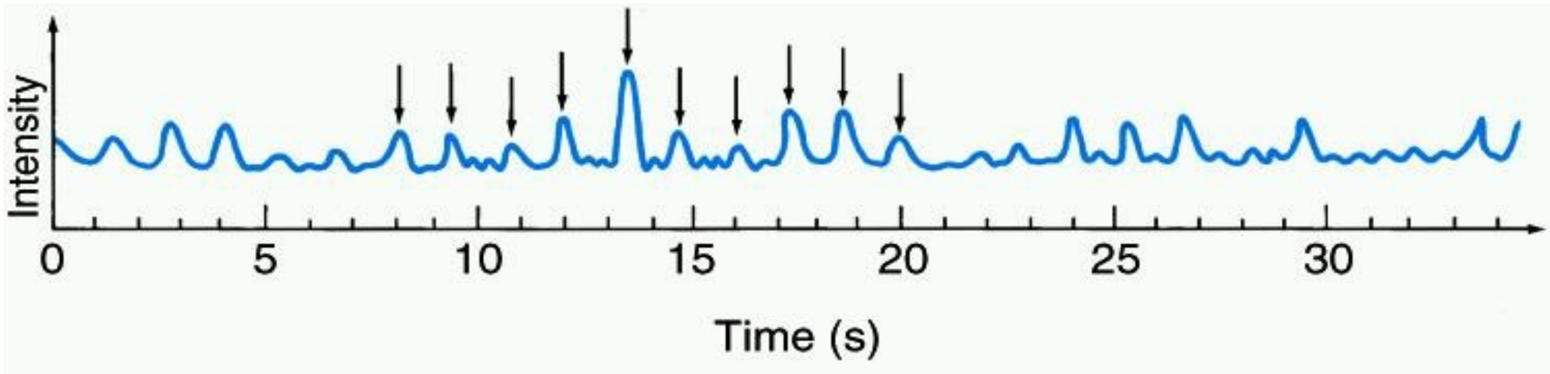
Pulsars



Discovery of LGM1 by Jocelyn Bell and Tony Hewish (Cambridge) in 1967. Nobel Prize to Hewish and Ryle in 1974.

Pulse periods observed from 0.001 sec to 76 seconds

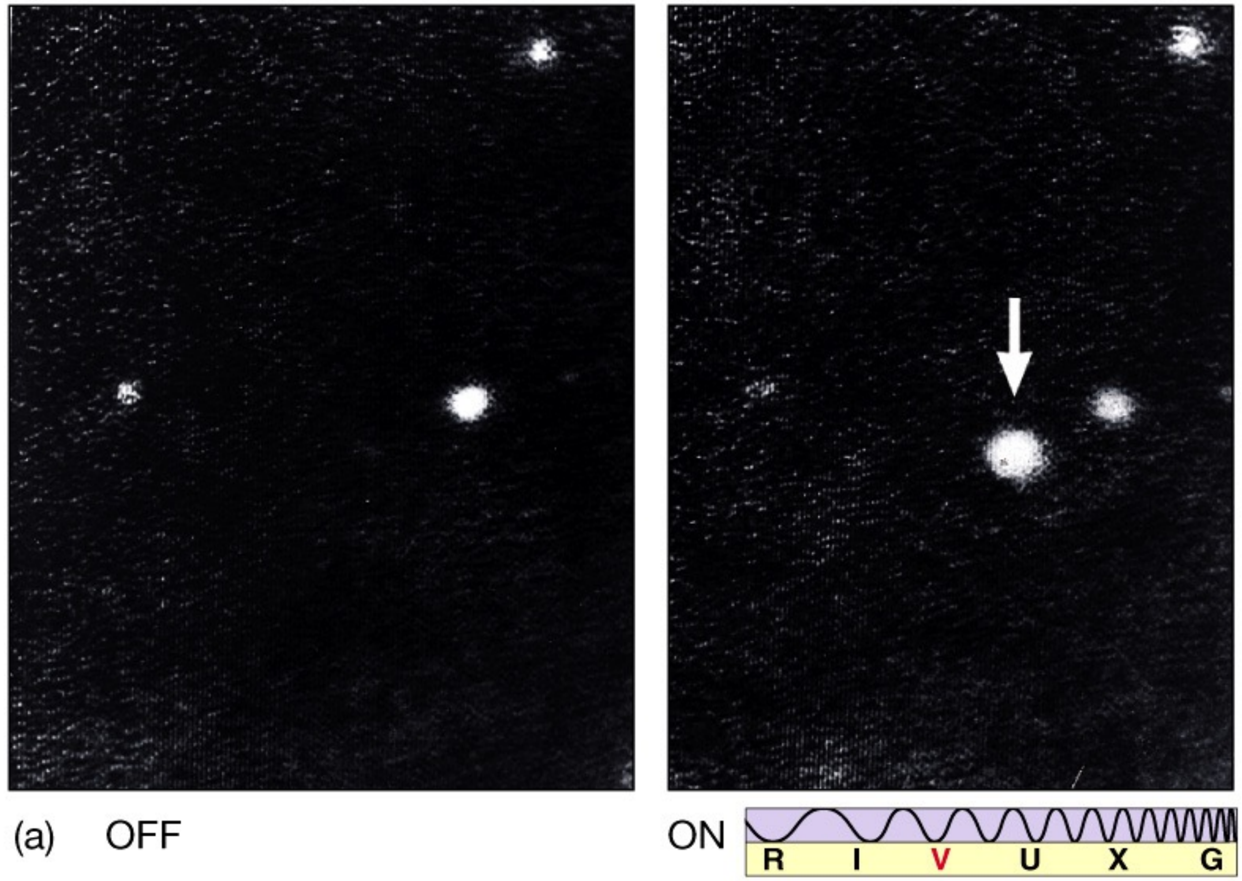
Explanation: "beamed" radiation from rapidly spinning neutron star.

Usually neutron stars are pulsars for 10^7 years after supernova.

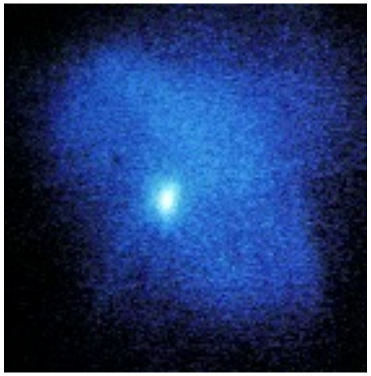
Study the Universe, See the World

Jocelyn Bell and Alan Rogers at URSI-2011 meeting in Istanbul

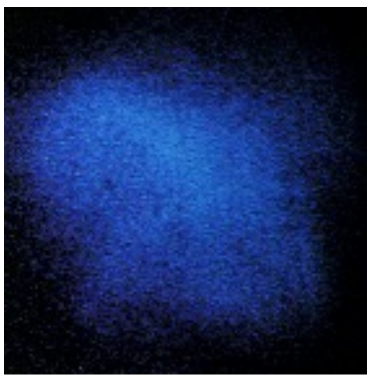
The Crab Pulsar



The Crab Pulsar



On



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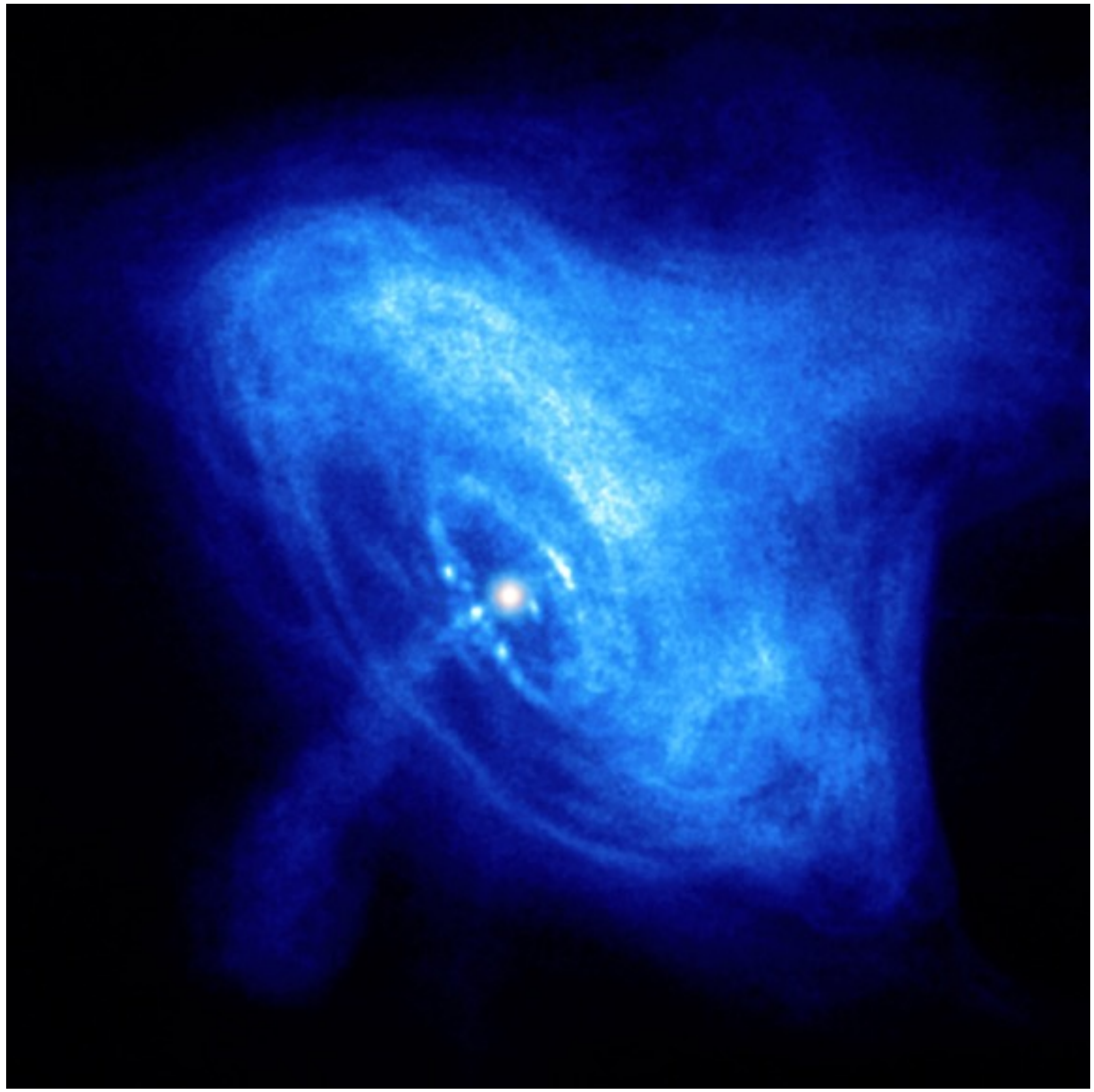
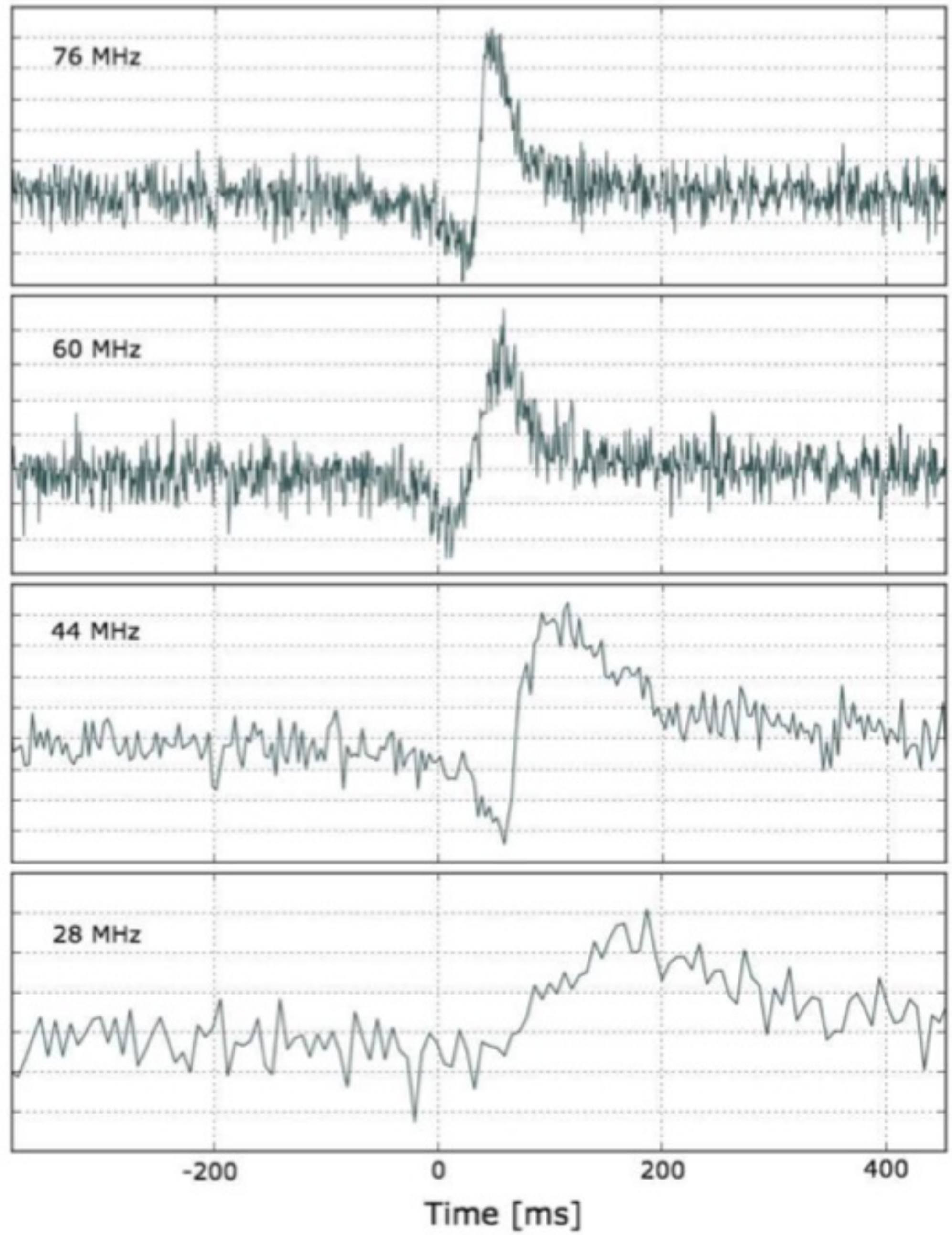


Chandra
X-ray
image

LWA Publication Highlights

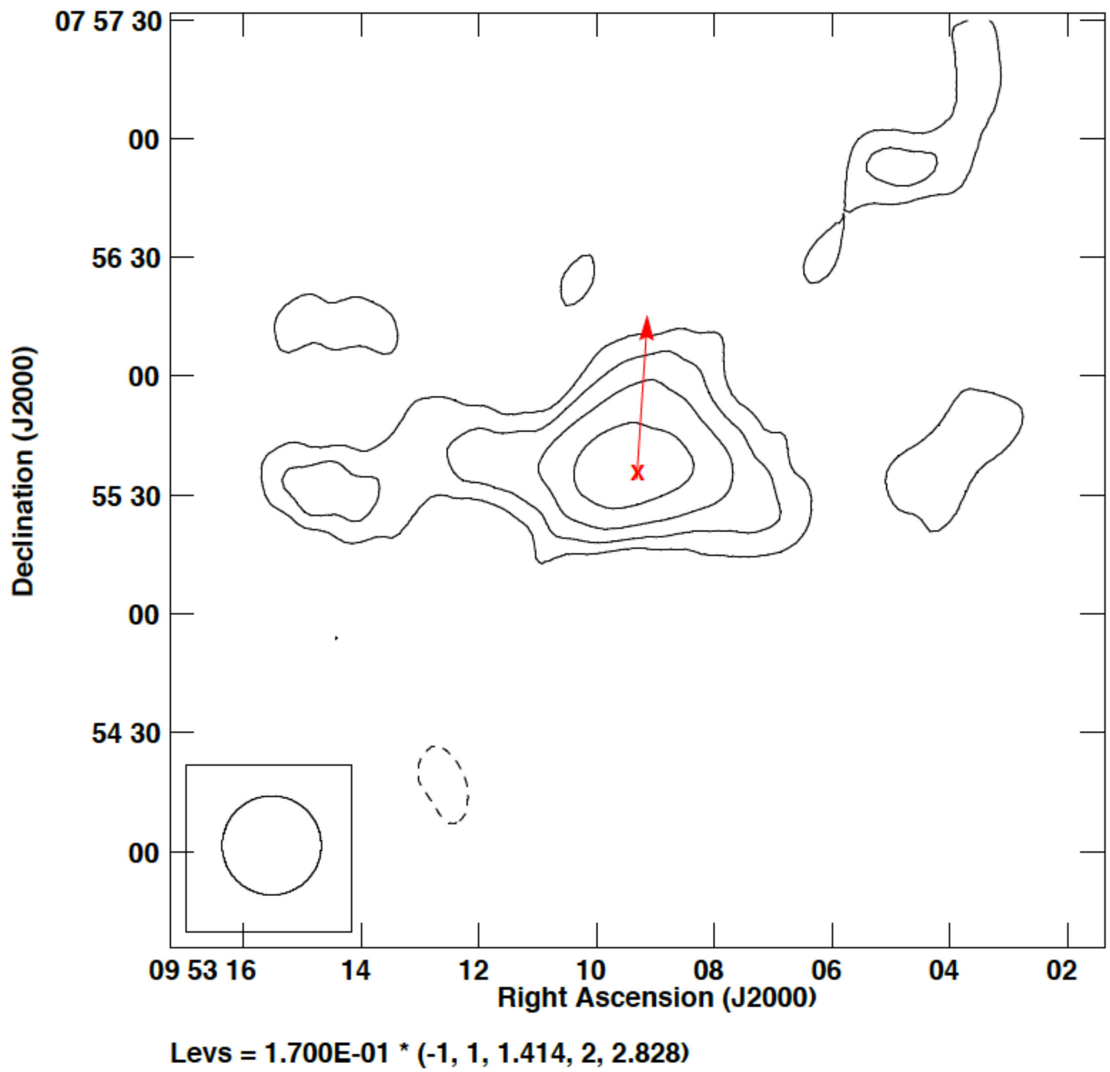
Crab Giant Pulses
Eftekhari et al. 2016

Note effect of scattering at low frequencies.

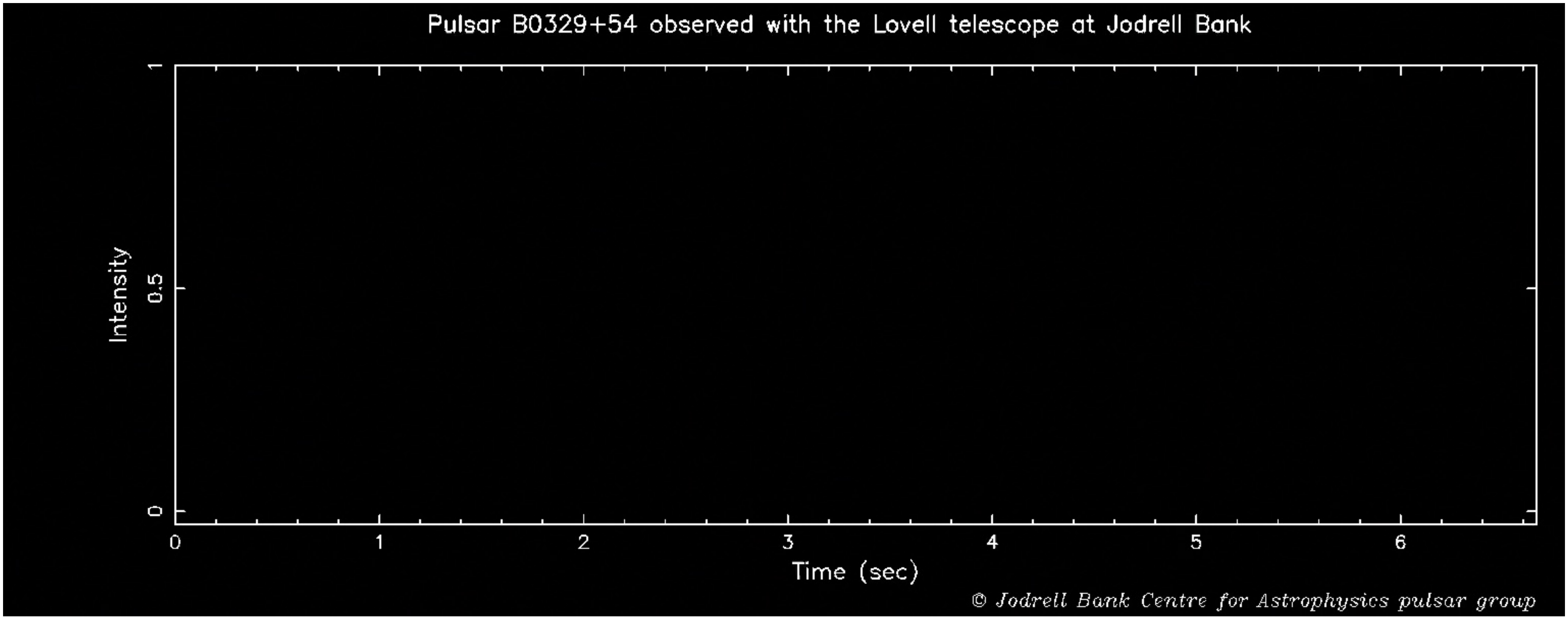


LWA Publication Highlights

Discovery of a Pulsar Wind Nebula Around B0950+08 with the ELWA
Ruan et al. 2020

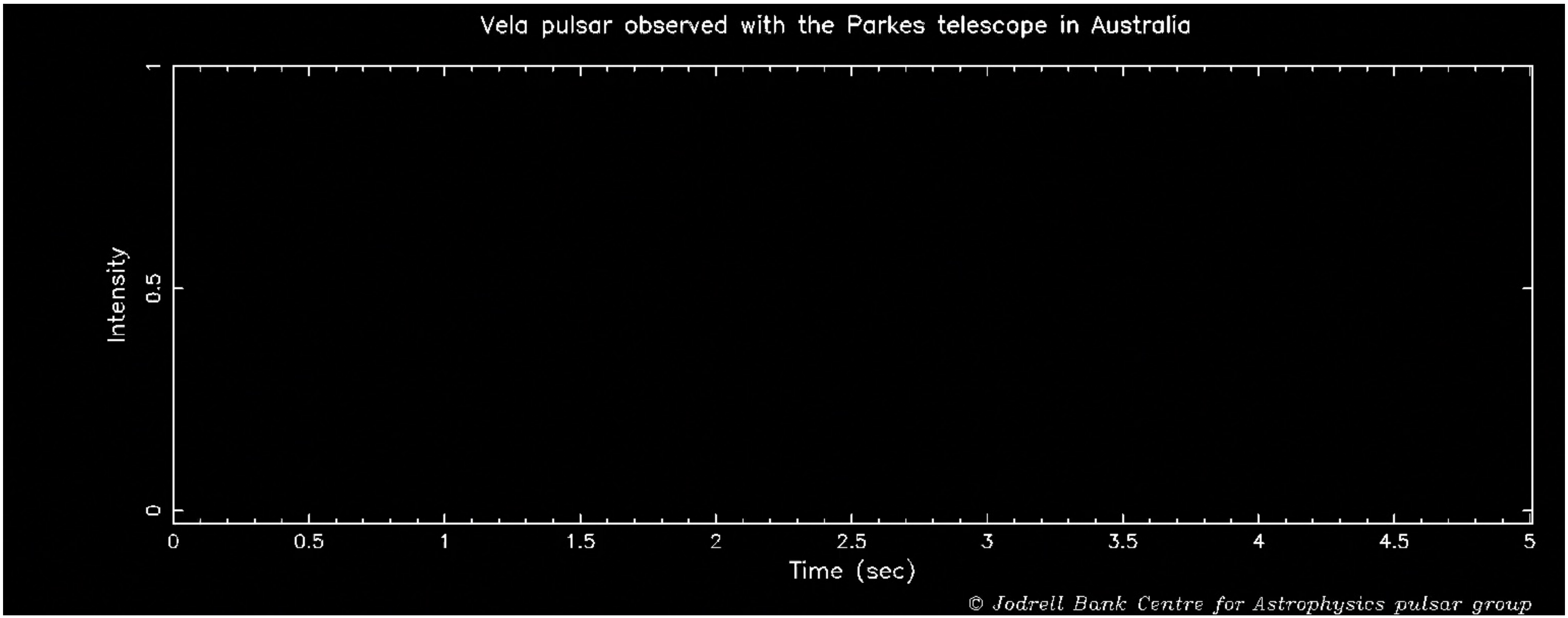


The Sound of Pulsars



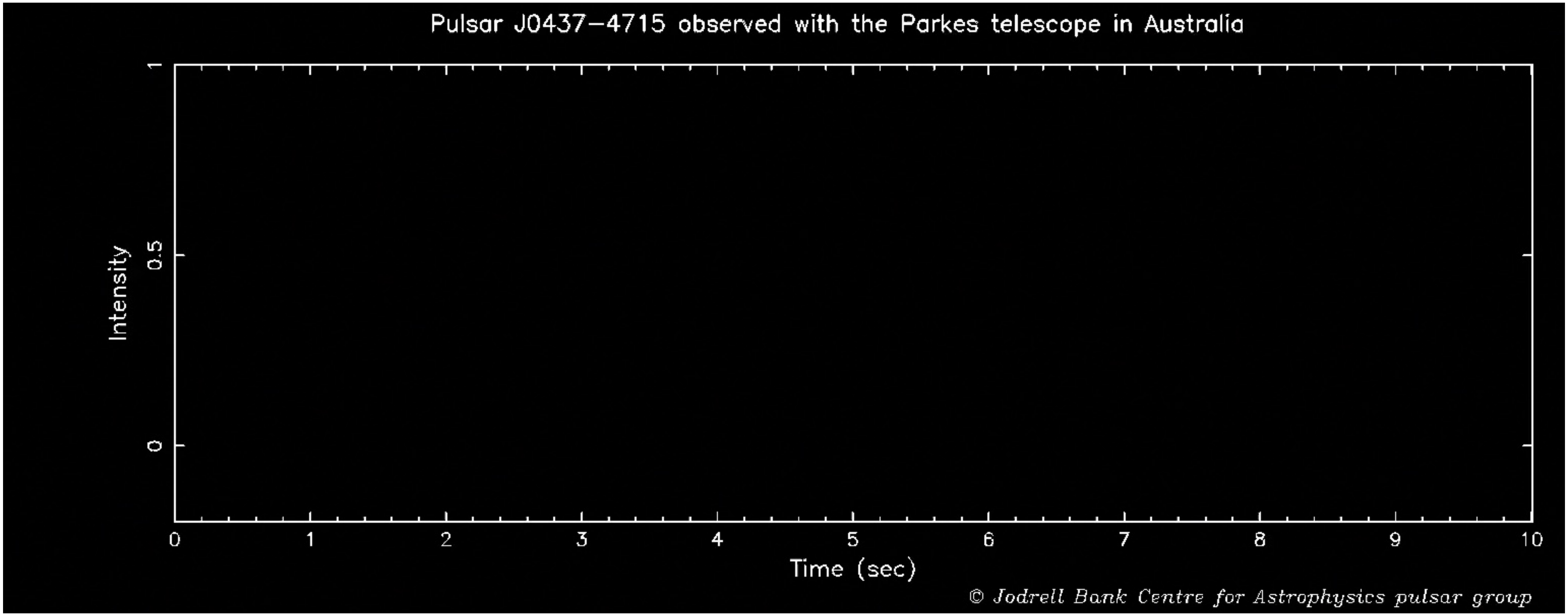
B0329+54, A bright pulsar with period 0.714520 sec

The Sound of Pulsars



Vela Pulsar, A young (age=10,000 years) pulsar with period 0.089 sec

The Sound of Pulsars

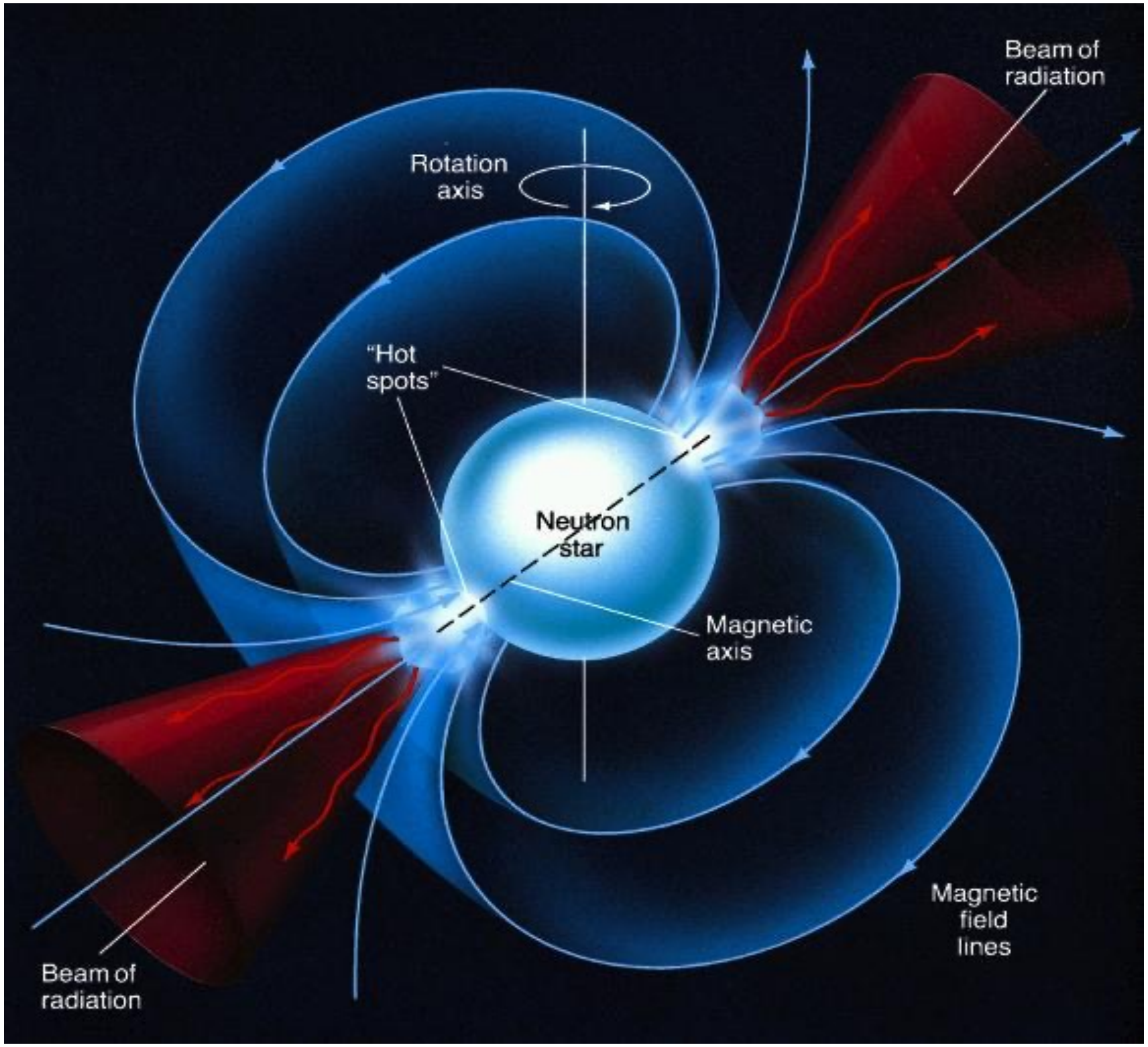


J0437-47 Pulsar, A millisecond (recycled) pulsar with period 0.005 sec

The Sound of Pulsars

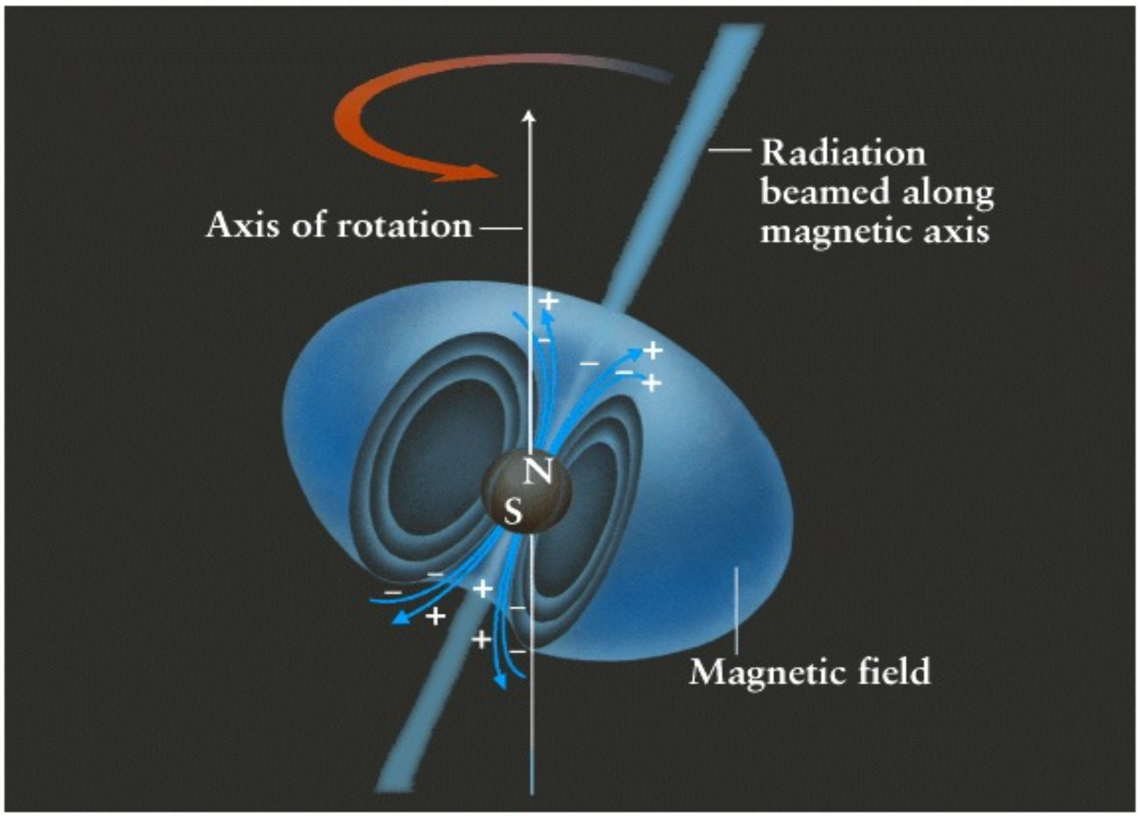
47 Tucanae, A globular cluster with 22 millisecond pulsars

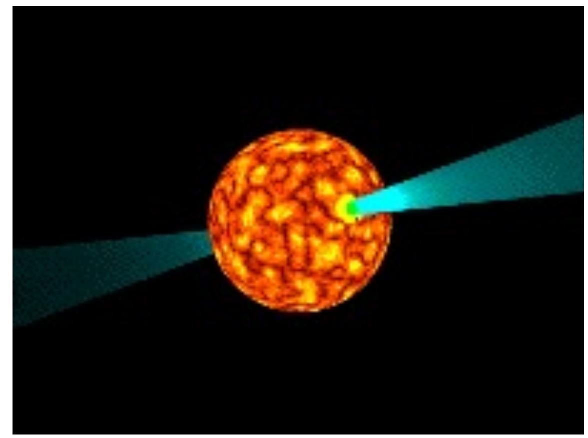
The Lighthouse model of a pulsar



Light-house model for pulsars

- Key point: axis of rotation is NOT aligned with the magnetic axis. Charged particles spiraling in magnetic field near poles radiate EM radiation (synchrotron radiation).



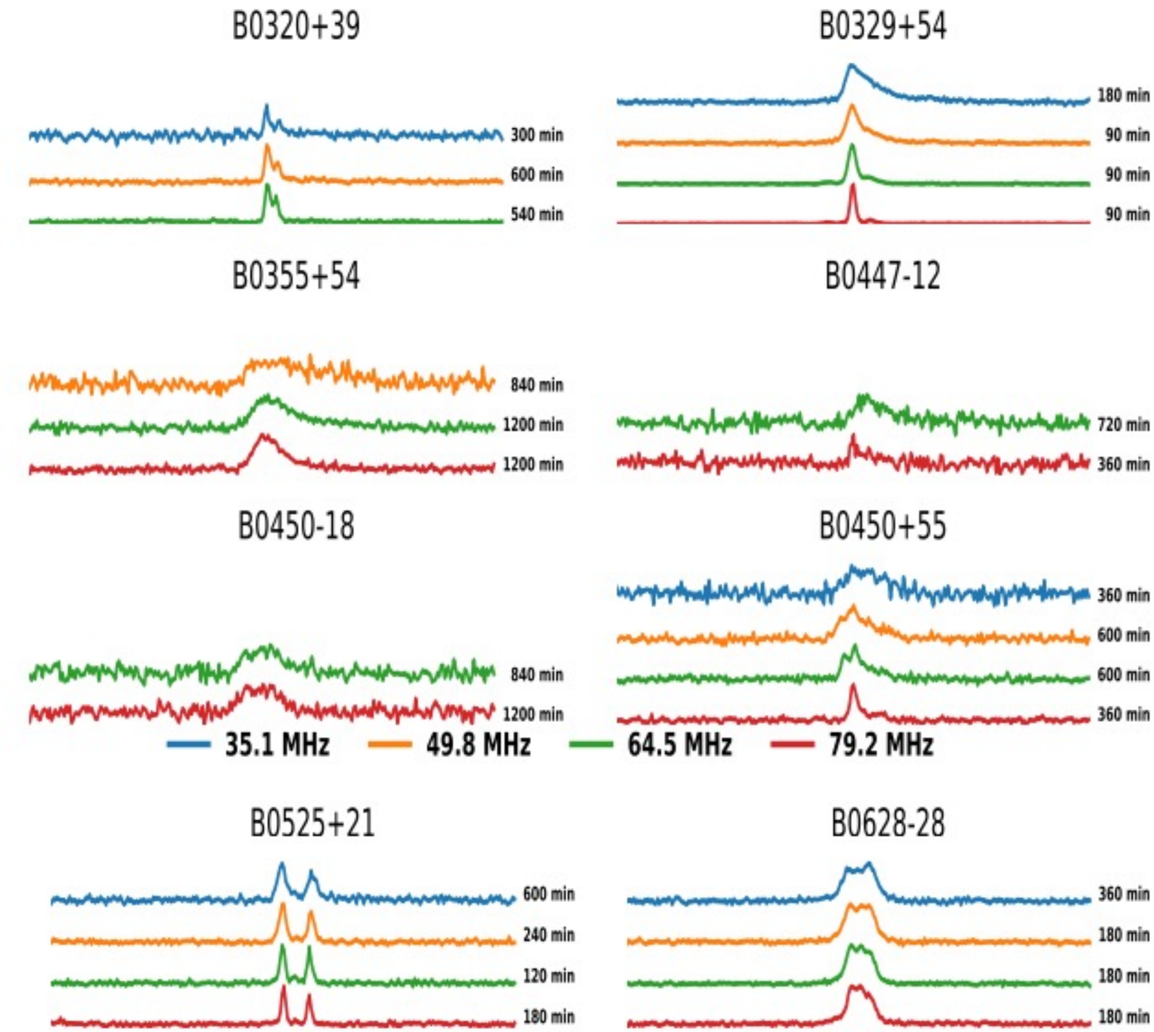


DEMO

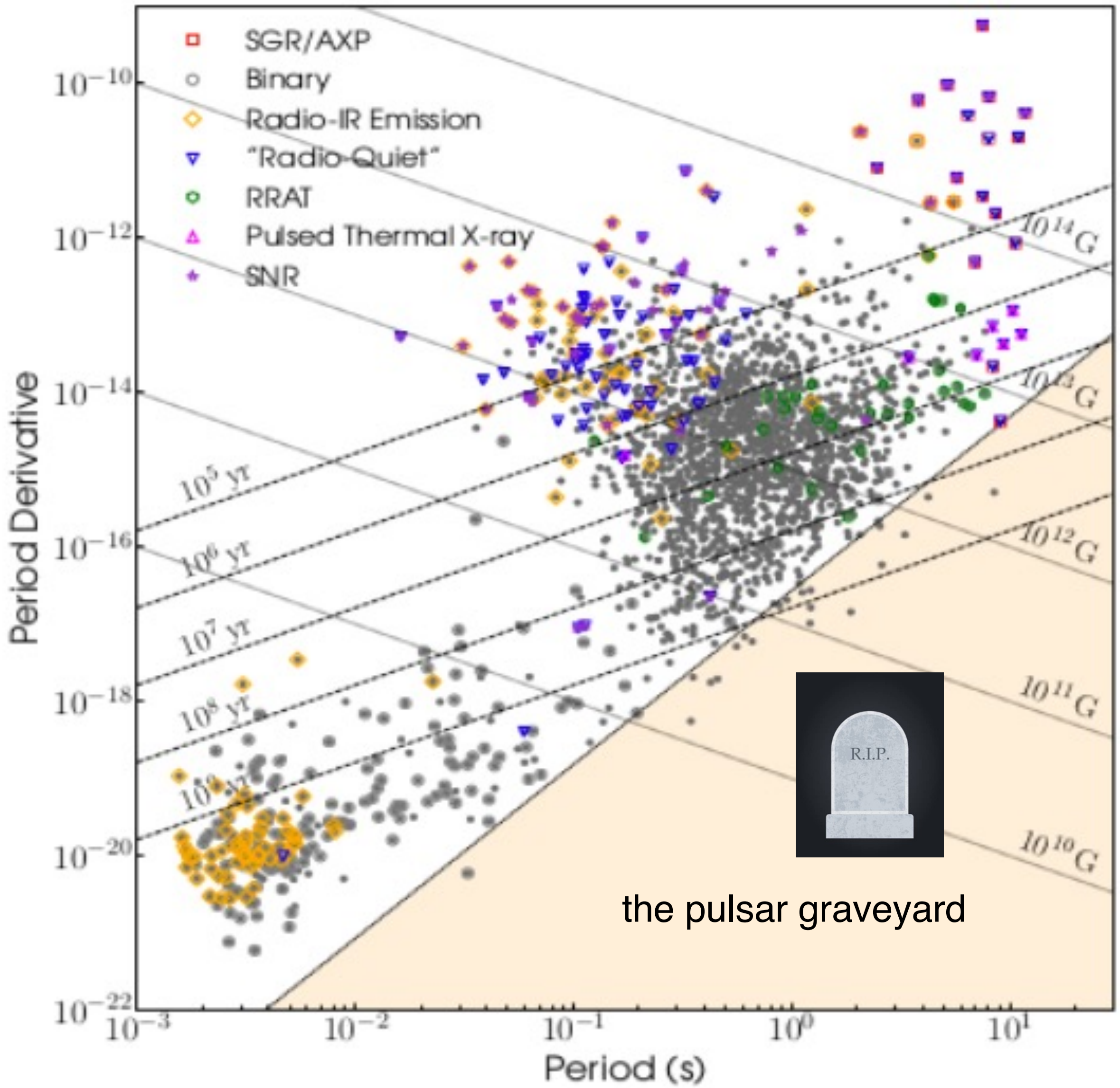
LWA Publication Highlights

Pulsar Monitoring of 100 pulsars with the LWA.

Kumar et al. 2024



Evolution of Pulsars



Rocks around the Clock

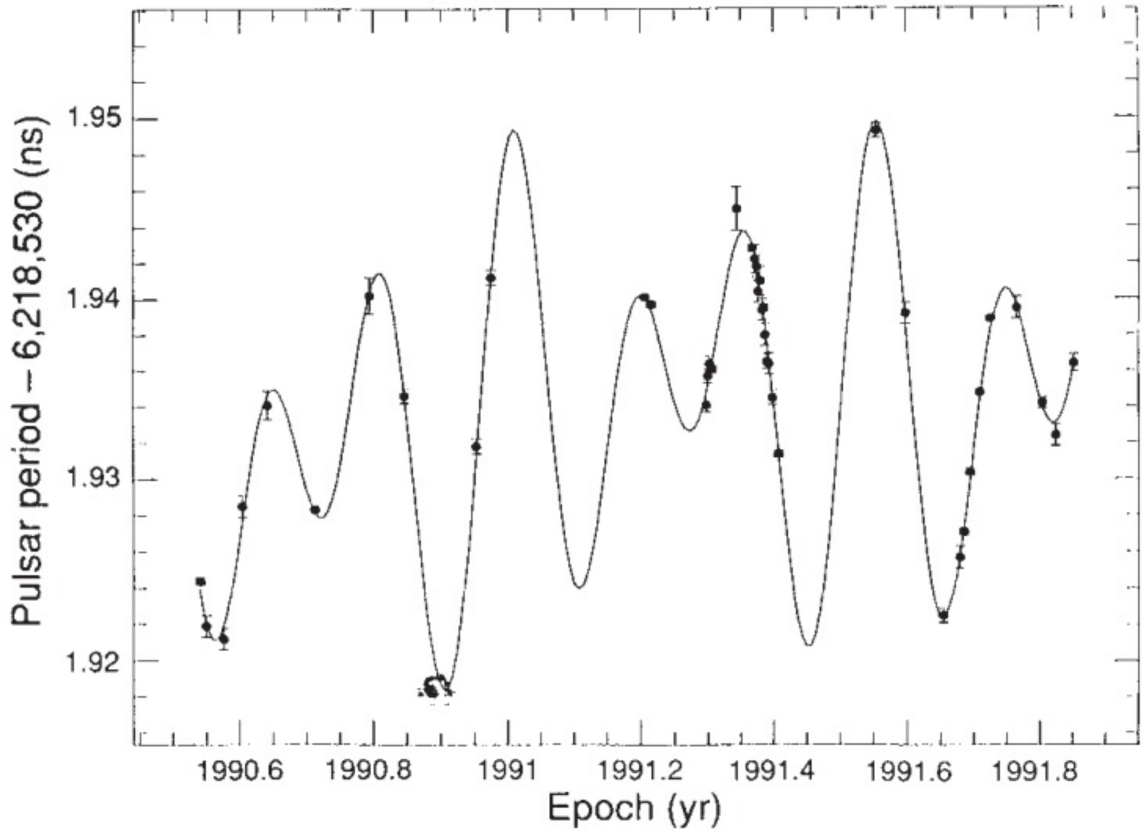
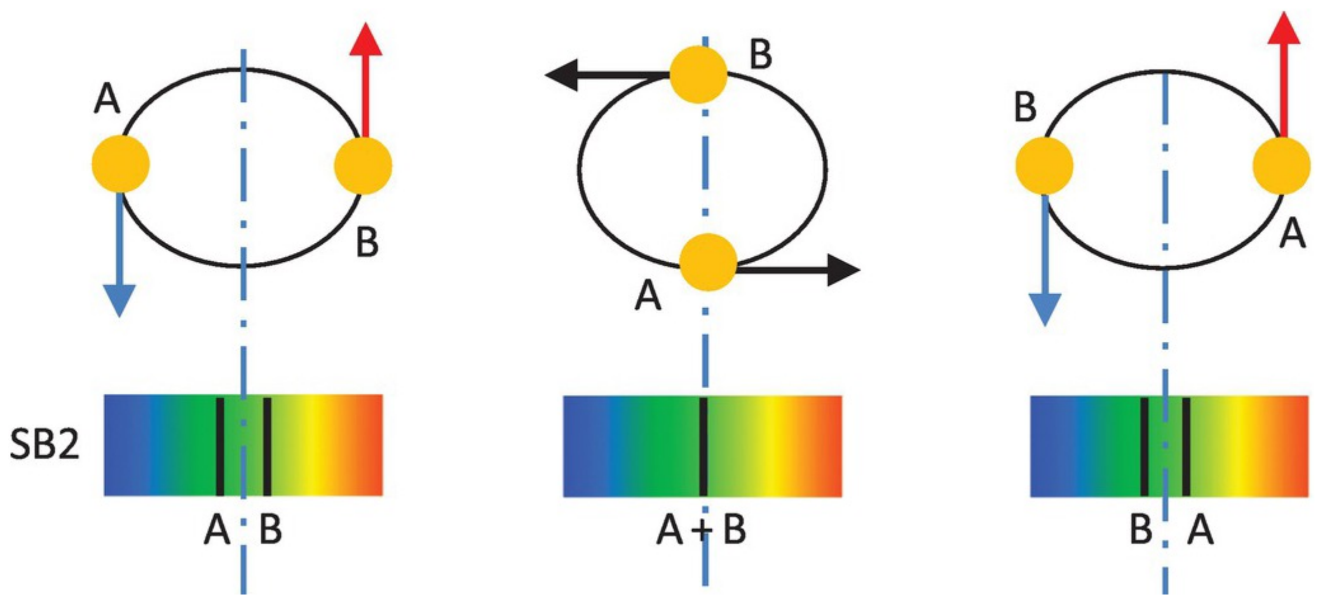


FIG. 3 Period variations of PSR1257 +12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257 +12 system.

Wolszczan & Frail 1992   Discovered the first extra-solar planets
Nobel Prize to Michel Mayor and Didier Queloz in 2019

Finding Masses of Stars and Planets

Worksheet: The components (A and B) of a binary star move along circular orbits. The distance between them is 1AU. You are observing this system in the plane of the orbit, and observe a periodic, maximum separation of the Hγ lines from the rest wavelength (434.04 nm) of 0.061nm as shown below. The shift is the same for both components. What are the masses of the individual stars in the system?



VLA/LWA1 Tour

- VLA Tour this Saturday Sept. 28
- Depart UNM at 7:30am from RH parking lot; 10am VLA+LWA1 tour Noon: lunch at picnic tables; return UNM ~3pm
- Drivers: Greg(4), Olwyn(4), Giovanna(4), Franco(3), Elizabeth(4)

- Bring
  – Sturdy shoes, hat, sunscreen, water bottle, snacks
  – Camera, $$$ if you want to shop at the Visitor Center
  – Lunch and extra water will be provided

Neutron Stars

Leftover core from Type II supernova - a tightly packed ball of neutrons.

Diameter: 20 km only!

Mass: 1.4 - 3(?) M_{Sun}

Density: 10^{14} g / cm^3 !

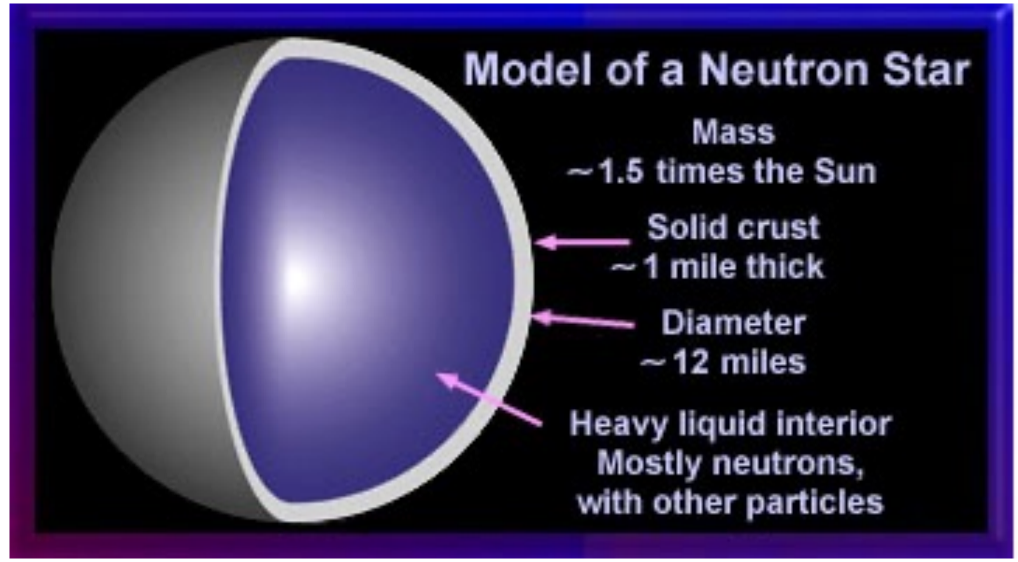
1 teaspoon = 1000 great pyramids

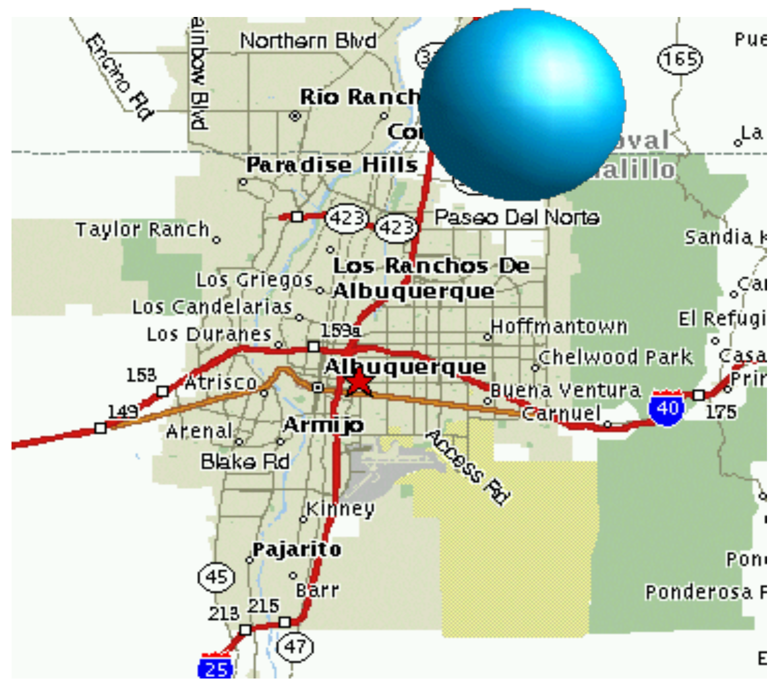
Surface gravity: 10^{12} higher

Escape velocity: 0.5c

Rotation rate: few to many times per second!

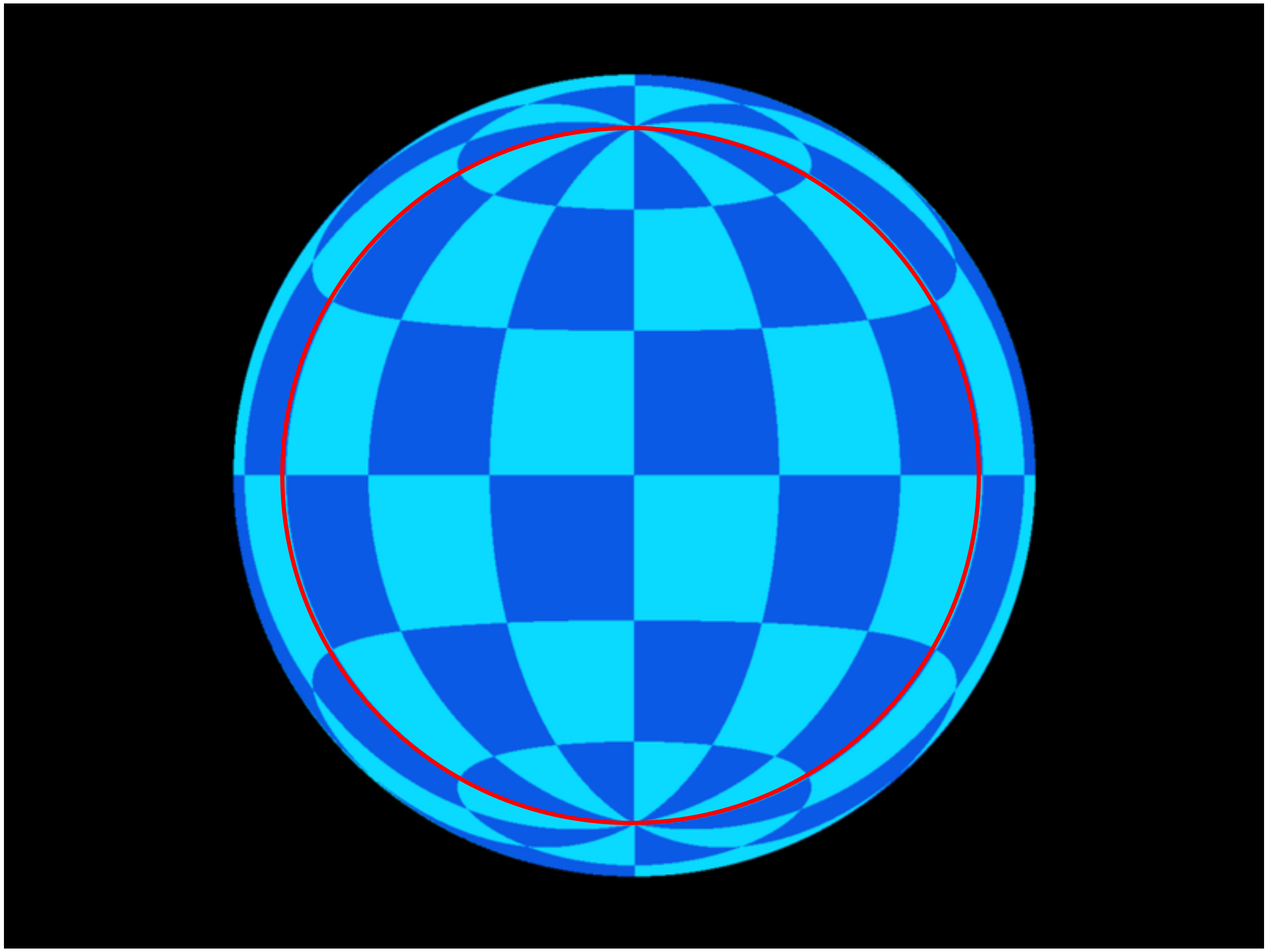
Magnetic field: 10^{12} x Earth’s



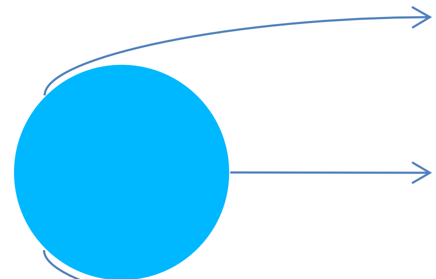


A neutron star over the Sandias?

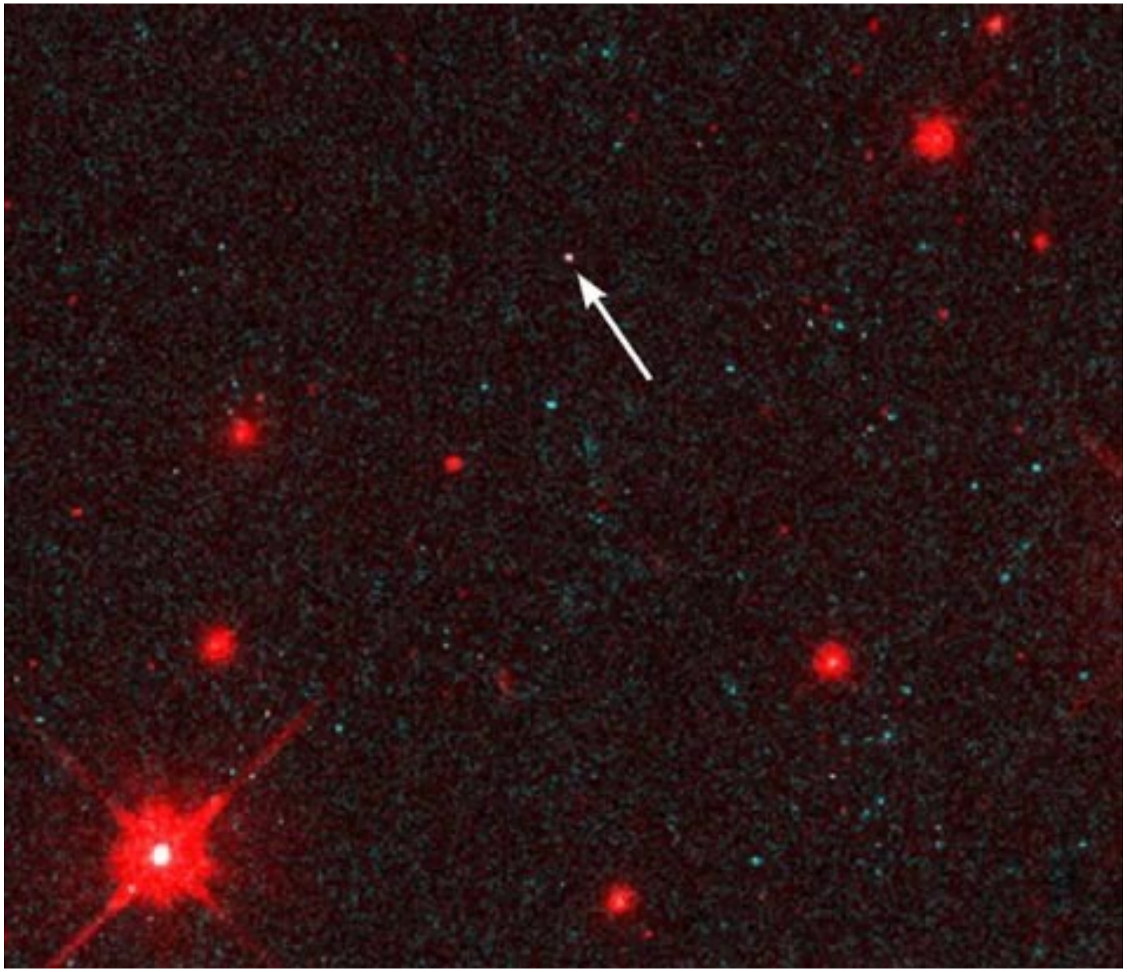
General Relativistic deflection of light



More than half the surface is visible at any one time!

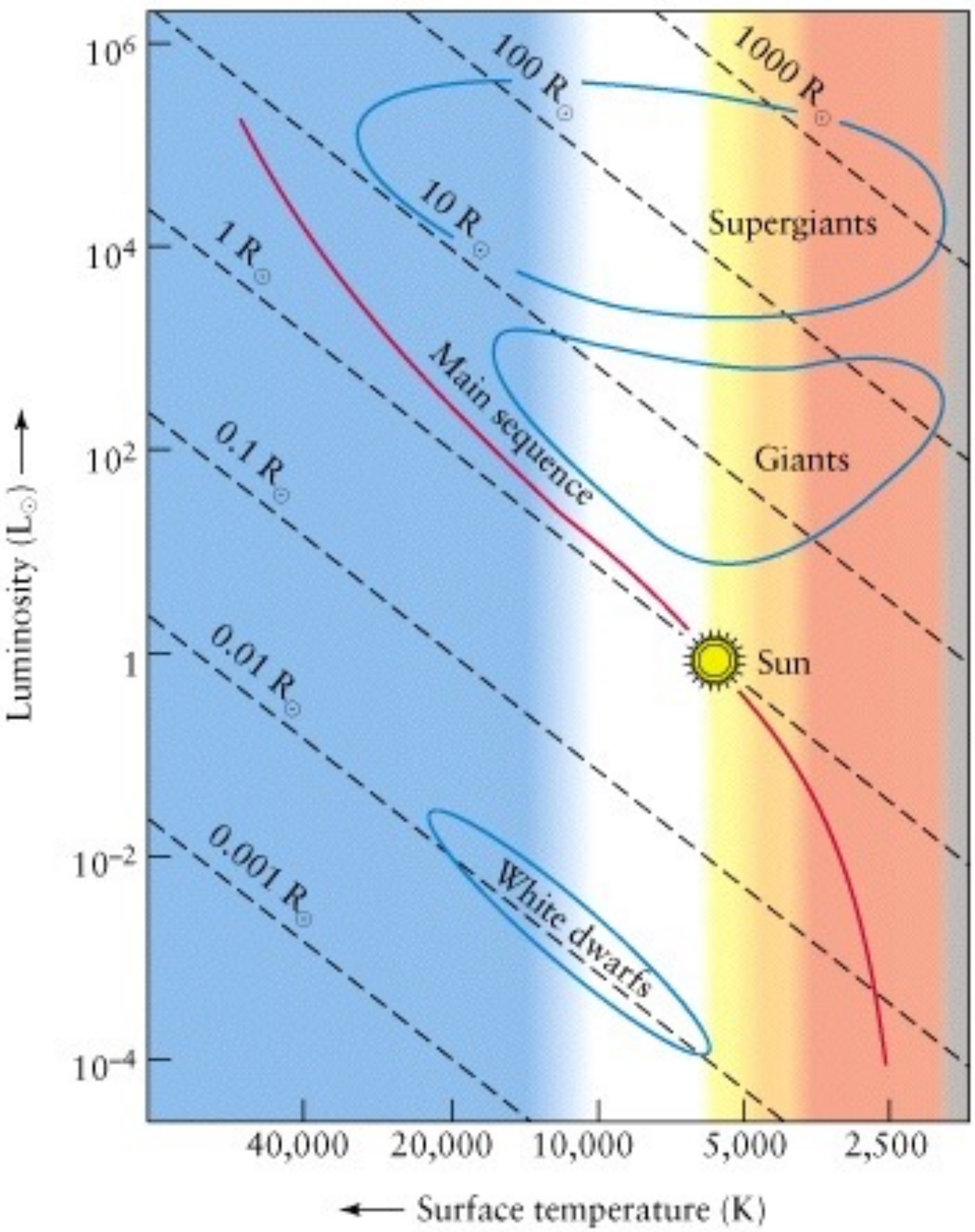


Each square is 30 degrees x 30 degrees



- Very dim, thus difficult to detect. Only a few isolated neutron stars have been imaged.

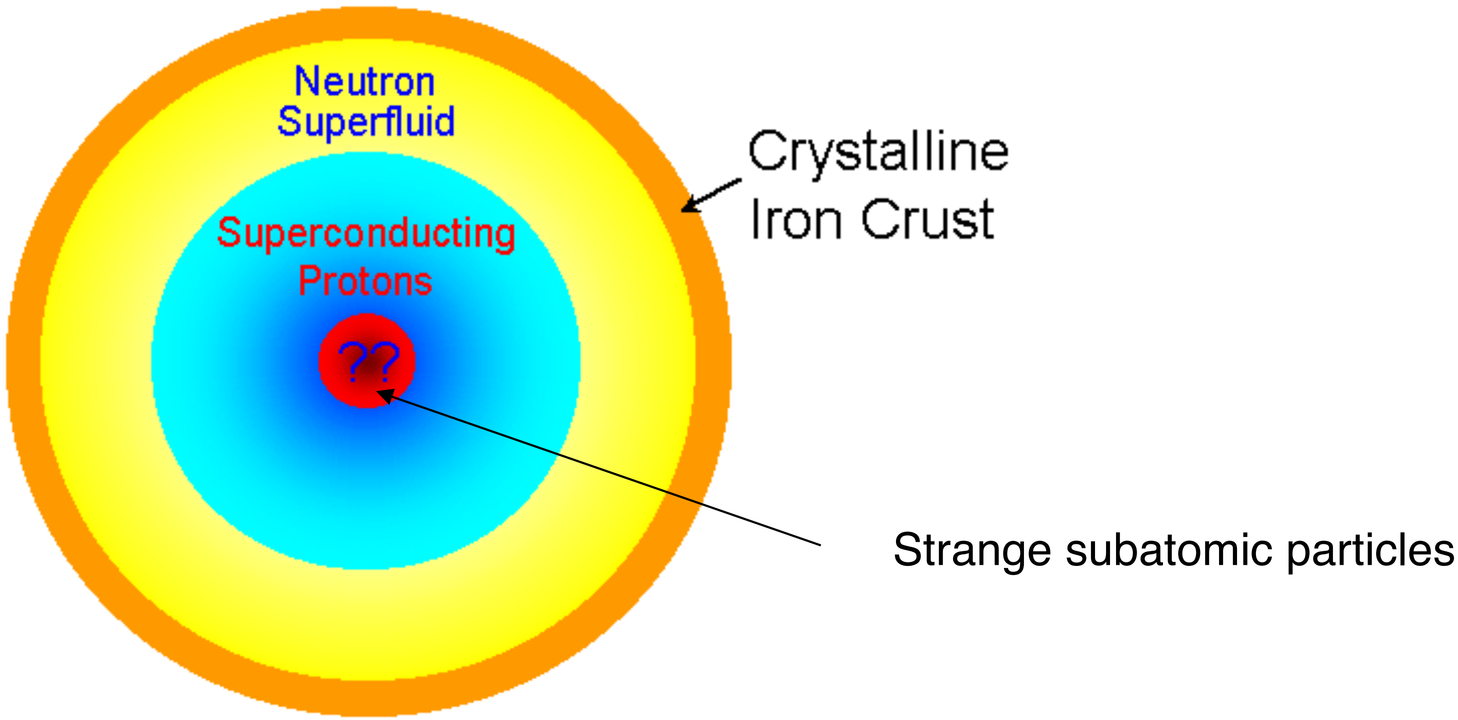
- About 10^8 estimated to exist in our galaxy, and we have detected around 2000 (the active pulsars)



- What makes the neutron star shine?
- Where would the neutron stars be on the HR diagram? Why?

Neutron star structure

- Surface is cooler, probably forming a solid crystalline crust (cf WD).
- Inside is exotic matter.



- Implies enormous magnetic fields. Why?

- The B-field of the star becomes concentrated as star collapses:
  (Magnetic field strength at surface) x *(surface area)* is conserved as star shrinks.

$$(B_{ms})(4\pi R_{ms}{}^{2}) = (B_{ns})(4\pi R_{ns}{}^{2})$$

- The surface area drops by factor of ~10^{10} as it shrinks to neutron star size, so magnetic field strength increases by factor of 10^{10}!

Mass limit to neutron stars

- Like white dwarfs and electron degenerate matter, neutron stars and neutron degenerate matter has an upper mass limit (~ 3 $M_{\odot}$). Most massive pulsar is J0952-0607 at 2.35 $M_{\odot}$

- When this is exceeded, the star collapses all the way to a black hole.

- This limit is not as well understood as the Chandrasekhar limit, since the pressure has two sources: degeneracy and the strong nuclear force.

Pulsars are incredibly accurate clocks!

Example: period of the first discovered "millisecond pulsar" is:

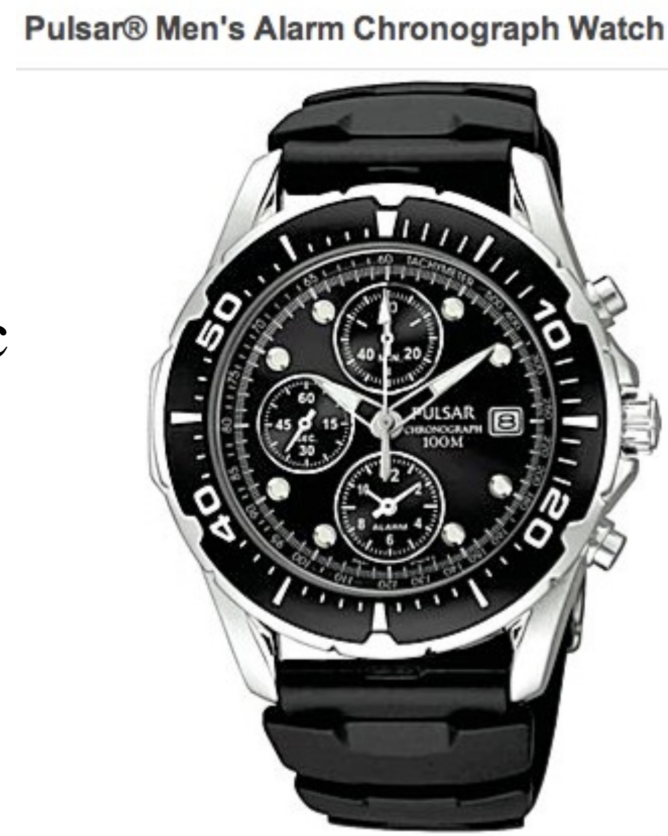
$$P = 0.00155780644887275 \text{ sec}$$

It is slowing down at a rate of

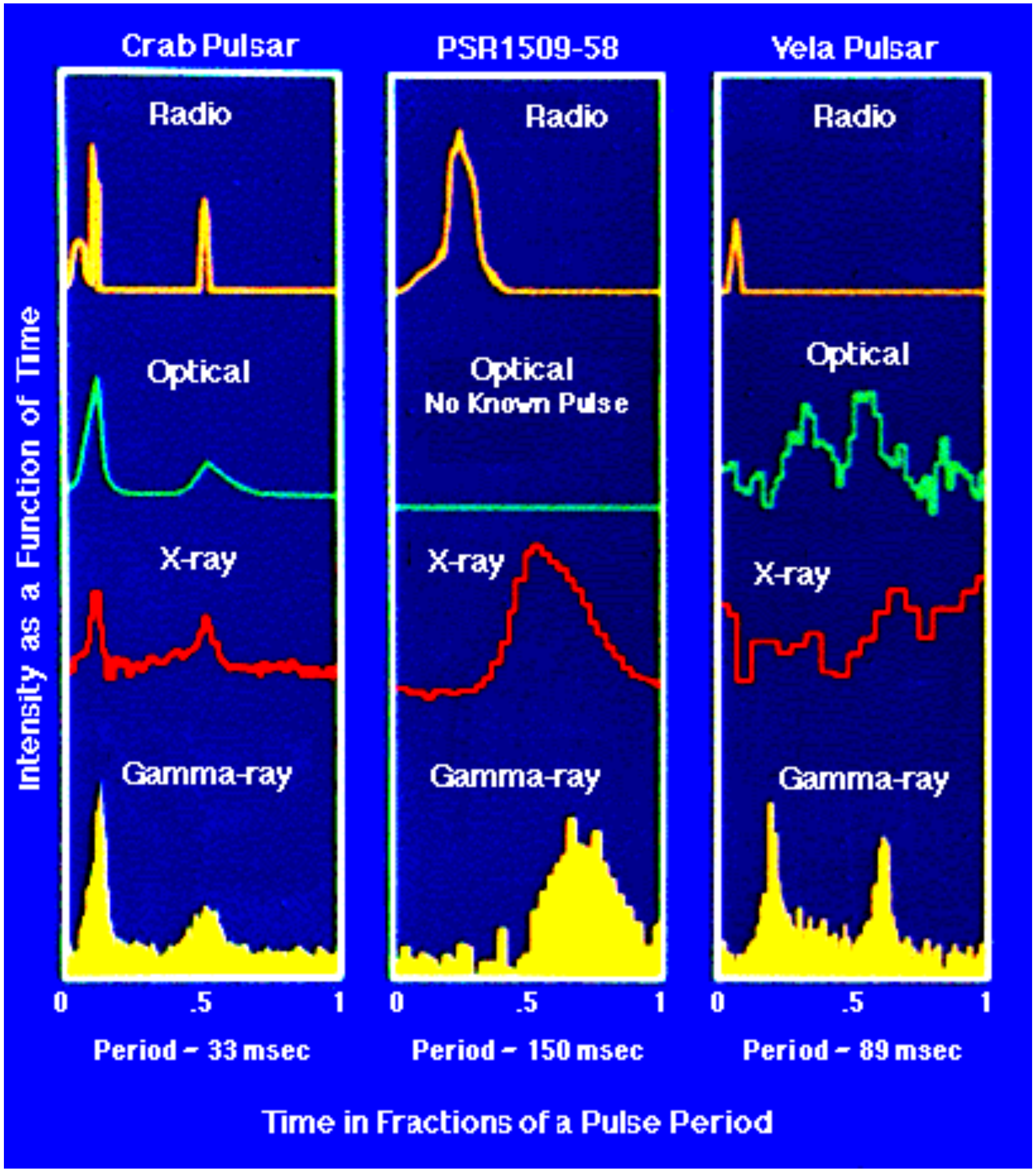
$$dP/dt = 1.051054 \times 10^{-19} \text{ sec/sec}$$

The slowing-down rate is slowing down at a rate of:

$$d(P)/dt^2 = 0.98 \times 10^{-31} \text{ /sec}$$

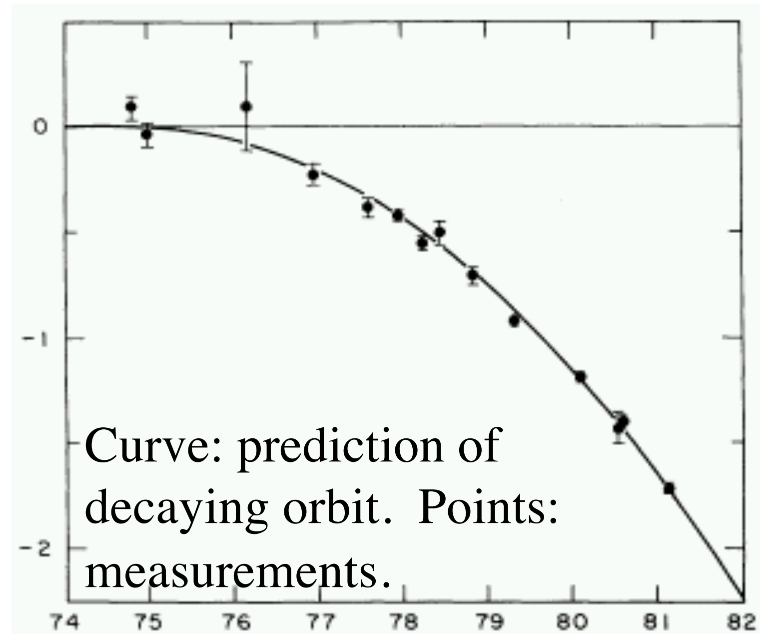


Multi-wavelength observations of Pulsars



Pulsar Exotica

Binary pulsars: two pulsars in orbit around each other.
Einstein predicted that binary orbits should "decay", i.e. the masses would spiral in towards each other, losing energy through "gravitational radiation". Confirmed by binary pulsar. (Nobel prize to Taylor & Hulse)

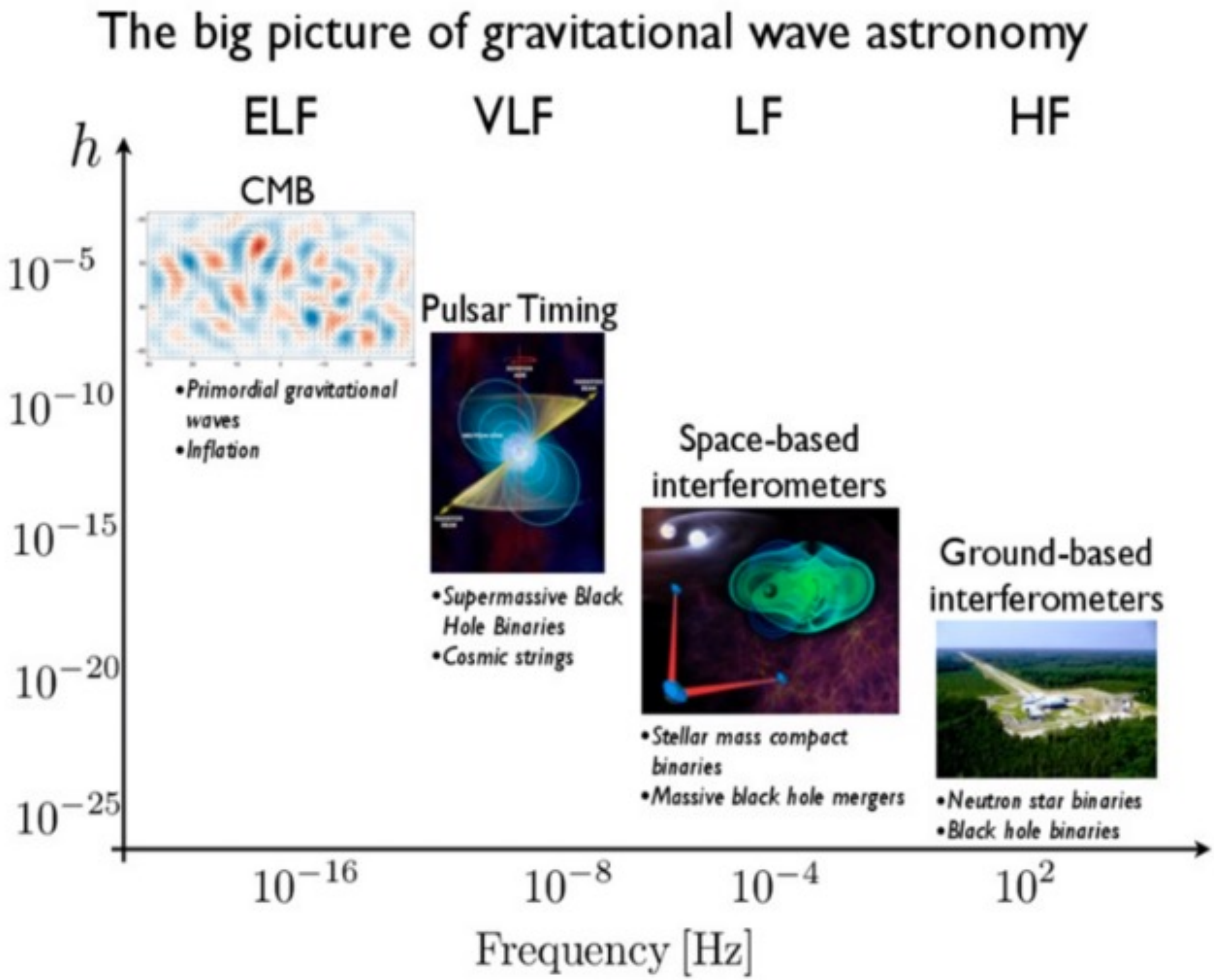


Curve: prediction of decaying orbit. Points: measurements.

year

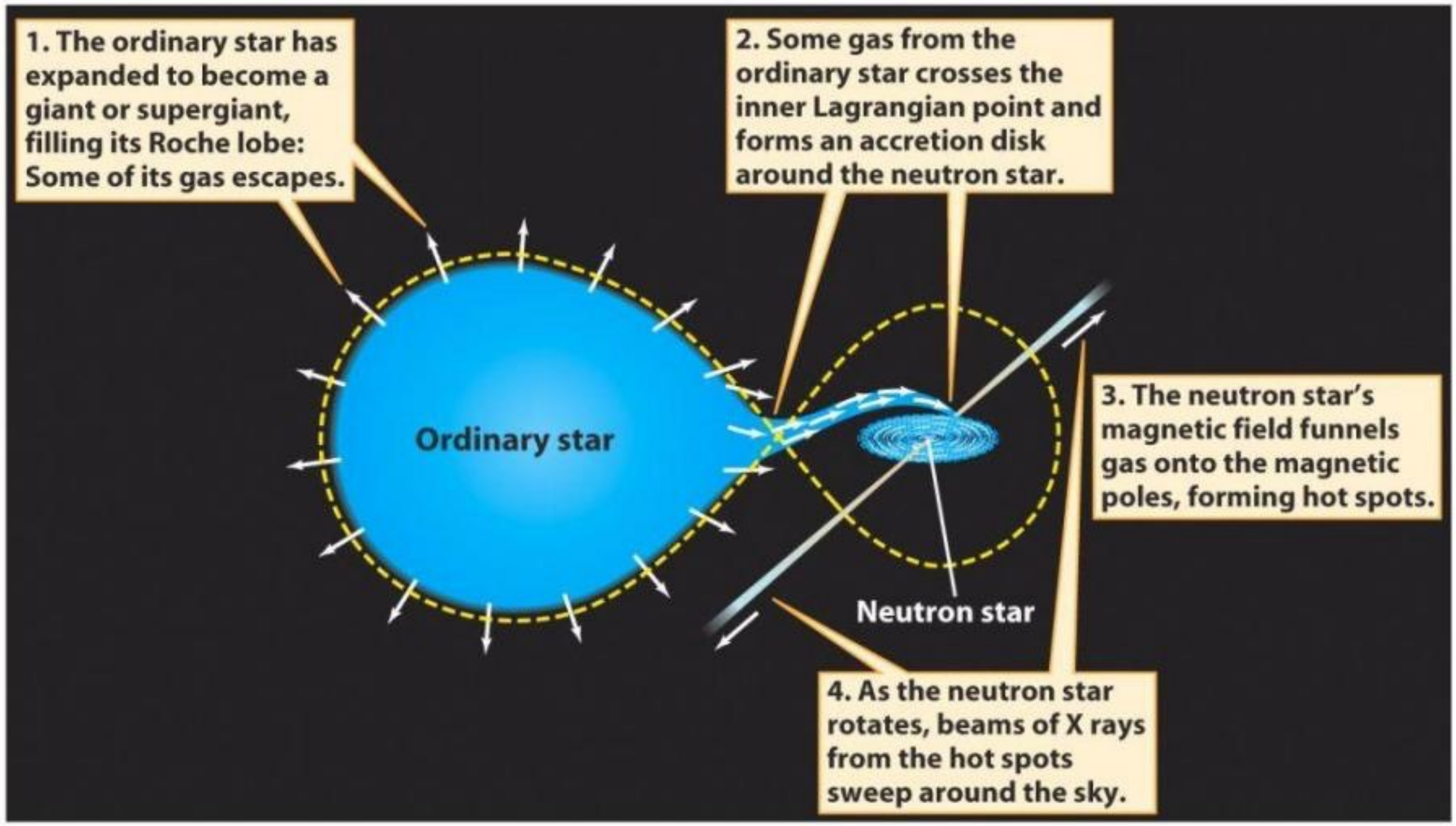
Planets around pulsars: Rare, just 1% of pulsars.
A pulsar was found in 1992 to have three planets!
Masses about 3 M_{Earth}, 1 M_{Earth}, and 1 M_{Moon} !

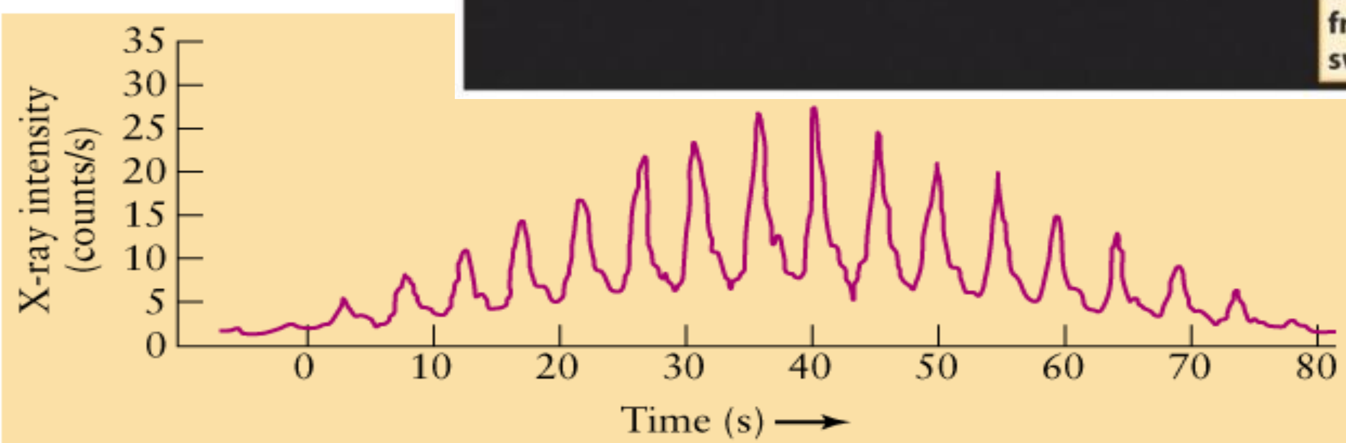
Gamma-ray Bursts: some pulsars produce bursts of gamma-rays, called Soft Gamma-Ray Repeaters or SGRs


The big picture of gravitational wave astronomy
ELF
VLF
LF
HF
h
CMB
•Primordial gravitational waves
•Inflation
Pulsar Timing
•Supermassive Black Hole Binaries
•Cosmic strings
Space-based interferometers
•Stellar mass compact binaries
•Massive black hole mergers
Ground-based interferometers
•Neutron star binaries
•Black hole binaries
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-16}
10^{-8}
10^{-4}
10^{2}
Frequency [Hz]

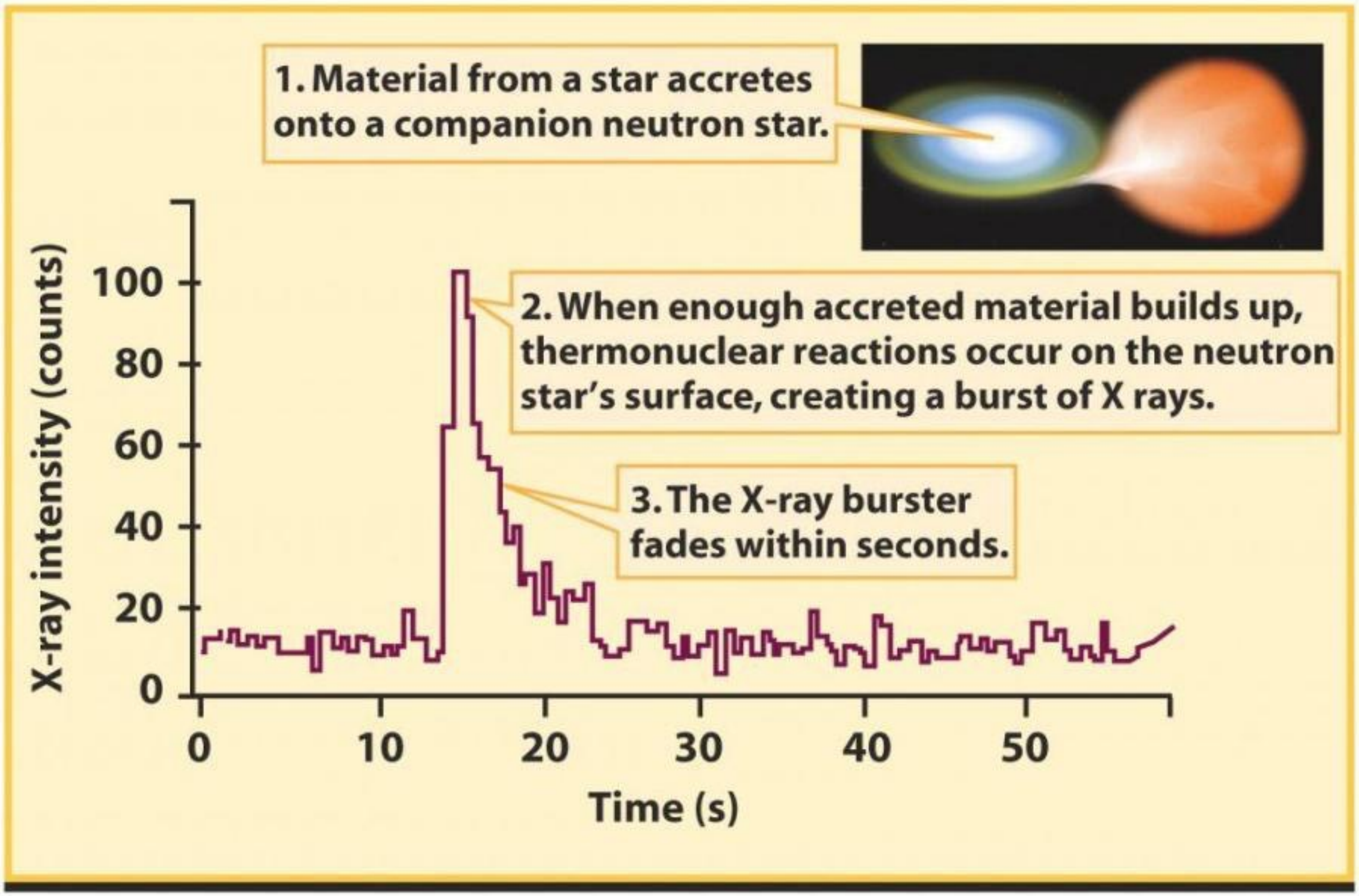
Pulsating X-ray sources

- ns pulses in close binary systems with evolving star.



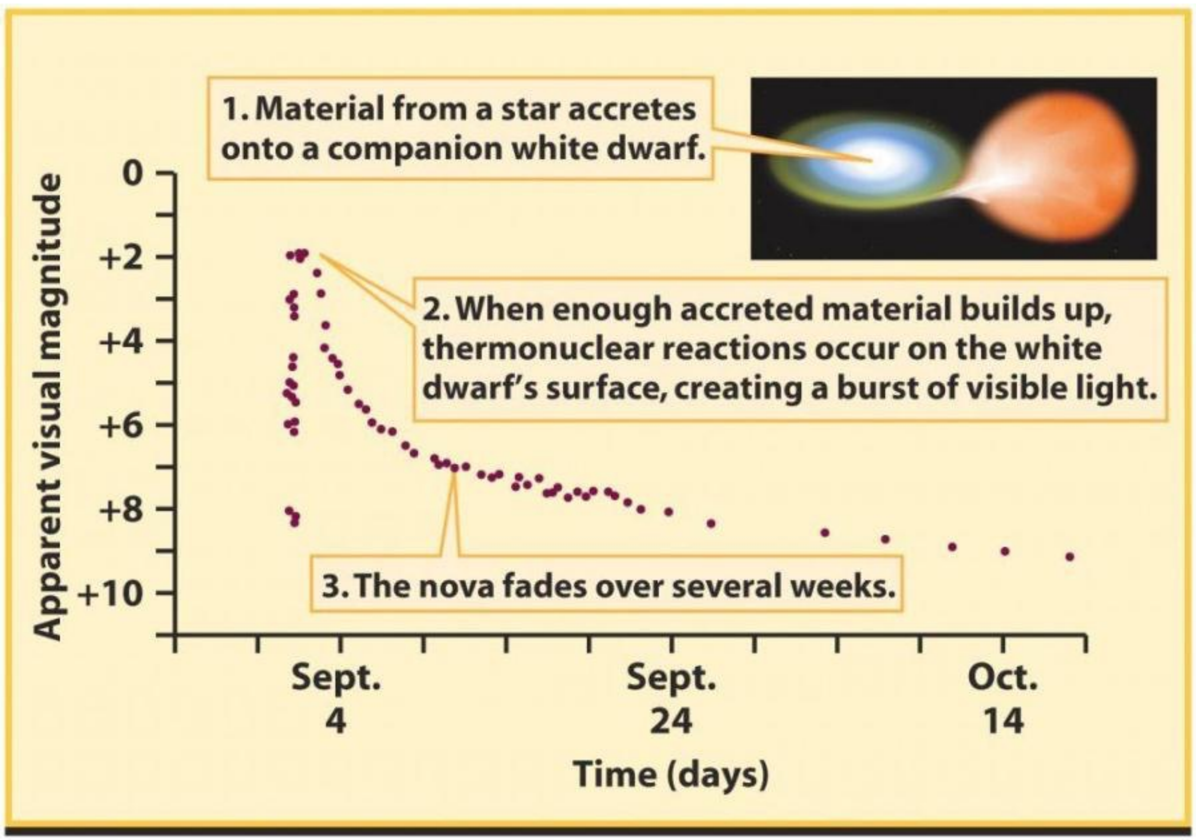


Caused by (sometimes repeating) nuclear explosions on or near the surfaces of neutron stars.



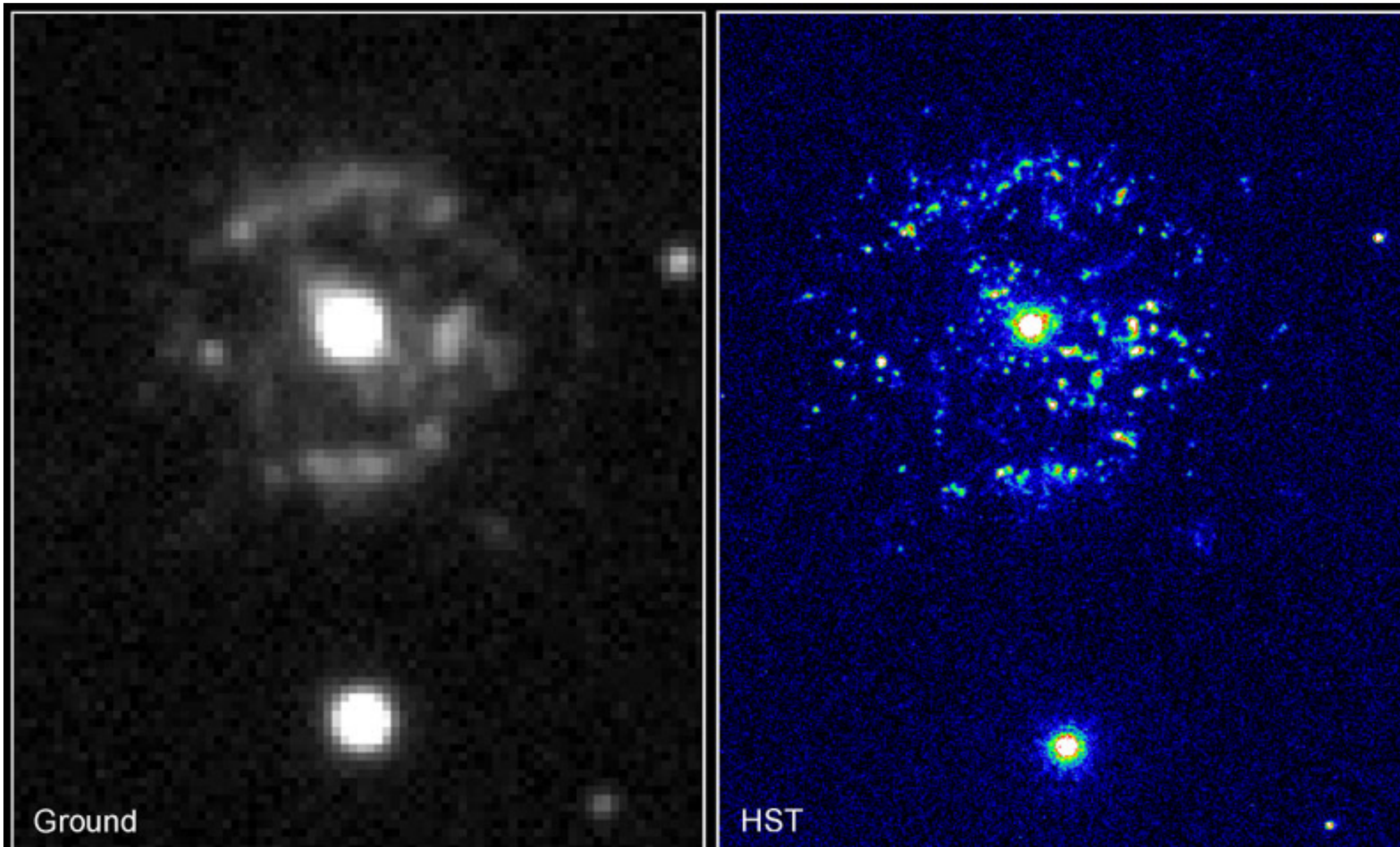
Novae

- Novae are similar to X-ray bursters, but occur in a close binary system with a White Dwarf instead of a neutron star.
- Accretion is weaker and will cause a hydrogen fusion outburst.
- Lower energy, so will emit in the visible, but sometimes up to gamma-rays



Novae ≠ supernovae!

- Both are thermonuclear detonations, but novae occur at or near the surface while supernovae occur in the core, and destroy star.
- At maximum, novae are around M = -9. Supernovae can be 10^4 times brighter, M = -19.
- A nova might repeat, but a supernova can't.



Recurring Nova T Pyxidis HST • WFPC2

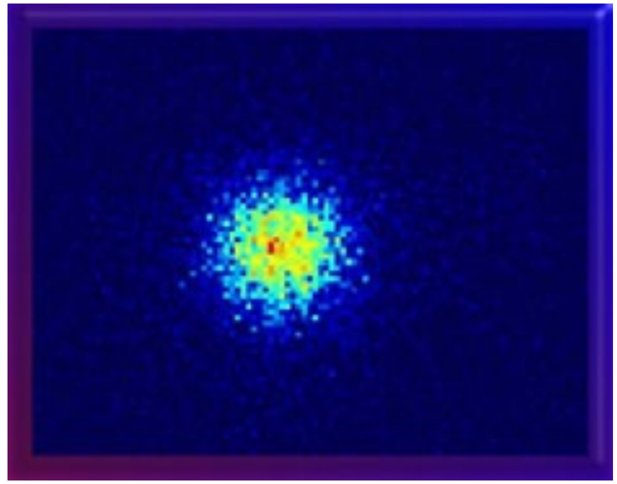
PRC97-29 • ST ScI OPO • September 18, 1997

M. Shara and R. Williams (ST ScI), R. Gilmozzi (ESO) and NASA

Soft Gamma-Ray Repeaters

$E_{iso} \sim$ a few10^{44} erg in gamma-rays

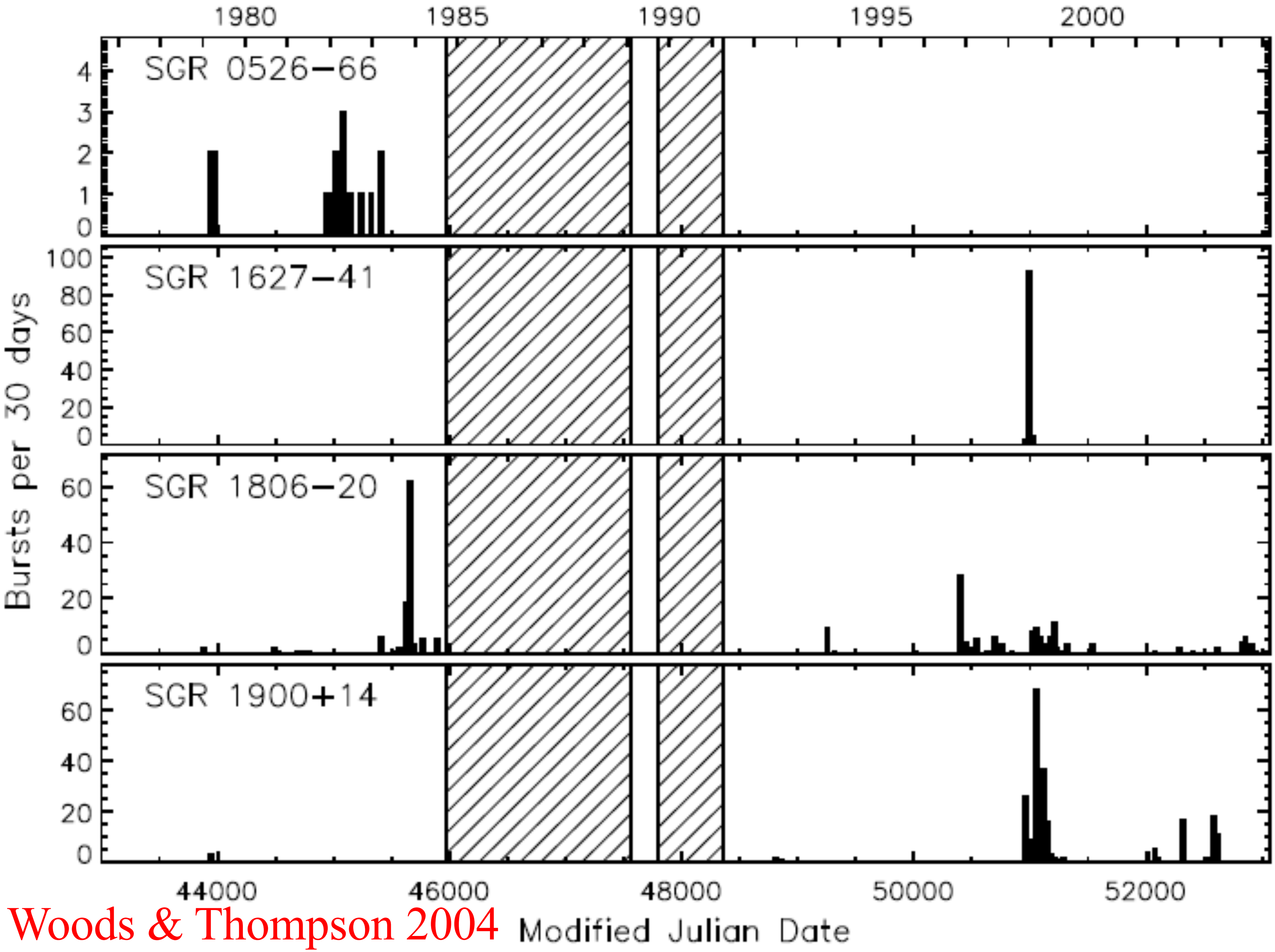
Where does this energy come from?



X-ray image

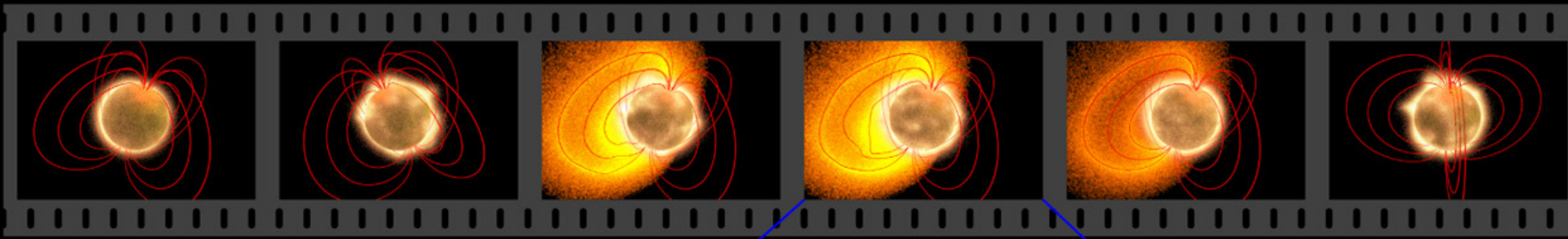
- Accretion? No sign of a disk
- Rotation? Not enough energy available
- Magnetic fields? Yes

Time history of the 4 confirmed SGRs:

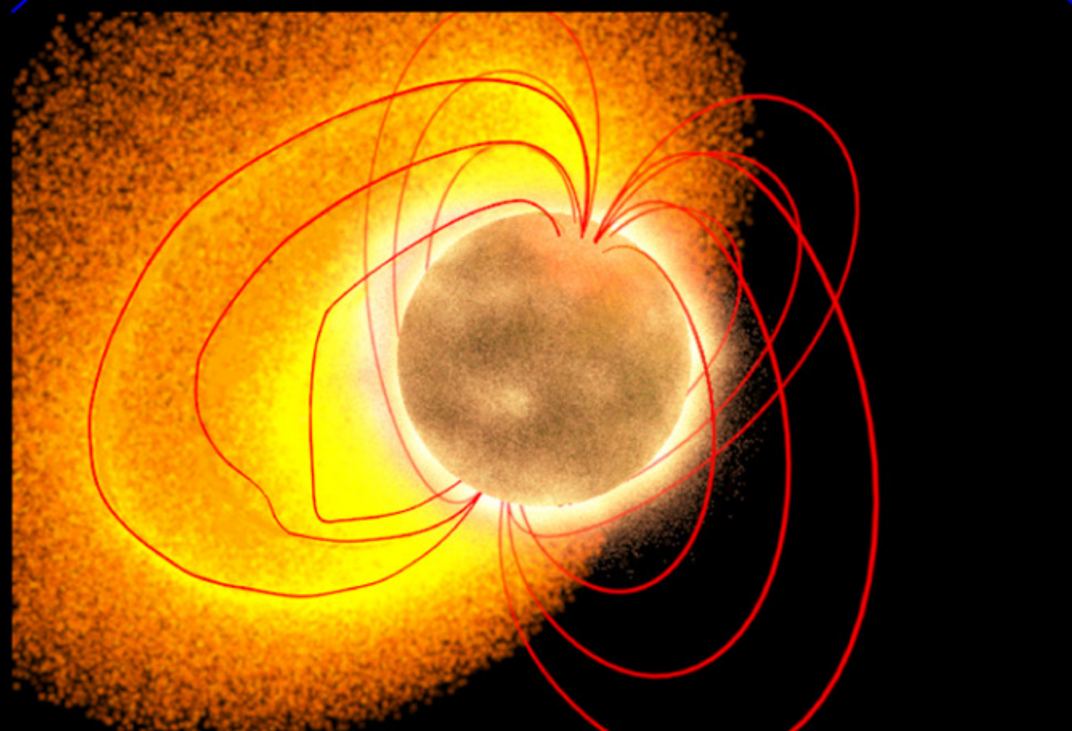


Woods & Thompson 2004

Magnetar burst sequence

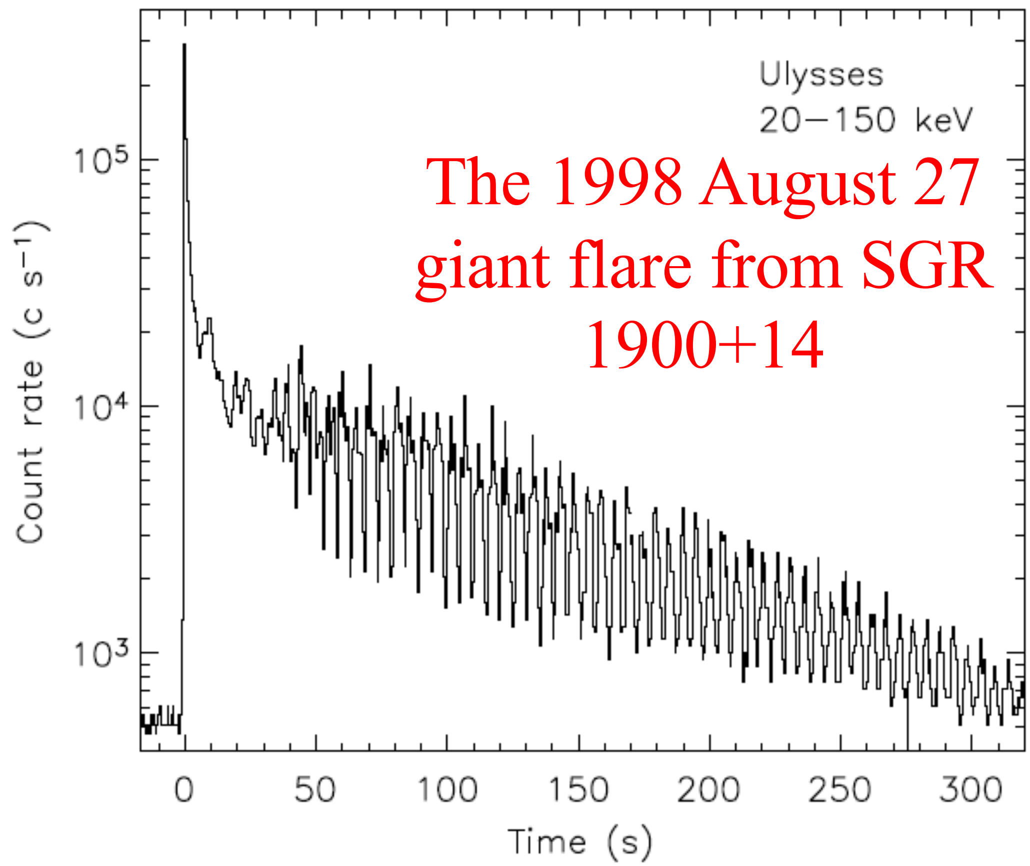


Adapted from
Duncan and Thompson
1992



Giant Flares from SGRs

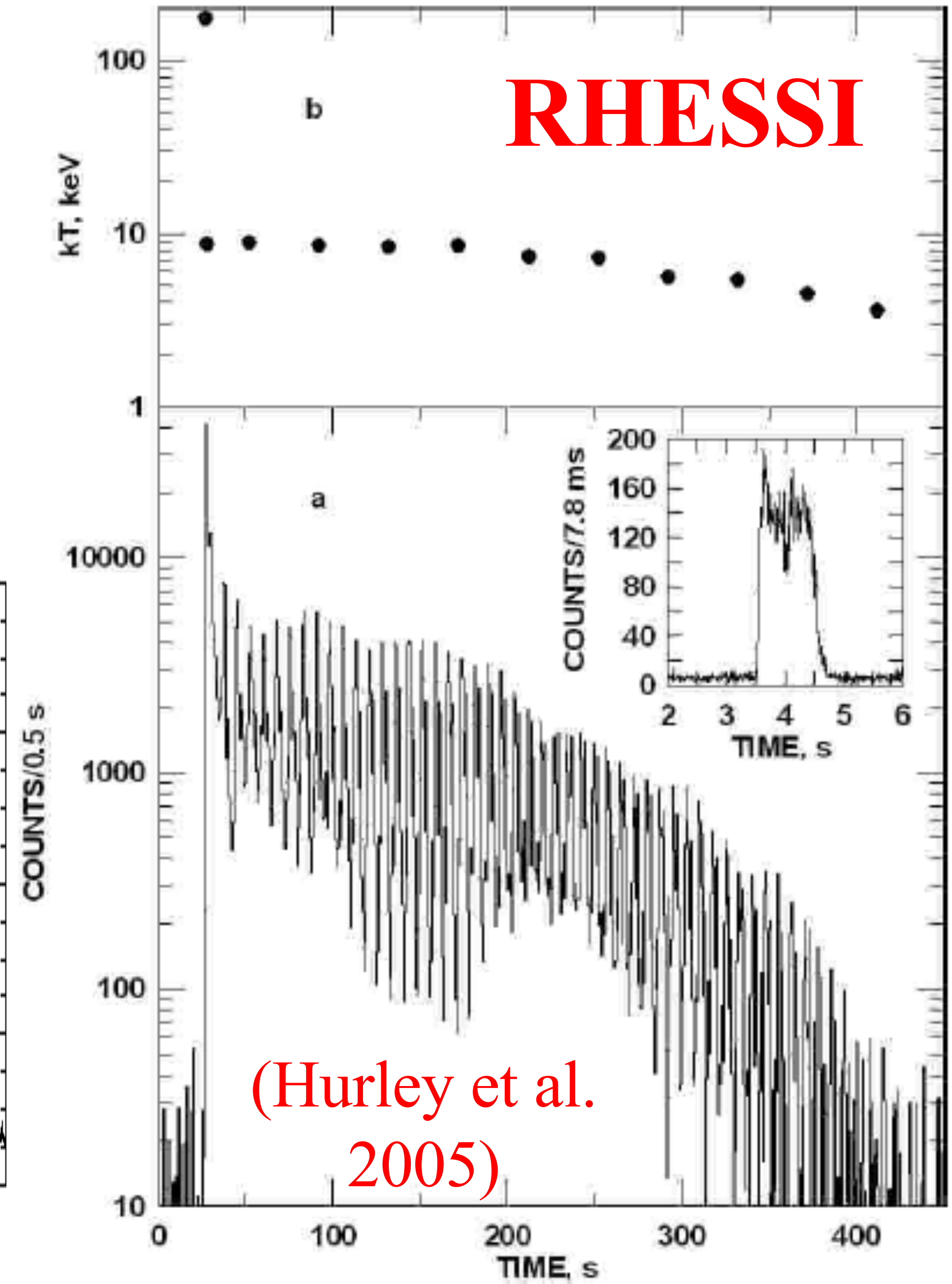
- Initial spike: $\mathbf{\Delta t} \sim 0.3$ s , $E_{iso} \sim$ a few10^{44} erg
    - hard spectrum
    - ~ ms rise time
- Pulsating tail
    - Lasts a few min.
    - Modulated at the NS rotation period
    - Softer spectrum



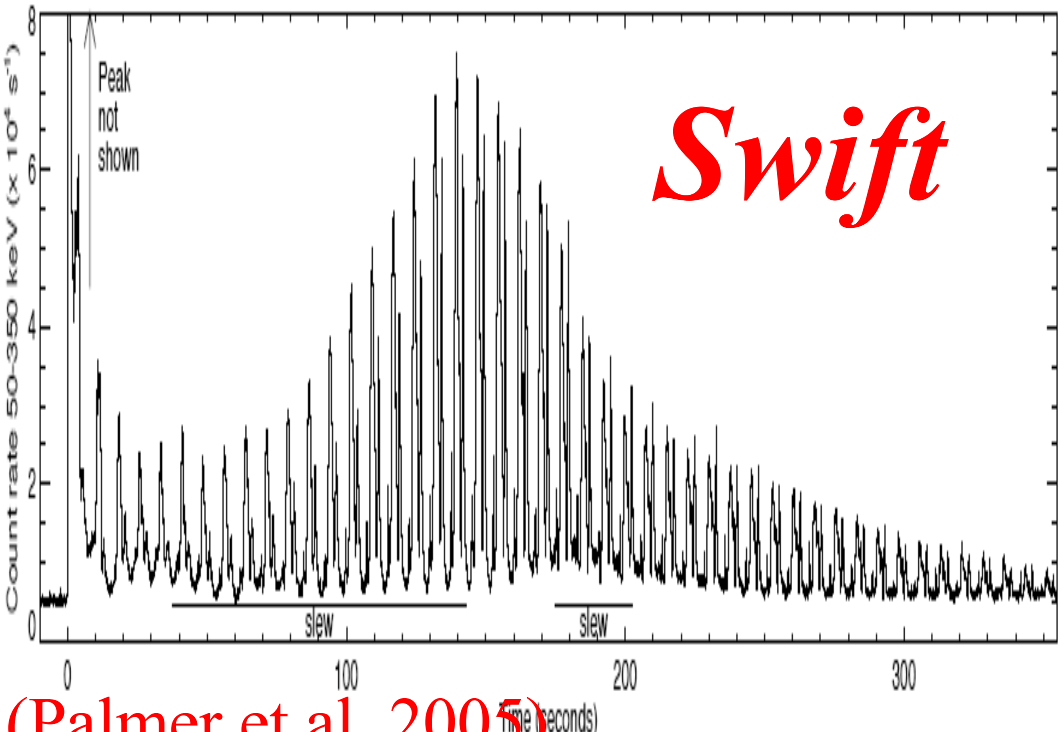
- Only 2 previous events ever recorded: in 1979 (SGR 0526-66 in LMC) & 1998 (SGR 1900-14)

The 2004 Dec. 27 SGR1806-20 Giant Flare

- was ~5° from the sun
- It's distance ≈ 15 kpc
- $E_{iso} \sim 10^{46}$ erg

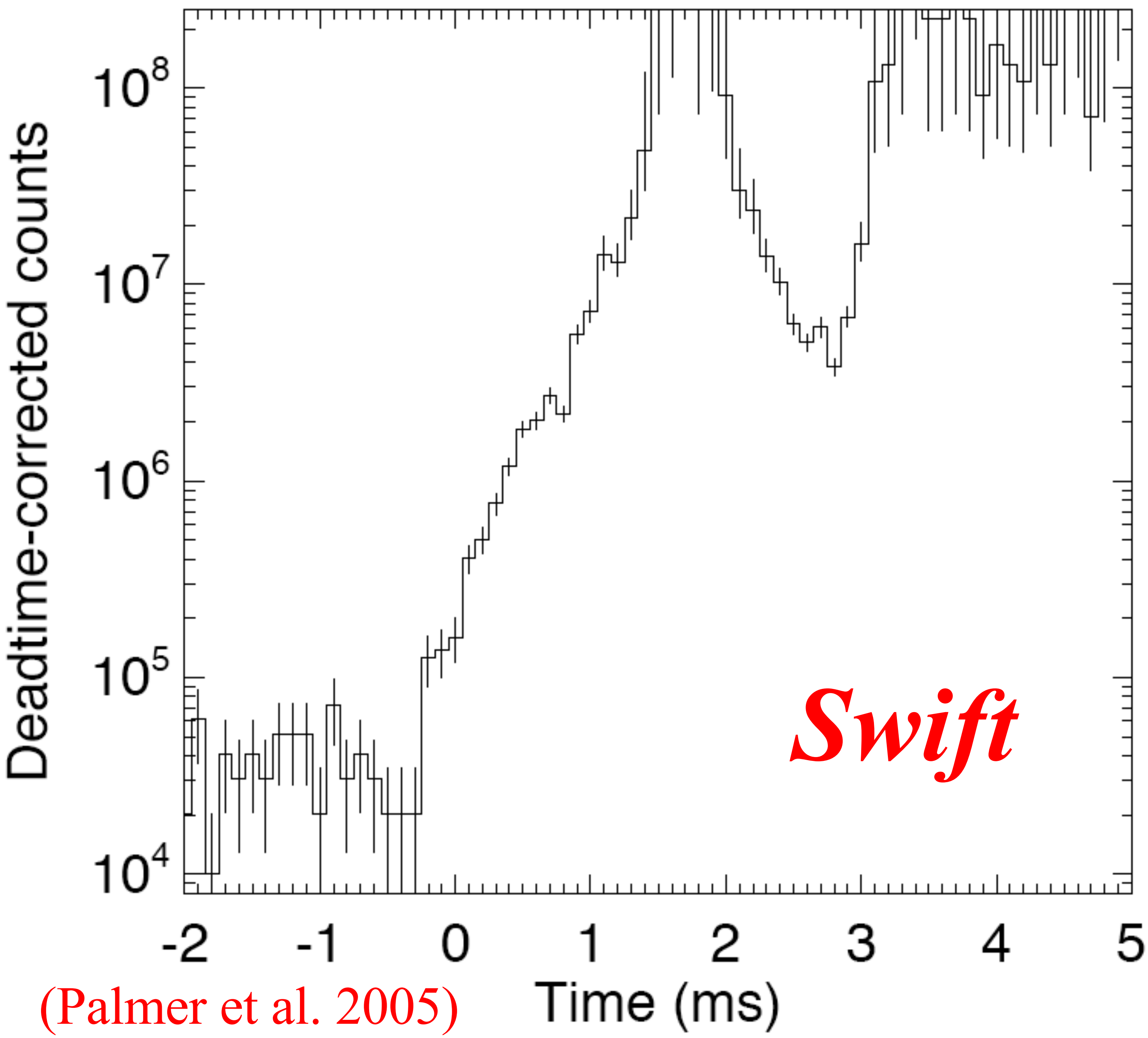


(Hurley et al. 2005)



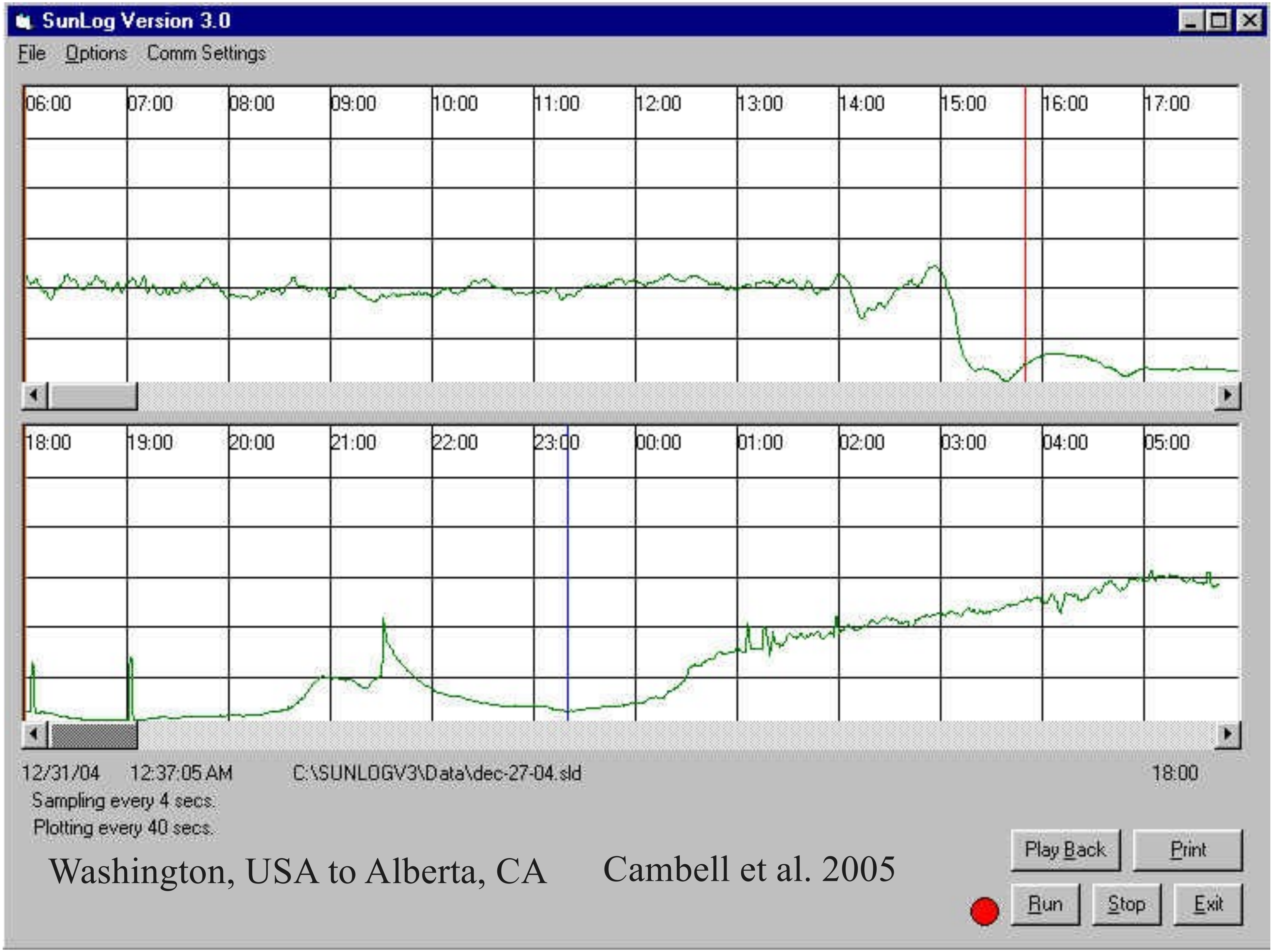
(Palmer et al. 2005)

Rise time: < 1 ms



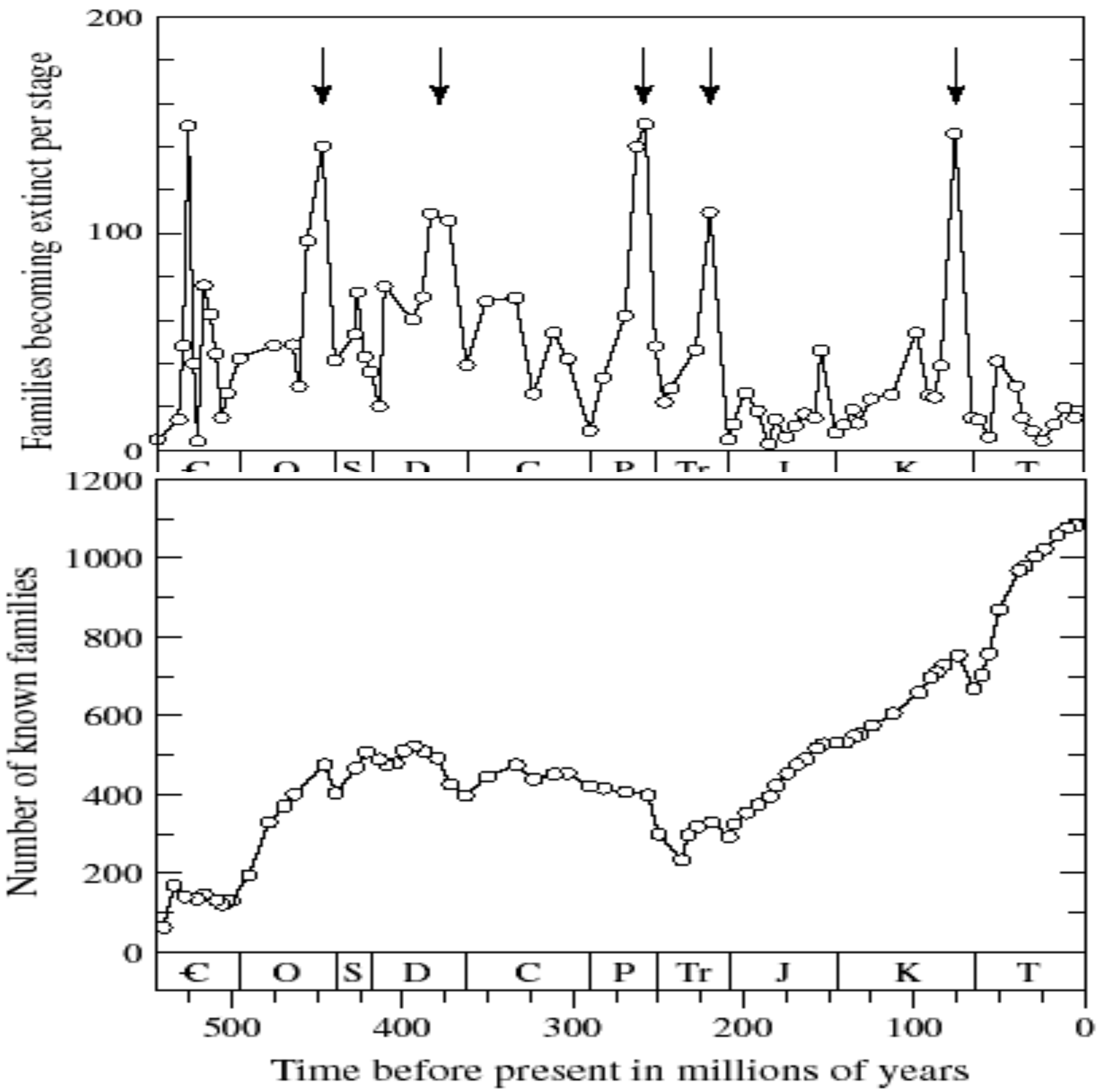
(Palmer et al. 2005)

Sudden Ionospheric Disturbance (SID)



Washington, USA to Alberta, CA Cambell et al. 2005

The Fossil Record is Marked by Mass Extinction Events

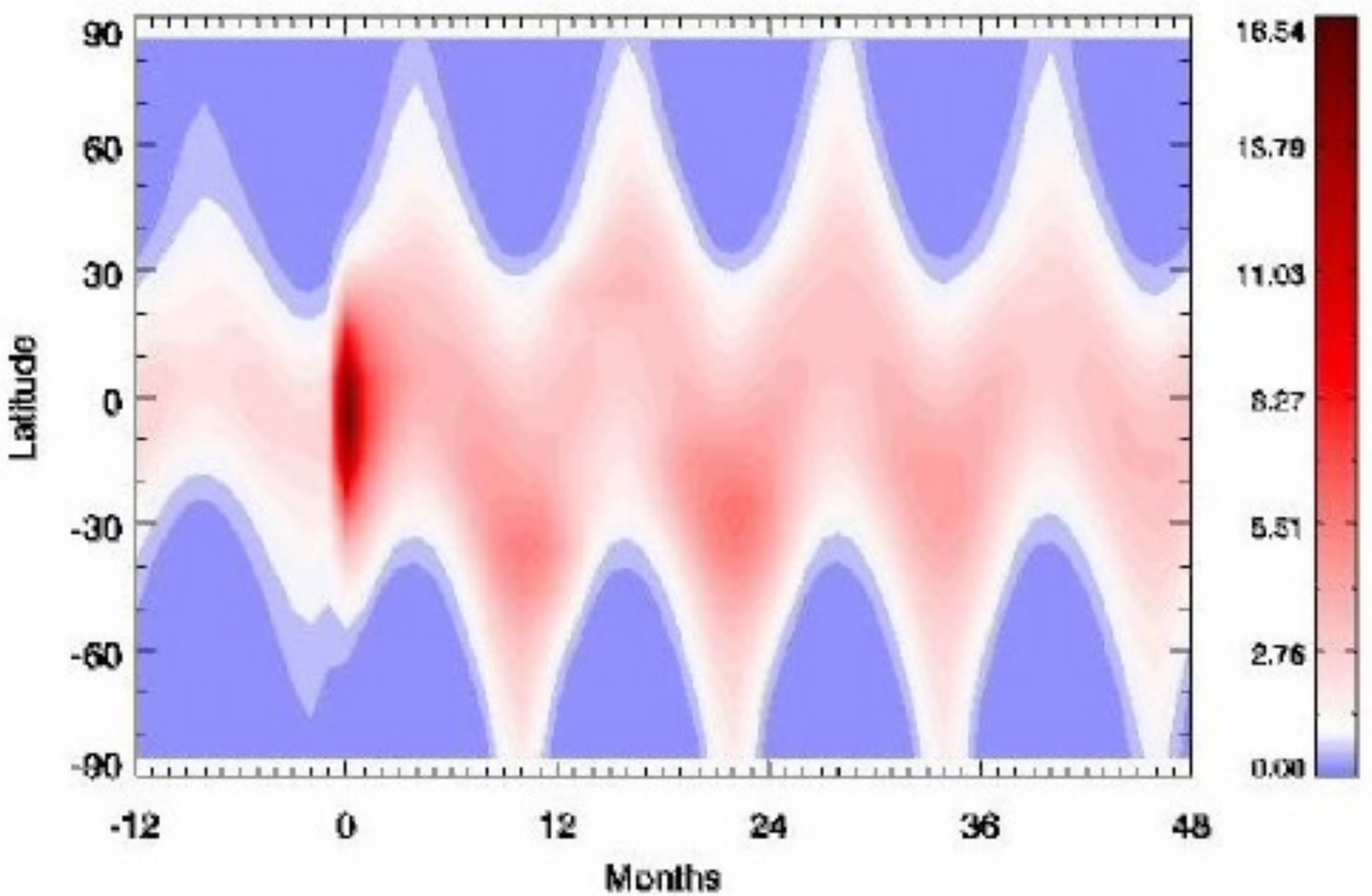


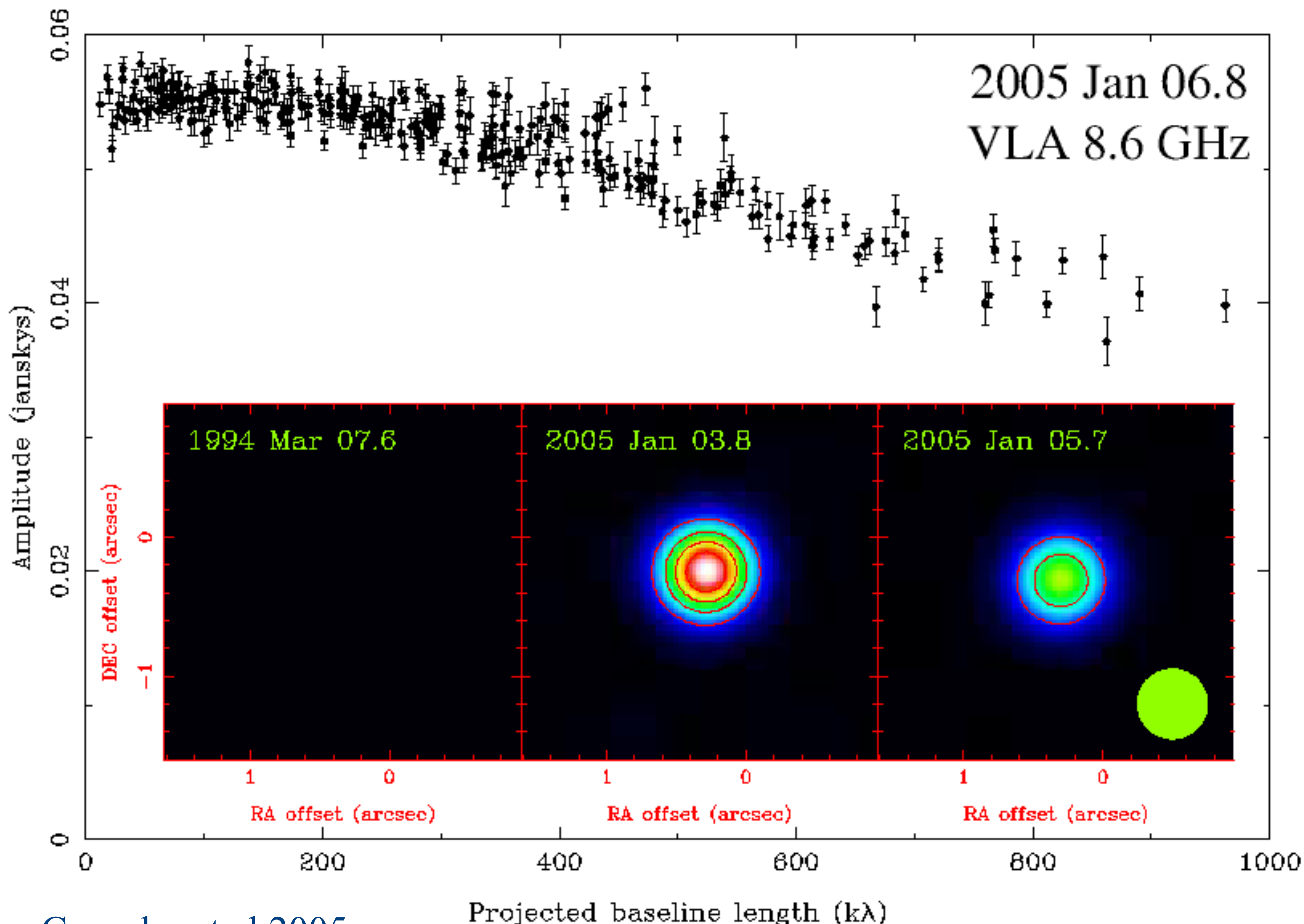
Extinction	Genus loss
End Ordovician	60%
End Devonian	57%
End Permian	82%
End Triassic	53%
End Cretaceous	47%

From Solé & Newman 2002

Effects of a nearby GRB on Earth

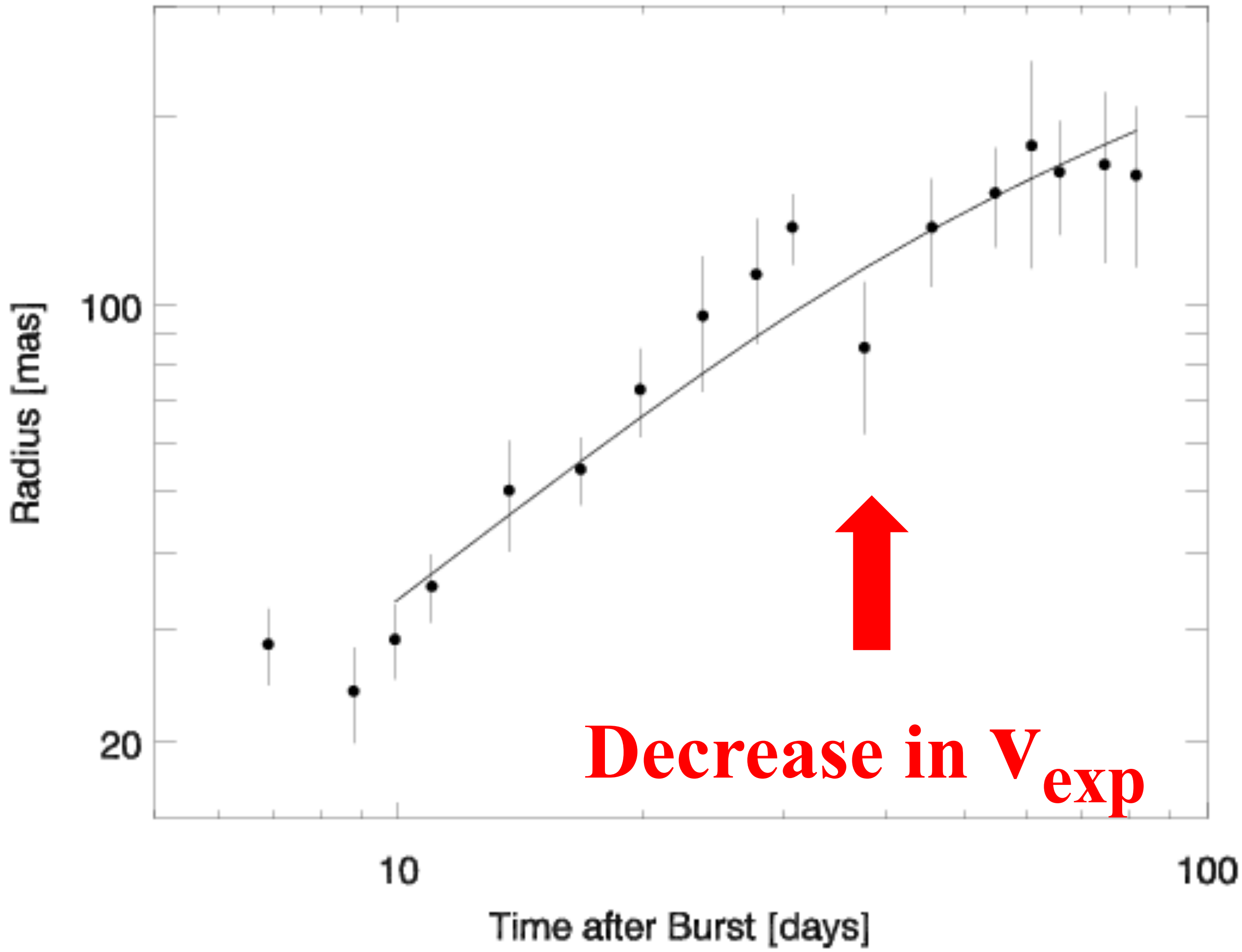
Melott et al. 2004





Gaensler et al 2005

Growth of the Radio Afterglow



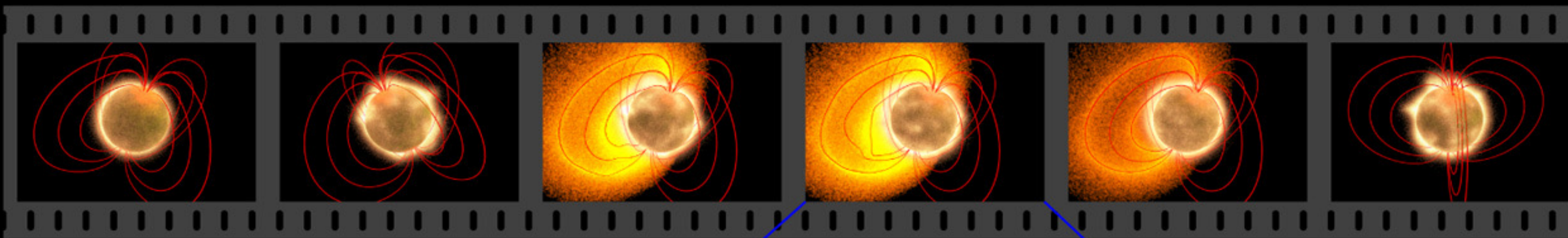
VLA
8.5 GHz

Size at
t+7 days
10^{16} cm
(1000 AU)

Velocity to
t + 30 days
~ 0.8 c

Taylor et al 2005

Magnetar burst sequence



Adapted from
Duncan and Thompson
1992

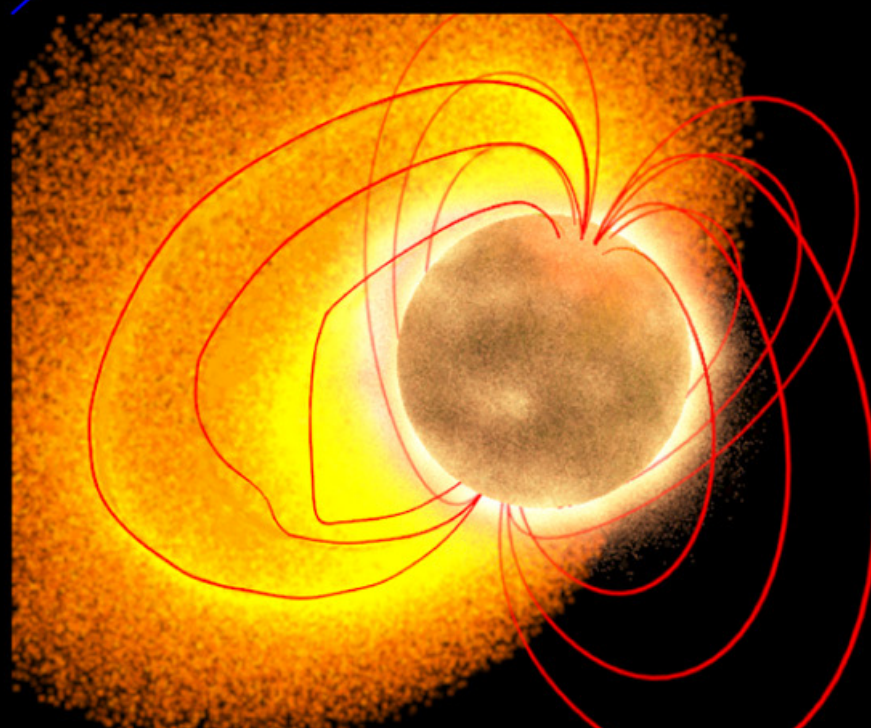
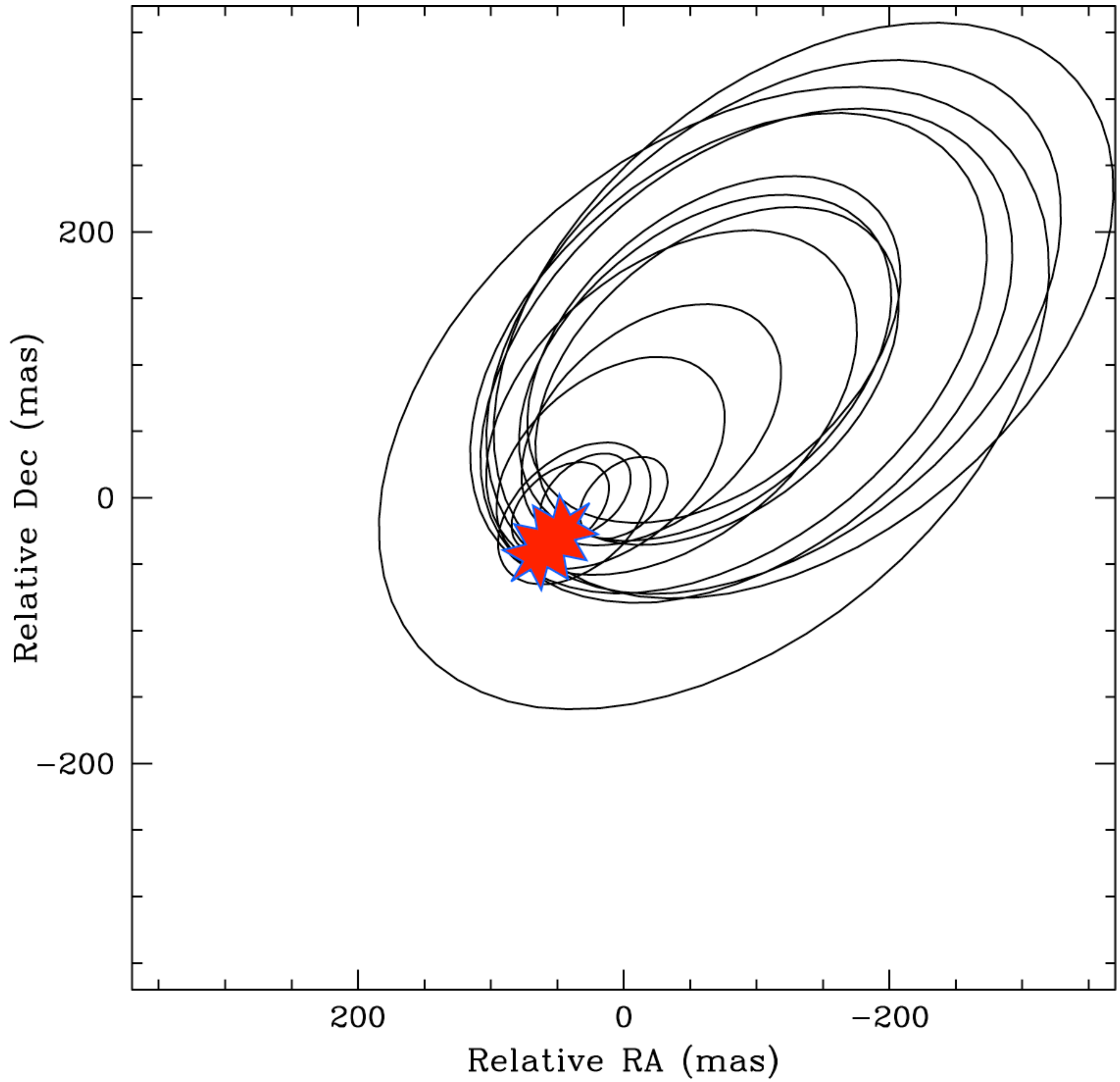


Image Evolution

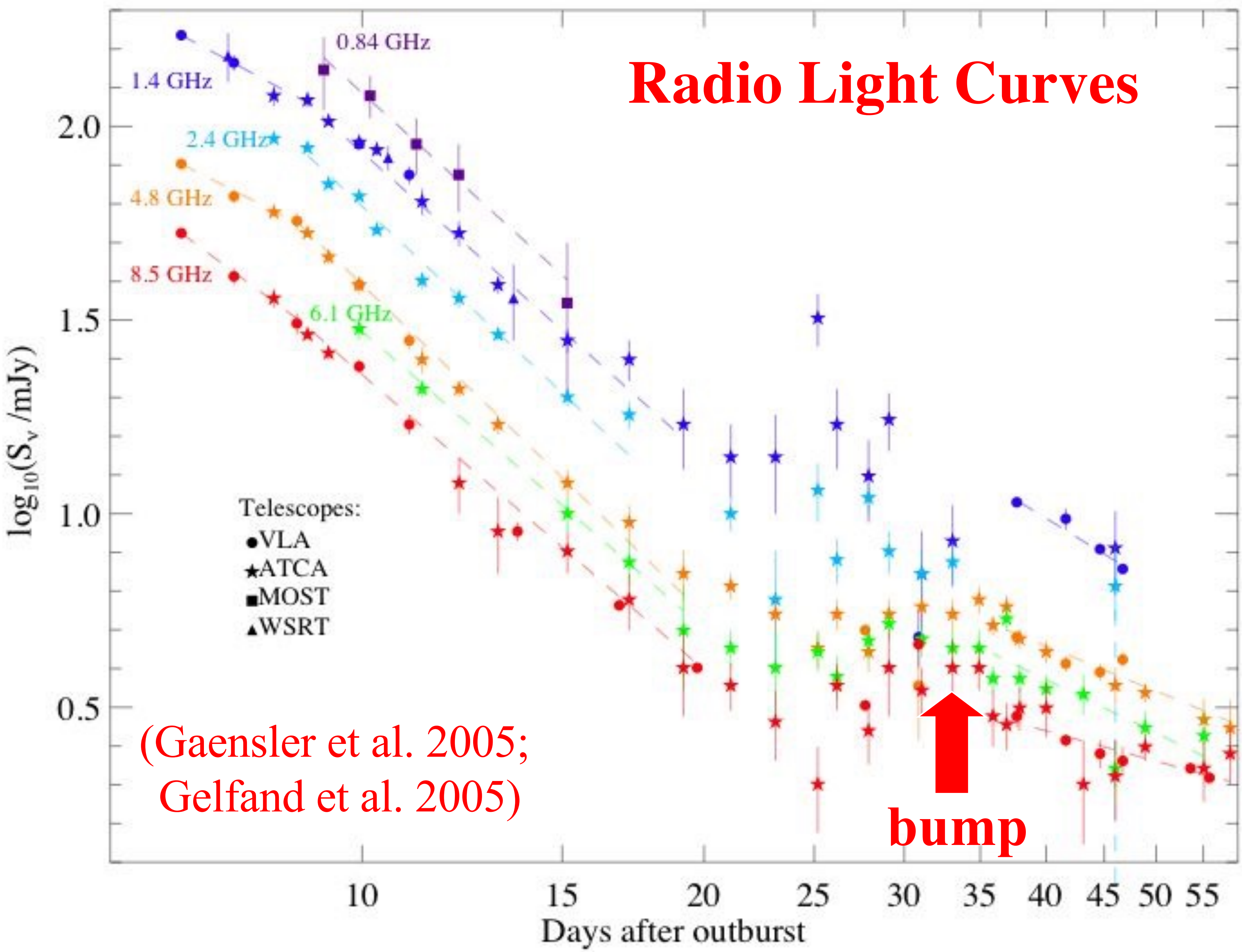
VLA 8.5 GHz

E ~ 10^45 ergs

One-sided (anisotropic) outflow



Taylor et al 2005



Radio Light Curves
0.84 GHz
1.4 GHz
2.4 GHz
4.8 GHz
8.5 GHz
6.1 GHz
Telescopes:
●VLA
★ATCA
■MOST
▲WSRT
(Gaensler et al. 2005;
Gelfand et al. 2005)
bump
2.0
1.5
1.0
0.5
log10(Sν /mJy)
10
15
20
25
30
35
40
45
50
55
Days after outburst