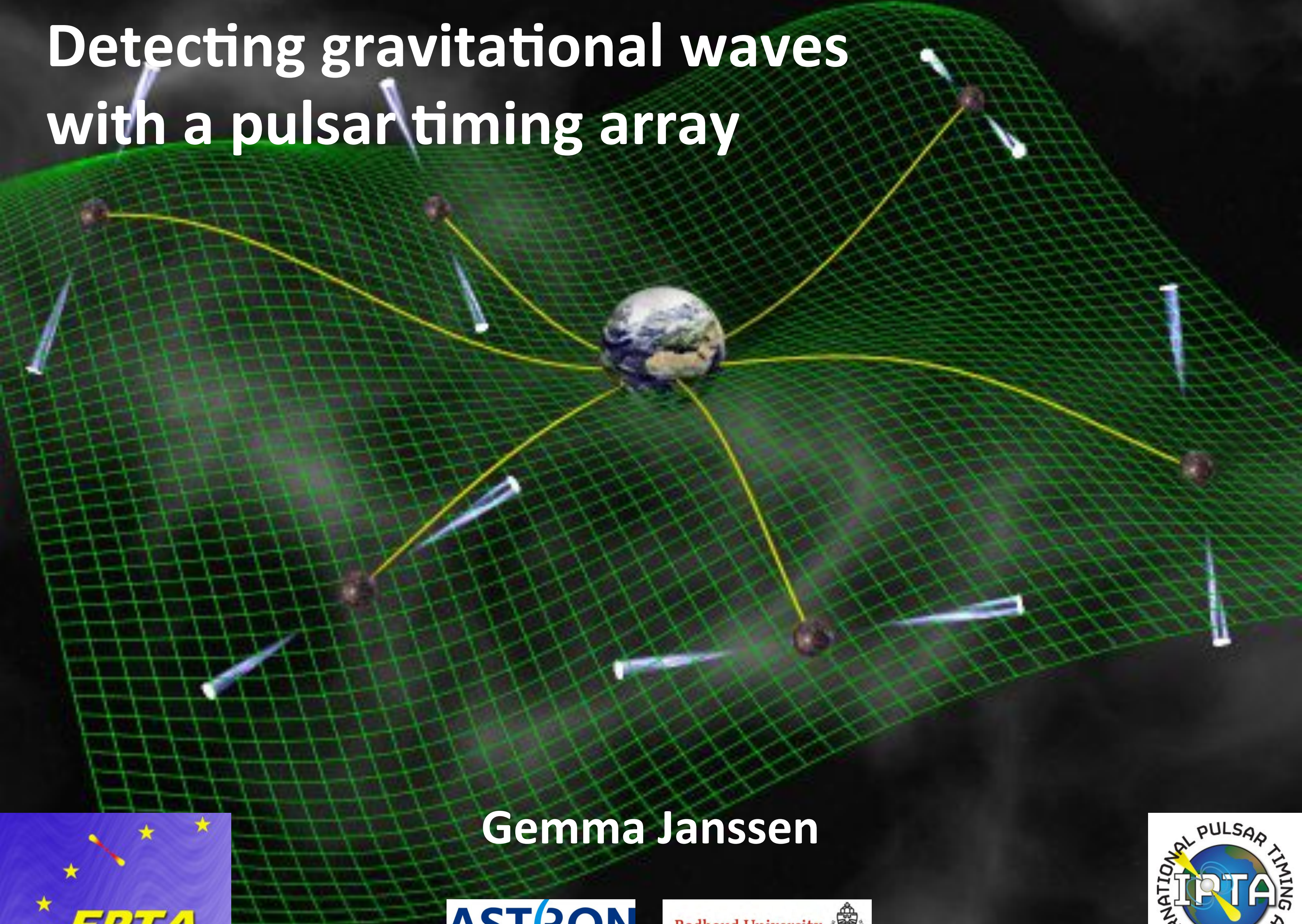
Detecting gravitational waves with a pulsar timing array



Gemma Janssen

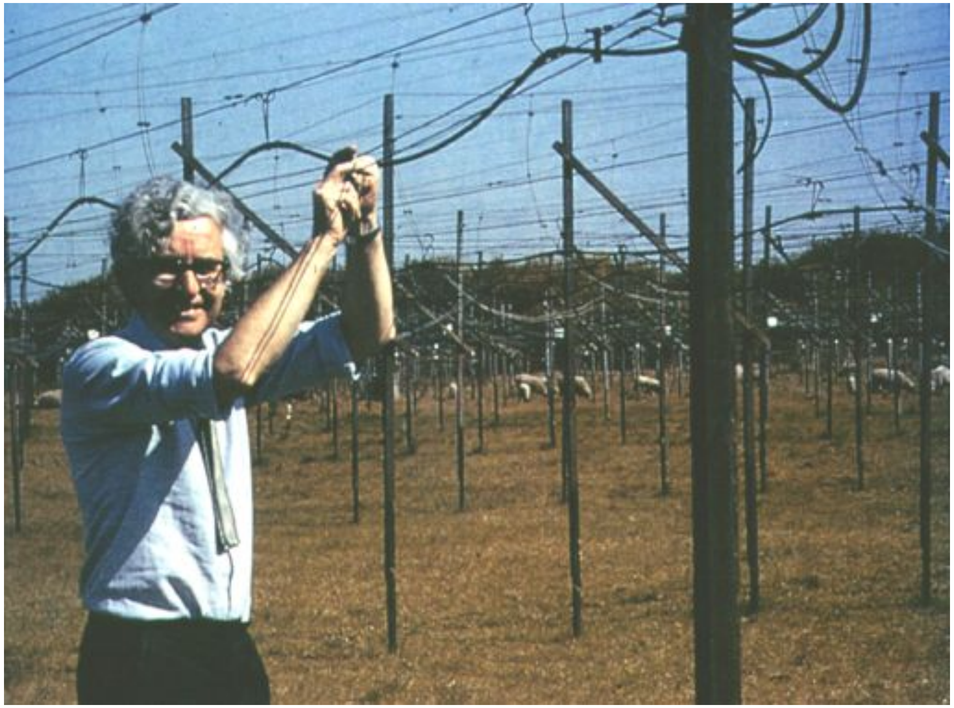
EPTA

ASTRON

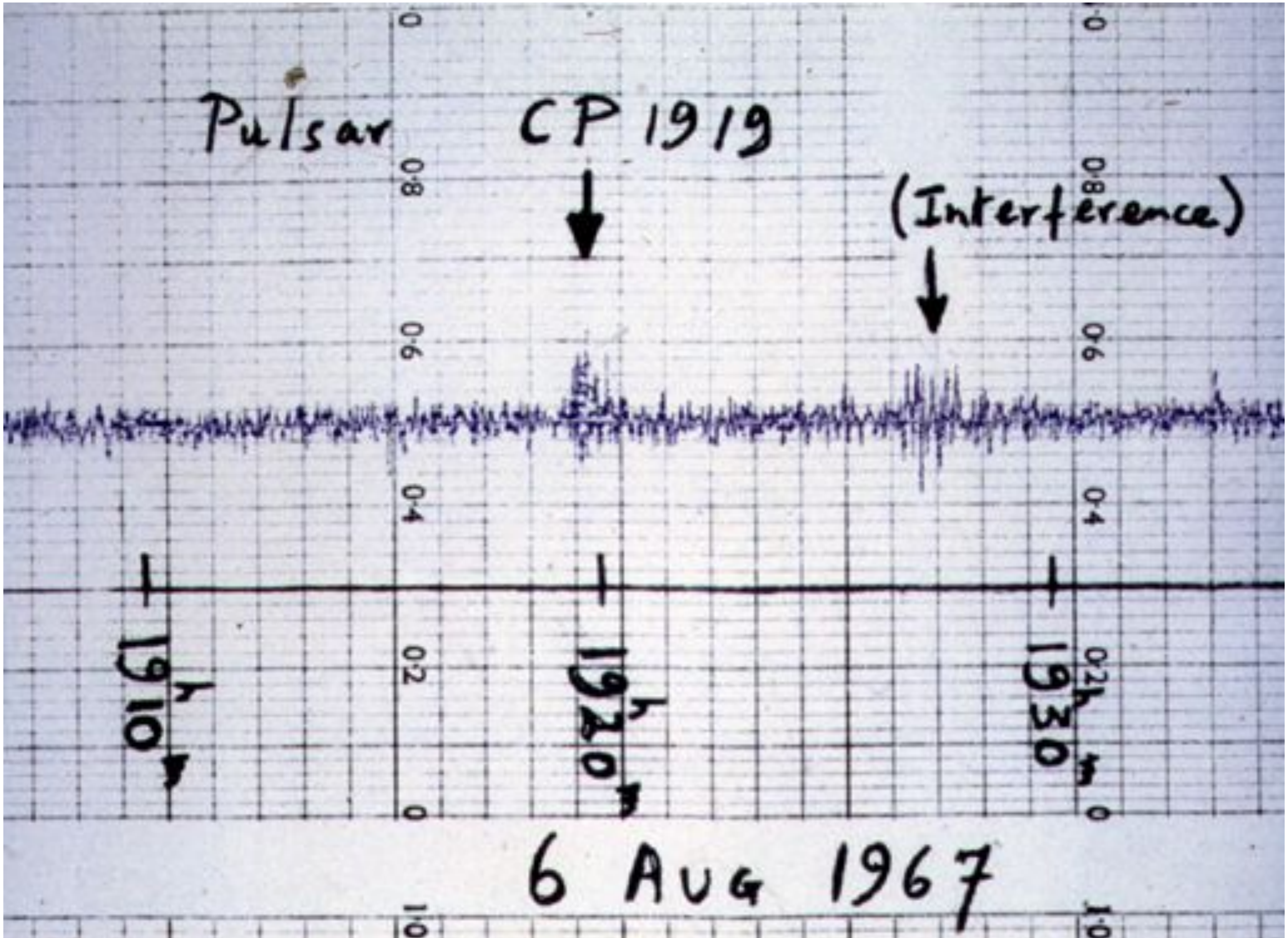
Radboud University

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

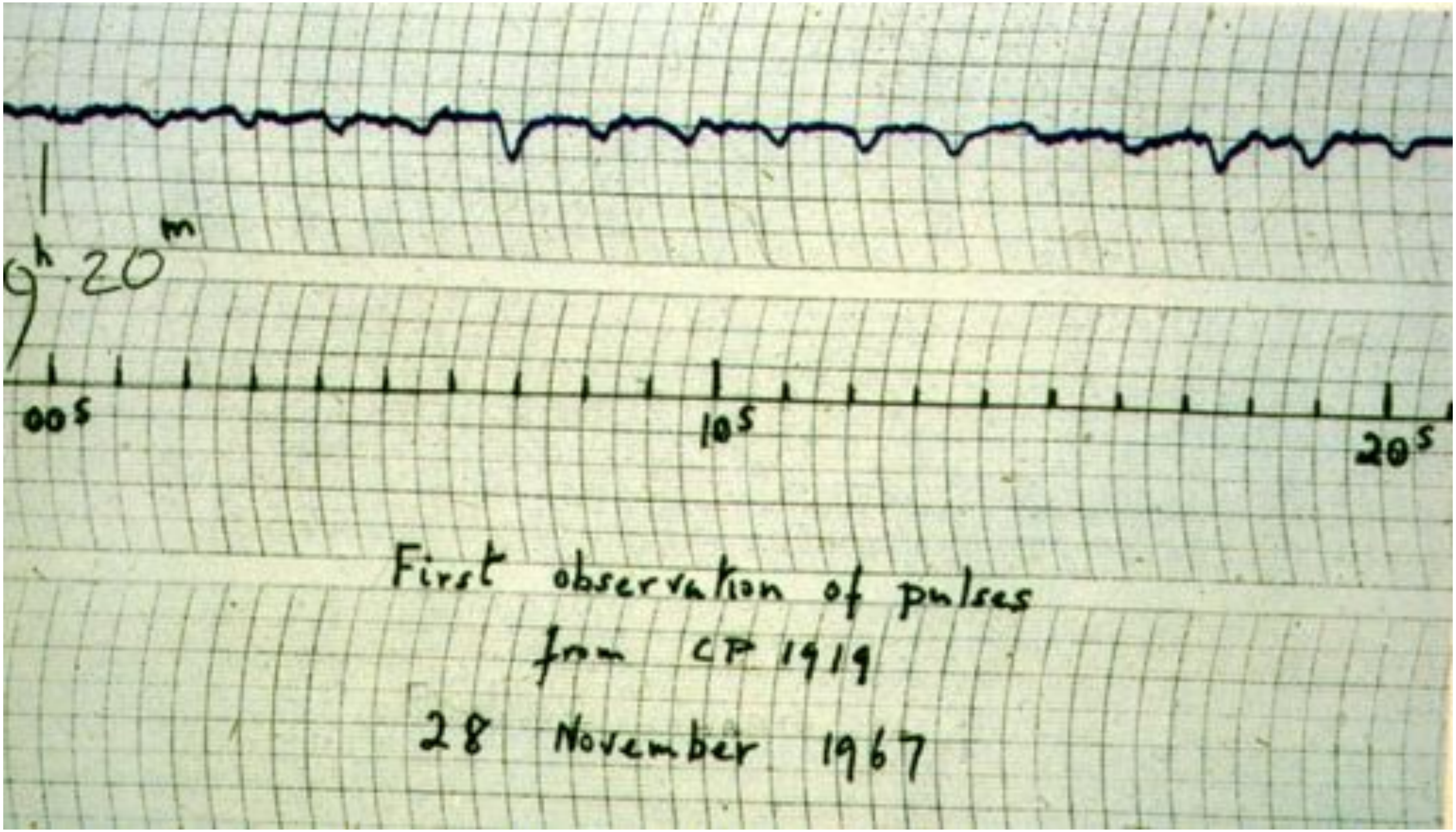
The discovery of pulsars



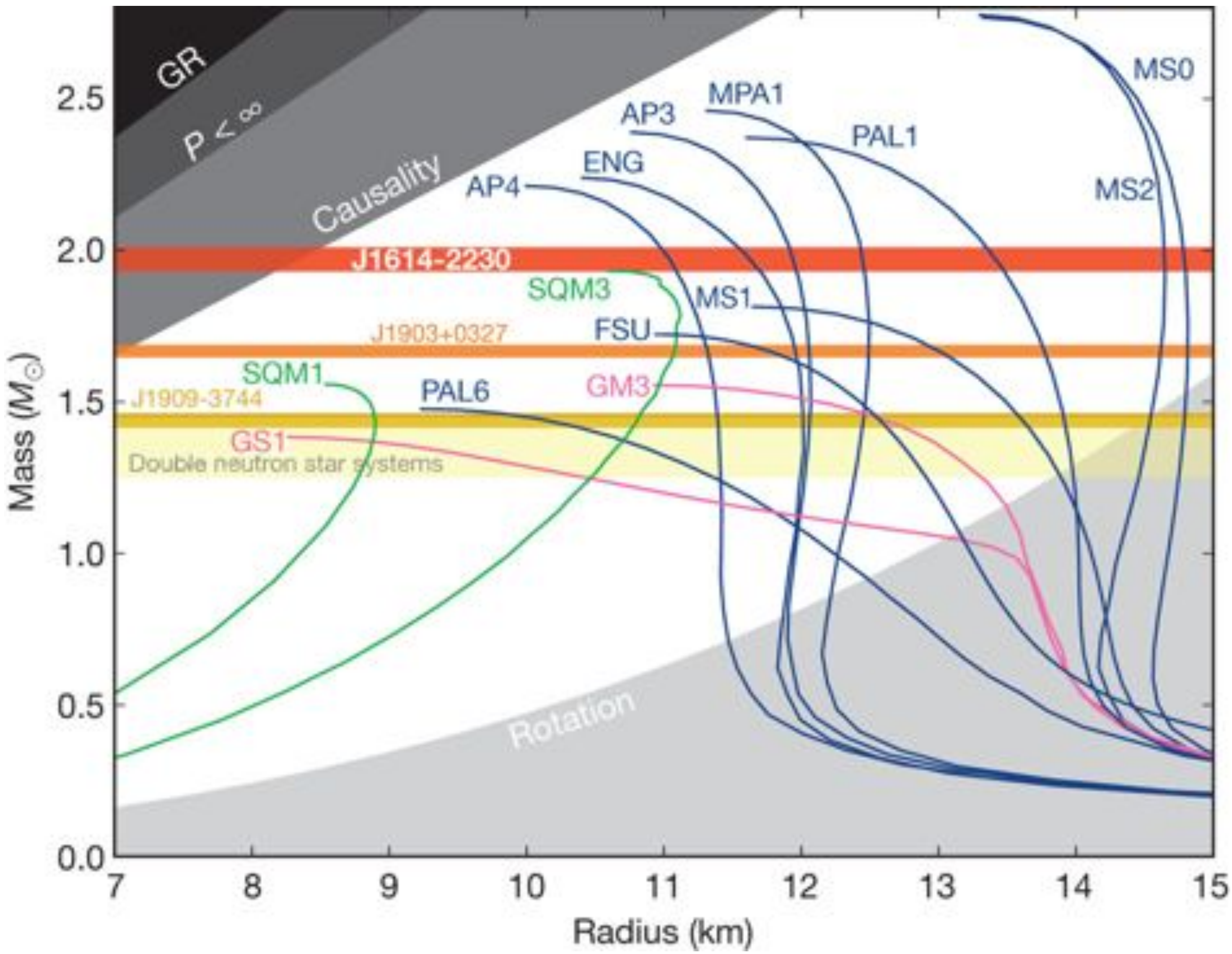
The first signal



The first signal

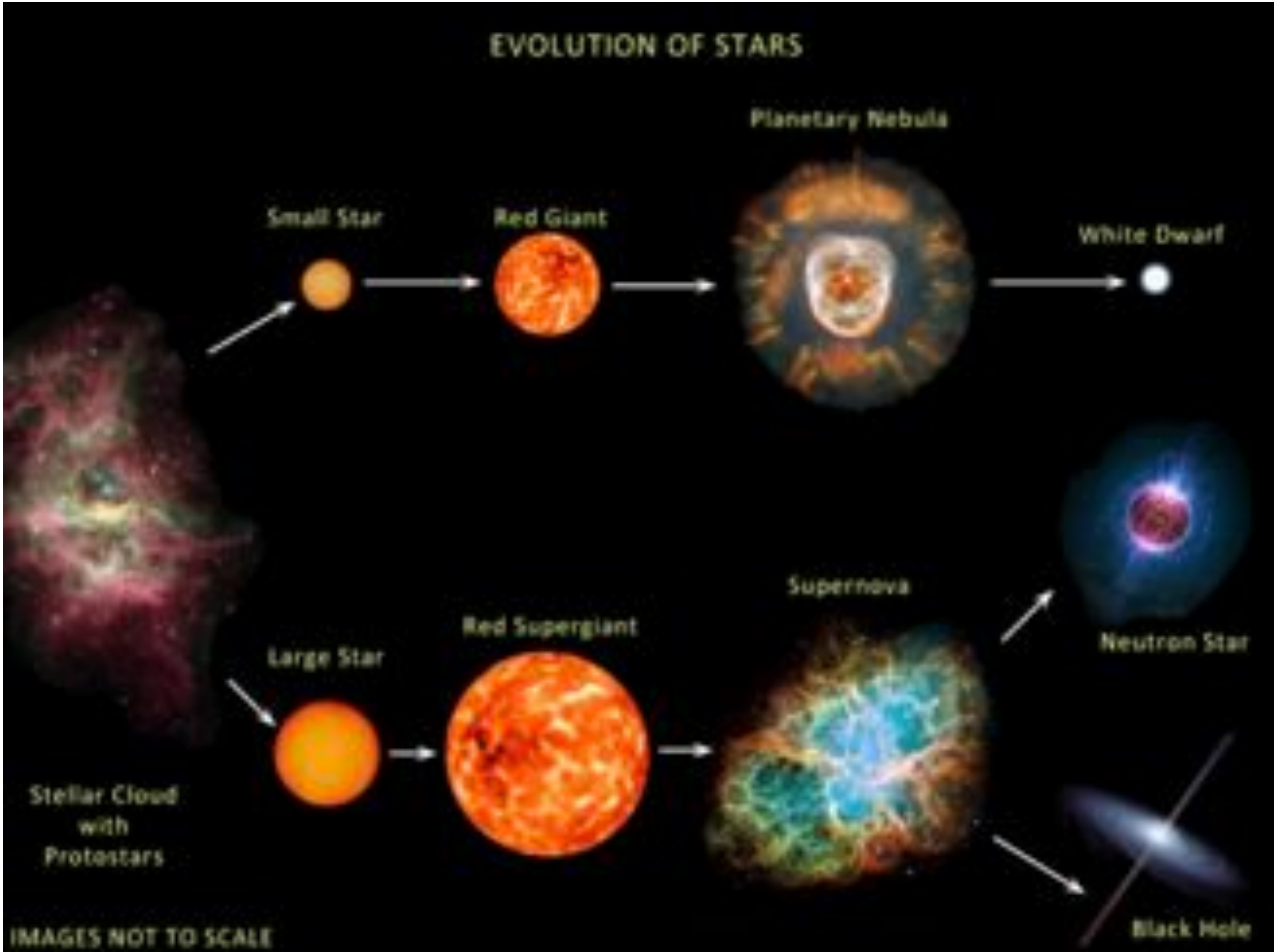


What is a neutron star?



Demorest et al., 2010, Nature, 467, 1081

Pulsars: end products of stellar evolution



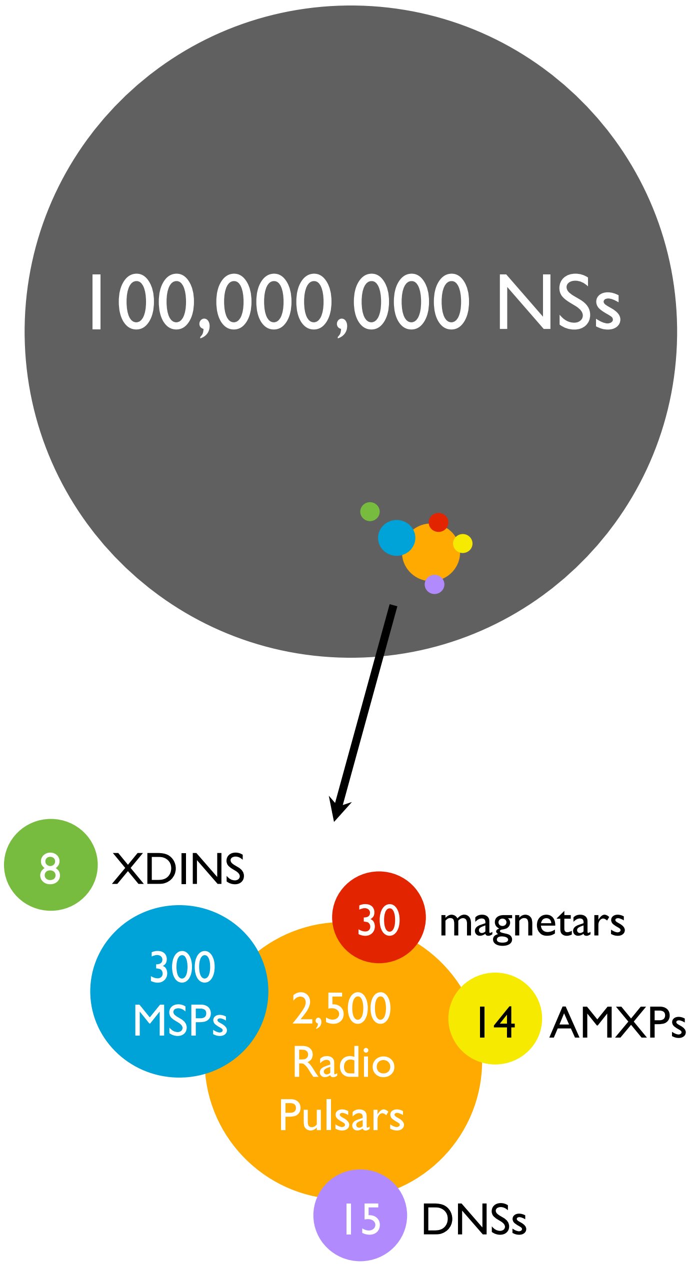
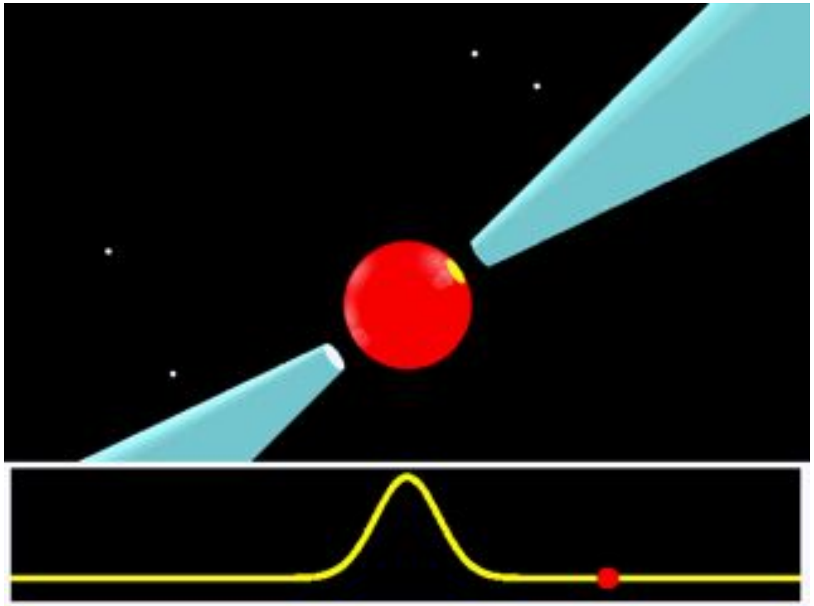


Image: Hessels

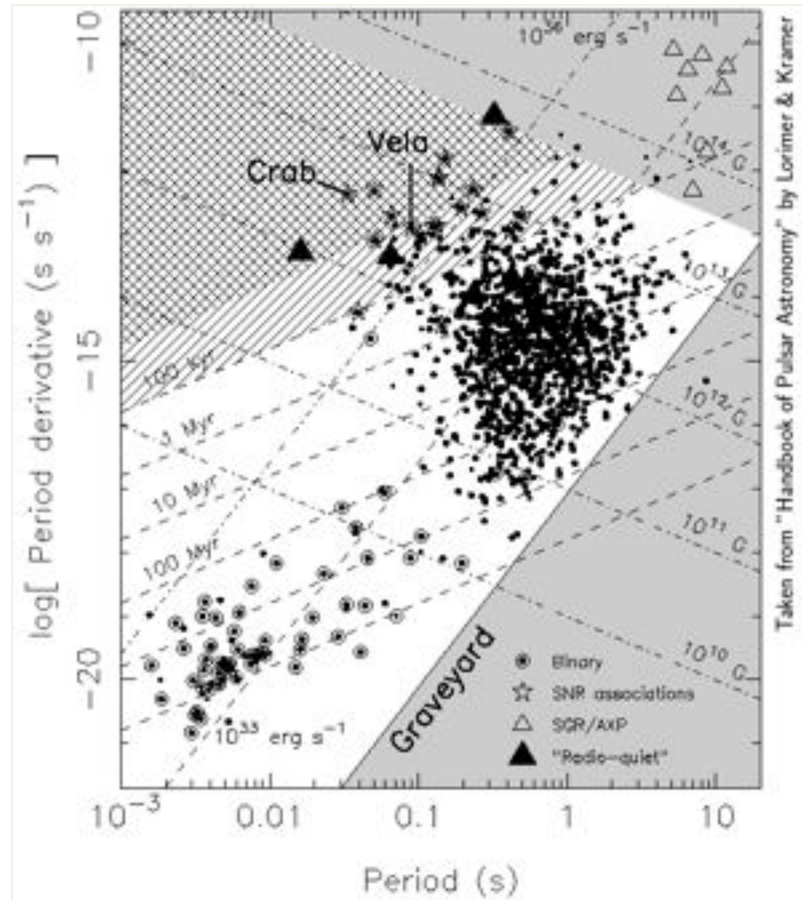
Pulsars and Neutron Stars

- There are thought to be ~100 million neutron stars in the Milky Way.
- The Galactic pulsar population is estimated to be around only 30,000 (0.03% of all neutron stars).
- Currently only 2,500 radio pulsars are known.

Pulsars: compact objects



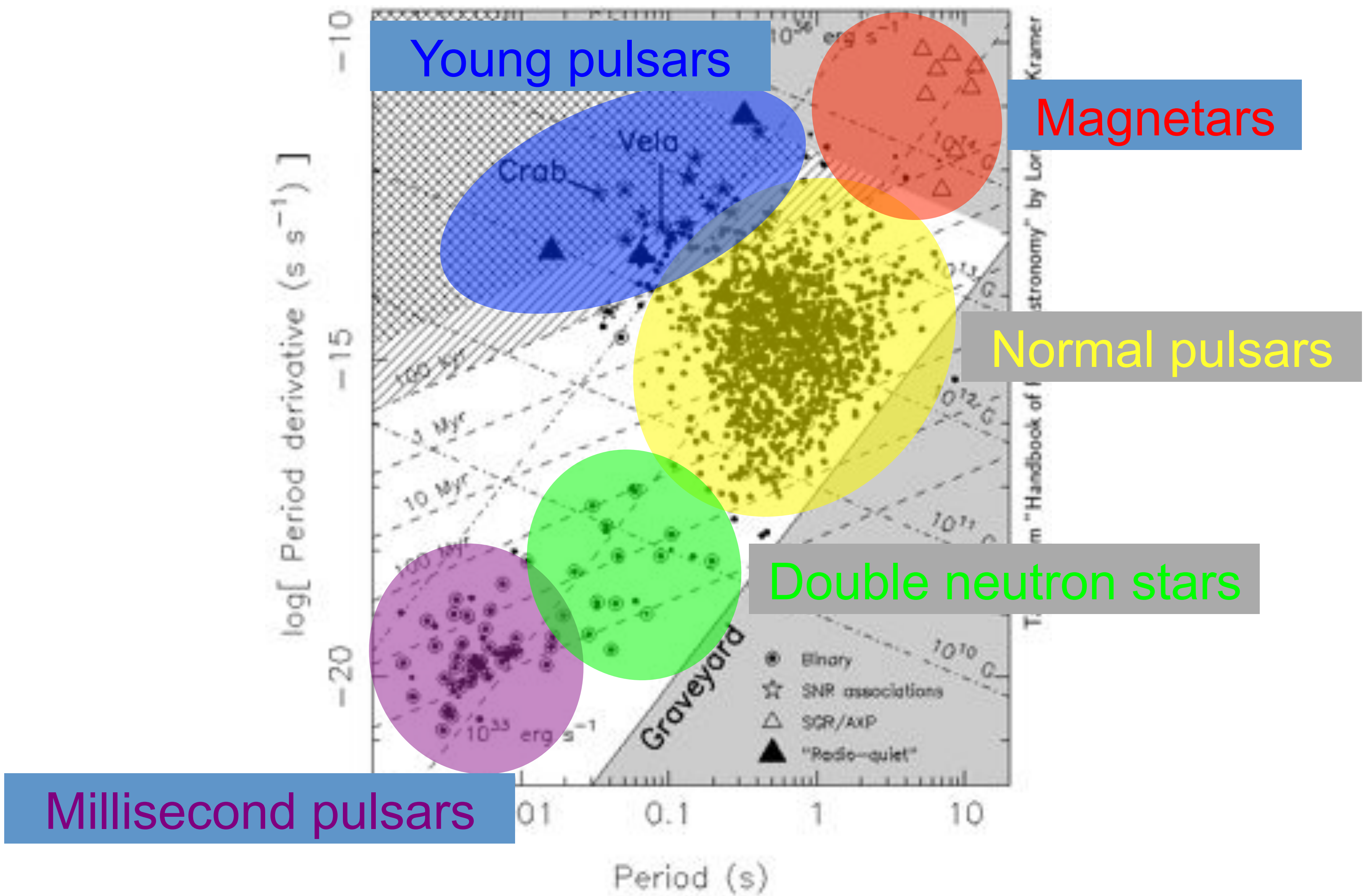
Highly magnetised,
rapidly rotating neutron stars



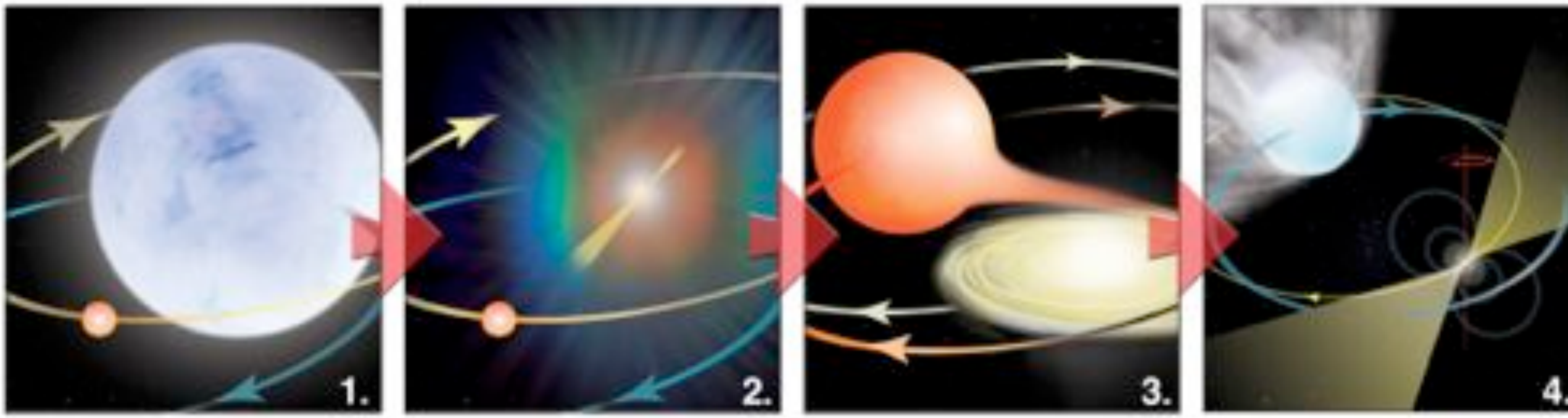
Pulsars are very stable rotators,
used as **cosmic clocks**

Figure: Pulsar Handbook (Lorimer & Kramer)

P-Pdot Diagram



Formation of Millisecond Pulsars
pulsar “recycling”



1. Start with a massive star with a lower-mass companion. (a binary system)
2. The massive star goes supernova and forms a young pulsar.
3. The companion evolves, fills its Roche lobe (gravitational equipotential), and begins mass transfer.
4. The accretion transfers angular momentum to the pulsar, thereby increasing its spin rate.

Pulsar observations in NL: Westerbork Synthesis Radio Telescope

Part of the European Pulsar Timing Array collaboration

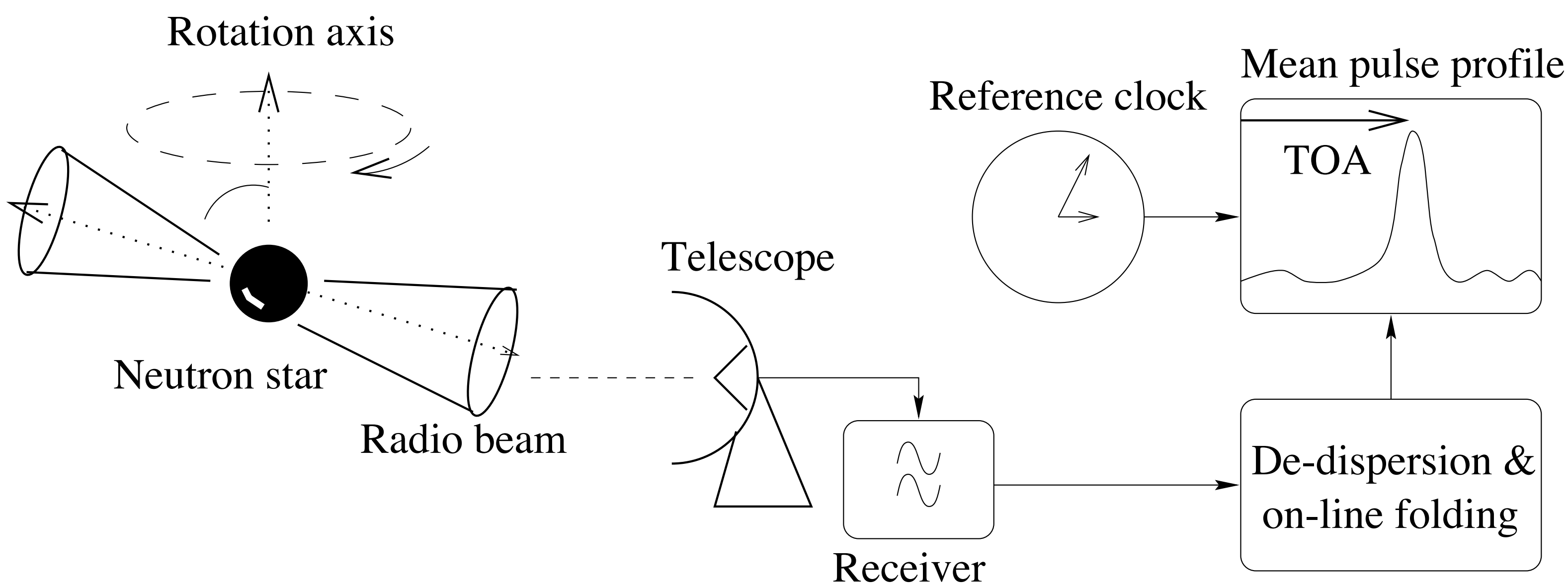
Pulsar observations in NL: Low-Frequency Array (LOFAR)

Pulsar timing observations at very low frequencies: 100-200MHz

VERY good for ISM work!

Pulsar Timing

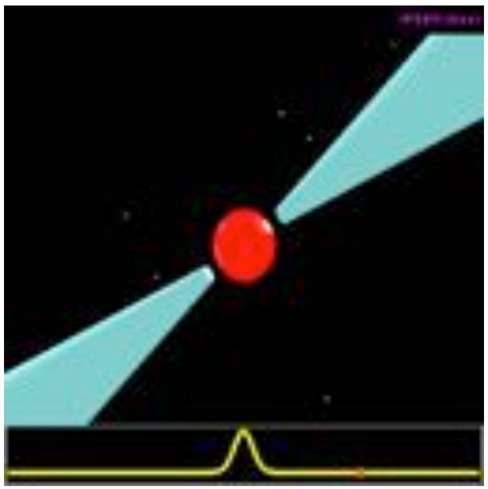
Pulsars are very stable rotators, use as cosmic clocks



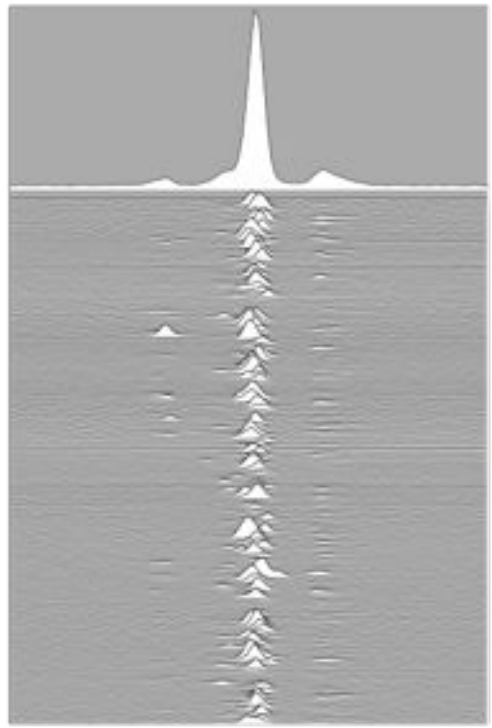
Pulsar timing is about measuring the arrival times of pulses at many different epochs and then determining a model for the physical effects that influence the *observed* rotation rate of the pulsar.

Figure: Pulsar Handbook (Lorimer & Kramer)

Pulsar Timing



Collect pulses in timing observation

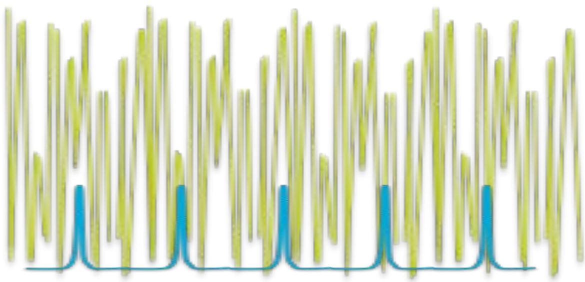


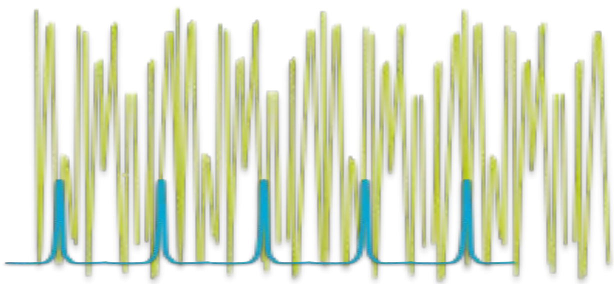
Dedisperse, fold and cross-correlate with template

54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688

Times of arrival ("**TOAs**", measured in Modified Julian Day)

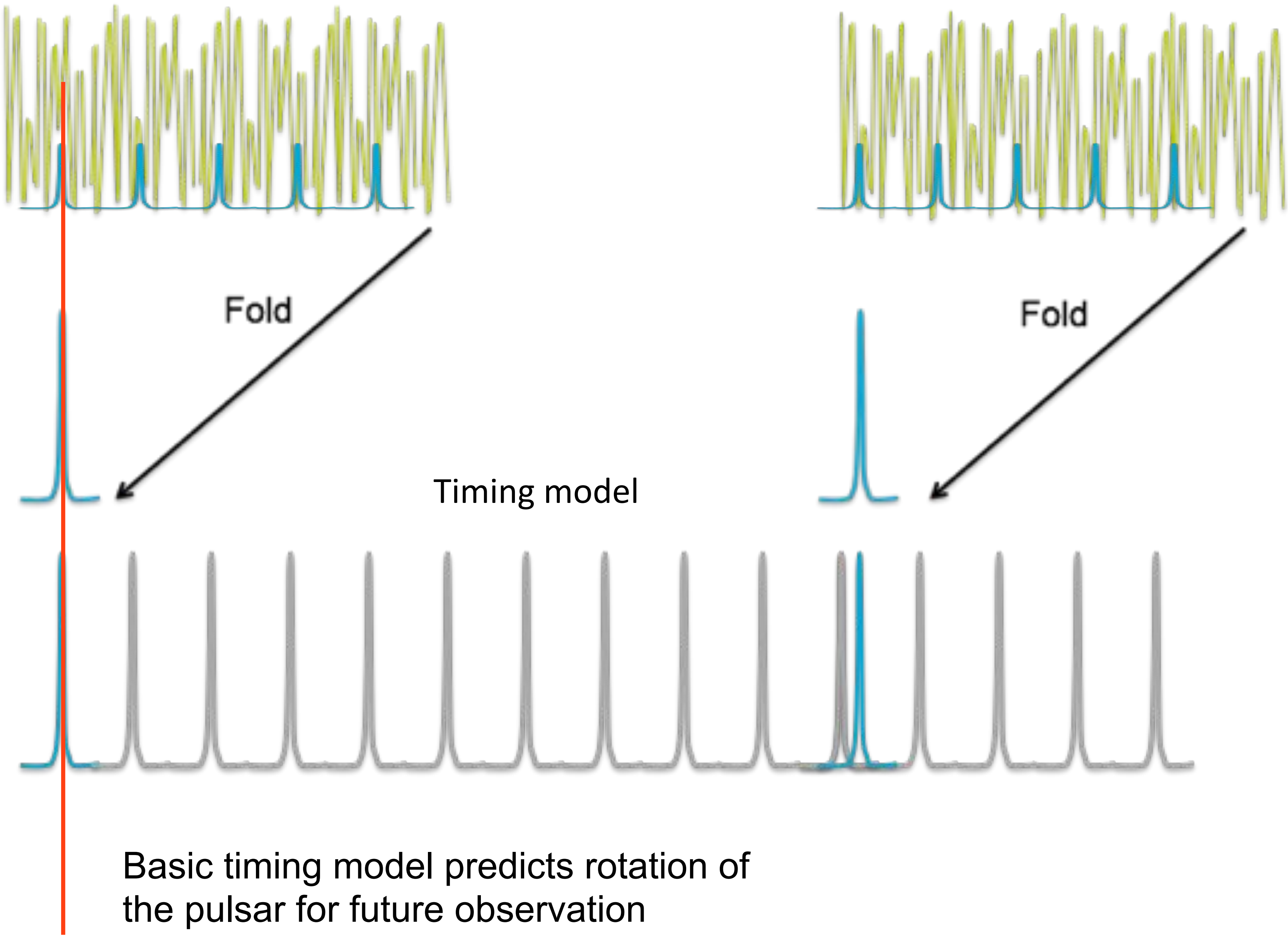
Pulsar Timing





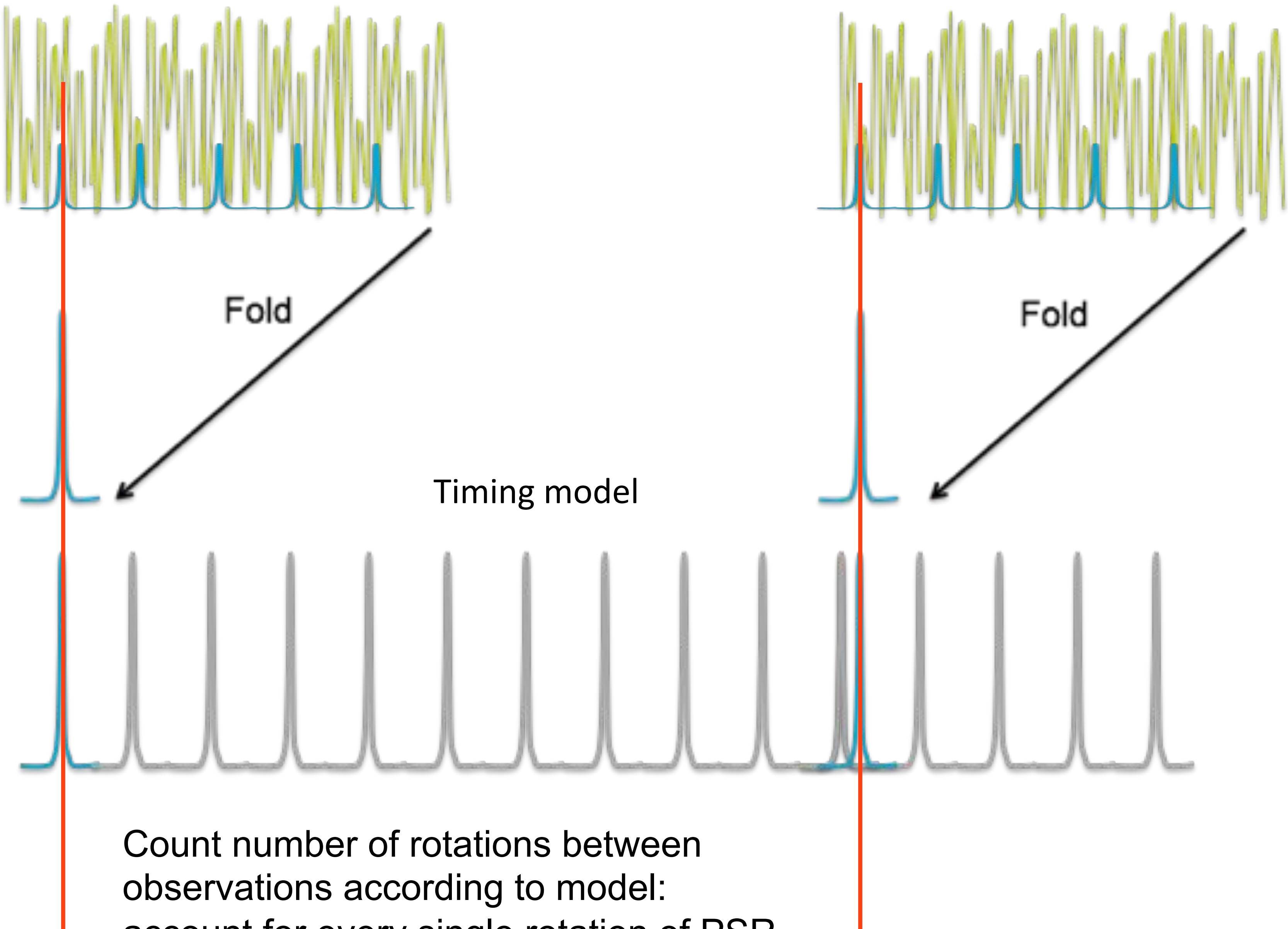
individual pulses are buried in the noise

Pulsar Timing



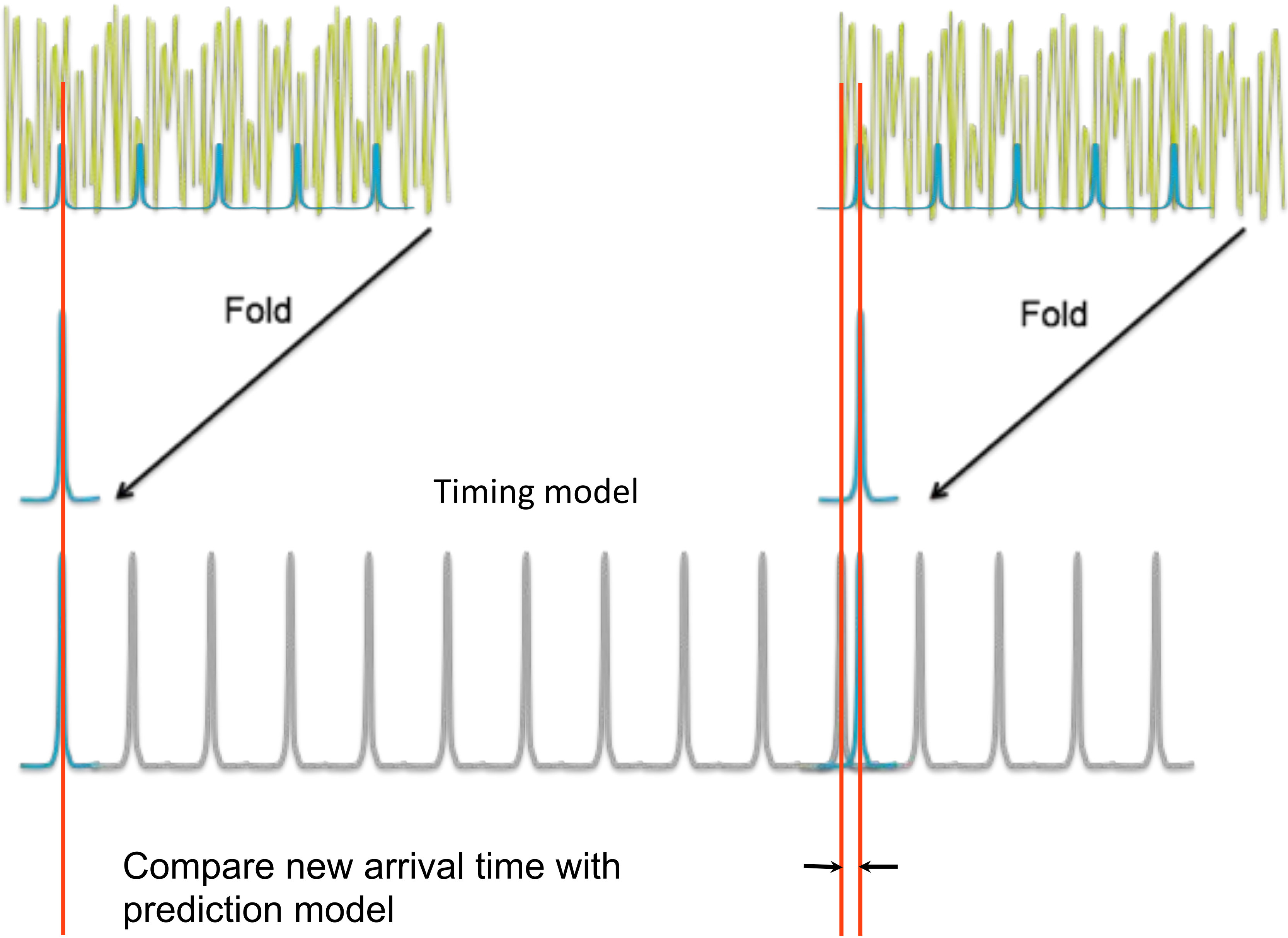
Basic timing model predicts rotation of the pulsar for future observation

Pulsar Timing



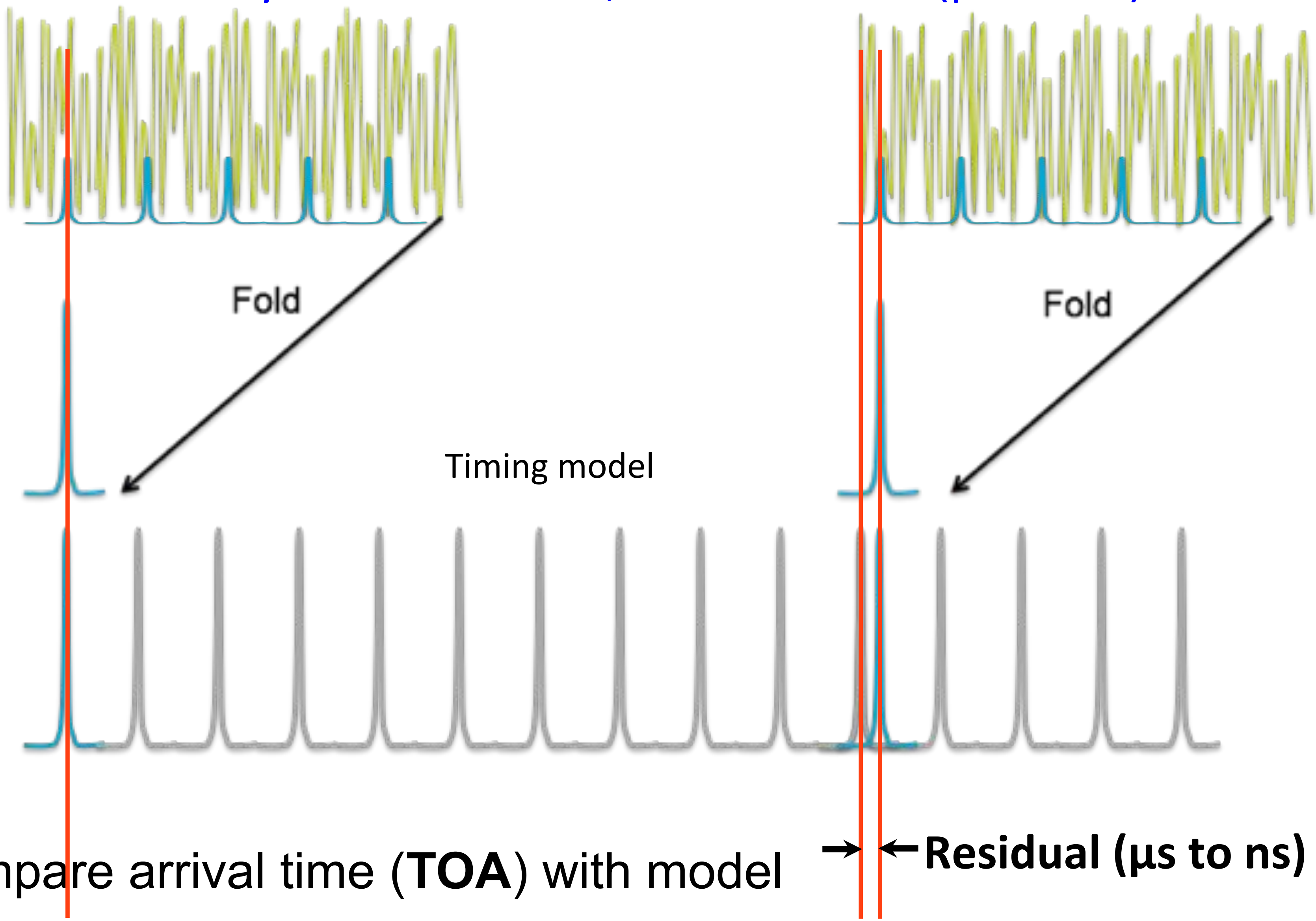
Count number of rotations between observations according to model: account for every single rotation of PSR

Pulsar Timing



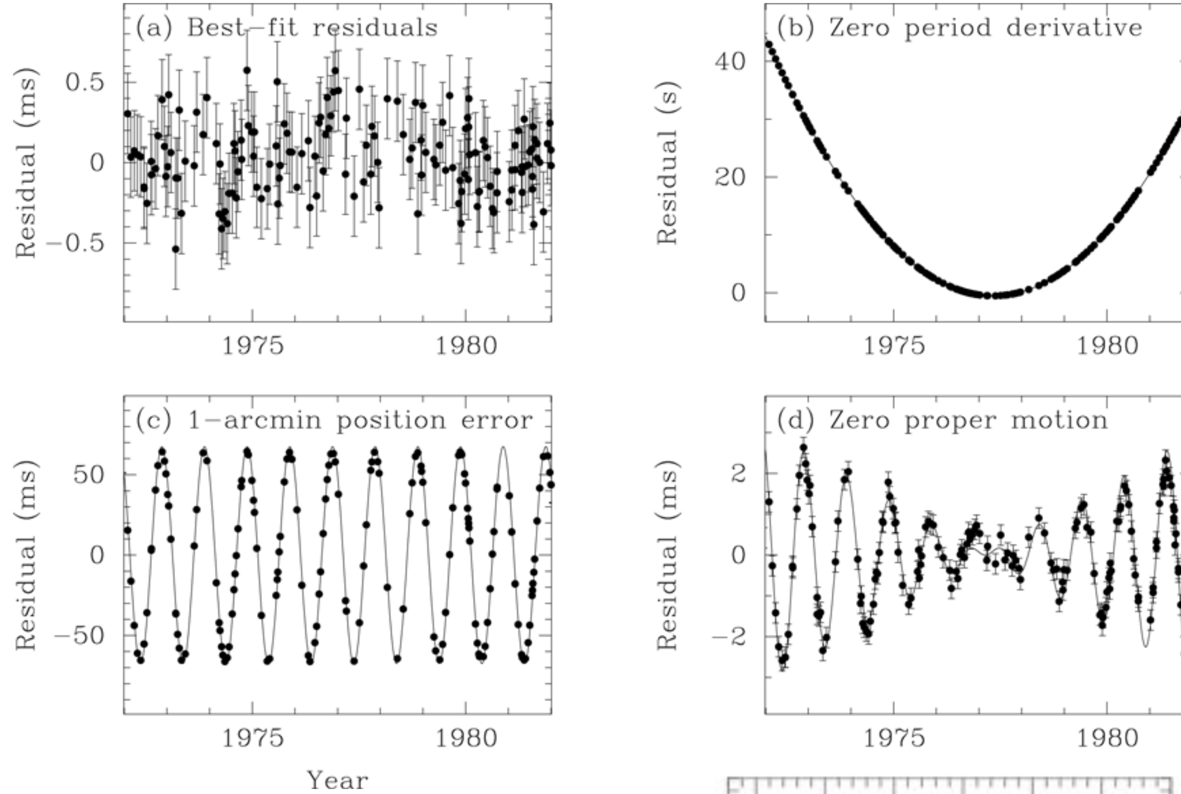
Pulsar Timing

Pulsars are very stable rotators, use as cosmic (perfect?) clocks



compare arrival time (**TOA**) with model

Pulsar timing: Residuals



Timing model contains:

-Rotational, astrometric, binary parameters

Unmodelled effects:

-measurement errors

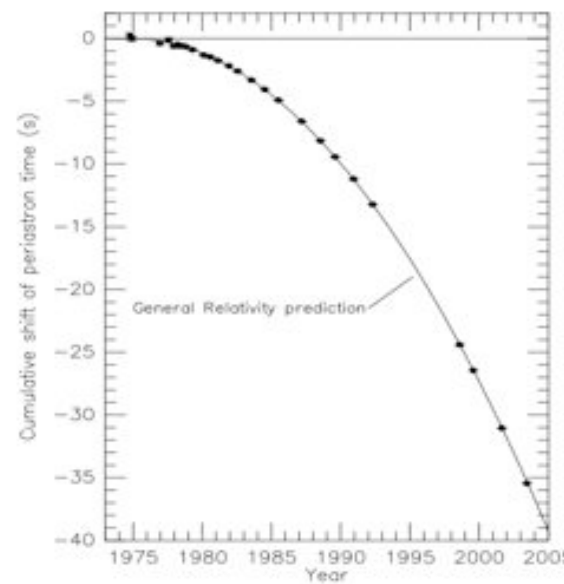
-spin irregularities

-interstellar weather effects

-gravitational waves

GWs first *indirectly* detected by pulsar timing

Nobel prize Hulse & Taylor 1993

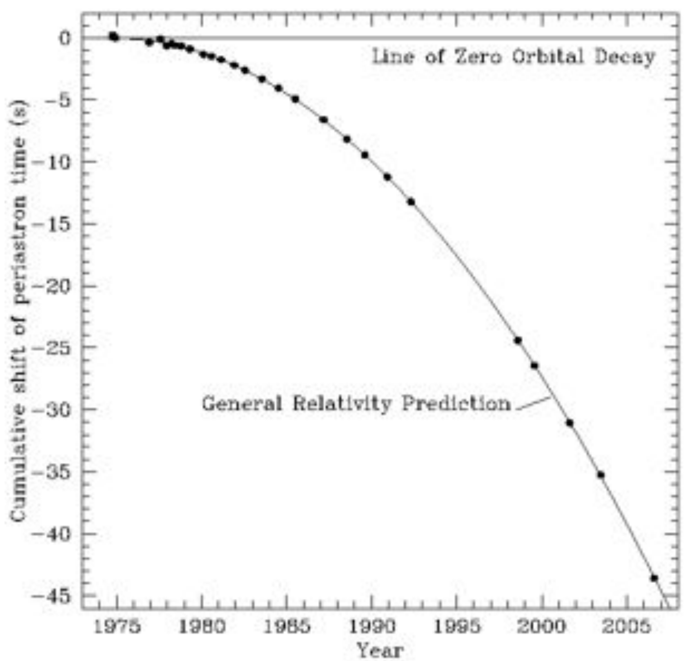


Figures: Pulsar Handbook (Lorimer & Kramer); Weisberg & Taylor

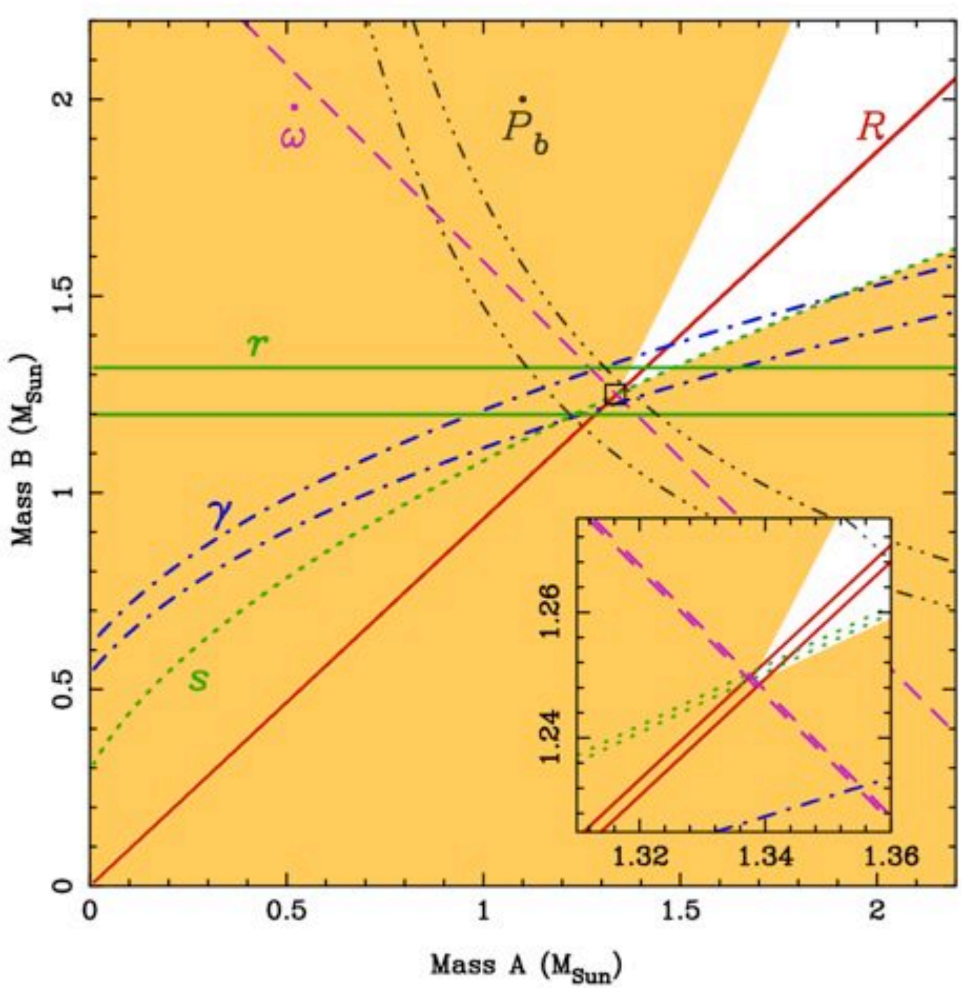
Nobel Prize Physics 1993

Russell Hulse & Joseph Taylor

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



The Double Pulsar: testing GR



Kramer et al. 2006

$$f(m_1, m_2) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_2 \sin i)^3}{(m_1+m_2)^2}$$

- Relativistic binary:
- Need post-keplerian parameters to model the binary orbit

- Periastron advance (wdot)
- Orbital Decay (Pbdot)
- Shapiro Delay (r,s)
- Time dilation / grav. redshift (gamma)

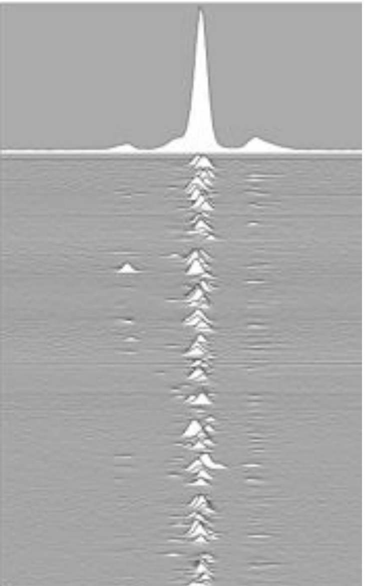
- When two PK parameters known: masses determined
- Multiple: test of GR

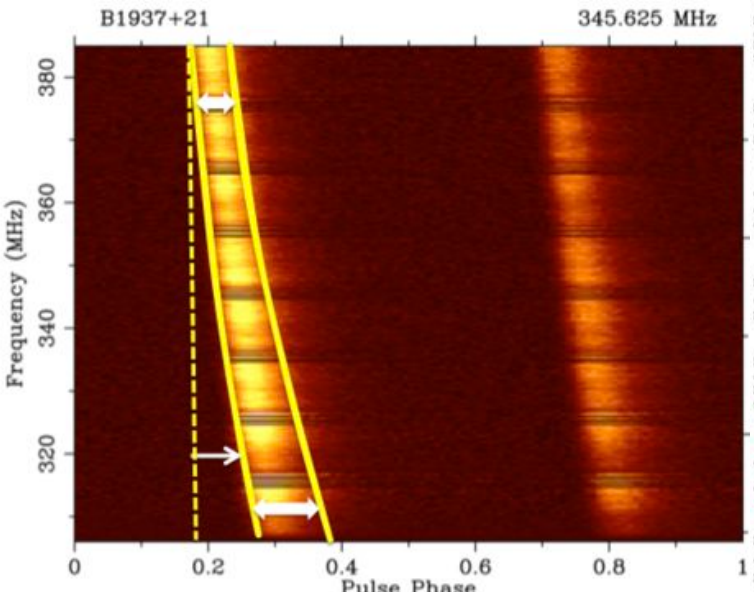
Influences on pulsar timing signals

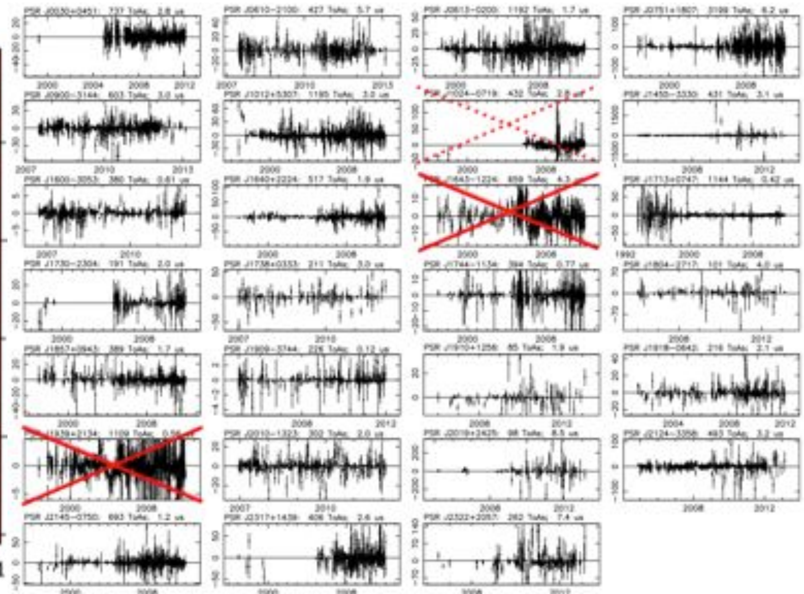
- Even when timing model is good, still effects that disturb quality of residuals

- Pulse jitter (30 ns): need minimum integration time to get stable profile; can't go to larger telescopes
- ISM effects (100 ns – 10 μs): Dispersion measure and scattering
- Timing noise (10 μs – 1 ms): Random rotational/magnetospheric/glitches

- **Need to understand and disentangle effects from potential GW signal (10ns)**

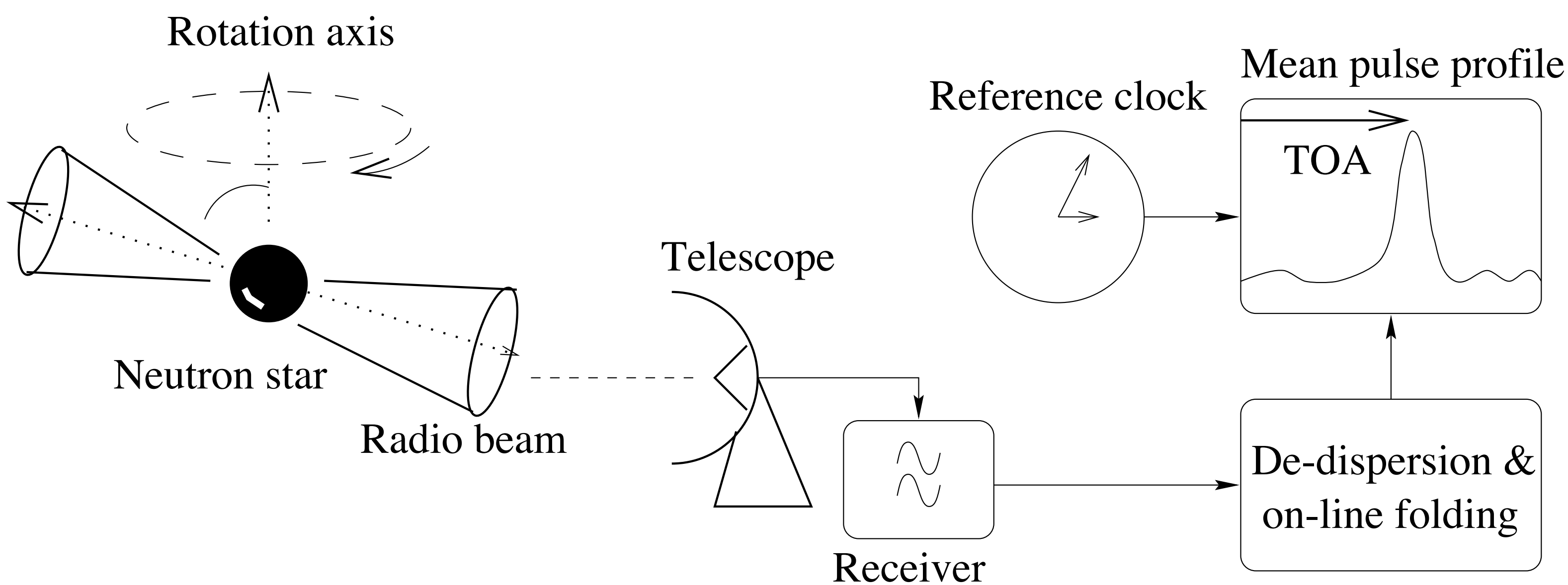






Pulsar Timing: a very powerful tool

Pulsars can probe a wide range of (astro)physics!



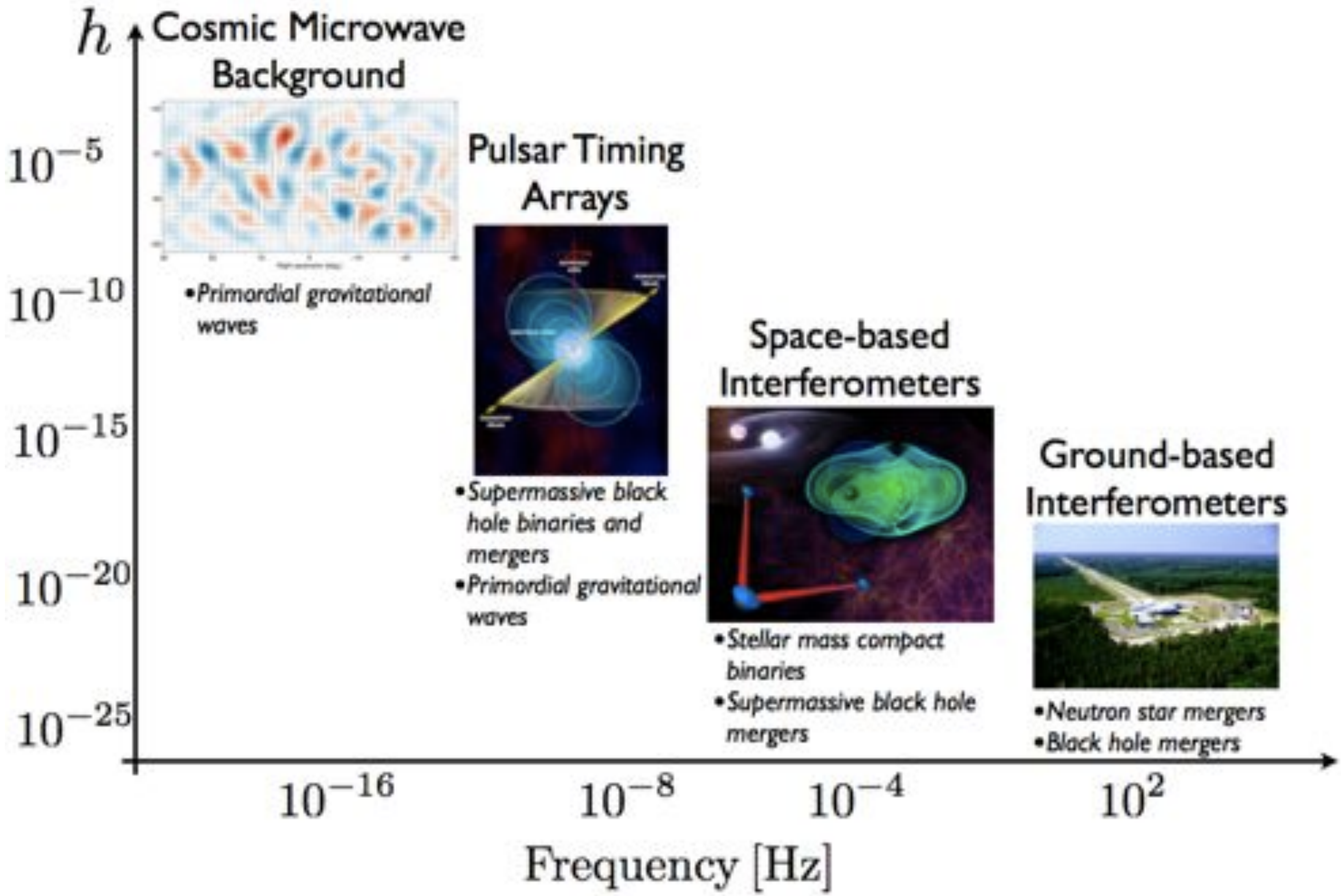
- Pulsar parameters
- Binary parameters
- Astrometry
- ISM studies
- Gravity tests (GR)
- Equation of state
- Emission mechanism
- Solar system ephemerides
- Clock offsets
- Gravitational wave astronomy

Figure: Pulsar Handbook (Lorimer & Kramer)

Using pulsars to detect GWs

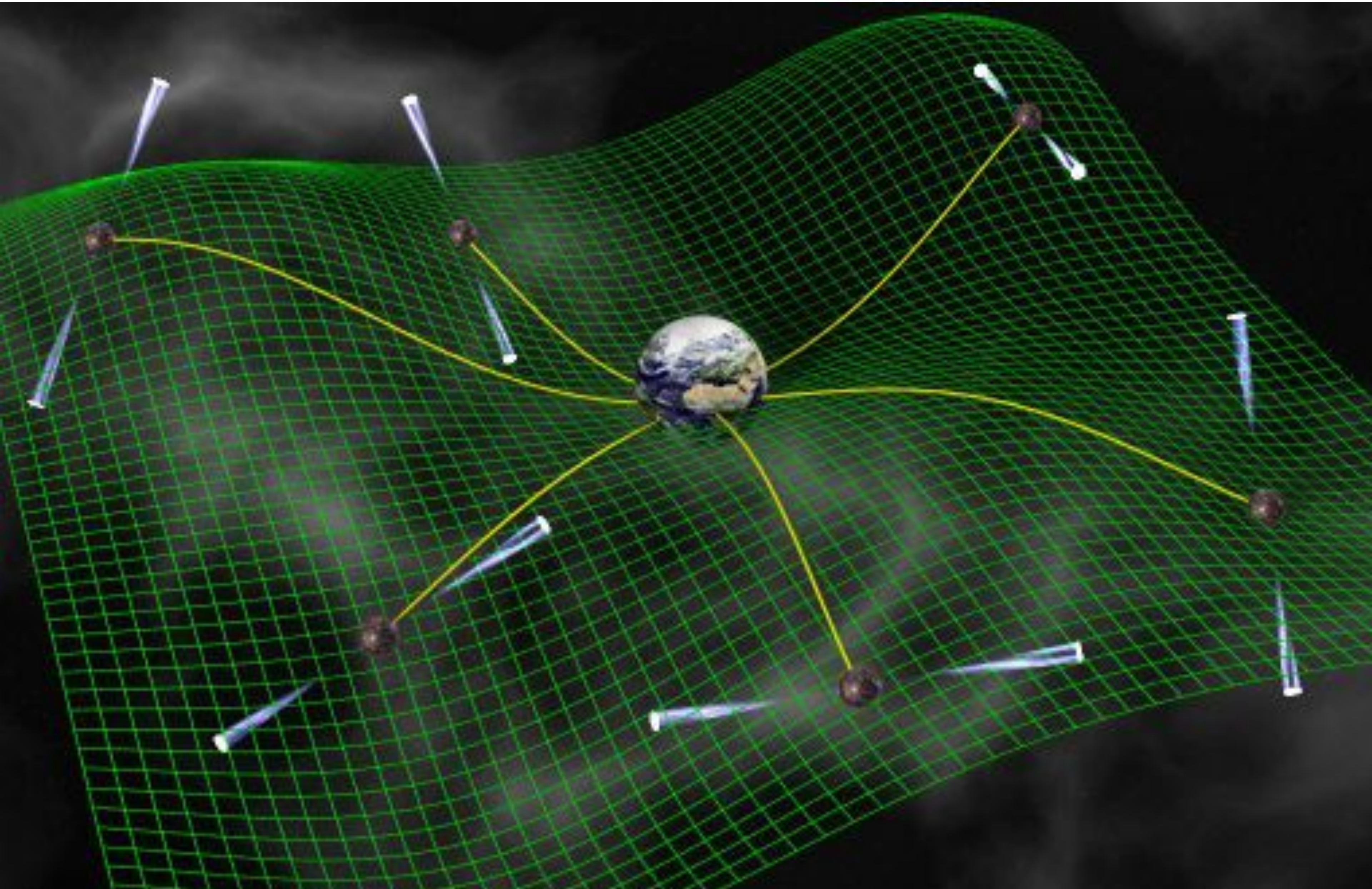
- What does a GW signal look like in pulsar timing data?
- What sources generate the GW signals in the PTA bands?
- Which of the GW sources are we (most) sensitive to?
- What signal will a PTA detect first?
- When will we detect GWs with a PTA?

GW experiments



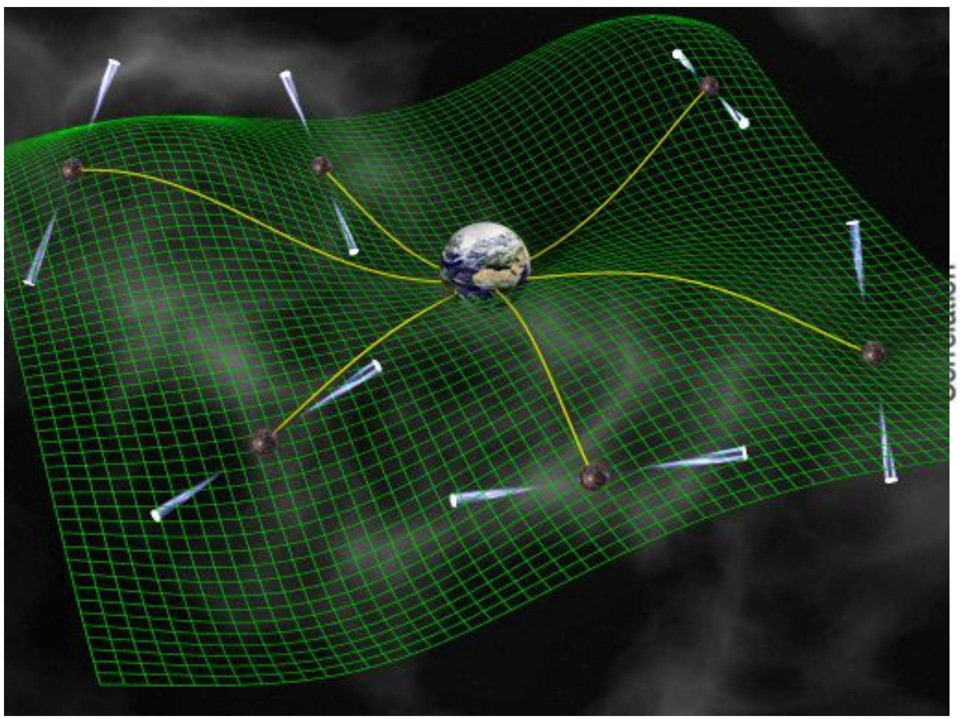
(Figure: Siemens)

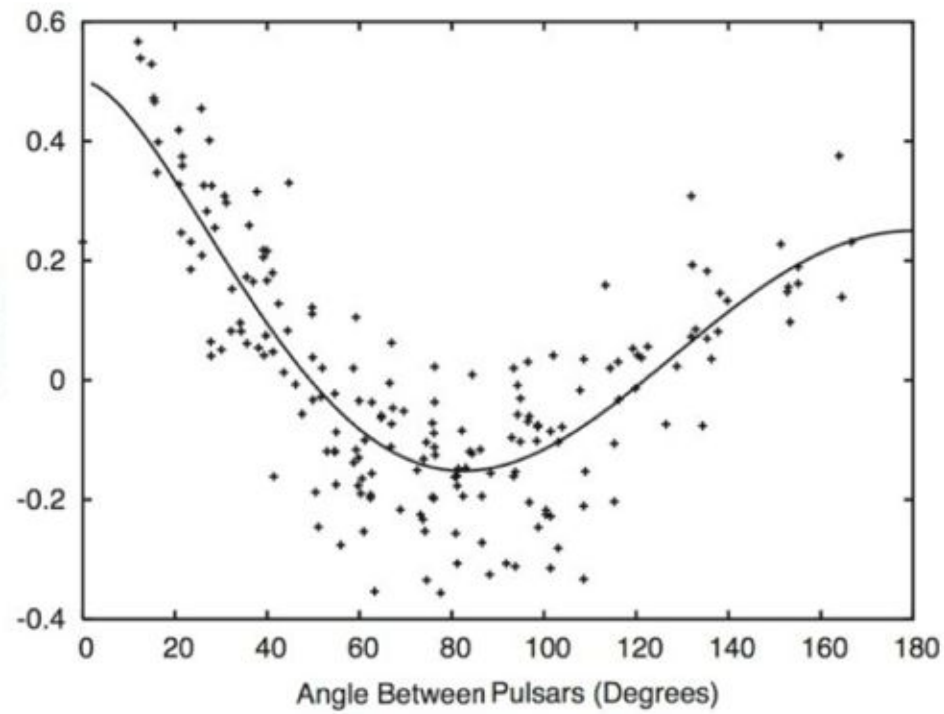
Pulsar Timing Array:
A galaxy-scale gravitational wave detector



Detecting GWs with a Pulsar Timing Array

- Pulsars are endpoints of a galaxy-scale detector
- GWs distort space-time at the pulsars and the Earth
  Earth term & Pulsar term



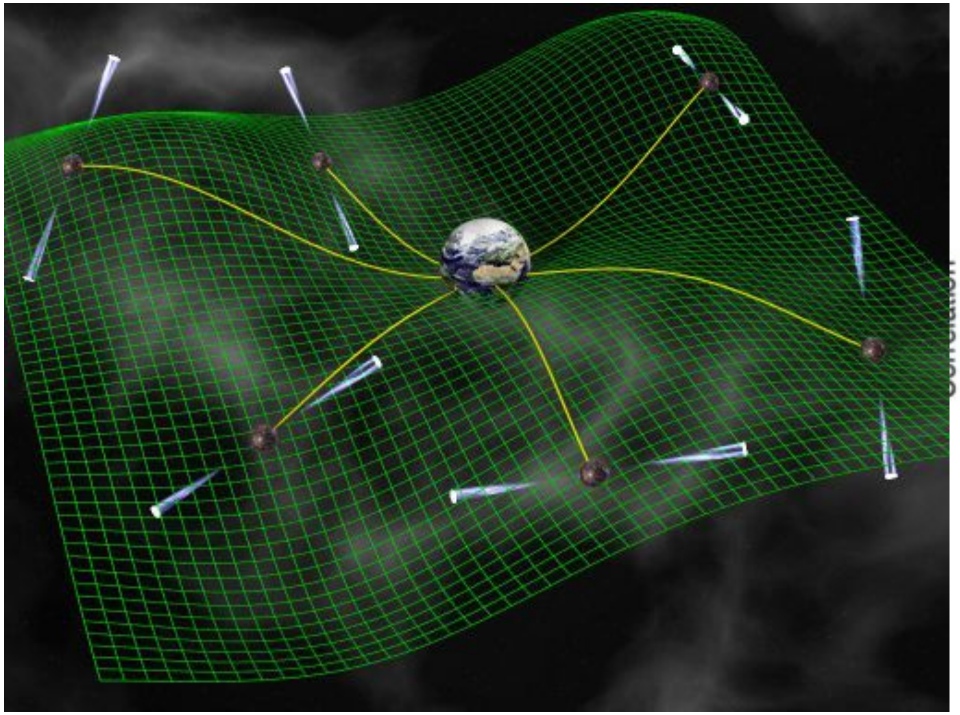


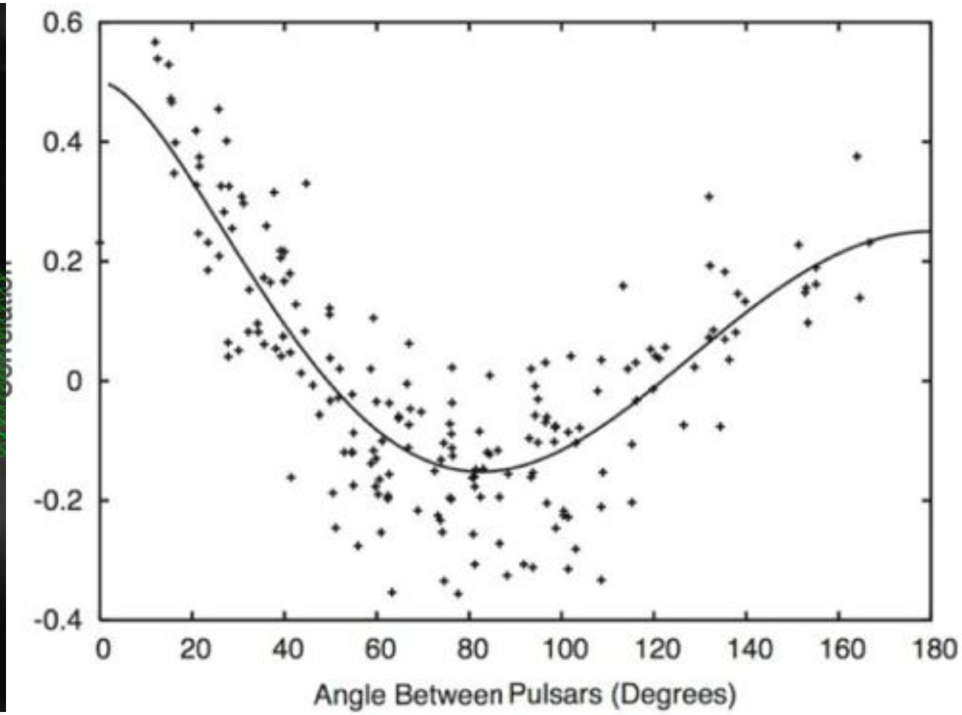
Hellings & Downs 1983 - Figure: Champion/Hobbs

Detecting GWs with a Pulsar Timing Array

- Earth-term: residuals are correlated for pulsar pairs dependent on separation angle on the sky
- Correlations in TOAs due to GW signal is quadrupolar: Hellings & Downs curve

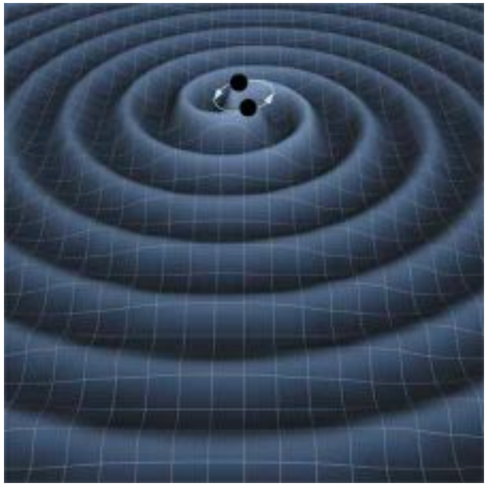
- **Need multiple pulsar-pairs on the sky for detection**

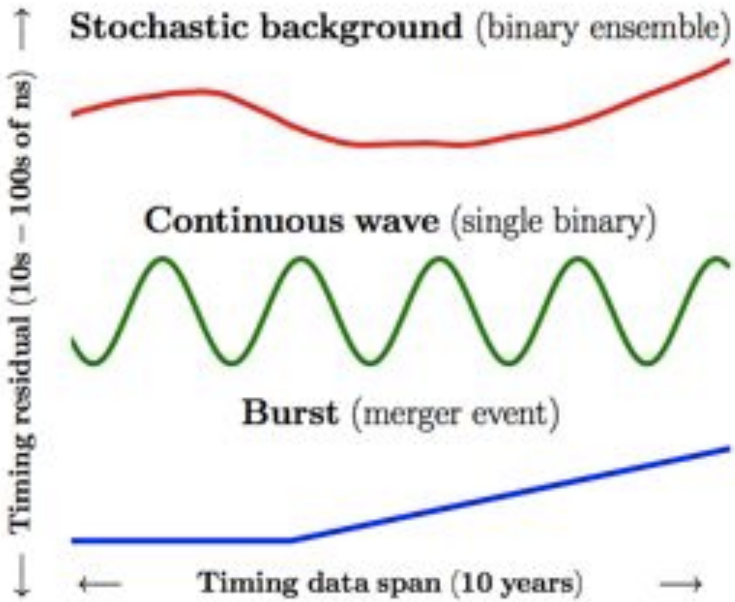




Hellings & Downs 1983 - Figure: Champion/Hobbs

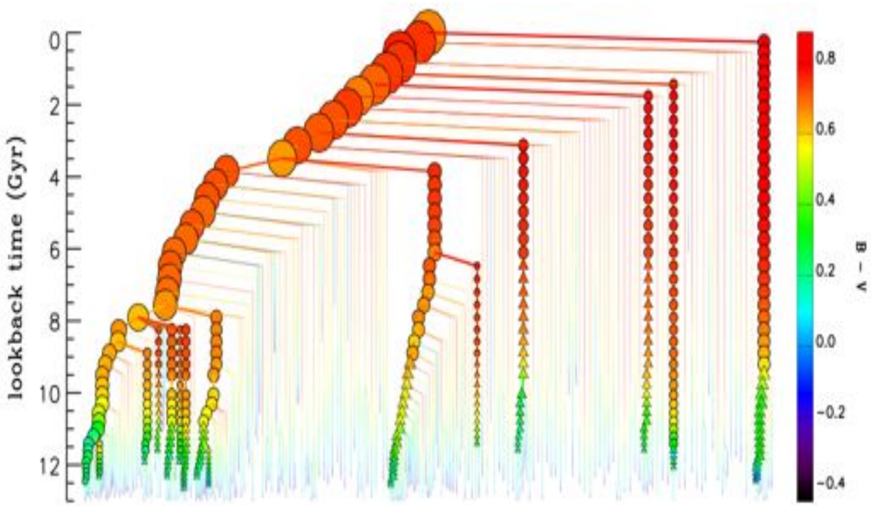
GWs from supermassive black hole binaries



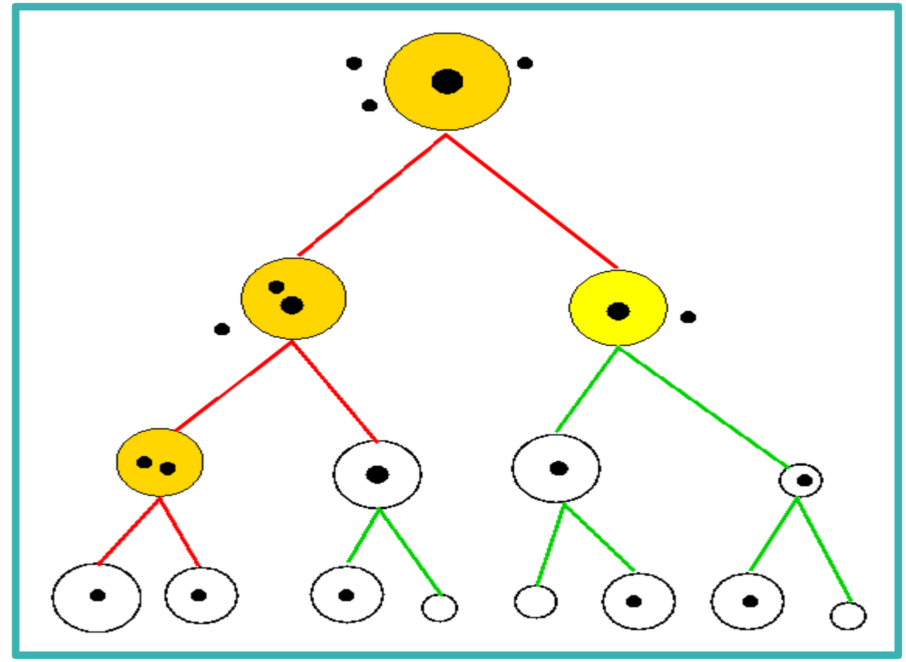


(Figure: Siemens)

PTA main sources: SMBH binaries



From De Lucia et al 2006



Volonteri Haardt & Madau 2003

-There are ~10^9 MW equivalent galaxies at *z*<1
-Suppose each galaxy has 1 merger at *z*<1
-If a binary emits at few nHz for ~1Myr

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r)$$

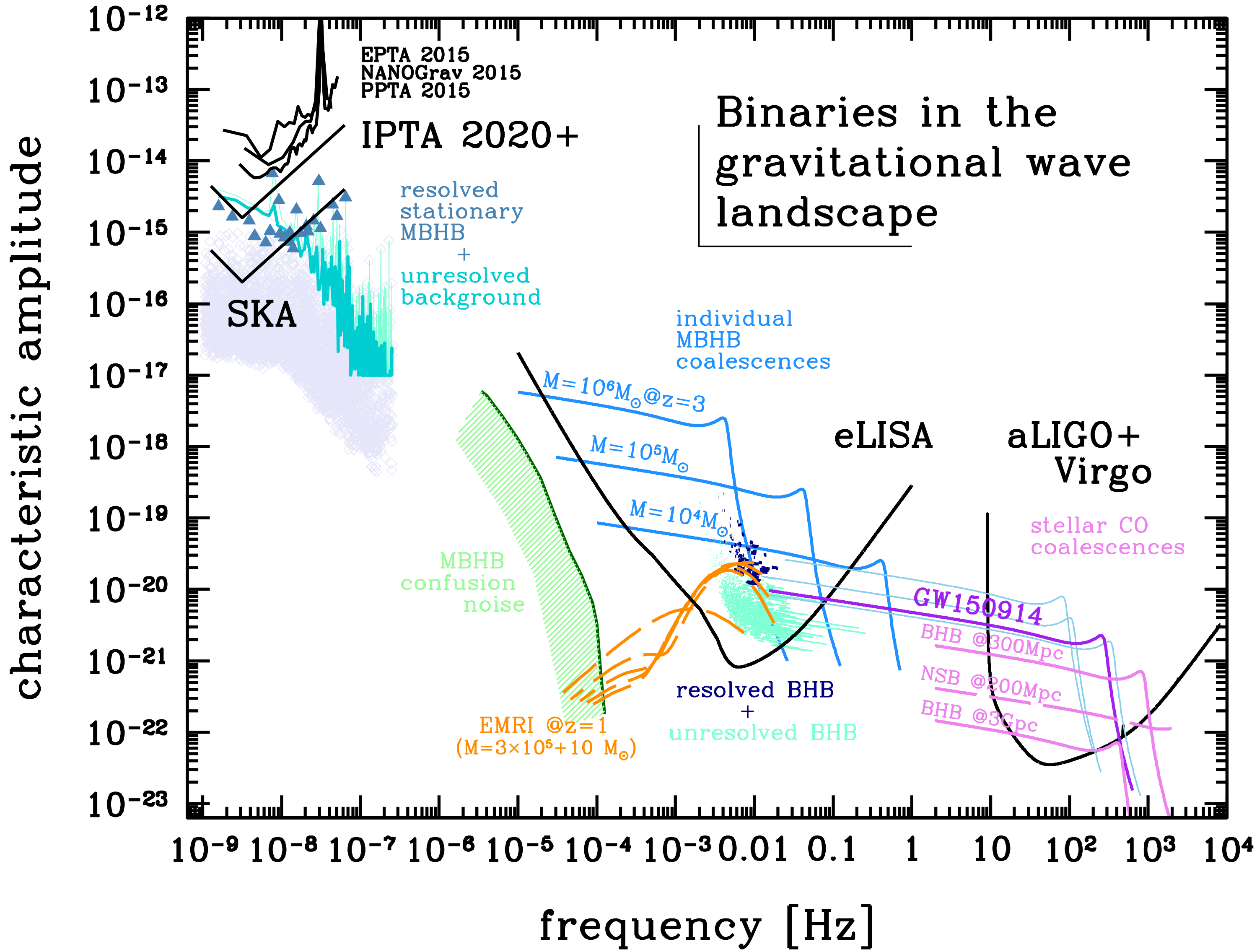
There are 10^5 SMBH binaries in the PTA band at any time!

$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

(Slide: Sesana)

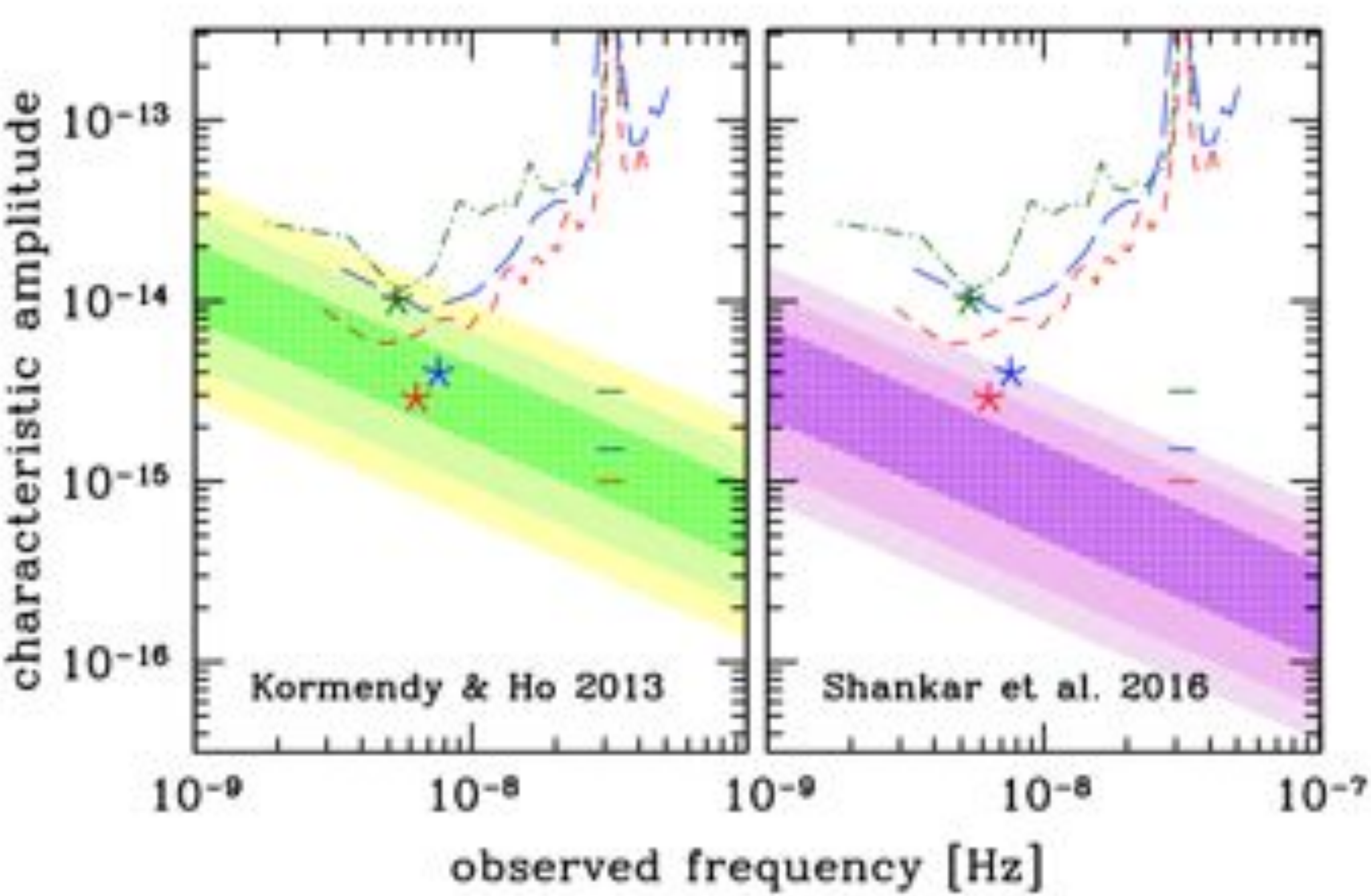
PTA as a nHz gravitational wave detector

GW sources: SMBHBs; cosmic strings; cosmological



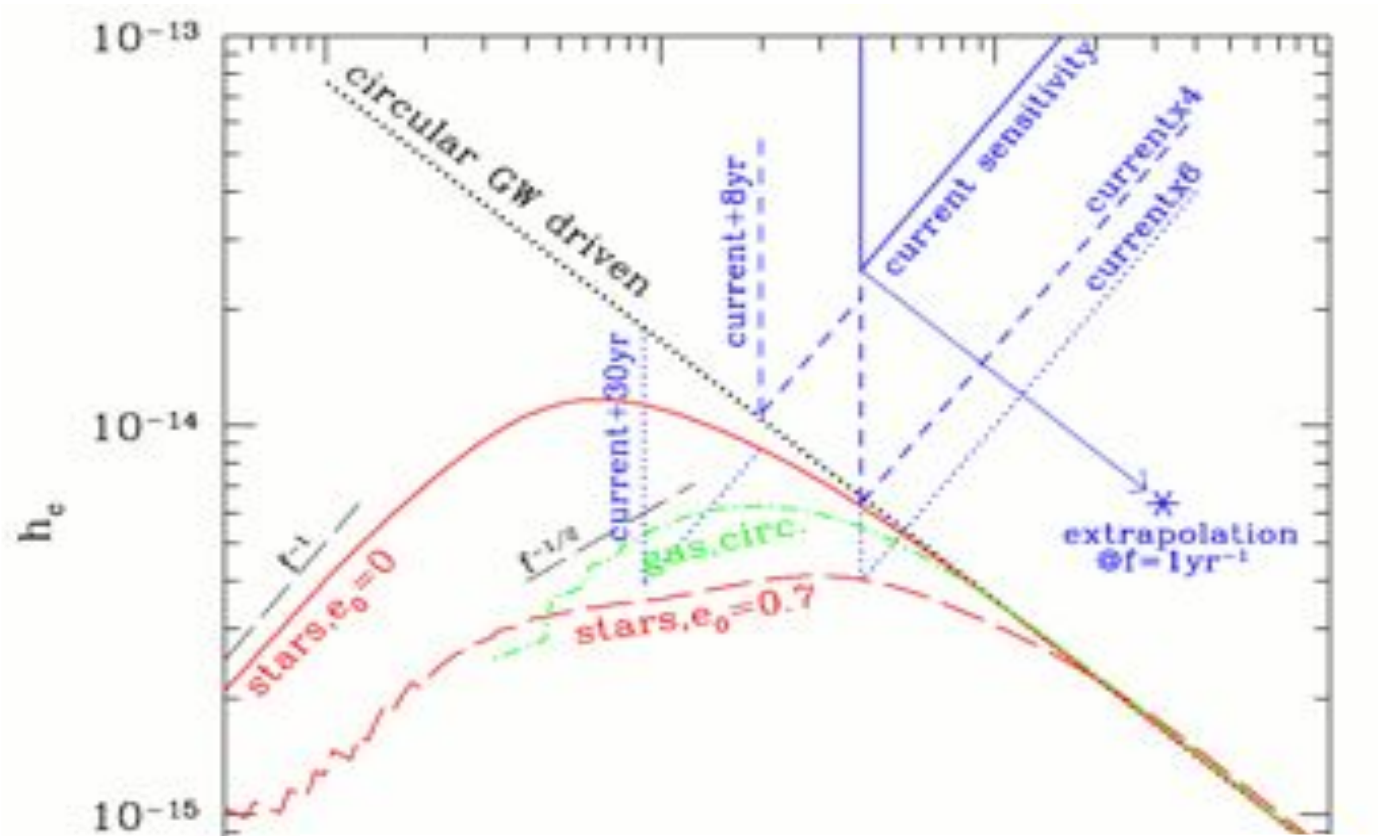
SKA GW astronomy: Janssen et al. PoS(AASKA14)037 Figure: Sesana

GWB amplitude predictions



(Sesana et al. 2016)

GWB shape predictions; the effect of the environment

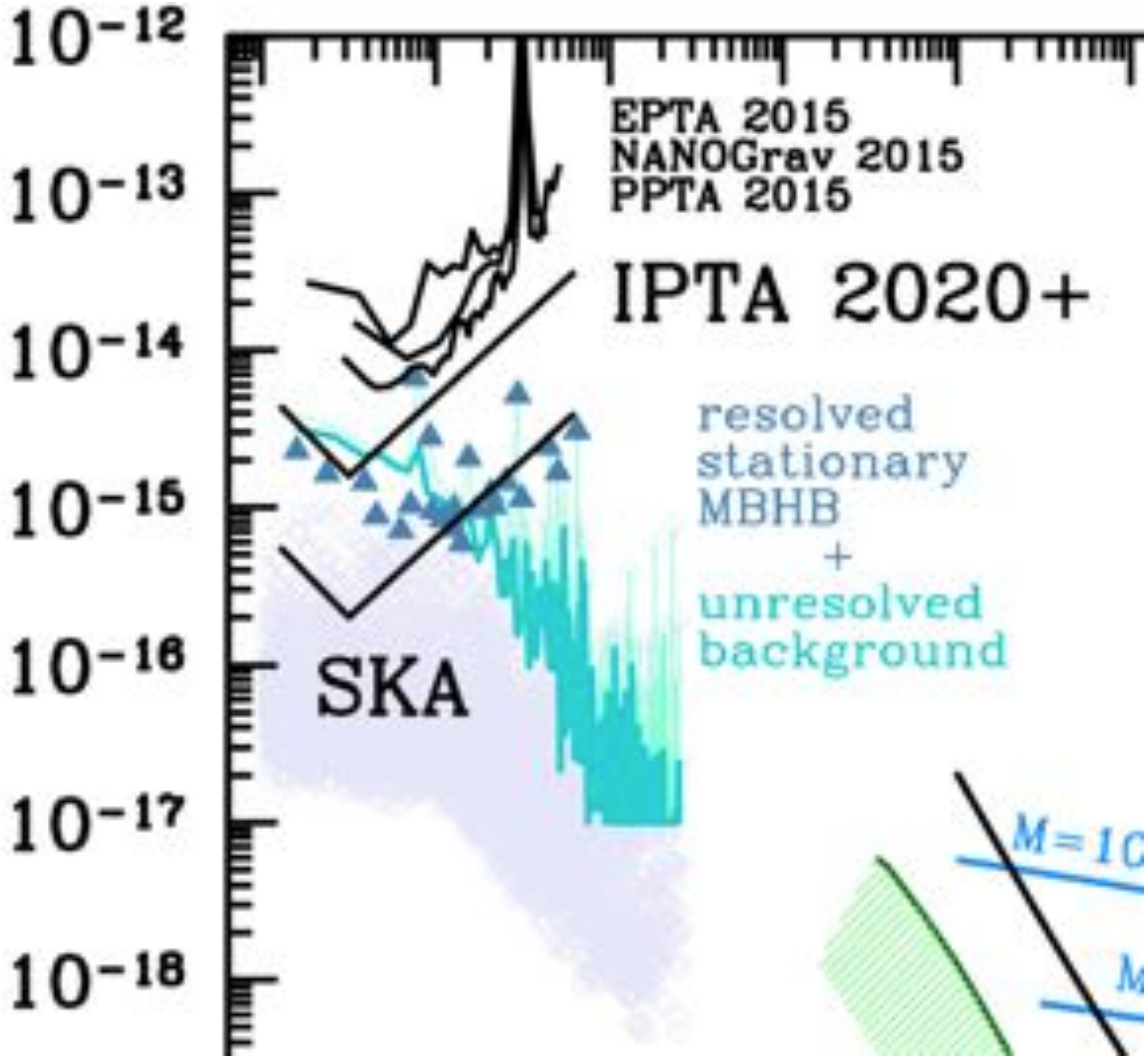


Turnover not a huge problem: $P(f) \propto h_c^2 f^{-3}$

Still benefit from red power GW spectrum for next ~20 years

(Kocsis & Sesana 2011, Sesana 2013, Ravi et al. 2014)

Current limits are getting interesting



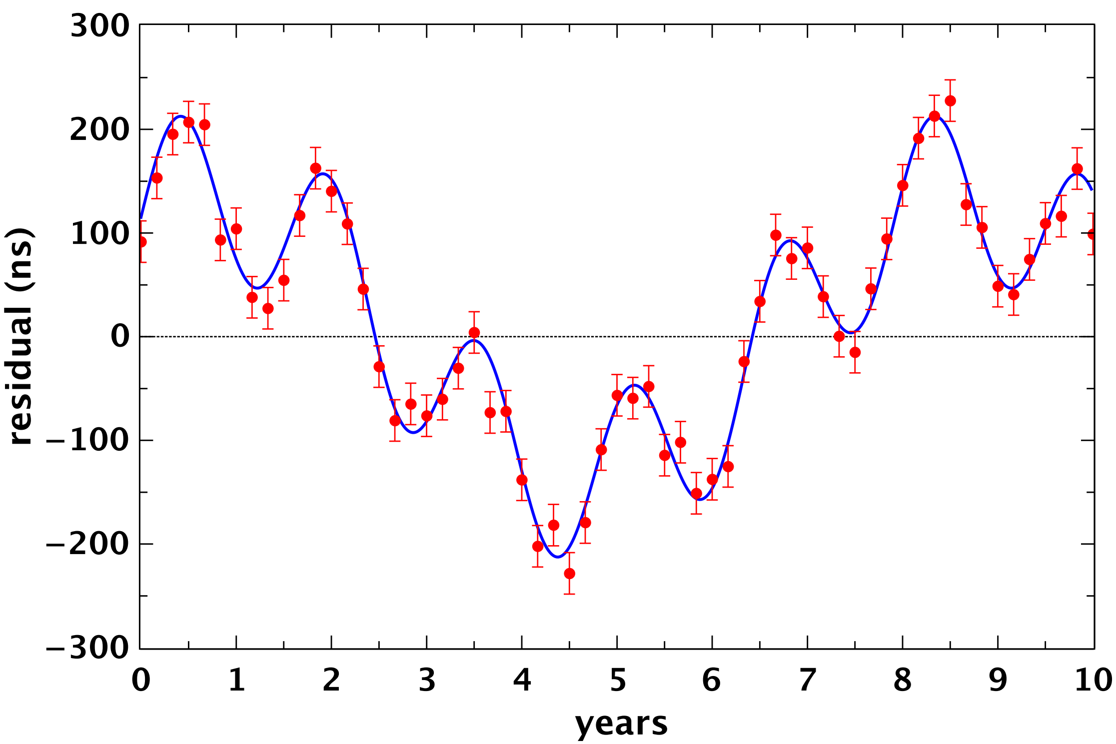
~10^{-8} Hz

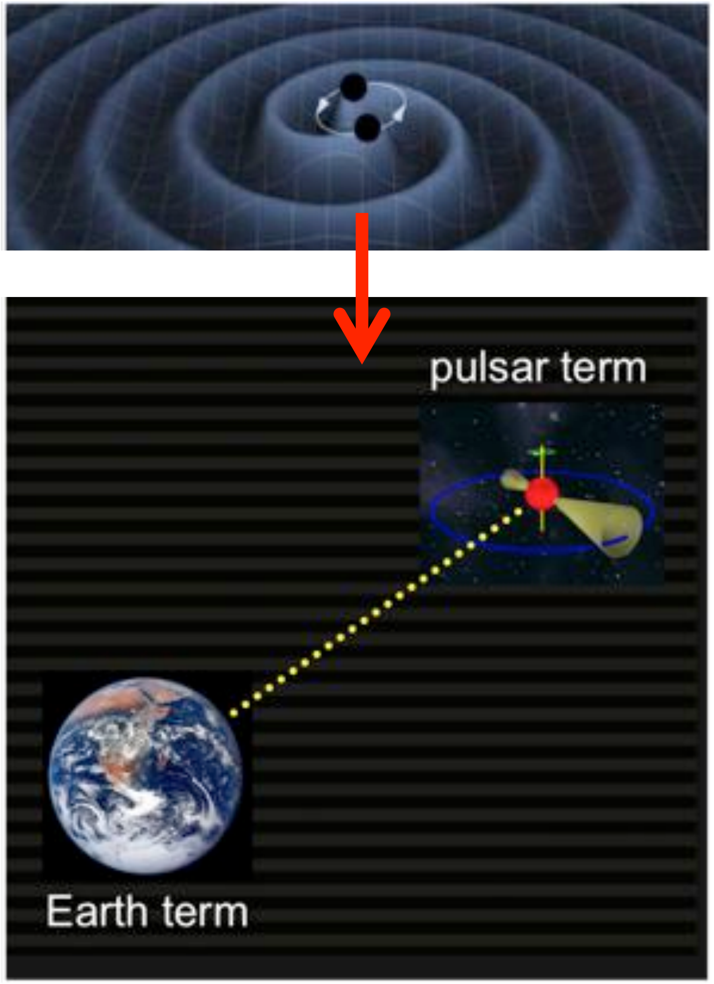
(Figure: Sesana)

Detecting a single GW source using pulsar timing

- Each SMBHB produces periodic signal; possibly above GW background
- Signal contains information from two distinct epochs

- Difficult to distinguish from other timing effects





Pulsar timing array GW detections

- PTA detections are **different** from LIGO/VIRGO/eLISA
  - nHz GWs = periods of years!
  - Require years of integration, evidence will build up over years
- Definition of a detection important
  - Different signatures for GW Background, single sources, bursts
  - False-alarm probabilities and understanding of other noise sources
  - Tests on data to assess noise statistics etc
- Verification and validation/reproducibility
  - Simulations, multiple pipelines, quadrupolar nature, signal strength vs time
  - What data products/software/detection algorithms to release

What is required for a PTA GW detection?

- Detecting gravitational waves requires:
  - Long-term stable pulsars
  - Timing models that include all non-GW effects
  - Understanding of other red noise processes in the timing data

- What do we need for that:
  - A lot of MSPs
  - A lot of observing time -> total time = max GW period
  - A lot of TOAs
  - Checks across instruments, pulsars, etc
  - Noise component modelling, analysis techniques

A Amplitude
N_p # of pulsars
c cadence
σ pulsar RMS
T obs time

- And… **SKA**! (Phase-I Key Science Goal: fundamental physics with NS)
  - Testing GR in the strong-field regime
  - Detecting nHz gravitational waves

The European Pulsar Timing Array

- Collaboration of pulsar groups working with 5 (6) large radio telescopes, observing programmes coordinated (including NL: WSRT and LOFAR)
- Long-term timing programmes at all telescopes: more data!
- Theory/analysis groups -> GW source predictions, analysis methods, detection protocols

Three PTAs in existence: Europe, North America and Australia

Working together as the International pulsar timing array

http://www.ipta4gw.org

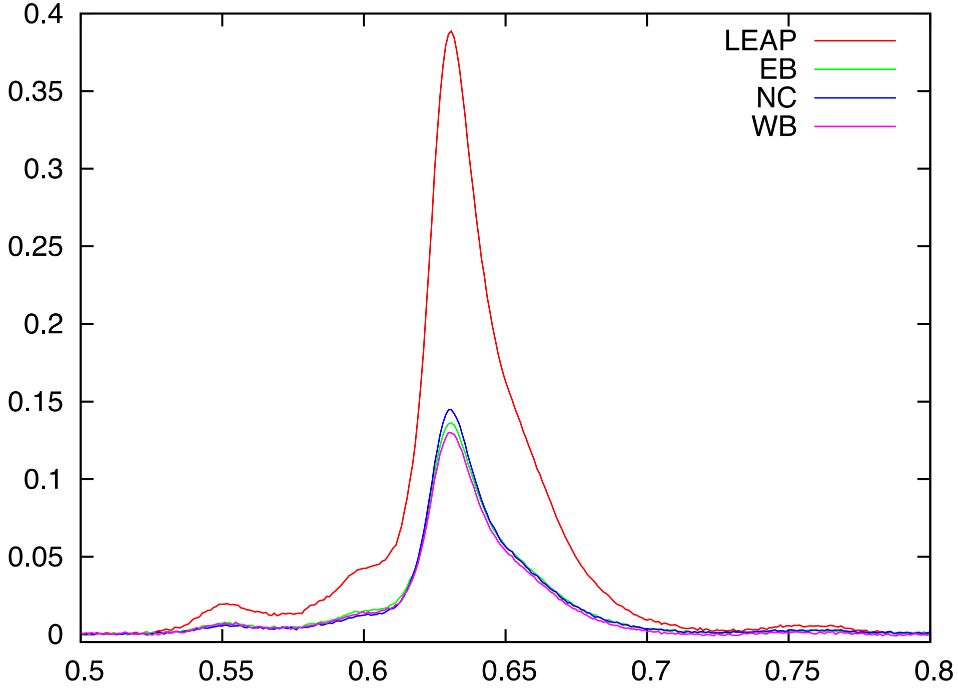
Looking forward towards SKA: MeerKAT, SKA1-Low, SKA1-Mid

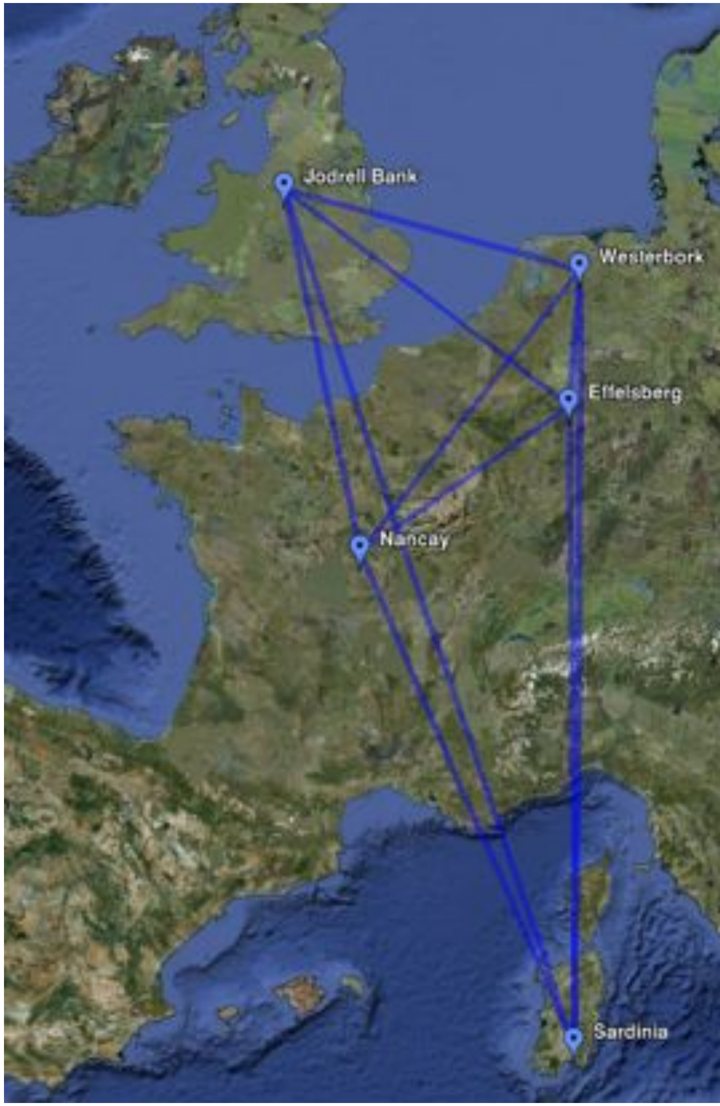




Improving sensitivity: larger telescope

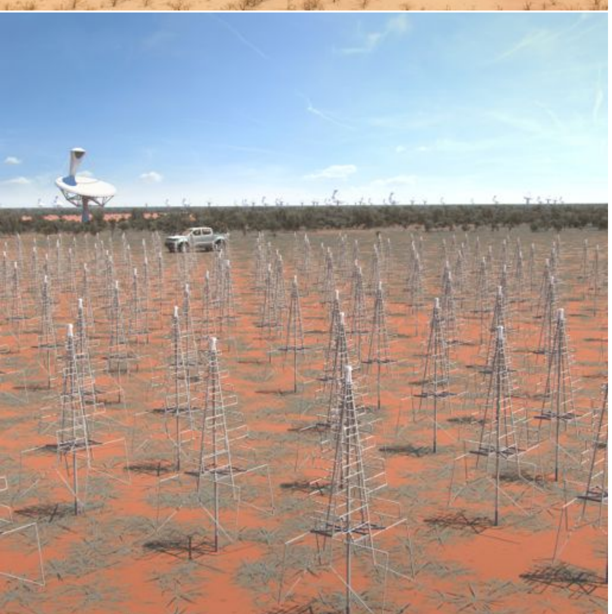
- LEAP: Large European Array for Pulsars
- Real-time coherent addition of large European telescopes
- Fully steerable dish of 200m
- Calibration of instrumental delays between telescopes
- Improvement in timing precision by order of magnitude





http://www.leap.eu.org

Future outlook: the SKA



Key science project:

gravity tests with pulsars

(both GR tests in binaries and GWs)

Meerkat -> SKA1-Mid:

Intermediate frequencies (1-3^{+}GHz)

High-precision timing and searches

SKA1-Low:

Low frequencies (<350MHz)

Searches and ISM monitoring

SKA GW astronomy: Janssen et al. PoS(AASKA14)037

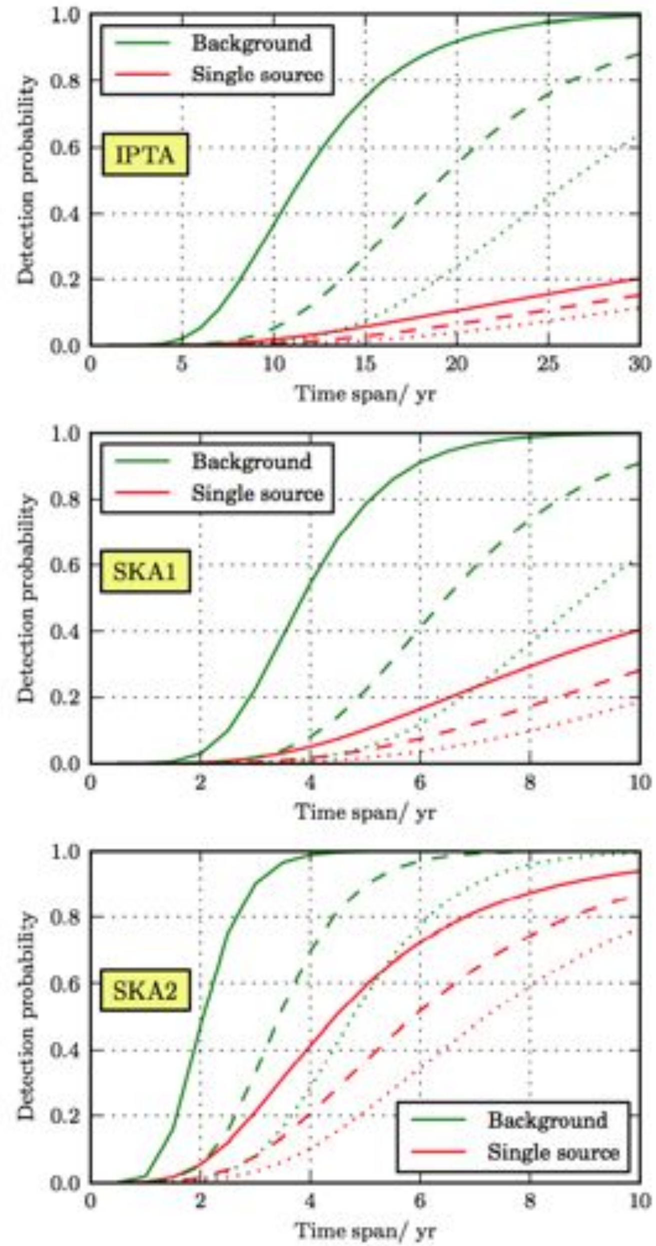
From limit to detection to GW astronomy

IPTA is getting close already!

SKA1 – more pulsars, better sensitivity will 'easily' make a first detection

SKA2 – will do GW astronomy

A Amplitude
N_p # of pulsars
c cadence
σ pulsar RMS
T obs time



Rosado, Sesana & Gair 2015, MNRAS 451, 2417

The Role of SKA in GW detection/astronomy

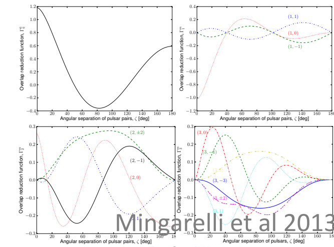
- GW characterization

SKA1 :

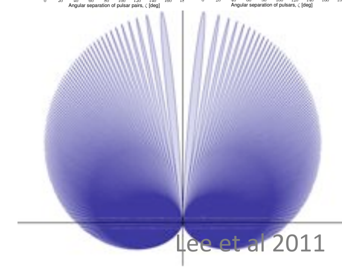
- Confirmation of the signal
- Source identification (characterize spectrum)
- Background characterization (anisotropy search)
- Source localization

(Full-)SKA science: GW astronomy

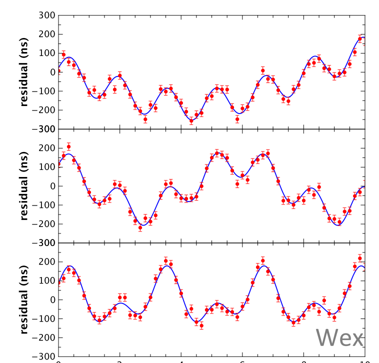
- Constrain/study Galaxy evolution
  - Input for EM counterpart studies
- Characterization of inspiral phase of SMBHBs
- Tests of gravity
  - Polarization properties
  - Mass of graviton



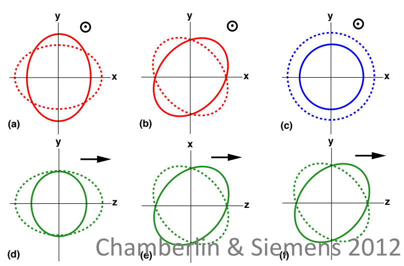
Mingarelli et al 2013



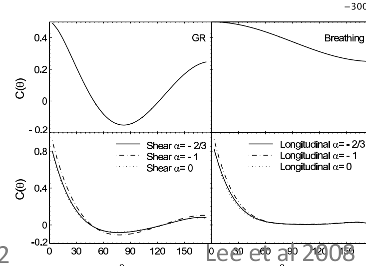
Lee et al 2011



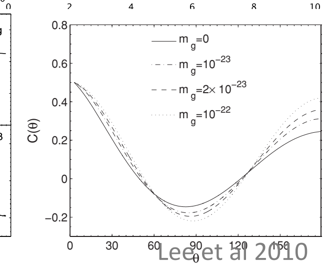
Wex



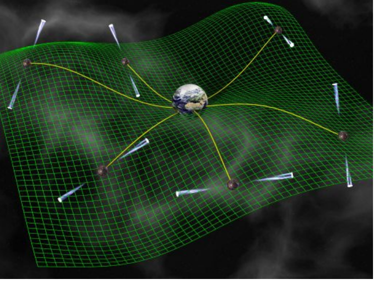
Chamberlin & Siemens 2012



Lee et al 2008



Lee et al 2010



Summary

- Pulsar timing can be used to detect GWs at nanohertz frequencies
- Before GW signals can be detected, other sources of noise need to be understood/measured/corrected
- However, IPTA GW limits close to predictions

- First detection of GWB expected with IPTA in 5-10 yrs, maybe less. The S/N will have to grow over time.
- SKA KSP: gravity tests with pulsars
- SKA will characterize GW signals and do GW astronomy

Thank you!

PhD project available: Testing gravity by timing pulsars with the SKA