Pulsar timing and black holes

Robert Ferdman
Jodrell Bank Centre for Astrophysics
University of Manchester

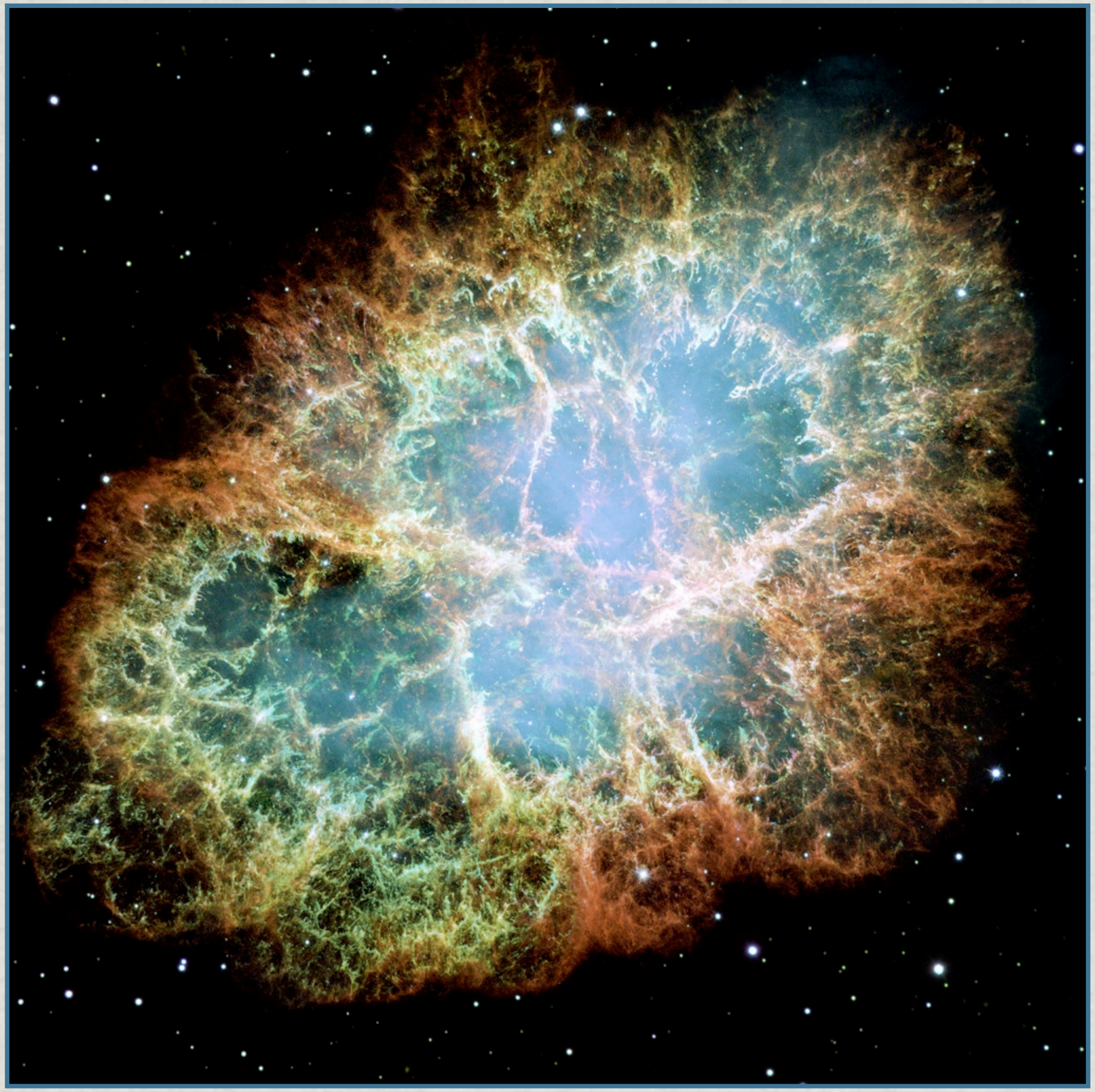
Born-again stars

Massive stars: ~8-15 $M_\odot$

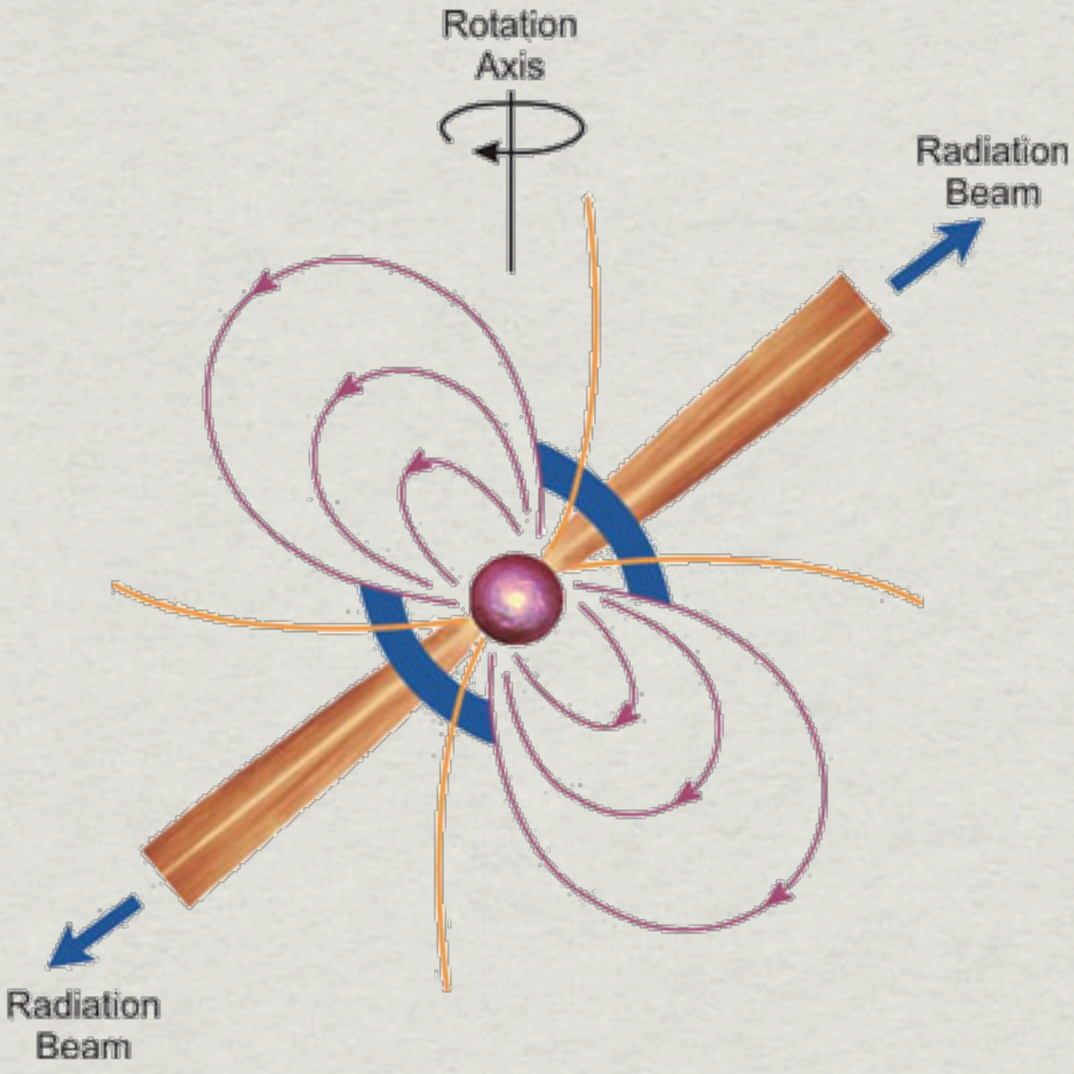
- core collapse SN
- others?

Neutron star remnant

- nuclear densities
  → highly exotic conditions!
- mass ~1.4 $M_\odot$
- radius ~10 km
- strong magnetic field!



Pulsars: cosmic lighthouses



Pulsars: cosmic lighthouses

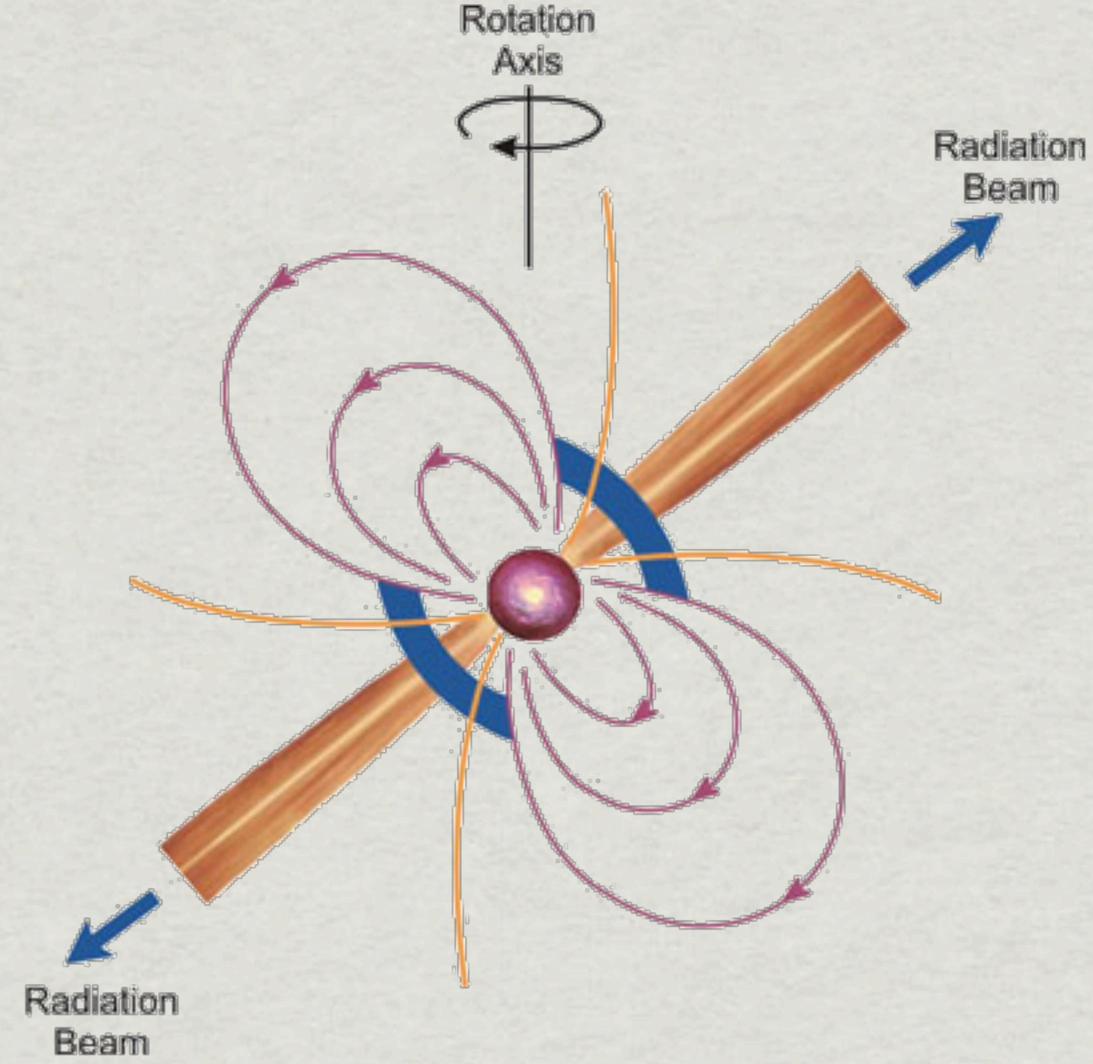
Spin axis, magnetic axis not aligned

- each rotation → pulse

Spins on axis once every ~ms-sec

Spin *down*

- magnetic dipole radiation
- at the expense of rotational energy



Pulsars: cosmic lighthouses

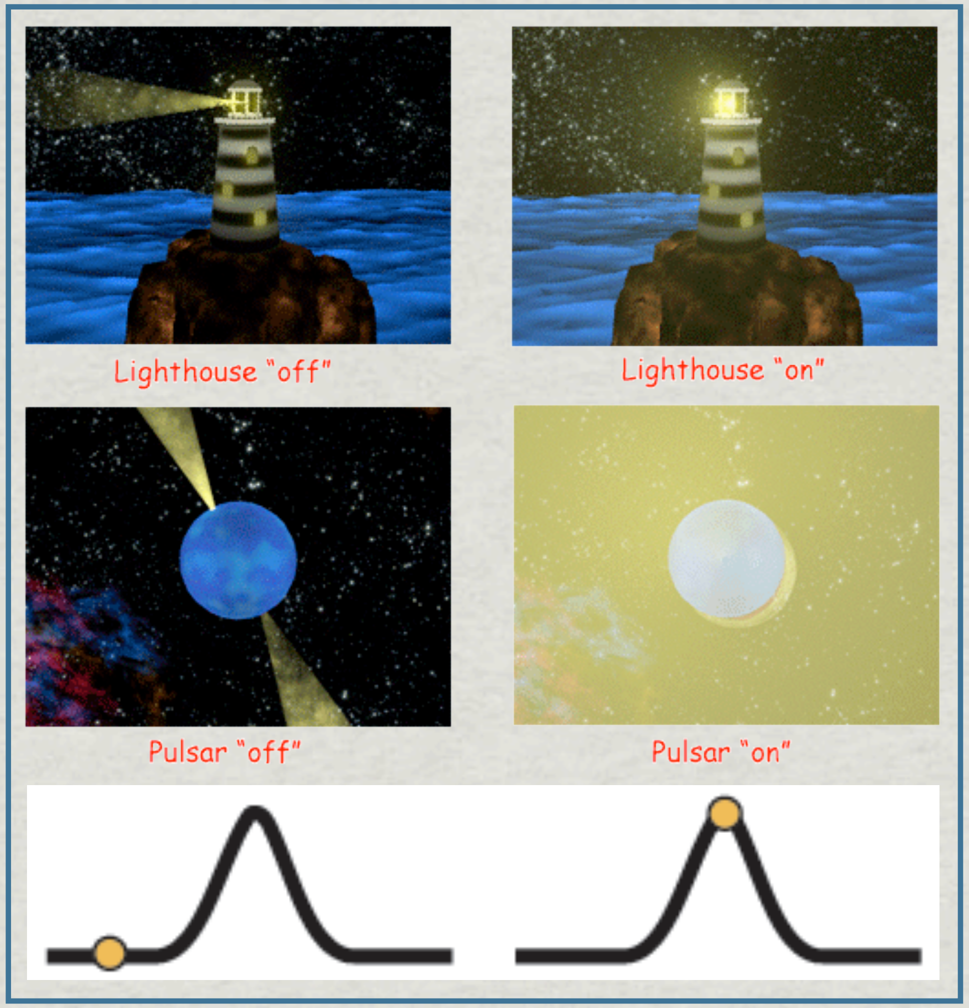
Spin axis, magnetic axis not aligned

- each rotation → pulse

Spins on axis once every ~ms-sec

Spin *down*

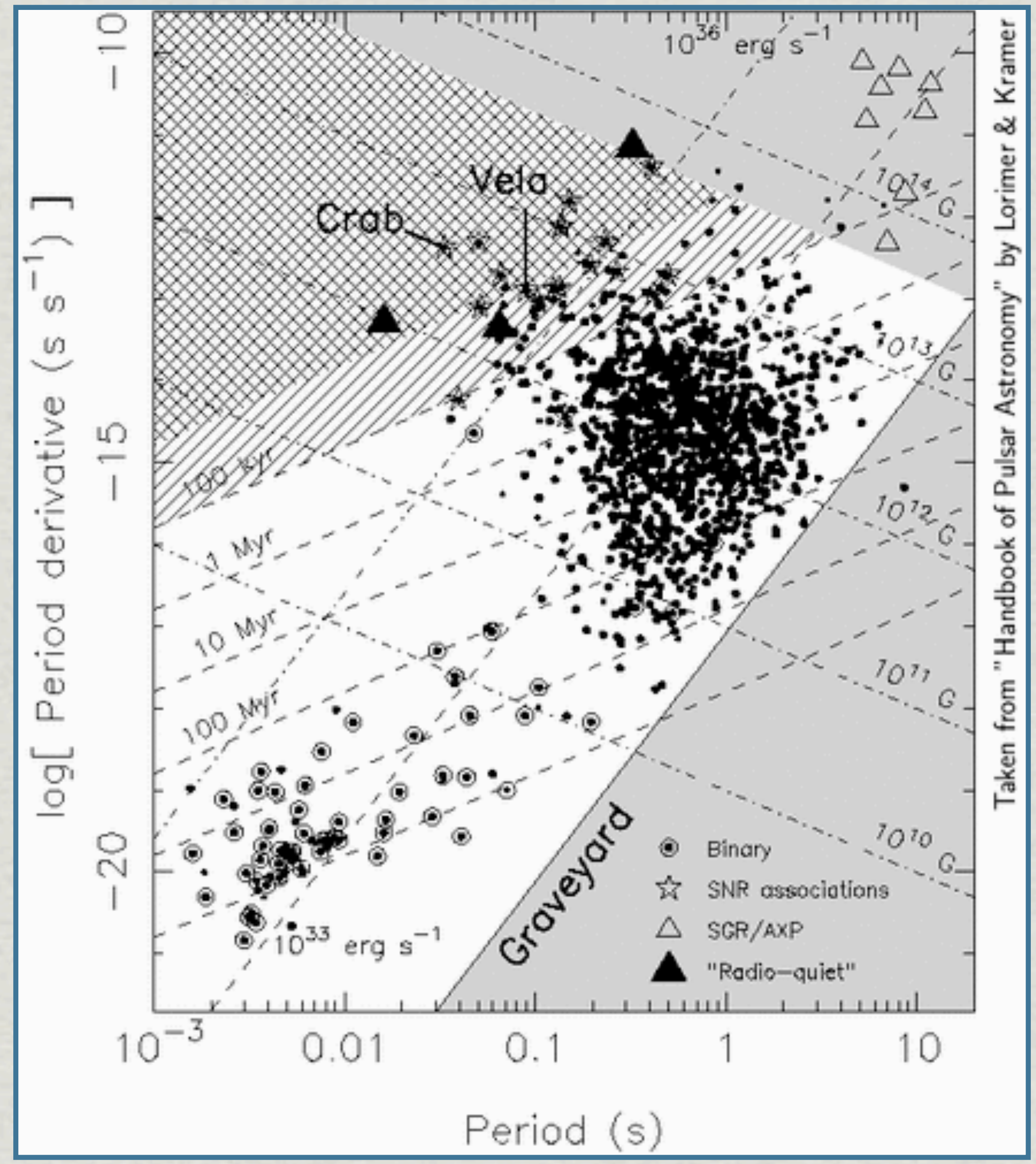
- magnetic dipole radiation
- at the expense of rotational energy



Pulsars: cosmic lighthouses

Two principal populations:
young vs. recycled

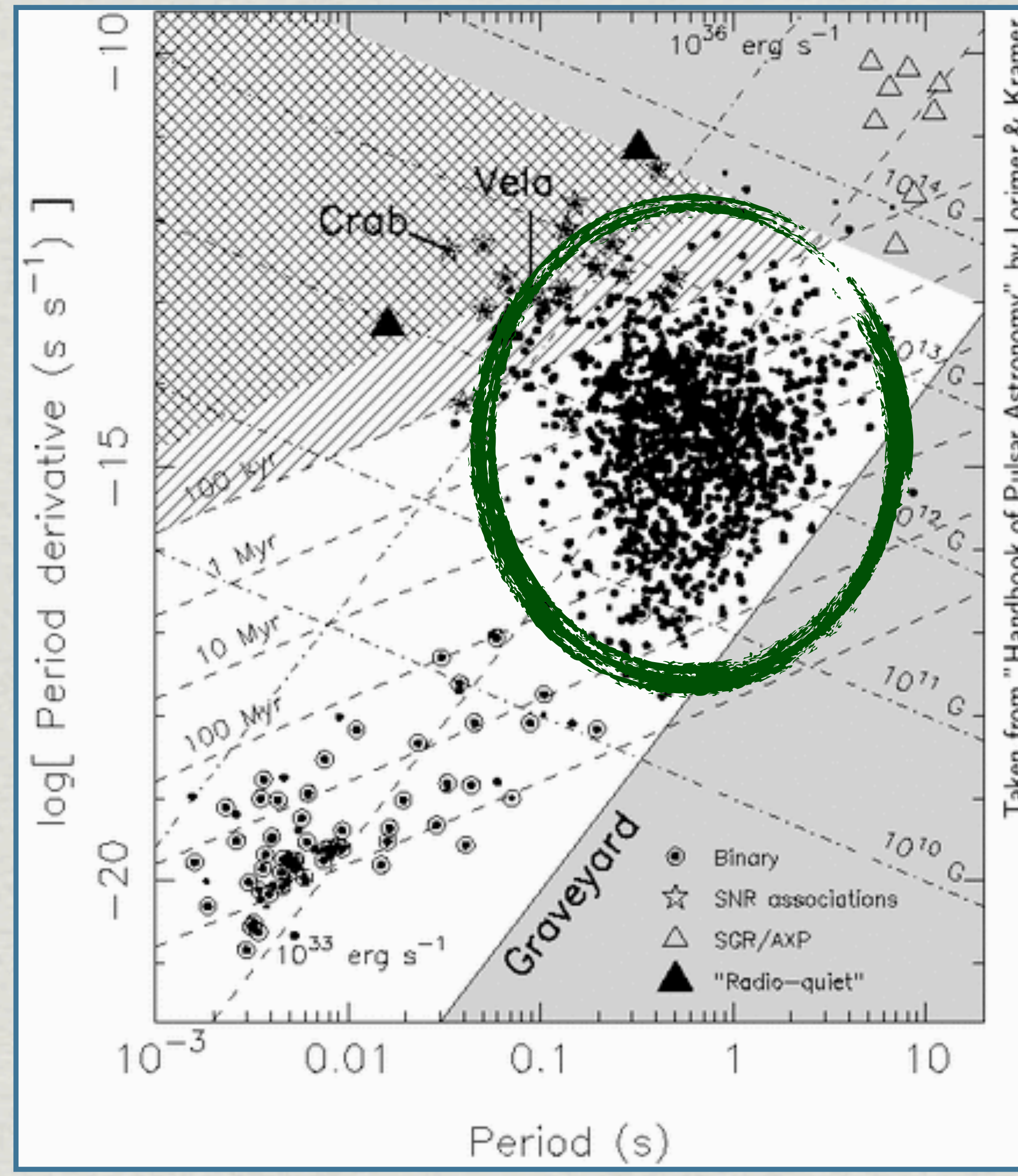
- **young** (age ~ 10^5 - 10^8 yr)
  → P ~ 10^{-15} s/s
  → B ~ 10^{12} G
- **recycled** (age ~ 10^9-10^{10} yr)
  → P ~ 10^{-20} s/s
  → B ~ 10^8-10^{10} G



Pulsars: cosmic lighthouses

Two principal populations:
young vs. recycled

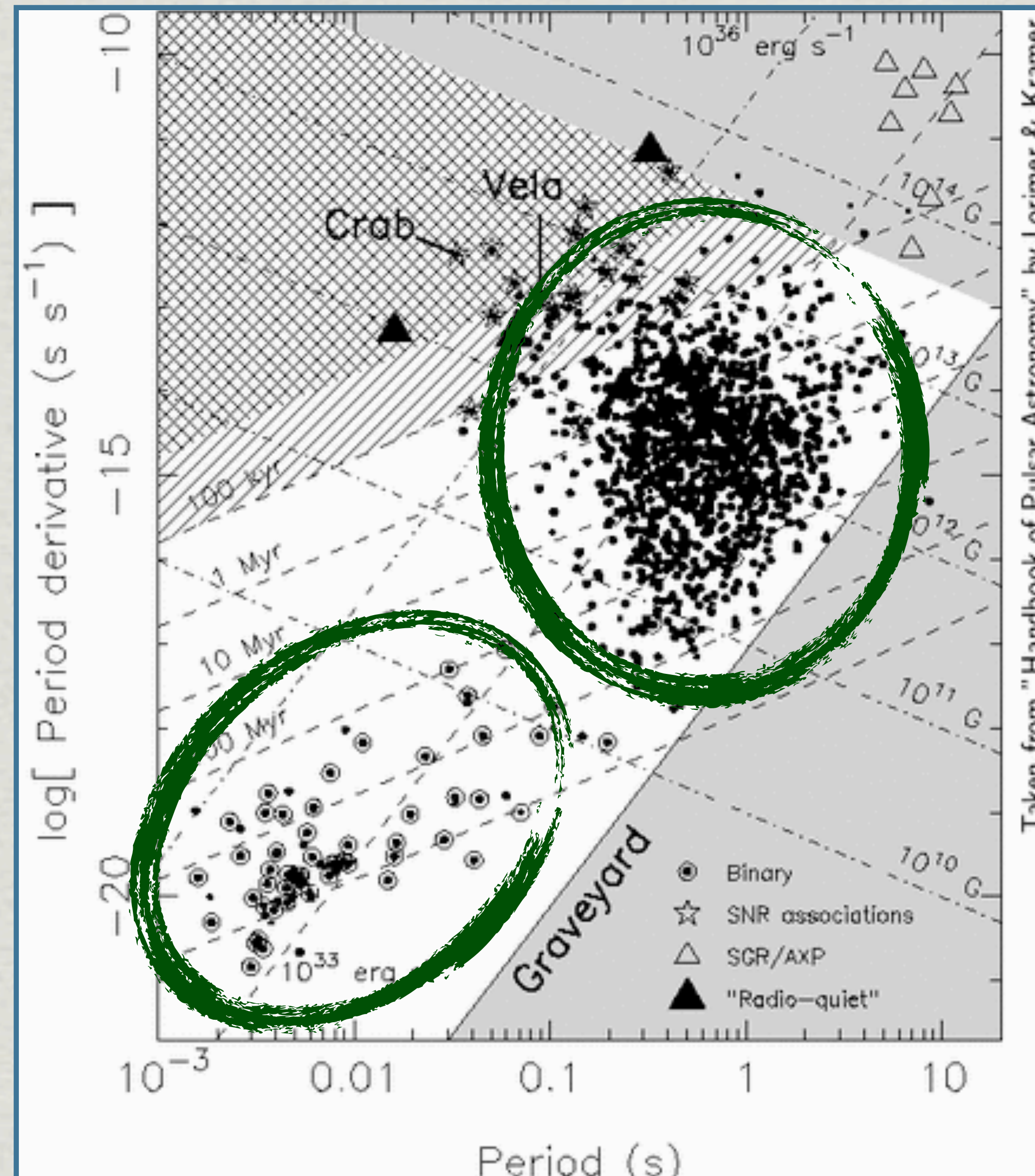
- **young** (age ~ 10^5 - 10^8 yr)
  → P ~ 10^{-15} s/s
  → B ~ 10^{12} G
- **recycled** (age ~ 10^9-10^{10} yr)
  → P ~ 10^{-20} s/s
  → B ~ 10^8-10^{10} G



Pulsars: cosmic lighthouses

Two principal populations:
young vs. recycled

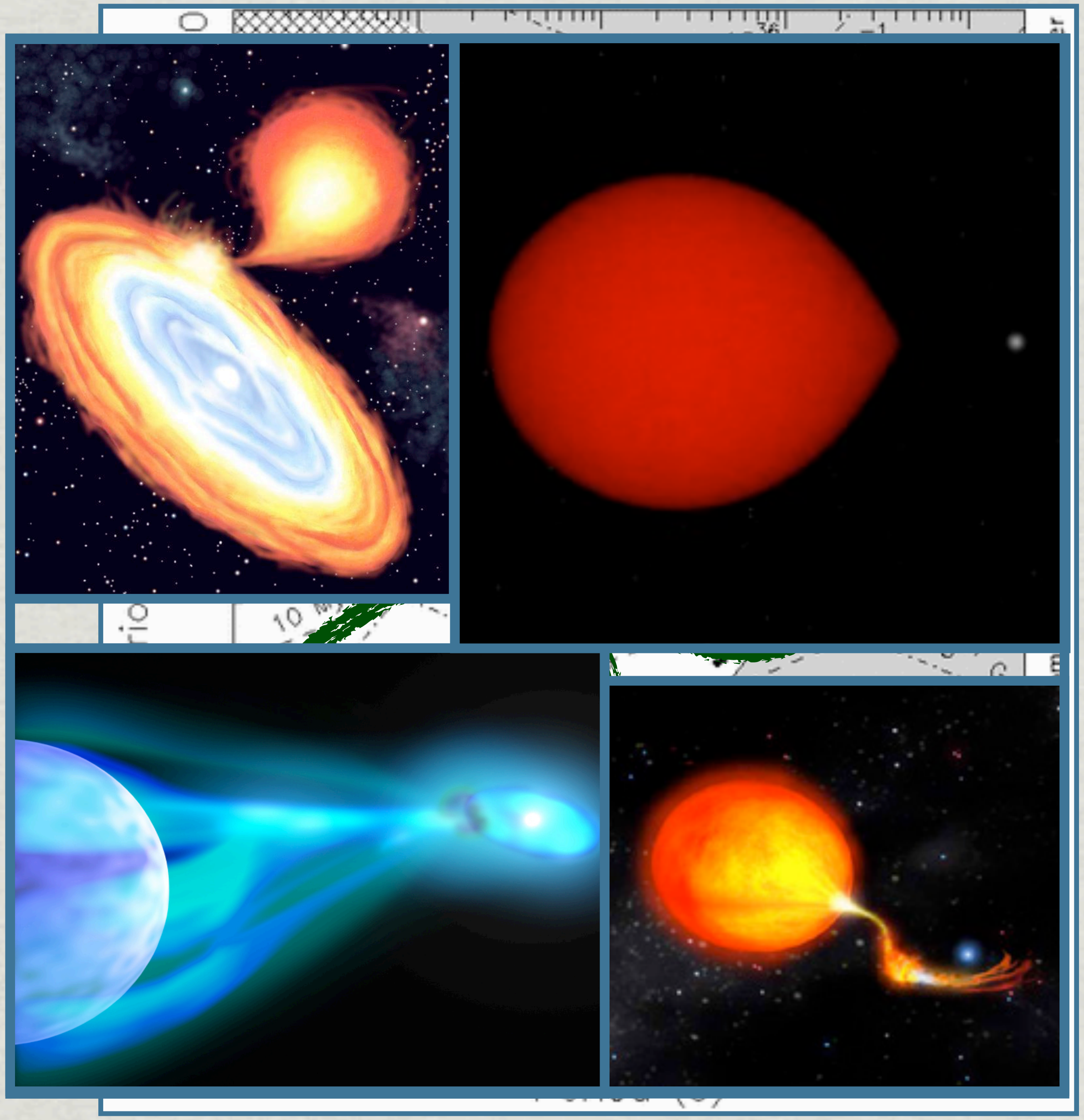
- **young** (age ~ 10^5 - 10^8 yr)
  → P ~ 10^{-15} s/s
  → B ~ 10^{12} G
- **recycled** (age ~ 10^9-10^{10} yr)
  → P ~ 10^{-20} s/s
  → B ~ 10^8-10^{10} G



Pulsars: cosmic lighthouses

Two principal populations: young vs. recycled

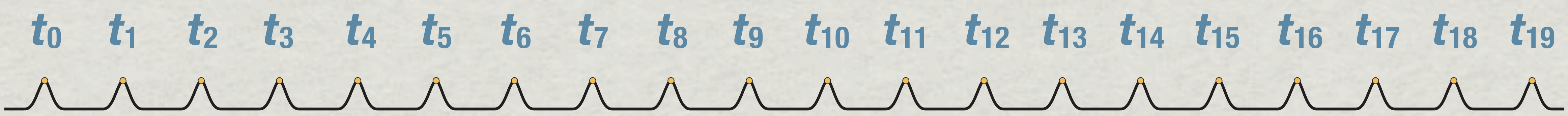
- **young** (age ~ 10^5 - 10^8 yr)
  → $\dot{P}$ ~ 10^{-15} s/s
  → B ~ 10^{12} G
- **recycled** (age ~ 10^9-10^{10} yr)
  → $\dot{P}$ ~ 10^{-20} s/s
  → B ~ 10^8-10^{10} G



Spun up due to accretion of matter/angular momentum from companion

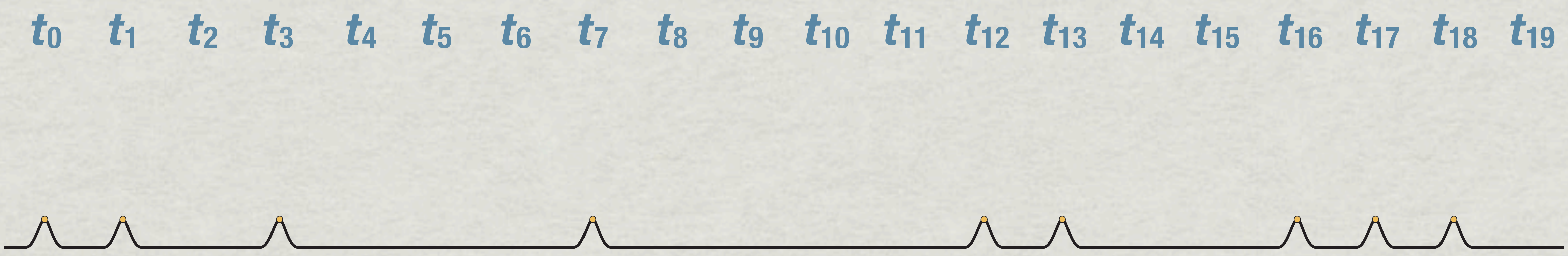
Pulsar timing in a millisecond

Pulsar timing in a millisecond



Pulsar timing in a millisecond

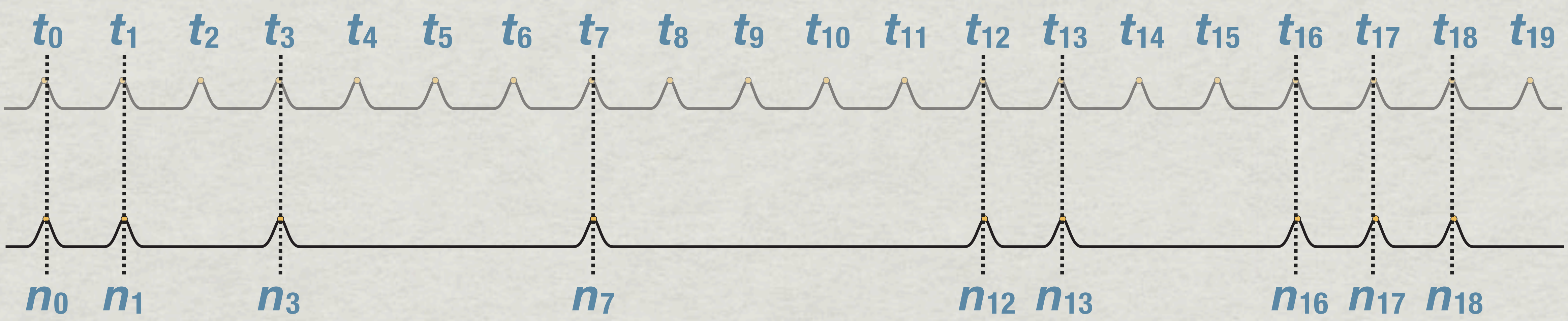
Record pulse times of arrival (TOAs)



Pulsar timing in a millisecond

Record pulse times of arrival (TOAs)

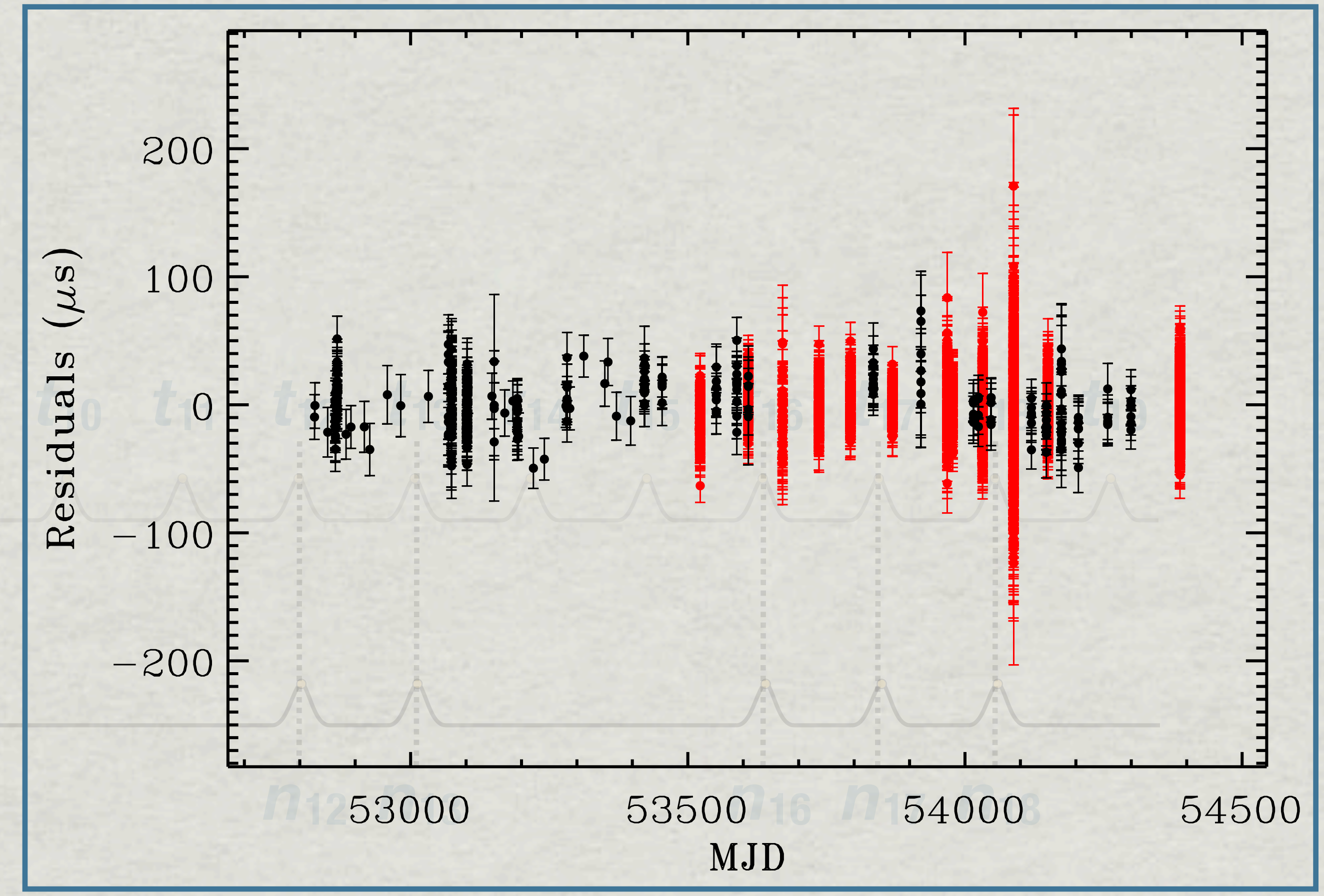
- label each incoming pulse based on ephemeris



Pulsar timing in a millisecond

Record pulse times of arrival (TOAs)

- label each incoming pulse based on ephemeris
- new data ➞ update model
- **timing residuals**
  ➞ (*observed – model*)

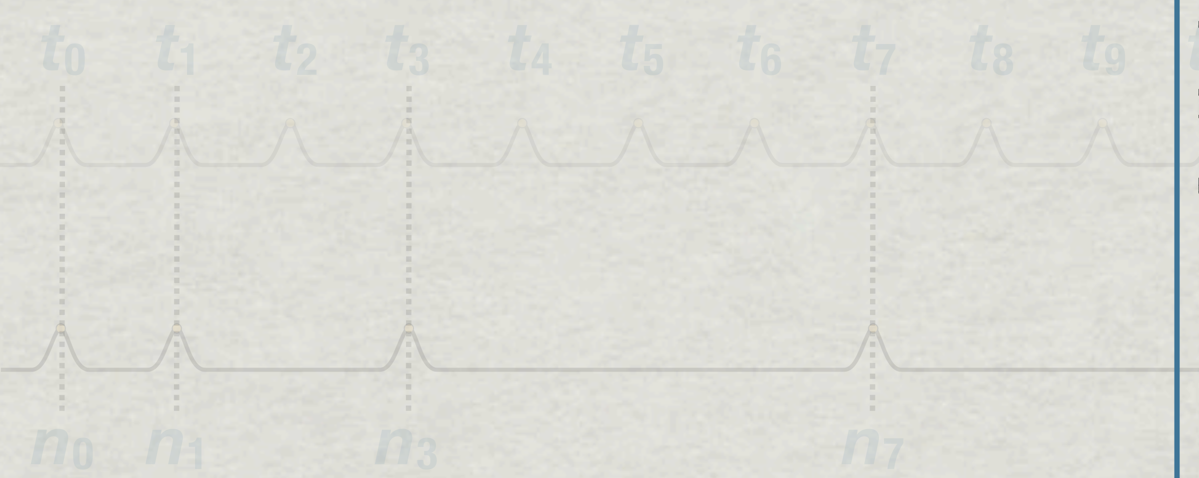


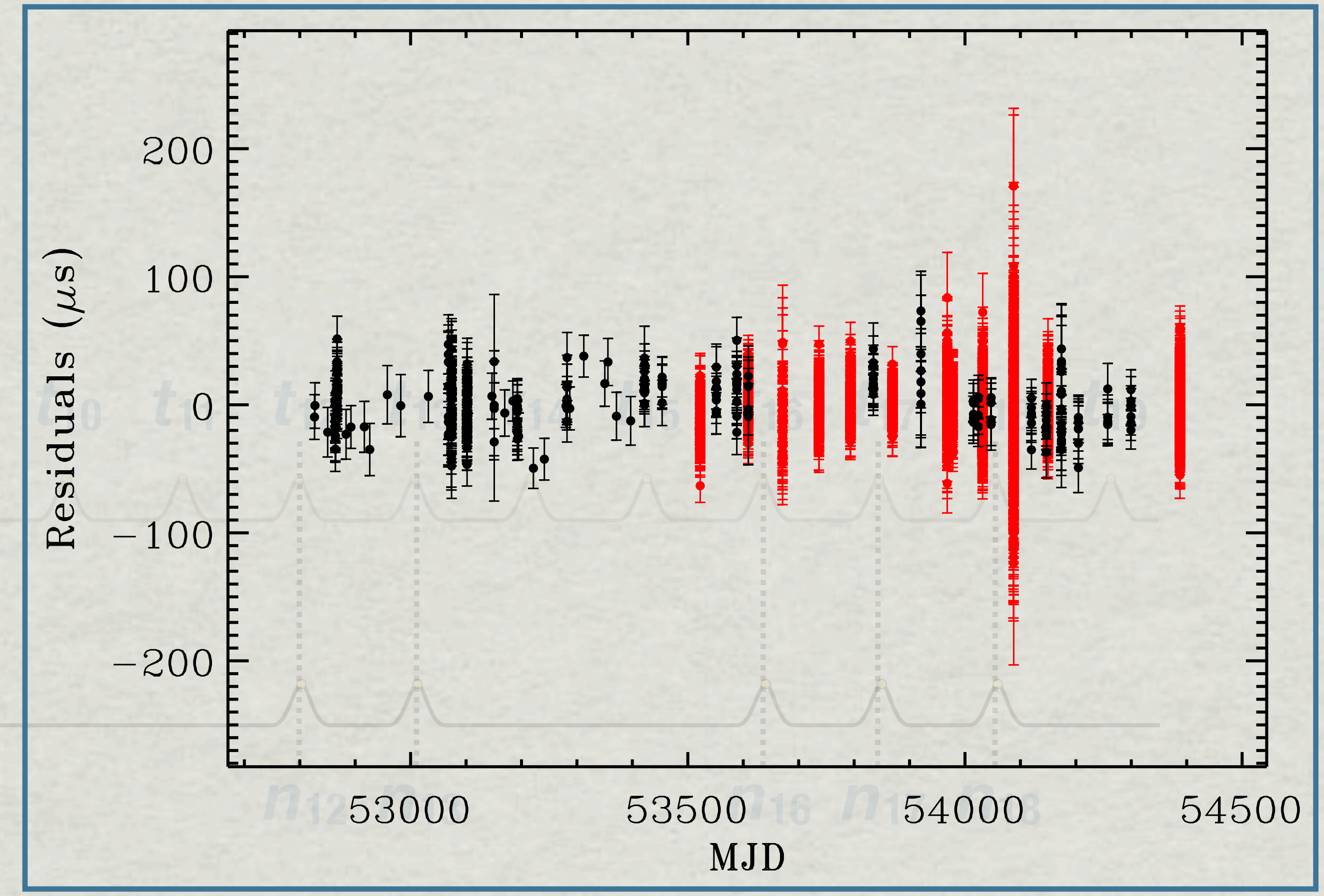
(Ferdman et al., in prep.)

Pulsar timing in a millisecond

Record pulse times of arrival (TOAs)

- label each incoming pulse based on ephemeris
- new data → update model
- **timing residuals**
  → (*observed – model*)





(Ferdman et al., in prep.)

Phase connection → account for each rotation of NS

- powerful -- how we get such high timing precision

What goes into the timing model?

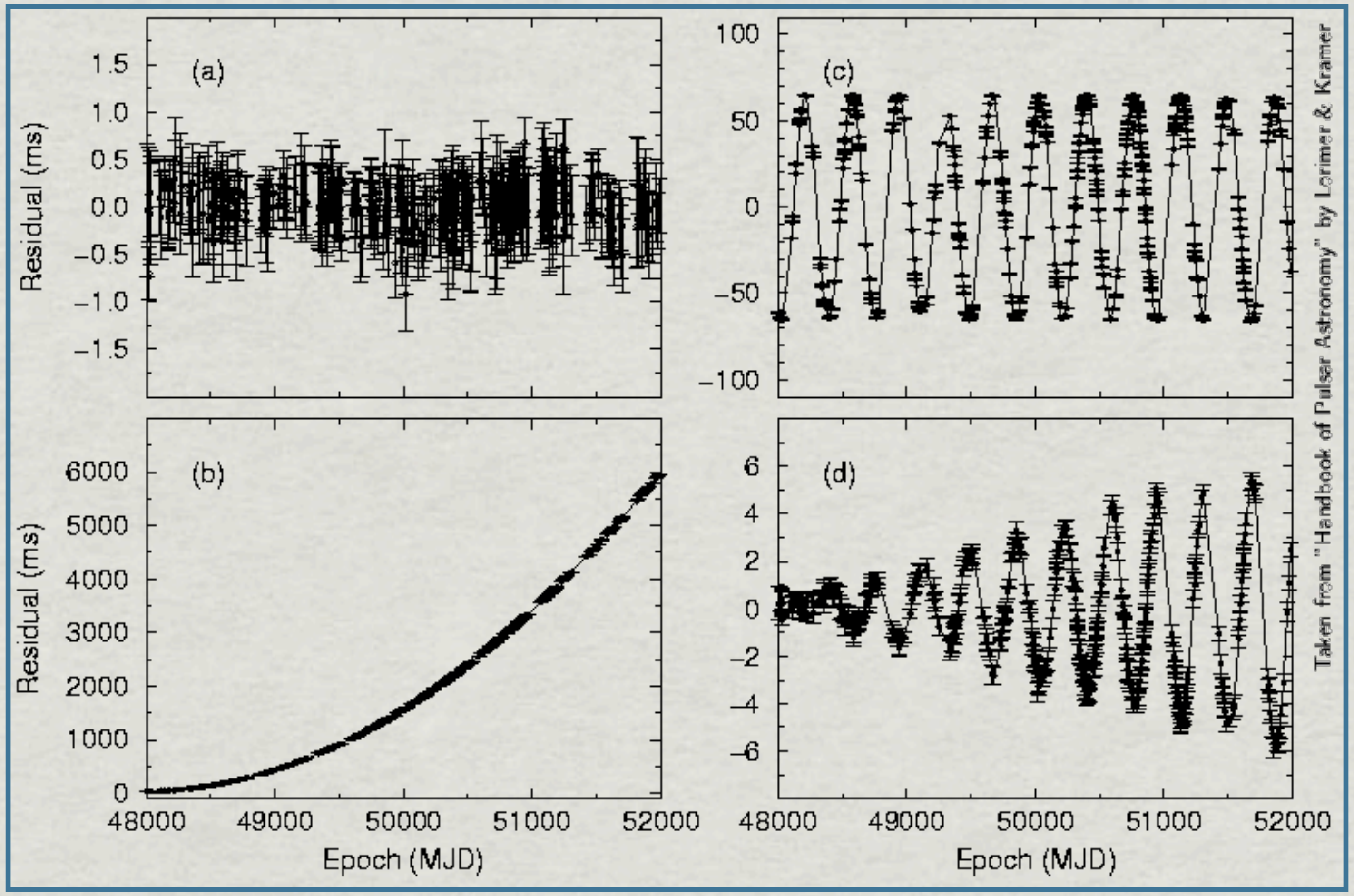
Isolated, slow pulsar

- Spin, spin-down
- Earth, solar system motions
- pulsar position, proper motion
- interstellar dispersion

What goes into the timing model?

Isolated, slow pulsar

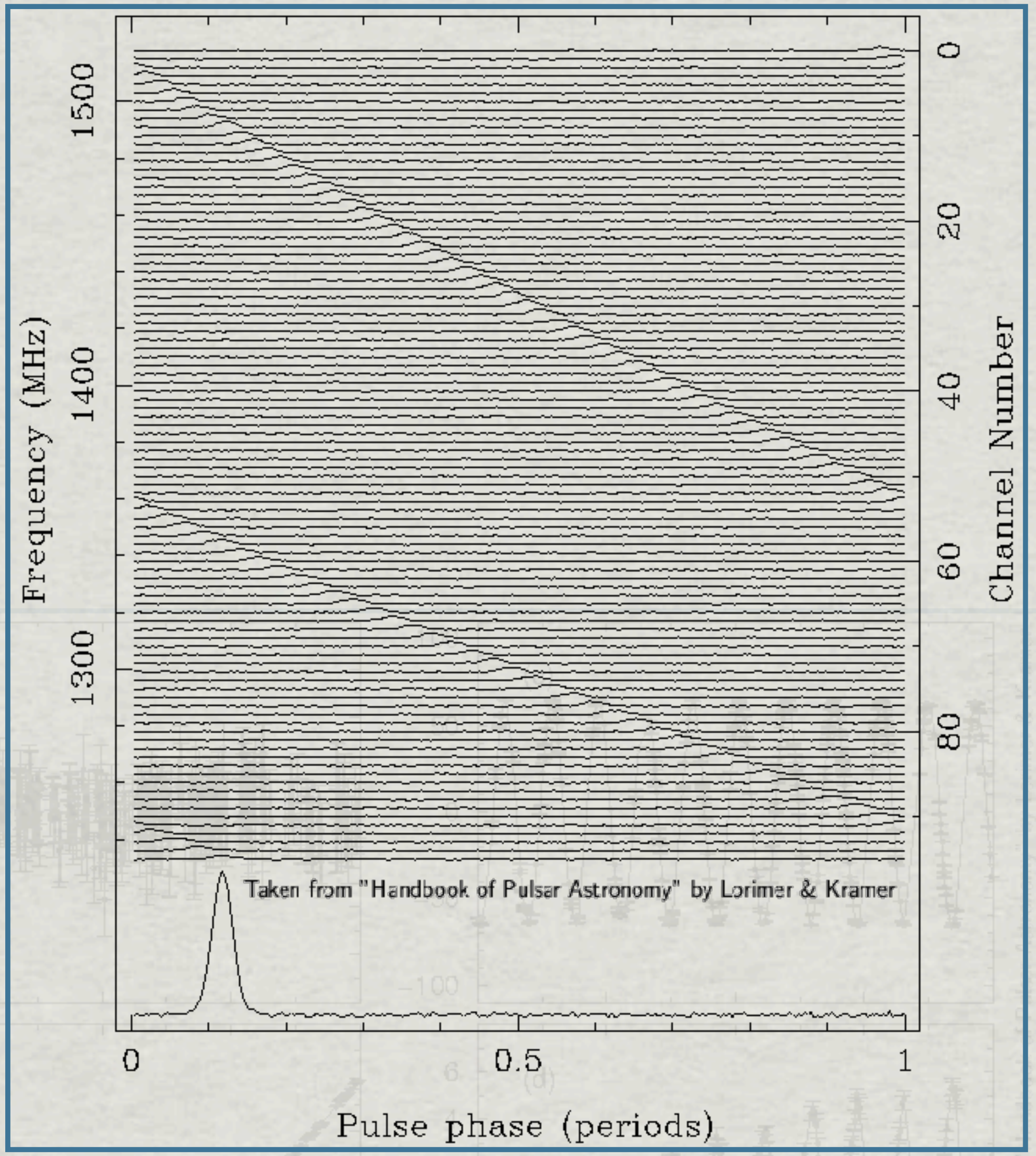
- Spin, spin-down
- Earth, solar system motions
- pulsar position, proper motion
- interstellar dispersion

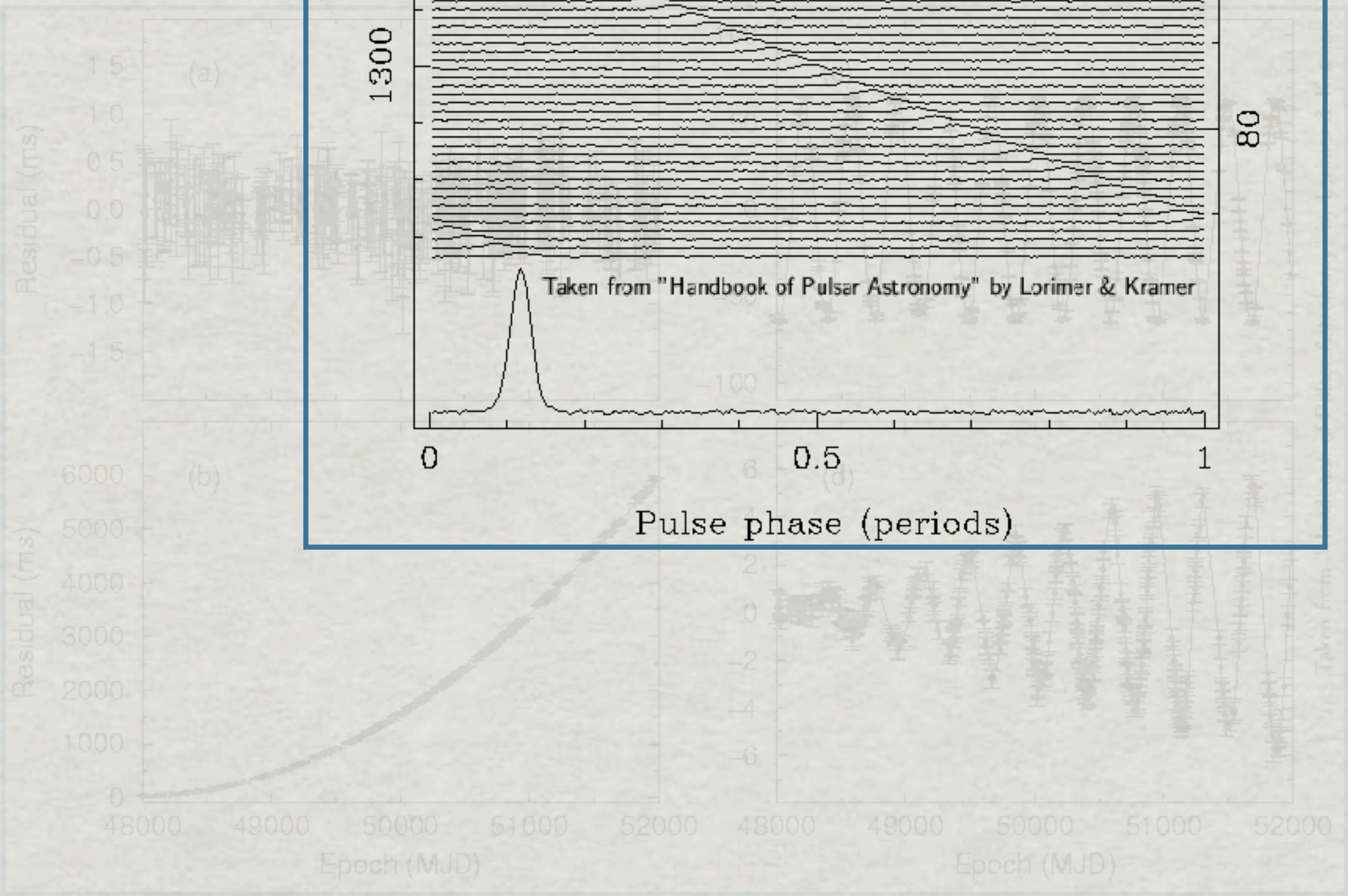


What goes into the timing model?

Isolated, slow pulsar

- Spin, spin-down
- Earth, solar system motions
- pulsar position, proper motion
- interstellar dispersion



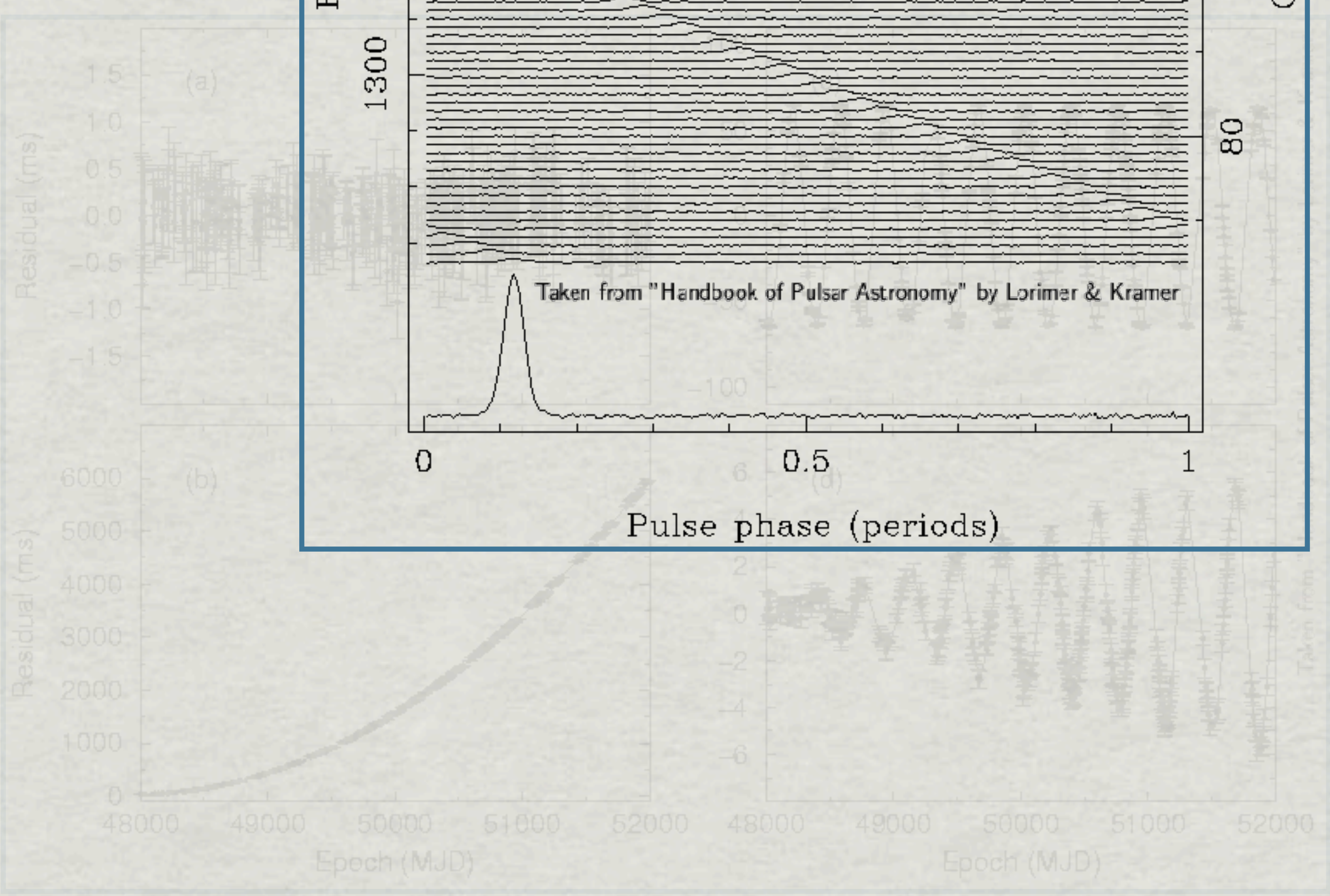


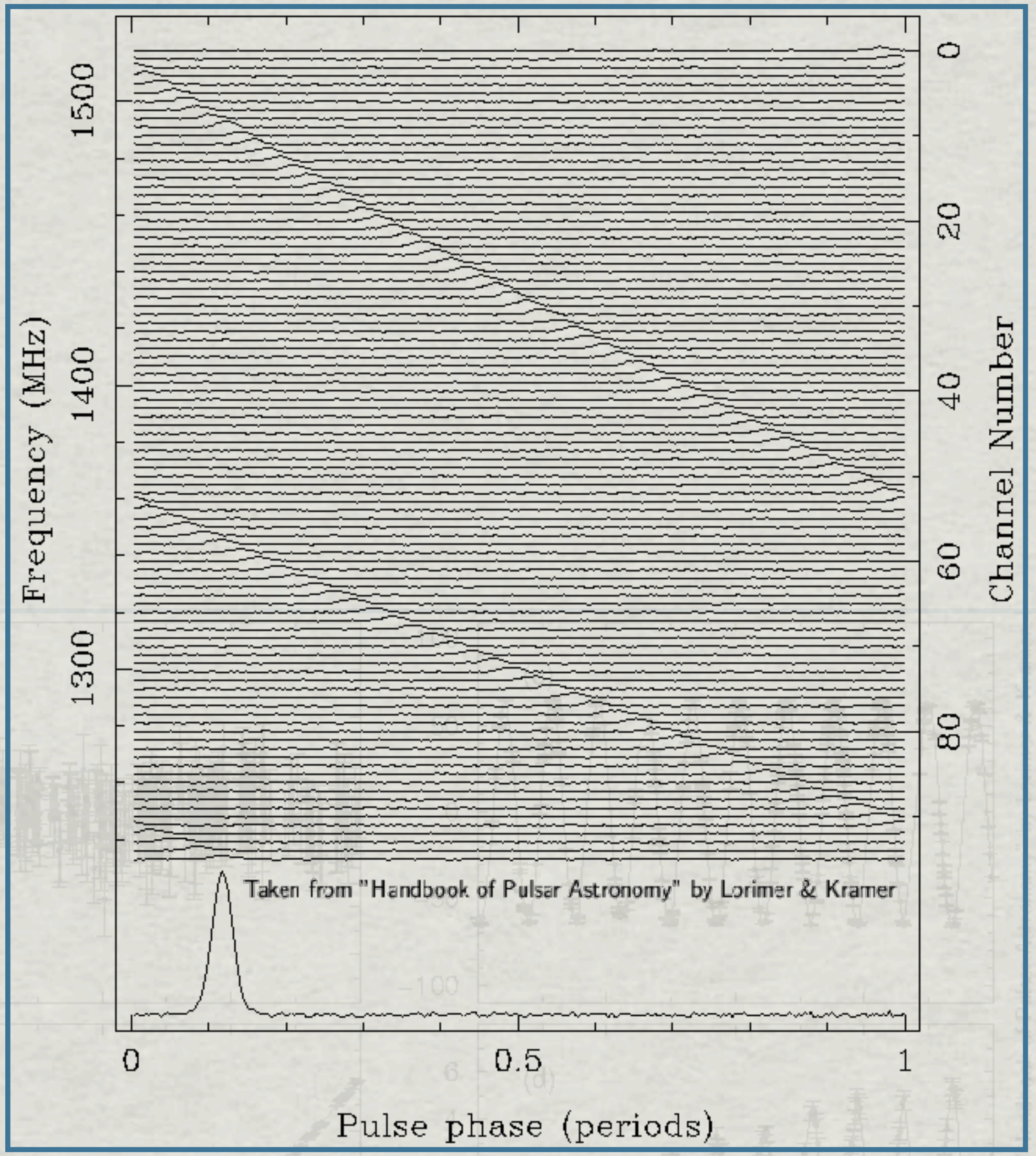
What goes into the timing model?

Isolated, slow pulsar

- Spin, spin-down
- Earth, solar system motions
- pulsar position, proper motion
- interstellar dispersion

Aim of timing model: account for and remove each possible delay





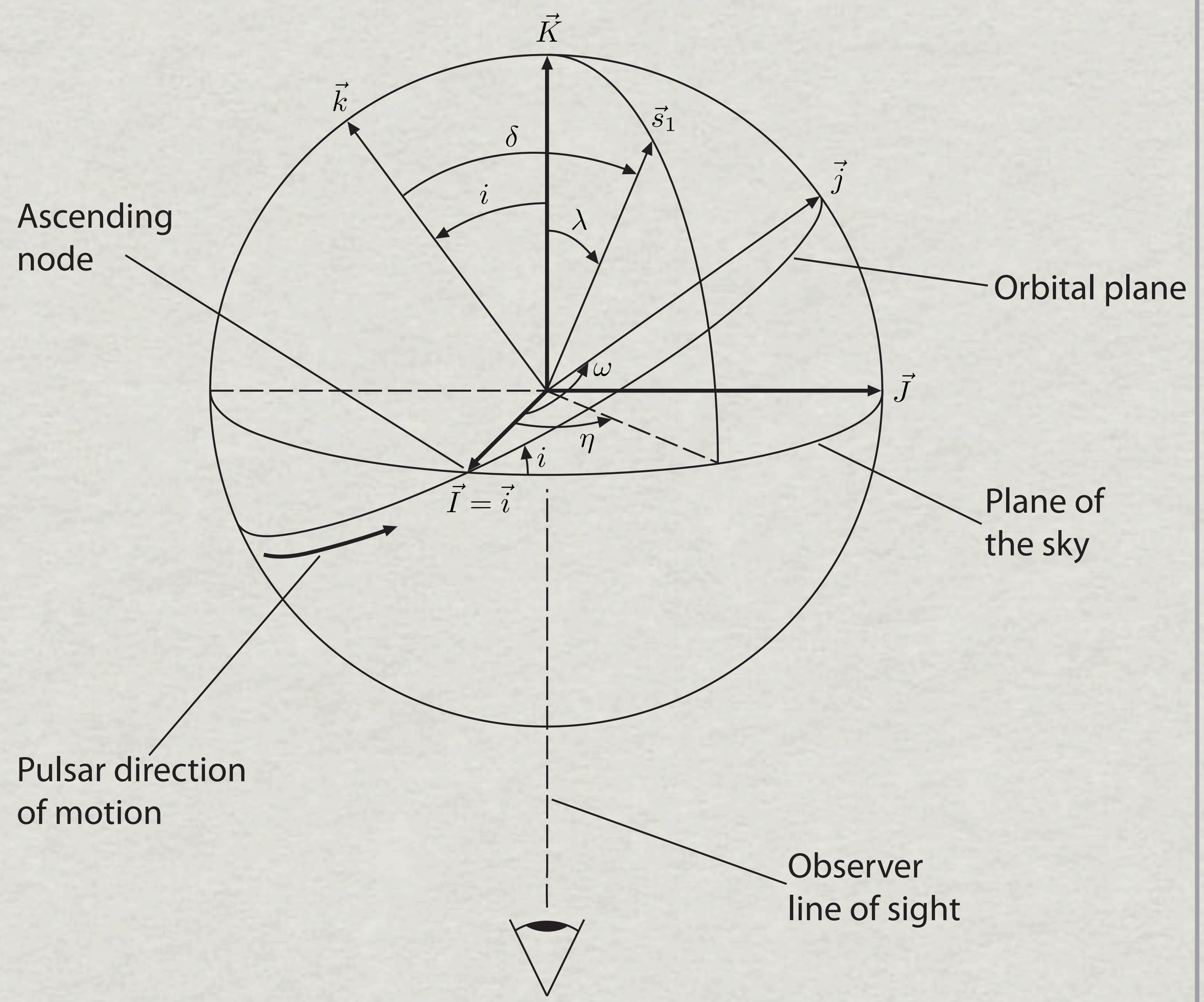
Pulsar binary systems

More complex → more delays:

Orbital parameters

- orbital period
- eccentricity
- longitude of periastron
- time of periastron passage
- projected semimajor axis

- if system is relativistic...



Post-Keplerian parameters

Corrections to Keplerian orbital parameters

PK parameters are theory-independent

Dependencies are different depending on theory of gravity

- GR, for example (e.g., Damour & Deruelle 1986; Damour & Taylor 1992, PRD, 45, 1840):

Post-Keplerian parameters

Corrections to Keplerian orbital parameters

PK parameters are theory-independent

Dependencies are different depending on theory of gravity

- GR, for example (e.g., Damour & Deruelle 1986; Damour & Taylor 1992, PRD, 45, 1840):

$$\dot{\omega} = 3T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} (m_1+m_2)^{2/3}$$

$$\dot{P}_b = -\frac{192\pi}{5} T_\odot^{5/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1-e^2)^{-7/2} \frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

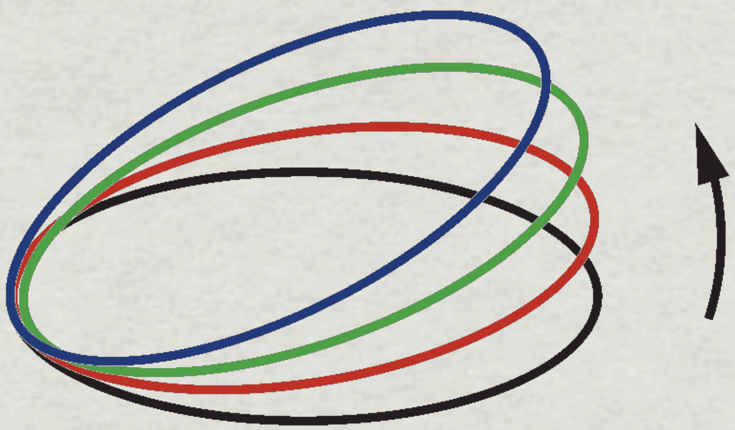
$$\gamma = T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{1/3} e \frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$

$$r = T_\odot m_2$$

$$s = T_\odot^{-1/3} \left(\frac{P_b}{2\pi}\right)^{-2/3} x \frac{(m_1+m_2)^{2/3}}{m_2} = \sin i$$

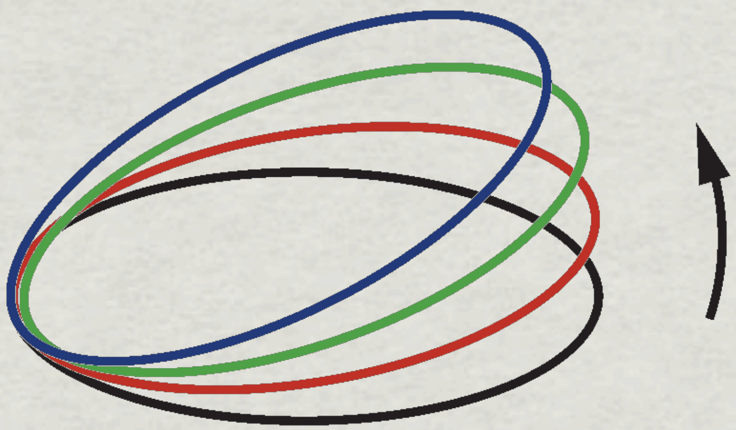
Post-Keplerian parameters

Post-Keplerian parameters

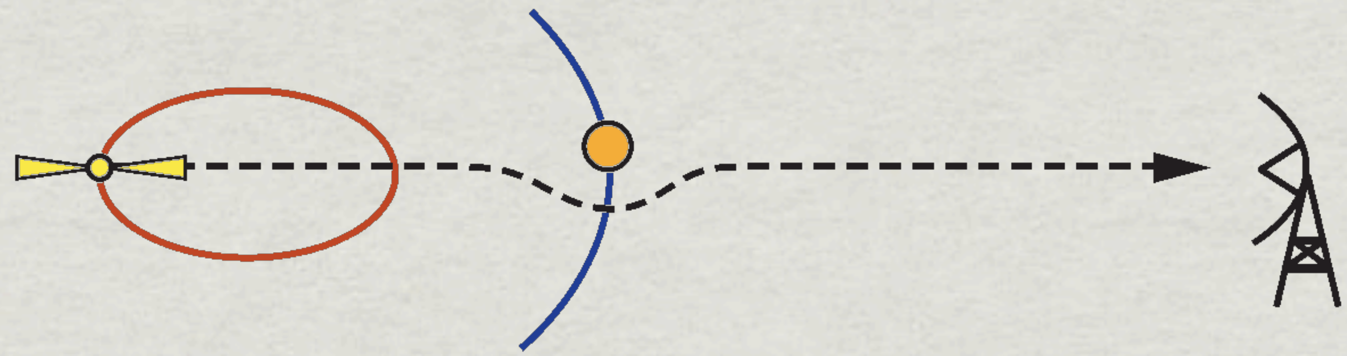


orbital precession ($\dot{\omega}$)

Post-Keplerian parameters

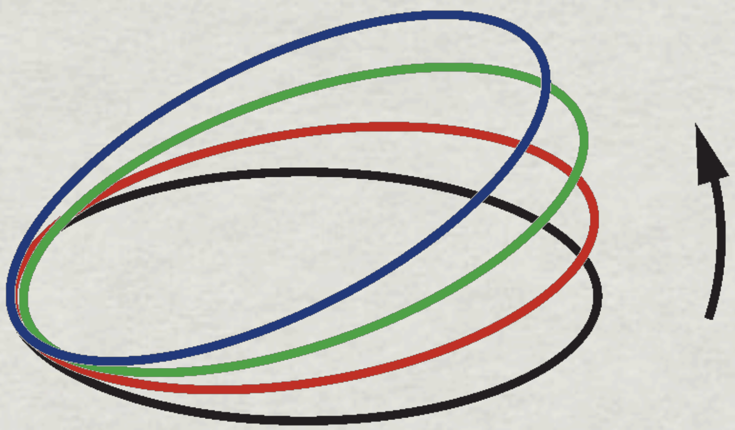


orbital precession ($\dot{\omega}$)

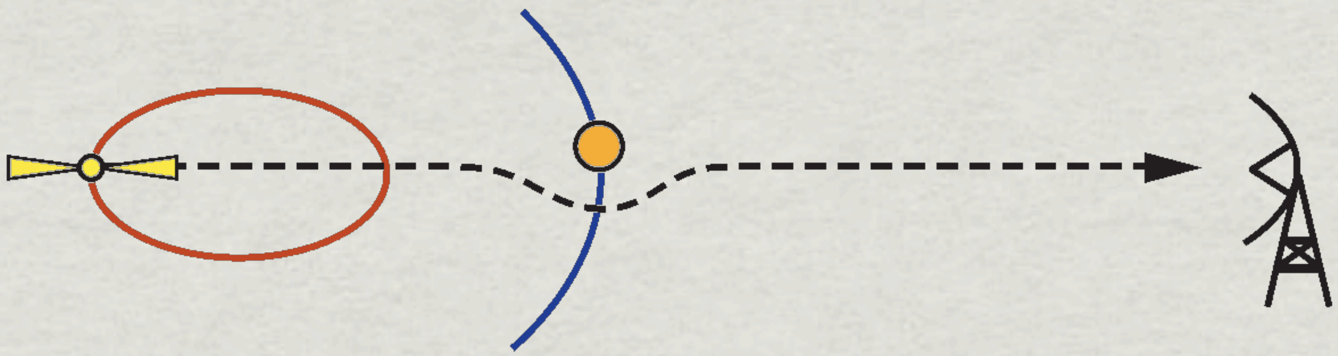


Shapiro delay (*r, s*)

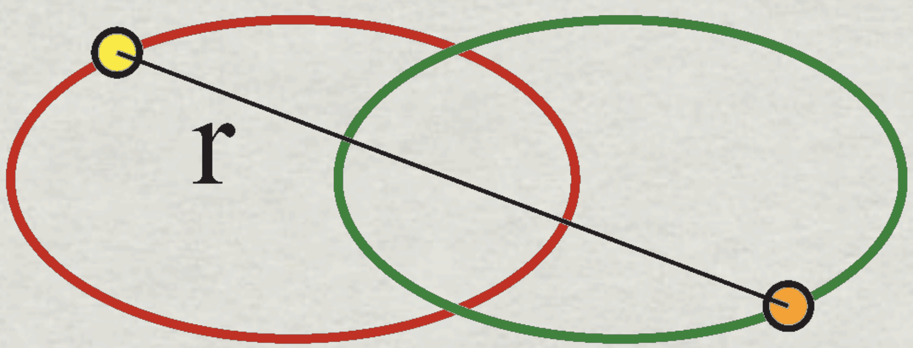
Post-Keplerian parameters



orbital precession ($\dot{\omega}$)

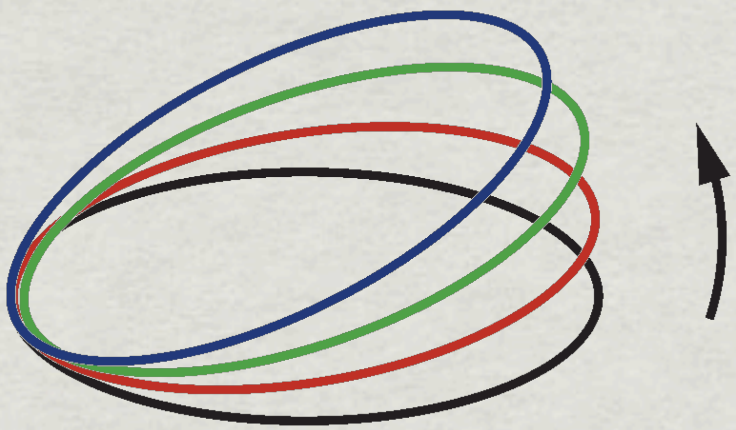


Shapiro delay (r, s)

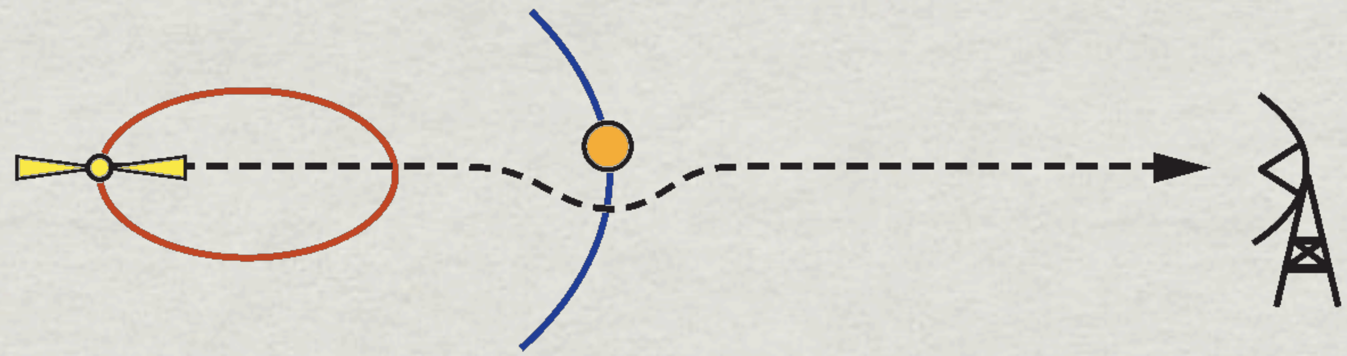


gravitational redshift/
time dilation (γ)

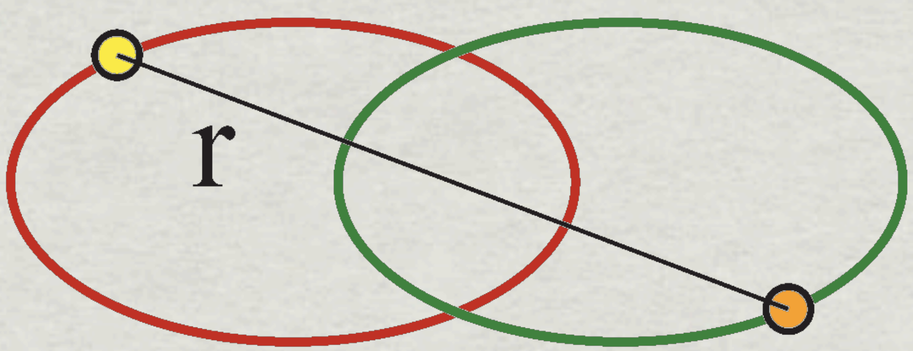
Post-Keplerian parameters



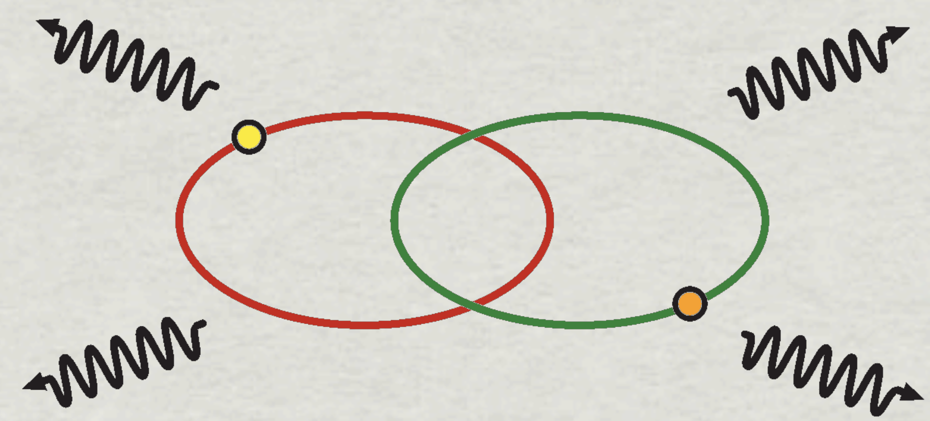
orbital precession ($\dot{\omega}$)



Shapiro delay (*r, s*)

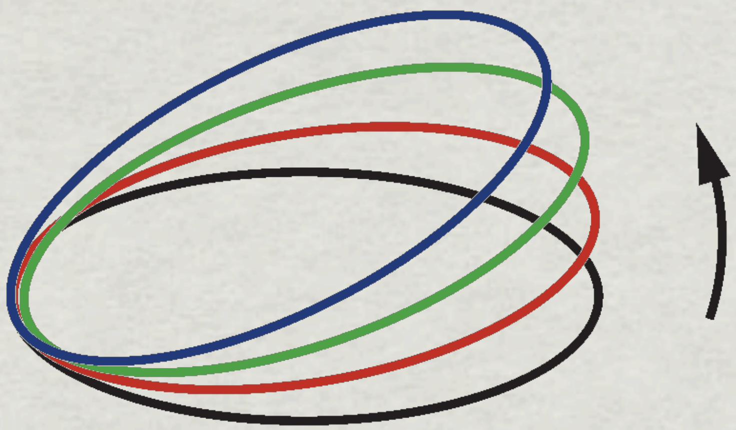


gravitational redshift/
time dilation (γ)

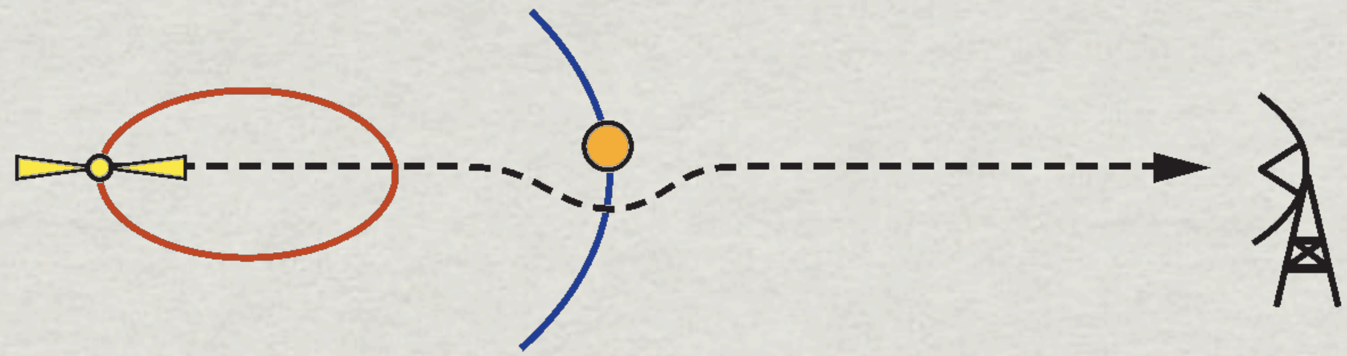


orbital decay ($\dot{P}_b$)

Post-Keplerian parameters

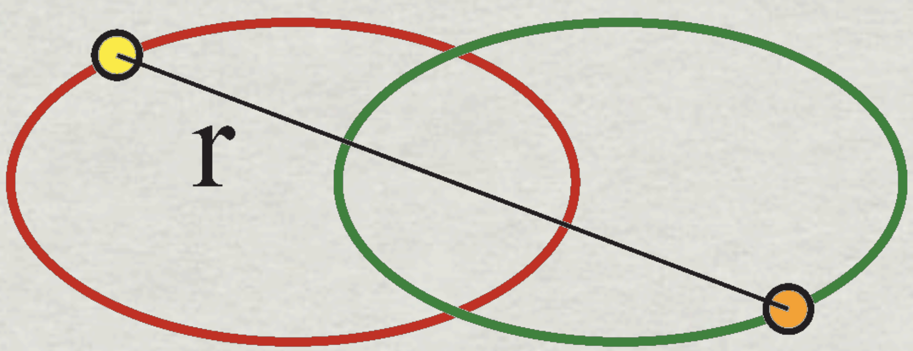


orbital precession ($\dot{\omega}$)

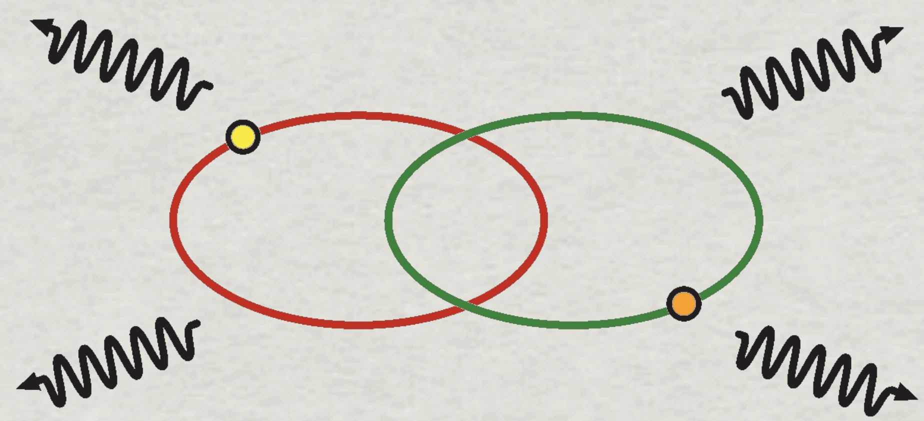


Shapiro delay (r, s)

Any two ⇒ masses

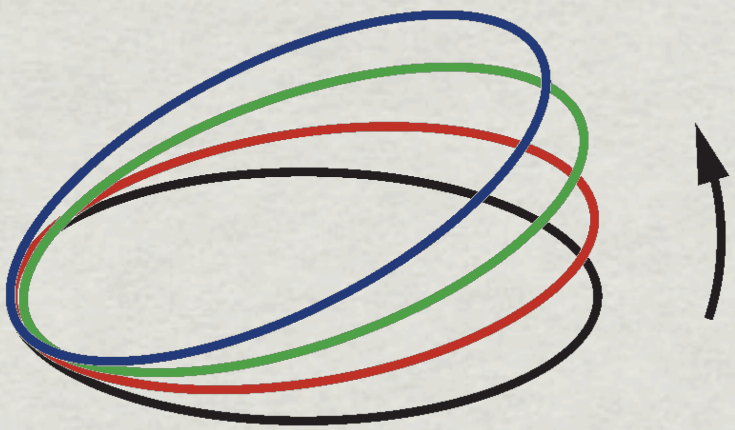


gravitational redshift/
time dilation (γ)

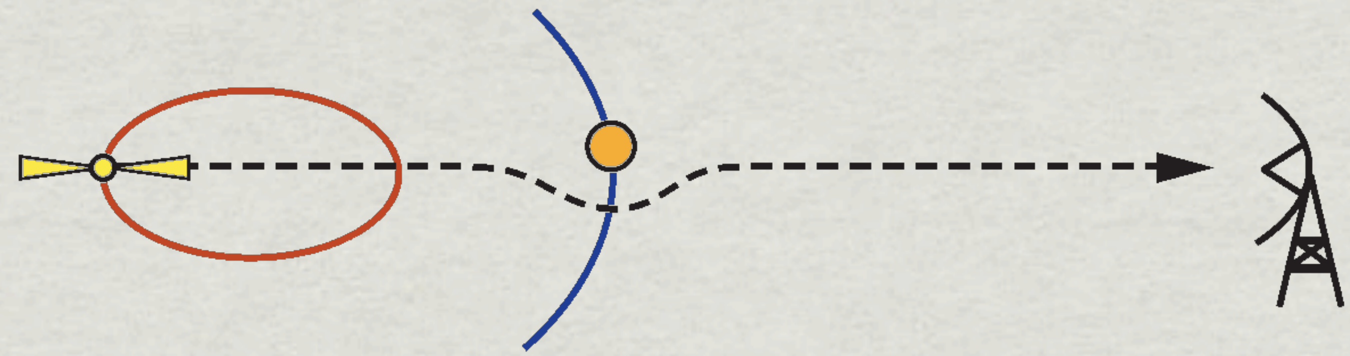


orbital decay ($\dot{P}_b$)

Post-Keplerian parameters



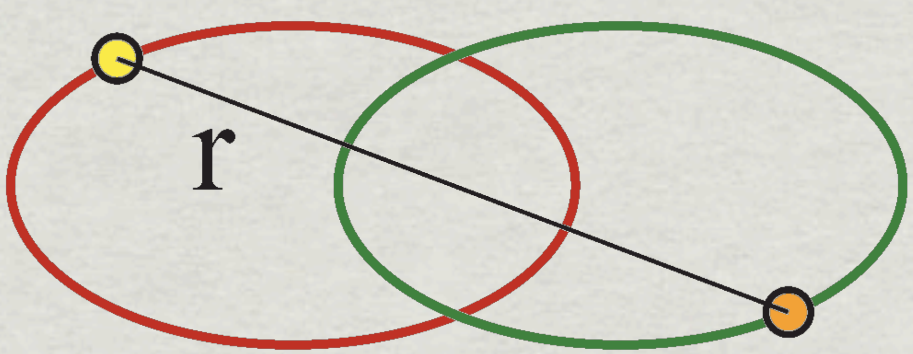
orbital precession ($\dot{\omega}$)



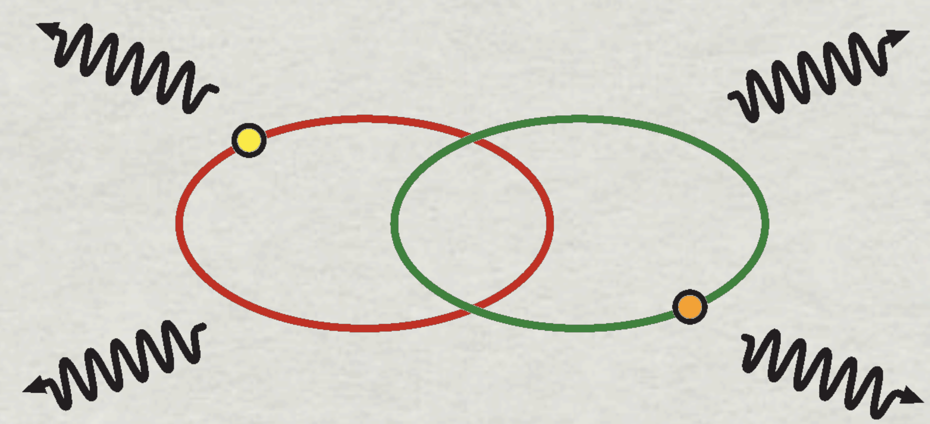
Shapiro delay (*r*, *s*)

Any two ⇒ masses

≥ three ⇒ GR test

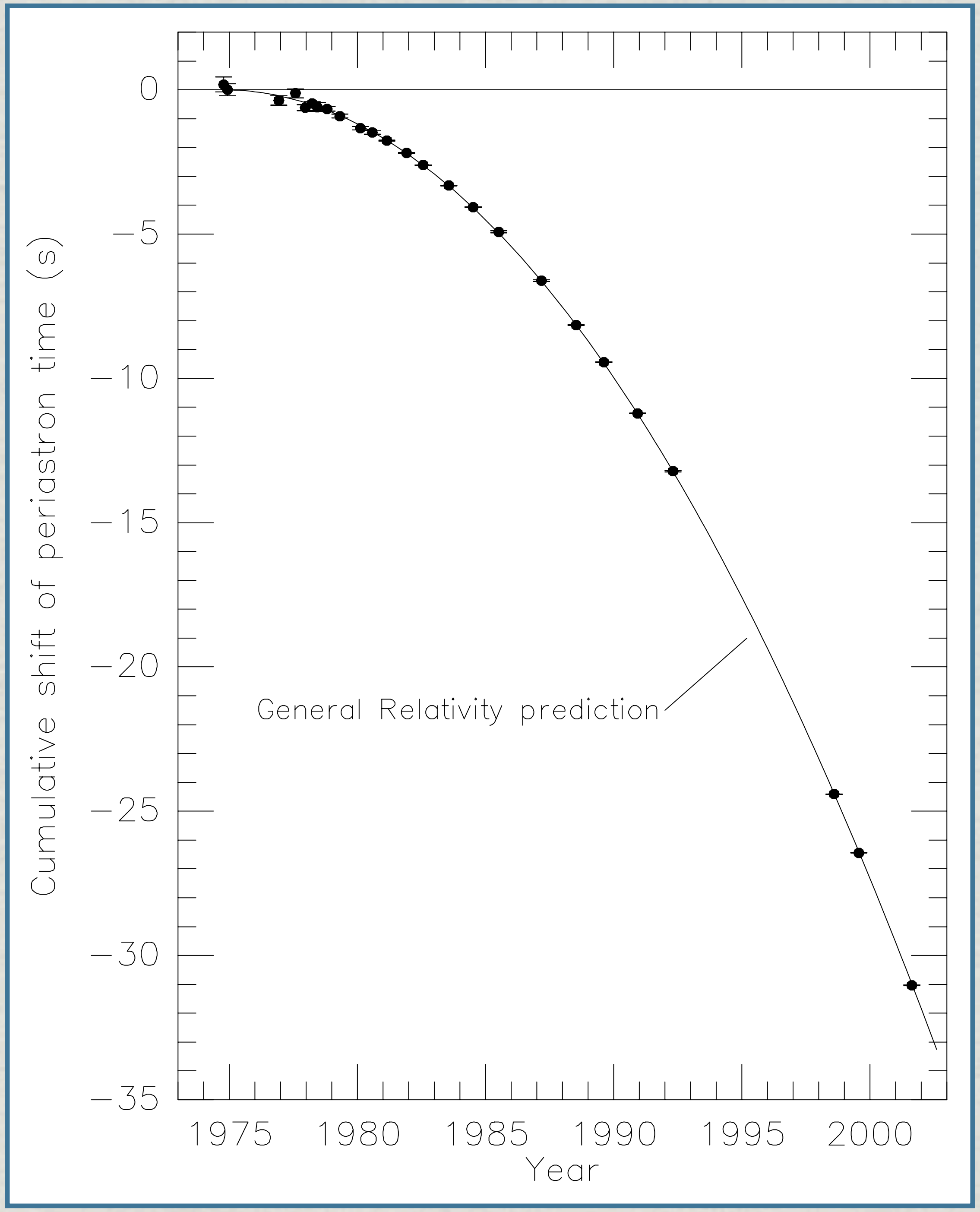


gravitational redshift/
time dilation (γ)



orbital decay ($\dot{P}_b$)

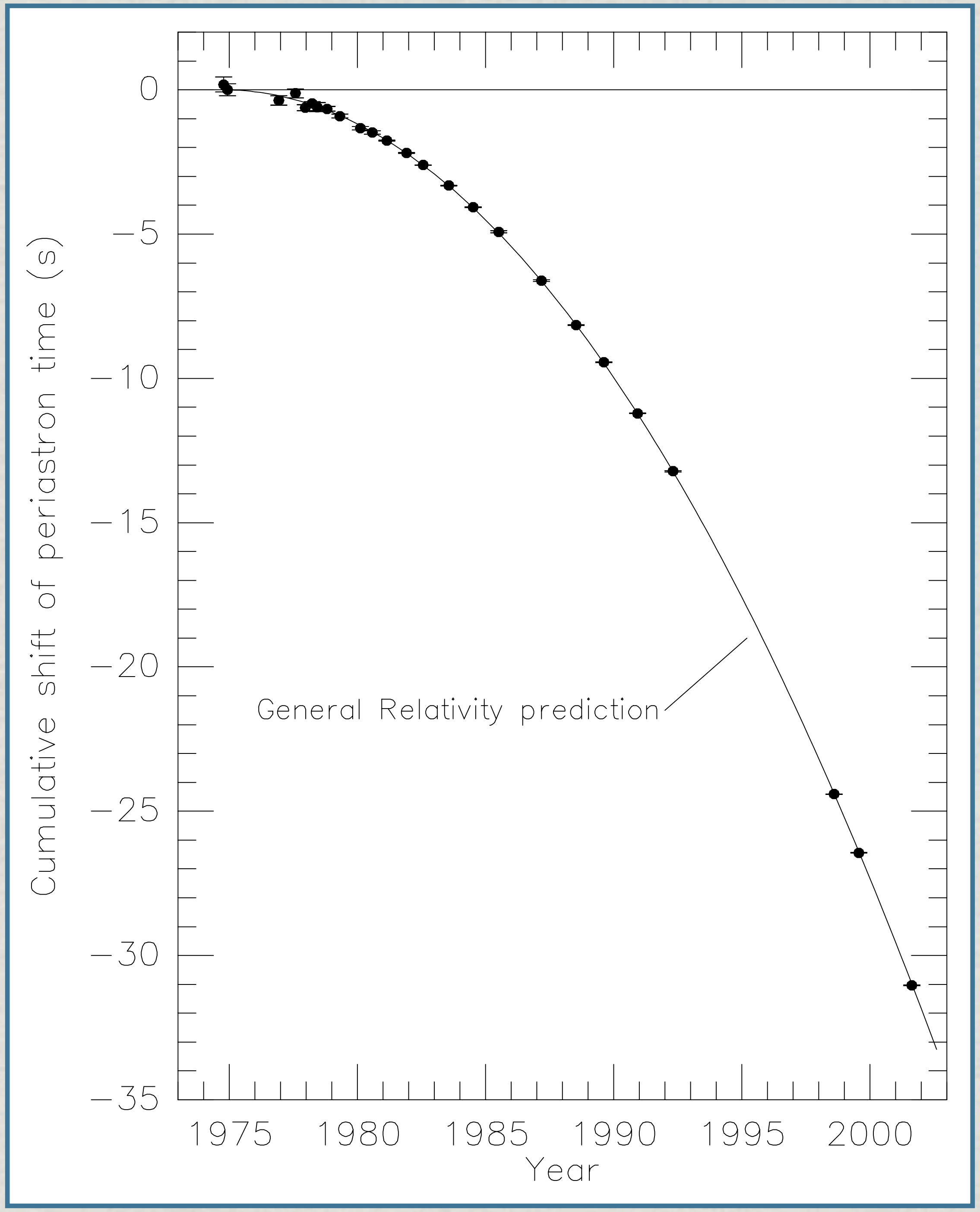
Pulsars as GR probes



J. Weisberg, private communication

Pulsars as GR probes

GR tests since discovery of first binary pulsar:



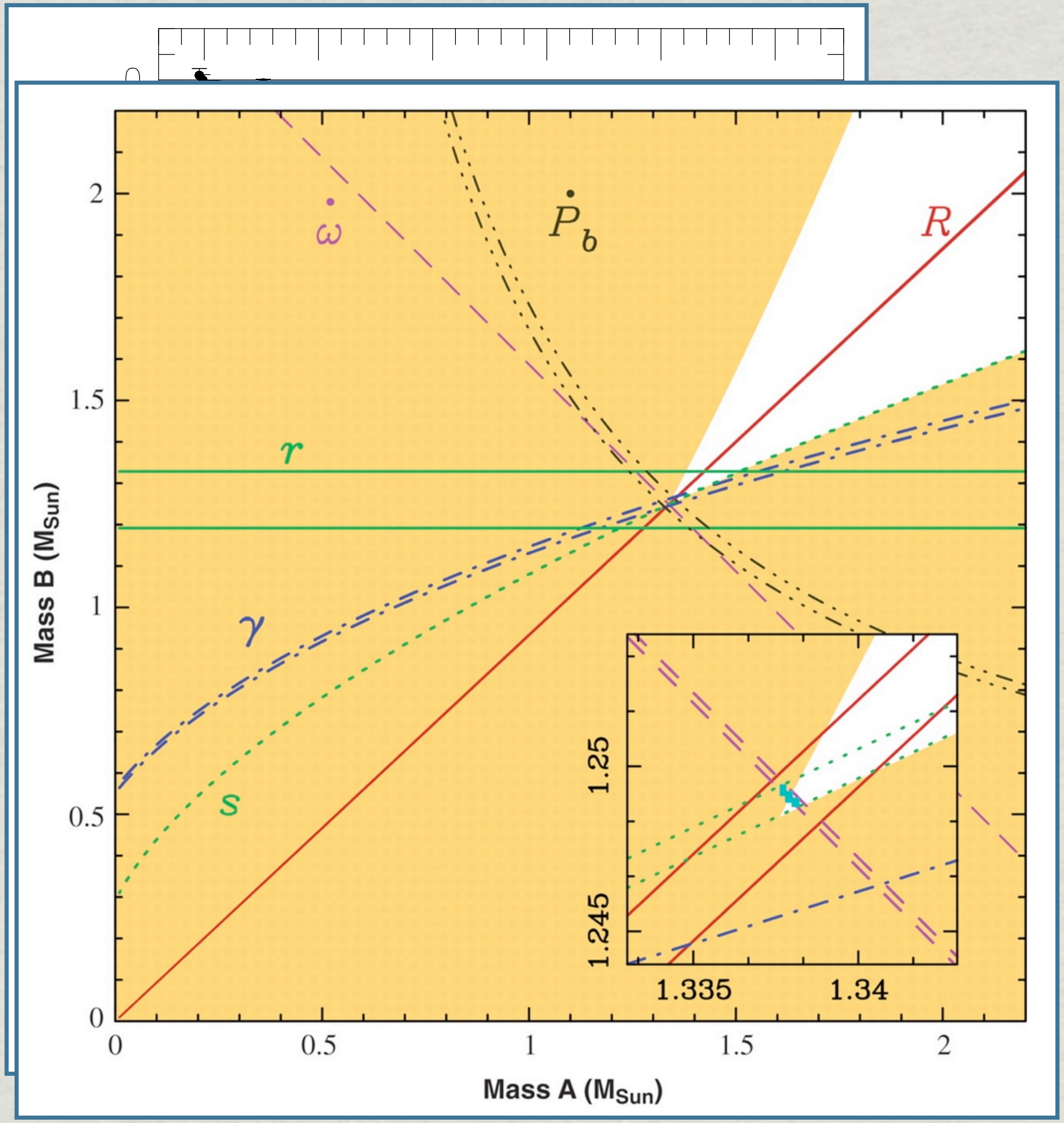
J. Weisberg, private communication

Pulsars as GR probes

GR tests since discovery of first binary pulsar:

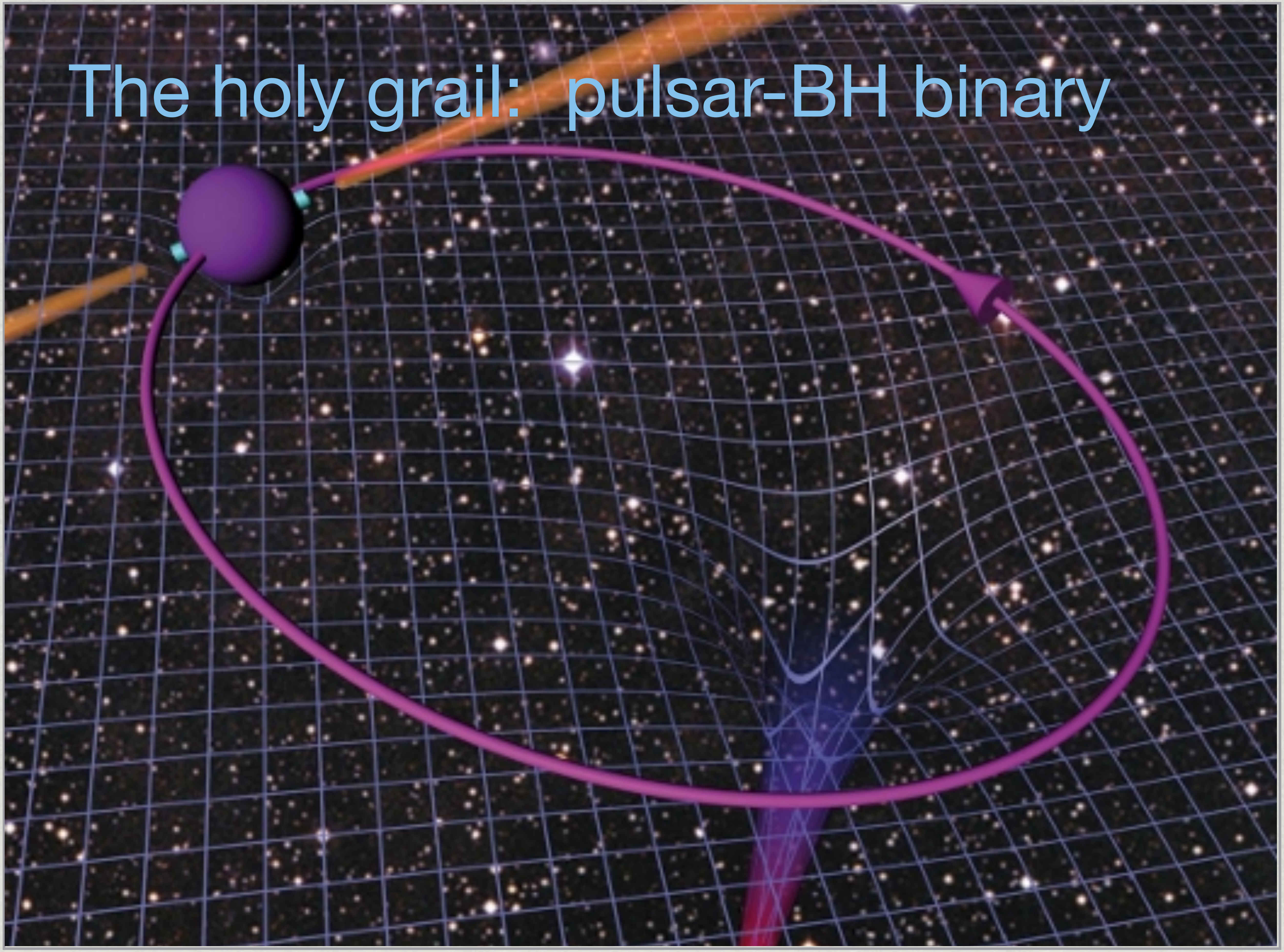
Double pulsar
PSR J0737–3039A/B

- Shapiro delay s consistent to within 0.05%
- most precise strong-field test



Kramer et al. 2006, Science, 314,

The holy grail: pulsar-BH binary



The holy grail: pulsar-BH binary

Further GR tests

- beyond first-order PN corrections, dipole radiation, ...

Black hole/system properties

- mass
- spin-orbit coupling
- effects of BH quadrupole moment

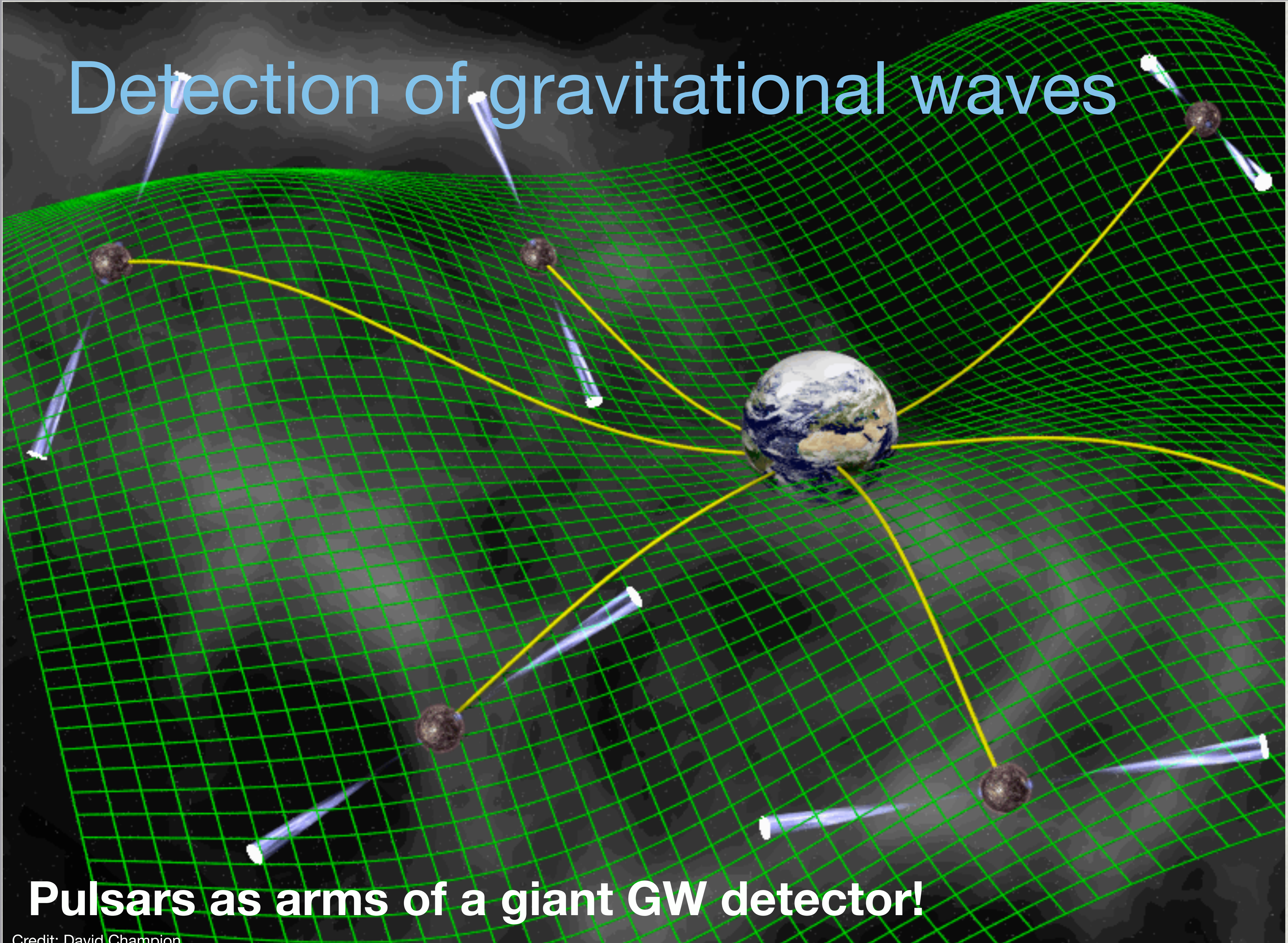
What we really want is a close black hole-millisecond pulsar binary

- highly relativistic, precise timer

Intermediate-mass BH/pulsar?

- some tests not currently possible with SMBHs

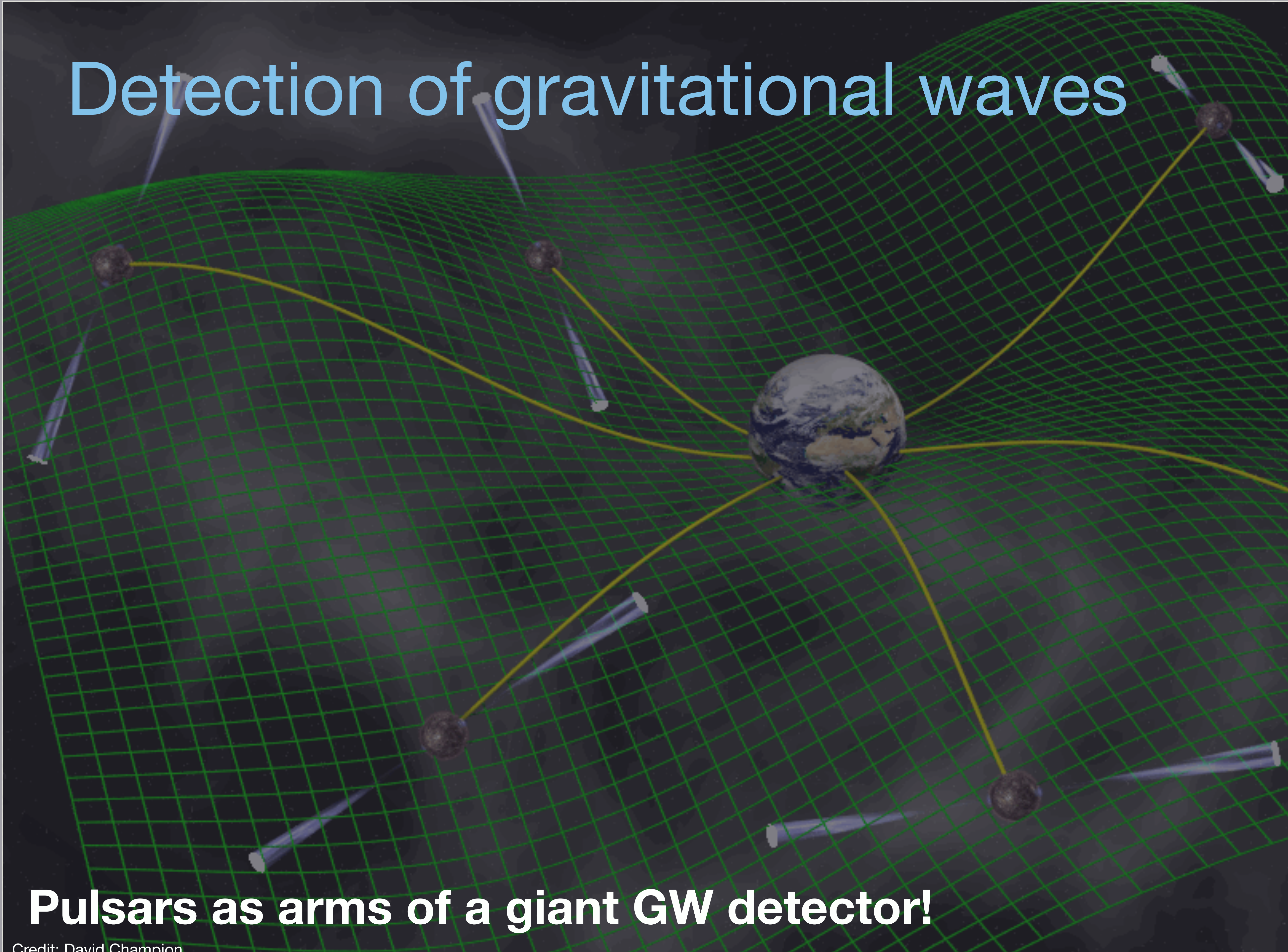
Detection of gravitational waves



Pulsars as arms of a giant GW detector!

Credit: David Champion

Detection of gravitational waves



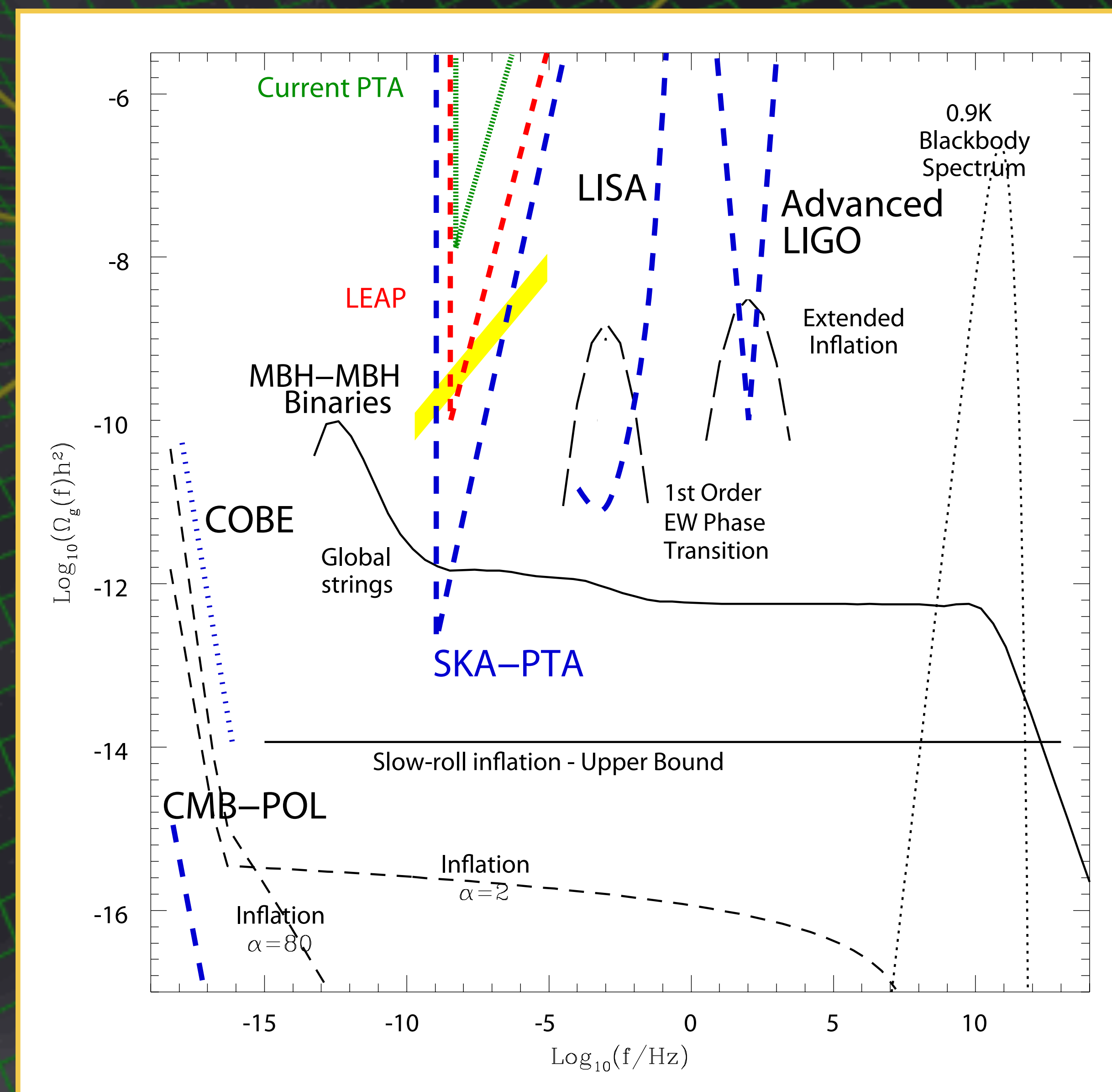
Pulsars as arms of a giant GW detector!

Credit: David Champion

Detection of gravitational waves

Direct detection through common effect on arrival times

- period ~ observation time
  - nHz regime
- coalescence of SMBHs due to galaxy mergers
- stochastic GW background

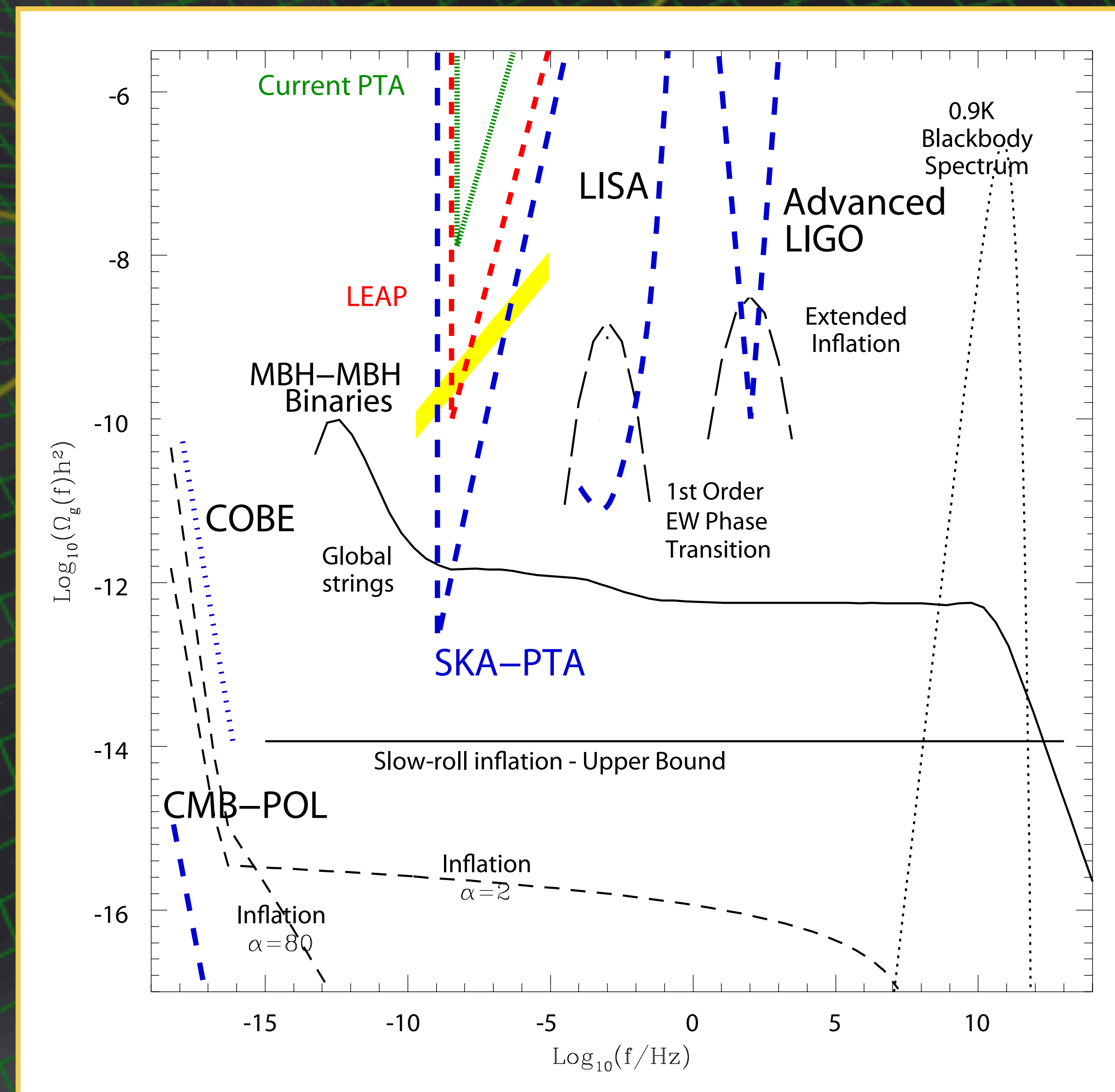


Credit: David Champion

Detection of gravitational waves

Direct detection through common effect on arrival times

- period ~ observation time
  - nHz regime
- coalescence of SMBHs due to galaxy mergers
- stochastic GW background
- characteristic residual correlation spectrum

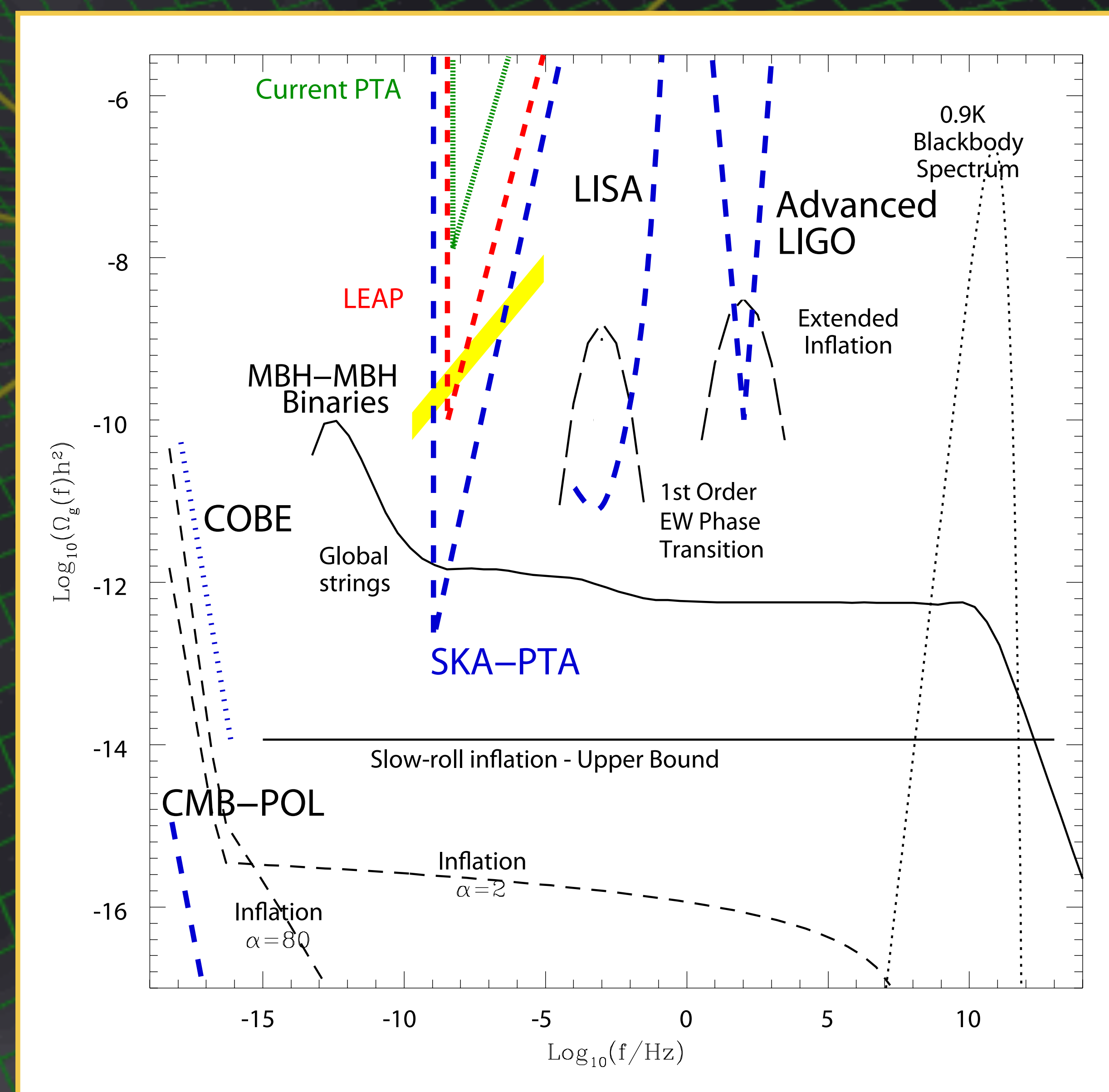


Credit: David Champion

Detection of gravitational waves

Direct detection through common effect on arrival times

- period ~ observation time
  - nHz regime
- coalescence of SMBHs due to galaxy mergers
- stochastic GW background
- characteristic residual correlation spectrum
- need ~ 20 pulsars at ~100 μs precision timed for about 5-10 years

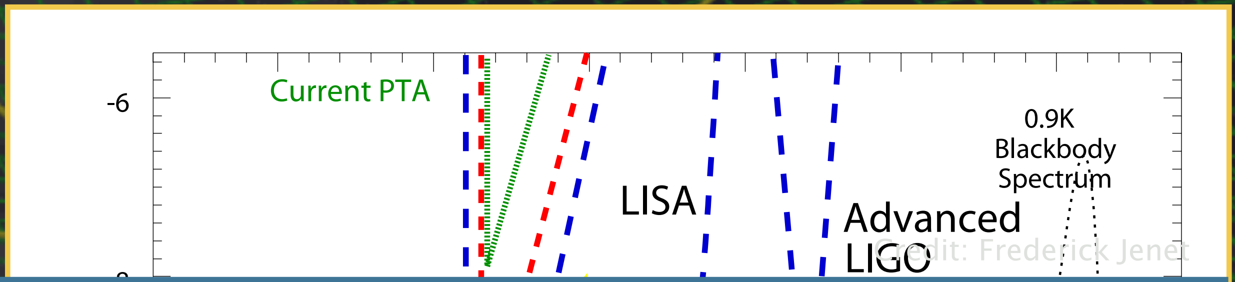


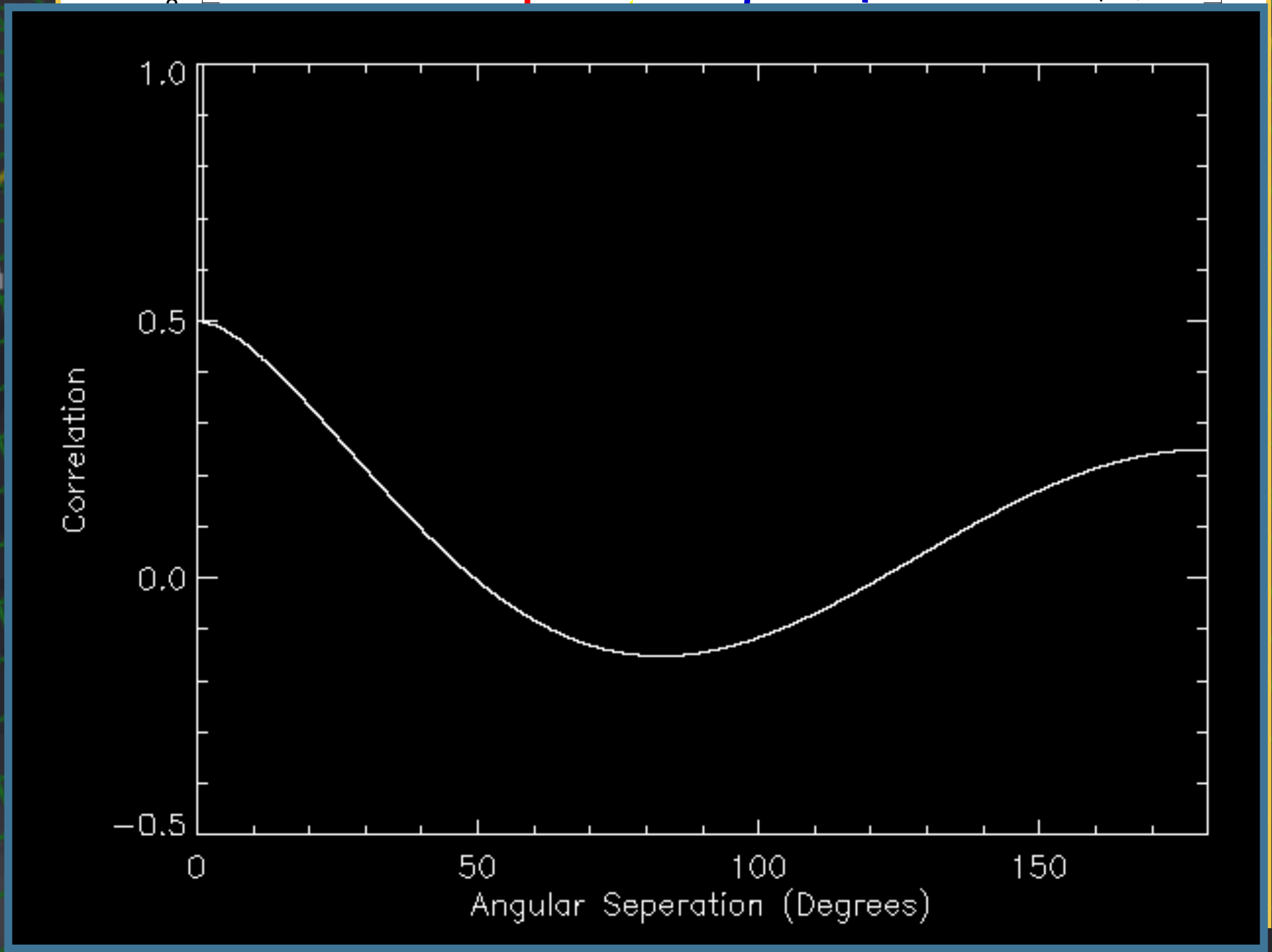
Credit: David Champion

Detection of gravitational waves

Direct detection through common effect on arrival times

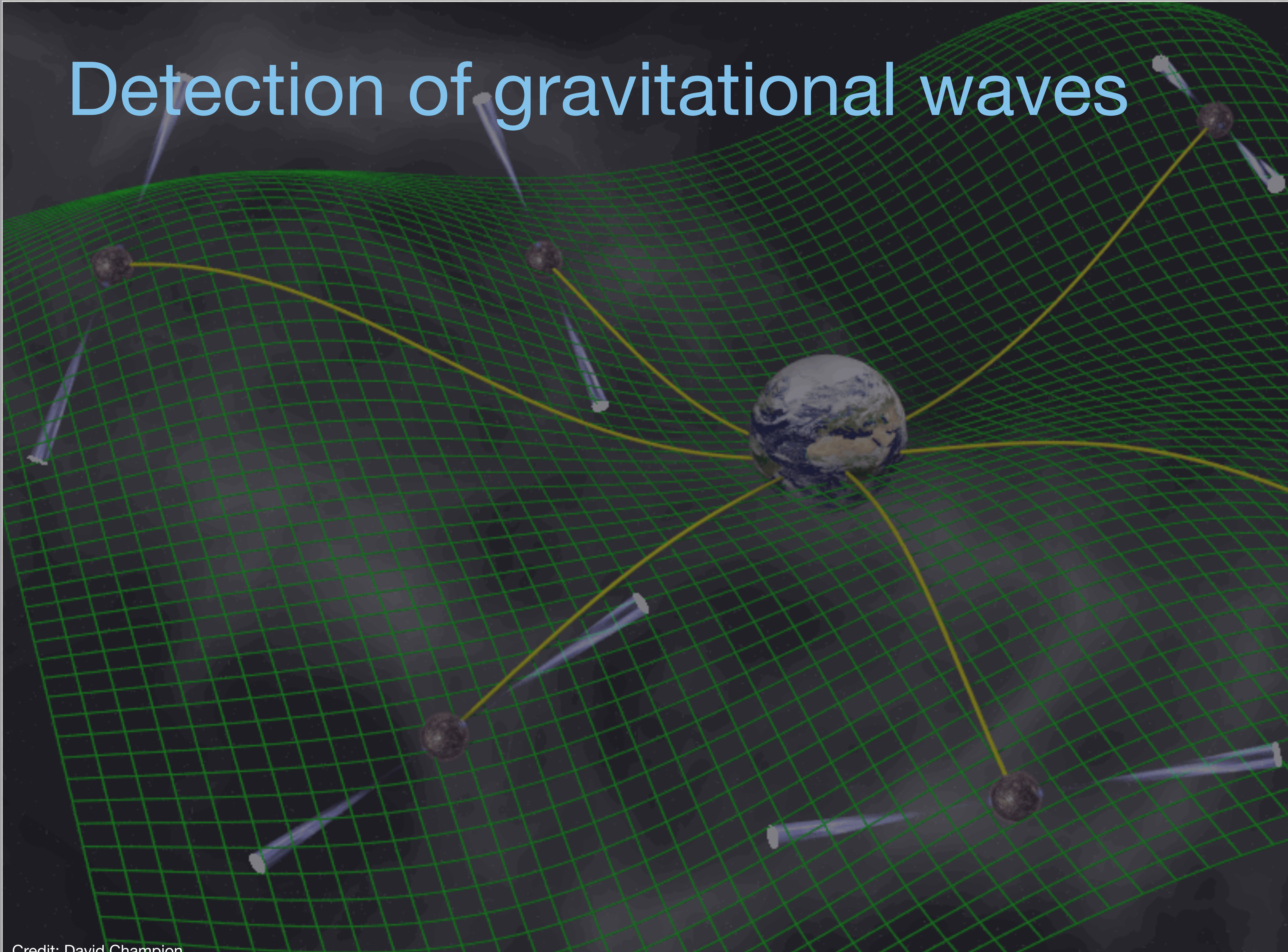
- period ~ observation time
  - nHz regime
- coalescence of SMBHs due to galaxy mergers
- stochastic GW background
- characteristic residual correlation spectrum
- need ~ 20 pulsars at ~100 μs precision timed for about 5-10 years
  - well-distributed





Credit: David Champion

Detection of gravitational waves

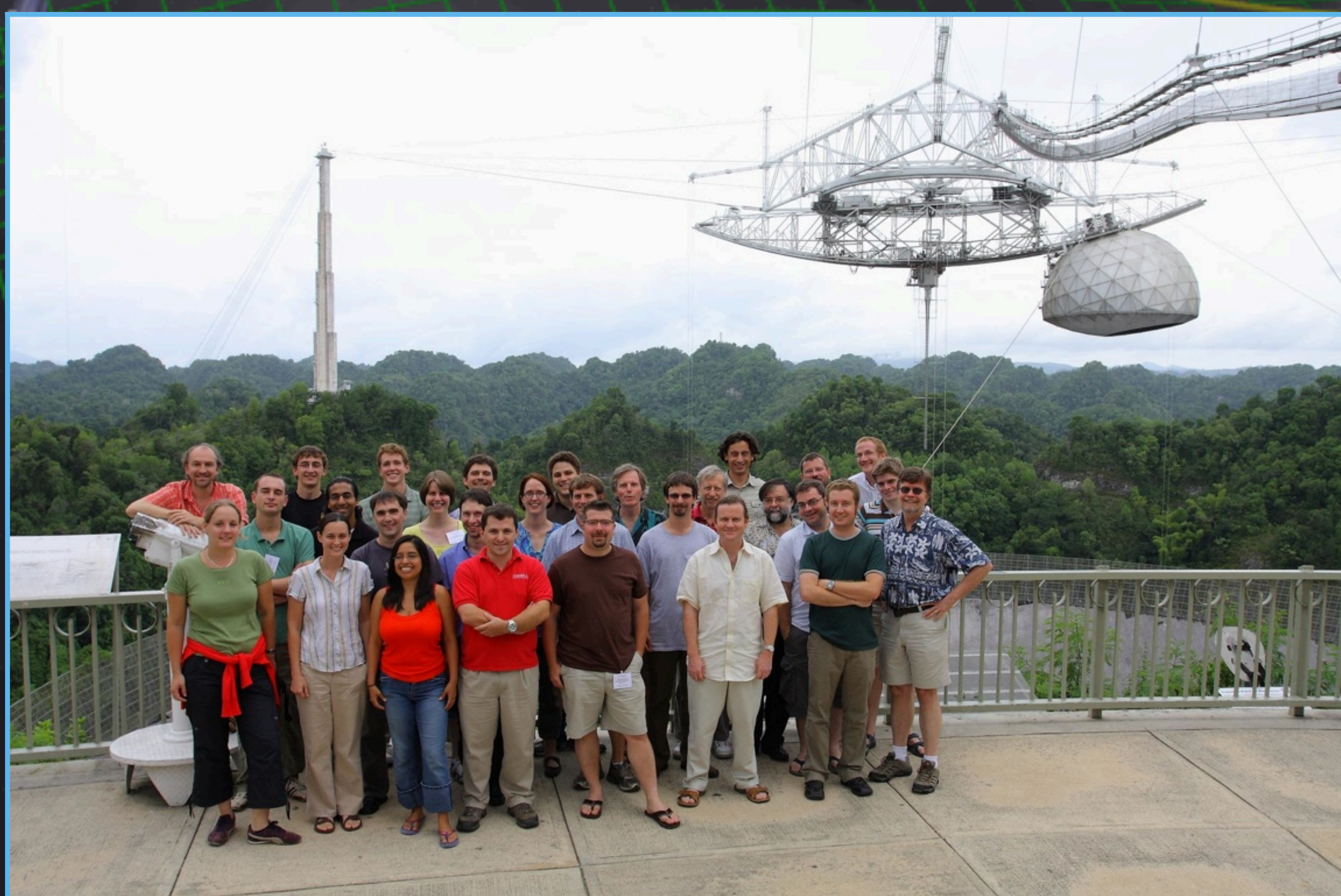


Credit: David Champion

Detection of gravitational waves

International effort

- Europe, North America, Australia

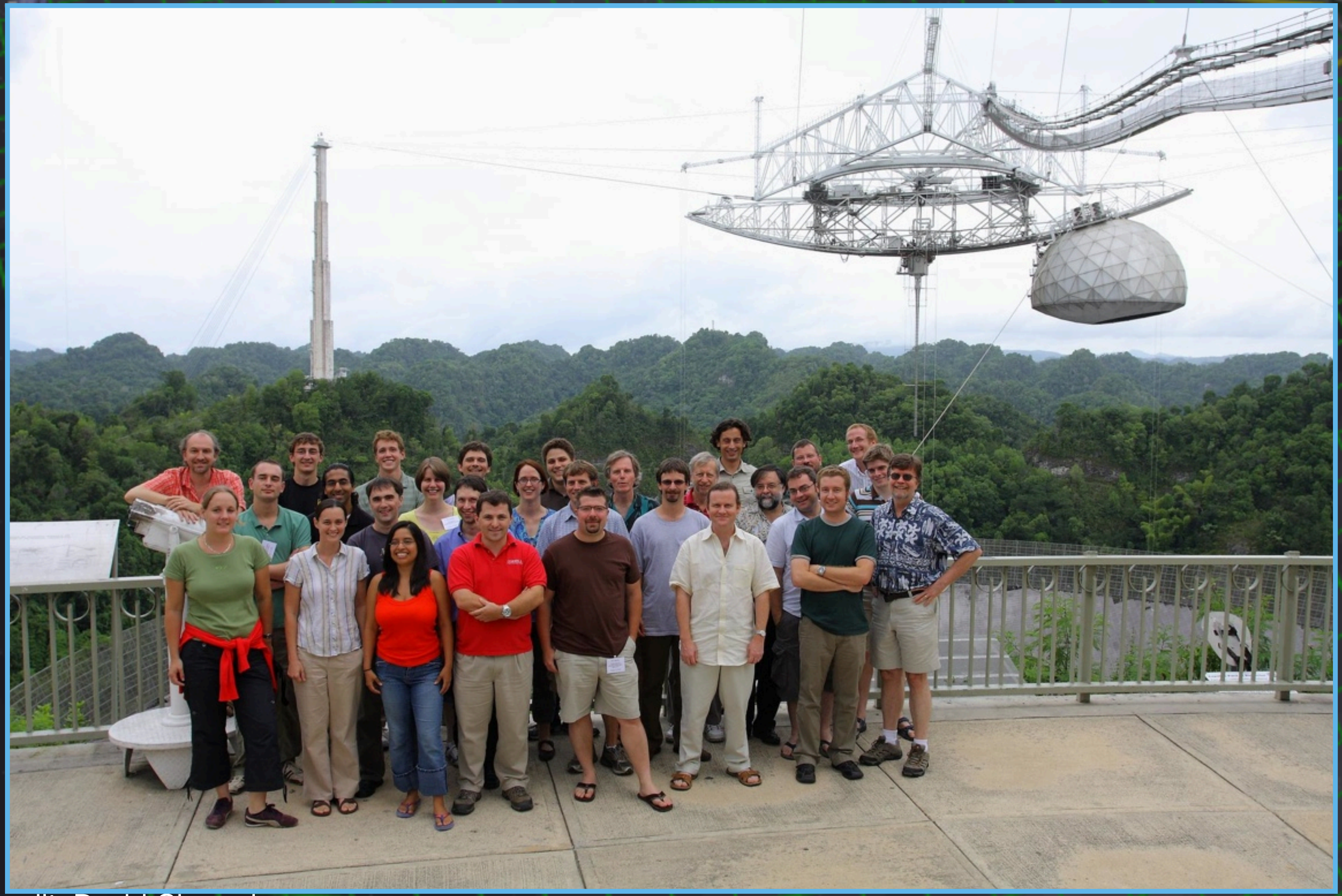


Credit: David Champion

Detection of gravitational waves

International effort

- Europe, North America, Australia
- **Europe:** Large European Array for Pulsars (LEAP)

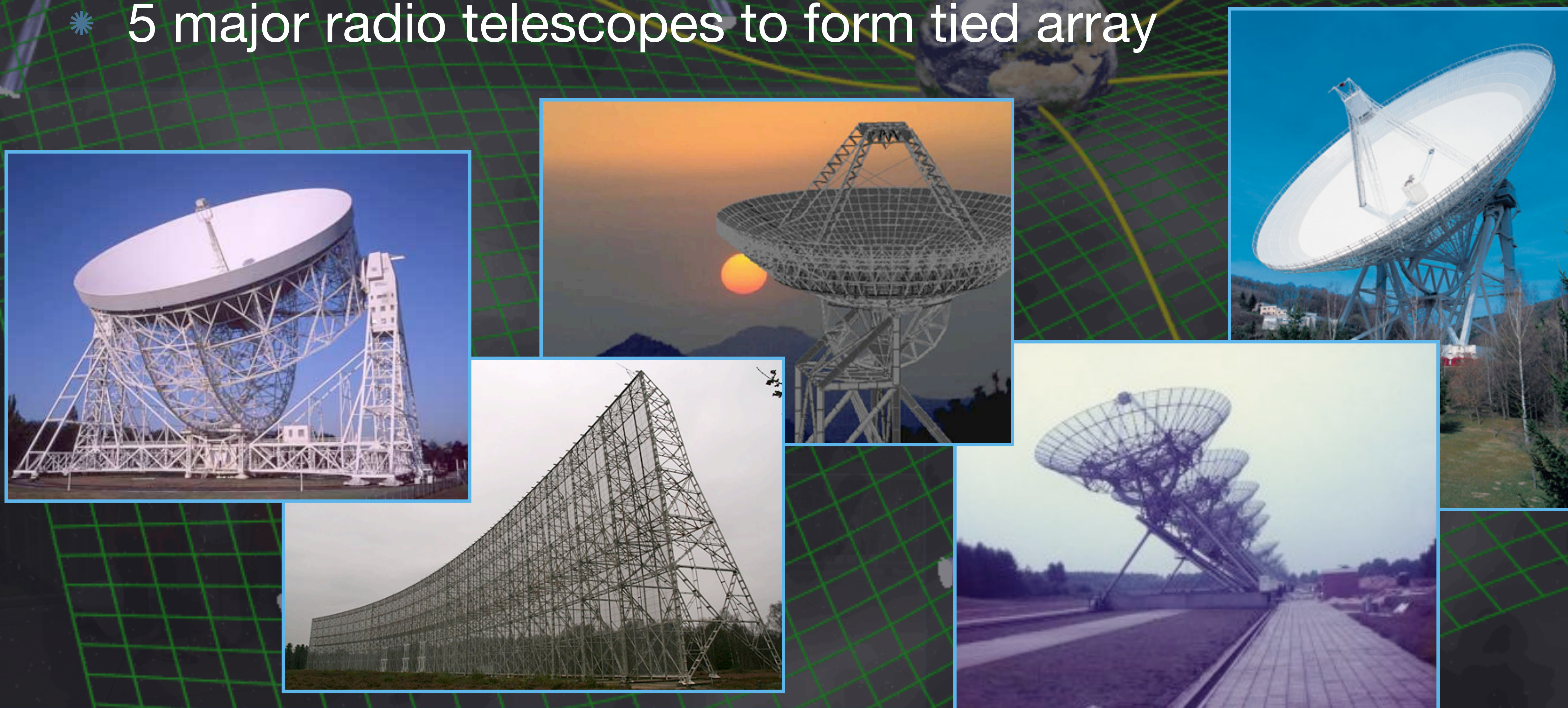


Credit: David Champion

Detection of gravitational waves

International effort

- Europe, North America, Australia
- **Europe**: Large European Array for Pulsars (LEAP)
- 5 major radio telescopes to form tied array



Credit: David Champion

Detection of gravitational waves

International effort

- Europe, North America, Australia
- **Europe**: Large European Array for Pulsars (LEAP)
- 5 major radio telescopes to form tied array

Future astrophysics

- individual source detection
- alternative gravity theories
- nature of galaxy mergers
- SKA?

Credit: David Champion

Pulsar timing and black holes

Robert Ferdman
Jodrell Bank Centre for Astrophysics
University of Manchester