Pulsars, eVLBI, GWs and LEAP

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Collaborators: Vlemmings, Kramer, EPTA, ...

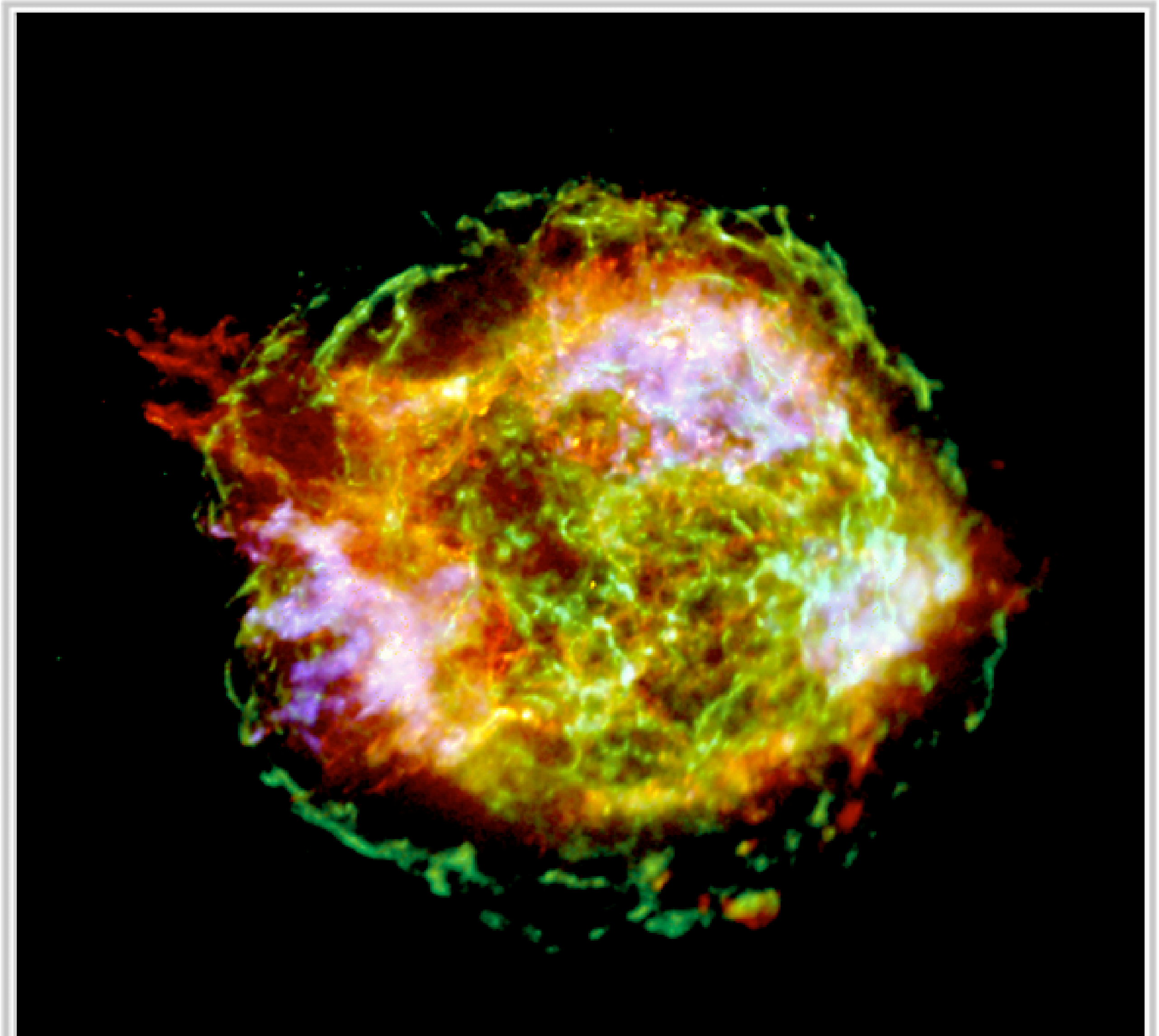
8th eVLBI - Madrid `09

Outline

- What are pulsars?
- What science goals are related to VLBI?
- Some Future Northern Hemisphere pulsar surveys
- The case for rapid positional determination
- Existing VLBI projects
- Why eVLBI?
- Gravitational Waves and pulsars
- The LEAP project

Pulsars

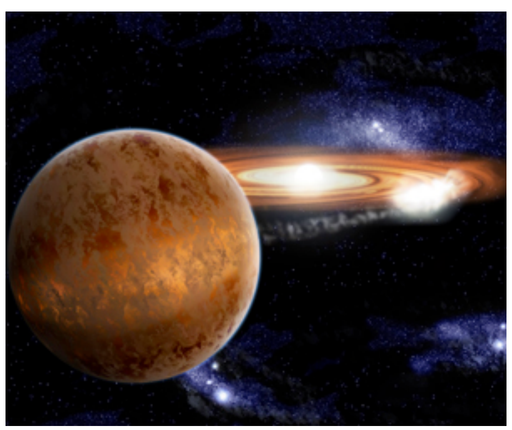
- Remnant of SNe
- Rotating Neutron Stars
- $M = 1.4M_{\odot}$, $R=10km$
- P = 0.0013 - 8.5 s
- $B = 10^{8} - 10^{14}$ G
- Mainly Radio emitters
- Emit in narrow beam
- Clock like stability
- Matter at high density
- Tests of gravity theory
- Extreme plasma physics


Cas A - X-ray - Chandra/NASA

P-Pdot Diagram

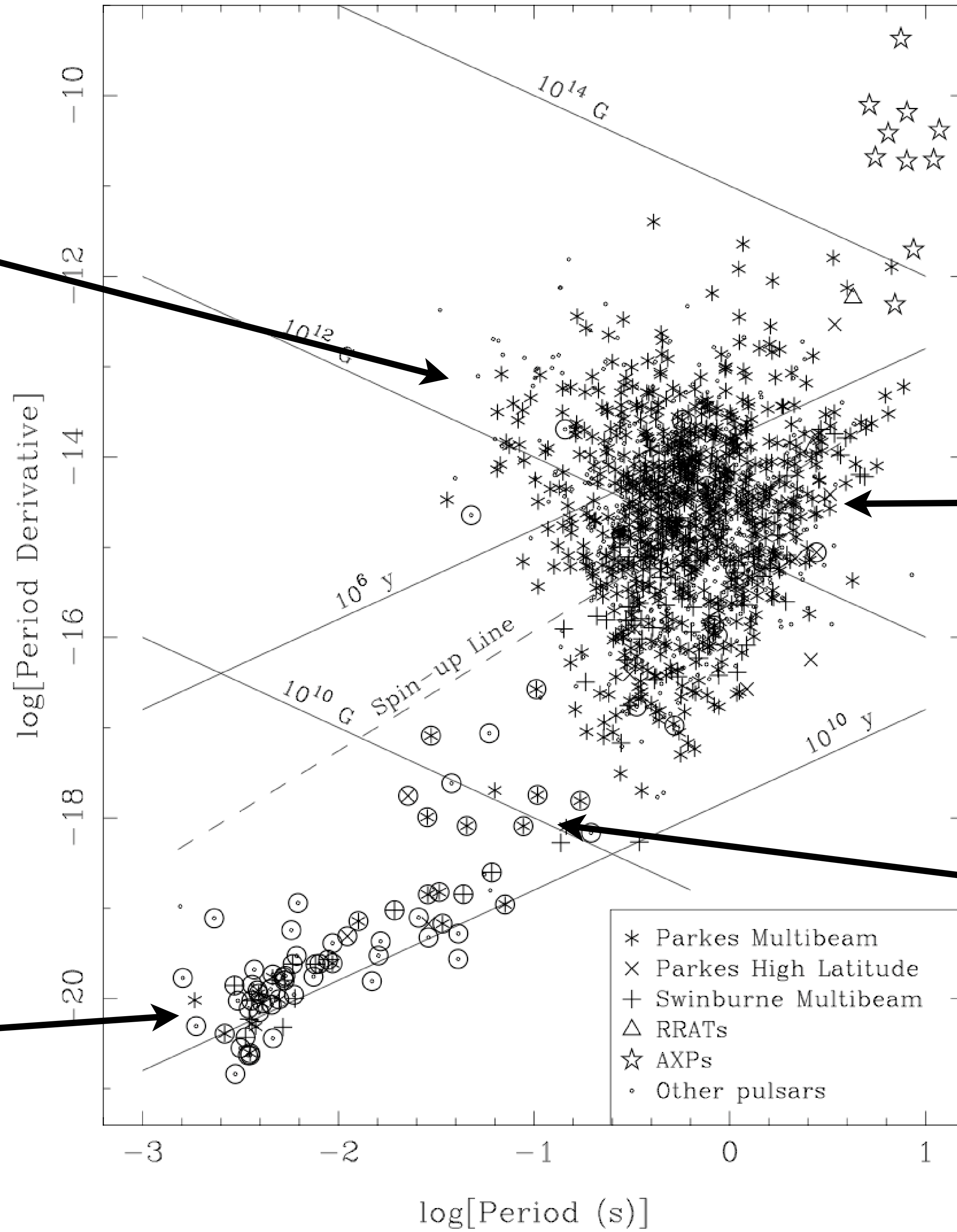
Young PULSARS

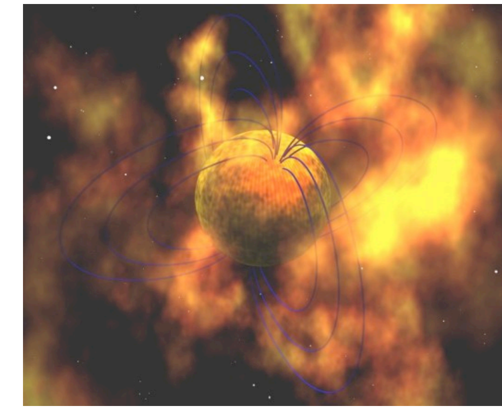
- Spin FAST
- Associated SNRs
- Energetic
- GLITCH



Millisecond Pulsars

- Spin VERY FAST
- Usually BINARY
- VERY STABLE
- Best CLOCKs





MAGNETARS

- Spin SLOWLY
- VERY High B
- Not ROT^{N} POWERED
- FEW RADIO

"NORMAL" PULSARS

- BULK of PSRs
- Great PSR STUDIES
- LOTS GOING ON
- NOBEL PRIZE

Double Neutron STARS

- Spin QUITE FAST
- Great FOR GR TESTS
- INCL. DOUBLE PSR
- NOBEL PRIZE

Pulsars & (e)VLBI

Pulsar Origins:

- SNR associations
- NS birth sites in stellar clusters / OB associations
- True ages

Astrophysics:

- NS atmospheres, cooling curves etc. need absolute distances

Evolution:

- NS distribution and population velocities

Environments:

- Galactic electron density
- local ISM

Reference frame ties

- Pulsar Timing in Solar reference frame vs. VLBI astrometry wrt quasars vs Optical counterparts

Astrometry

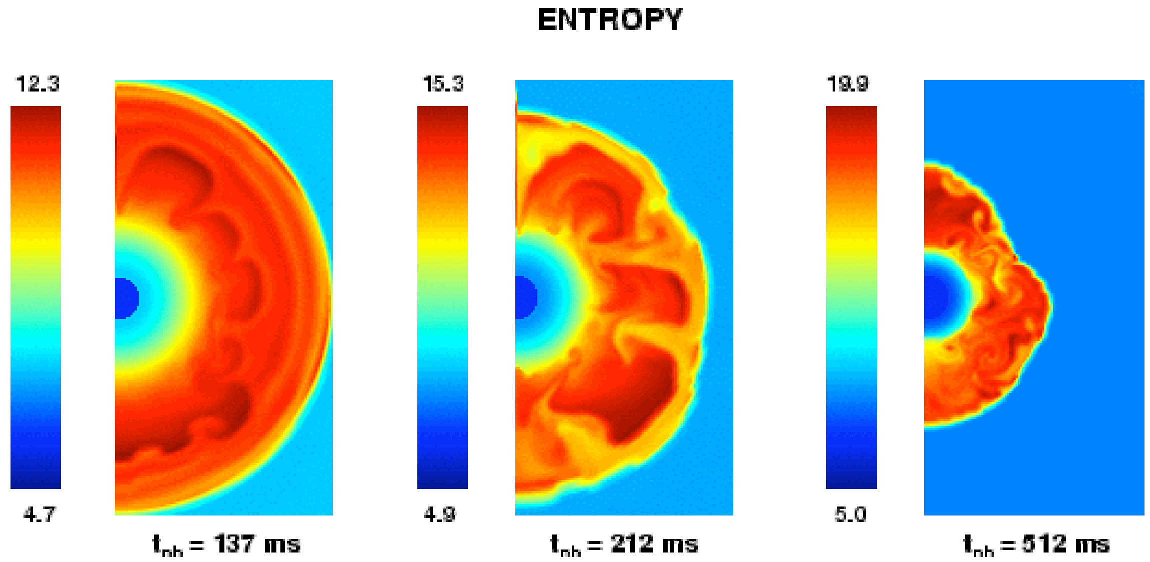
Large area northern sky surveys finding many new pulsars.

Parallaxes and proper motions essential for:

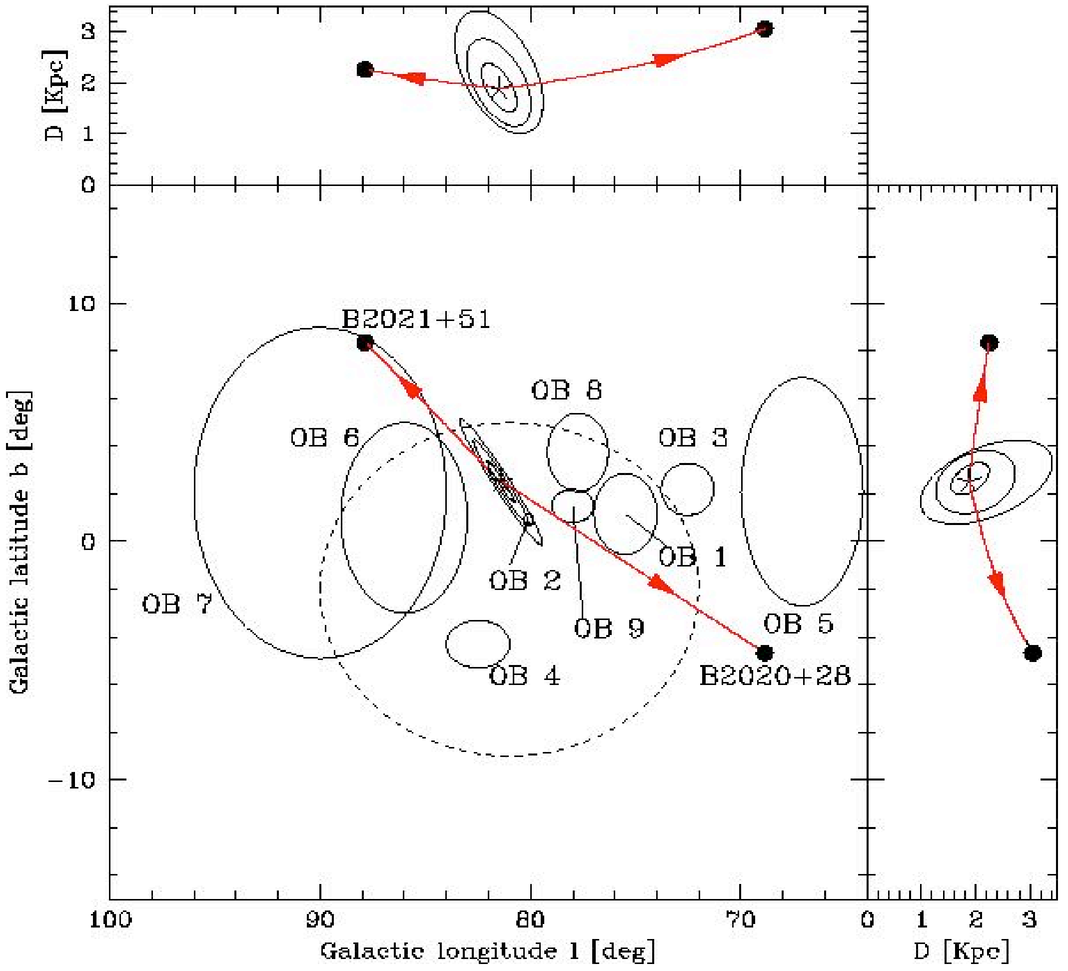
Pulsar velocities: SNe physics, Pulsar birth places, SNR assoc.

Parallaxes in particular, but also proper motions, impossible for non-MSP pulsars

B2021+51 and B2020+28 originate from same binary!!



Large velocities measured for some pulsars strongly constrain kick scenarios



Vlemmings et al. 2005

Northern Hemisphere Pulsar Surveys

- PALFA - 1.4 GHz 7 Survey along narrow strip around plane, running for few years, found ~50 pulsars expecting hundreds
- GBT drift scan - 350 MHz survey of large pieces of Northern Sky, survey complete but processing ongoing expecting ~100-200 pulsars
- LOFAR - All sky 150 MHz survey. Expected to find up to 1000 new radio pulsars, many of which will be nearby.
- Effelsberg Multi-beam - 1.4 GHz 7 beam system will survey along the plane initially but then move to all sky. Expecting hundreds of pulsars
- Many, many new pulsars in the Northern sky!

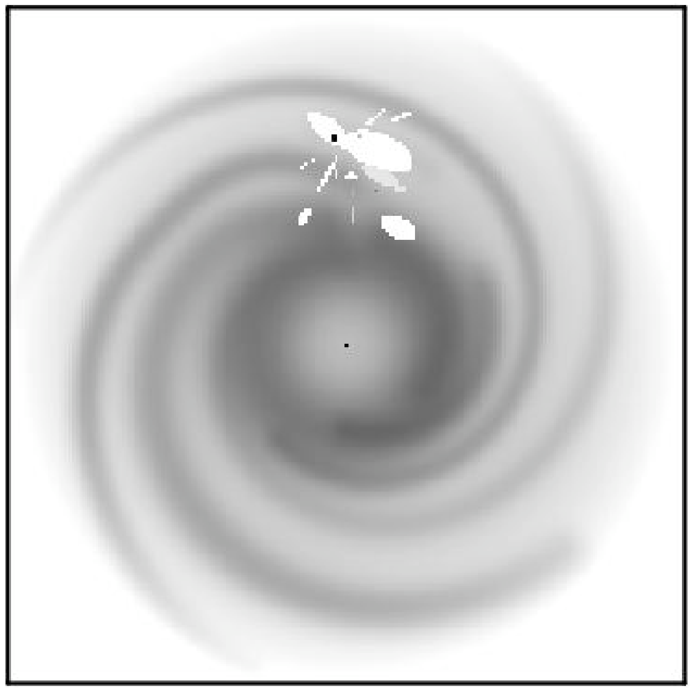
Accurate Positions Quickly

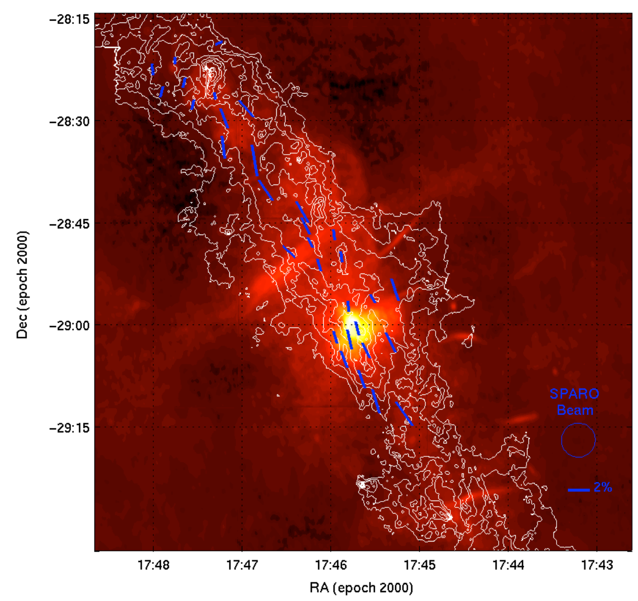
- Pulsar timing gives in general good positions
- However this takes up to 1 year due to covariance with the period derivative
- An accurate VLBI position can be obtained more rapidly than that allowing:
  - Multi-wavelength follow up, e.g. binary pulsars, energetic pulsars, Magnetar-like.
  - More rapid determination of period-derivative and thus classification of potentially interesting sources

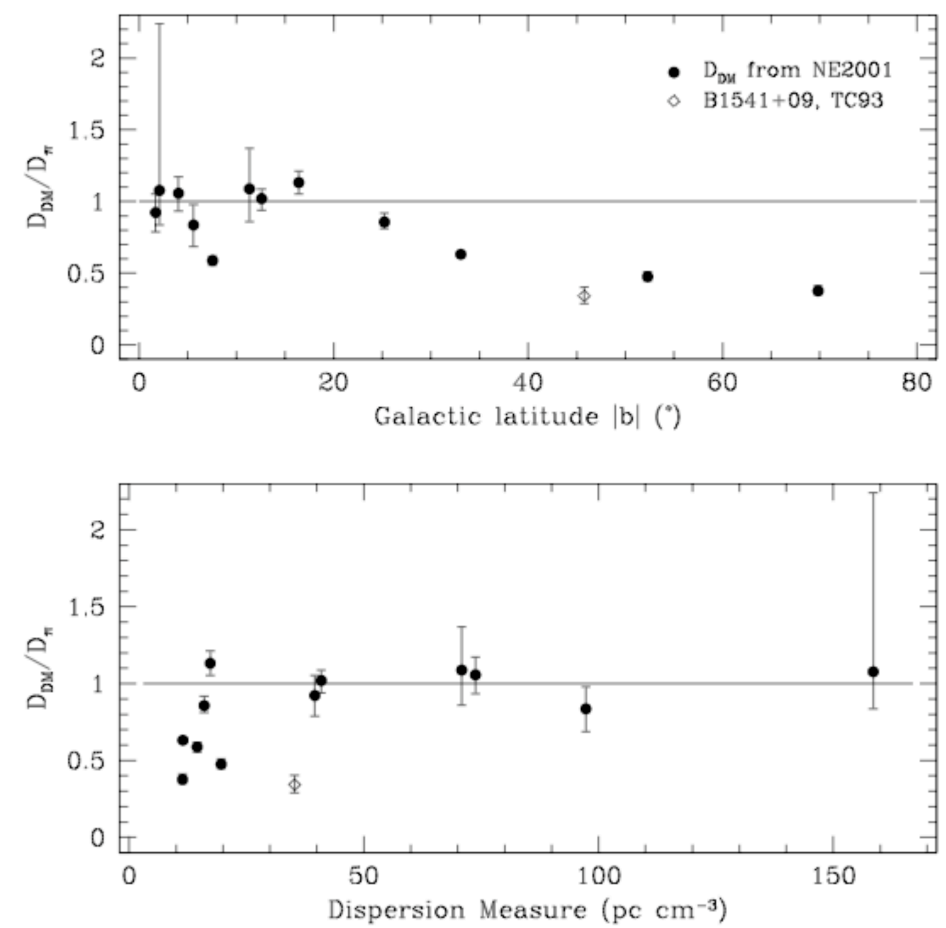
ISM studies

Parallaxes and proper motions essential for:

Understanding ISM properties, especially locally, combine Dispersion measure and Rotation Measure and distances to get good handle on magnetic fields.







Pulsar distances compared with Dispersion Measure (DM) distances

- ~20% uncertainty in DM distances
- High latitude discrepancy due to larger ISM scale height or ISM irregularities
  - More consistent with 1.8 kpc scale height (much larger!) from Gaensler et al. (2008)
  - Though data of Vlemmings, Brisken et al implies a slightly smaller scale height.

Astrometry

Parallaxes and proper motions essential for:

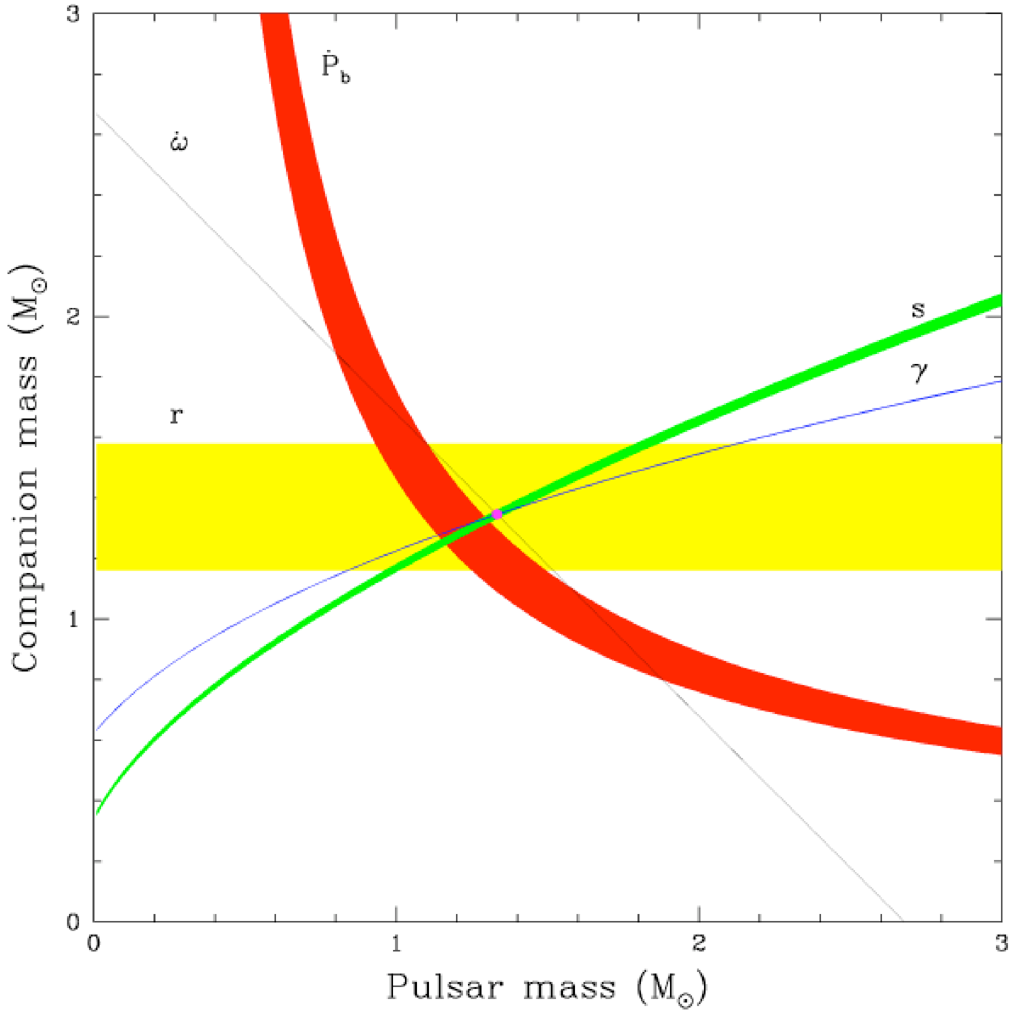
Precise tests of GR require accurate distances and velocities

e.g. PSR B1913+16 & B1534+12

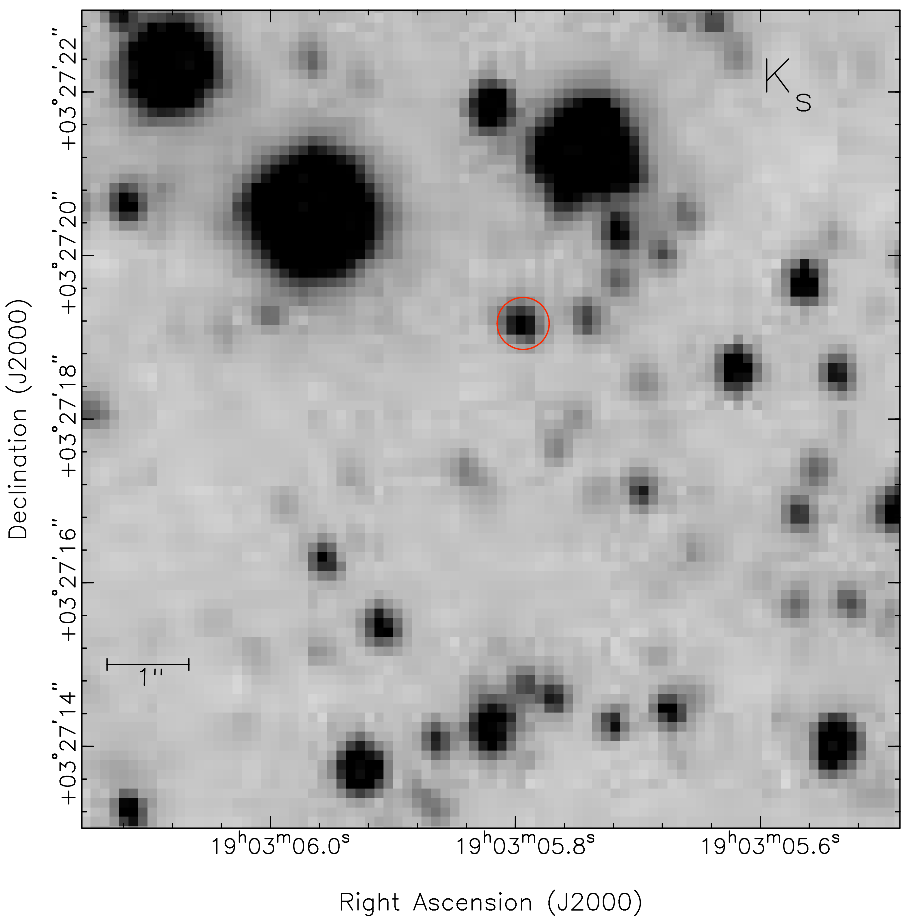
More accurate measures of Pdot and timing noise.

More accurate positions in the presence of pulsar timing noise (young pulsars), multi-wavelength follow up and SNe/PWN associations

Mass-Mass diagram B1534+12



MSP J1903+0327

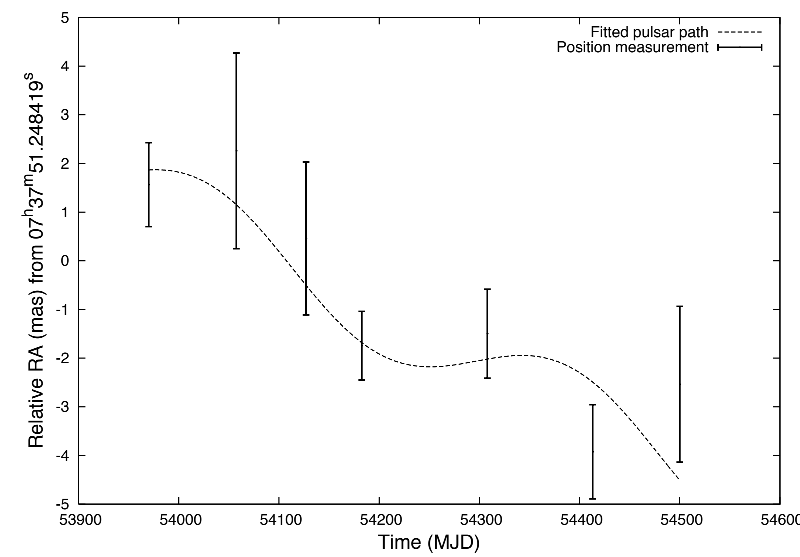


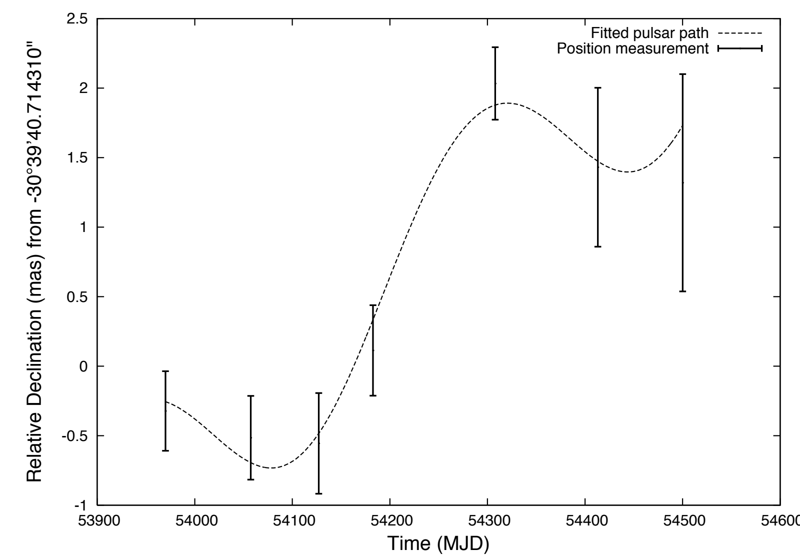
Parallax to the Double Pulsar

Deller, Bailes, Tingay Science Feb 2009

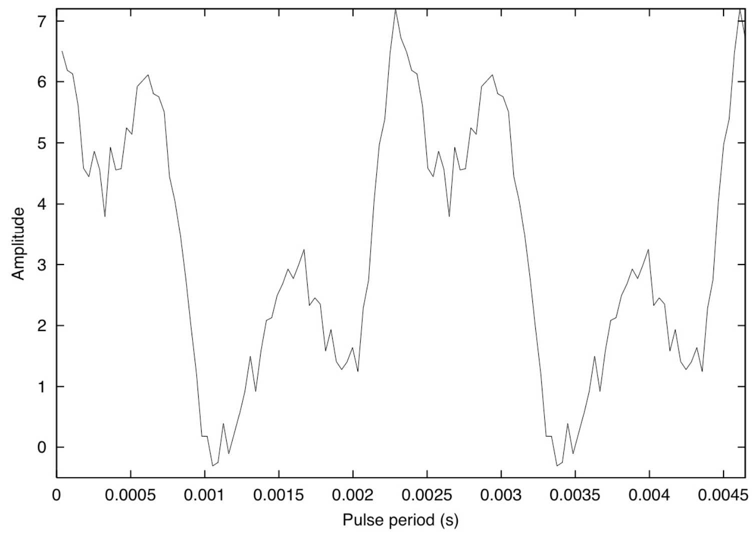
- Unique system which provides most stringent tests of GR in the strong field regime
- Current limits indicate GR correct to 0.05%
- Ultimate limit will depend on accurate distance and velocity determination
- Distance measured using LBA as 1100 kpc
- Twice as far away as previously thought and thus affects contributions from differential Galactic rotation, acceleration in Galactic potential and Shklovskii affect
- Can get limit of 0.01% with these corrections
- Also drastically decreased number of DNSs

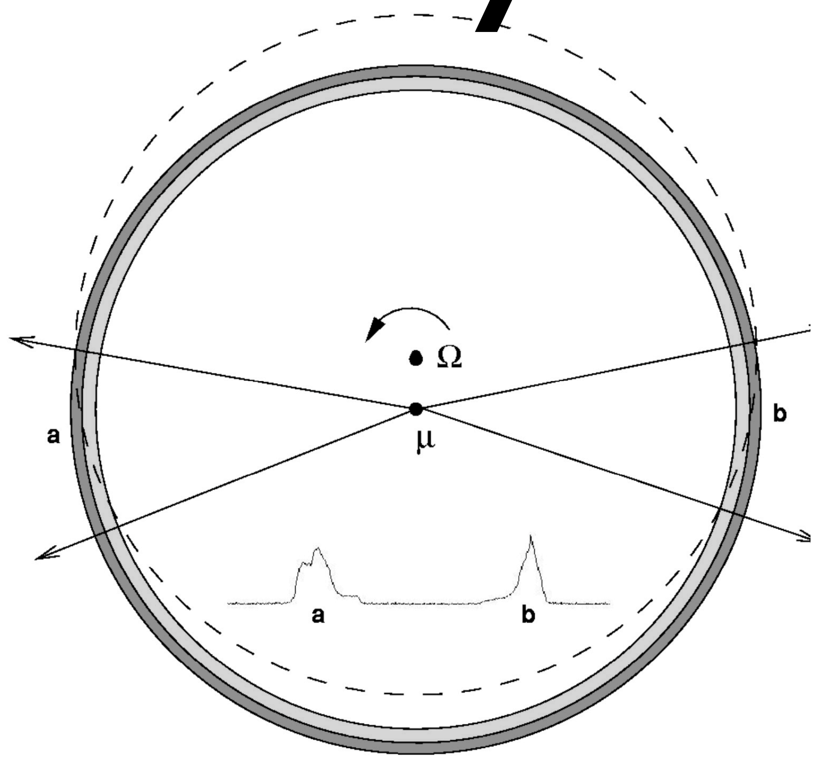
Proper motion of the System





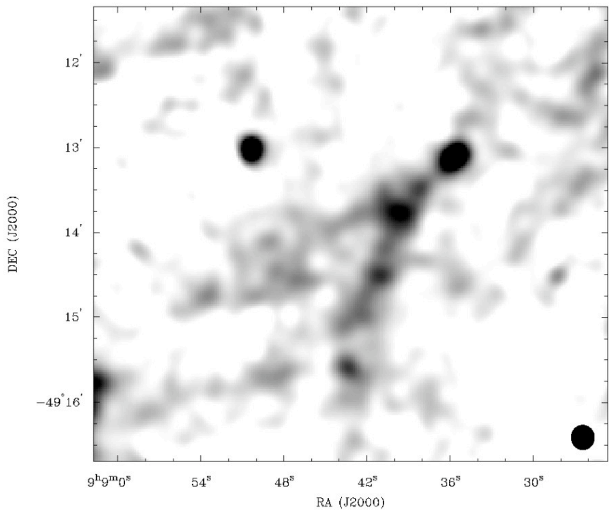
Pulsar Emission Physics



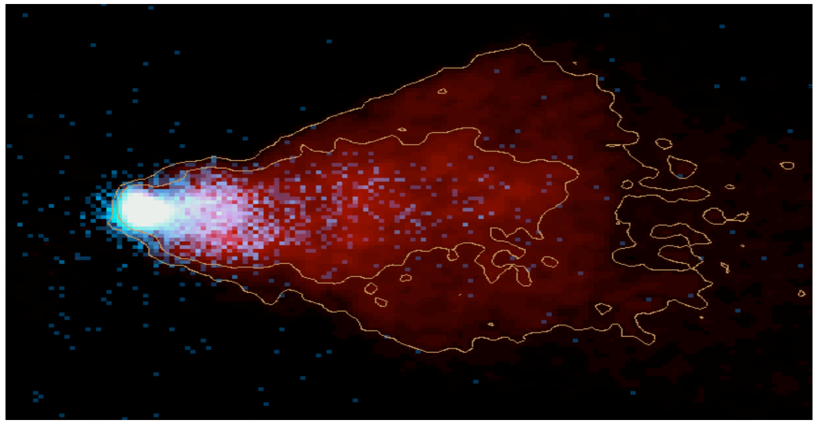


- Fermi and Agile providing excellent new information on emission site
- Commensurate radio observations of wide profile pulsars important, but off-pulsar component undetected in pulsar backends
- VLBI required to show unresolved, can be used to study primary particle acceleration sites and mechanisms (polarisation).
- Probe structure of magnetosphere.

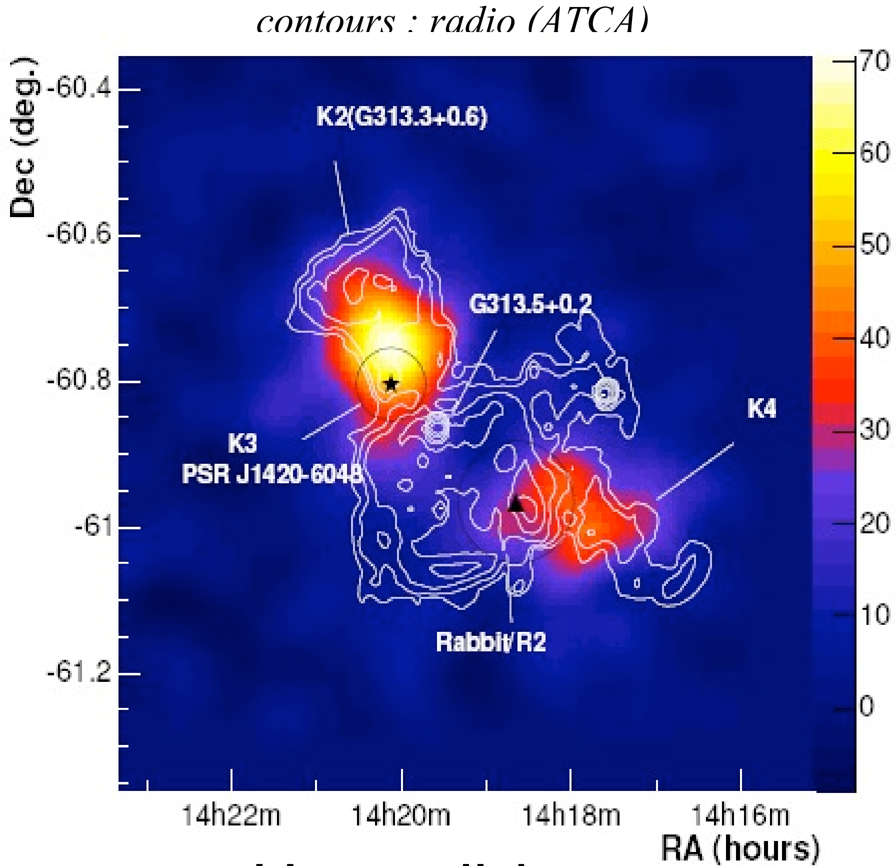
Environments



Stappers et al



Gaensler et al



Hess collaboration

Interesting gamma-ray results!

- Vast majority of dipole spin energy from pulsar lost in a wind
- Only obs when interacts with ISM, large numbers now being found at TeV gamma-rays.
- Small in radio, but can resolve inner shocks with high resoln. also probes different ages and energetics of electrons.
- Combine with other wavelengths can do calorimetry

Projects

- VLBA - Chatterjee, Brisken, Vlemmings et al
  - 14 new parallaxes/proper motions were measured including: fastest directly measured (B1508+55) and furthest B1541+09 at 7.2 kpc
- LBA - Deller, Bailes, Tingay et al
  - 7 new parallaxes/proper motions - software correlator
- eπ - eMerlin Legacy project: PIs Vlemmings and Stappers
  - 160 hours for first epoch & feasibility review, 520 hours thereafter

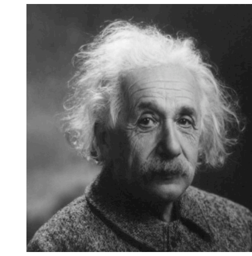
the eMERLIN Pulsar Interferometry Project

- Pulsar gating SNR increase by factor 2-5
- C-band:
  - 2 GHz bandwidth gives 15 μJy in 2 hours
  - initially 30 pulsars, ~10 with in-beam calibration
  - 0.2 mas astrometric accuracy, >200 SNR
- L-band:
  - 400 MHz bandwidth gives 45 μJy in 2 hours
  - initially 90 pulsars, all should have in-beams cals.
  - 0.5 mas astrometric accuracy, >280 SNR
- Final sample of 60 pulsars based on calibrator situation
  - should yield proper motions and ~40 parallaxes, more than doubling the current sample
  - serendipitous
    - the ‘off’-gate can detect weak pulsar wind nebulae
    - 20 square degree images down to 5σ of 30/90 μJy (C/L-band)
    - monitoring mas-scale variability of extra-galactic reference sources

Pulsars & eVLBI

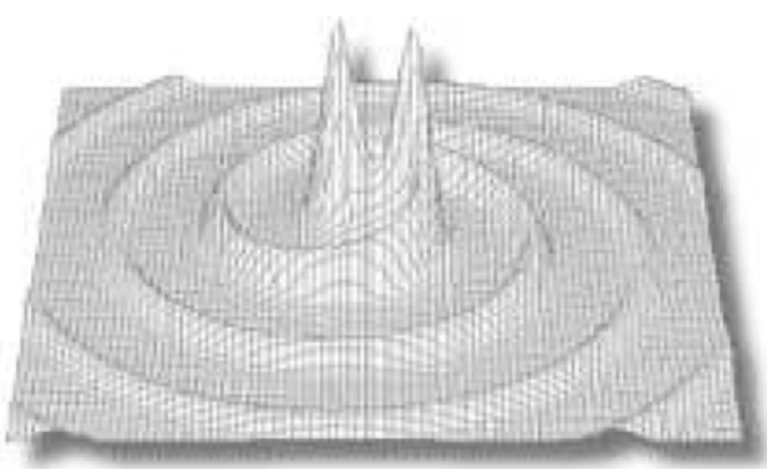
- Rapid turn around between observations and data acquisition
- Excellent sensitivity
- Pulsar binning mode to win 2-5 times more sensitivity
- Sufficiently large numbers of frequency channels to dedisperse
- Regular sessions to allow for rapid follow up of new discoveries
- The increased sensitivity to have more in beam calibrators

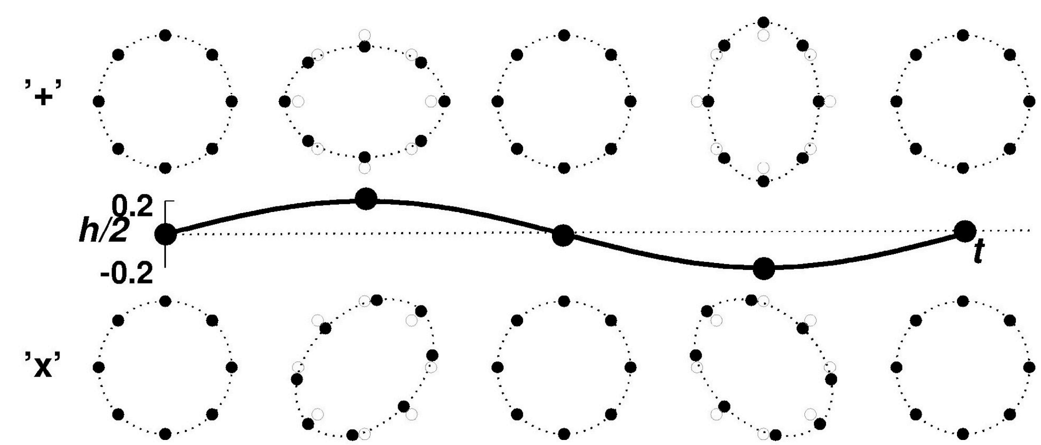
Gravitational Waves



c. 1947, Princeton University

- Most important untested prediction of Einstein
- In GR the GWs propagate at *c* (i.e. the graviton has zero mass) in other theories this is different.
- GWs are produced by accelerated masses (cf EM)
- The flux falls off as r^{-2} also like EM waves
- First radiative multipole is quadrupole and not the dipole
- GWs transverse, e.g. distorts circles into ellipses
- Opaque to EM radiation and barely affected by matter



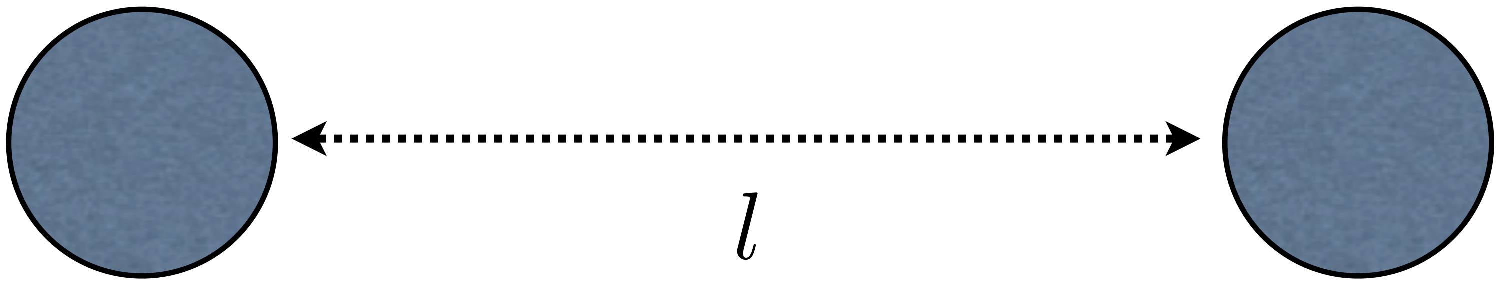


The strain

Amplitude of a gravitational wave can be expressed as:

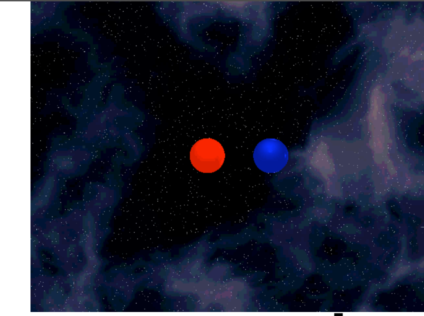
$$h = 2\frac{\delta l}{l}$$

this relative deformation is called the strain



- GWs are part of the curvature of space and not time
- They deform proper distances and not rate clocks run

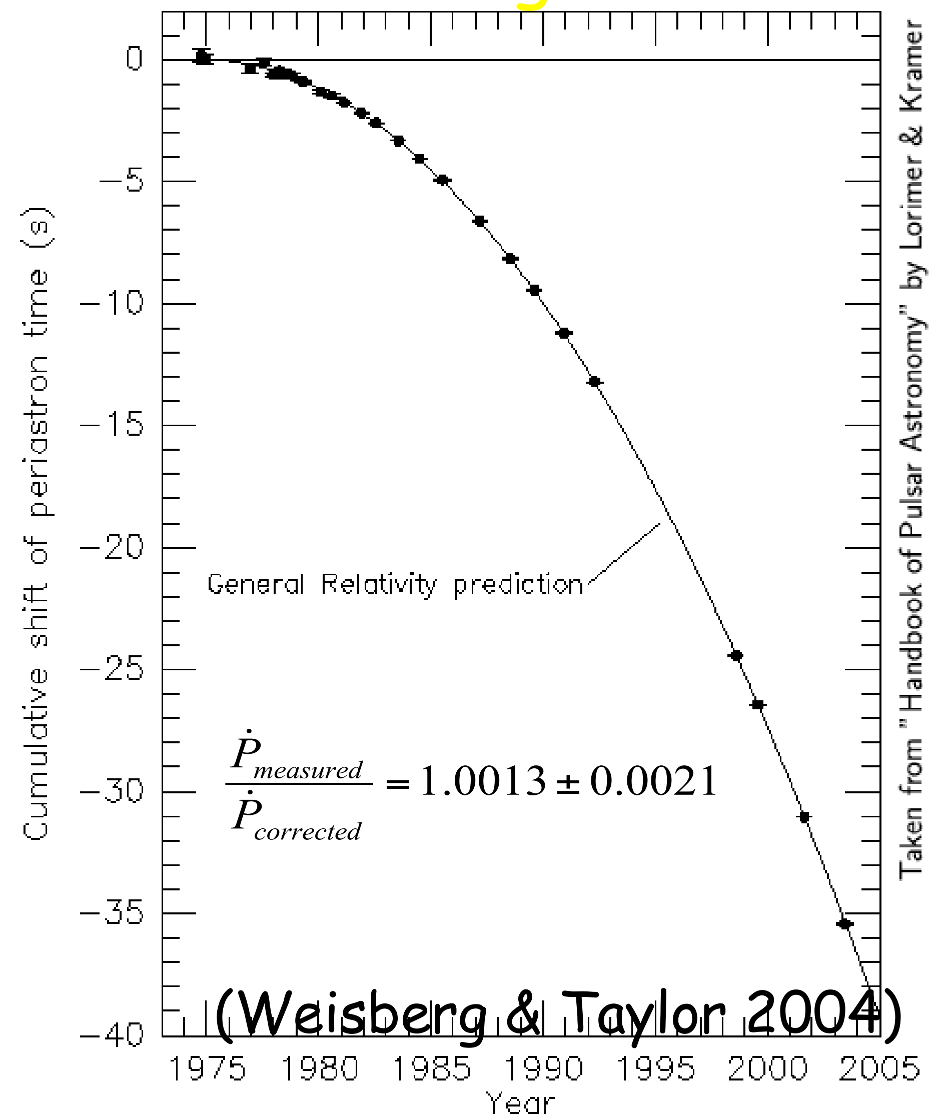
Do they exist?



- In 1975 Hulse & Taylor discovered a double neutron star binary
- Only one of the NSs is visible as a pulsar, P = 59ms
- The large masses and P_b = 7h 45m mean prime GW emitter.

Evidence for grav. waves!

$$\dot{P}_{b,GR} = -\frac{192\ \pi\ G^{5/3}}{5\ c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2}\ \times \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\ m_p\ m_c\ (m_p+m_c)^{-1/3}.$$



(Weisberg & Taylor 2004)

c Nobel Foundation, 1993

c Nobel Foundation, 1993

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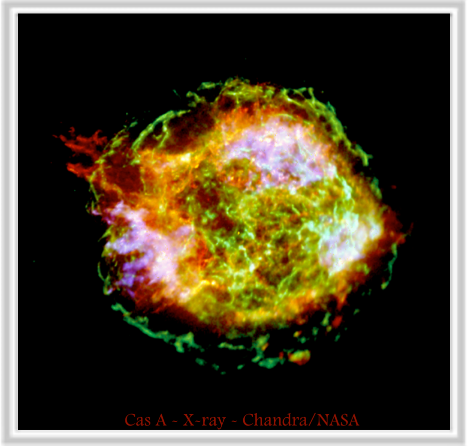
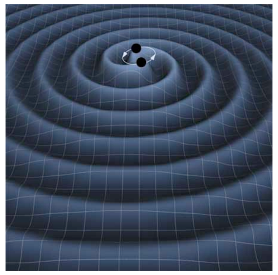
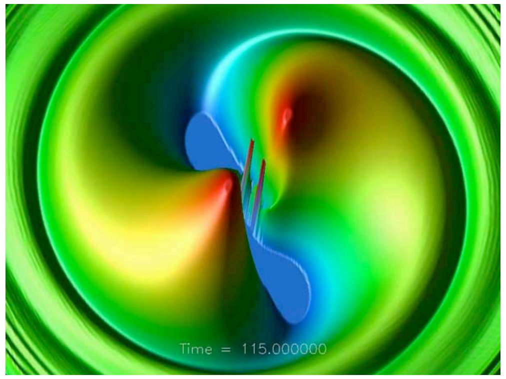
What are some of the sources?



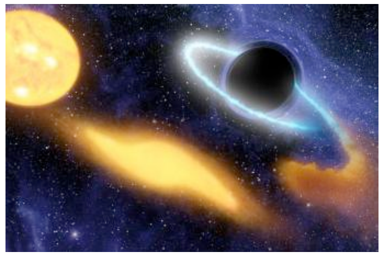
- Gravitational collapse, e.g. SNe, GRBs



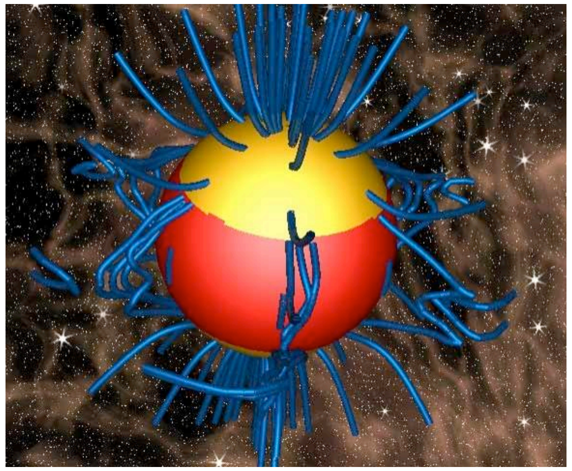
- Binary Stars WD-WD, NS-NS,...



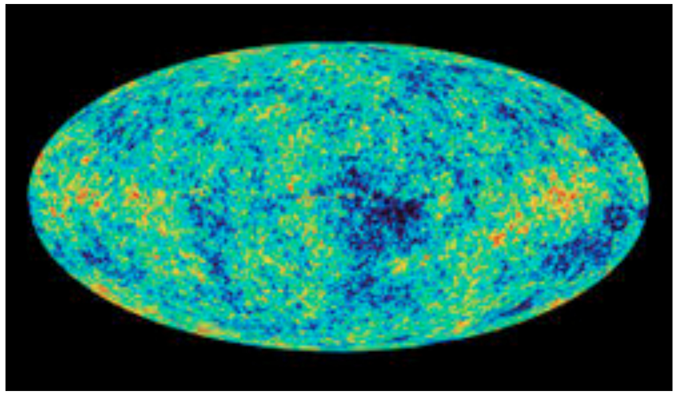
- Merging binaries NS-NS, NS-BH, BH-BH



- Capture events



- Spinning distorted Neutron Stars
- Background sources



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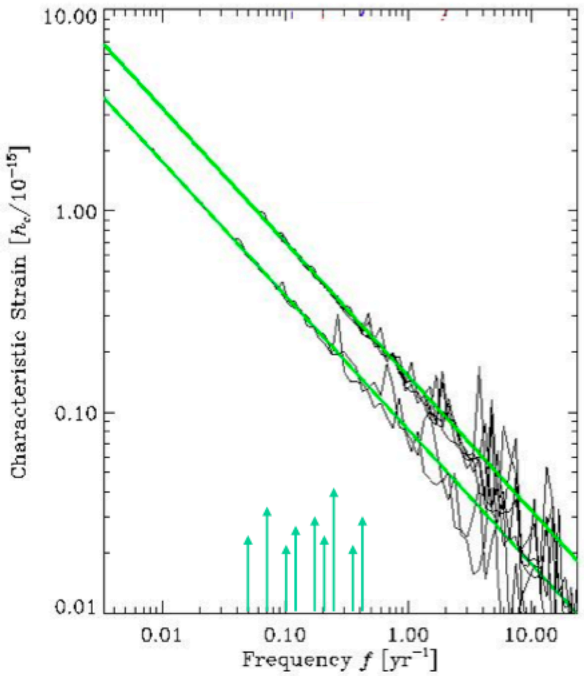
Supermassive Blackholes

- Now well established that most/all galaxies have supermassive BHs at the center.
- Merging is needed in cosmological simulations
- In the early universe may have been large numbers of merging galaxies and thus BHs
- Spectrum of mergers thought to be power law



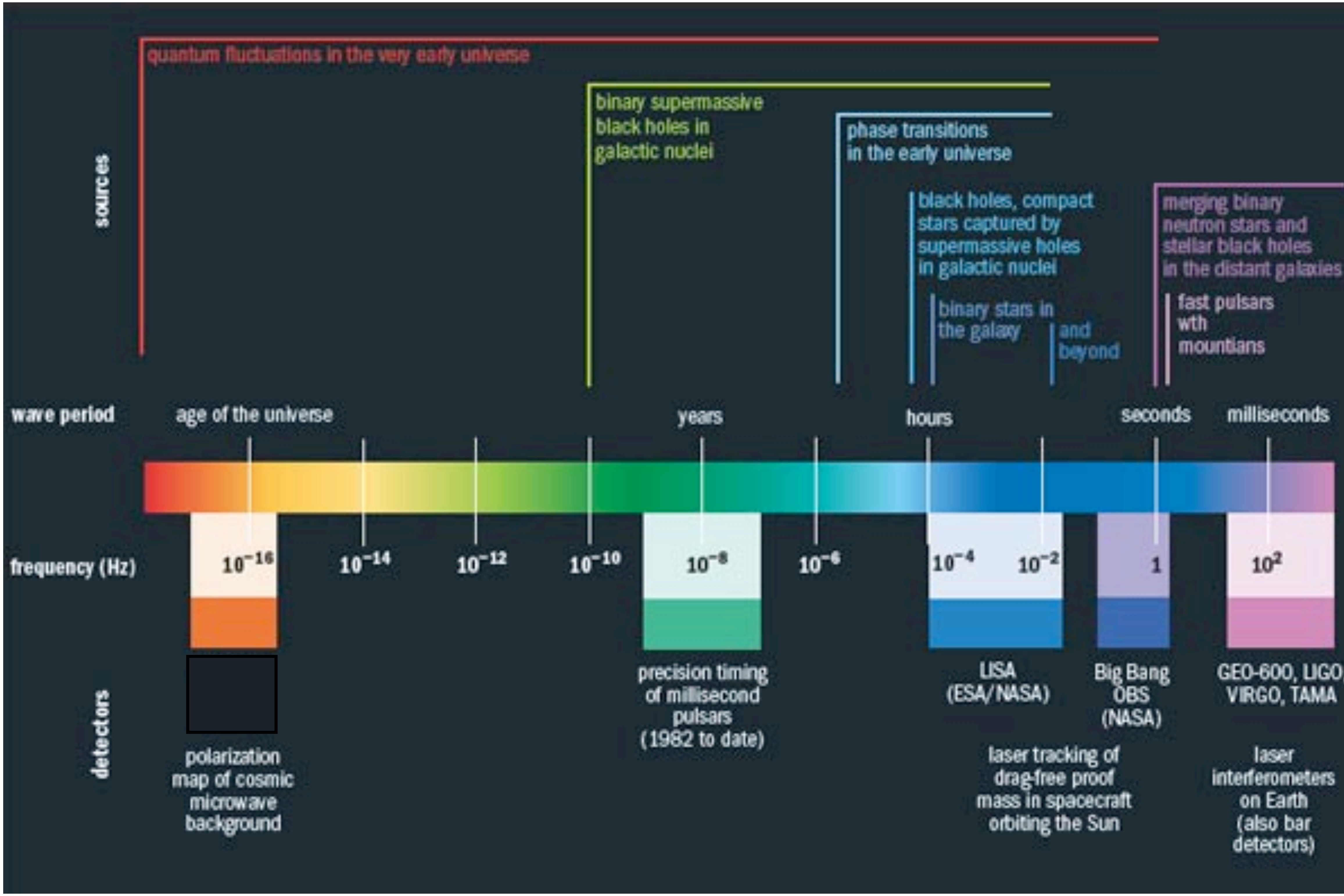
Amplitude = 10^{-15} - 10^{-14}
α = -2/3

e.g. Backer & Jaffe but see Sesana et al 2008 which indicates more complex

Cosmic Strings & Relic GWs

- Cosmic Strings
  - Loops form and oscillate and emit GWs
  - New Loops are formed from strings
  - There is a whole range of loop sizes
  - This leads to a stochastic background of GWs
  - Expected spectrum has slope -7/6
  - Amplitude is in range 10^{-16}-10^{-14}
- Waves from Planck Era amplified by Inflation
  - Might be seen in at all frequencies
  - Most likely only detected in CMB band
  - Physics of the BB, inflation and equation of state of early universe
- Phase Transitions in Very Early Universe
  - As universe expanded, fundamental forces decoupled from each other; phase transition at each decoupling produced gravitational waves; GW's redshifted with expansion
  - Probe high-energy physics, e.g. strength of electroweak phase transition; probe topological defects & evolution of inhomogeneities produced by phase transition

GW Spectrum

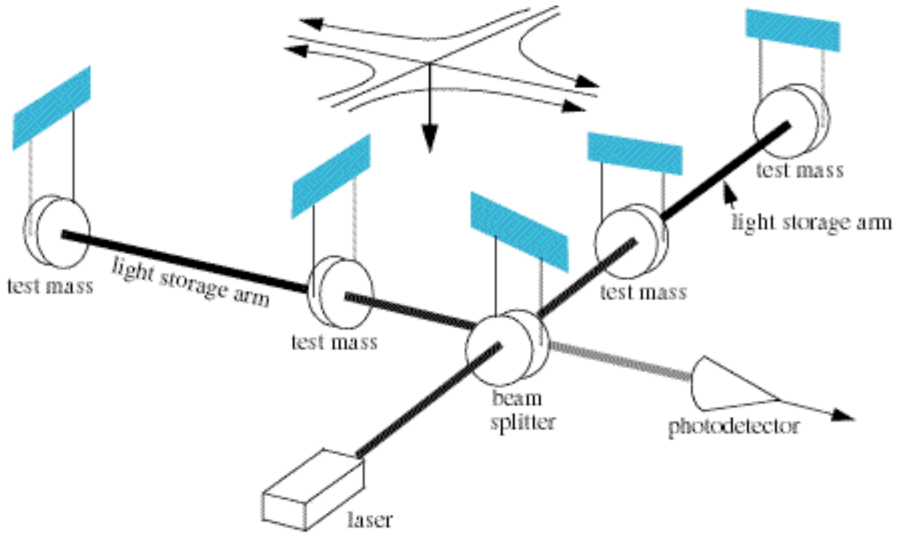


images.iop.org

How are gravitational waves detected?

- The passage of a gravitational wave causes a change in the proper distance between objects. So anything traversing that distance will be sensitive to that change

- The amplitude of this displacement is very small! A “large” amplitude GW will change the length of 1m by 10^{-20}m



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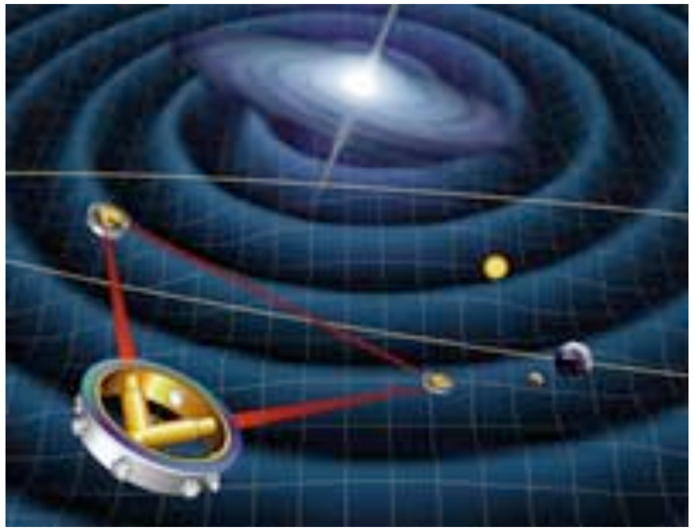

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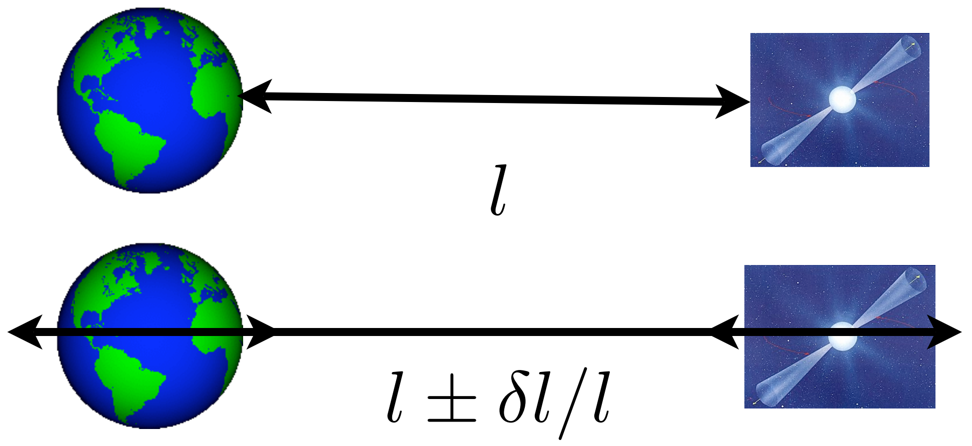
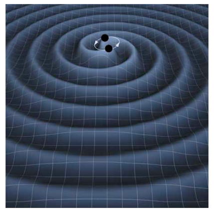
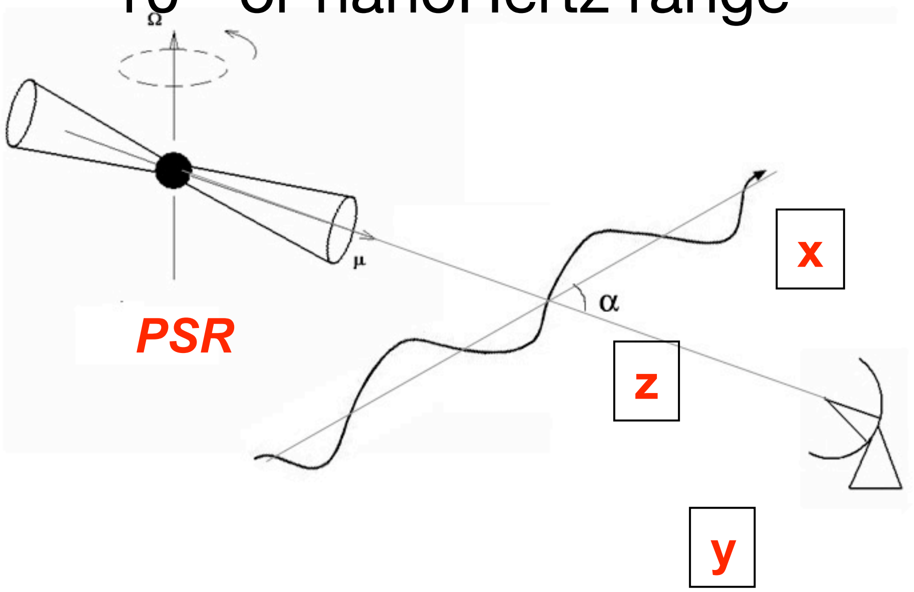
Using Pulsars to detect GWs

- PSR and Earth can be considered as end masses of a free-mass gravitational wave antenna
- Relative motion of the masses is monitored by observing the Doppler shift of the pulsar arrival times
- Frequencies in range ~1/yr up to 1/(length of data span) they are therefore in the 10^{-8} - 10^{-9} or nanoHertz range





Na



$$\frac{\Delta\nu}{\nu} = -\frac{1}{2}\int \frac{\partial h_{zz}}{\partial t}\, dl$$

Earth term Pulsar Term

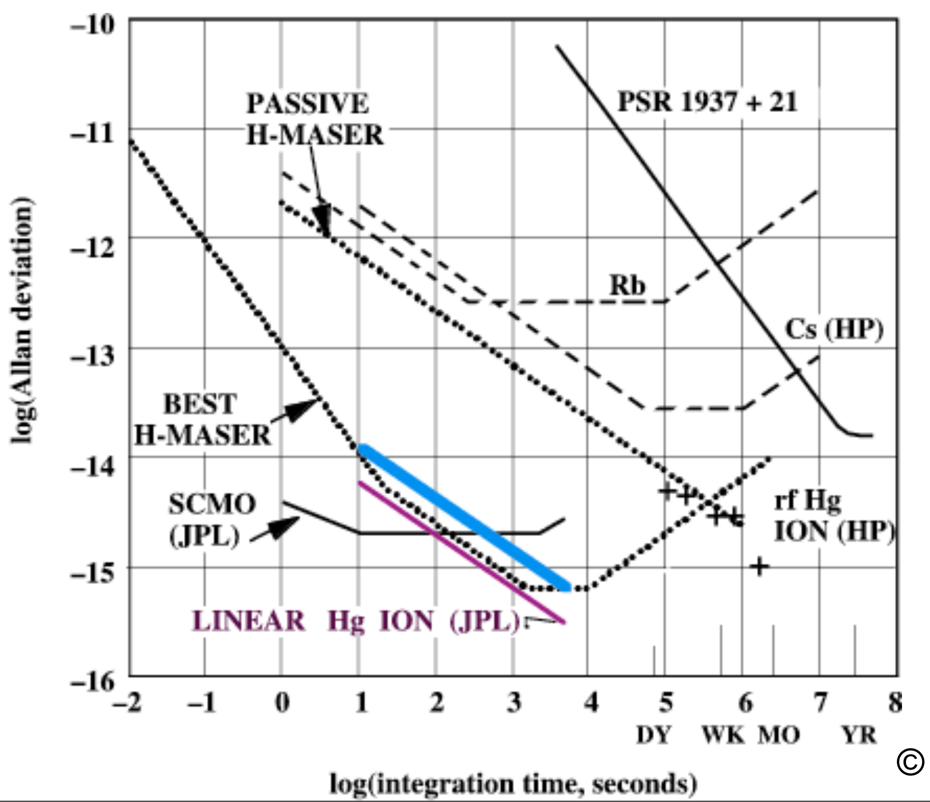
$$\frac{\Delta\nu}{\nu} \sim \frac{1}{2}\cos 2\phi\left[1-\cos\alpha\right]\left[h(t) - h(t - D - D\cos\alpha)\right]$$

distance

polarisation

Why are pulsars good for detecting them?

- The extremely large moment of inertia of pulsars means that they are exceptionally stable rotators
- The very regular arrival times of the pulsars mean that they are very good clocks, they rival the best atomic clocks
- By measuring changes in the rate in which these clocks run we can measure changes in the proper distance to the source, thus we have a very long interferometer.

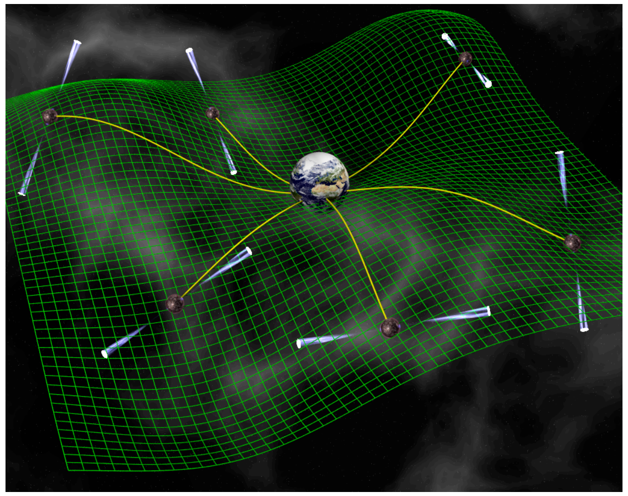


Pulsar Timing Array

- Single pulsar limits are constraining they suffer from noise intrinsic to the pulsar itself
- Combining the signals of many pulsars can remove that dependence
- The effect of GWs is uncorrelated at the locations of the pulsars but correlated at the location of the Earth!

Correlation for each pair of pulsars gives

$$\zeta(\theta) = \frac{3}{2}x\log(x) - \frac{x}{4} + \frac{1}{2} + \frac{1}{2}\delta(x)$$

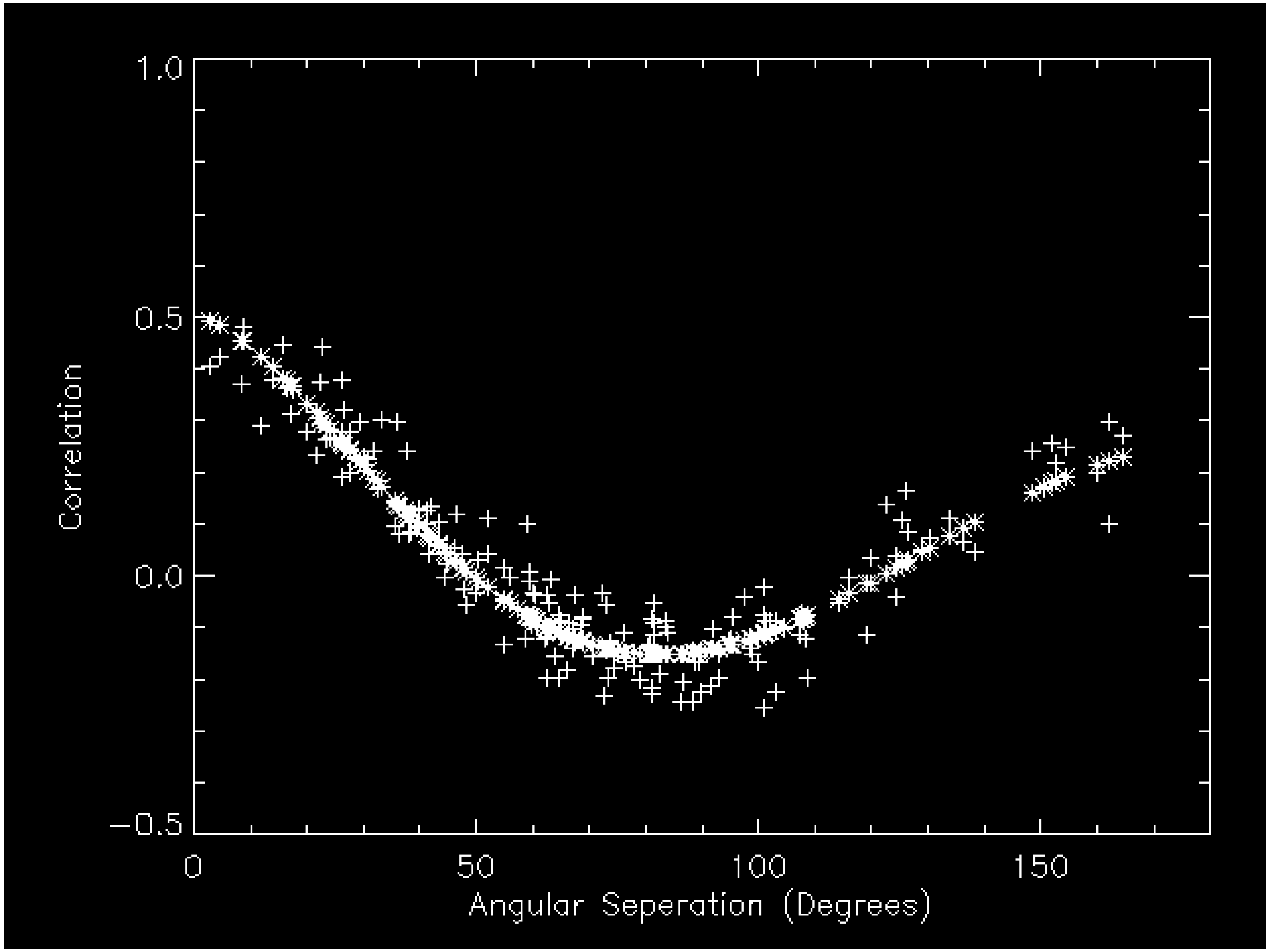


Champion & Kramer

$$x = (1 - \cos(\theta))/2$$

where θ is the angle between the pulsars

Correlation



e.g. Jenet et al 2005, 2006

What might be needed to detect it?

- Observations of at least 20 MSPs over a period of at least 5 years.
- MSPs must be well distributed across the sky i.e. lots of angles between pulsars
- Sufficiently long timeline to be able to get the spectral slope
- Timing precision, i.e. Average difference between the timing model and the actual TOAs of 100ns or better for the entire sample!
- How detection significance improves with timing precision, number of pulsars, observation baseline is area of study.

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The competition

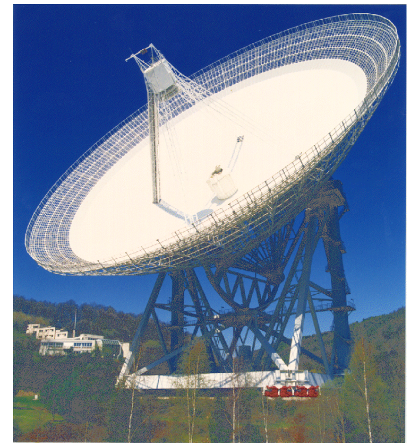
PPTA

✳ Longest running, started ~3/4 years ago
✳ Best funded, through grants to Manchester, Bailes and Jenet
✳ Developed lots of excellent tools
✳ Currently achieving the best results
✳ Fundamentally limited by the size of the dish

nanoGrav

✳ Just getting started as a collaboration
✳ Two of the best telescopes in the world
✳ Excellent record in high precision timing
✳ Limited number of sources
✳ Limited amount of telescope time

EPTA



- Larger total number of arrival time measurements
- Commensurate scheduling will allow for improved binary and yearly phase coverage
- A wide range of frequencies can be sampled and then compared in quasi-simultaneous sessions.
- Simultaneous same frequency observations can be used to check polarisation calibration and overall timing offsets.
- Telescope, Instrumentation, or Observatory clock based errors can be quickly identified and corrected. (e.g. 1937+21)
- Only disadvantage is the lack of a really big telescope...

LEAP

- Large European Array for Pulsars
- Combine signals from all telescopes coherently
- Equivalent of largest dish on Earth, but can point anywhere in the sky
- Best sensitivity and best flexibility!
- 5 year project thought up by BWS/MK funded through MK’s ERC grant
- 7 postdocs spread throughout Europe (2 in Manchester) + equipment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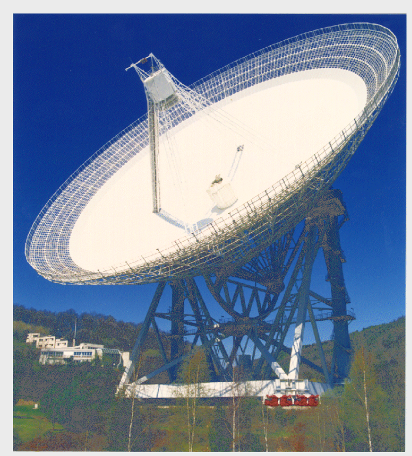
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SRT

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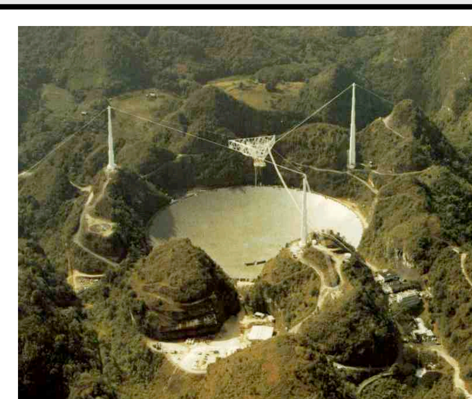
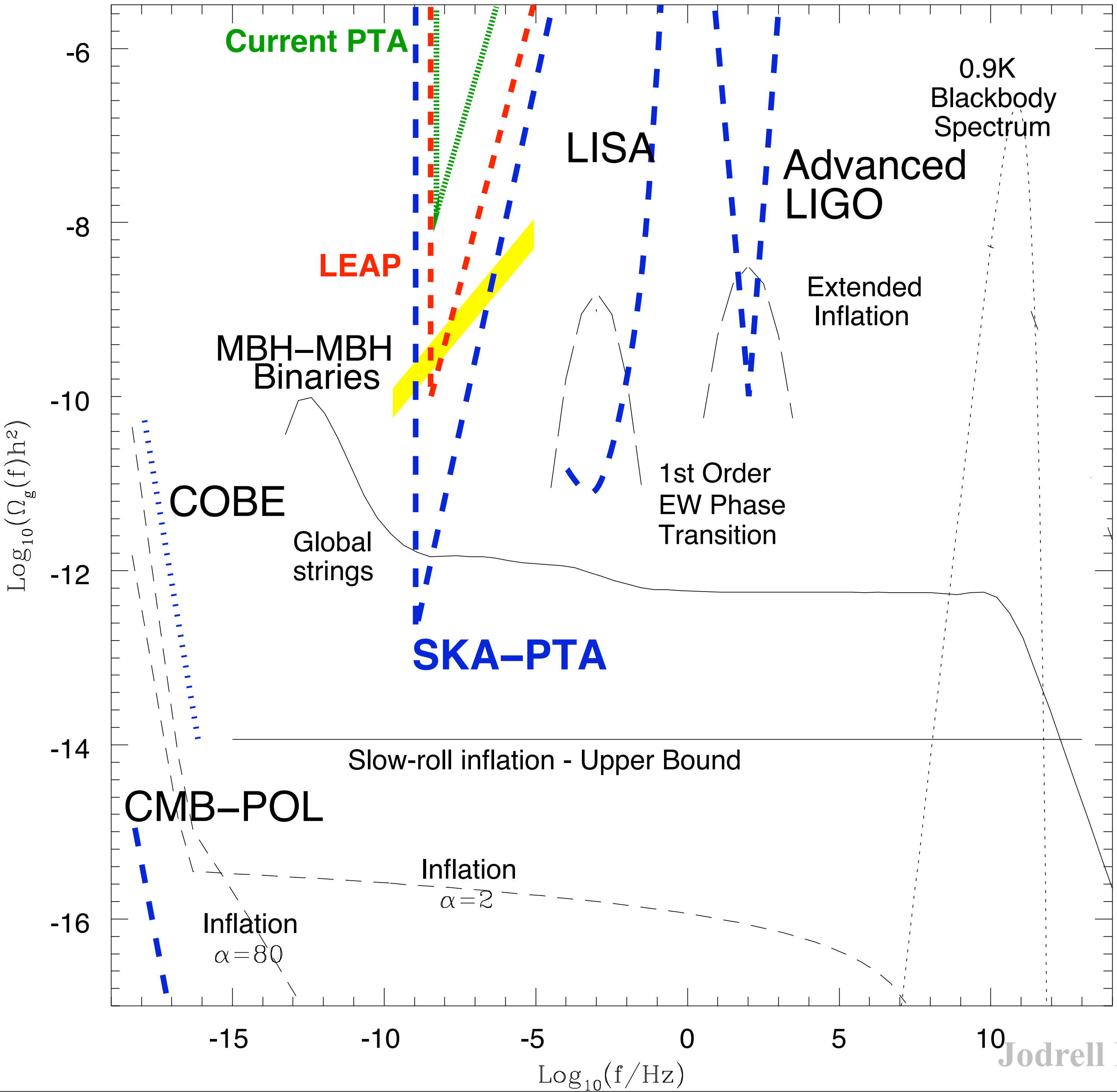


The gravitational wave spectrum



The Practicalities

- Baseband record to disk at least 100 MHz of bandwidth at all telescopes at a central frequency near 1380 MHz
- Observe calibrators, before, during?, after pulsar observations
- Observing sessions of up to 24 hours (34.5 Terabytes of data per telescope!)
- Transport data to Jodrell Bank to be processed on a 560 node cluster
- Use calibrators to determine phases, apply these to the pulsar data, generate baseband data streams
- Data streams processed using standard pulsar tools.

Issues

- Will it work! Should do, scale up from WSRT...
- Different backends, currently have 3 telescopes with same backend, two unique.
- Different beam shapes (also in VLBI so ok? and only interested (to start with) in point source
- How often do we need to go to a calibrator? Can we use the pulsar to calibrate?
- Is there enough computing power for the software correlator?
- Nancay doesn't have a maser, but they do do high precision timing.
- Can we get the timing issues sorted out?

Where does eVLBI come in?

- Advice, and lots of it!
- All of the issues mentioned previously are similar to those faced with eVLBI
- Practicalities of implementations and use of software correlators, especially with non-hetrogeneous data
- Potential of using fibre connections for data transport, but 100 MHz BW means 400 MByte/s data rates (8-bit)
- Potential for incorporating this capability into future generation correlators?
- Expanding beyond the present 5 telescopes

Conclusions

- VLBI is an important part of the pulsar astronomers toolbox and eVLBI makes it more accessible
- The mantra for pulsars with the SKA is "Find them, Time them, VLBI them" but there is no reason not to start now
- The astrometric parameters being derived in the current projects are proving invaluable for studies varying from SN physics to birth places to tests of GR
- With the LEAP project we believe we have an excellent chance to be the first to directly detect GWs.