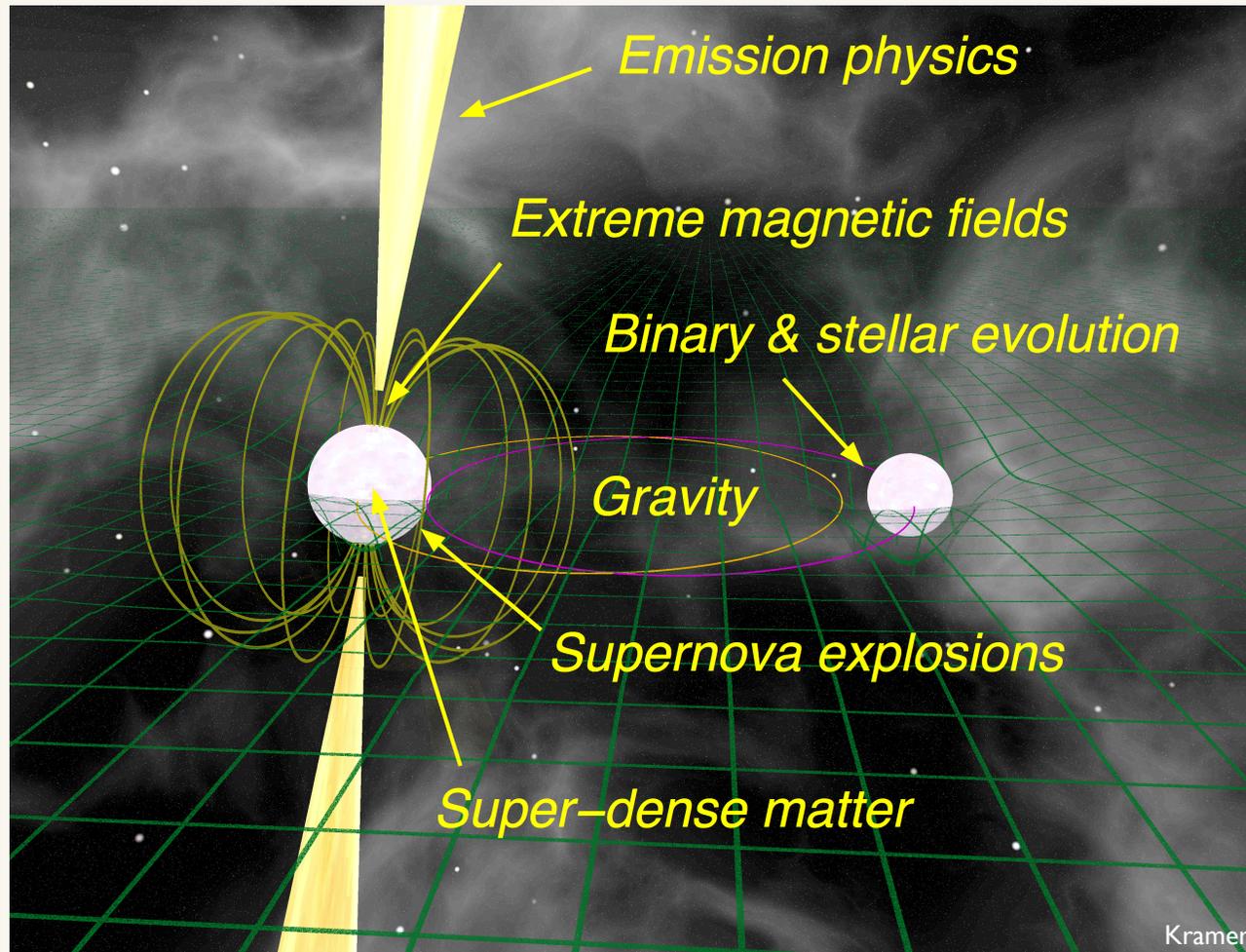
Surnis et al. 2023

PSR J2251-3711

PSR J0901-4046

WHAT CAN WE USE THEM FOR?

PULSARS ARE VERY SENSITIVE TO TOOLS FOR MEASURING ANYTHING THAT CAUSES A CHANGE IN THE TIME BETWEEN PULSES.



RECORD BREAKERS

HIGH PRECISION MEASUREMENTS

Spin parameters:

- ❖ Period: 2.947108069160717(3) ms (Reardon et al. 2015) Note: 3 atto seconds!

Orbital parameters:

- ❖ Period: 0.1022515592973(10) day (Kramer et al. 2021)
- ❖ Projected semi-major axis: 424 214 903(27) m (Kramer et al. 2021)
- ❖ Eccentricity: 0.087 777 023(61) (Kramer et al. 2021)

Masses:

- ❖ Masses of neutron stars: 1.33819(2) / 1.24887(1) M_{\odot} (Kramer et al. 2021)
- ❖ Mass of WD companion: 0.19730(4) M_{\odot} (Archibald et al. 2018)
- ❖ Mass of millisecond pulsar: 1.4359(3) M_{\odot} (Archibald et al. 2018)
- ❖ Mass of Ceres: $4.8(4) \times 10^{-10} M_{\odot}$ (Caballero et al. 2018)

Relativistic effects:

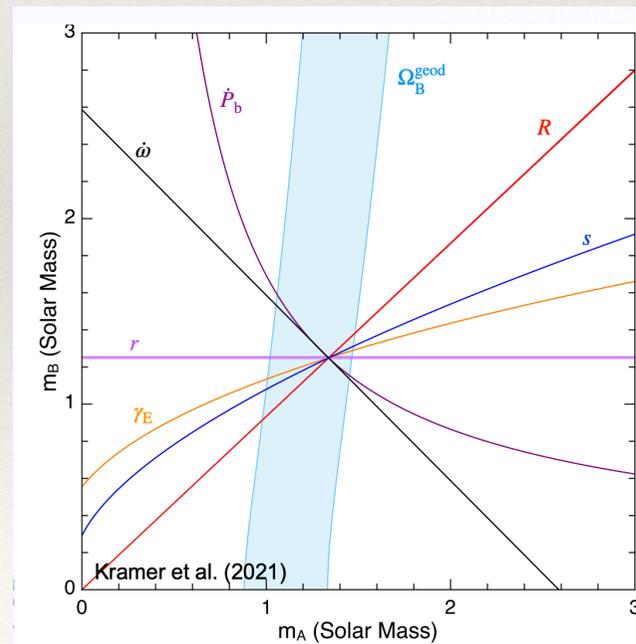
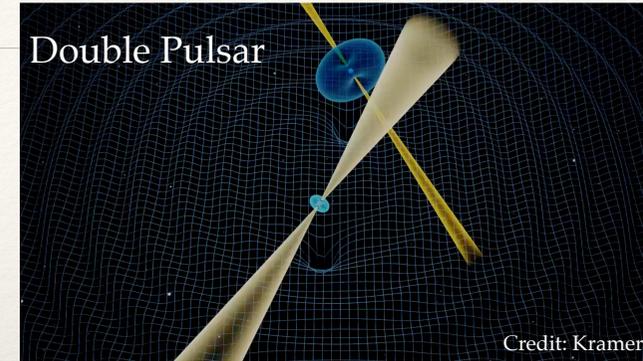
- ❖ Periastron advance: 16.89932(1) deg/yr (Kramer et al. 2021)
- ❖ Einstein delay: 4.2992(8) ms (Weisberg et al. 2010)
- ❖ Orbital GW damping: 7.152(1) mm/day (Kramer et al. 2021)

Fundamental constants:

- ❖ Change in $(dG/dt)/G$: $(-0.1 \pm 0.9) \times 10^{-12} \text{ yr}^{-1}$ (Zhu et al. 2018)

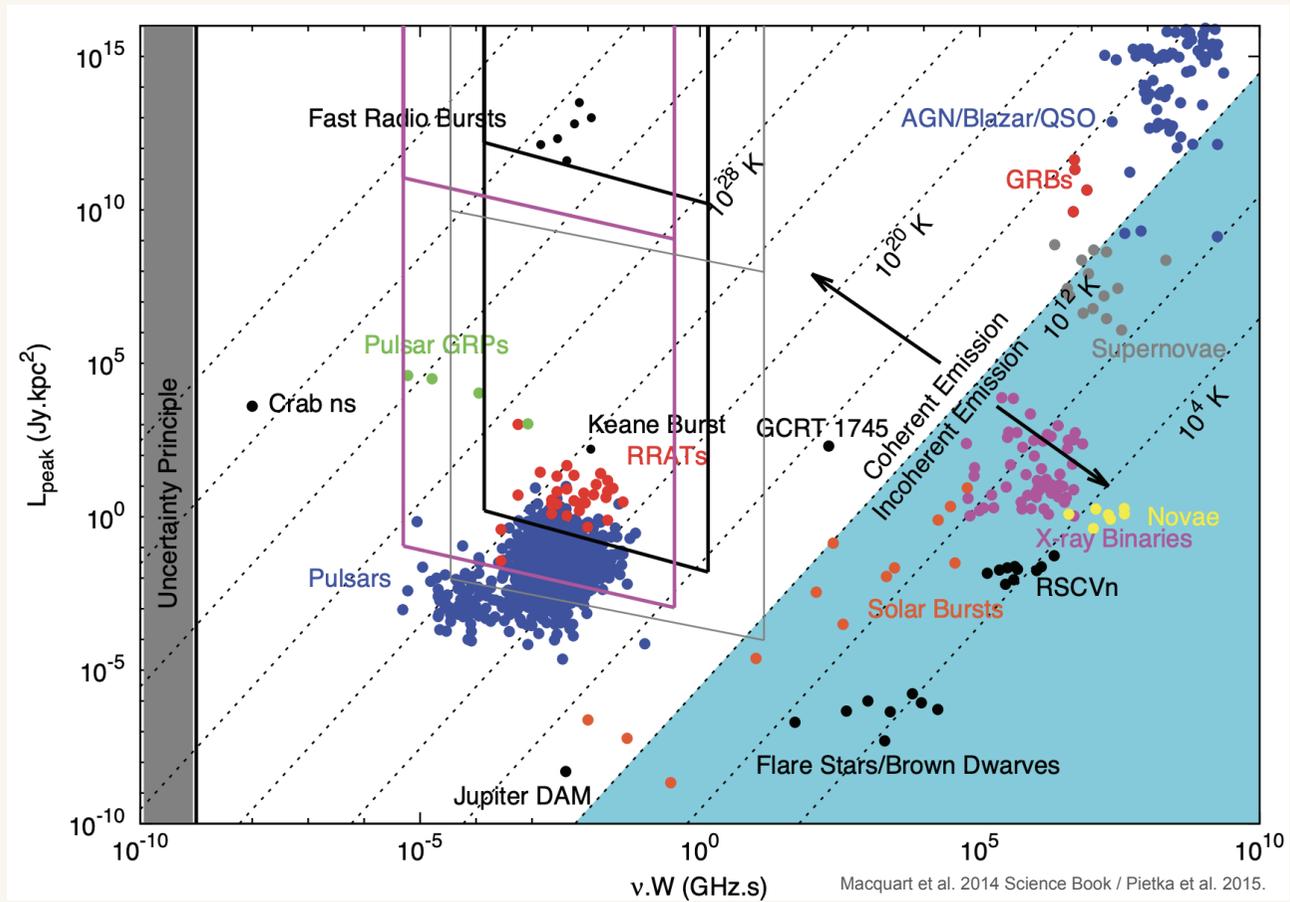
Gravitational wave detection:

- ❖ Change in relative distance: 30m / 1 lightyear (EPTA, NANOGrav, PPTA)



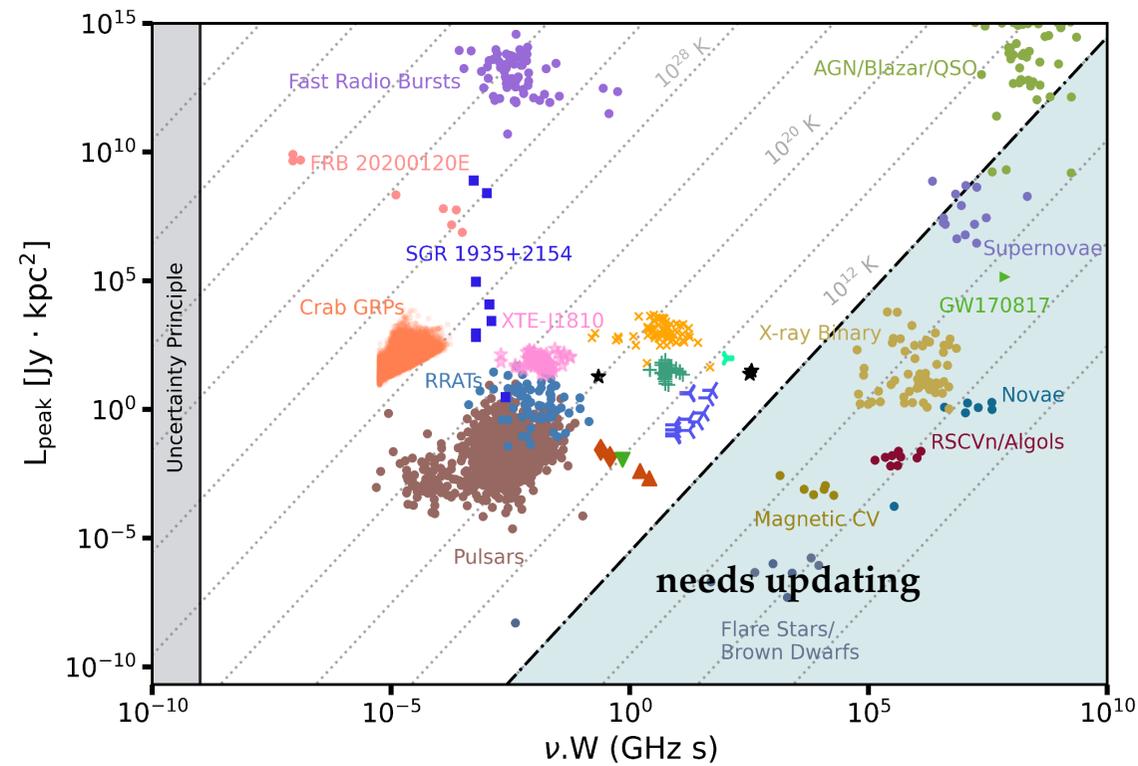
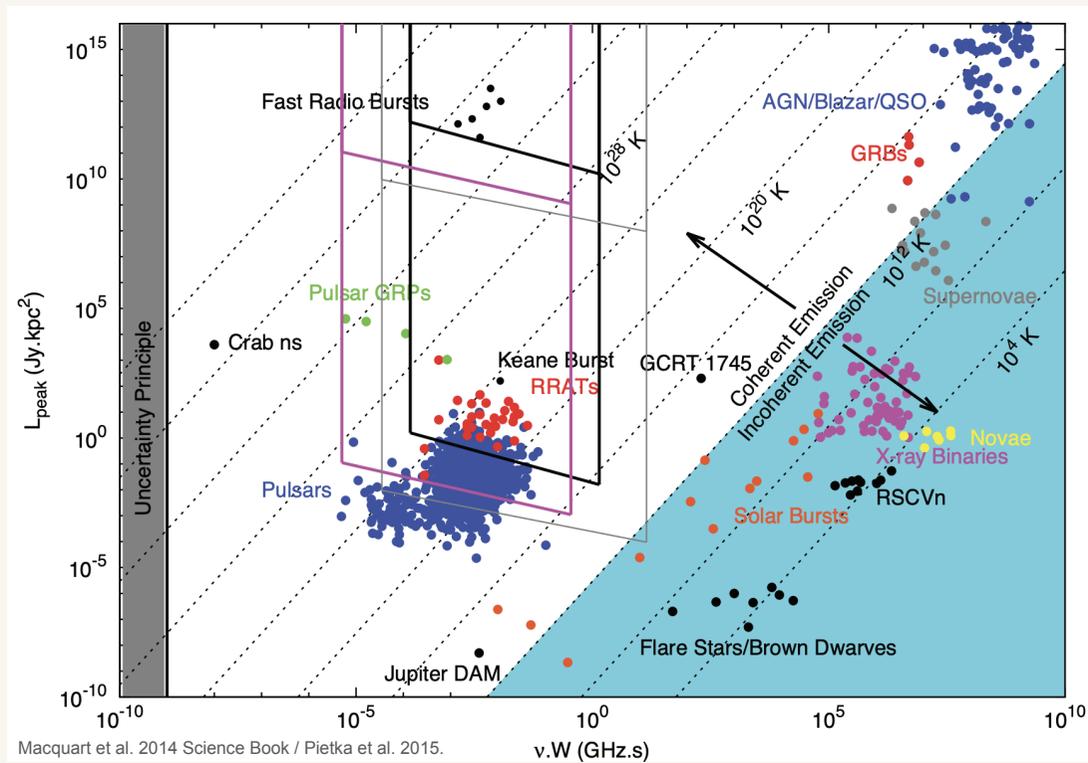
WHAT THINGS LOOKED LIKE IN 2014 (SKA SCIENCE BOOK)

TRANSIENT PHASE SPACE



WHERE ARE WE NOW?

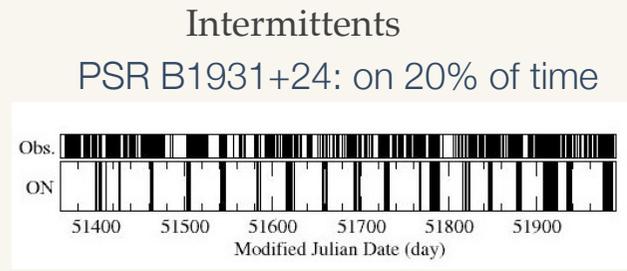
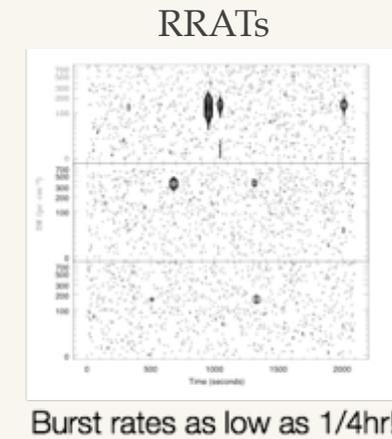
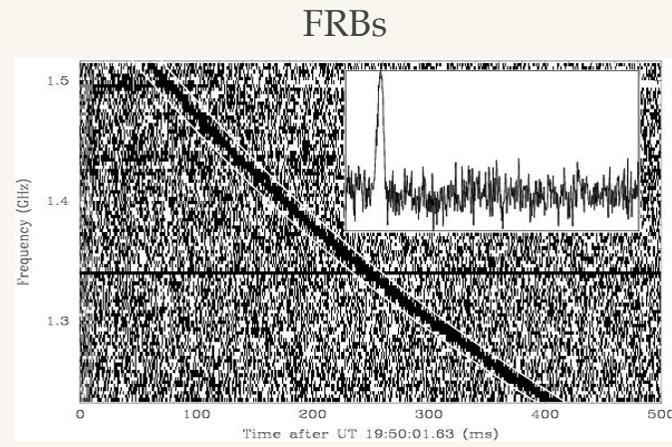
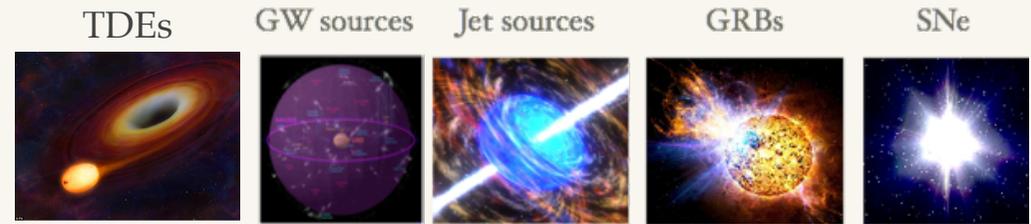
TRANSIENT PHASE SPACE



Anything that varies on Seconds++ Timescales

FAST TRANSIENTS

- Ultra-high-energy particles
- The Sun (Type II and III bursts)
- Flare Stars
- Brown dwarfs (scaling from NSs?)
- Planets (Jupiter, Saturn, Exoplanets (low freq?))
- ETI
- Fast Radio Bursts
- Annihilating black holes, coalescing NSs
- Supernovae
- Neutron Stars, e.g. RRATs, Nullers, Burpers, “sometimes a pulsars”,
radio magnetars, etc....
- EM counterparts to GW sources, Advanced LIGO on similar timescale
- Tidal Disruption events
- Interacting binaries... WD, other?



BACK TO THE FUTURE — SINGLE PULSE SEARCHES

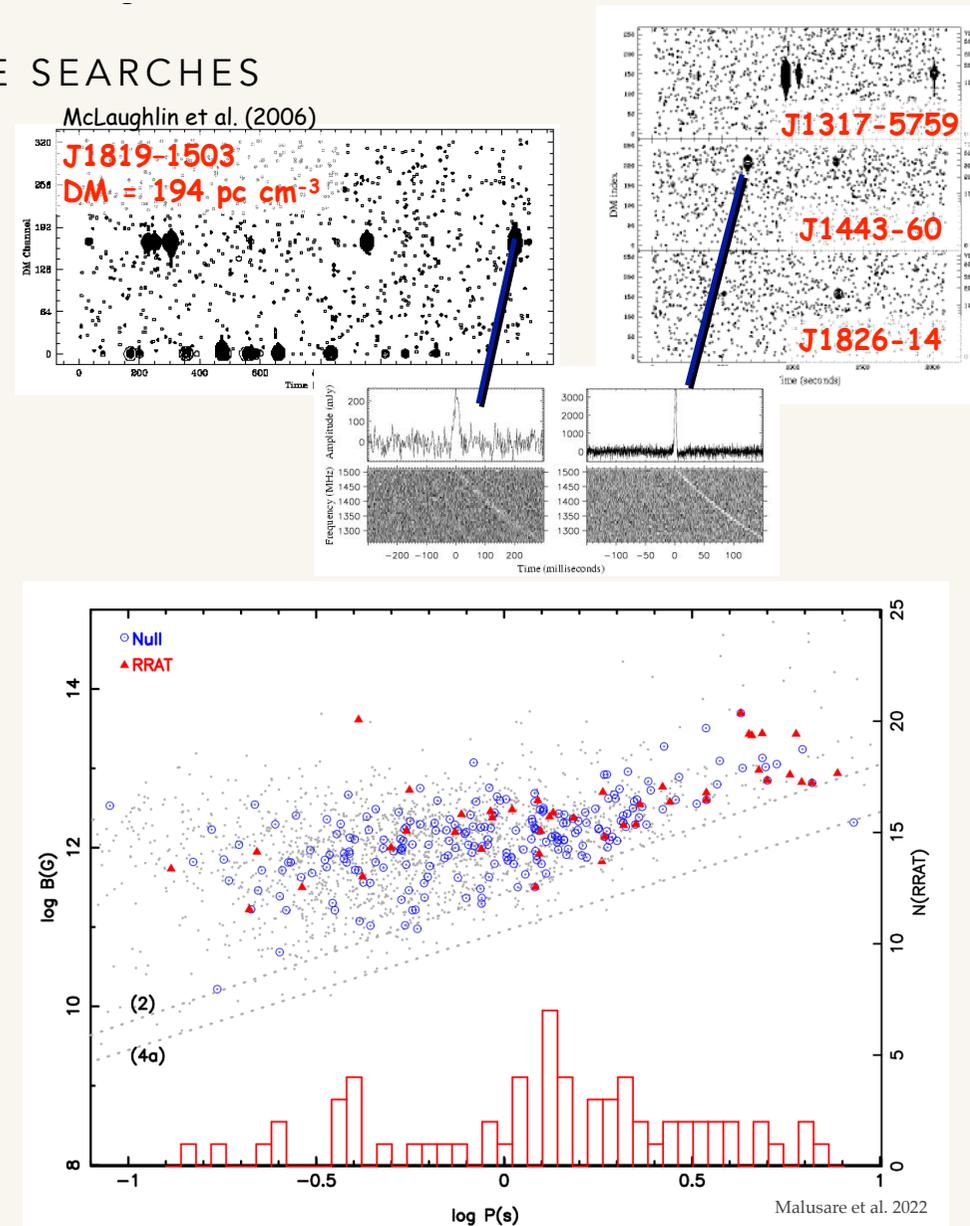
RRATS

- RRATs were first discovered in 2006 - McLaughlin et al. 2006
- Seen in reprocessing of pulsar search data and not seen in periodicity search.
- Seen over a period range of ~ 0.1 — 10 s — tend to be longer period.
- Perhaps some correlation with approaching the death valley.
- Many still only seen one or a handful of pulses.
- Some later seen to have weaker emission between the bright pulses.
- Already at discovery suggestive that there are more RRATs than pulsars
- Only a couple seen as a high energy source — Magnetar like.
- They are also seen to glitch.
- Keane & Kramer (2008) suggested an overall NS birth rate problem.
- Relies on raw sensitivity of the telescopes to discover them!

“A RRAT is a repeating radio source, with underlying periodicity, which is more significantly detectable via its single pulses than in periodicity searches.”

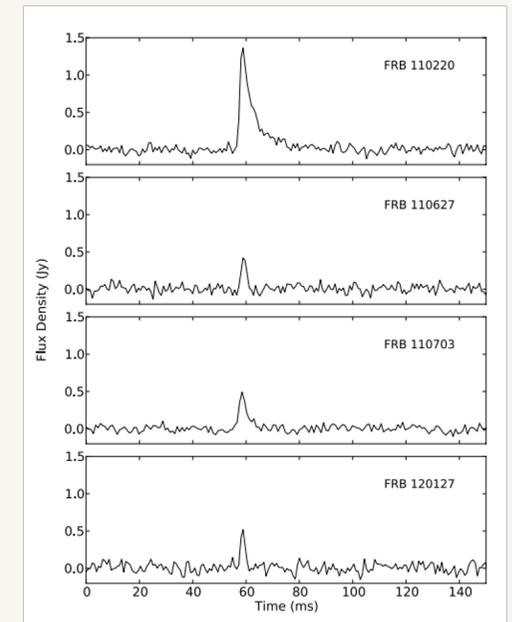
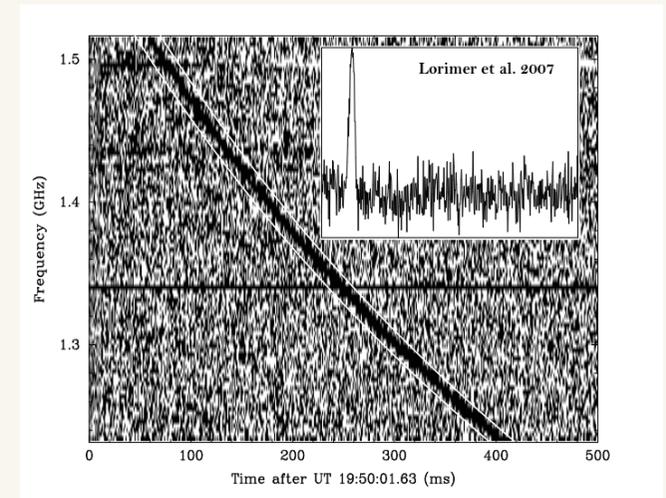
Keane & McLaughlin 2011

Also recognised that this definition may be dependent on nature of observation.



FRBS: A SUMMARY

- Short Duration bursts of radio emission
- Extremely energetic events ($< 10^{44}$ erg s^{-1}) from $z_{\text{spec}} \sim 0.03$ to > 1 galaxies
- $\sim 5,000$ events/sky/day
- Some repeat! — No strict periodicity (??)
- Some show very long term (days) periodicities — binarity?
- Detected from 110 MHz to 8 GHz (observed)
- Not yet definitively seen at wavelengths other than radio (extragalactic).
- No statistically significant counterpart yet



Thornton et al. 2013

FRB MODELS

Two main types of models: Magnetospheric origin & Shock wave models

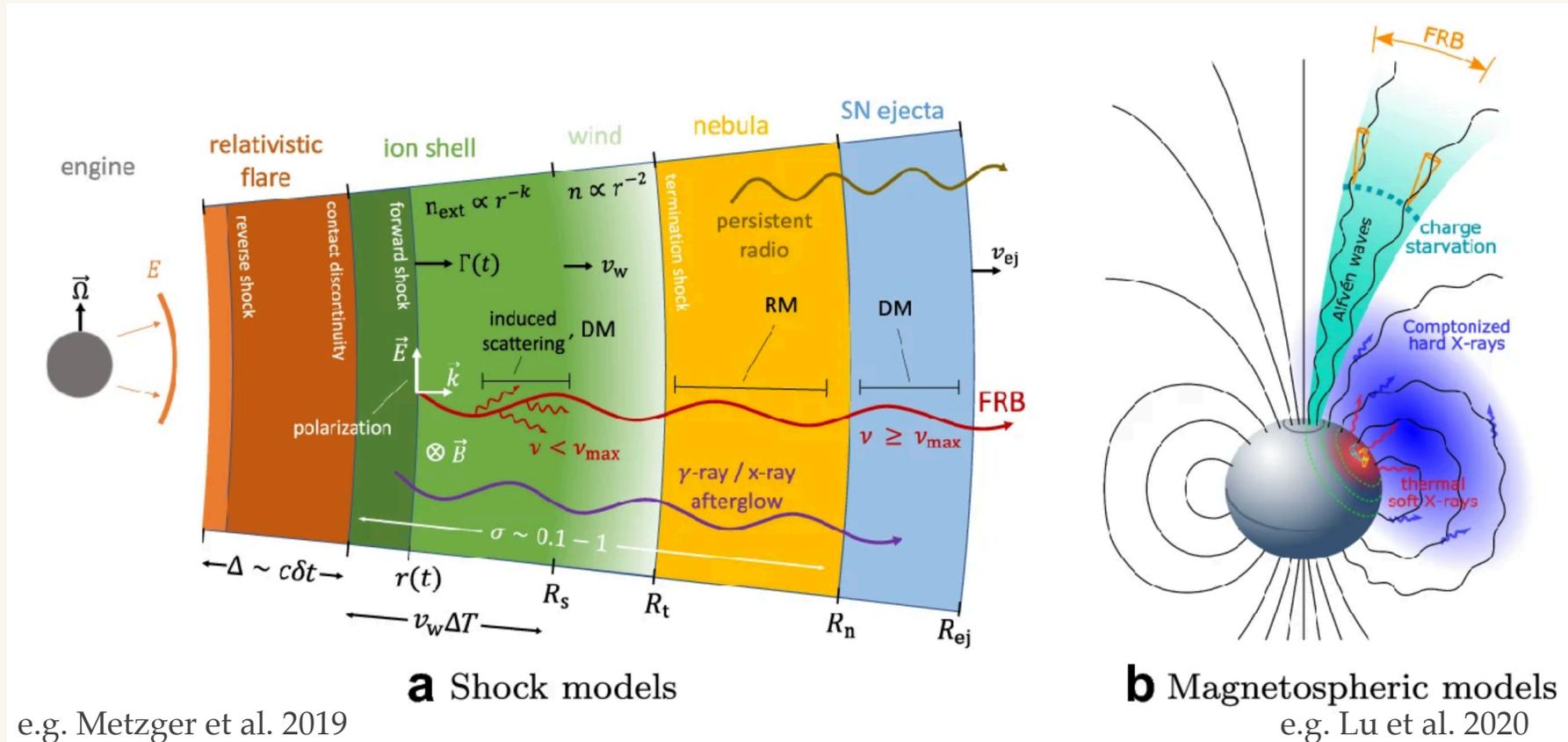


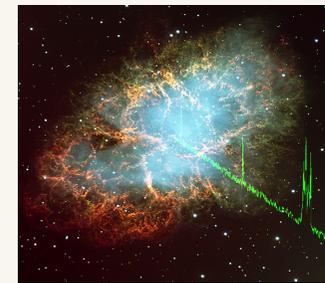
Image from Petroff, Hessels & Lorimer 2022.

www.frbtheorycat.org

FRB MODELS

Two main types of models: Magnetospheric origin & Shock wave models

Magnetars:	Pulsars:	White dwarfs:	Compact-object mergers:
<ul style="list-style-type: none"> ▶ Young magnetar from SLSN ▶ Magnetar from CCSN ▶ Magnetar from DNS merger 	<ul style="list-style-type: none"> ▶ Pulsar giant flares ▶ Young SNR pulsars 	<ul style="list-style-type: none"> ▶ WD from WD-WD merger ▶ White dwarf collapse (AIC) 	<ul style="list-style-type: none"> ▶ NS-NS merger ▶ WD-WD merger ▶ NS-BH merger ▶ BH-BH merger

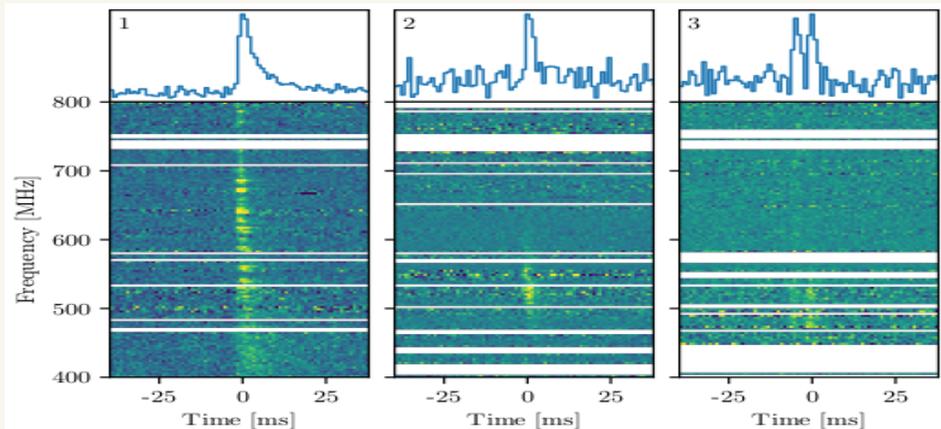


Nasa and van Leeuwen.

FRB CLASSES

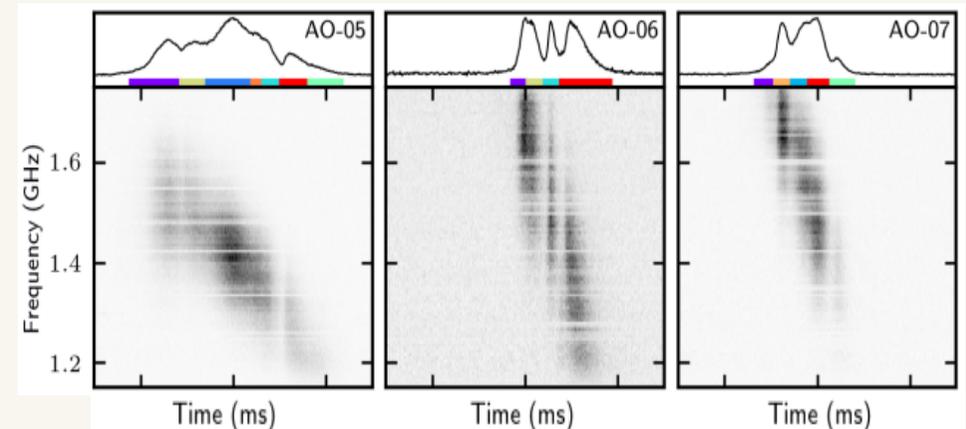
One-offs

- Thousands detected [TNS, CHIME/FRB+2021]
- Discovered in 2007 [Lorimer+2007]
- Morphologies: single broadband, single narrowband, multicomponent [Pleunis+2021]
- At least 30% complex bursts. [e.g. Pastor-Marazuela+2023,2025]



Repeaters

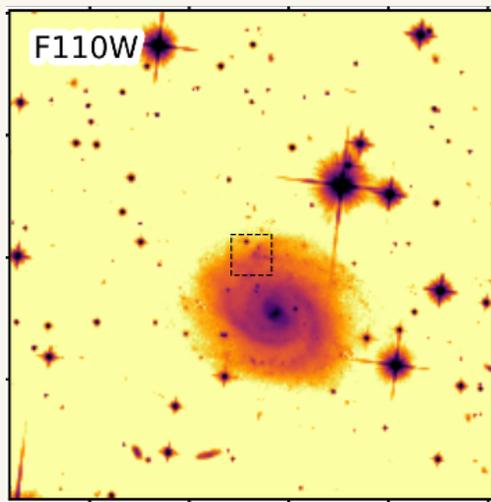
- >60 published
- Discovered in 2016 (FRB20121102A) [Spitler+2016]
- Two(++) are known to be periodically active [CHIME+2020, Rajwade+2020, Cruces+2021, Pastor-Marazuela+2021]
- Morphology: multicomponent, downward drift in frequency (sad trombone effect) [Hessels+2019]



UNVEILING AND UTILIZING FRBS

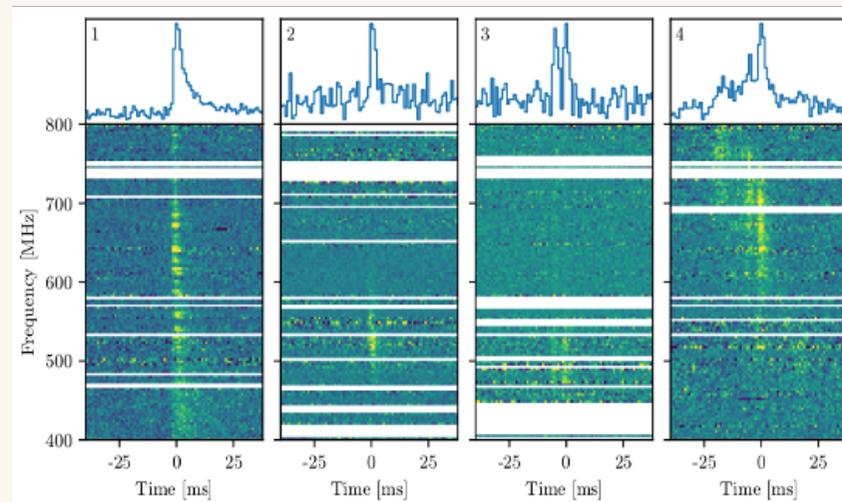
Production site

- How do the progenitors of FRBs form and evolve?
- What is their origin(s)?
- How do they influence their environment



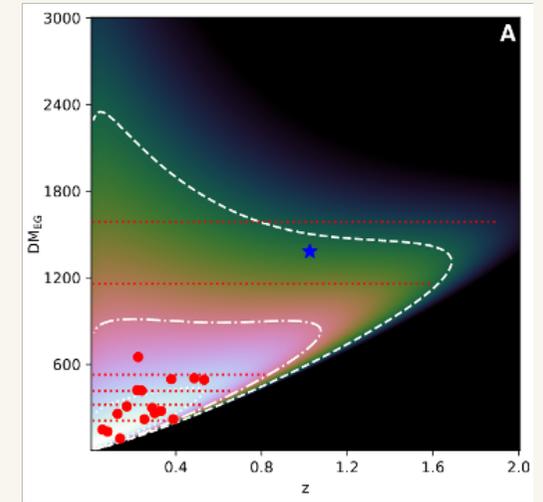
Emission process

- What is the underlying physics of these energetic bursts?
- What is the influence of site and propagation?
- How long can they shine for?



Cosmological probes

- What do they reveal about matter distribn & structure of the Universe?
- What can they tell us about the state and history of the Universe.
- Constrain H_0 , reionisation epochs

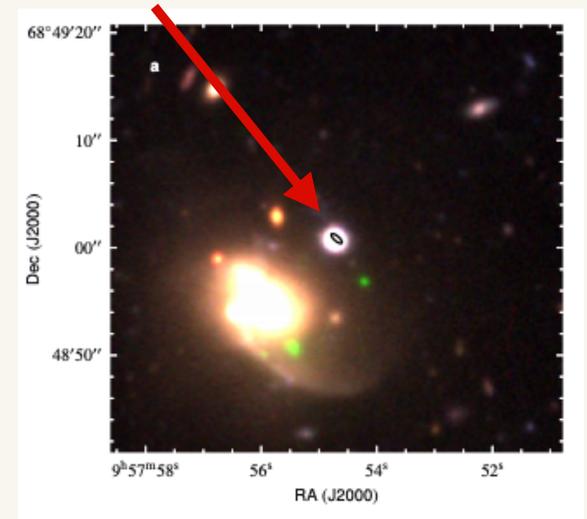


YET MORE PROPERTIES....

FRBS

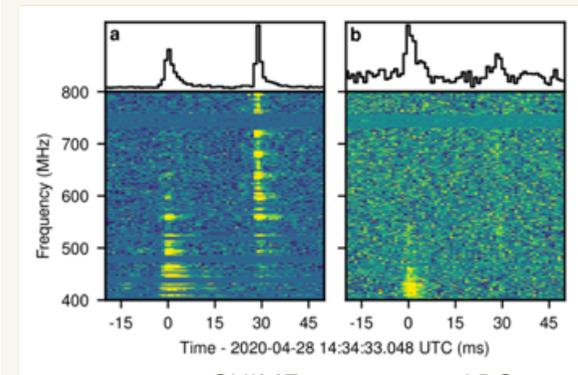
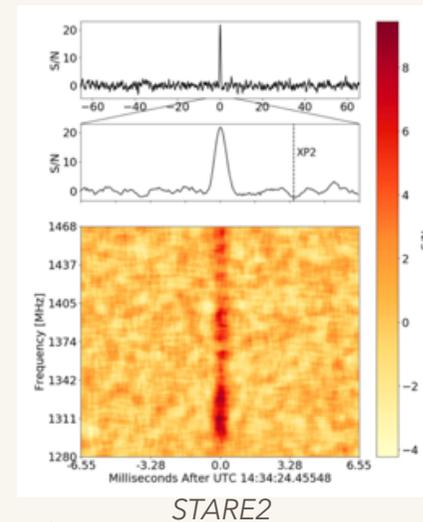
- Many thousands are now known
- Dozens of host galaxy associations
- One association of and FRB with a globular cluster.
- Some show evidence for Persistent Radio Source
- No underlying spin periodicity definitely confirmed.
- Associations with NSs for at least some
 - FRB-like emission from magnetar SGR 1935+2154
 - Complex radio emission seen that resembles NSs
 - Polarisation properties sometimes similar
 - BUT still significant differences in some cases
- New instruments being built / improved to localise hundreds

GLOBULAR CLUSTER IN M81



Kirsten et al. 2022

Kochanek et al. 2020

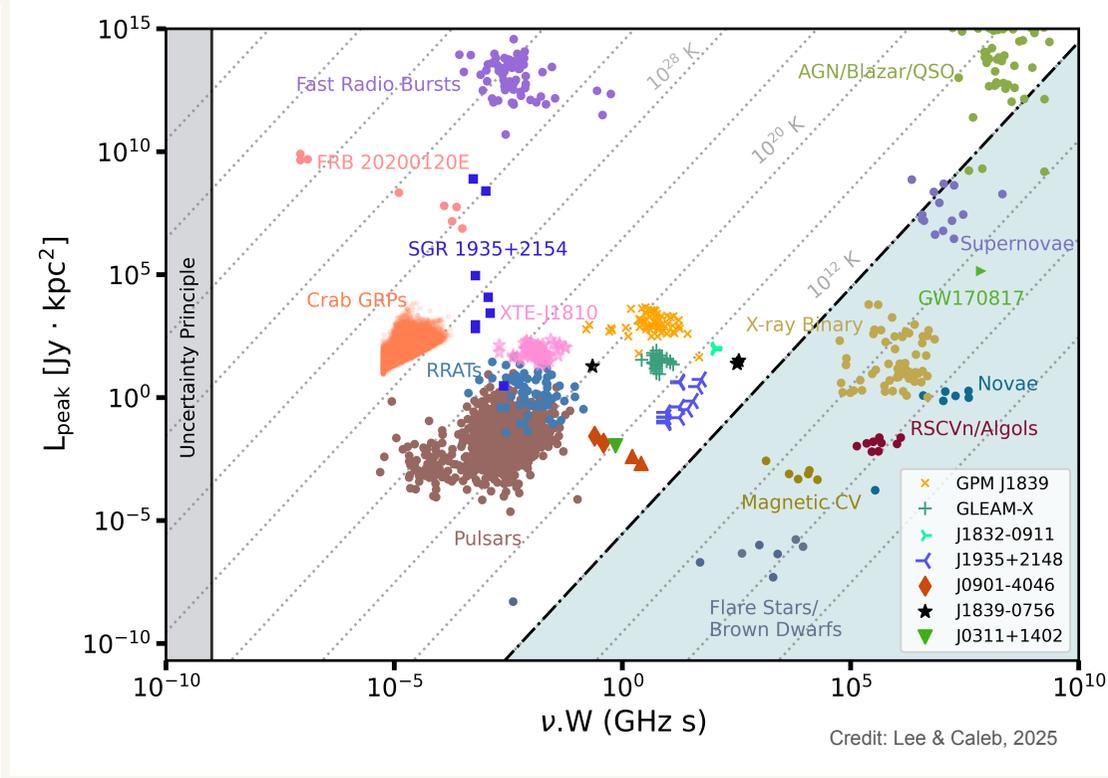
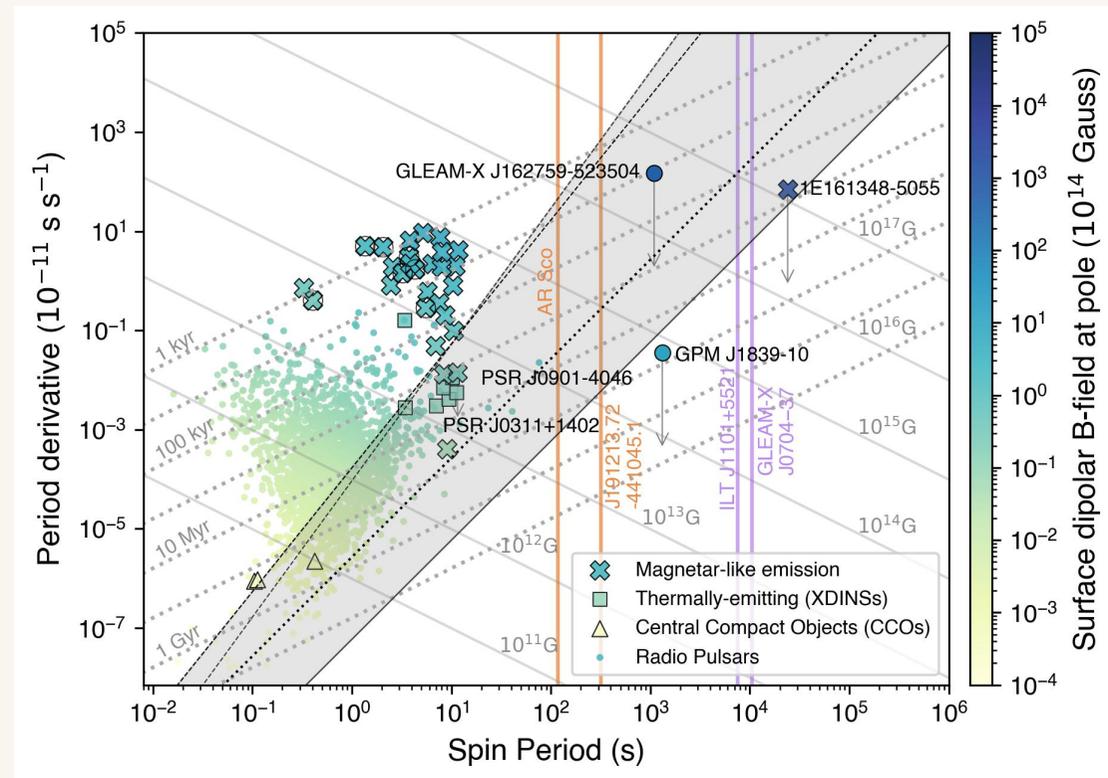


Kochanek et al. 2020

SGR 1935+2154 DETECTION

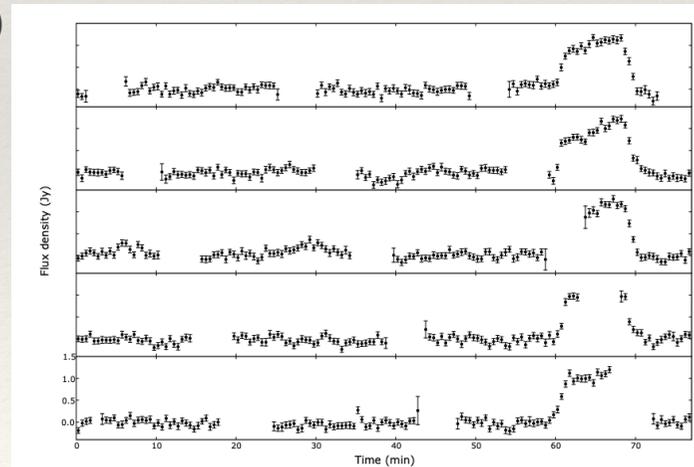
AND THE BEAT GOES ON.

THE (EVEN) LONGER PERIOD ONES

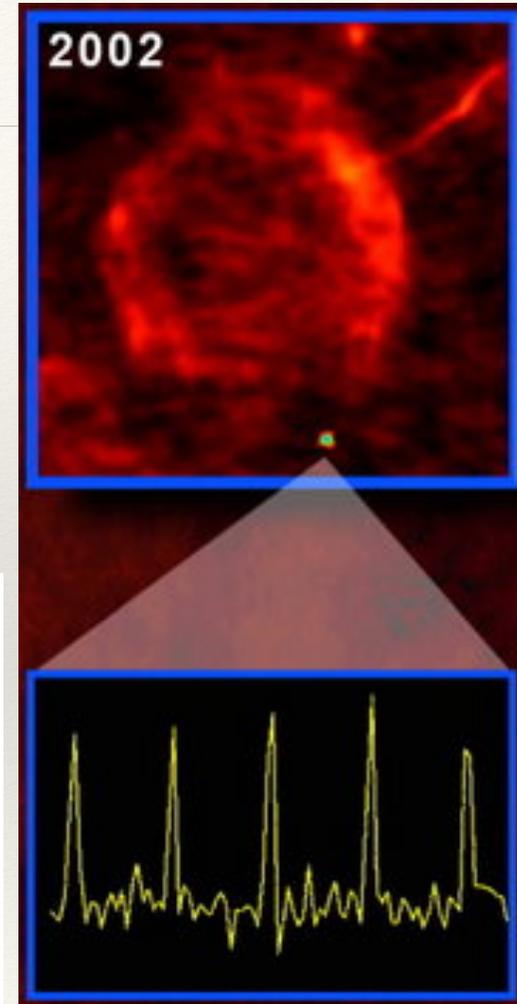


GCRT 1745-3009

- Found while monitoring near GC
- Detected at 90cm / 330 MHz
- 5*10min bursts in 7 hours (1 Jy) in 2002
- approximately every 77 minutes
- Single bursts in 2003(0.5 Jy) & 2004 (50 mJy)
- no high energy emission
- $d > 80$ pc, $T_b > 10^{12}$ K => coherent
- $d < 70$ pc, incoherent, flare star?
- 2004 detection => $S \propto \nu^{-13.5 \pm 3}$



Spreeuw et al, 2009



Hyman et al, 2005,2006,2007

GCRT 1745-3009: Models

Double Pulsar

Turolla, Possenti & Treves 2005

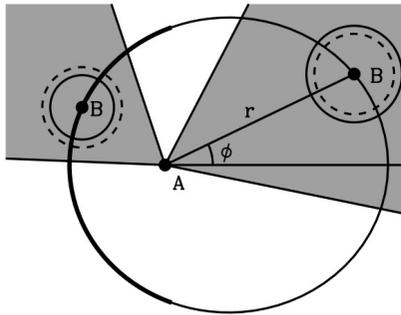


FIG. 1.— A cartoon of the putative double NS system in GCRT J1745-3009. The orbit of star B relative to star A has $e = 0.4$. The dashed and full circles represent the position of B's light cylinder and of the shock, respectively (not to scale). Along the portion of the trajectory close to periastron and marked with a heavy line the shock is inside the light cylinder. The shaded areas show the wind of A (for illustrative purpose only).

A transient white dwarf pulsar

Zhang & Gil 2005

- Bursting epoch when stronger sunspot-like
- magnetic fields emerge into the WD polar cap
- during which the pair production occurs.
- $P_{\text{spin}} = 77$ minutes
- Beam width = 10 minutes
- Favoured by Spreeuw et al. 2009

A precessing pulsar

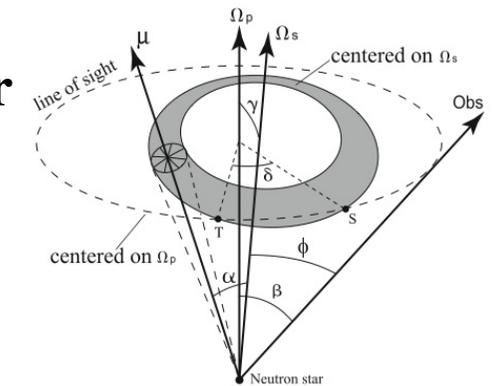
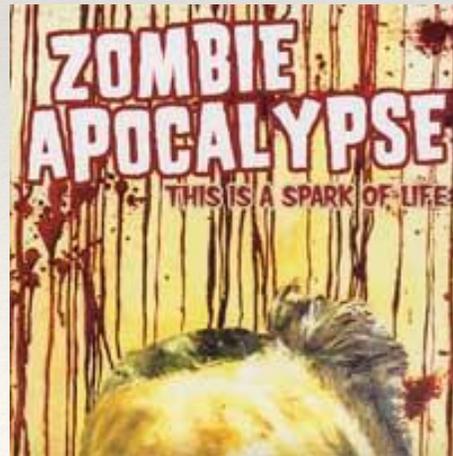


Figure 1. Geometry of a precessing pulsar. α is the angle between the magnetic axis μ and the spin axis Ω_s . β is the angle between the line of sight "Obs" and the precession axis Ω_p . ϕ is the angle between the line of sight and Ω_s . An observer can only detect radio bursts between "S" and "T", over an angle δ , which, in our model, is set to be $\delta = 2\pi(10/77)$ to fit the ratio of the observed burst duration to the period.

A zombie pulsar

Zhang, Gil & Dyks 2006

Only see downward emission.



Zhu & Xu 2006

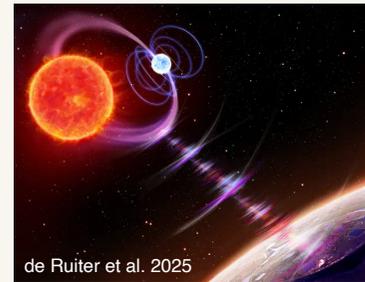
Pulsar must also be variable

A RANGE OF DIFFERENT SOURCE CLASSES

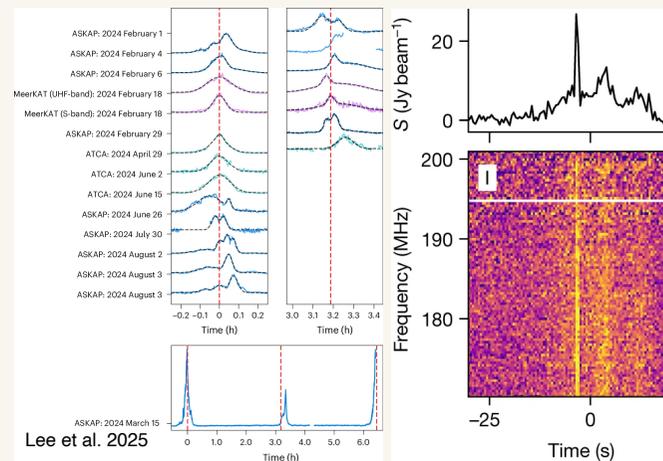
THE (EVEN) LONGER PERIOD ONES

- After 2 decades this field has been reinvigorated.
- Approximately a dozen LPTs have been discovered.
- Revolution is down to image plane searches with MWA, ASKAP, LOFAR and MeerKAT has joined the party too.
- Grouped together by properties such as:
 - Bright radio emission that exceeds spin-down energy
 - Long periods, short duty cycles
- But have a wide range of emission properties otherwise.
- and have different classifications (where known).
- Polarisation (Stokes V) also revealing new sources/properties
- There are also the radio emitting WD Systems, e.g. AR Sco.

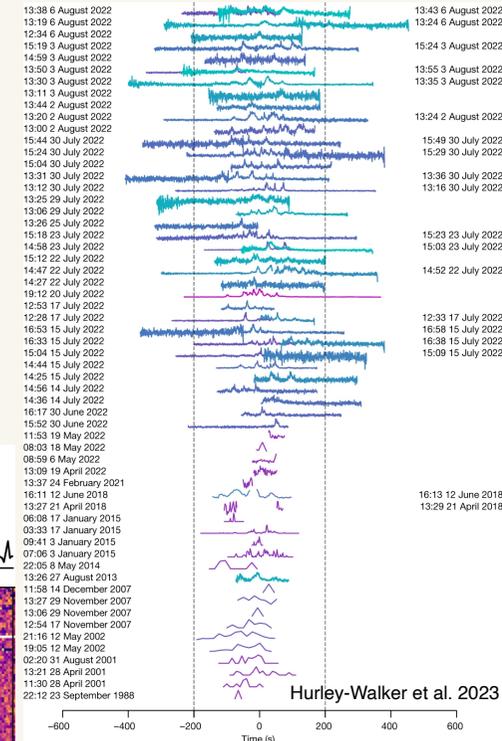
ILT J1101+5521 7 and GLEAM-X J0704-37
WD-M-Dwarf binary systems



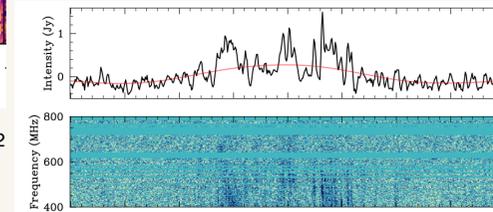
ASKAPs J1935+2148, J1839-0756 & GLEAM-X
J162759.5-523504.3: Magnetar/NS?



GPM J1839-10 — Also WD-MD?



CHIME J0630+25 — NS?



See <https://lpt.mwa-image-plane.cloud.edu.au/published/tables/1> for a list.

STILL LOTS TO DISCOVER AND LEARN!

SUMMARY

- There are a wide range of manifestations of neutron stars!
- In the form of pulsars they can tell us a lot about:
 - The physics of emission across the electromagnetic spectrum
 - The physics of extreme magnetic fields
 - Binary and stellar evolution
 - Test theories of gravity
 - Tell us about the nature of the Universe - structure / BHs ++
 - The physics of super dense matter
- There are also many manifestations of transients!
- In the form of FRBs they can (potentially) tell us about:
 - The nature and distribution of the intergalactic medium / missing baryons
 - Properties of galaxies such as content, B-fields, winds, turbulence, formation
 - The physics of the extremely energetic emission process(es)
 - Potential as cosmological probes (epochs of reionisation / H_0 ++)
- In other forms we are only just starting to learn what they can tell us about:
 - Stellar evolution, emission physics, properties of compact objects....