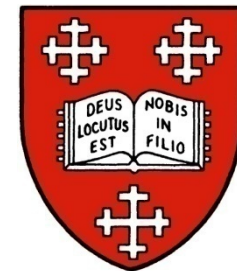


What pulsars have done to (and for) physics

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Topics

- Introduction to pulsars (aka neutron stars)
- Pulsars and gravity
- Pulsars and gravitational radiation
- Structure and mass of neutron stars
- Pulsars and the equivalence principle



INTRODUCTION TO PULSARS (PULSATING RADIO SOURCES)

Stellar evolution - formation

Pleiades or Seven Sisters



Stars 10 – 30 times solar mass (e.g. Pleiades, Betelgeuse);
sequence of exothermic fusion reactions in core,
ending with Fe-Ni core.

Large Magellanic Cloud – SN1987a

Fe – Ni is *endothermic*.
Core collapses; outer 90 – 95% of star ejected;
'supernova' explosion

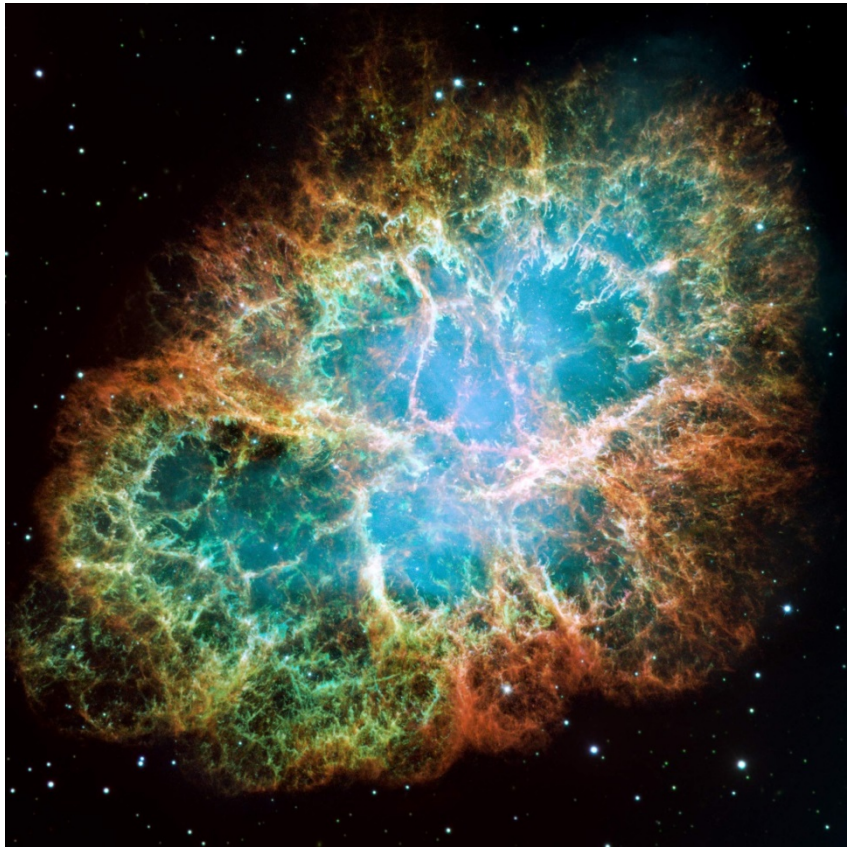


Before



After

Crab Nebula ~ 1000 yrs after SN



- Collapsed core is a neutron star or pulsar
- This nebula emits synchrotron radiation – kept energised by pulsar in its centre

INTRODUCTION TO PULSARS (PULSATING RADIO SOURCES)

Pulsar properties - overview

Overview

- Pulsars are small, very dense neutron-rich stars (neutron stars).
- Strong gravitational fields (and strong E and M fields); rapidly spinning.
- Probably formed in the explosion (supernova) that ends the life of a massive ($>10M_{\text{Sun}}$) star
- Primarily observed as pulsed, radio-emitting objects



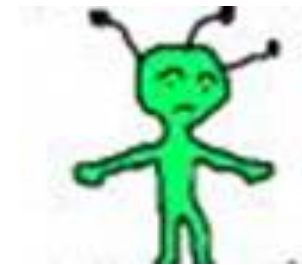
Properties of Pulsars 1

- Mass \approx few $\times 10^{27}$ tonnes (1.3 – 2 times mass of Sun)
- Radius ~ 10 km
- \therefore *average* density comparable with density of nucleus of an atom
- Strong surface gravity
- Tidal effects



Properties of Pulsars 2

- Bending of light – one can see over the horizon on a neutron star
- Red shift of light
- Time dilation– clocks tick two times slower than here on Earth



Properties of Pulsars 3

- Magnetic field of pulsar $\sim 10^8$ Tesla
(Frig magnet ~ 0.01 T, strong lab magnet ~ 10 T.)
- Voltage drops of up to 10^9 Volt/cm
- Extreme electro-magneto effects

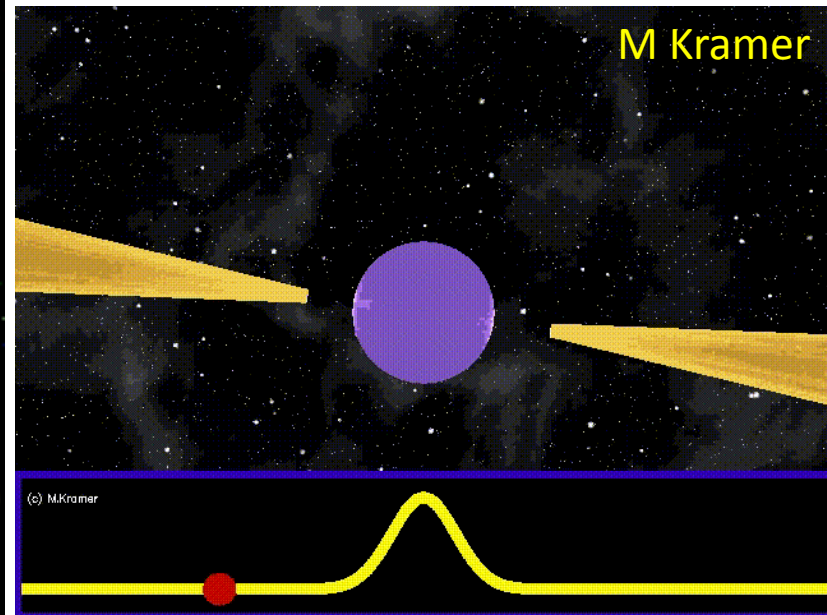
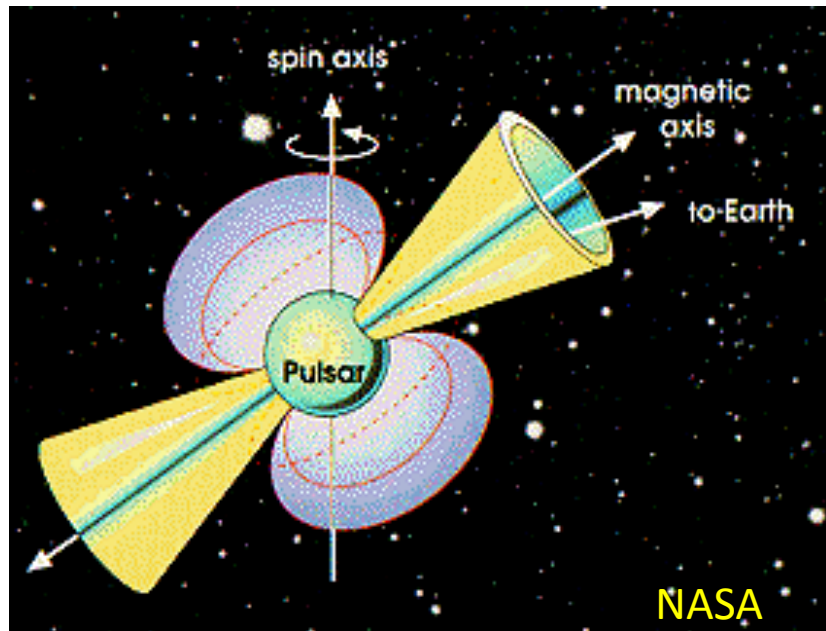


Properties of Pulsars 4

- All this rotates as a solid body
- Pulse period = rotation period
- Range observed $P = 1.4 \text{ ms}$ to $P = 10 \text{ s}$
- \therefore relativistic speeds



Pulsars (pulsating radio stars) model



- Star spins like a lighthouse, sweeping radio beam around the sky.
- We see a pulse each time beam sweeps across us.

Pulsars today

Pulsar population

- Seen in **RADIO**, (visible), X-rays and gamma rays
- About 2000+ known; ~20 visible; ~100 X-ray; ~100 gamma ray
- Of the 2000+; ~150 in binaries (one PSR-PSR); 1 triple system; a few with planets
- About 10^5 in the Galaxy



Pulsars and Gamma Rays



- Fermi satellite discovering pulsars that are barely or not seen in the radio but do give pulses in gamma rays.

Today – pulsar timing

- $10^{-12} > dP/dt > 10^{-21}$; comparable with best terrestrial clocks! Serve as clocks for **experimental relativity**.
- In spite of ‘timing noise’ (jitter, plasma turbulence, clock errors) for most stable can measure pulse arrival times to tens of ns.
- Through Doppler effect can measure radius of binary orbit to $5\mu\text{m}$.



PULSARS IN BINARY STAR SYSTEMS

Many examples of pulsar + 'ordinary' star

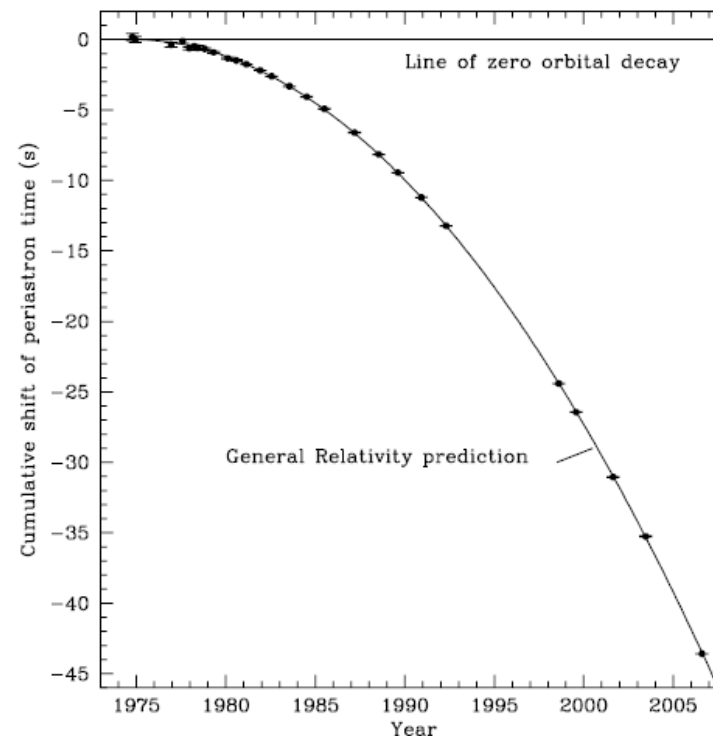
The binary pulsar – two neutron stars, one a pulsar

The double pulsar – two neutron stars, both pulsars

(Still no PSR – Black Hole binaries discovered)

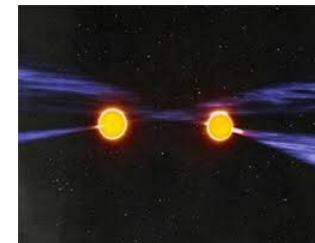
First detected binary system: evidence for the existence of gravitational radiation

- Hulse and Taylor: 1974
- Binary pulsar – PSR B1913+16. A double neutron star system whose orbit decays by 3.5m/yr, due to the emission of gravitational radiation. Orbital decay consistent with the predictions of General Relativity to within 0.3% (2010 figure)



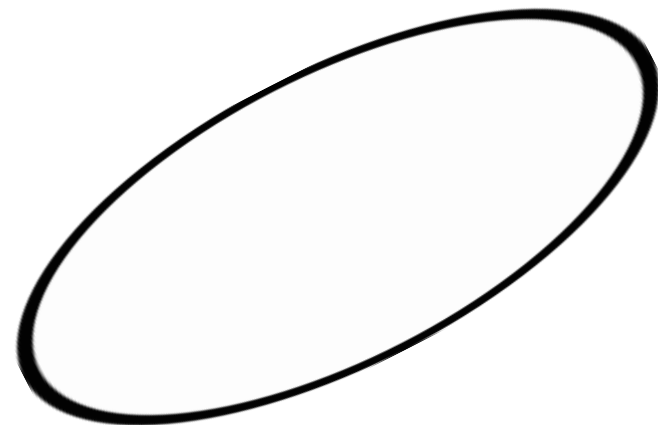
The Double Pulsar I

- Recently the first example of two pulsars orbiting each other has been discovered.
- Orbital period 2.4 hours (orbital diameter is half the Sun's diameter!) - relativistic
- The plane of the orbit is almost edge on, so we see eclipses of one pulsar by the magnetosphere of the other. ($\sin i \approx 1$)
- (The two pulsars have periods of 23ms and 2.8s)



Understanding Orbits

- Kepler showed us that to define an orbit we needed five parameters – the period, the length of the major axis, the eccentricity, and two quantities called the longitude and epoch of the periastron.



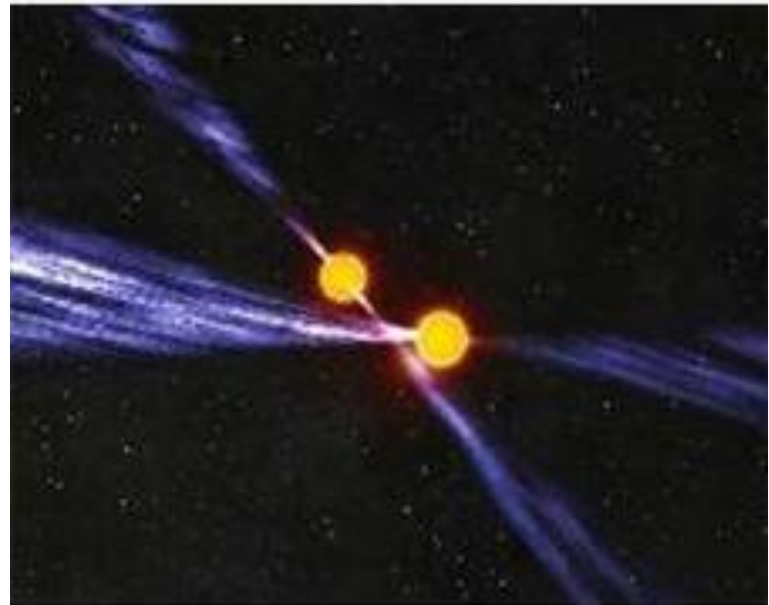
Understanding Orbits 2

- Relativity Theory showed that 5 *more* quantities are needed to explain orbits in extreme circumstances.
- They are: the advance of the periastron; the gravitational redshift; the change in the orbital period; and two quantities defining the 'Shapiro delay'. *Shapiro delay is temporal equivalent of bending of light by a massive body. $s = \sin i$.*



Close binary system

- The most relativistic system so far discovered
- This 'double pulsar' can be used to check out Einstein's theory of gravity in a strong field environment and (in time) exclude some other theories of gravity



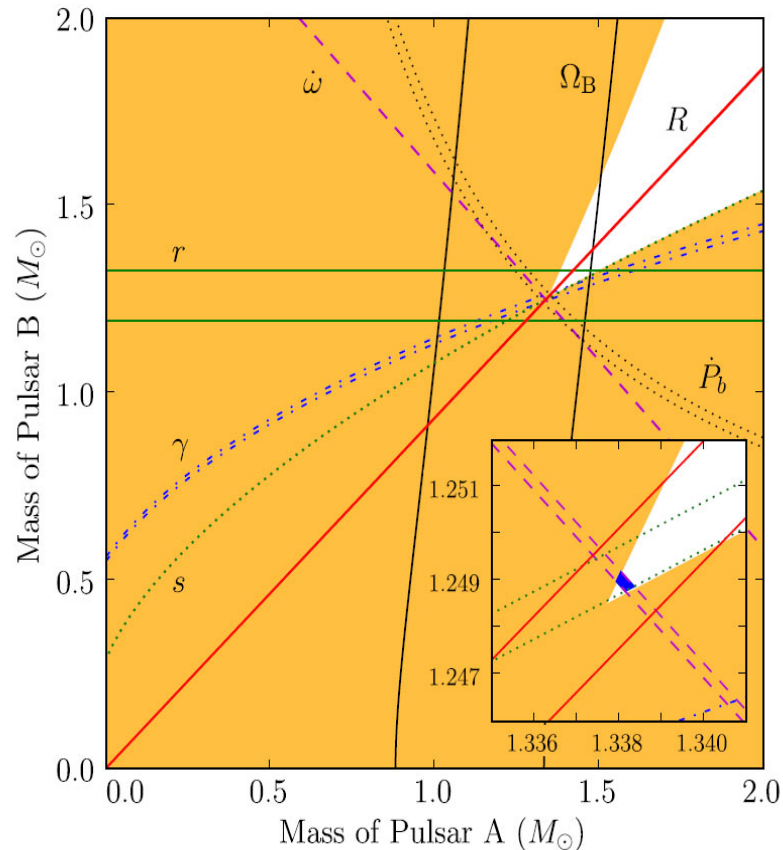
John Rowe

The Double Pulsar

- In the double pulsar the orbit is shrinking by $\sim 7\text{mm}$ per day.
- All 5 post-Keplerian parameters have been obtained; precession due to relativistic spin-orbit coupling has been measured; and determination of an independent value for the moment of inertia of a neutron star should follow soon.
- System is now over-constrained
 - 5 independent GR tests



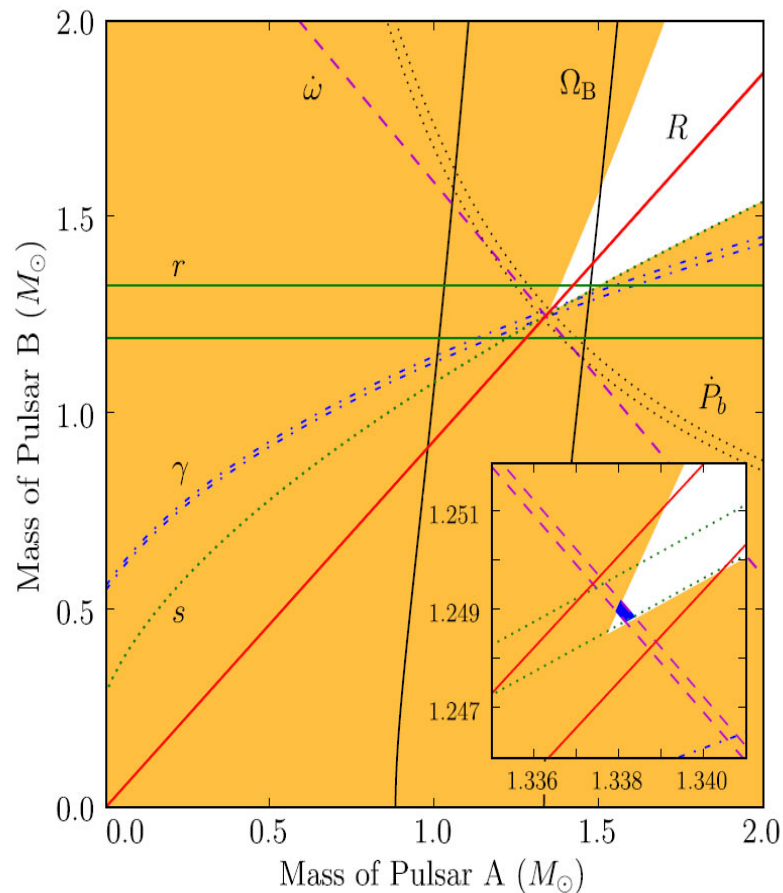
Mass-mass Plot



Bands are 68% confidence

- $\dot{\omega}$ = advance of periastron
- Υ = grav redshift
- dP_b/dt = change of orbital period
- R = ratio of masses
- Ω_B = precession rate of spin of PSR B
- r and s = Shapiro delay parameters

Testing General Relativity



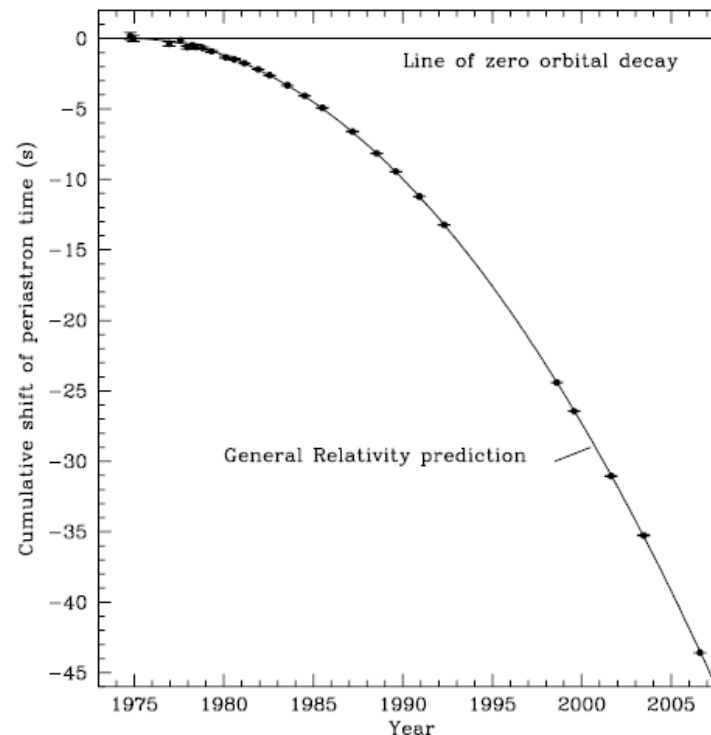
- If Einstein's theory of gravity correct then these parameters intersect at a point.
- Theory OK to within 0.02%; space for other theories significantly squeezed.
- See work of M Kramer (Bonn) et al

Searching for Gravitational Radiation

General Relativity predicts that where there is acceleration plus shape change gravitational radiation will be emitted.

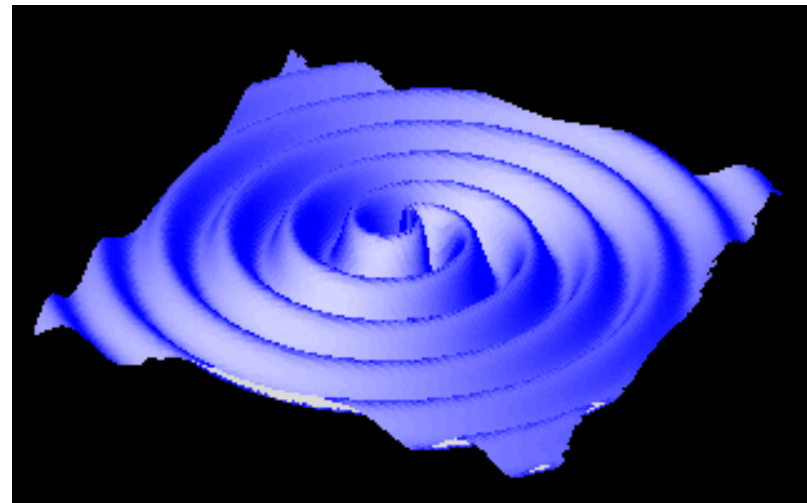
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What is Gravitational Radiation?

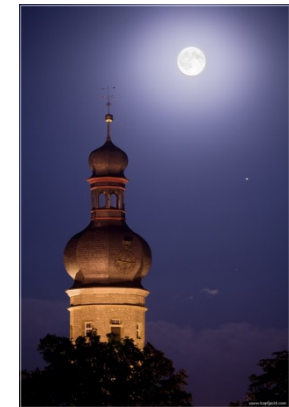
1. “Ripples in/of space-time”
2. Transverse waves
3. Travel at c ; carry energy, mom and ang mom.



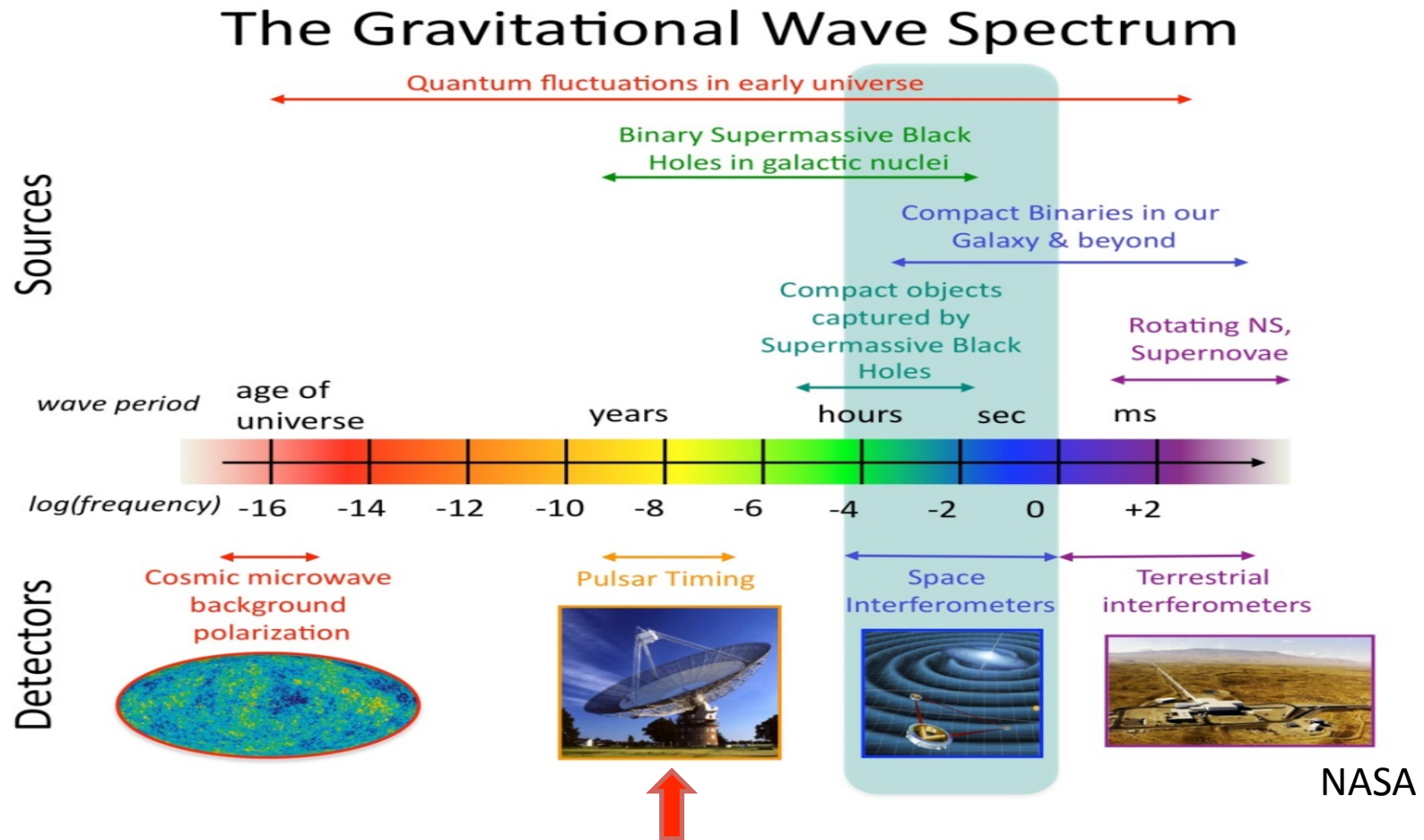
Wikimedia; simulation of merger of two neutron stars

Gravitational Radiation – the waves themselves 2

- Not absorbed or scattered
- Can be gravitationally lensed
- Amplitude goes as $1/d$
- Quadrupole
- According to GR no dipole component

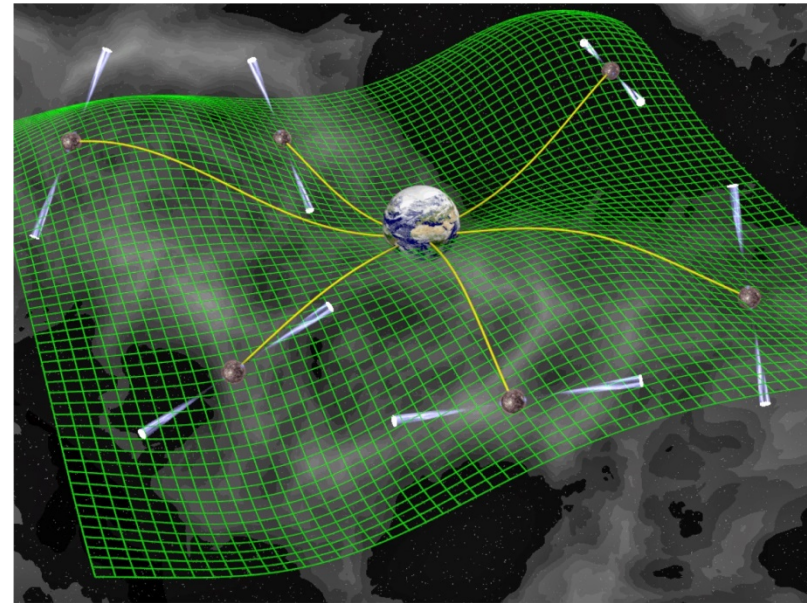


Sources - overview



Pulsar timing array

- Array of very stable pulsars continually monitored
- Gravitational radiation produces relative motion of earth cf pulsar array – Doppler shifts in P



MPI for Radio Astronomy

Limit from PSR timing array

- So far no detection, but interesting stochastic upper limit. 11 years' data.
- Suggests SMBH merger nos/theories wrong.
- Shannon et al., *Science*,
349, 1522 – 5, 2015



PULSAR MASS AND INTERIOR STRUCTURE

Sketch of structure

Pulsar/neutron star; surface to centre

- 10 -11 km journey, surface to centre;
- **ten-orders** increase in density – 10^7 kg/m^3 to 10^{18} kg/m^3 (several times nuclear density)
- Many models! For example -
 - a) surface, 10^7 kg/m^3 , thin, strong iron polymer
 - b) body-centred cubic lattice; high Fermi energy
 - c) high Fermi energy means beta decay prohibited; nuclei neutron enriched



VERY condensed matter physics contd

- d) further in, inverse beta decay allowed; nuclei become even fatter with excess neutrons
- e) at $4 \times 10^{14} \text{ kg/m}^3$ **neutron drip** out of nuclei
- f) superfluid neutrons and lattice
- g) superfluid rotation quantised – Feynman-Onsager vortices
- h) magnetic field in flux tubes – two kinds of ‘spaghetti’, crossing each other, + rapid rotn

Near centre of neutron star

- i) nuclear 'pasta' shapes (gnocchi, spaghetti, lasagna, Swiss cheese) just outside of nuclear density
- j) nuclear density $2 \times 10^{17} \text{kg/m}^3$
- k) inside nuclear density – lack of data!
 - quark-gluon plasma?
 - Mesons?
 - Bose-Einstein condensate?
 - ??????????



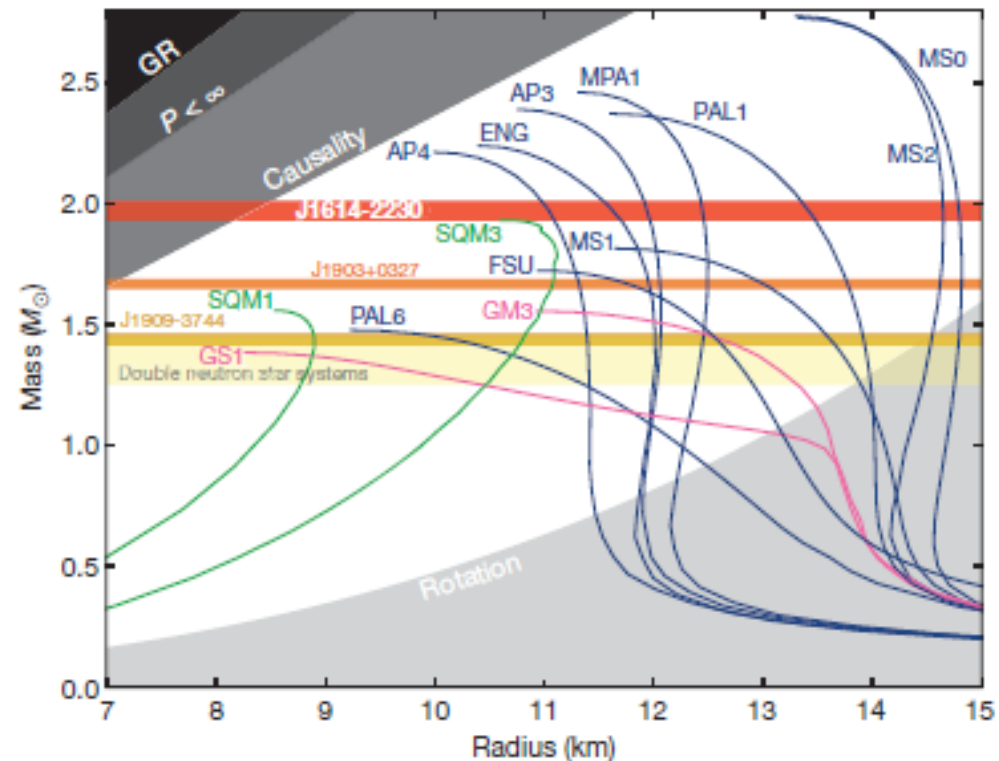
Large Mass Pulsars

- Can obtain the masses of a star in a relativistic binary
- Large mass pulsar discriminates between models for Equation of State
- Reaching several times nuclear density in core
- Now know of 2 pulsars with mass $\sim 2M$
- See also theoretical work of P Haensel (Warsaw) and J Stone (Oak Ridge National Lab).



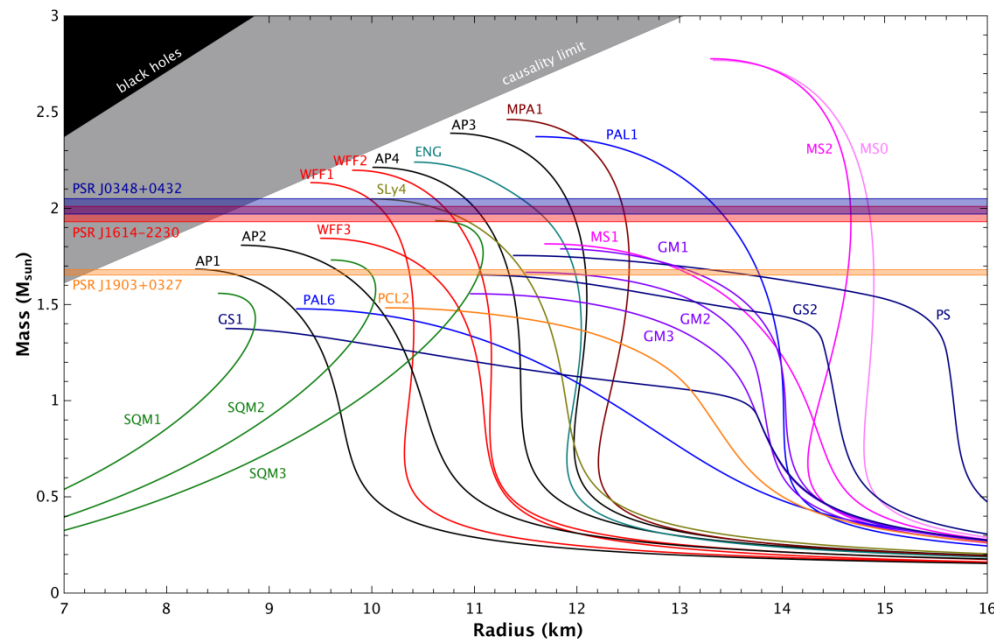
Pulsar mass $\sim 2M_{\text{sun}}$; constrains the equation of state

- Green – strange quarks
- Pink – nucleons + exotic
- Blue – nucleons



Demorest et al. Nature 467, 1081, 2010

Antoniadis et al, Science 340, 448, 2013



PSR 0348+0432; 2.4hr orbit;
WD companion. First massive
PSR in relativistic orbit.

- This PSR good test-bed for gravity – to search for scalar fields
- Had to consider dipolar GW (scalar-tensor theories). Watch evolution of orbit!

Testing **strong equivalence** principle

Equivalence principle (EP)

- Weak EP – objects of different composition and mass will have same acceleration due to gravity.
- Strong EP – in addition bodies with different self-gravity will have the same acceleration due to gravity - gravitational motion depends only on position and velocity. GR includes strong EP, but some theories of gravity do not.



Weak gravity test

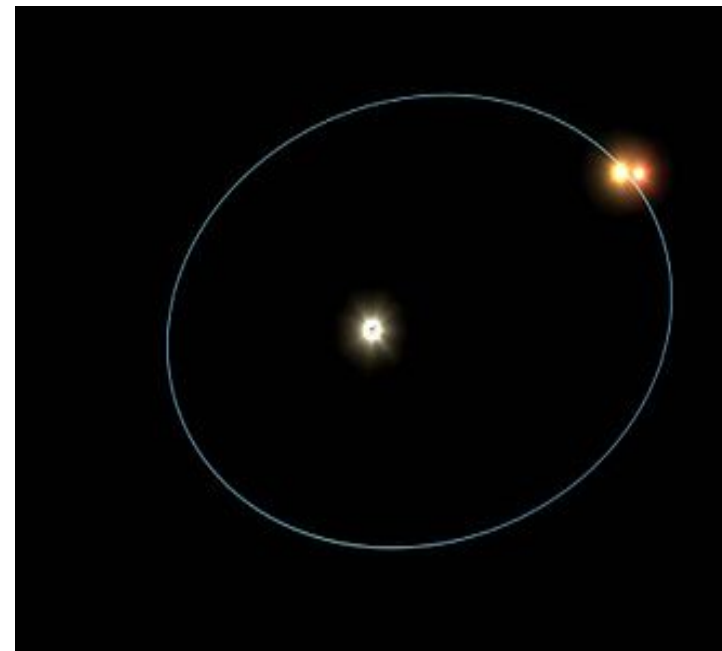
- Astronaut on moon dropping falcon's feather and hammer
- Also studied with solar system bodies
- Good to 1 part in 10^{14}



Repeat of Apollo 15 demo by astronaut Dave Scott

Pulsar triple system

- Pulsar orbiting a white dwarf star
- The pair orbiting another white dwarf star
- PSR self gravity \gg WD self gravity
- Do pulsar and its close companion star move the same way in the gravitational field of the other star?



What do we look for?

- If the pulsar and its companion fall at different rates the parameters of their binary orbit will change and the eccentricity will point toward the external field
- Work in progress – rumours! Watch this space!



Conclusions

- So far Einstein's theory has stood up to all the tests
- But pulsar astronomers not done yet!
- Problems with GR – singularities, and meshing GR with quantum physics
- Hunch that at some level the theory wrong/inadequate



The End

