Millisecond Pulsars

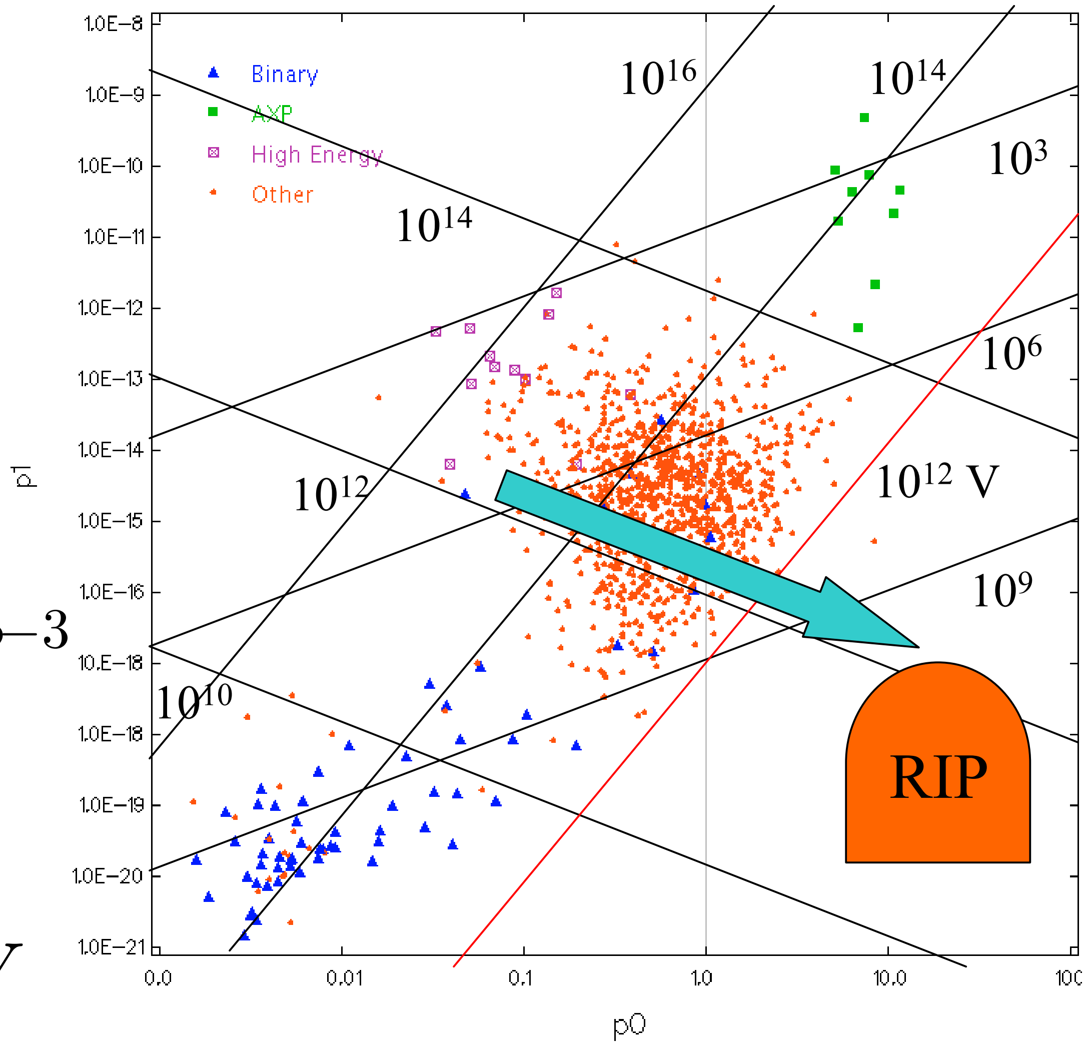
P-P-Dot Diagram (Again)

- A rotating neutron star lies at a high voltage relative to infinity.
- If the voltage is too low, no pulsar: DEATH LINE

$$\dot{E} = I\Omega\dot{\Omega} = -4\pi \dot{P} P^{-3}$$

$$\phi \sim \frac{\Omega^2 R^3 B_p}{2c^2}$$

$$4 \times 10^{20} \dot{P}^{1/2} P_1^{-3/2} V$$



How to get a millisecond puslar?

- A normal pulsar will spin down due to dipole radiation and join the pulsar graveyard.
- To become a millisecond pulsar,
  - The neutron star must be spun up to a millisecond period

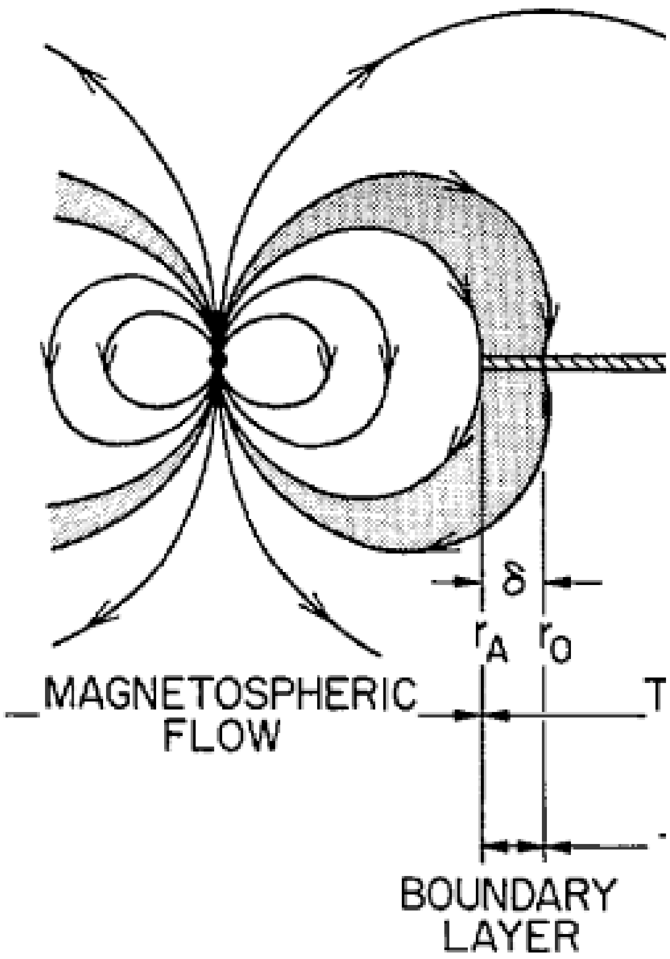
A Clue

- Many (but not all) millisecond pulsars are in binaries.
- Accretion can spin up a neutron star.
- A neutron star only has to accrete a little matter to get spun up to a millisecond period (Problem 1).

Spinning up the neutron star

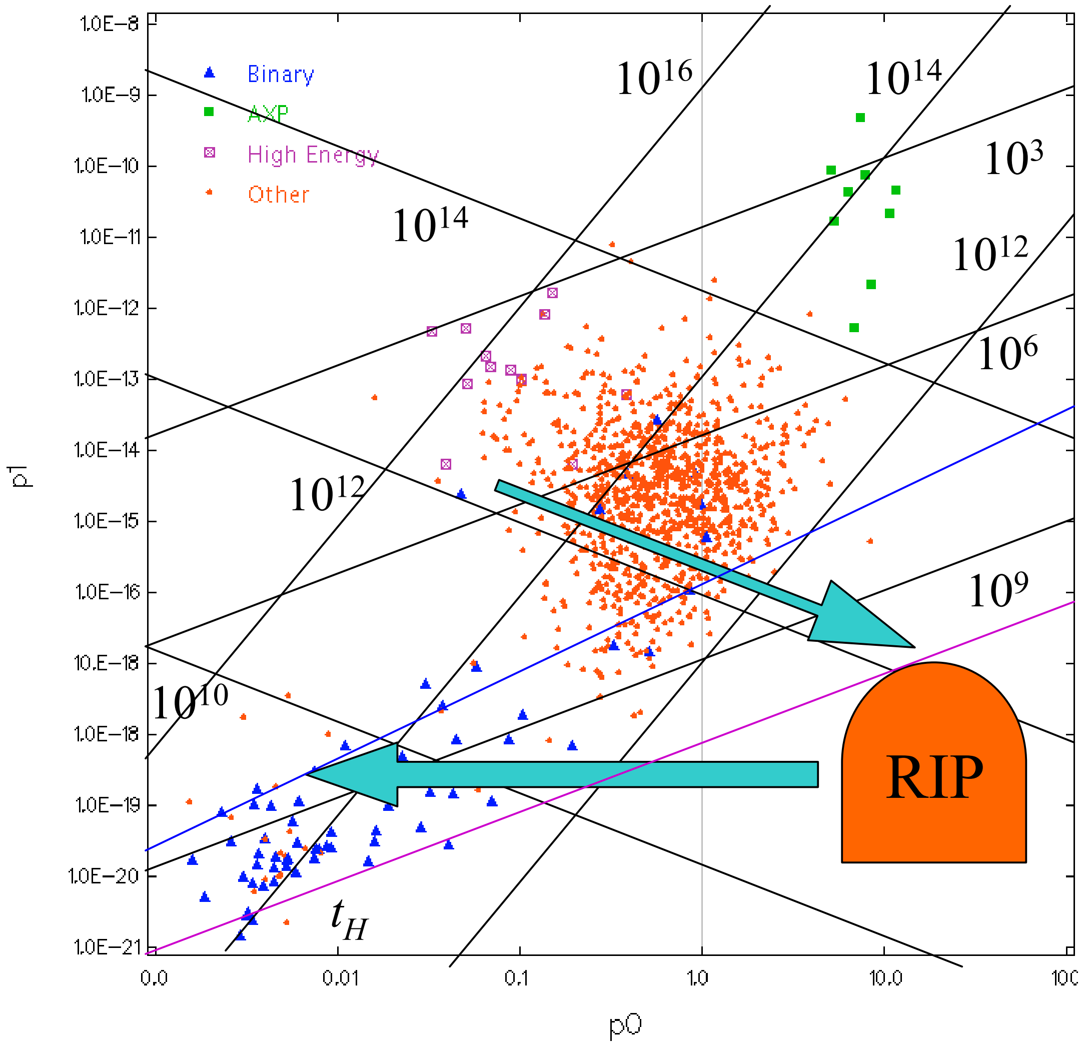
- Let’s assume that the disk can spin up the neutron star as long as some portion of it is rotating faster that the neutron star, so the critical frequency is

$$\Omega^2 r_A^3 = GM$$



Rebirth

- If the star accretes at the Eddington rate, the star ends up along the BIRTH LINE (Problem 2)
- $\tau = t_H$



But that's not all.

- If a typical neutron star got spun up like this, it would end up with a one-second period (Why?)

But that's not all.

- If a typical neutron star got spun up like this, it would end up with a one-second period (Why?)
- If the magnetic field started out at $\sim 10^{10}$G, then you would end up with a millisecond pulsar.

How to get a millisecond puslar?

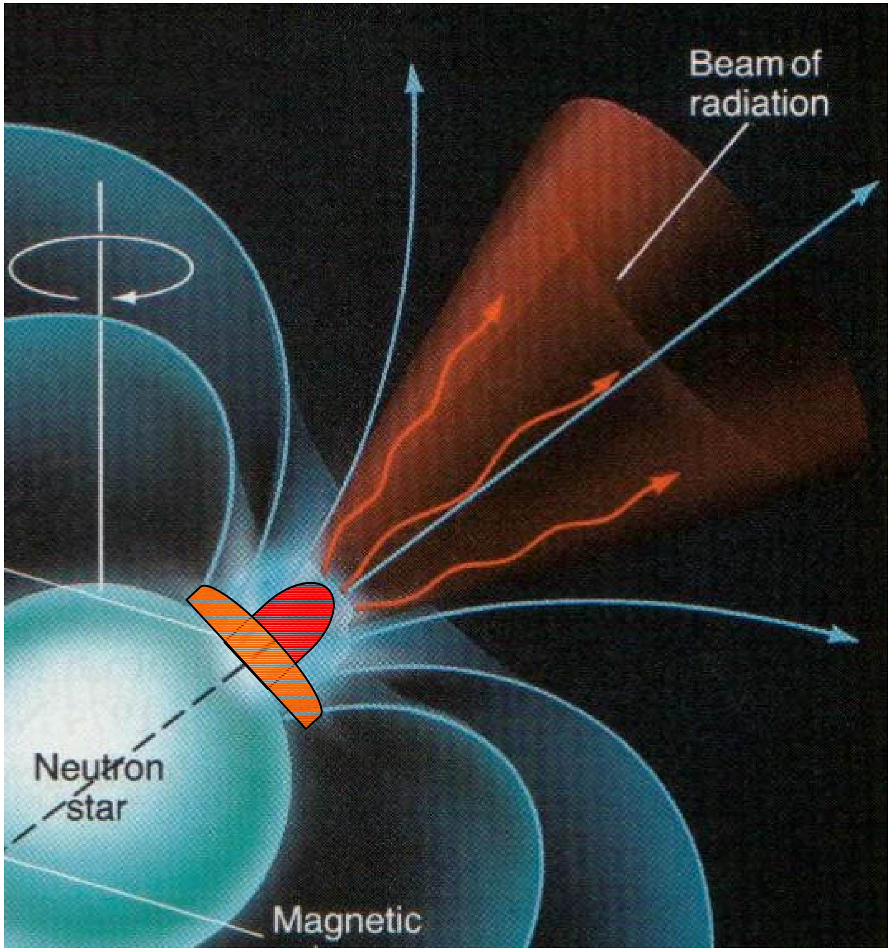
- A normal pulsar will spin down due to dipole radiation and join the pulsar graveyard.
- To become a millisecond pulsar,
  - The neutron star must be spun up to a millisecond period, **and**
  - The magnetic field must go away.
- There aren't enough neutron stars born with such low fields.

Magnetic Field and Plasma

- MHD: in magnetohydrodynamics with infinite conductivity the magnetic flux passing through a parcel of plasma is conserved: **“Flux Freezing”**
- A corollary is that the flux is conserved.
- So MHD can move the field but can’t destroy it.

First, move the field.

- Accreted material piles at the magnetic poles.
- Gravity makes the material spread out over the surface of the star, dragging the magnetic field with it.
- Like combing down a cowlick.

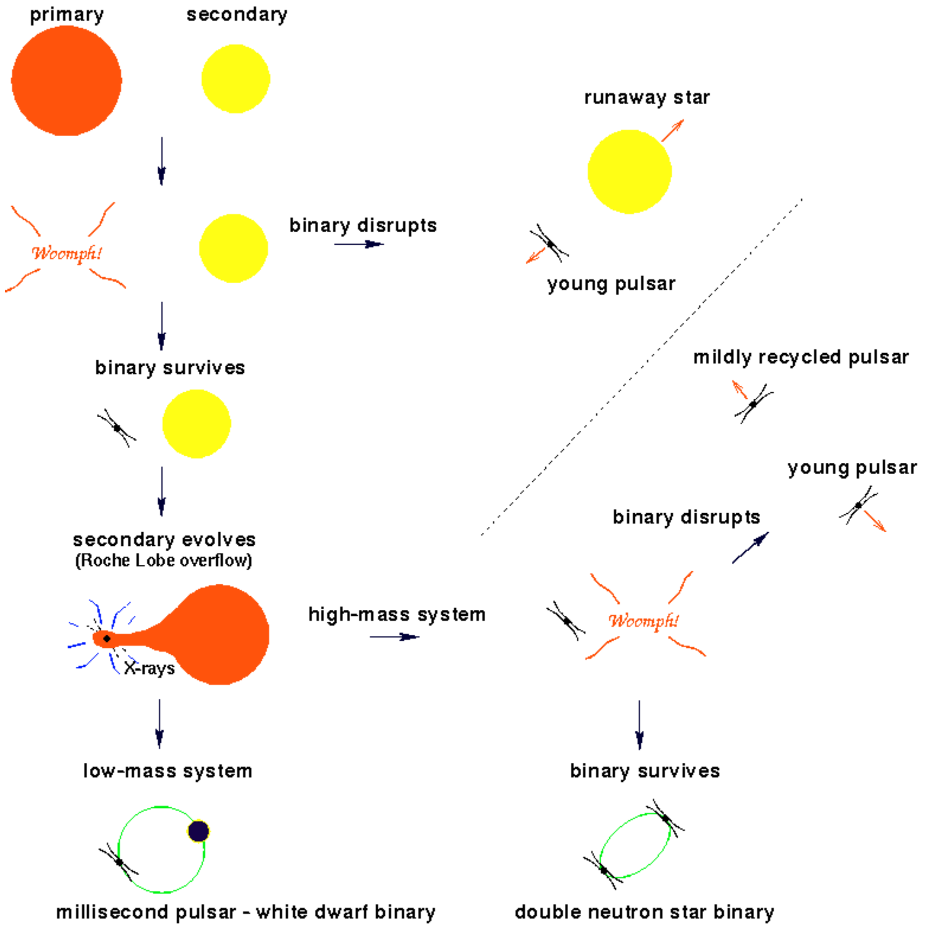


Second, get rid of the field.

- Once the accretion stops the field may pop up again.
- We have assume that the conductivity is infinite. Because it is finite, the magnetic field can move relative to the plasma and pop out.
- Also the resistance can dissipate the currents that anchor the field.

To summarize...

- People try to understand the formation of millisecond pulsars through binary evolution models and population synthesis.
- Only a small fraction of high-mass stars in binaries end up as millisecond pulsars.



An Alternative

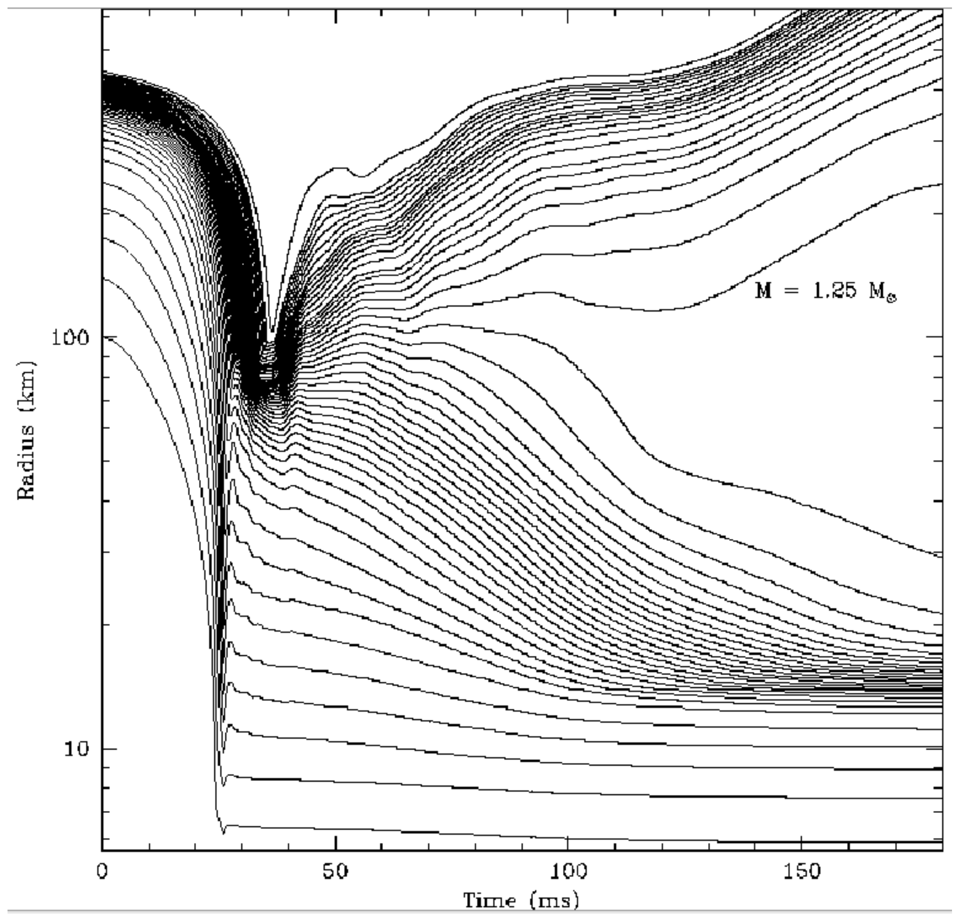
- Perhaps, we have misread the clue that millisecond pulsars are in binaries.
- White dwarfs are often in binaries and could accrete material and collapse to form a neutron star.

$$L \propto MR^2/P, P_{\rm WD} = P_{\rm NS} \left(\frac{R_{\rm WD}}{R_{\rm NS}} \right)^2 \approx 1000{\rm s}$$

$$\Phi \propto BR^2, B_{\rm WD} = B_{\rm NS} \left(\frac{R_{\rm NS}}{R_{\rm WD}} \right)^2 \approx 10^4 {\rm G}$$

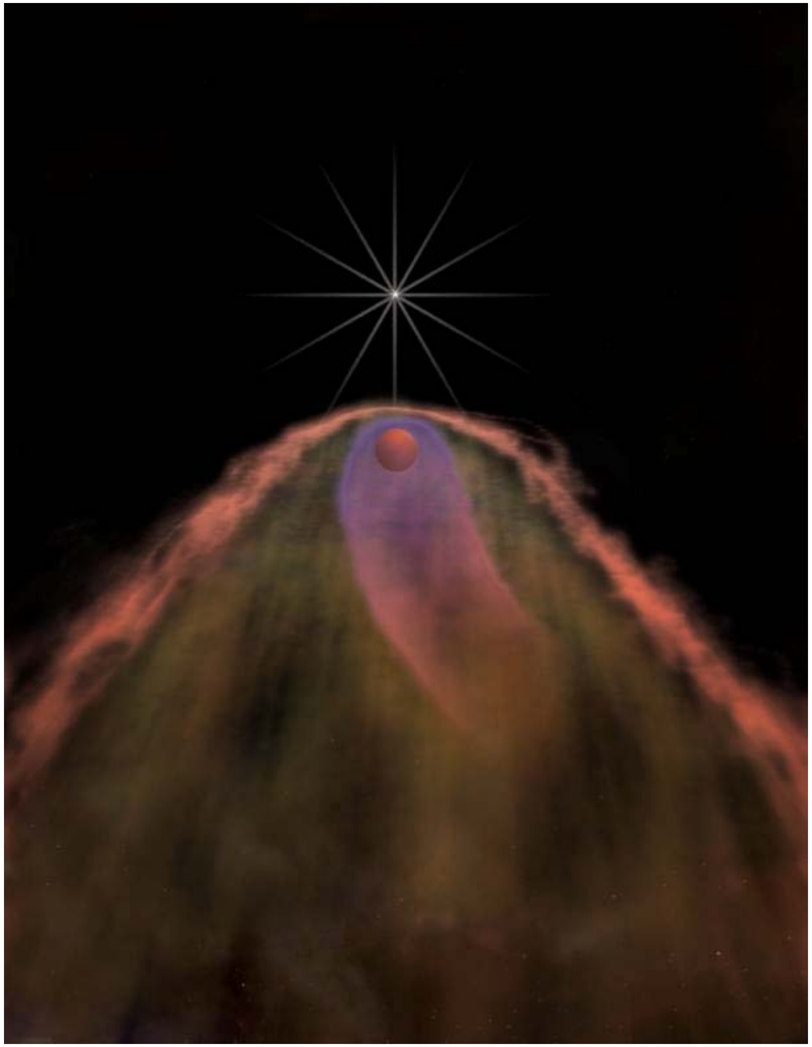
Accretion Induced Collapse of a White Dwarf

- Accreting white dwarfs are thought to result in Type Ia supernovae or have novae which cause their mass to decrease.
- Another option is that they collapse to a NS.
- Could help to explain a potential excess of MSPs relative to LMXBs in GCs.

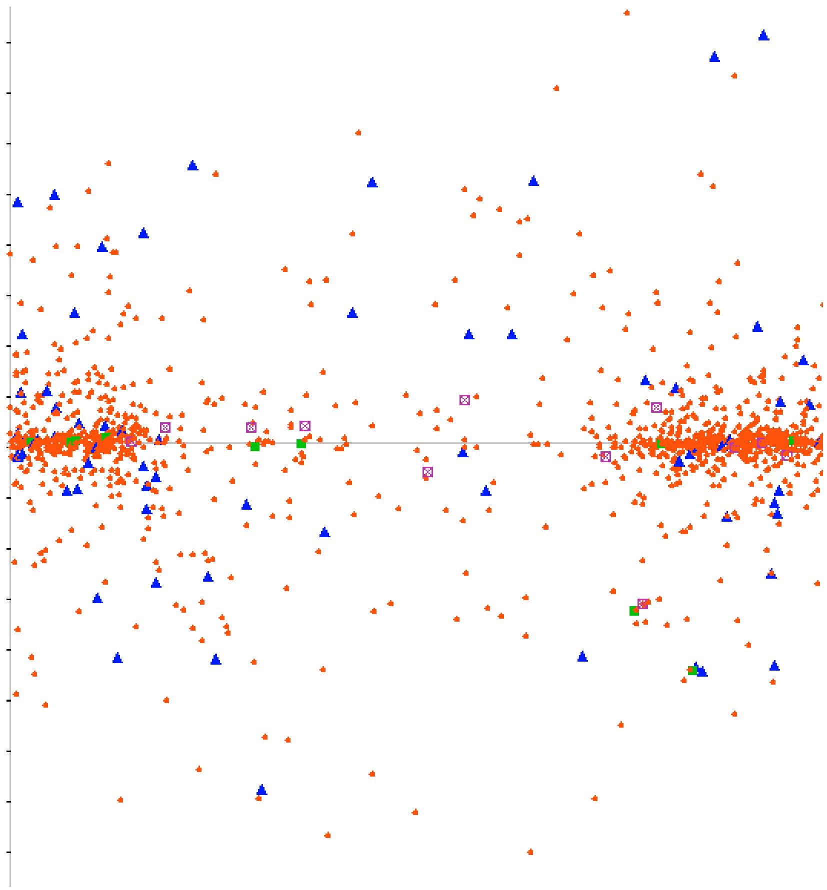


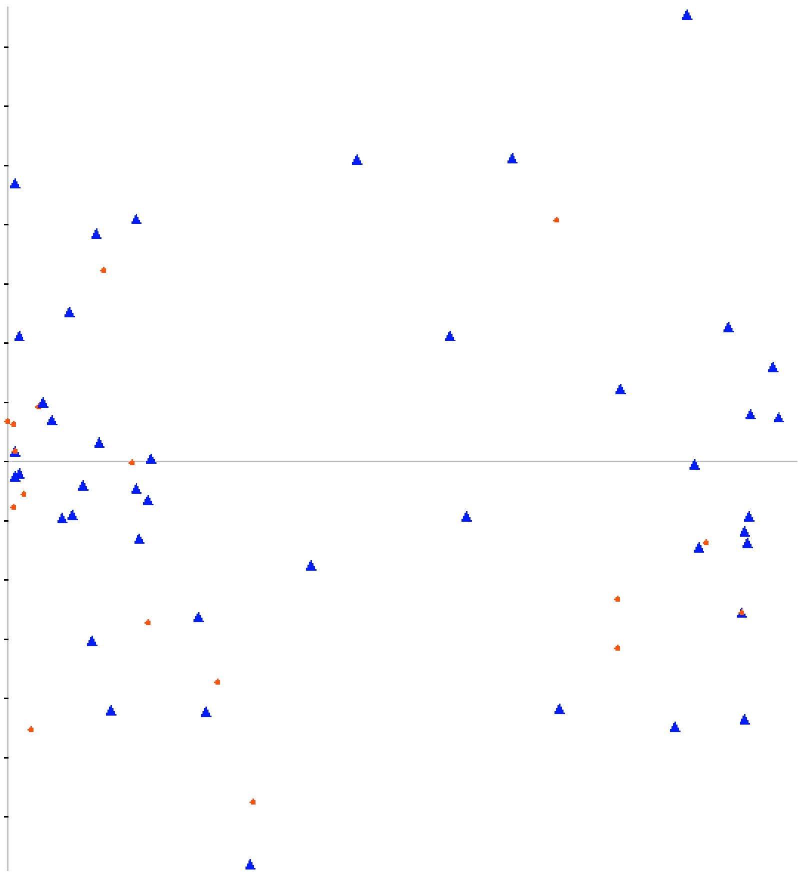
Isolated Millisecond Pulsars

- Many but not all millisecond pulsars are in binaries. How do the rest dump their partners?
  - Lose them through interactions with other stars (important in GCs)
  - Vaporize them
- The Black Widow Pulsar



Where are the MSPs?



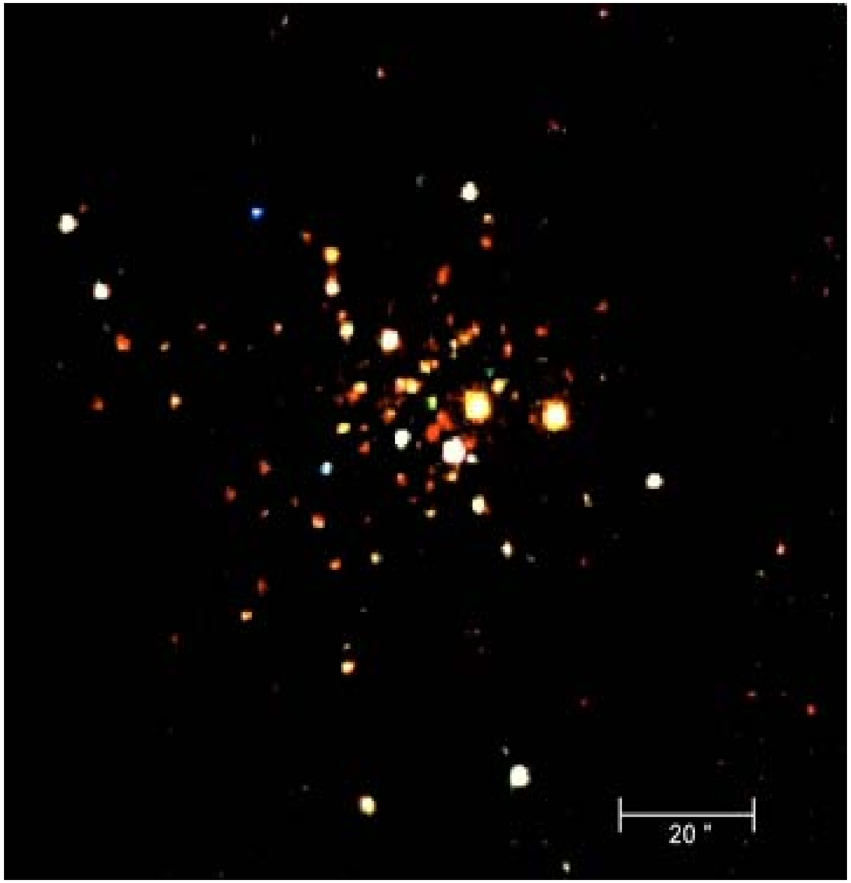


MSPs are hard to find.

- The pulse of a millisecond pulsar is on for a large fraction of the pulsar period.
- The dispersion of the plasma requires a narrow bandwidth to find the pulsar at all.

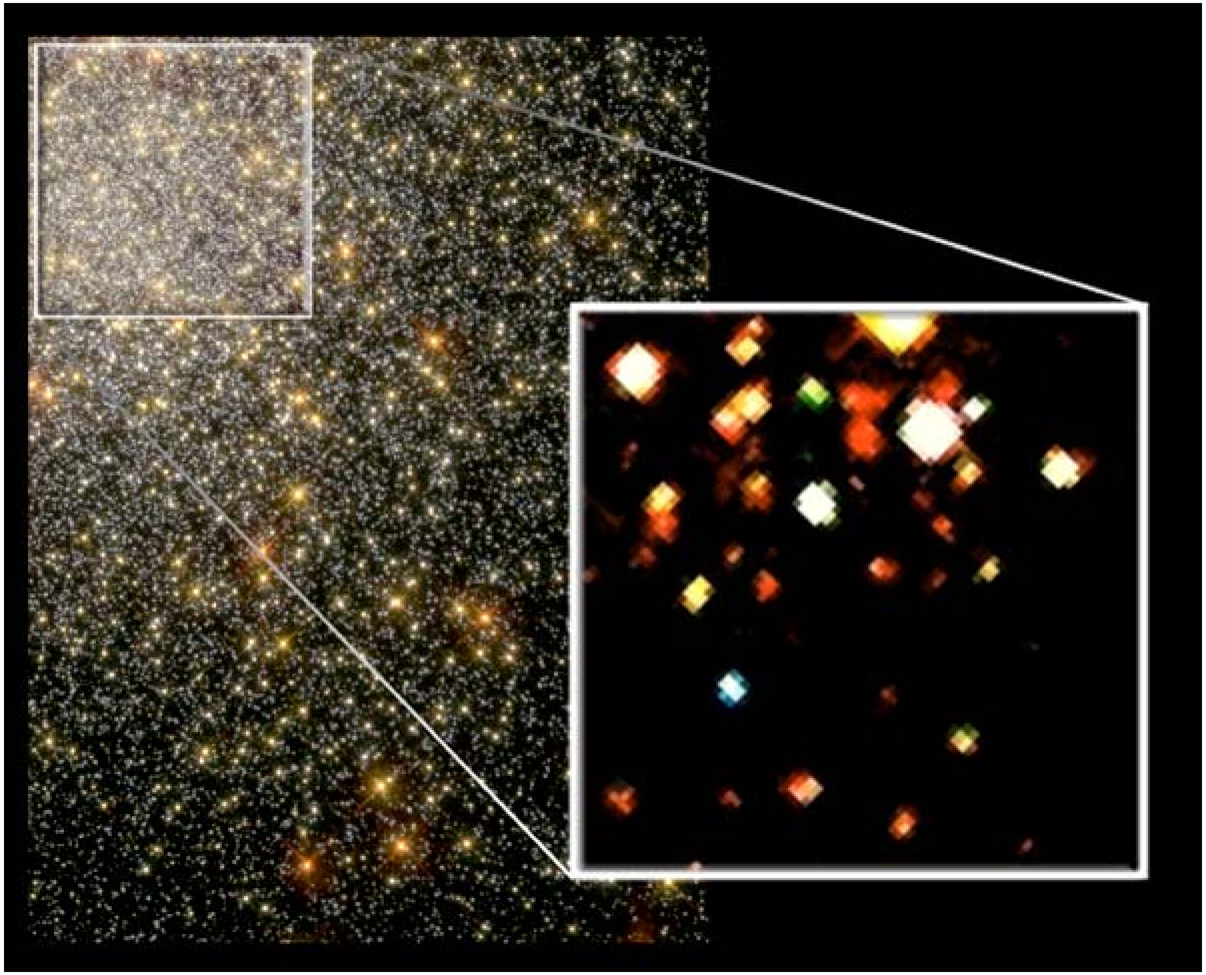
Where to find millisecond pulsars?

- Need lots of binary stars.
- LMXB epoch can last a billion years.
- Do you want to dump the companion?



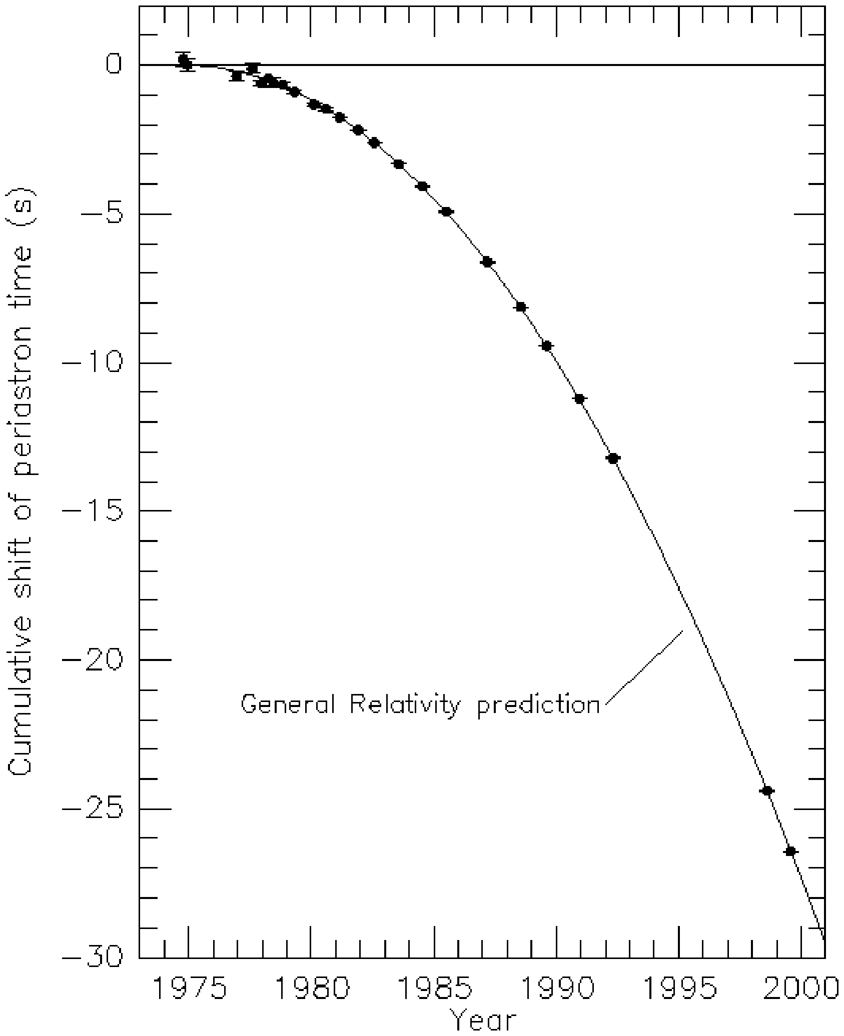
Collapsed Globular Clusters

- Hubble and Chandra images of the globular cluster 47 Tucanae



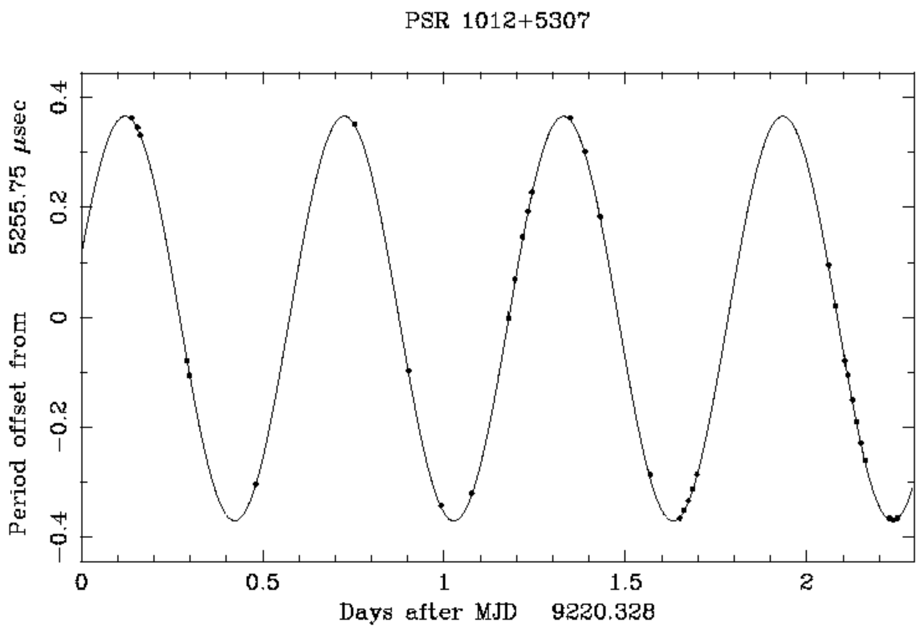
What can MSPs tell us? (1)

- Binary pulsars: tests of general relativity
  - The orbit of the Hulse-Taylor binary pulsar shrinks by 3.2 mm each orbit due to the emission of gravitational radiation.
  - In relativistic binaries the mass of both stars can be determined accurately.

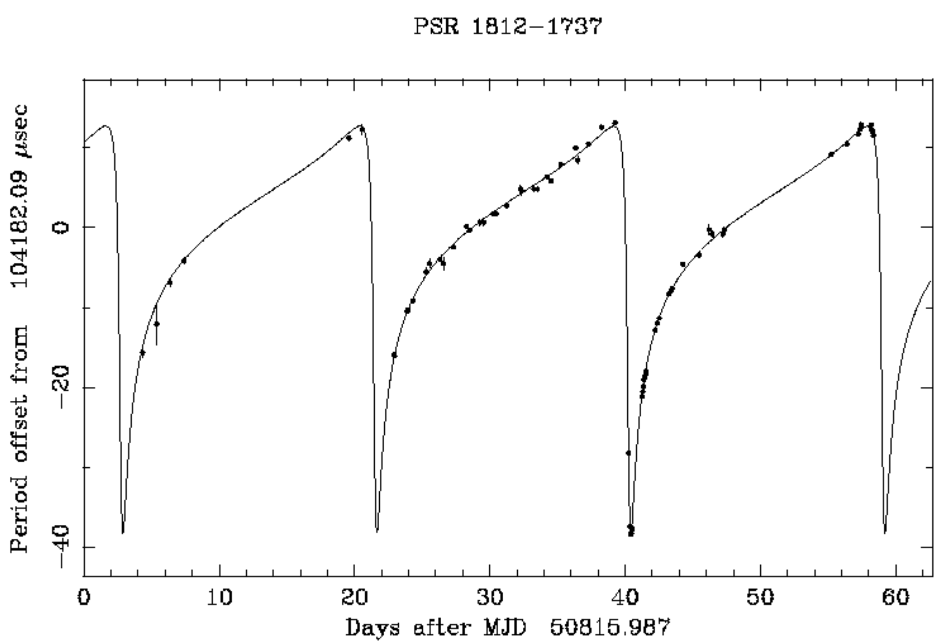


What can MSPs tell us? (2)
Two binary pulsars

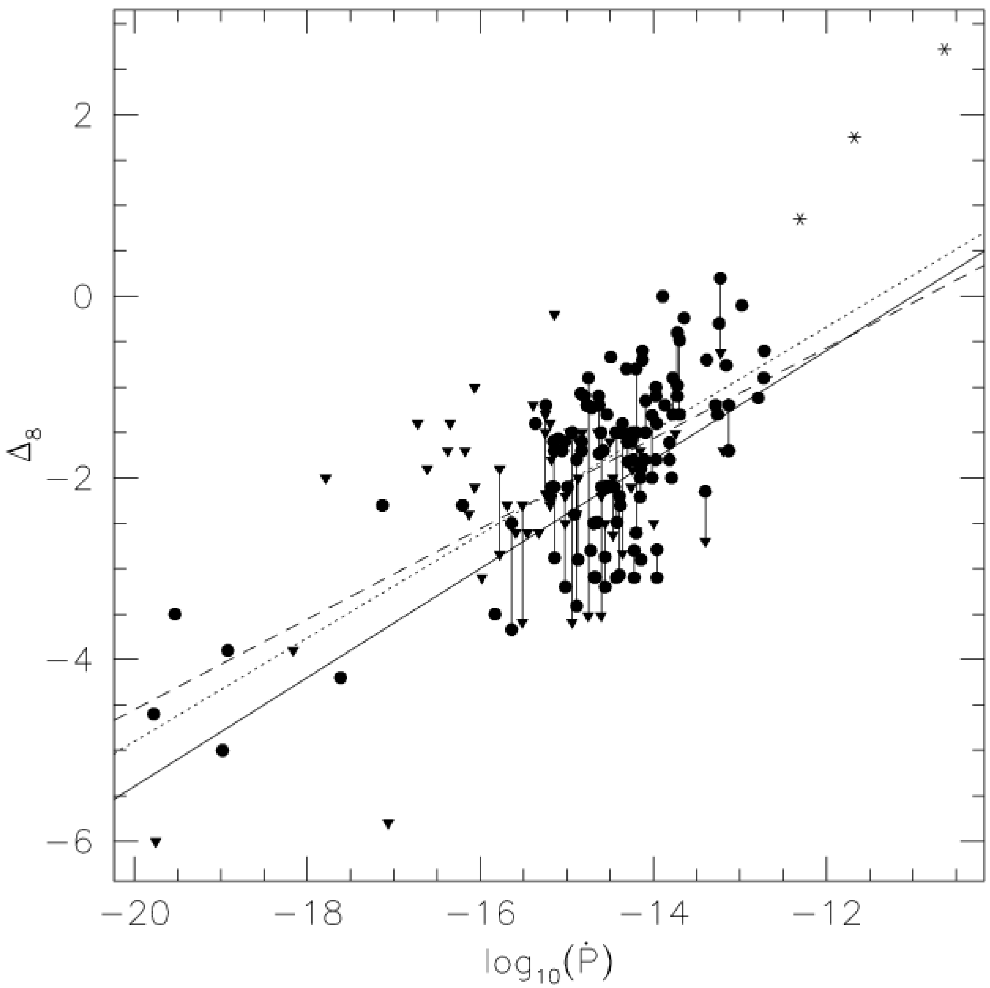
- Pulsars in binaries give hints to the formation of millisecond pulsars.

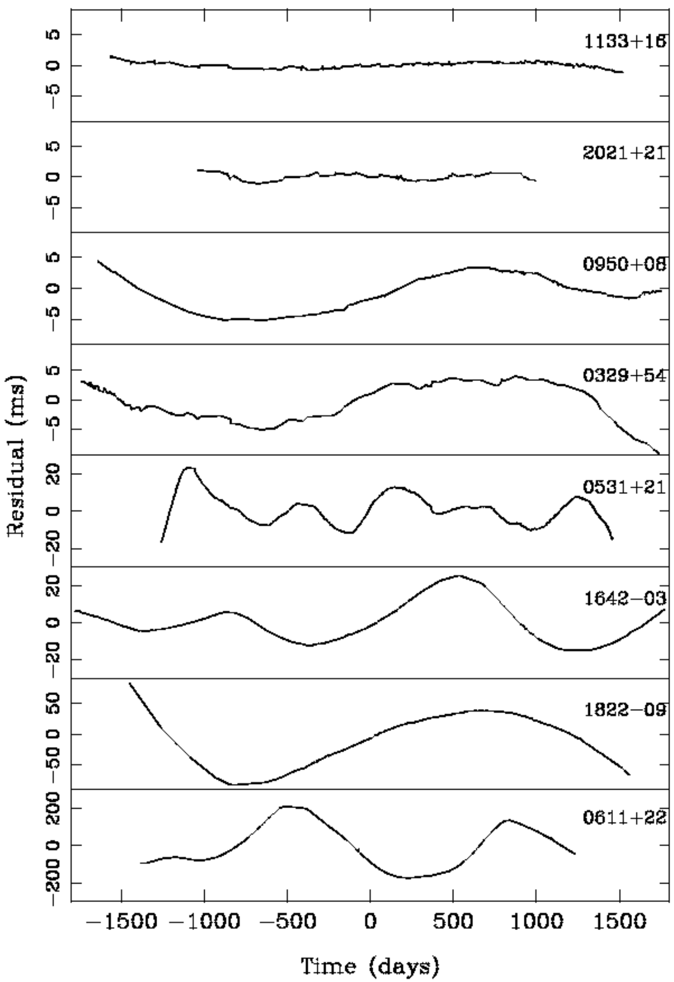


- The MSP has a lower mass companion in a circular orbit.



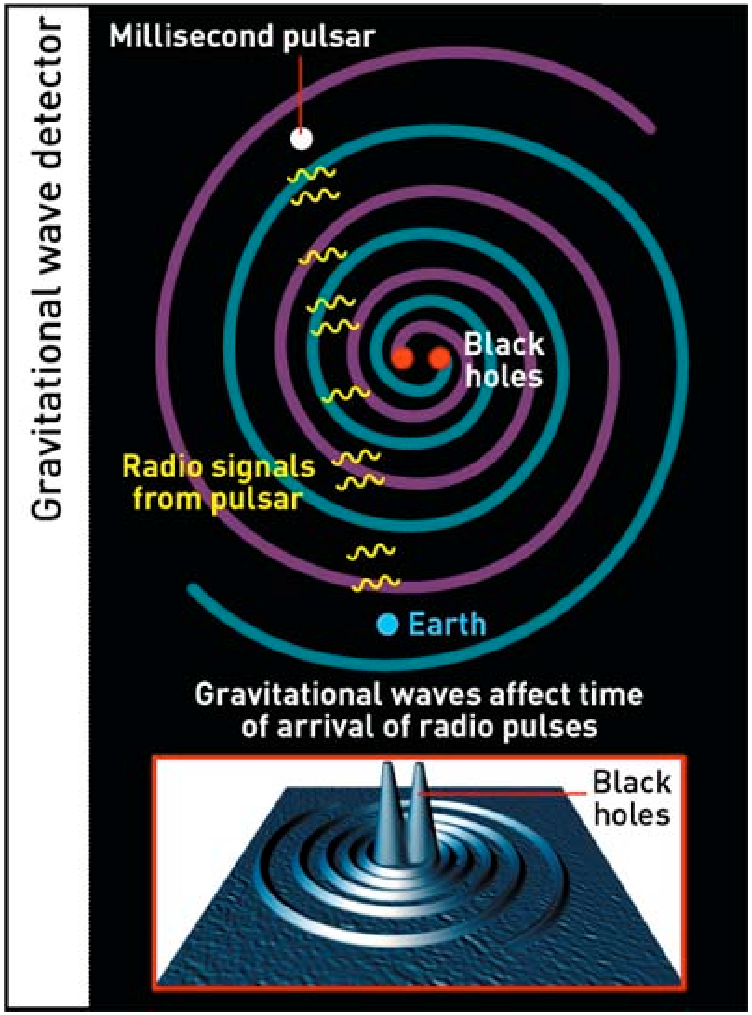
What can MSPs tell us? (3)





What can MSPs tell us? (4)

- Millisecond pulsars are as stable as Earthbound atomic clocks but they are across the Galaxy.
- Passing gravitational waves will change the arrival times mimicking timing noise.
- Many MSPs form a timing array.



What can MSPs tell us? (5)

- How fast can a neutron star spin?
  - The neutron star equation of state
    - Smaller neutron stars have larger maximal spin rates.
    - The quest for the submillisecond pulsar.
  - The viscosity of neutron-star interiors
    - If the interiors of neutron stars were inviscid, a rotating neutron star would emit gravitational radiation through the r-mode instability.