Pulsars, Magnetars, Black Holes (Oh My!):

The Wickedly Cool Stellar Undead

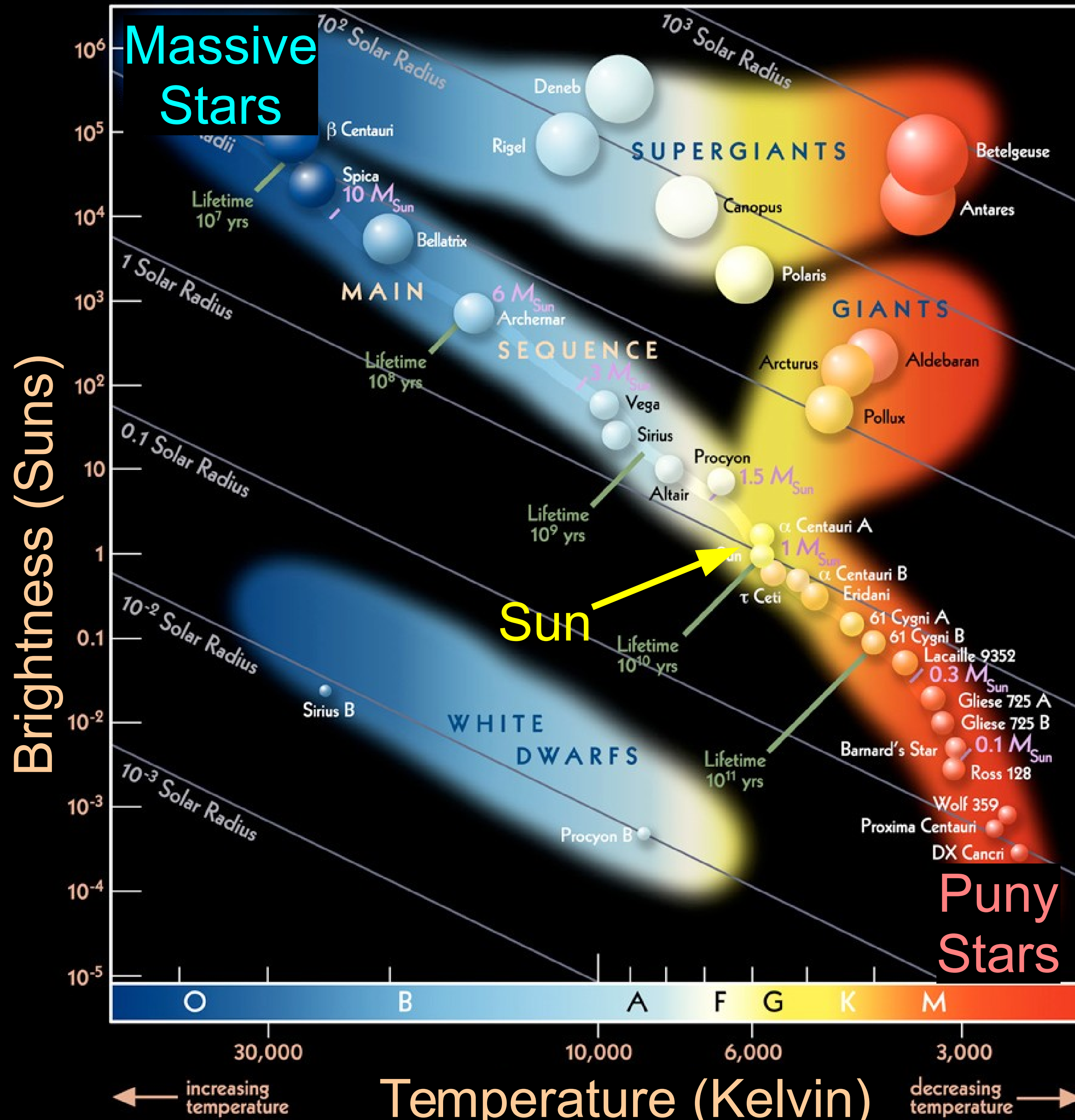
Scott Ransom
National Radio Astronomy Observatory /
University of Virginia

The Lives of Stars!

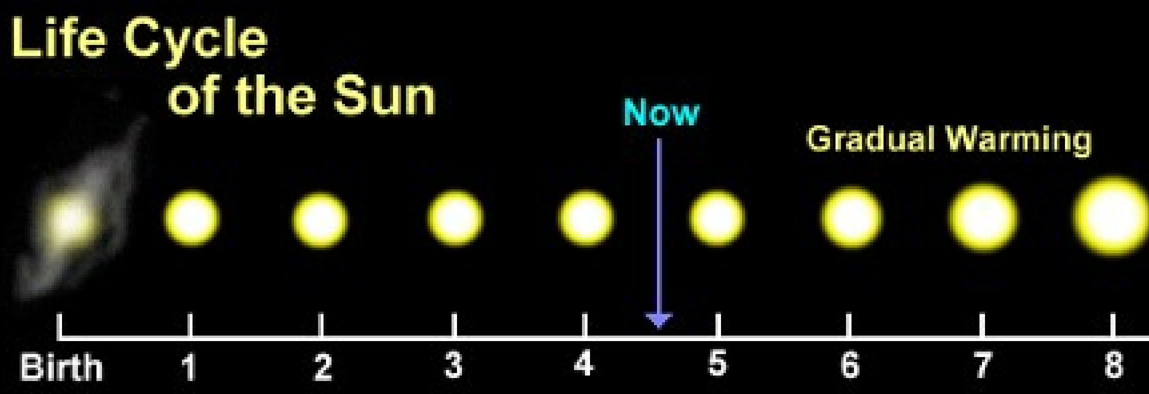
Hertzsprung - Russell Diagram

Color → Temperature

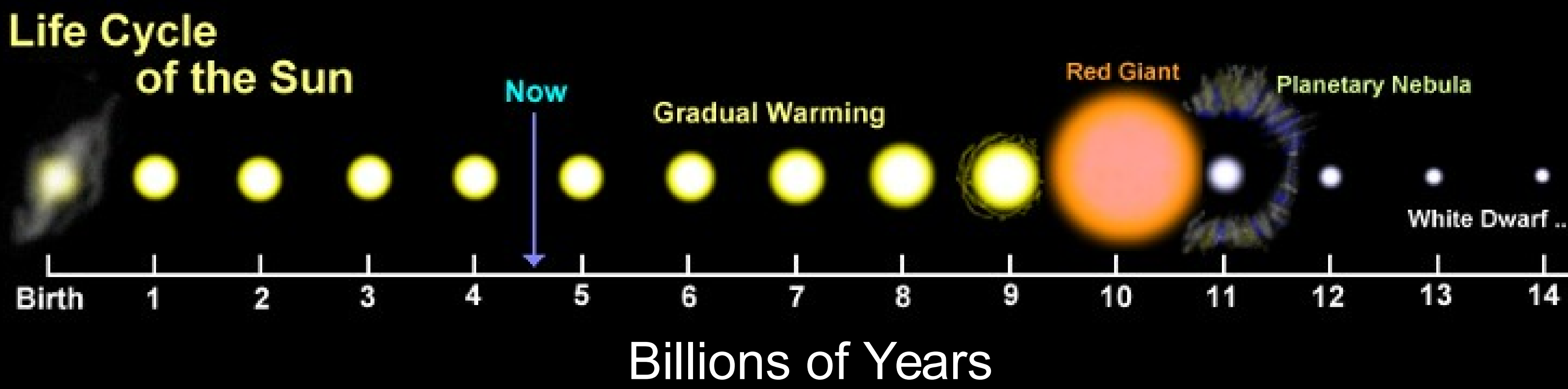
Mass + Temp + Size → Luminosity



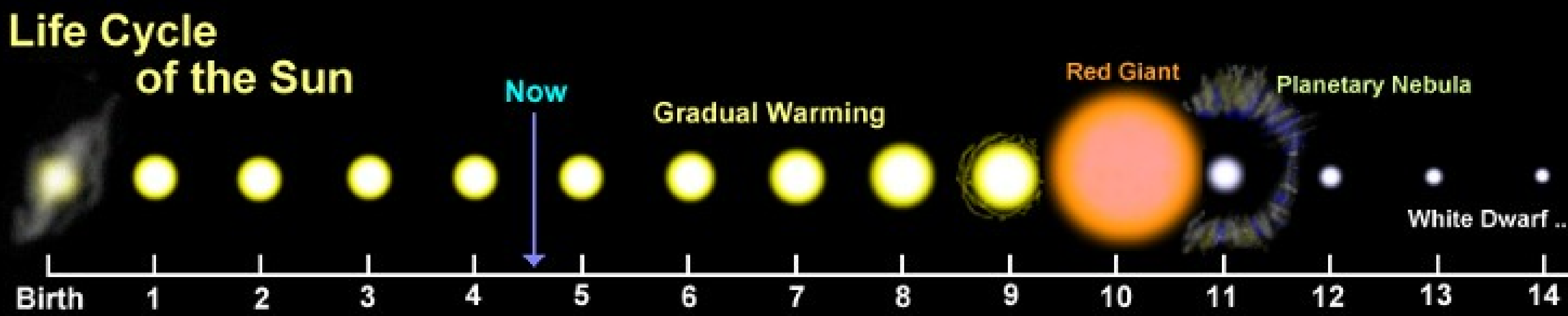
All stars shine by burning Hydrogen into heavier elements via fusion



Billions of Years



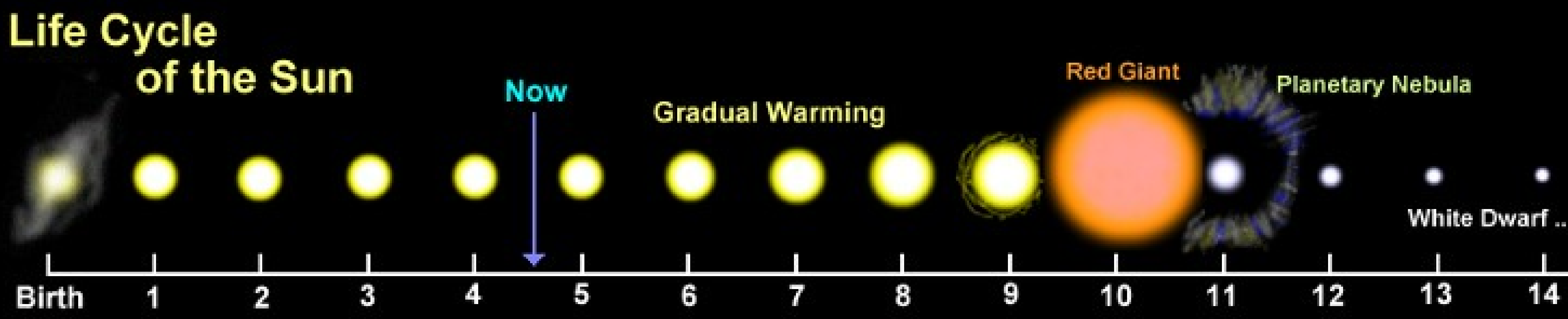
… but all stars eventually die.



Billions of Years

… but all stars eventually die.

The Sun will become a white dwarf

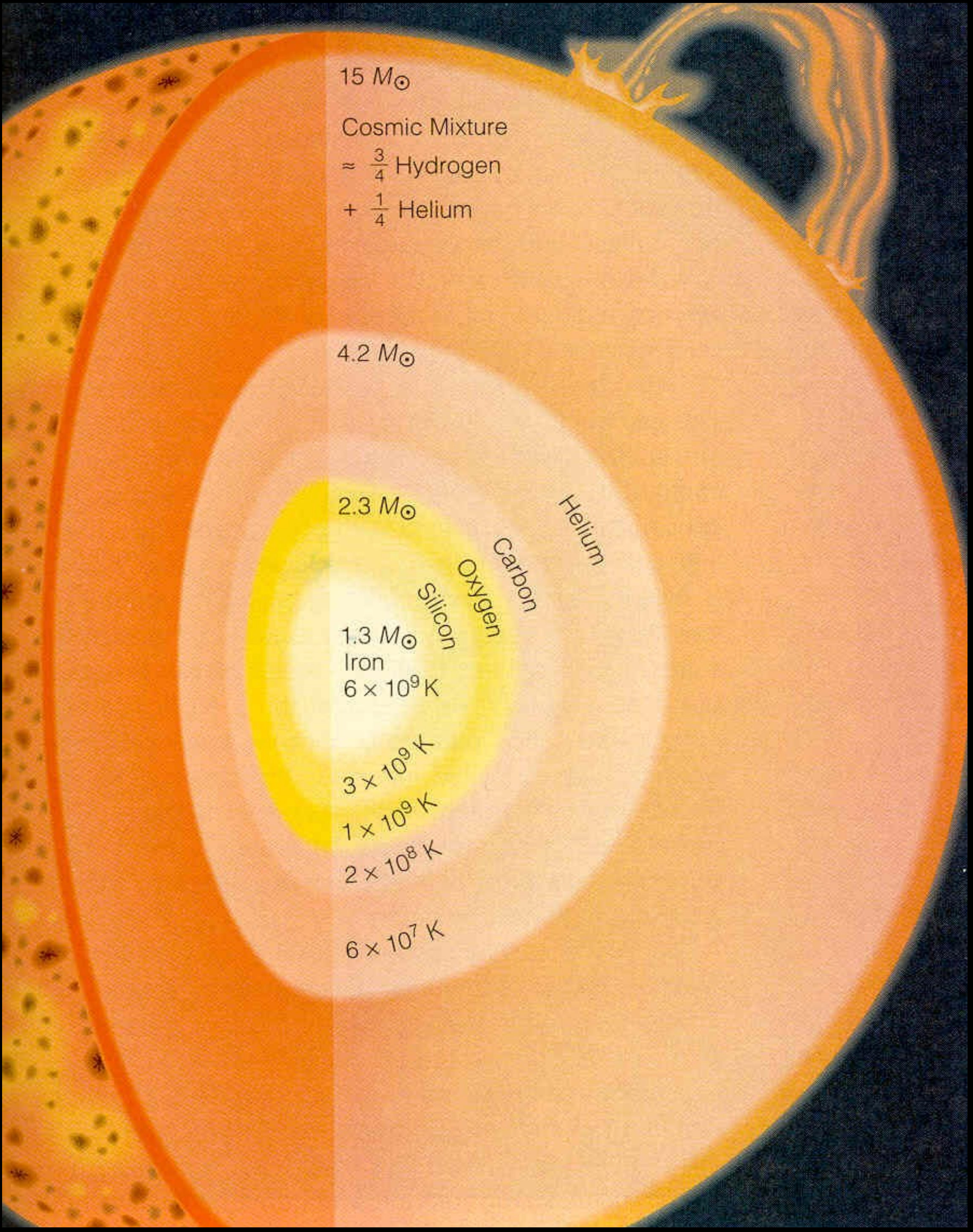


Billions of Years

… but all stars eventually die.

The Sun will become a white dwarf

...unfortunately, the Earth will kind of be in the way when it happens...



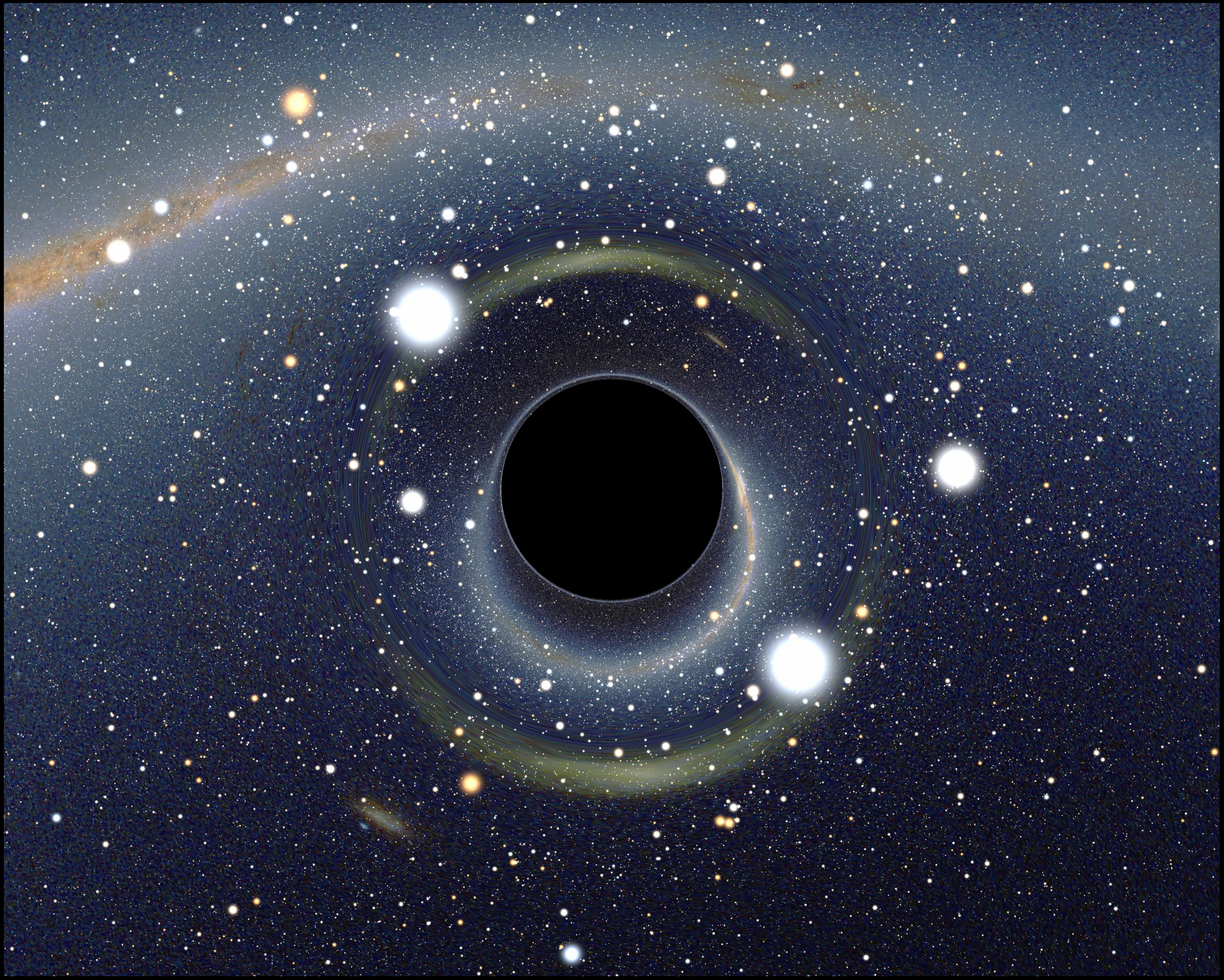
Inside a very massive star:

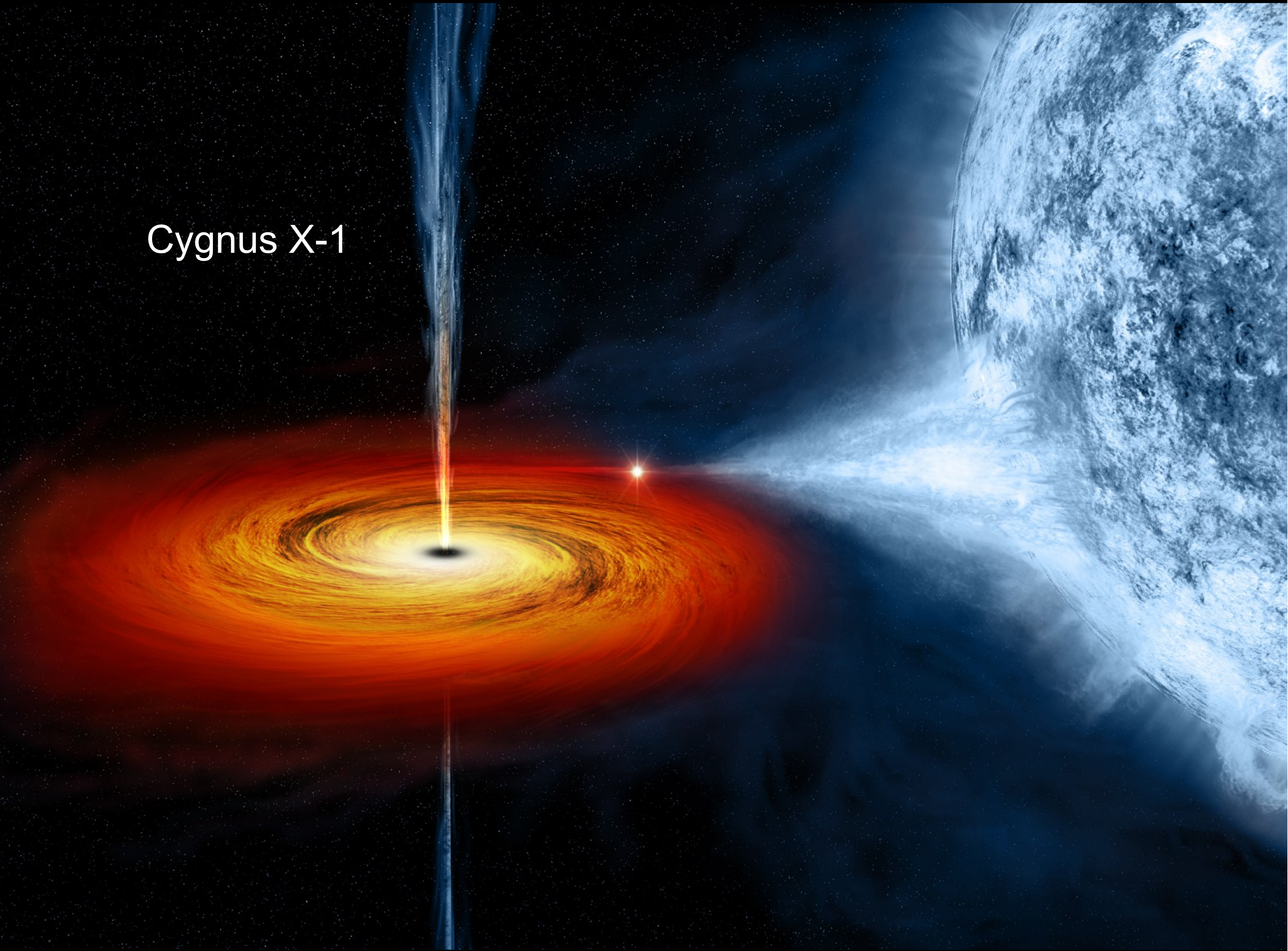
Massive stars fuse Hydrogen into many heavier elements:
(H → He → C → O → Si → Fe)

But, they can only do this while the fuel supply lasts…

The most massive stars....

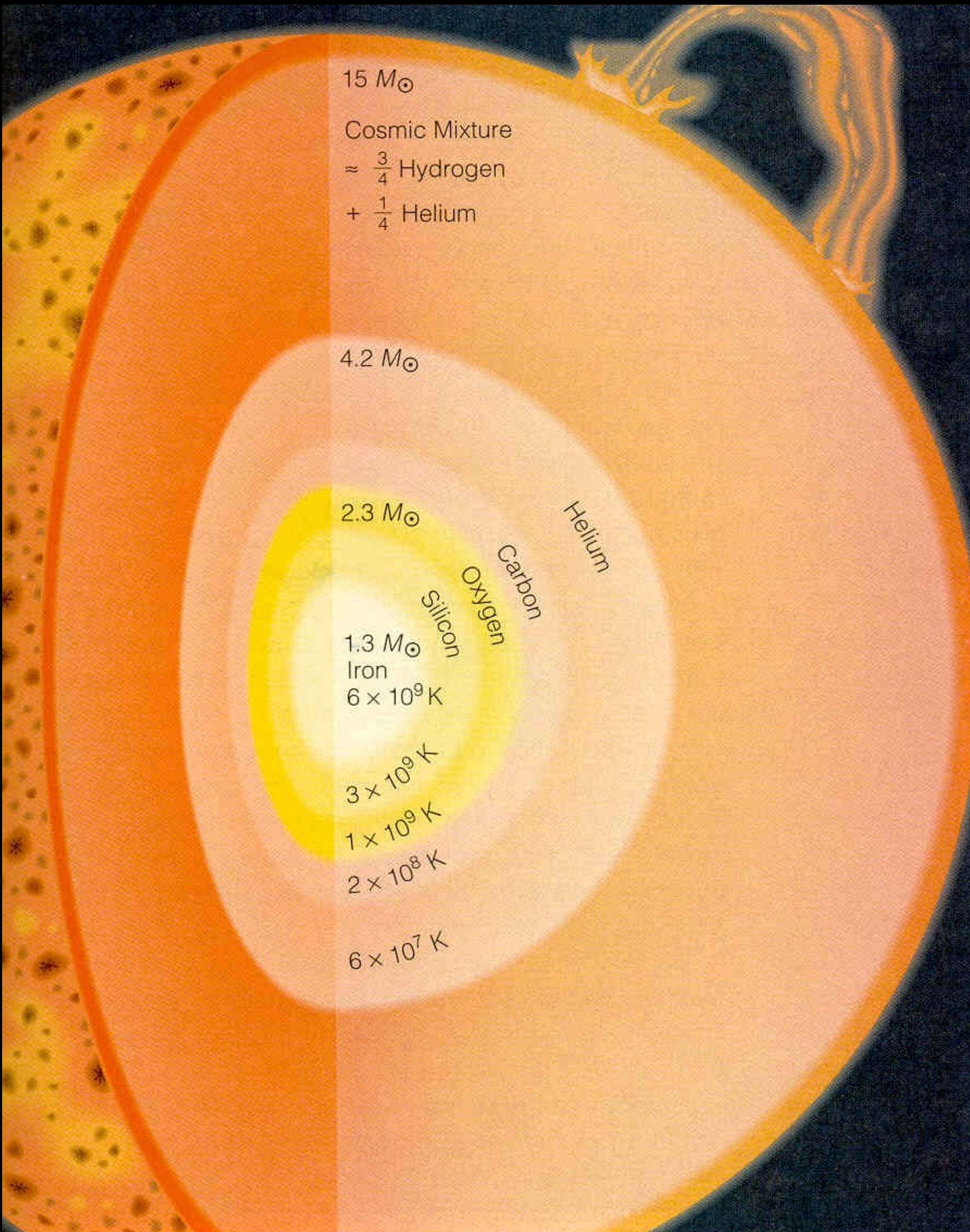
...collapse into black holes



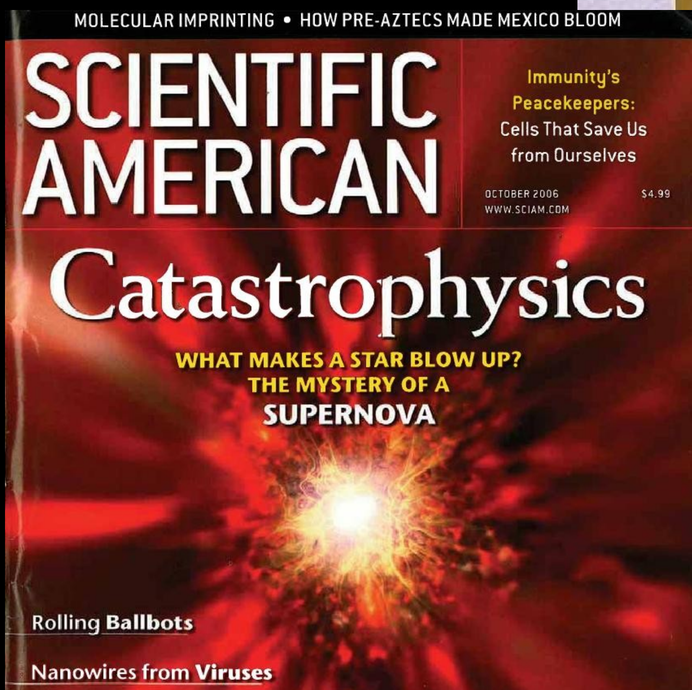

Cygnus X-1

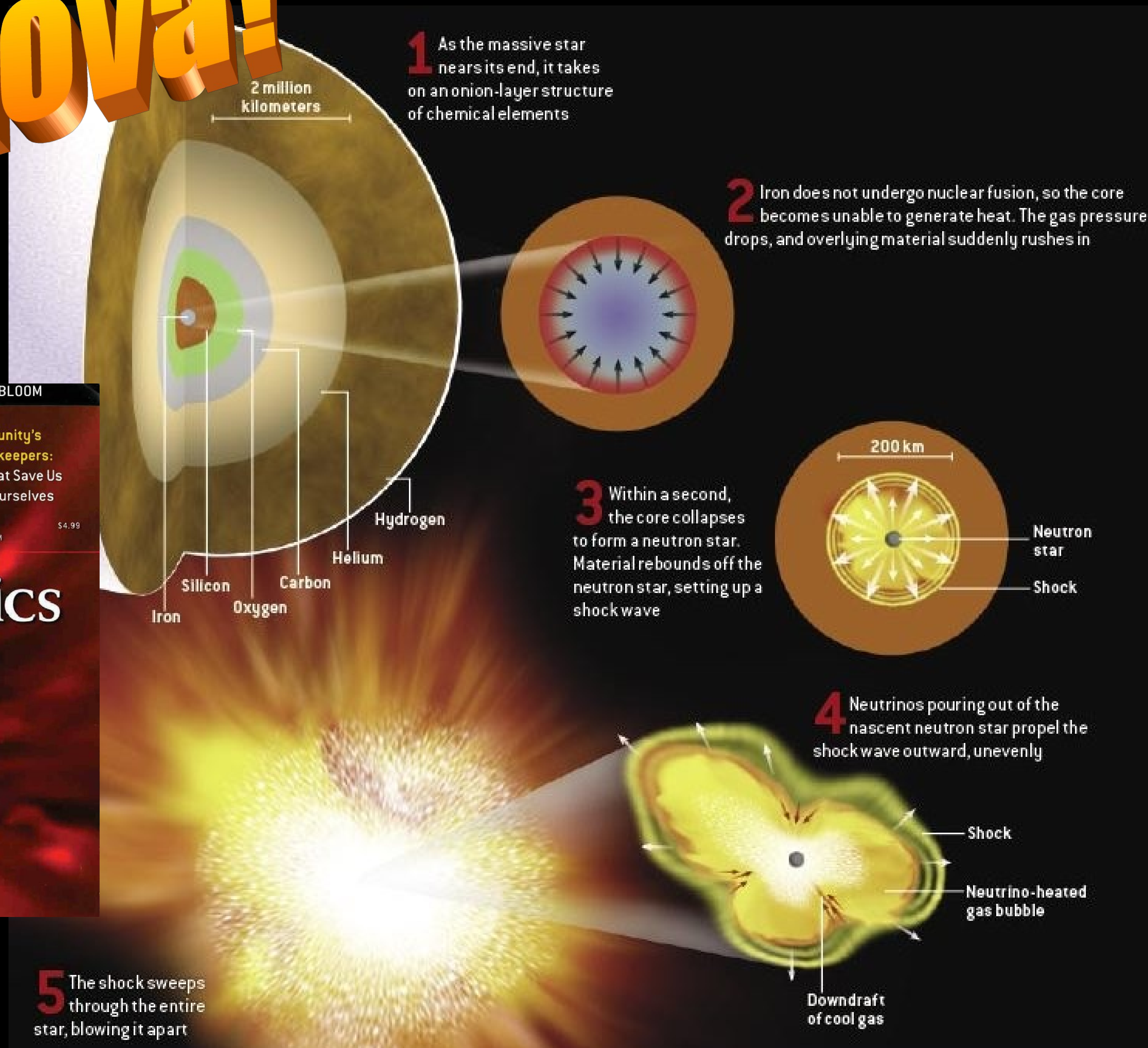
Inside a massive (but not *too* massive) star:

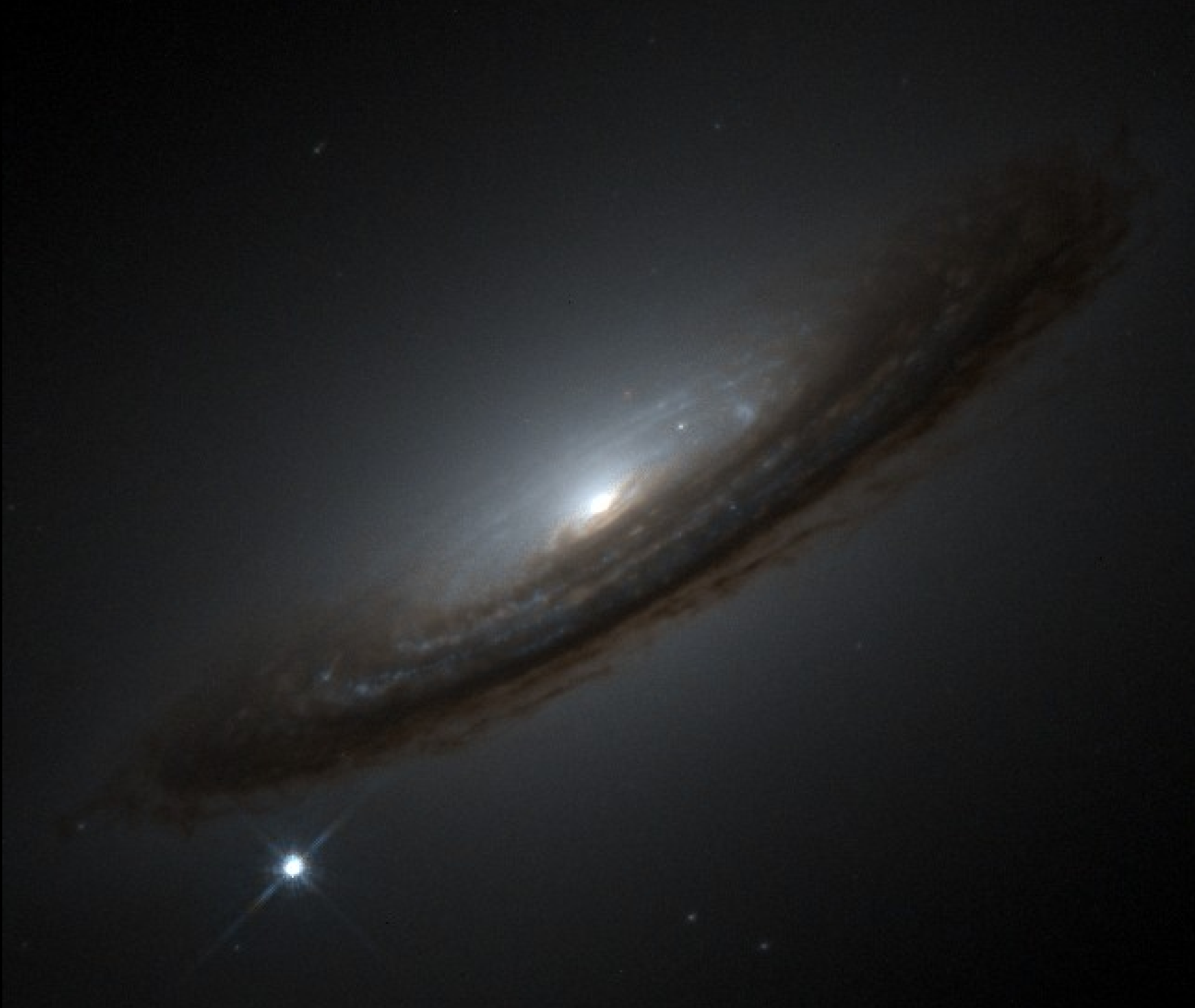
The core collapses into a Neutron Star

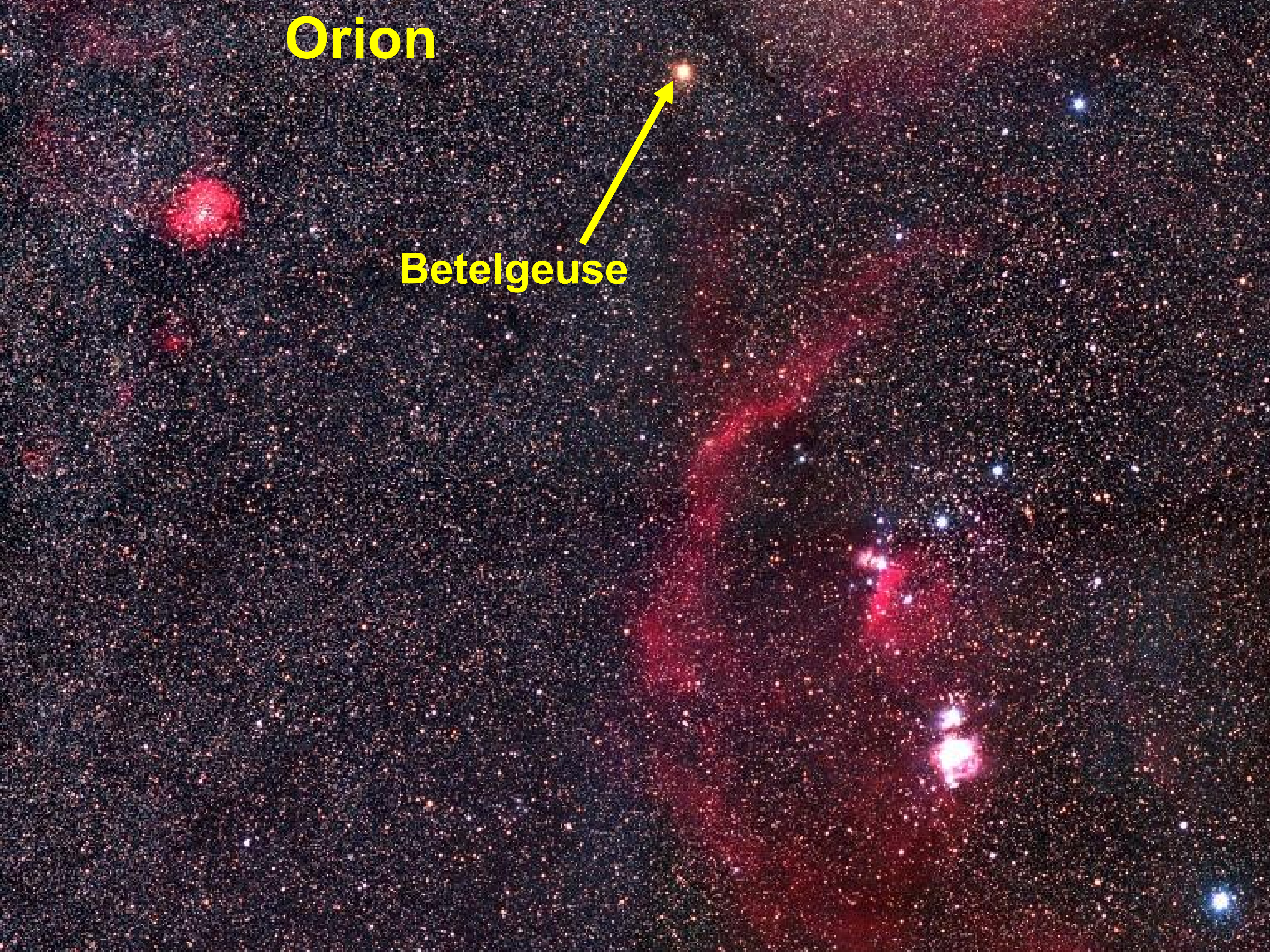


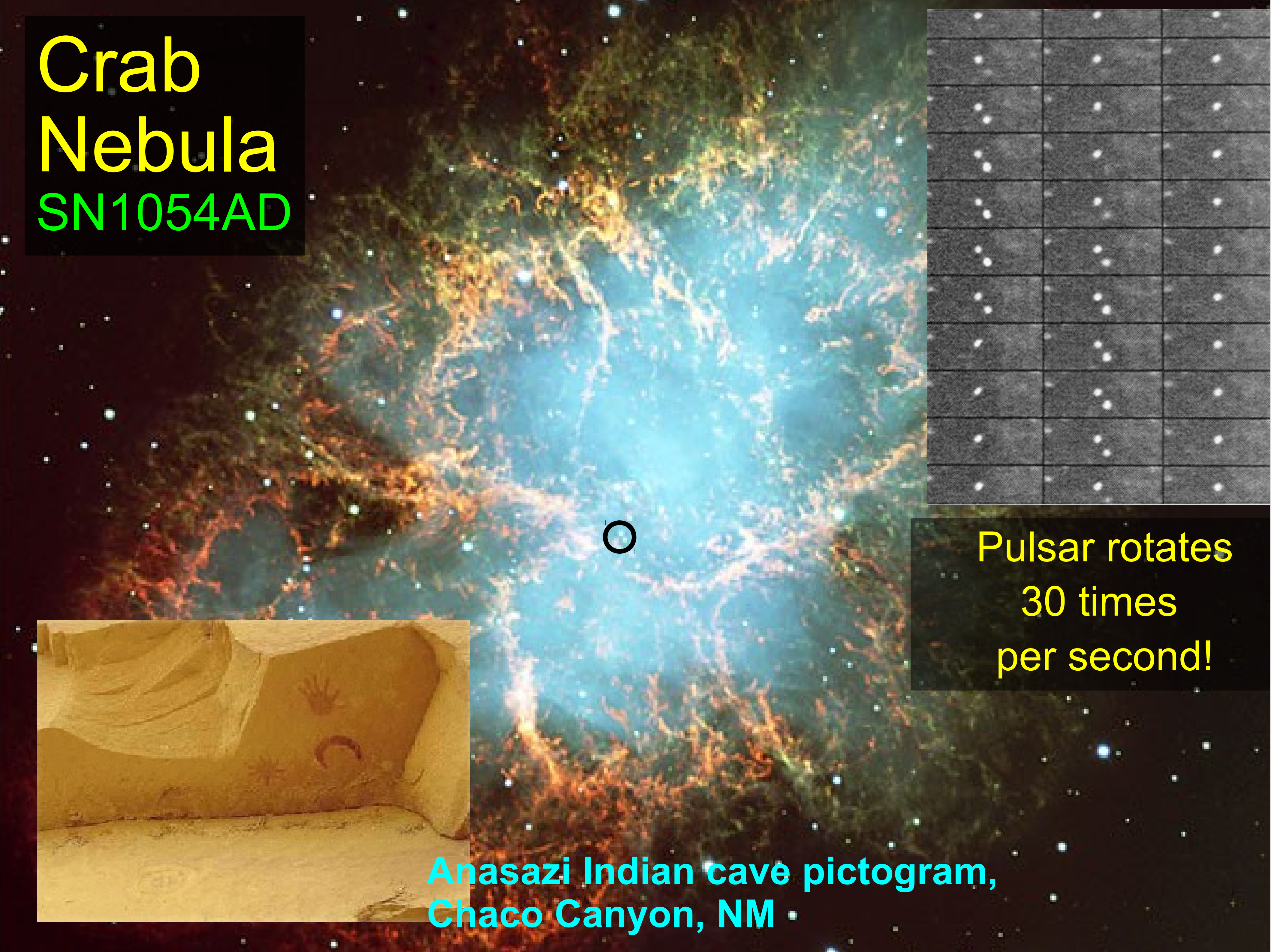
Supernova!


MOLECULAR IMPRINTING • HOW PRE-AZTECS MADE MEXICO BLOOM
SCIENTIFIC AMERICAN
Immunity's Peacekeepers: Cells That Save Us from Ourselves
OCTOBER 2006 WWW.SCIAM.COM $4.99
Catastrophysics
WHAT MAKES A STAR BLOW UP? THE MYSTERY OF A SUPERNOVA
Rolling Ballbots
Nanowires from Viruses


1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements
2 million kilometers
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in
200 km
3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave
Neutron star
Shock
4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly
Shock
Neutrino-heated gas bubble
Downdraft of cool gas
5 The shock sweeps through the entire star, blowing it apart

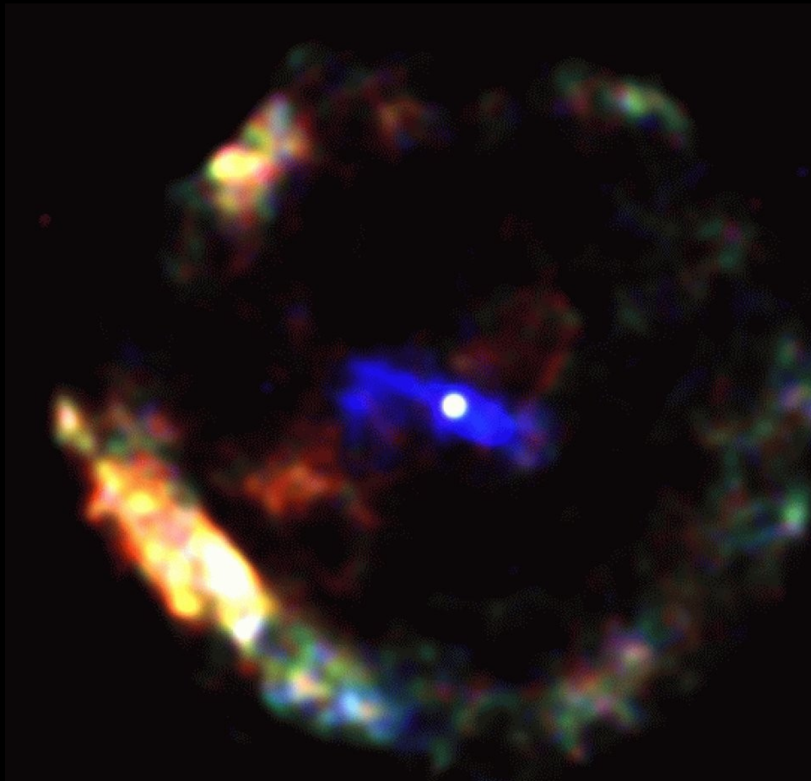



Orion
Betelgeuse


Crab
Nebula
SN1054AD
Pulsar rotates
30 times
per second!
Anasazi Indian cave pictogram,
Chaco Canyon, NM

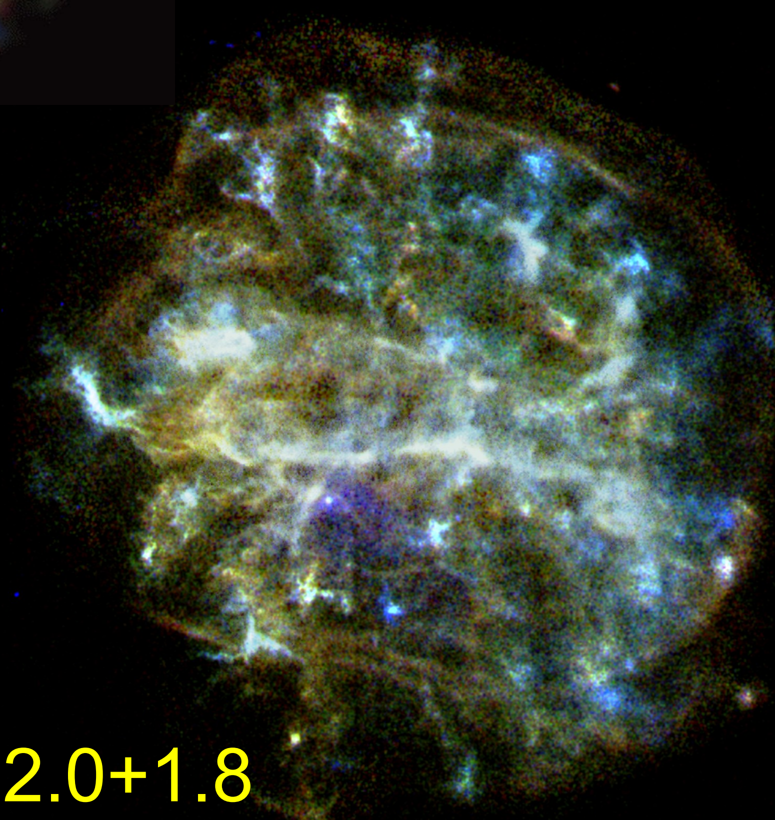
The Crab is visible at all energies!

Pulsars!



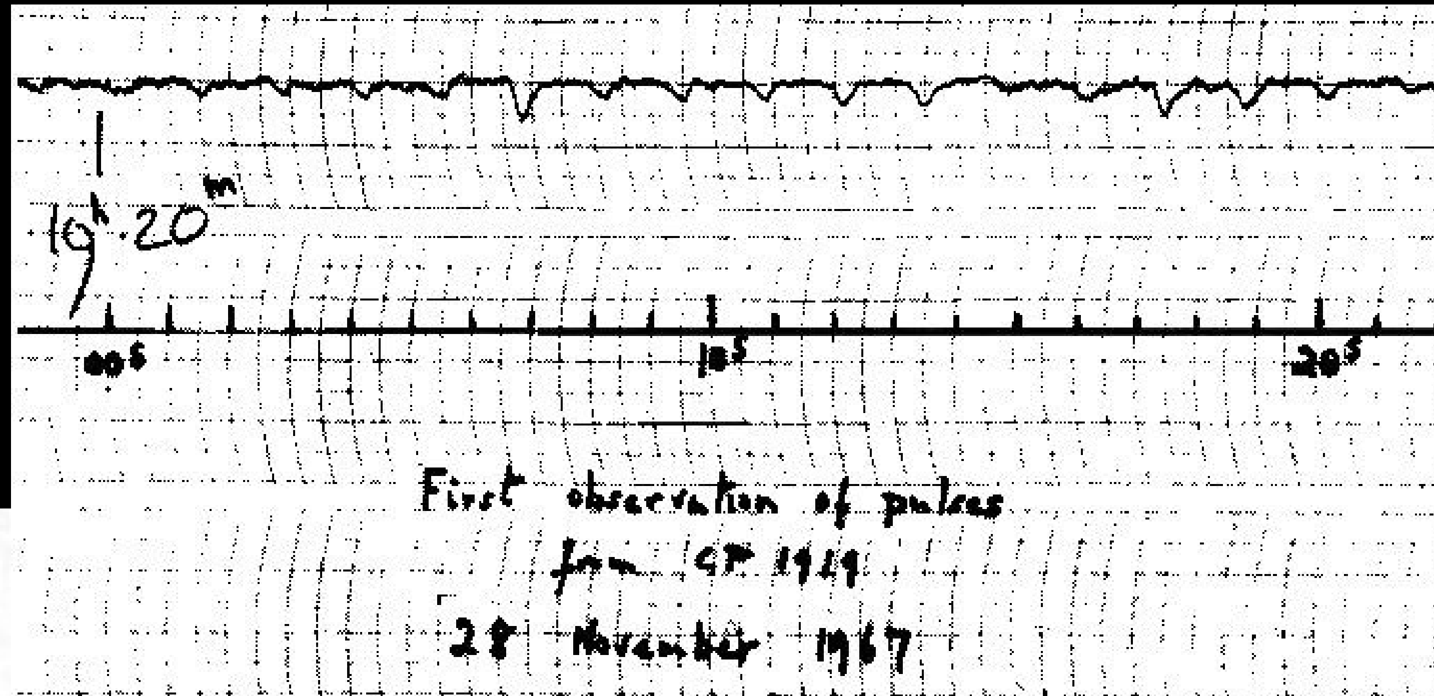
G11.2-0.3

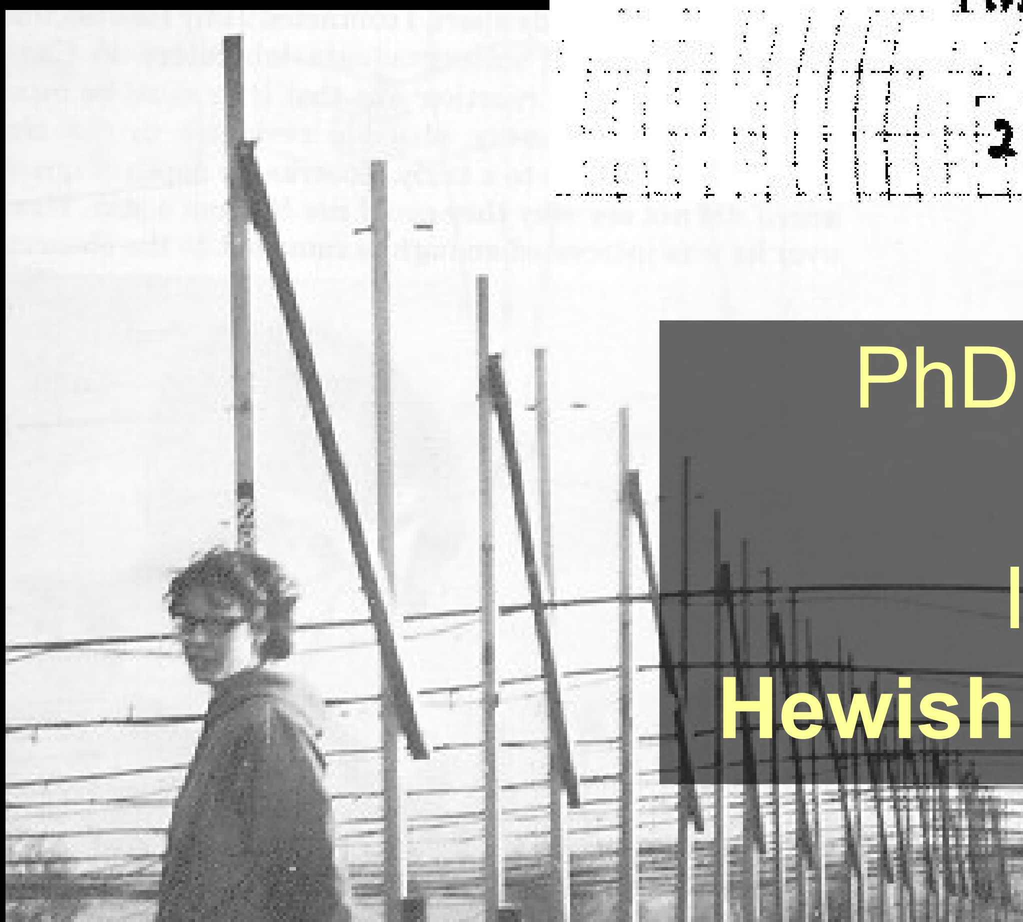
G21.5-0.9



G292.0+1.8

The Discovery of Pulsars



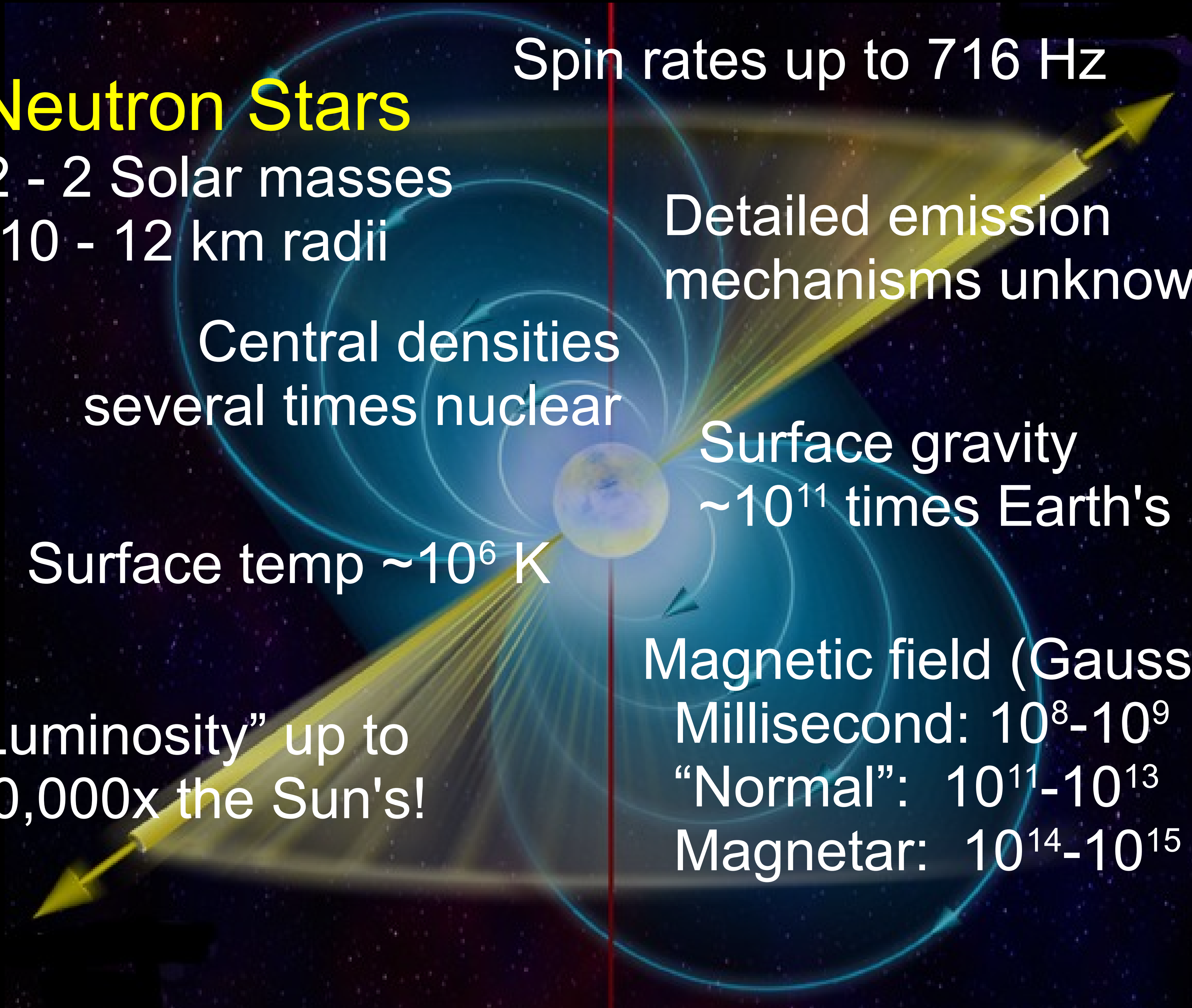


PhD student **Jocelyn Bell** and

Prof. **Antony Hewish**

Initially "**Little Green Men**"

Hewish won Nobel Prize in 1974



Neutron Stars

1.2 - 2 Solar masses
10 - 12 km radii

Spin rates up to 716 Hz

Detailed emission mechanisms unknown

Central densities several times nuclear

Surface gravity ~10^{11} times Earth's

Surface temp ~10^{6} K

Magnetic field (Gauss):
- Millisecond: 10^{8}-10^{9}
- “Normal”: 10^{11}-10^{13}
- Magnetar: 10^{14}-10^{15}

“Luminosity” up to 10,000x the Sun's!

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1.2 - 2 Solar masses
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Central densities
several times nuclear

These are exotic objects

Surface temp

"Luminosity" up to
10,000x the Sun's!

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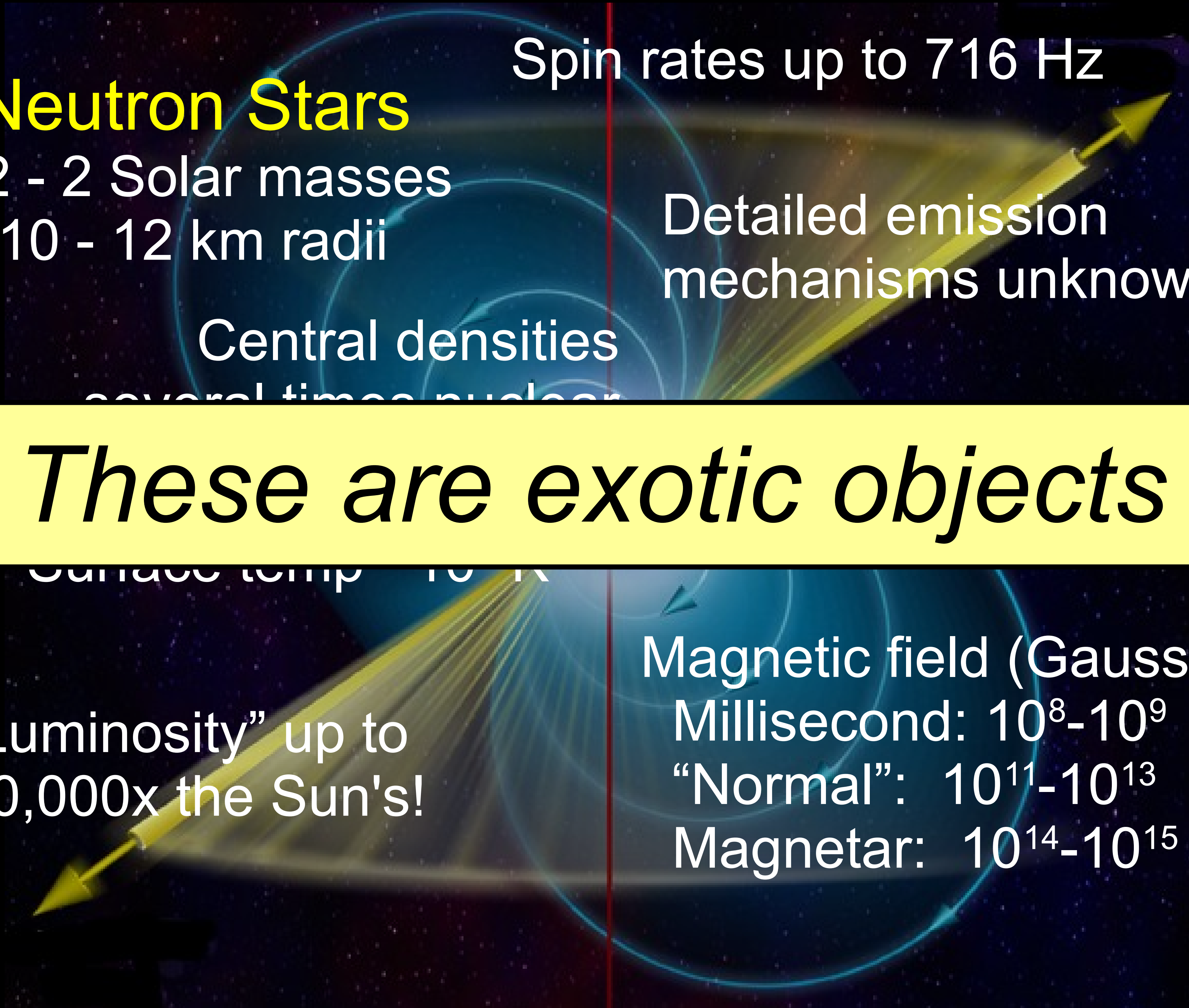
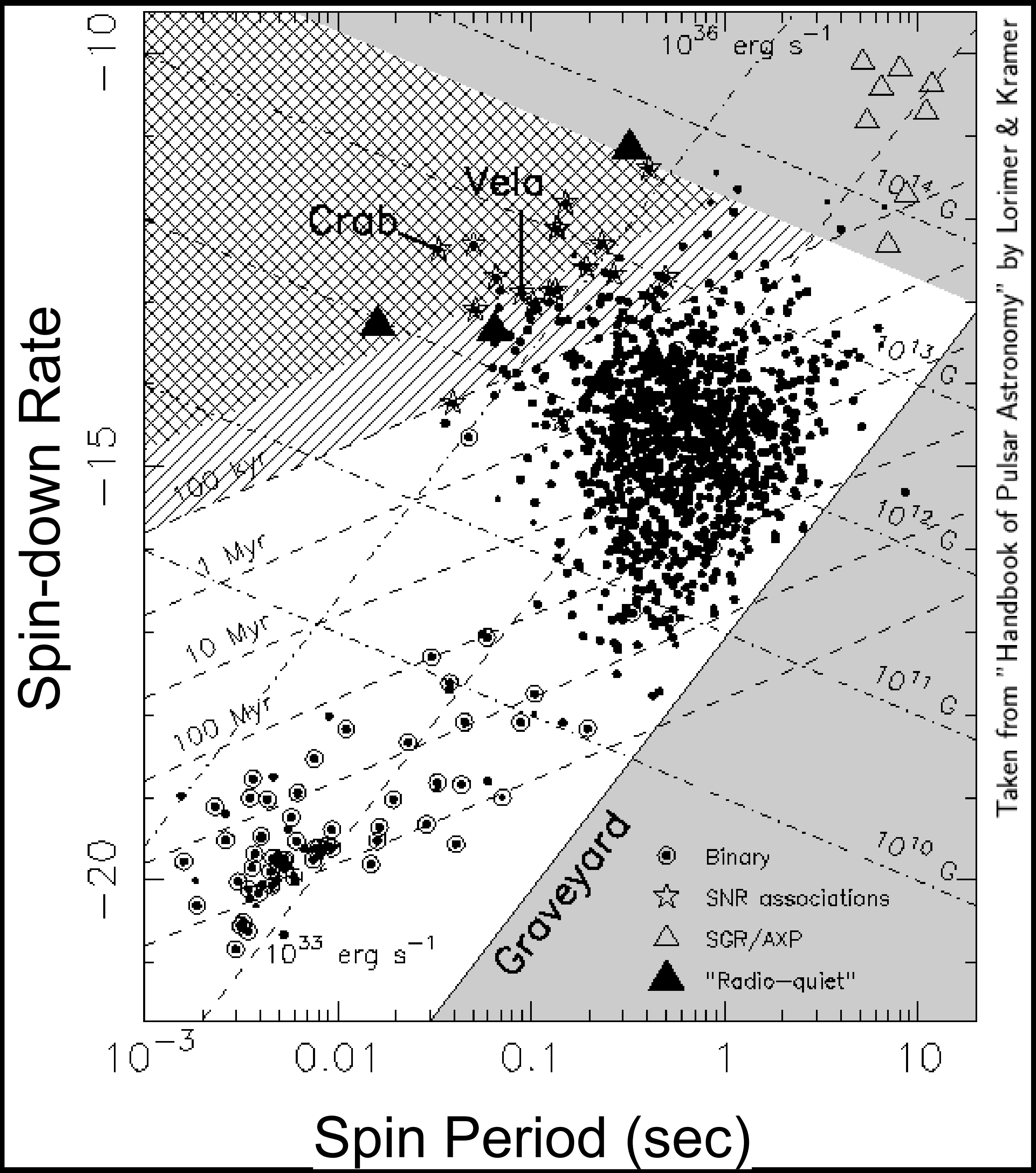


P-Pdot Diagram

Pulsar Astronomer's Hertzsprung-Russell Diagram

HR Diagram:
Temp (color) vs Luminosity

P-Pdot Diagram
Period vs Spindown rate

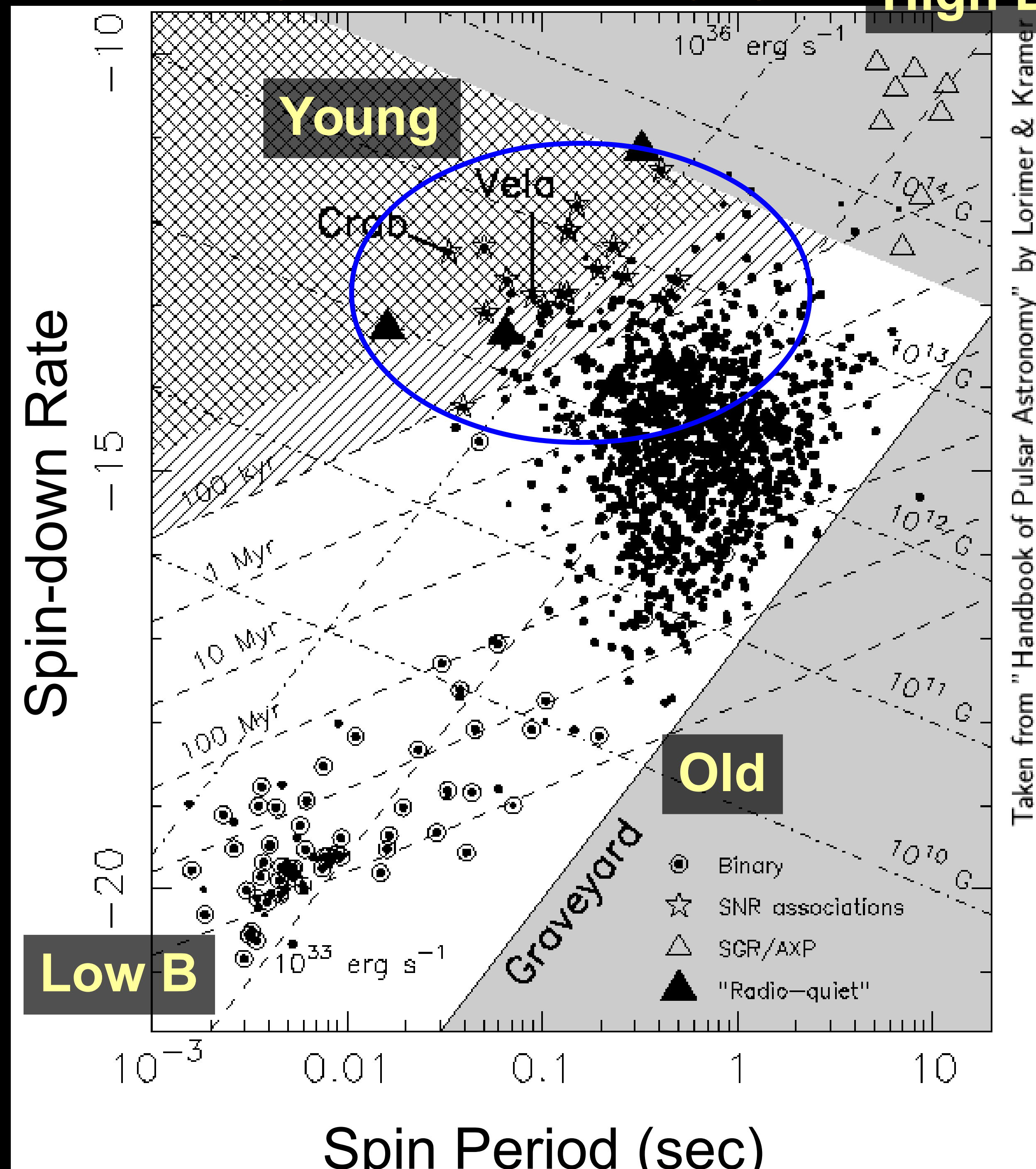


Pulsar Flavors

Young PSRs

(high B, fast spin, very energetic)

(Note: B = Magnetic Field Strength) →



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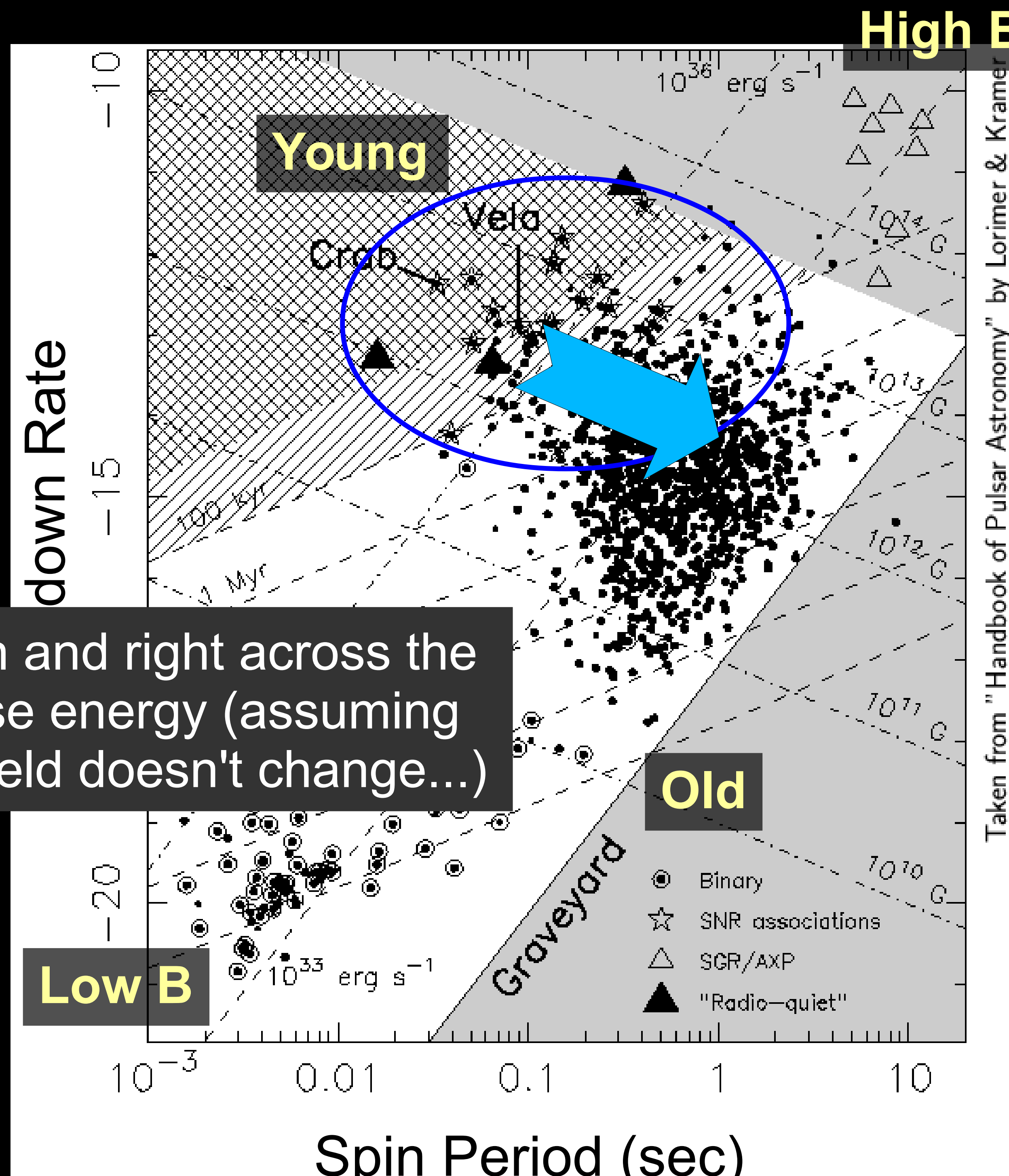


Pulsars move down and right across the diagram as they lose energy (assuming that the magnetic field doesn't change...)

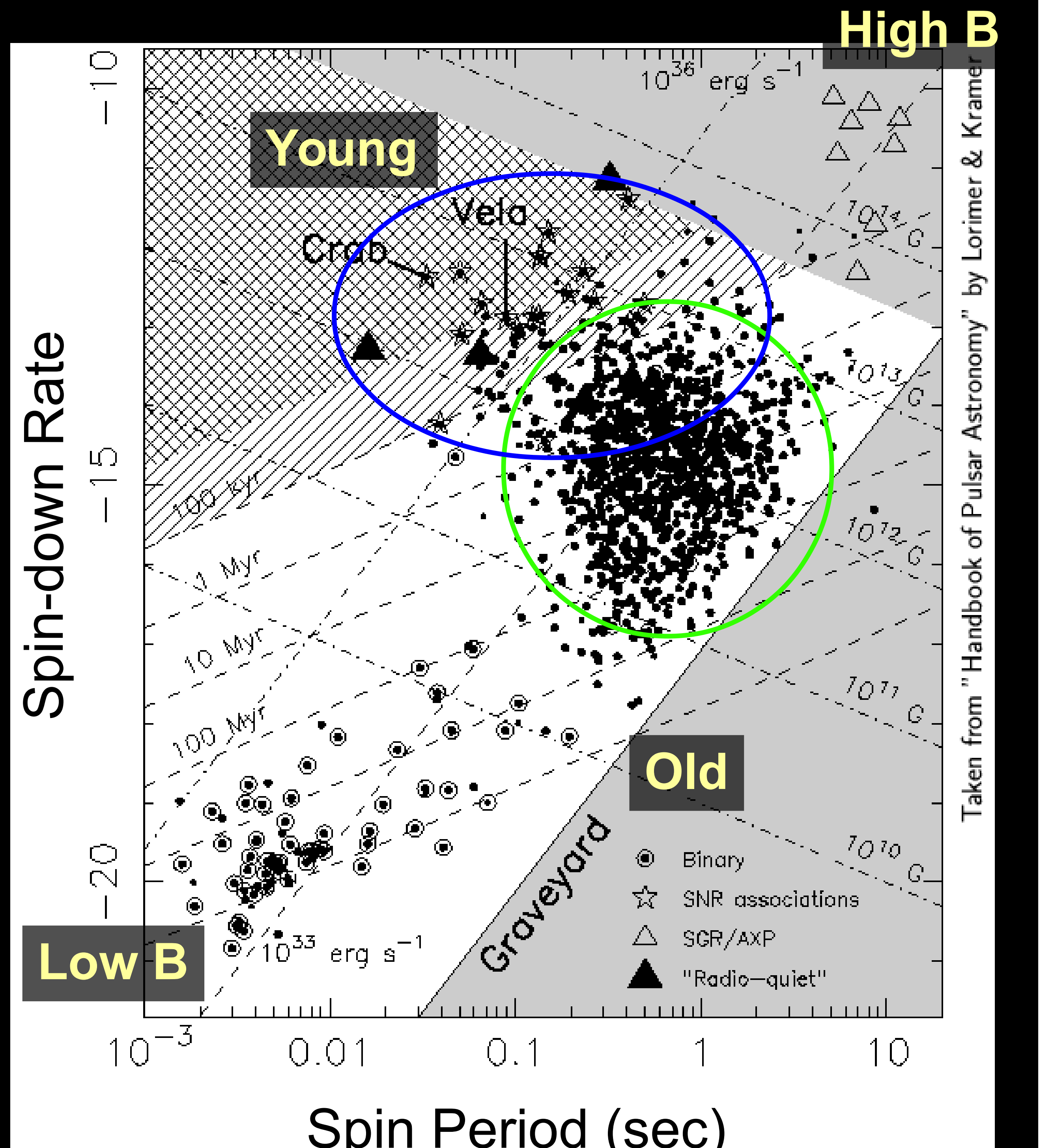
Pulsar Flavors

Young PSRs

(high B, fast spin, very energetic)

Normal PSRs

(average B, slow spin)



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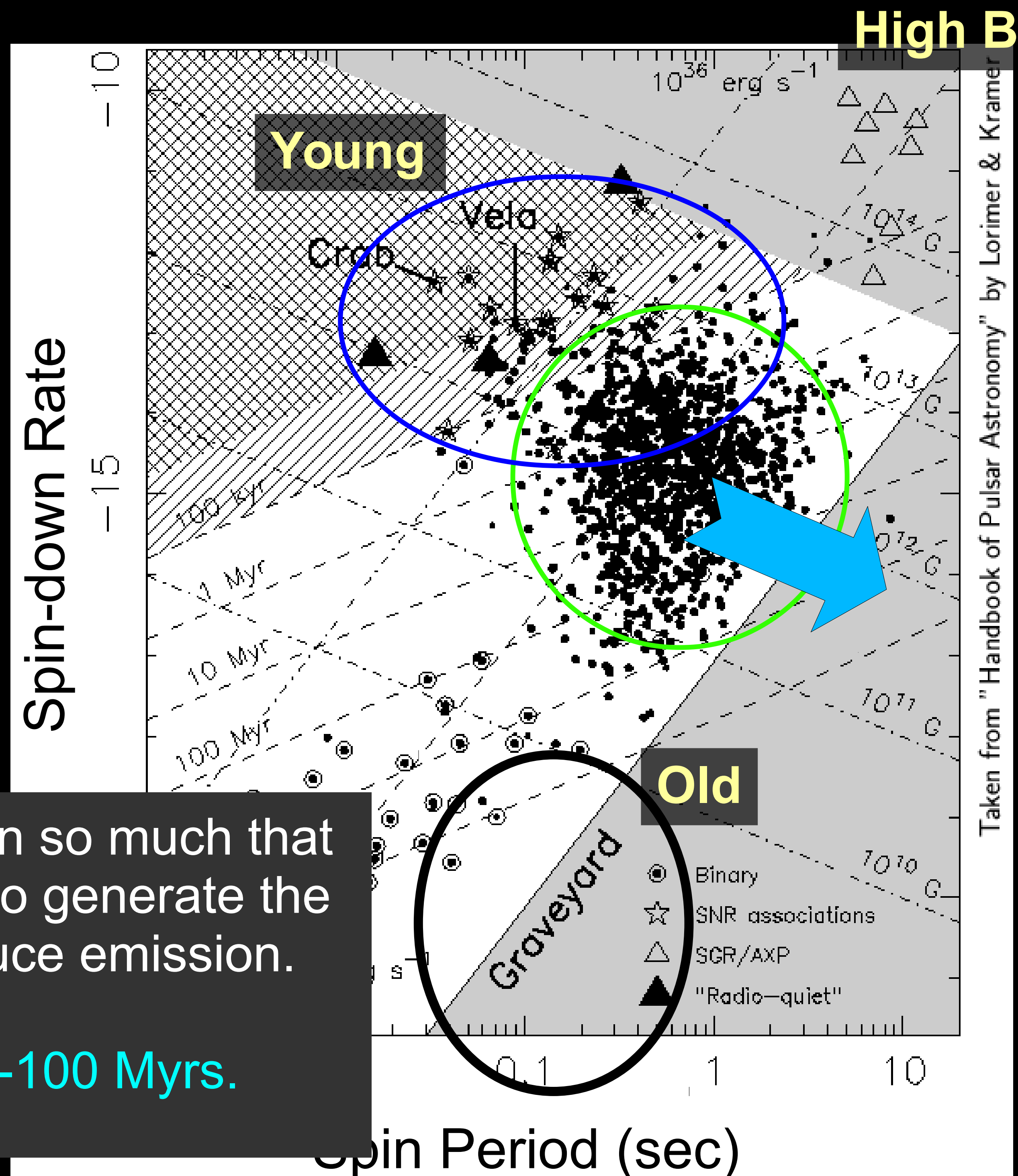
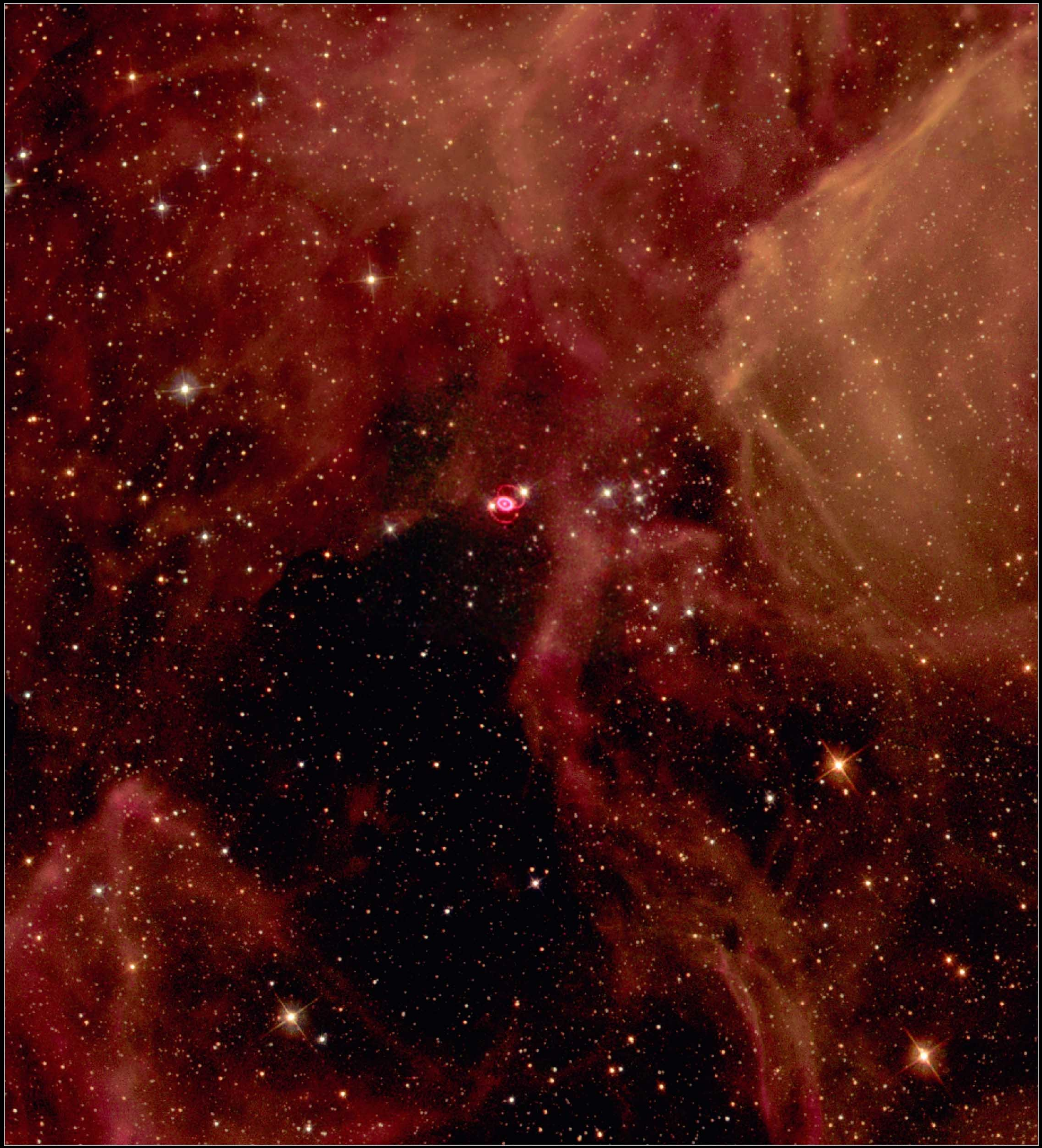


Eventually they slow down so much that there is not enough spin to generate the electric fields which produce emission.

Their lifetimes are 10-100 Myrs.

But not all supernovae produce pulsars…

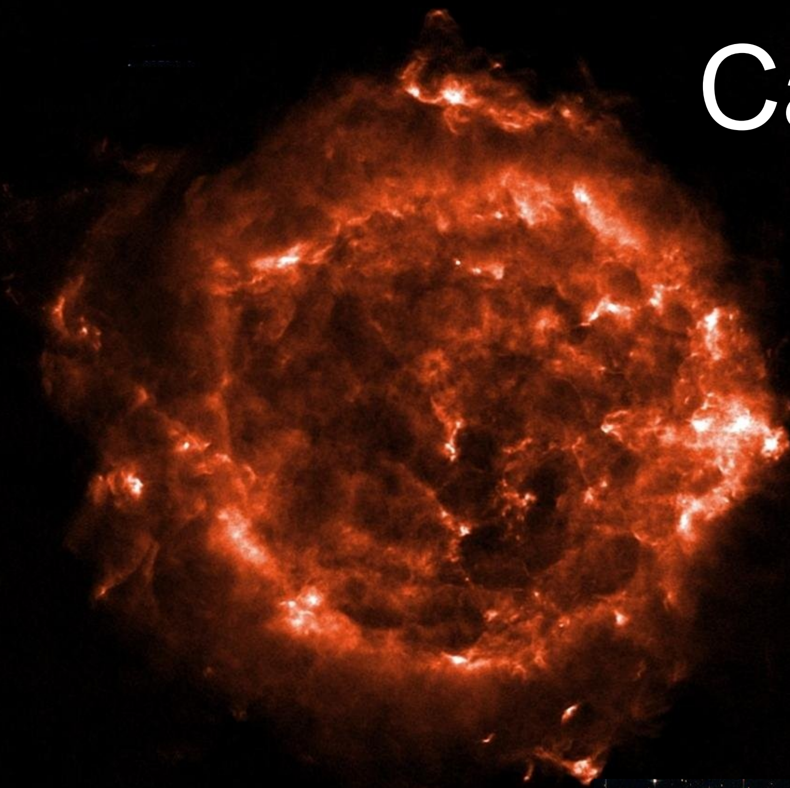
Supernova 1987A



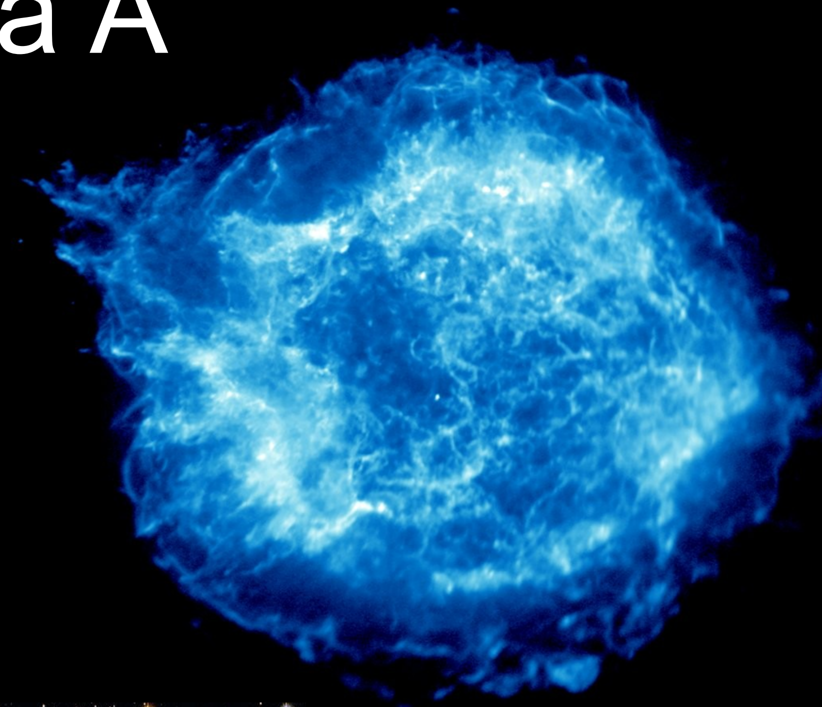
Hubble Heritage

PRC99-04 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

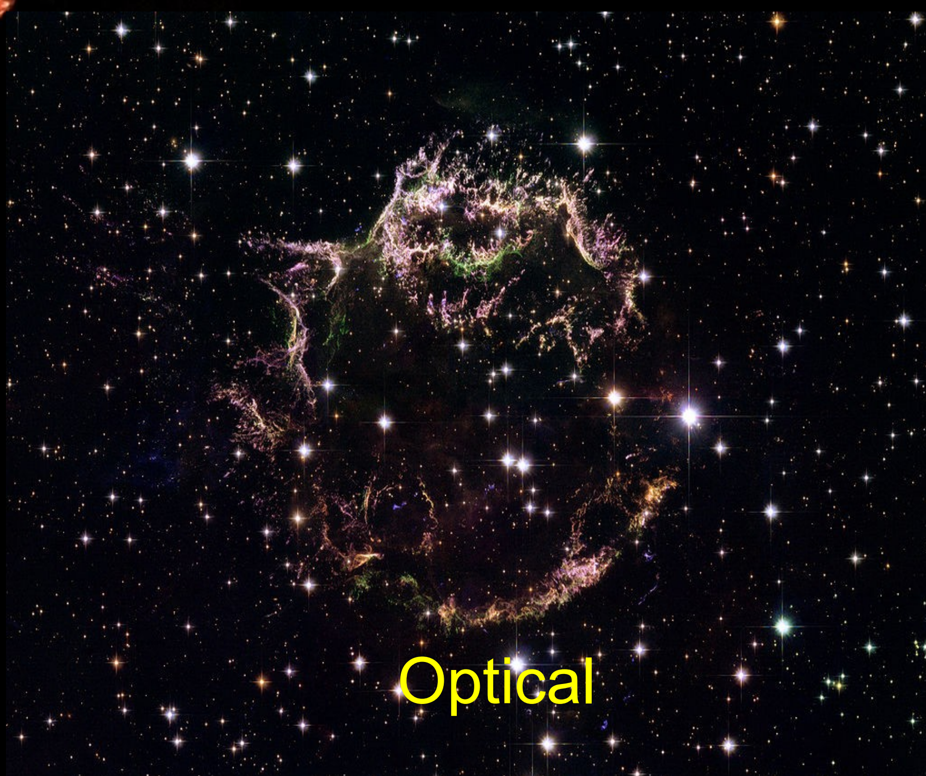
Cassiopeia A



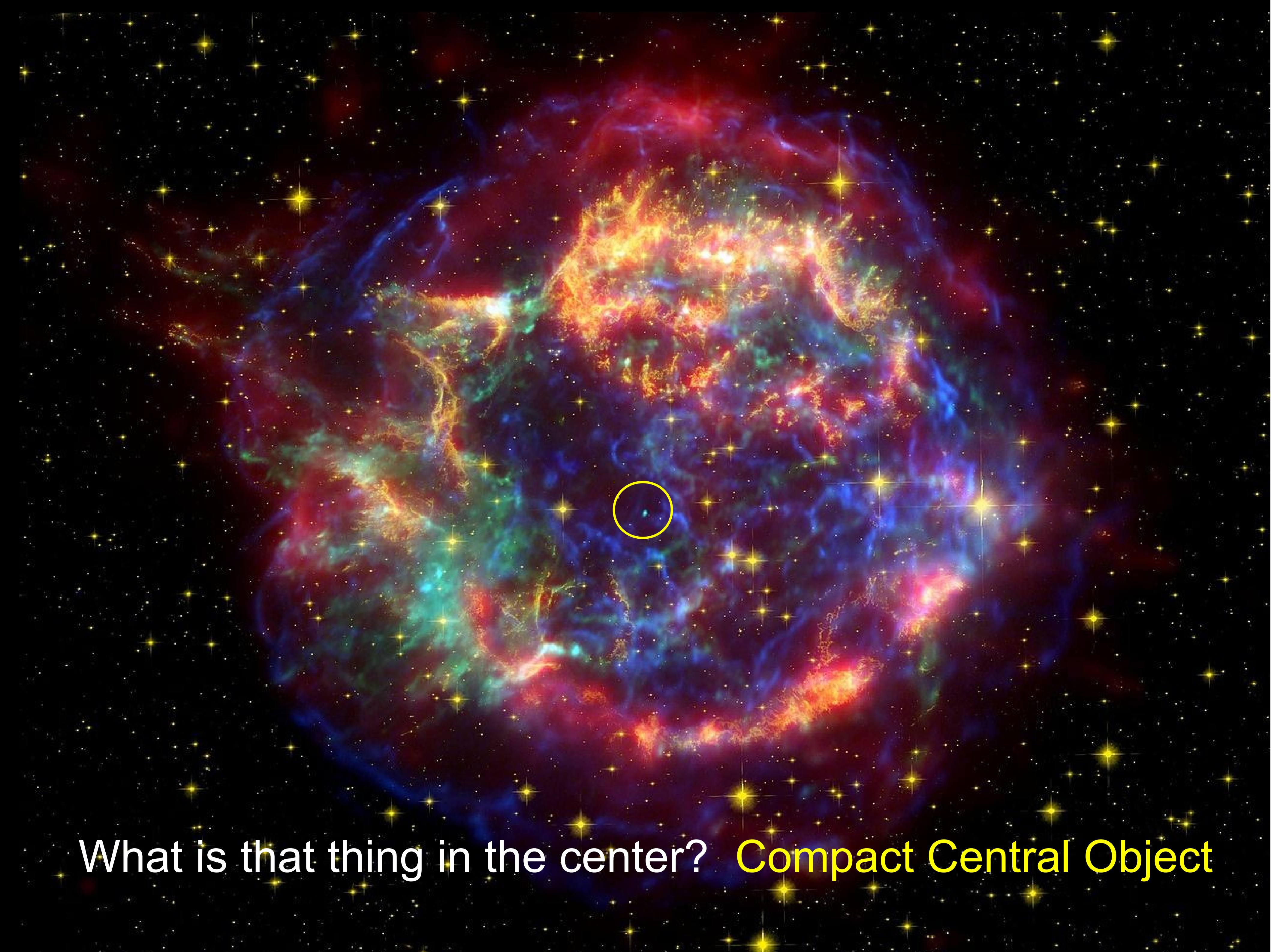
Radio



X-ray



Optical



What is that thing in the center? Compact Central Object

SNR Kes 73

Strange 12-sec X-ray pulsar…

Magnetar!

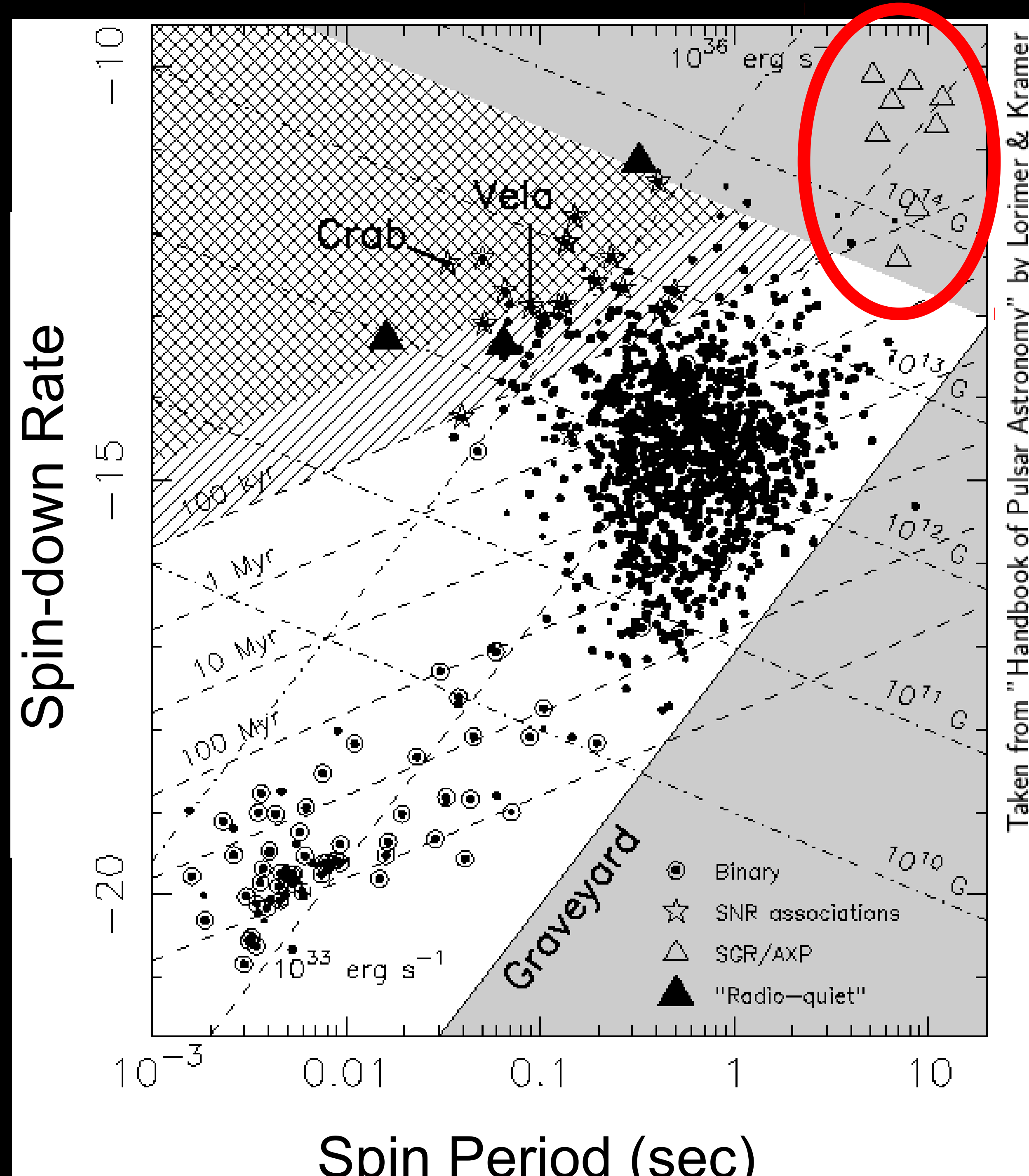
What's a Magnetar?

Neutron stars with extremely strong magnetic fields:

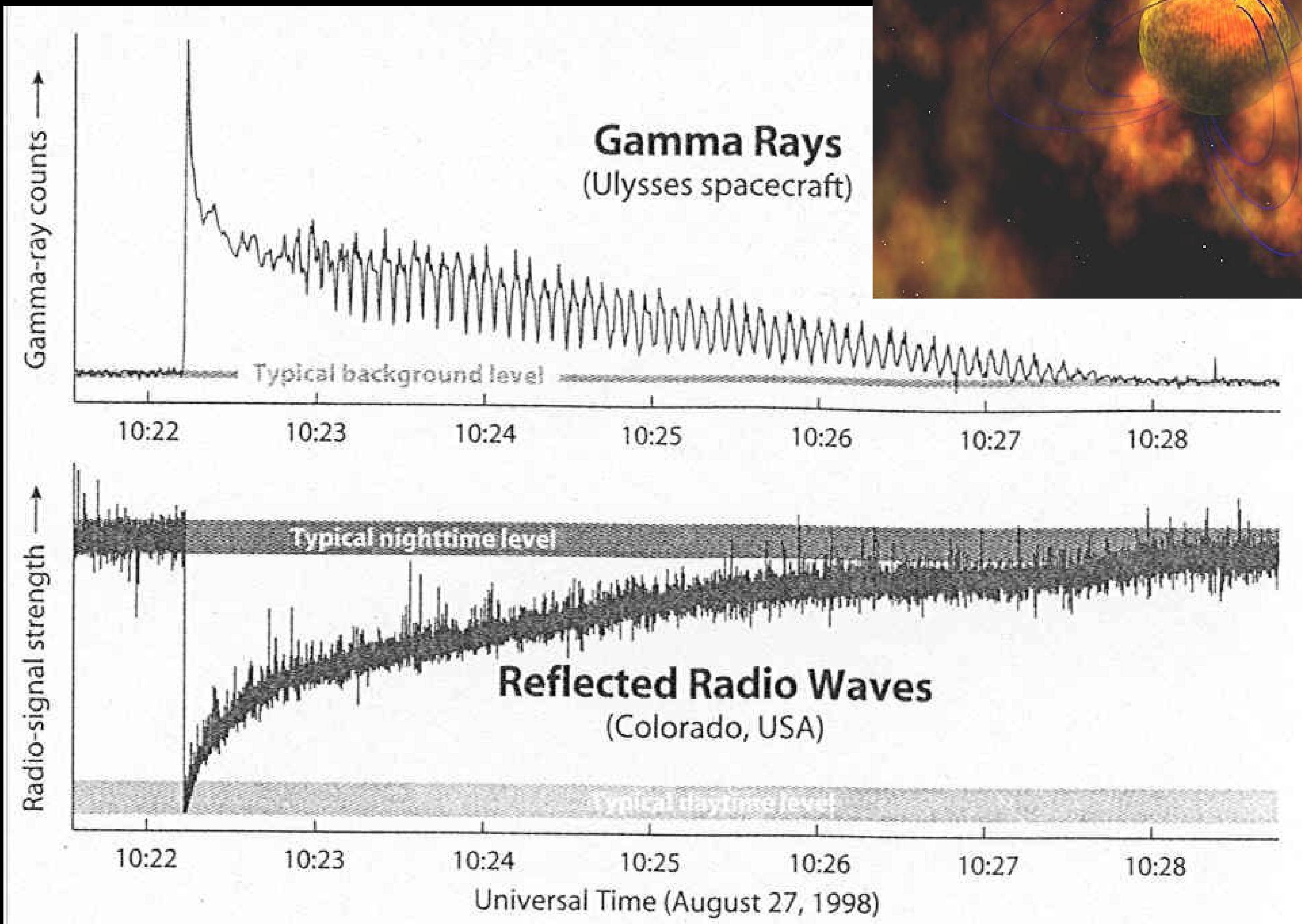
10^{14-15} Gauss

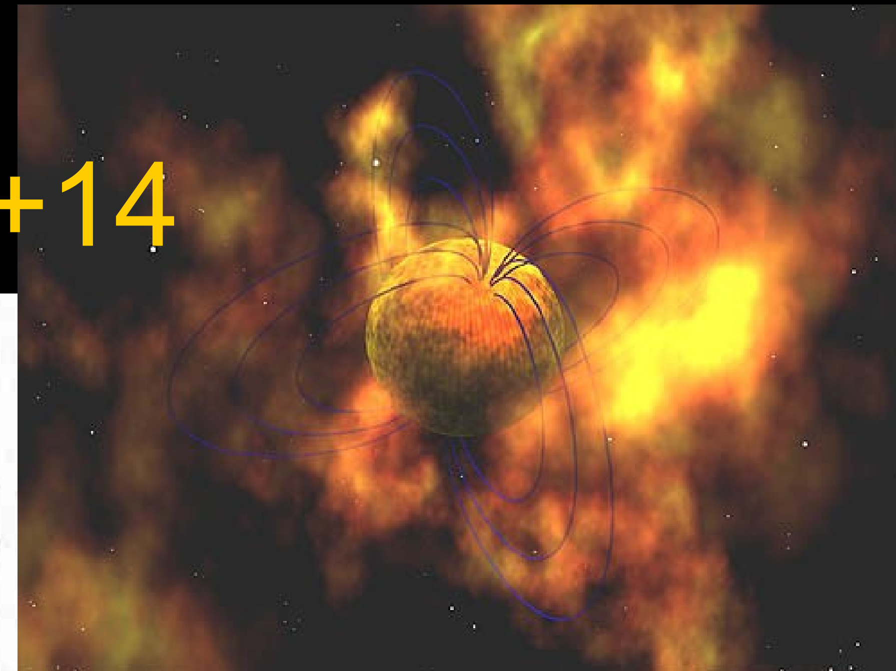
(~1000x stronger than normal PSRs)

Powered by decay of magnetic field, not rotation!



Giant X-ray Flares: Magnetar SGR 1900+14





Pulsar Flavors

Young PSRs
(high B, fast spin, very energetic)

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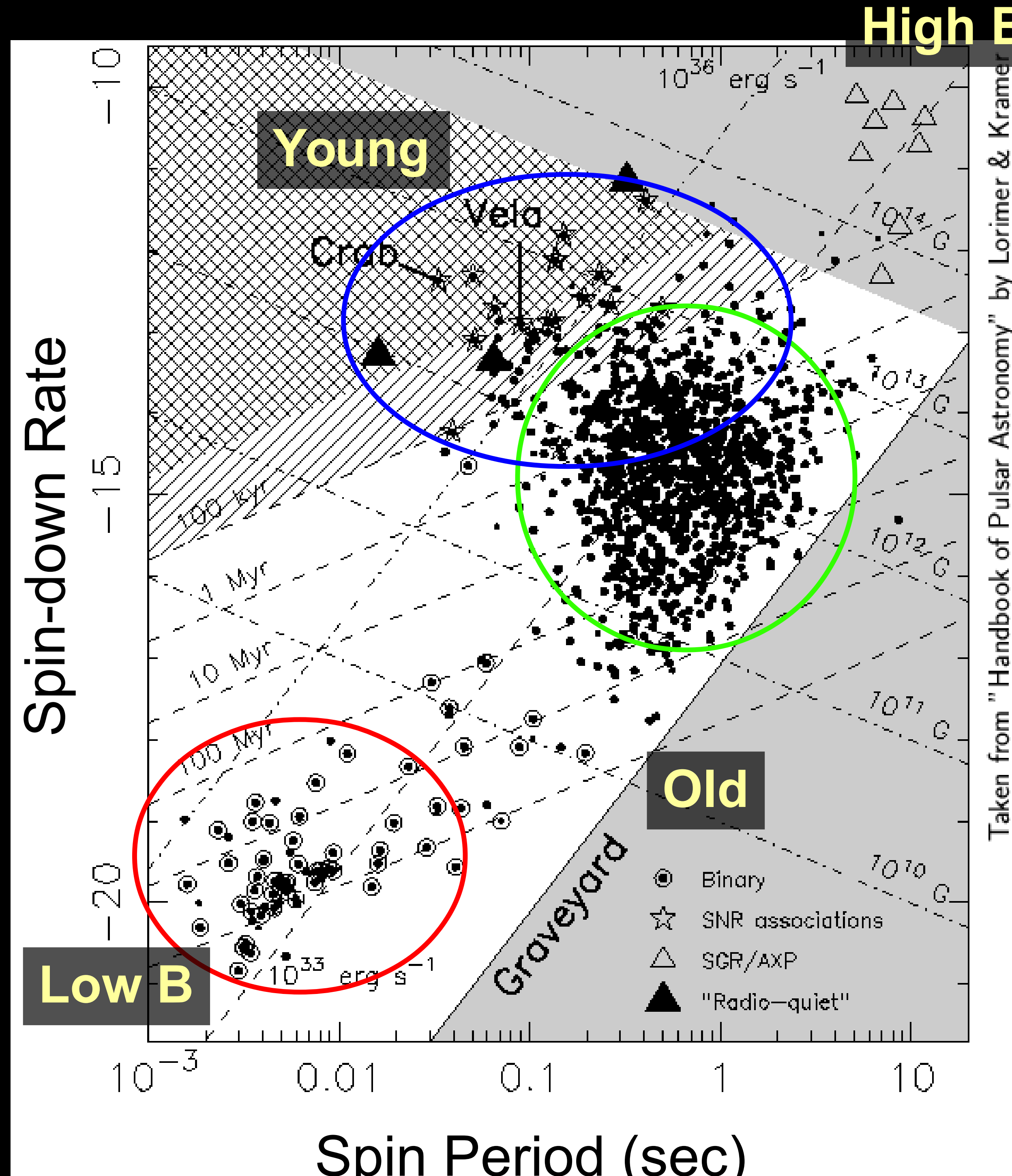
(average B, slow spin)

Millisecond PSRs
(low B, very fast, very old, very stable spin, best for basic physics tests)



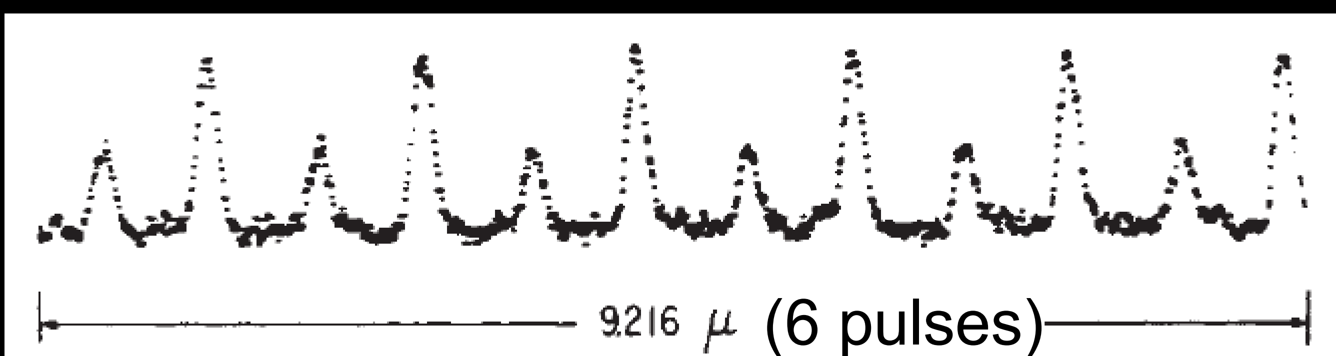
1982:

A millisecond pulsar

Nature Vol. 300 16 December 1982

D. C. Backer*, Shrinivas R. Kulkarni*, Carl Heiles*, M. M. Davis† & W. M. Goss‡

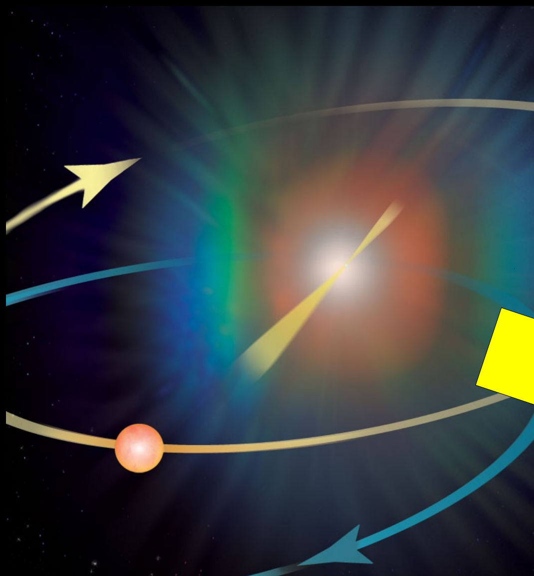
1.558 ms pulsar (640 Hz)!



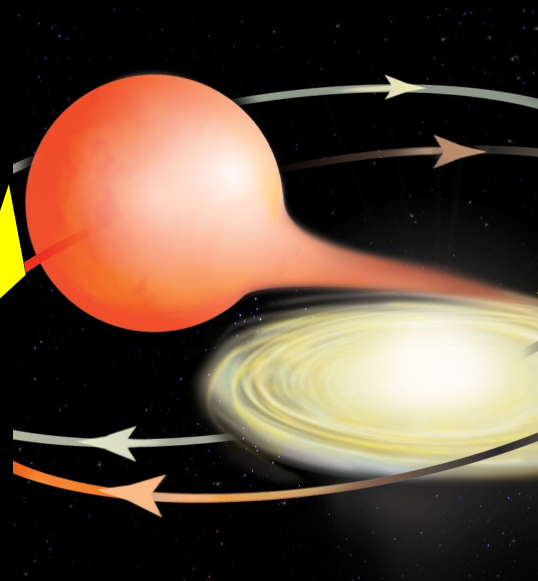

Courtesy Bob Rood

21x faster than Crab!
~half an octave above “Concert A”!

Millisecond Pulsars: via “Recycling”



Supernova produces a neutron star



Red Giant transfers matter to neutron star

Millisecond Pulsar emerges with a white dwarf companion

Picture credits: Bill Saxton, NRAO/AUI/NSF

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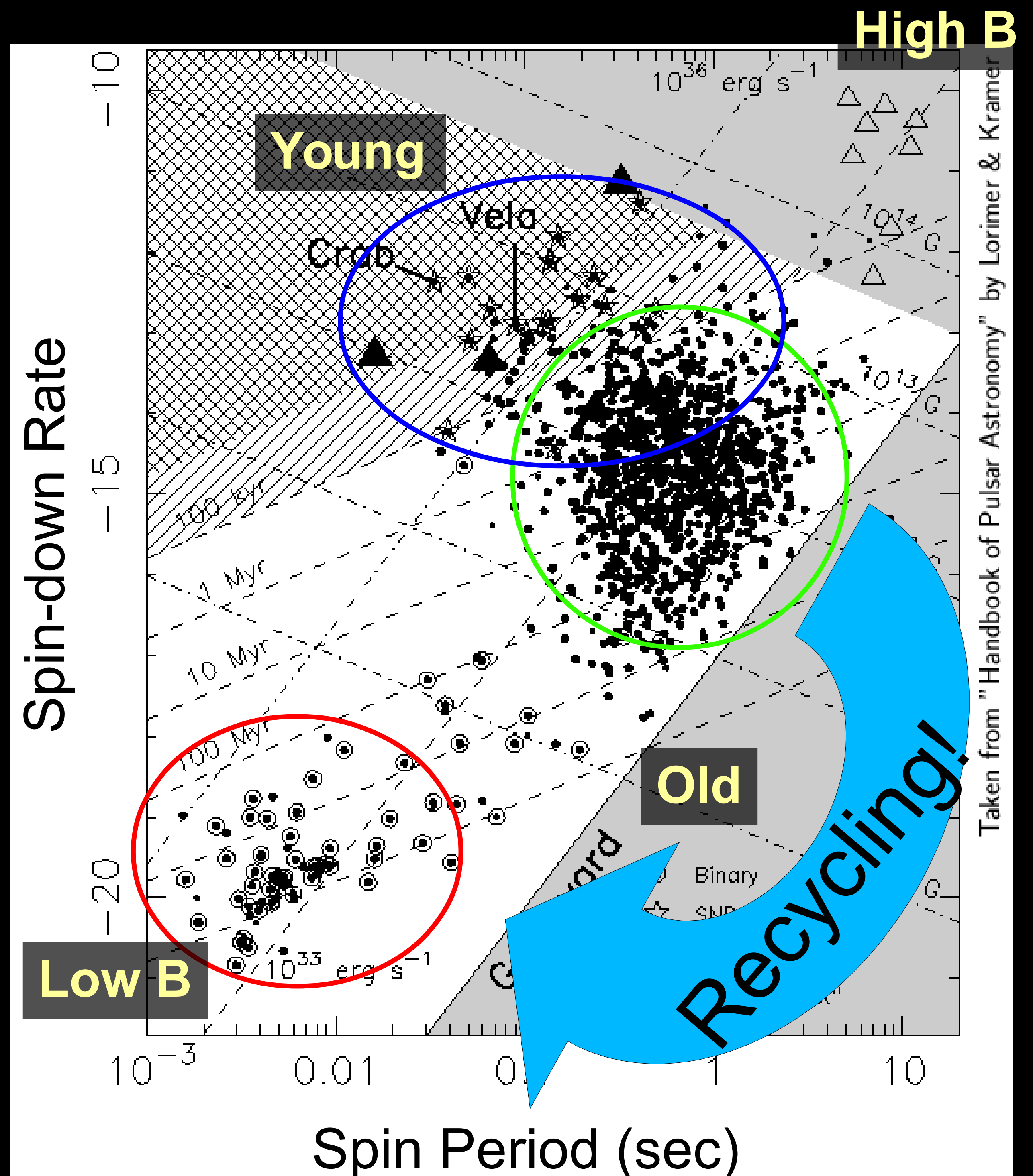

Pulsar Flavors

Young PSRs
(high B, fast spin, very energetic)

No
(a
slow spin)

Millisecond PSRs
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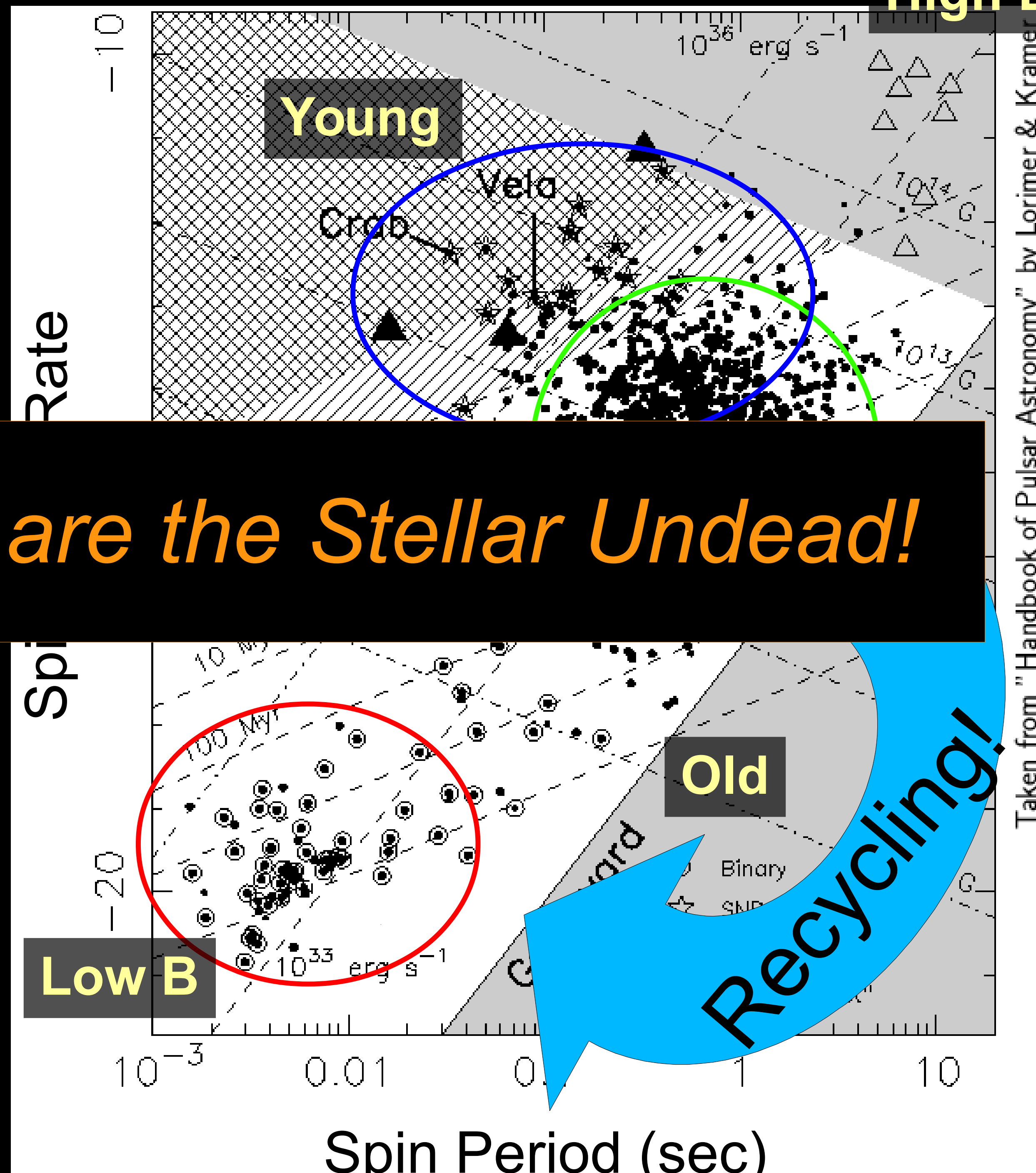
They really are the Stellar Undead!



Pulsars are Precise Clocks

PSR J0437-4715

At 7:30 EDT April 17 2014:

P = 5.7574519479244 ms

+/- 0.0000000000001ms

Pulsars are Precise Clocks

PSR J0437-4715

At 7:30 EDT April 17 2014:

P = 5.7574519479244 ms

+/- 0.0000000000001ms

The last digit changes by 1 every half hour!

Pulsars are Precise Clocks

PSR J0437-4715

At 7:30 EDT April 17 2014:

P = 5.7574519479244 ms

+/- 0.000000000000001ms

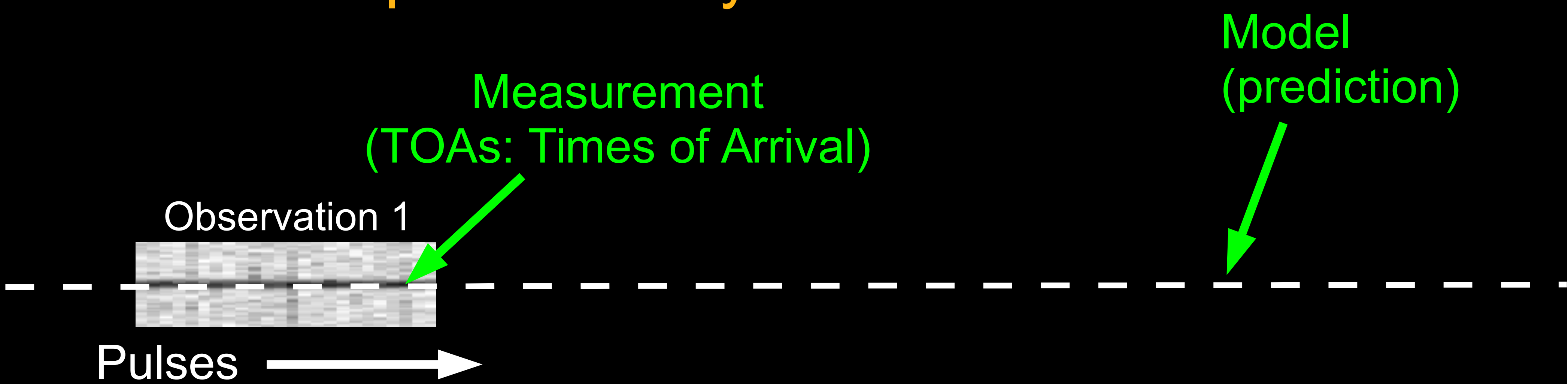
The last digit changes by 1 every half hour!

This digit changes by 1 every 500 years!

This extreme precision is what allows us to ***use pulsars as tools*** to do unique physics!

Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



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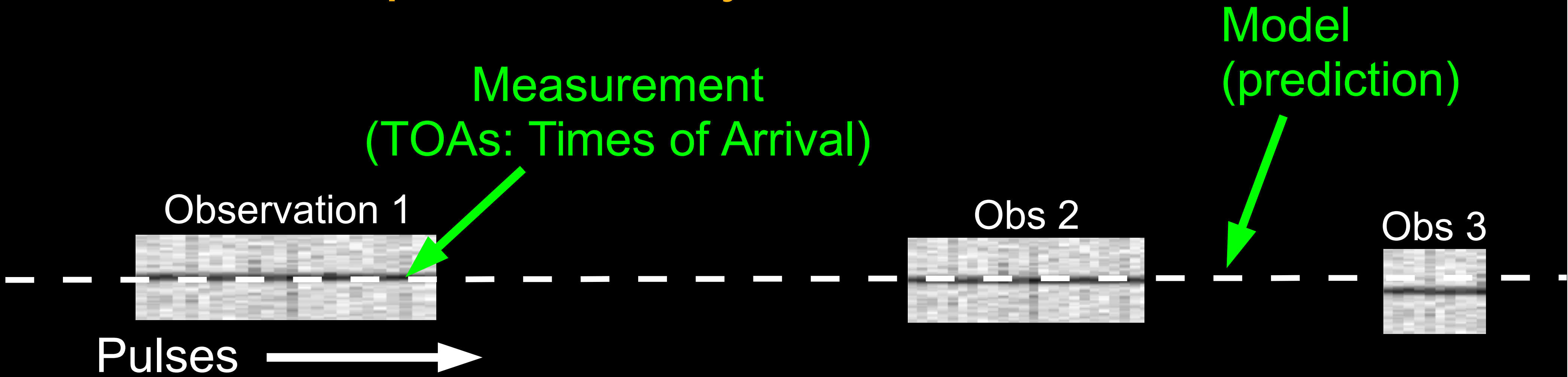

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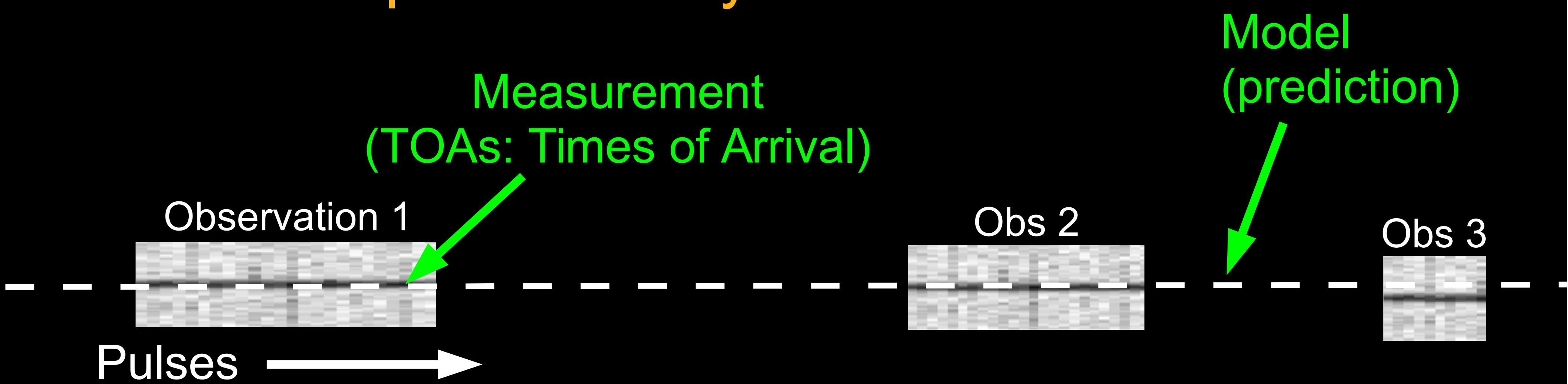
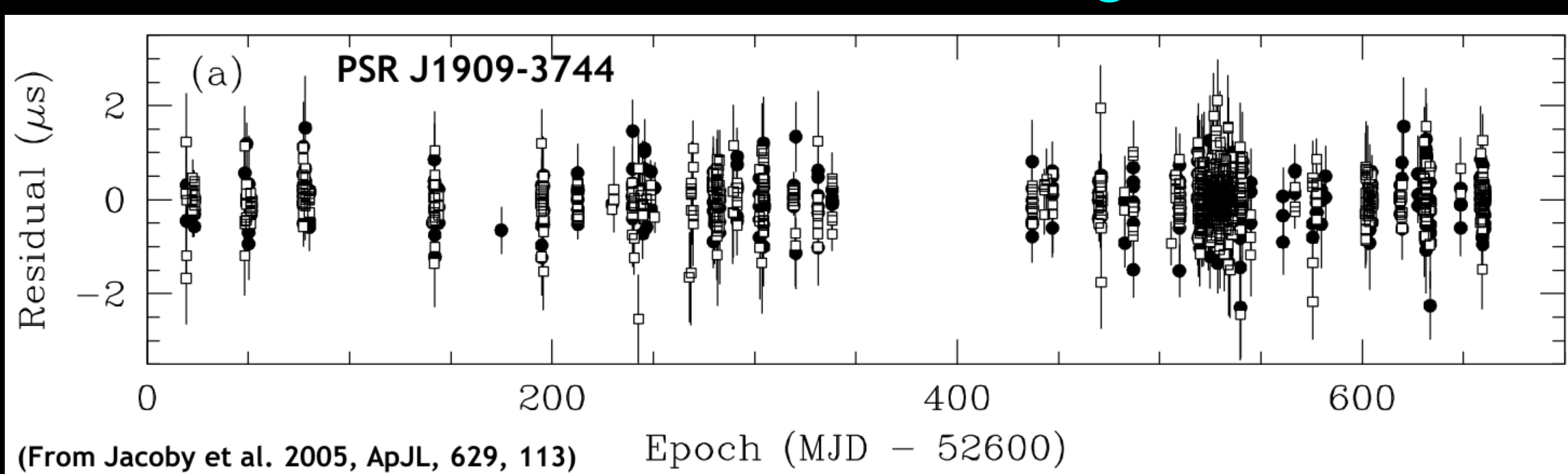


Measurement - Model = Timing Residuals



Predict each pulse to 200 ns over 2 yrs!

Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000) ...	$04^h37^m15^s.7865145(7)$
Declination, δ (J2000)	$-47°15'08''.461584(8)$
μ_α (mas yr^{-1})	121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_b (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_0 (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_2 ($M_\odot$) ...	0.236(17)
$\dot{P}_b$(10^{-12})	3.64(20)
$\dot{\omega}$ (° yr^{-1})	0.016(10)

Party Trick!

Orbit has a radius of about
1.44x the Sun's radius (~10^{11} cm)...

	meters
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1.44x the Sun's radius (~10^{11} cm)...

But it is so circular, and measured so precisely that the difference between semi-major and semi-minor axes is *18.59 +/- 0.01 cm*!

...meters	
	...7865145(7)
	...7461584(8)
	...121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annua...	
Pulse...	
Refere...	
Period...	
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Green Bank Telescope
(Green Bank, WV)

The US has
the best pulsar
telescopes in
the world!

Arecibo Telescope
(Puerto Rico)

The Binary Pulsar: B1913+16

First binary pulsar discovered at Arecibo Observatory by Hulse and Taylor in 1974

NS-NS Binary

P_{psr} = 59.03 ms

P_{orb} = 7.752 hrs

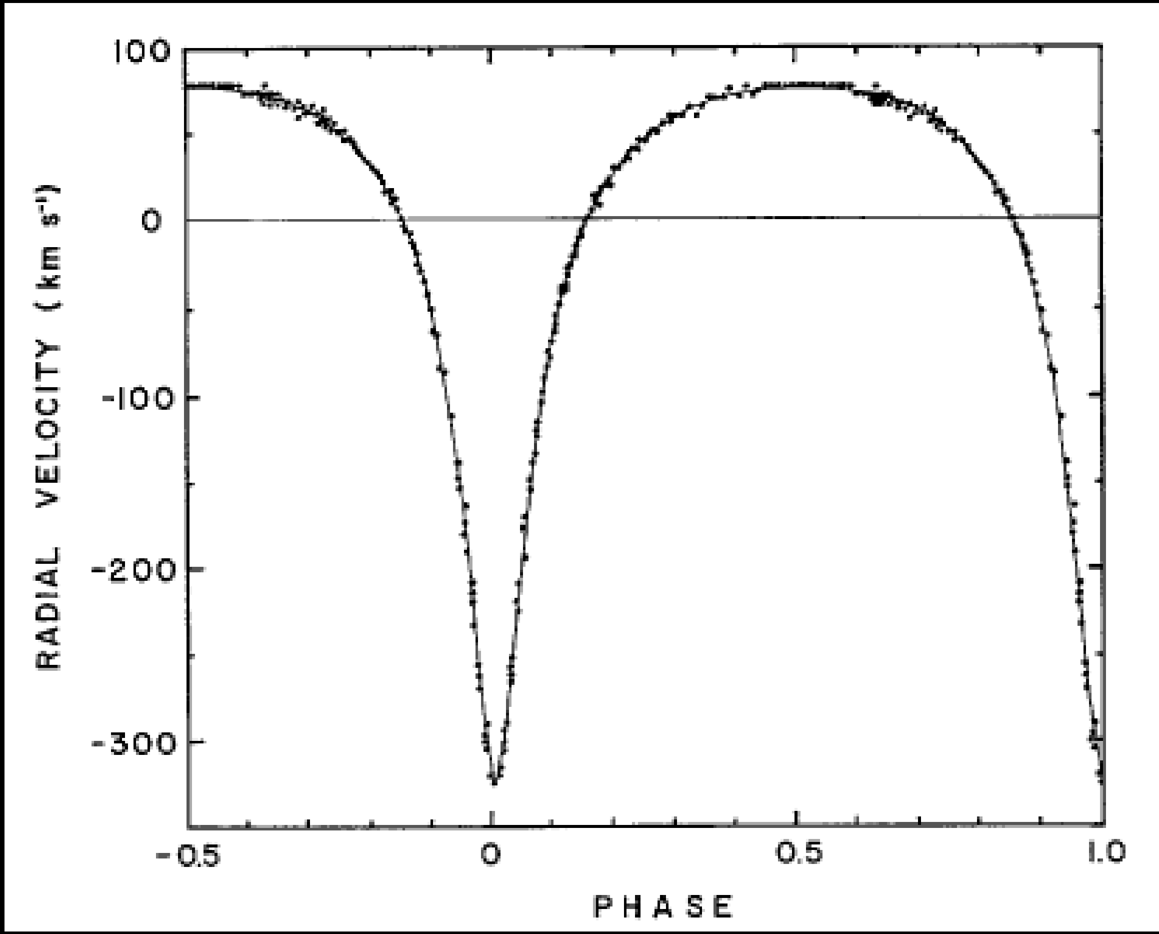
a sin(i)/c = 2.342 lt-s

e = 0.6171

$\dot{\omega}$ = 4.2 deg/yr

$M_c = 1.3874(7)\ M_\odot$

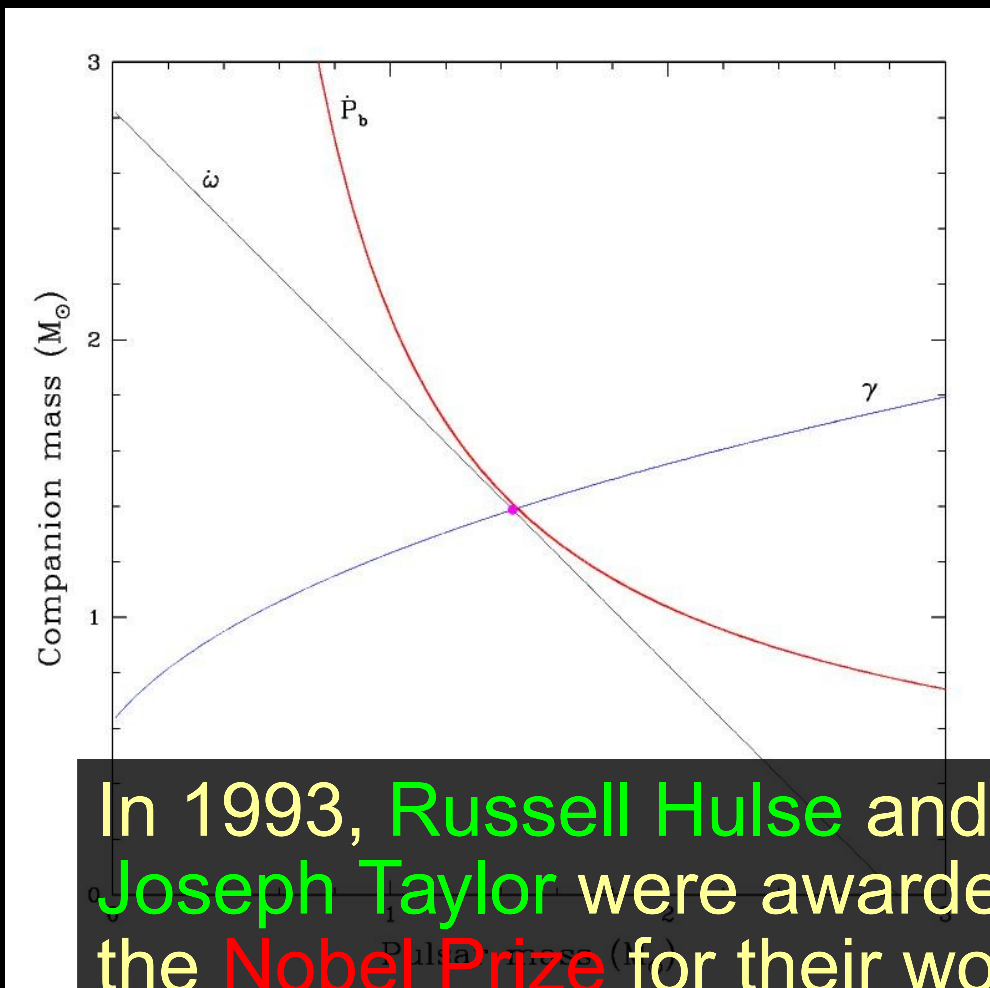
$M_p = 1.4411(7)\ M_\odot$



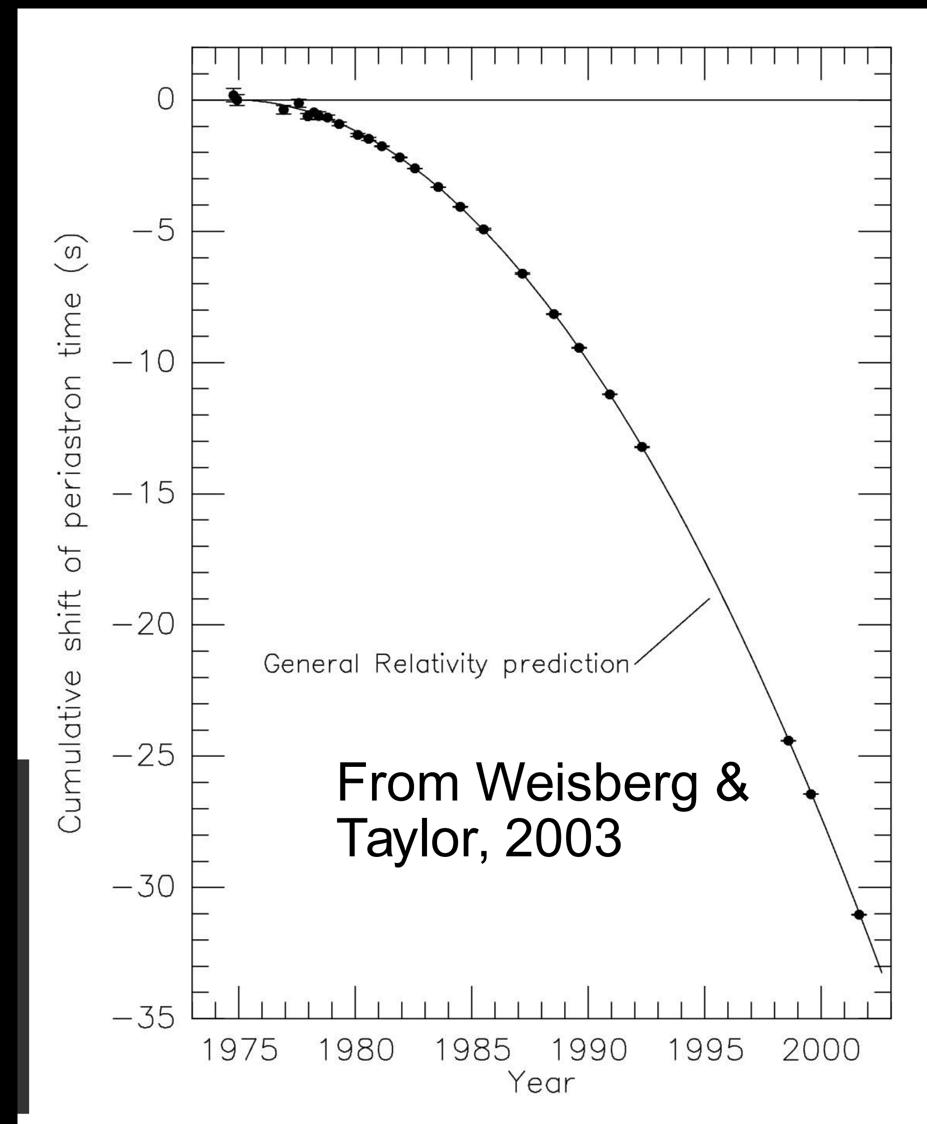
The Binary Pulsar: B1913+16

Three Relativistic Observables: $\dot{\omega}$, γ, $\dot{P}_{orb}$

Indirect detection of Gravitational Radiation



In 1993, Russell Hulse and Joseph Taylor were awarded the Nobel Prize for their work on PSR B1913+16!



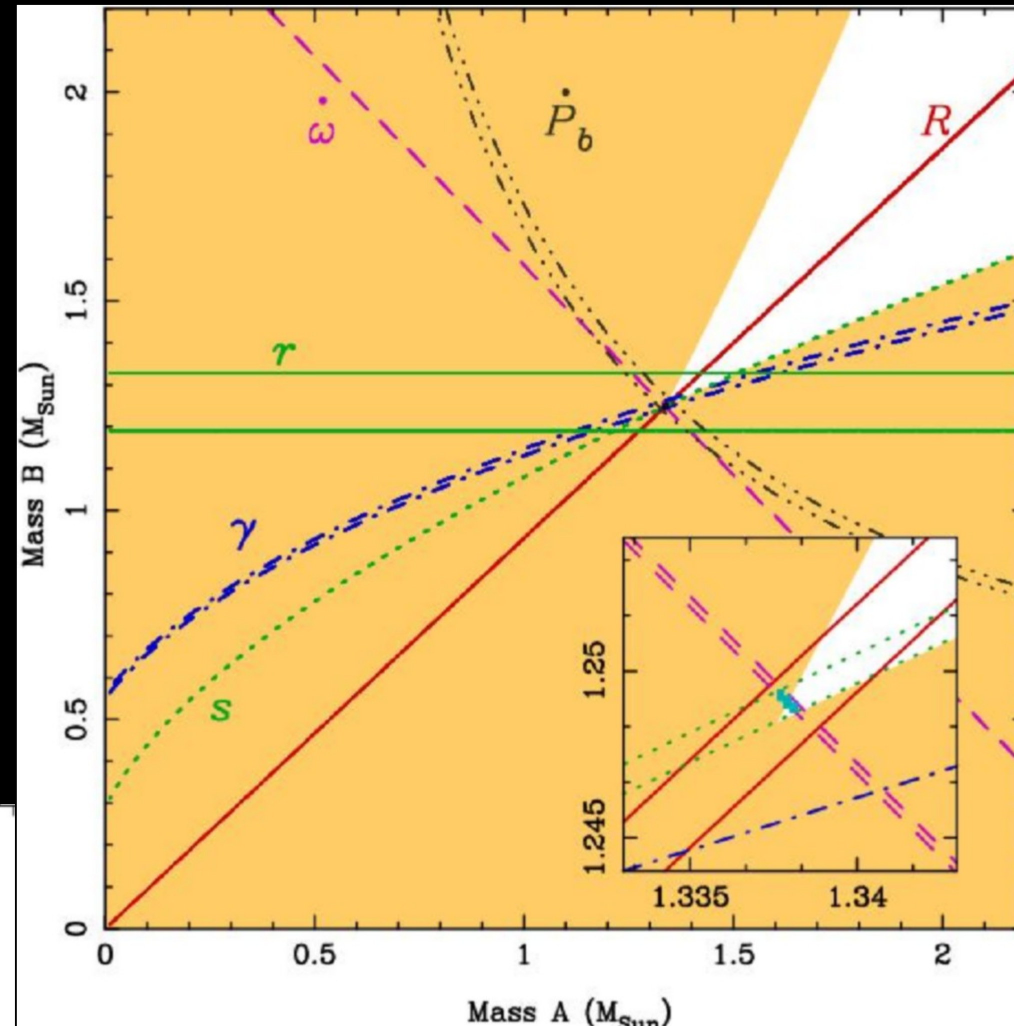
From Weisberg & Taylor, 2003

The Double Pulsar: J0737-3039

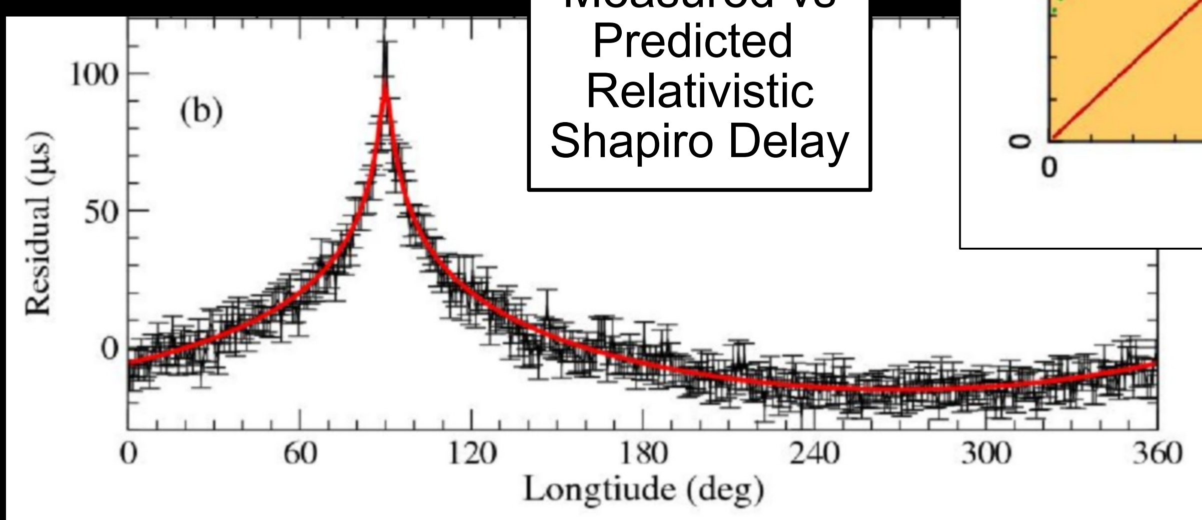
Faster spin, more compact orbit, edge on system, 6 relativistic observables, 2 pulsars!

Overall, much better than Hulse-Taylor binary PSR.

Currently GR tests to ~0.01%!

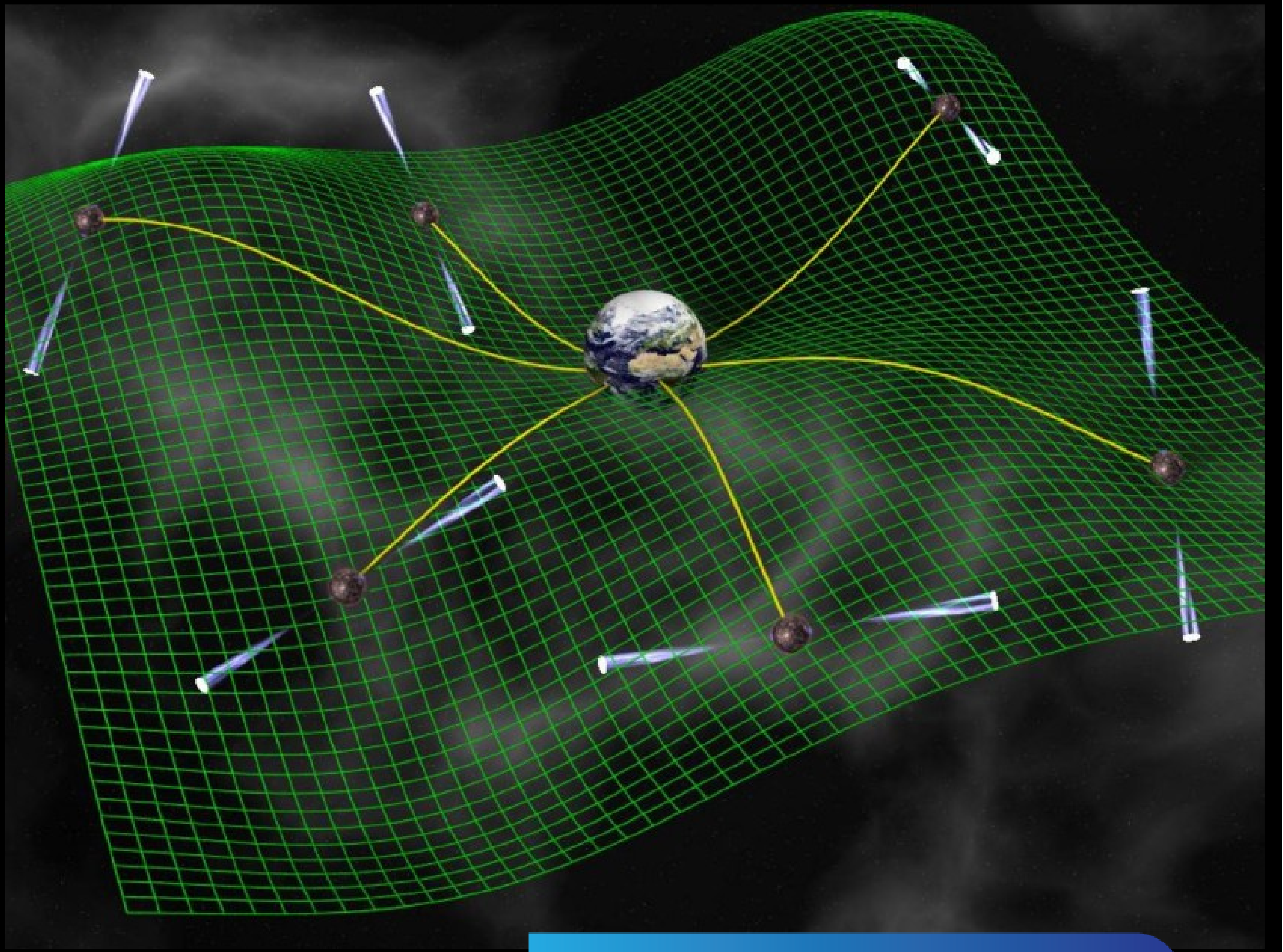


Measured vs Predicted Relativistic Shapiro Delay



Kramer et al., 2006, *Science*, 314, 97

Gravitational Wave Detection with a Pulsar Timing Array



- Looking for nHz freq gravitational waves from super massive black hole binaries
- Need really good MSPs
- Significance scales directly with the number of MSPs being timed.
- Must time the pulsars for 5-10 years at a precision of ~100 nanosec!
- North American (**NANOGrav**), European (EPTA), and Australian (PPTA) efforts

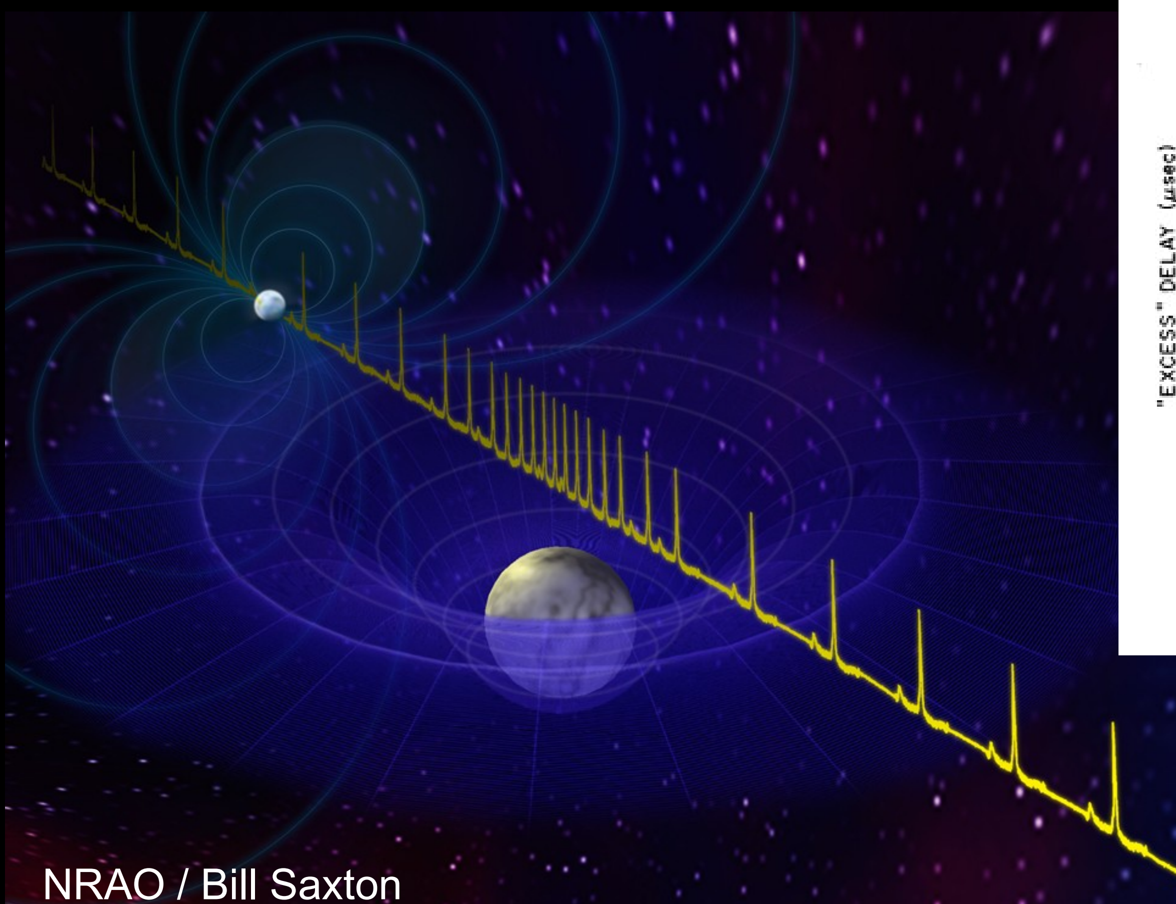
NANOGrav

Shapiro Delay

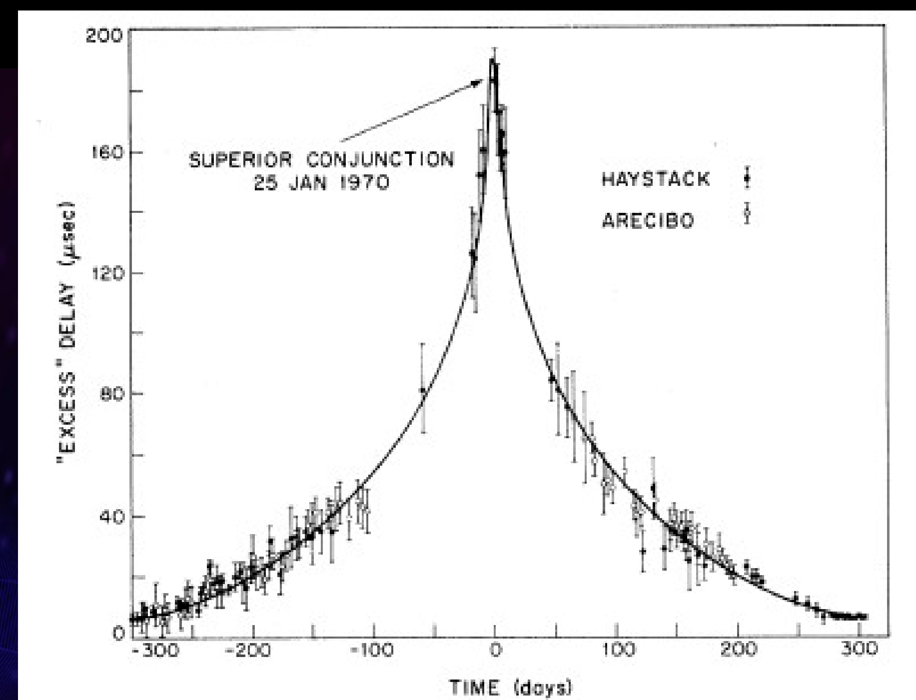
VOLUME 13, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1964

FOURTH TEST OF GENERAL RELATIVITY

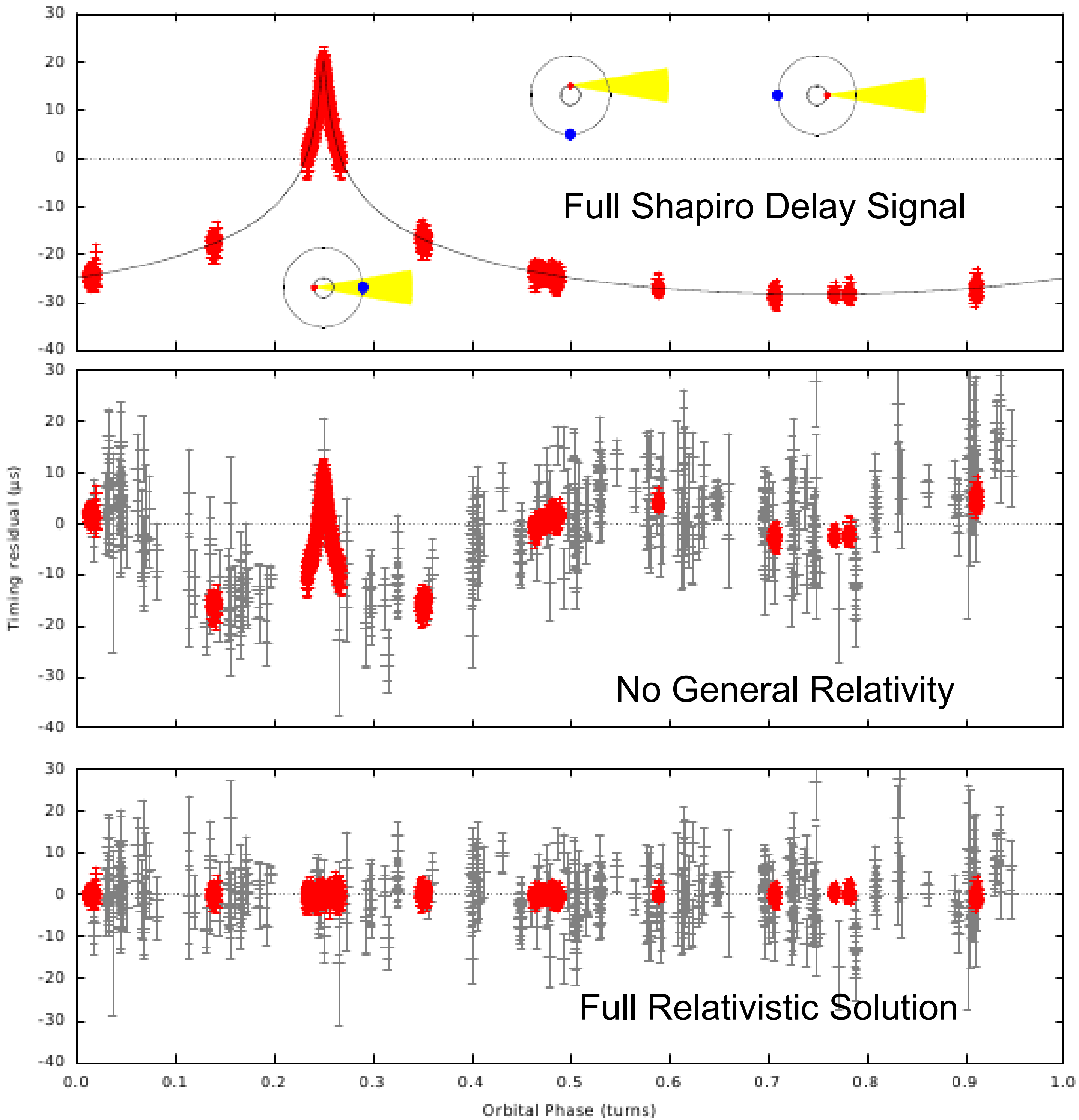
Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)

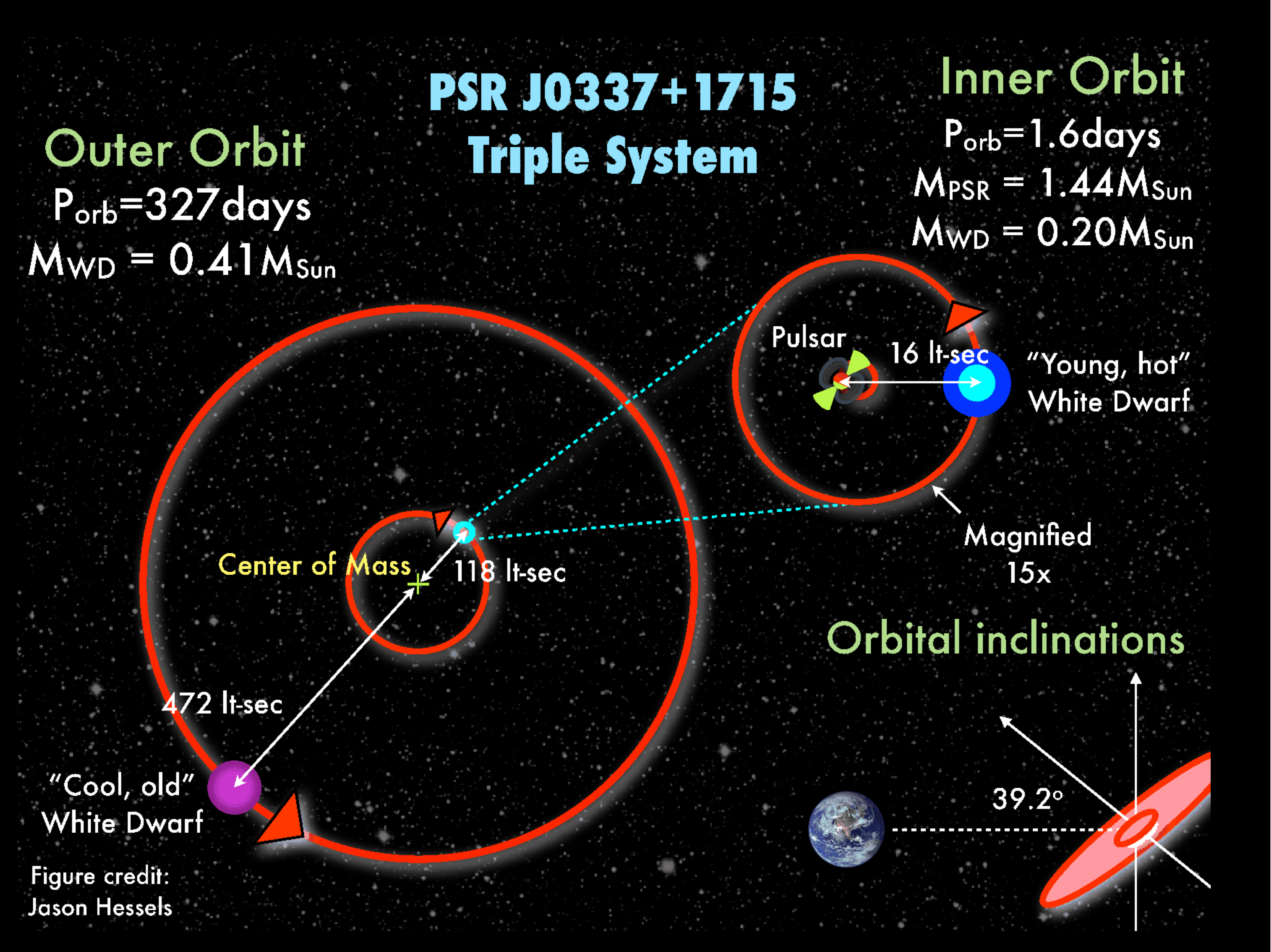


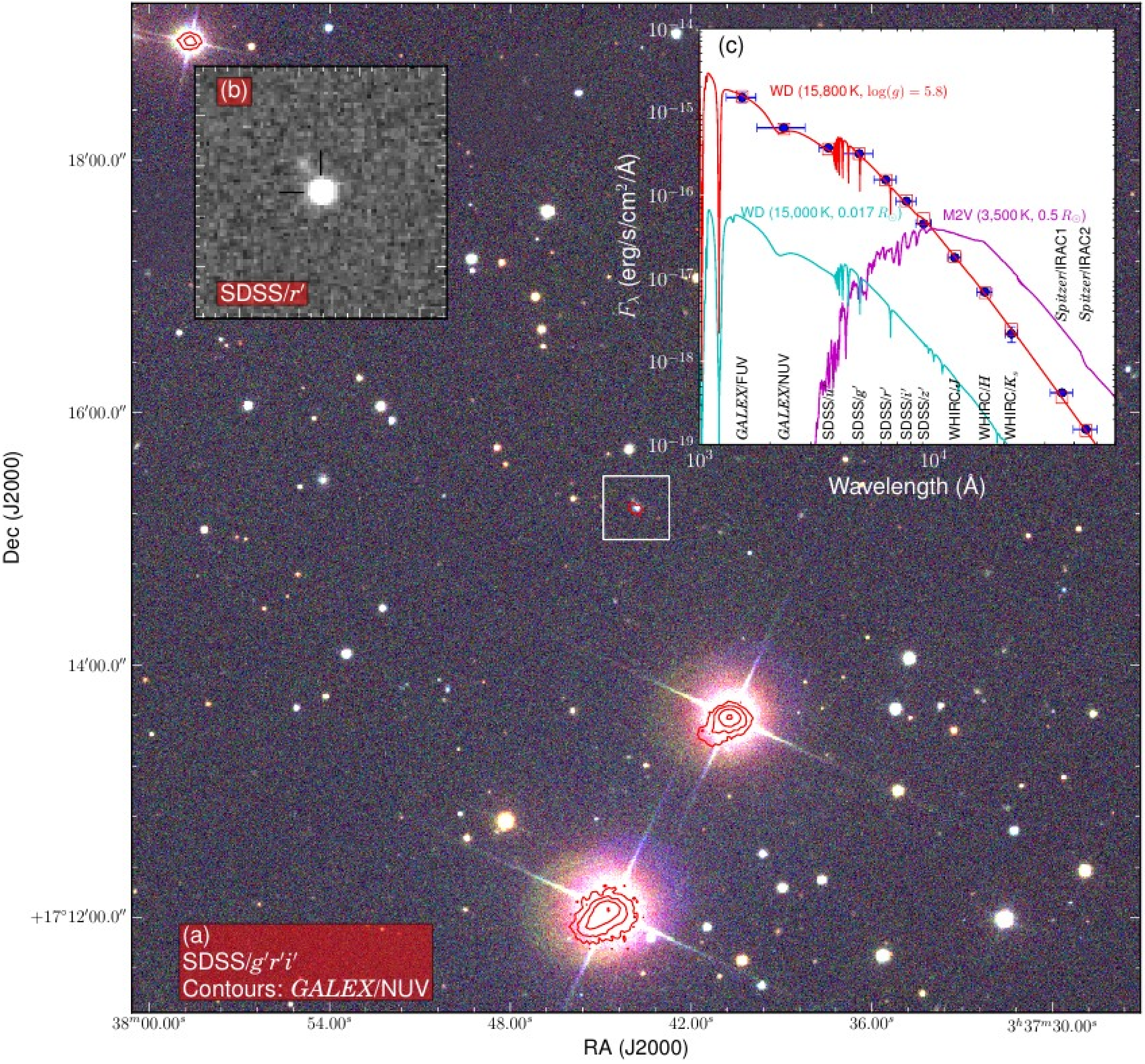
NRAO / Bill Saxton

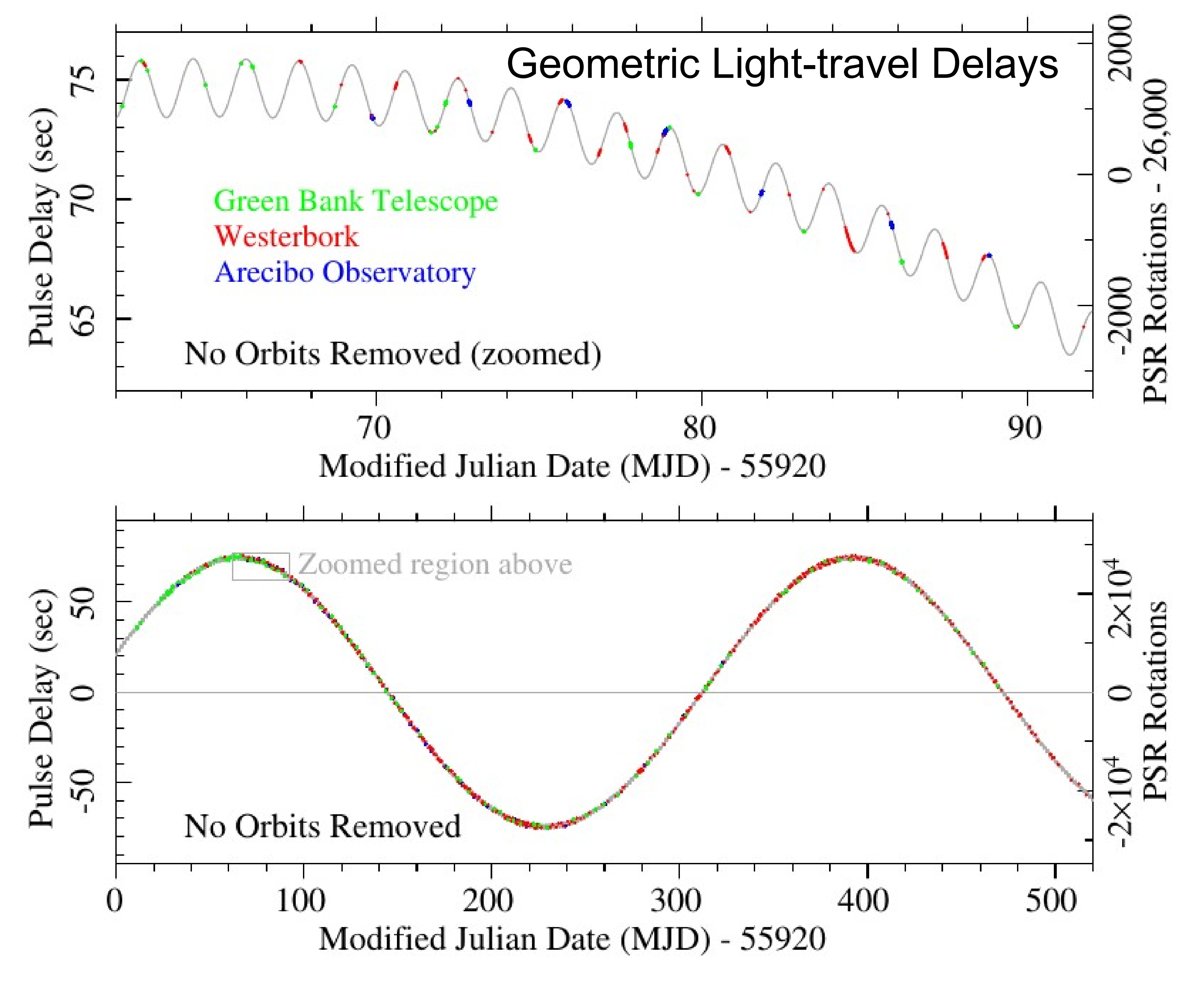


Irwin Shapiro 1964
Shapiro et al. 1968, 1971


Full Shapiro Delay Signal
No General Relativity
Full Relativistic Solution
Timing residual (μs)
Orbital Phase (turns)


PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels


(a)
SDSS/$g'r'i'$
Contours: $GALEX$/NUV
(b)
SDSS/r'
(c)
WD (15,800 K, $\log(g) = 5.8$)
WD (15,000 K, 0.017 $R_\odot$)
M2V (3,500 K, 0.5 $R_\odot$)
F_λ (erg/s/cm^2/Å)
Wavelength (Å)
$GALEX$/FUV
$GALEX$/NUV
SDSS/u'
SDSS/g'
SDSS/r'
SDSS/i'
SDSS/z'
WHIRC/J
WHIRC/H
WHIRC/K_s
$Spitzer$/IRAC1
$Spitzer$/IRAC2
Dec (J2000)
RA (J2000)
18′00.0″
16′00.0″
14′00.0″
+17°12′00.0″
38^{m}00.00^s
54.00^s
48.00^s
42.00^s
36.00^s
3^{h}37^{m}30.00^s


Geometric Light-travel Delays
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
Pulse Delay (sec)
PSR Rotations - 26,000
Modified Julian Date (MJD) - 55920
Zoomed region above
No Orbits Removed
Pulse Delay (sec)
PSR Rotations
Modified Julian Date (MJD) - 55920

What about the future?

- We only know of about 2000 out of 30,000+ pulsars in the Galaxy!
  - Many of them will be "Holy Grails"
    - Sub-MSP, PSR-Black Hole systems, MSP-MSP binary
- Several new huge telescopes... eventually Square Kilometer Array

The stellar undead are amazing.

(and I work on this stuff everyday!)