Vikram Ravi

Caltech – Millikan fellow

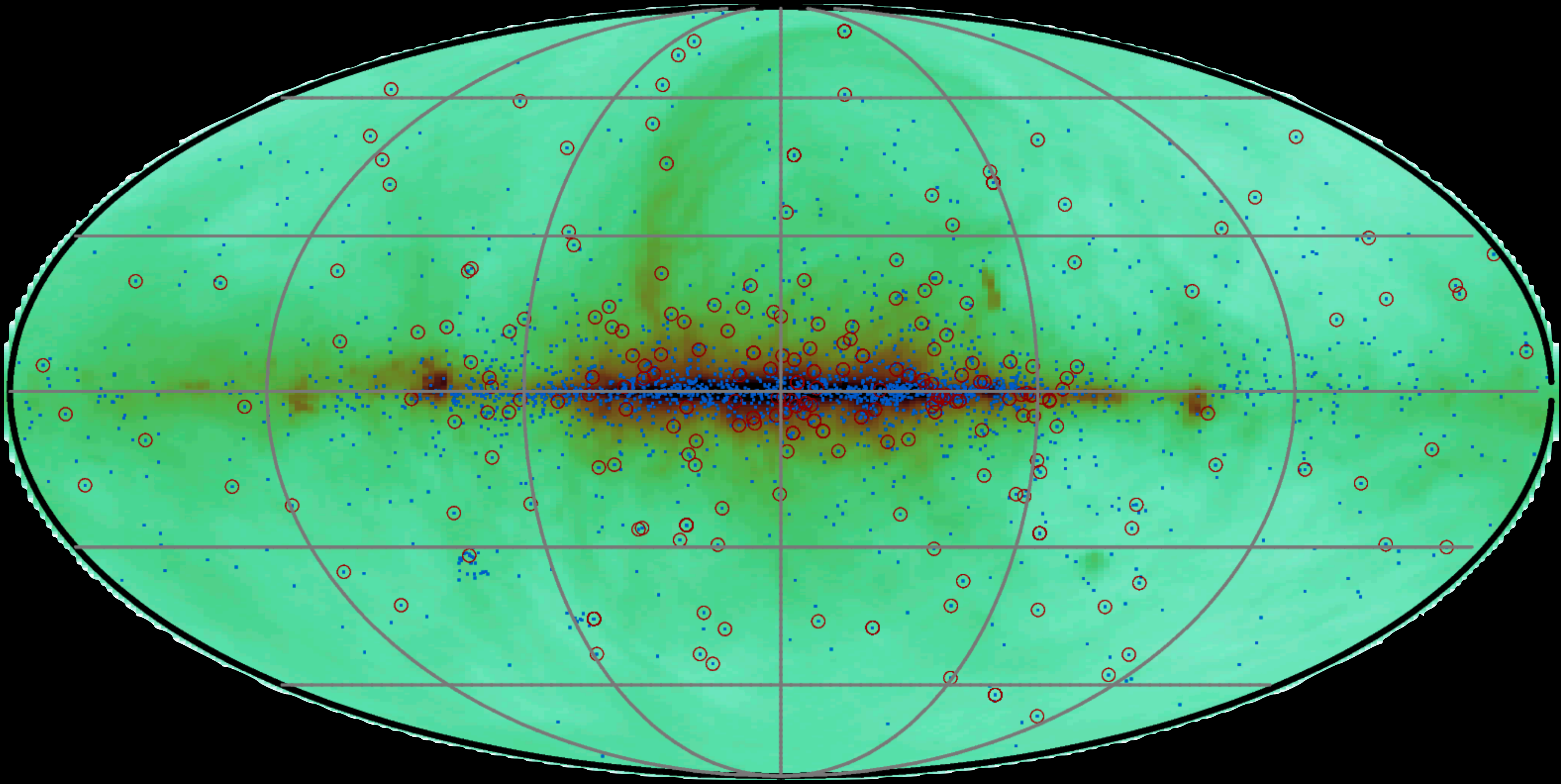
Pulsar timing and gravitational waves

Credit: Swinburne Astronomy Productions / Vikram Ravi

http://www.astro.caltech.edu/~vikram/

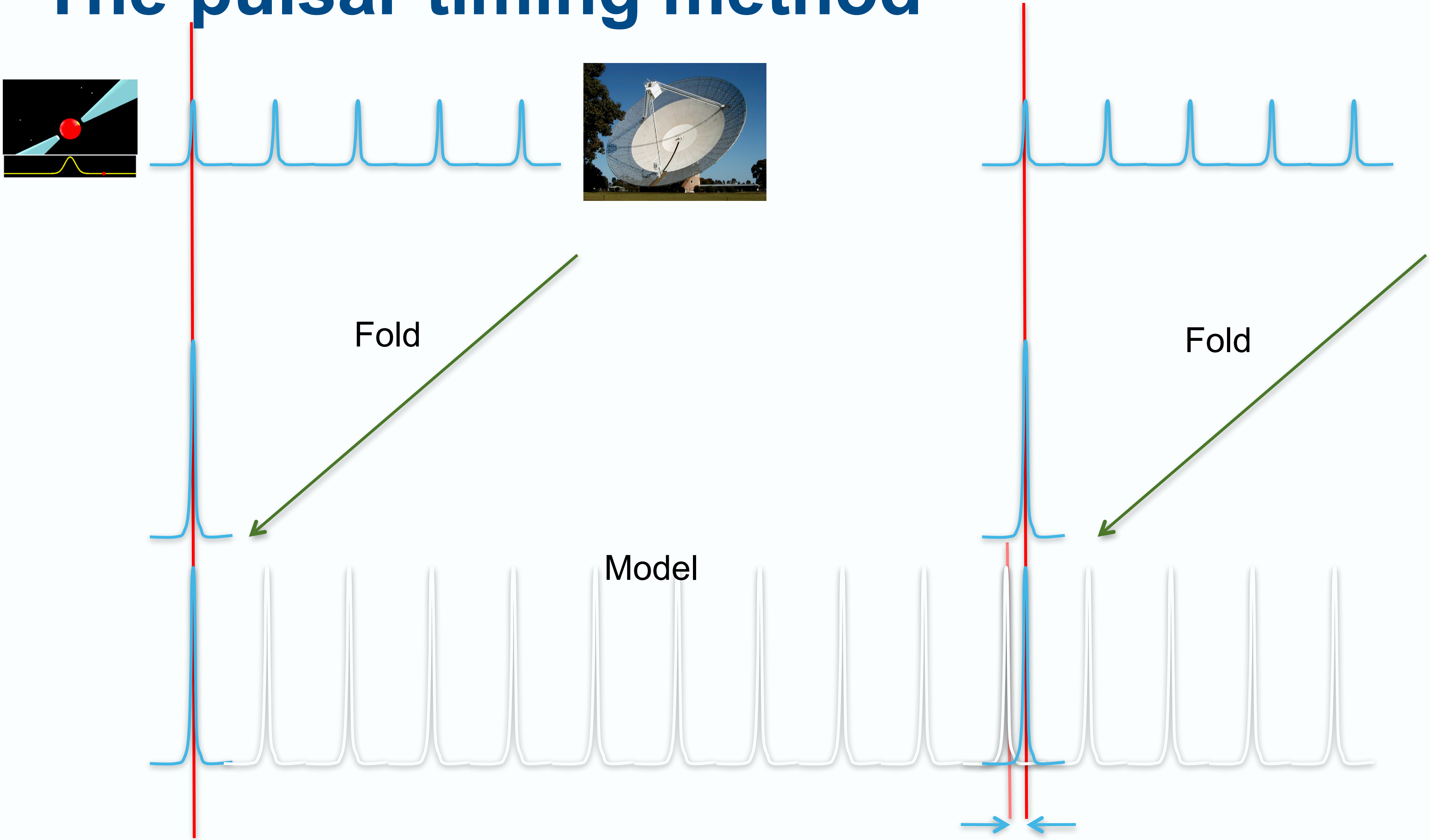
1. Pulsars are ridiculously awesome objects!
2. Gravitational-wave detection in pulsar timing measurements is practicable
3. Pulsar-timing constraints on GWs from binary supermassive black holes are currently of astrophysical interest

In ATNF pulsar catalog: 2573 pulsars, 323 with P<20 ms



Slide from D. Champion

The pulsar timing method



Fold

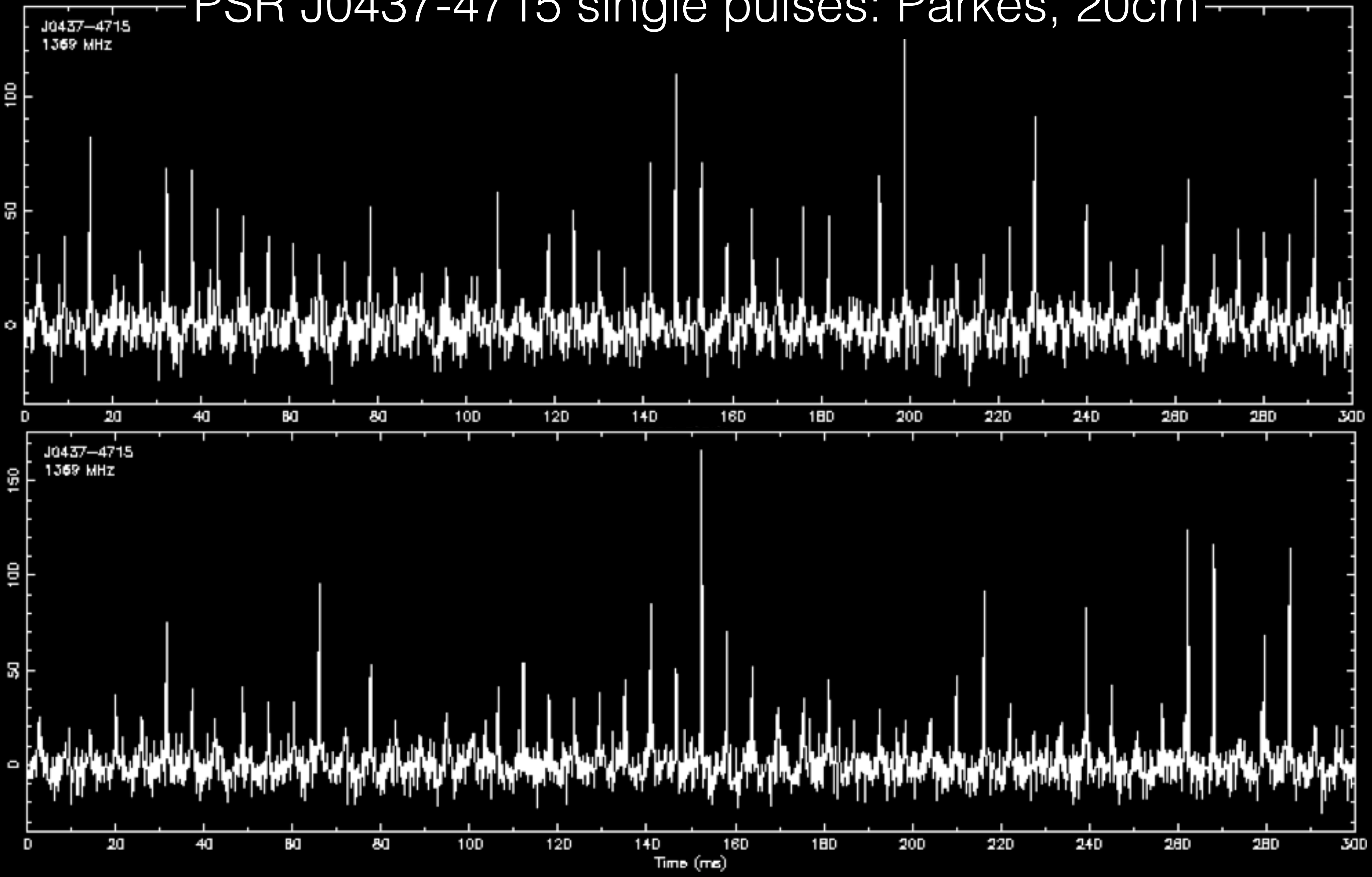
Fold

Model

TOA (measured using the observatory clock)

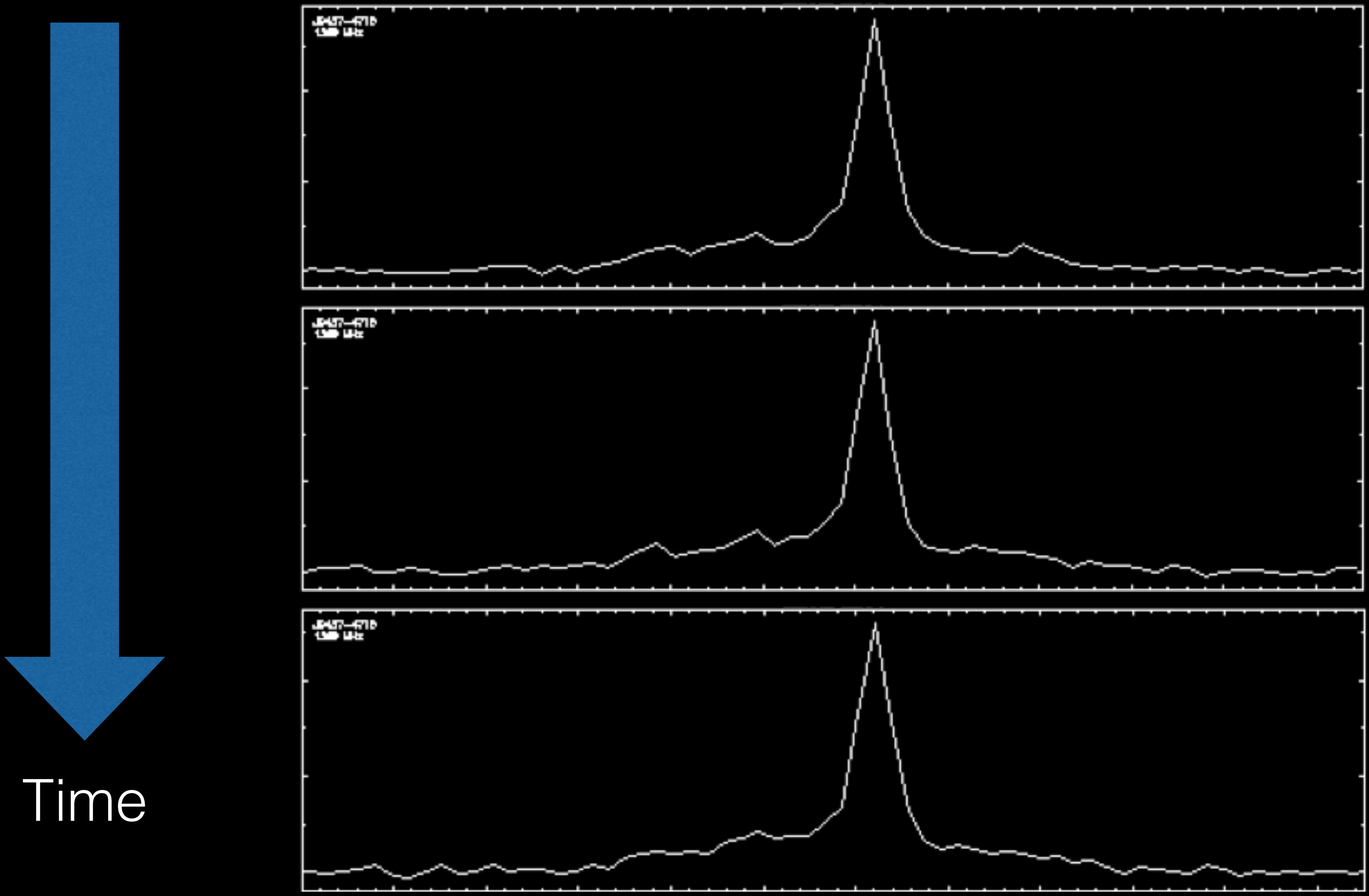
Residual

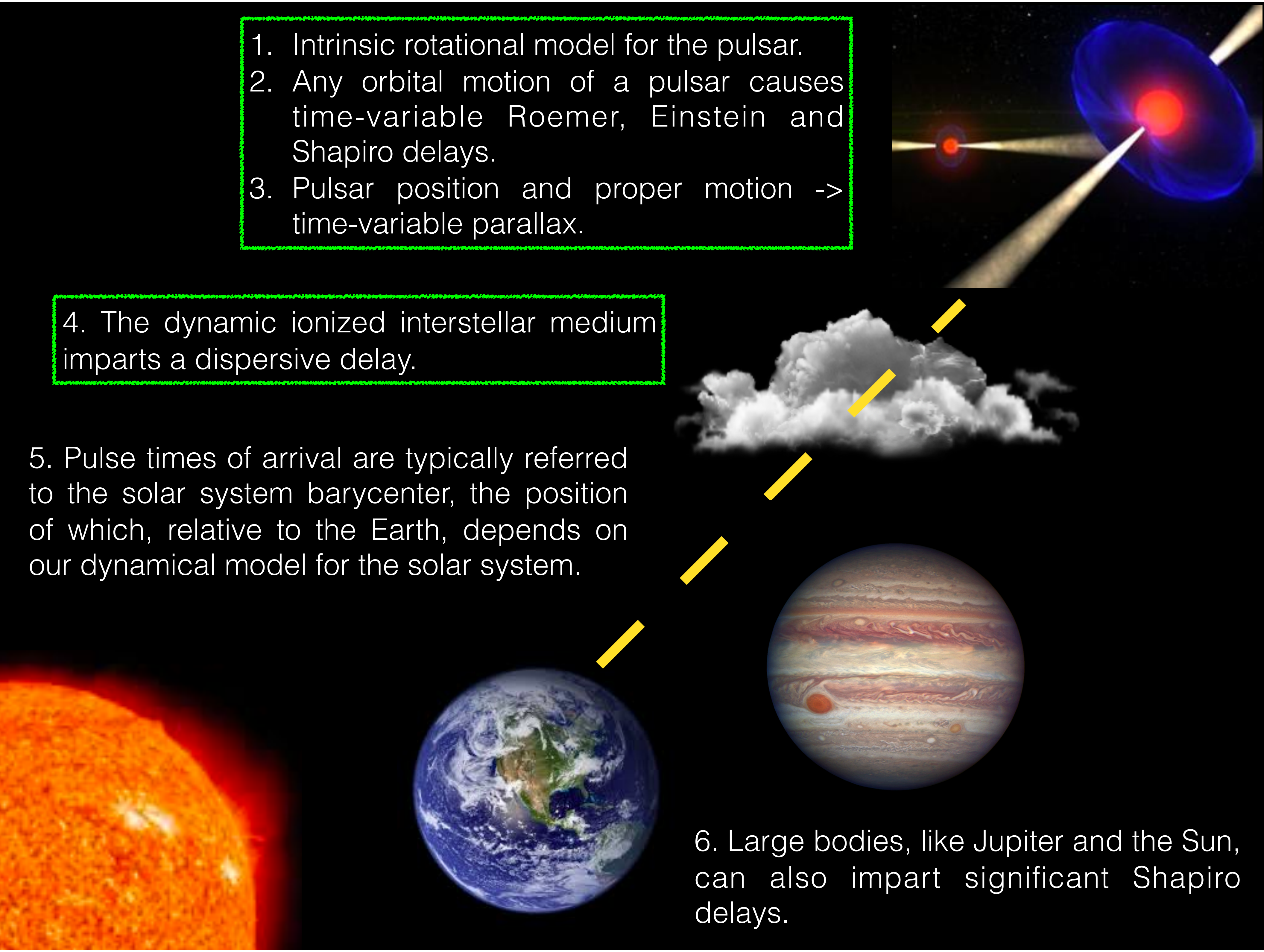
PSR J0437-4715 single pulses: Parkes, 20cm



PSR J0437-4715 after folding approx. 173 pulses.

These **mean pulse profiles** are still stochastic quantities!

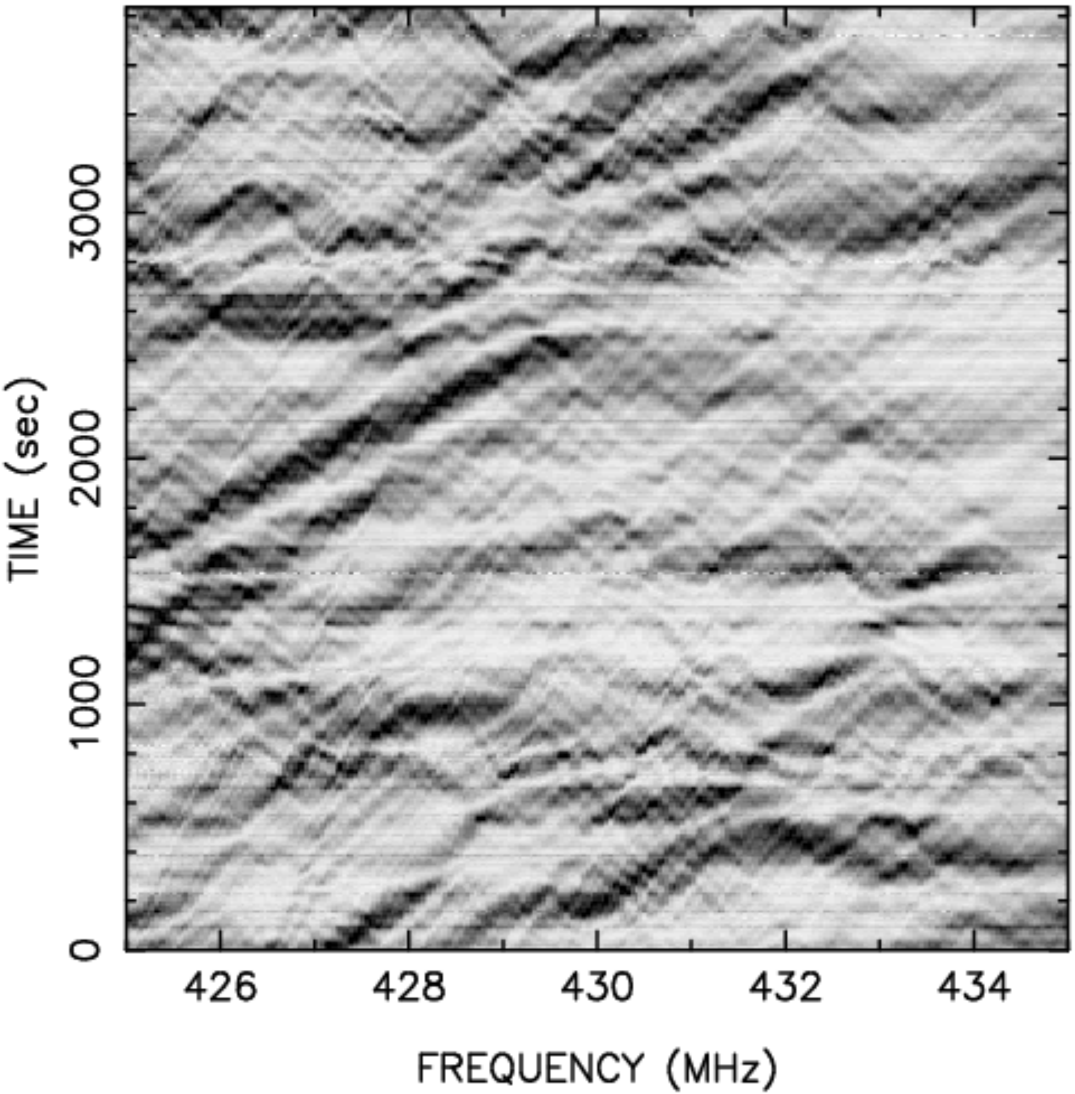




1. Intrinsic rotational model for the pulsar.
2. Any orbital motion of a pulsar causes time-variable Roemer, Einstein and Shapiro delays.
3. Pulsar position and proper motion -> time-variable parallax.
4. The dynamic ionized interstellar medium imparts a dispersive delay.
5. Pulse times of arrival are typically referred to the solar system barycenter, the position of which, relative to the Earth, depends on our dynamical model for the solar system.
6. Large bodies, like Jupiter and the Sun, can also impart significant Shapiro delays.

Pulsar radiation is **scattered** in the interstellar medium, often resulting in interference fringes on the Earth. Scattering effects, like pulse profiles, are chromatic.

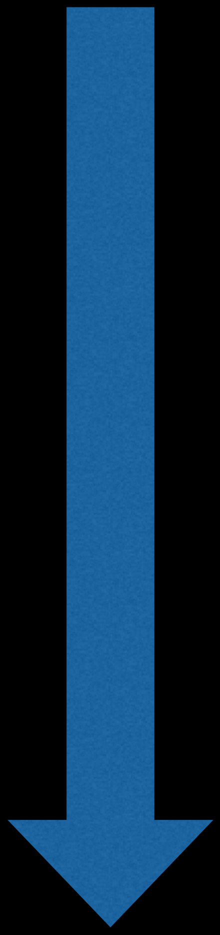
Time



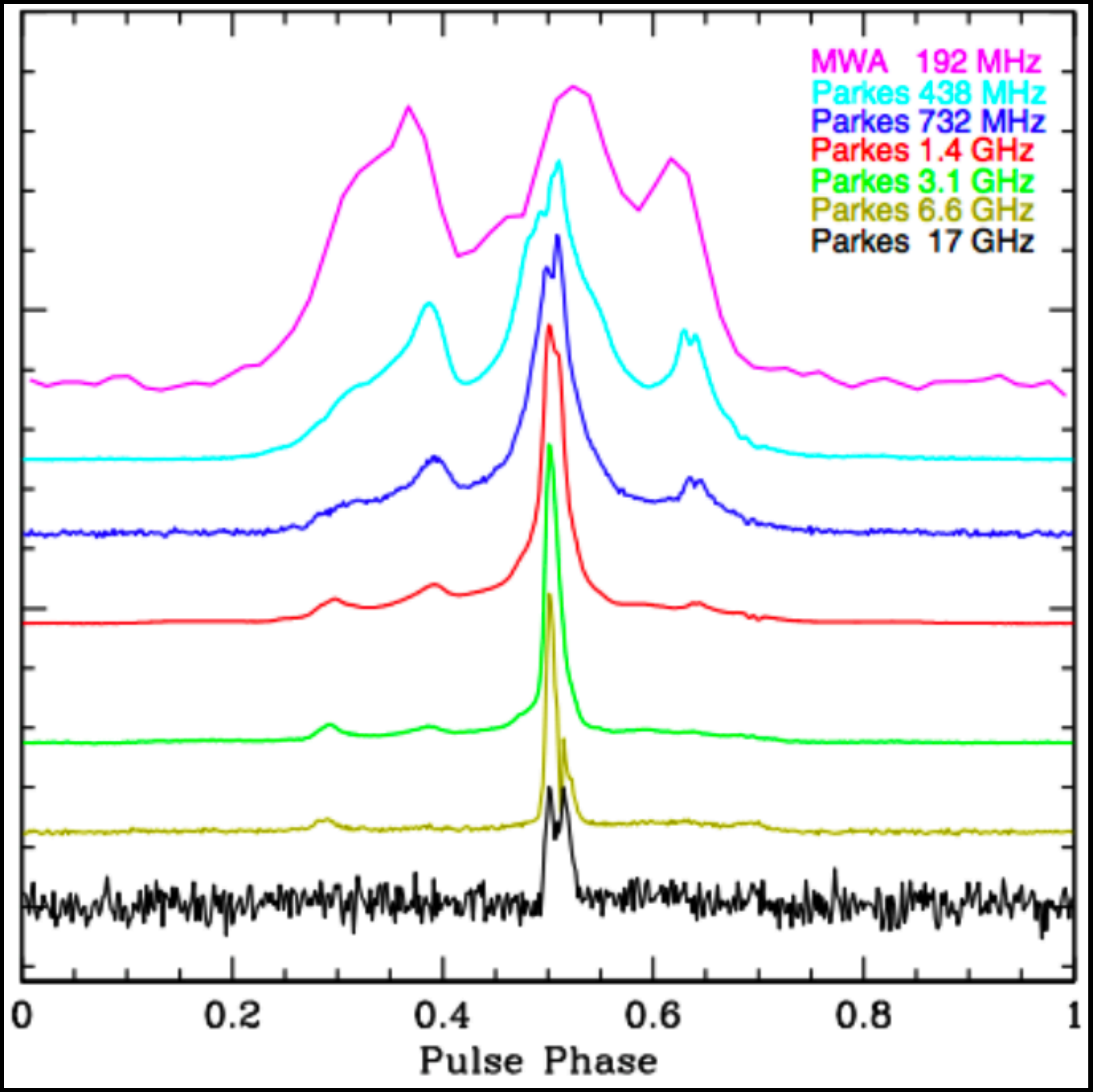
Frequency

Haverkorn et al. (2013)

Pulsar mean profiles are **frequency-dependent**



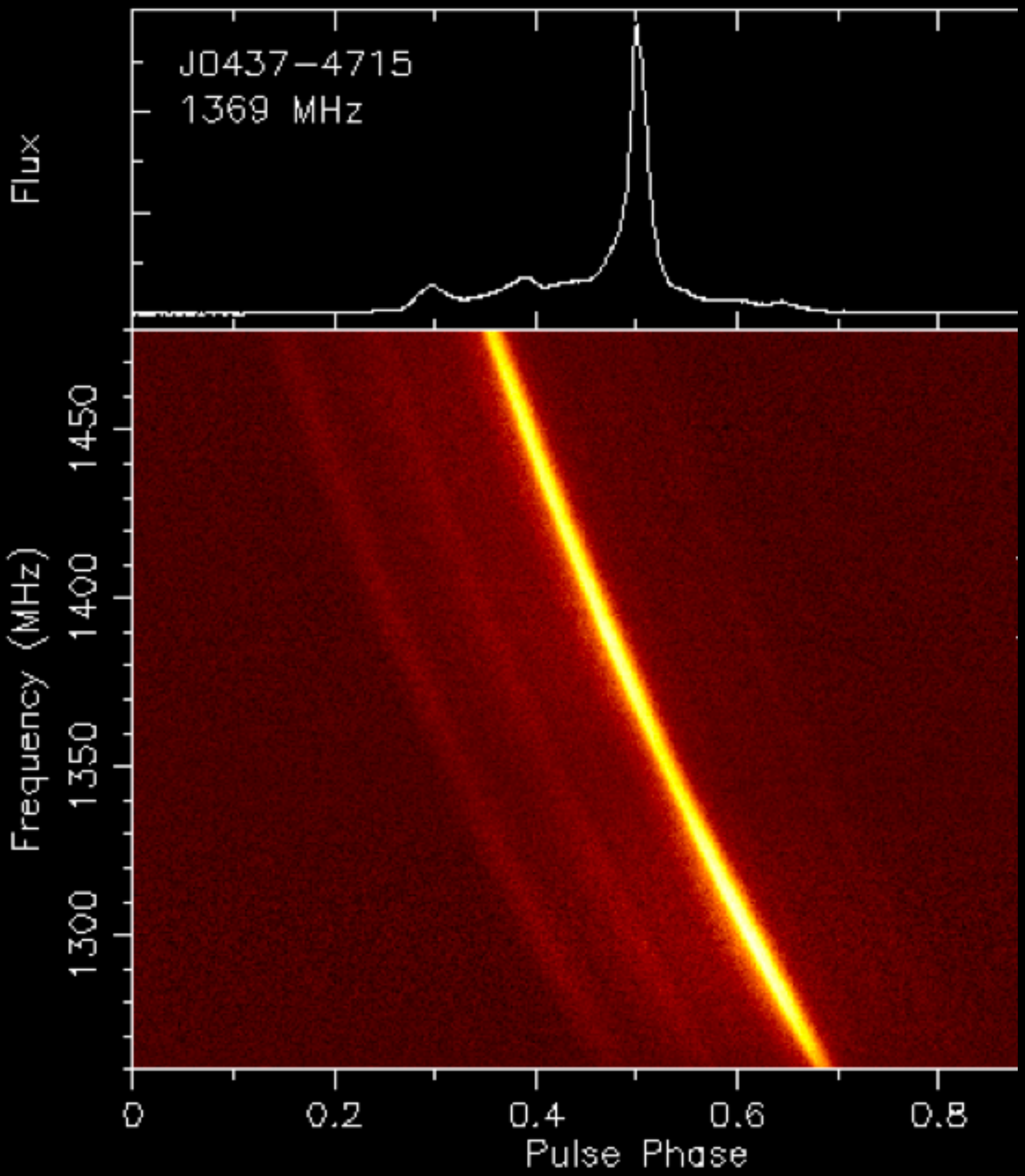
Frequency

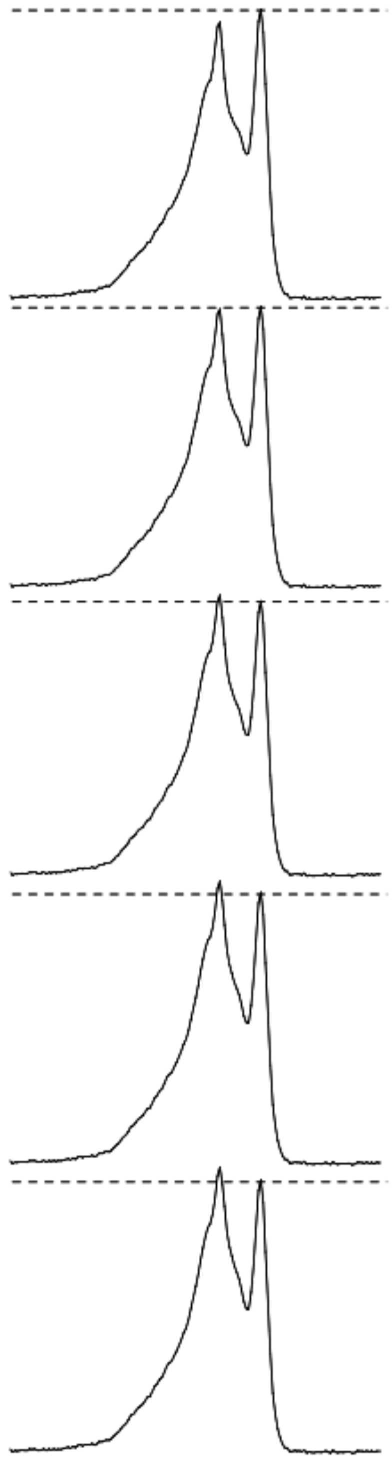


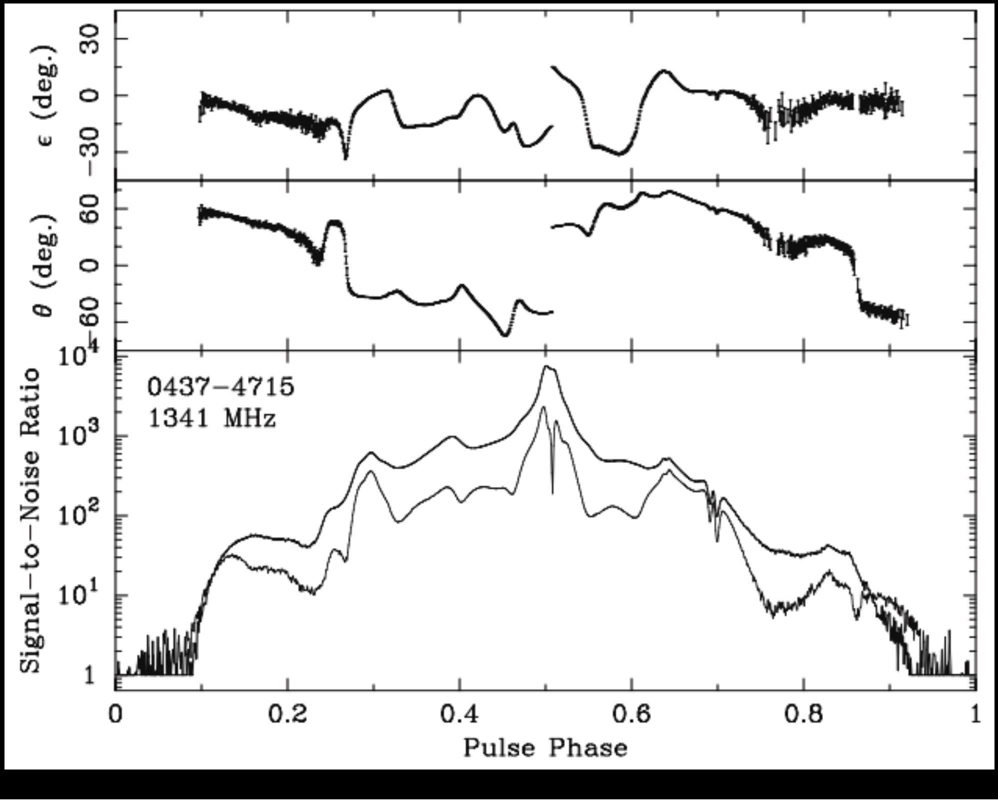
Bhat et al. (2014)

Pulsar radiation is **dispersed** in the interstellar medium, and the amount of dispersion changes with time.

Frequency



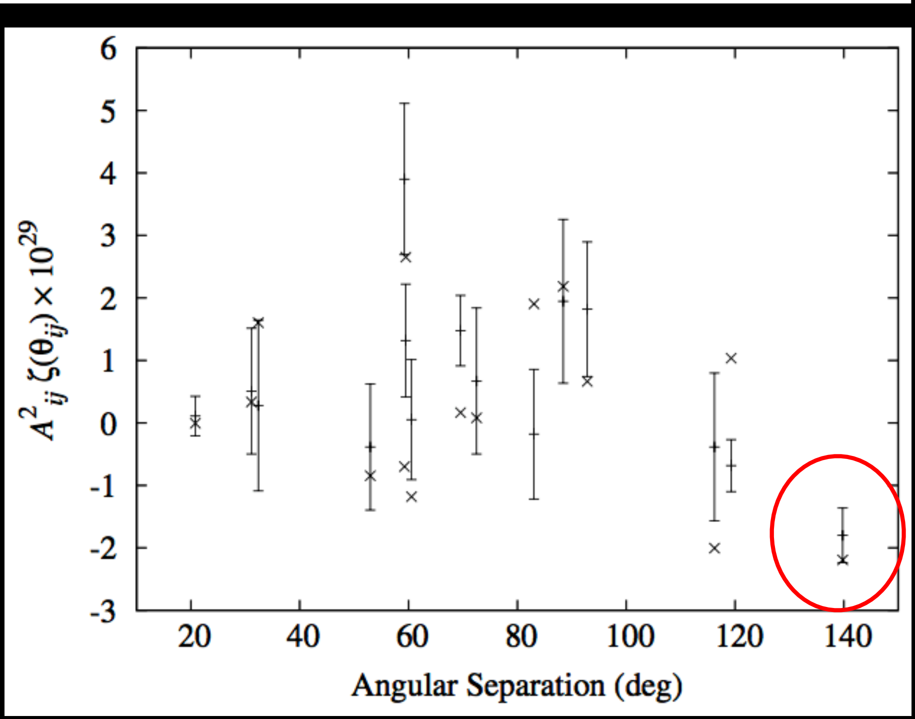




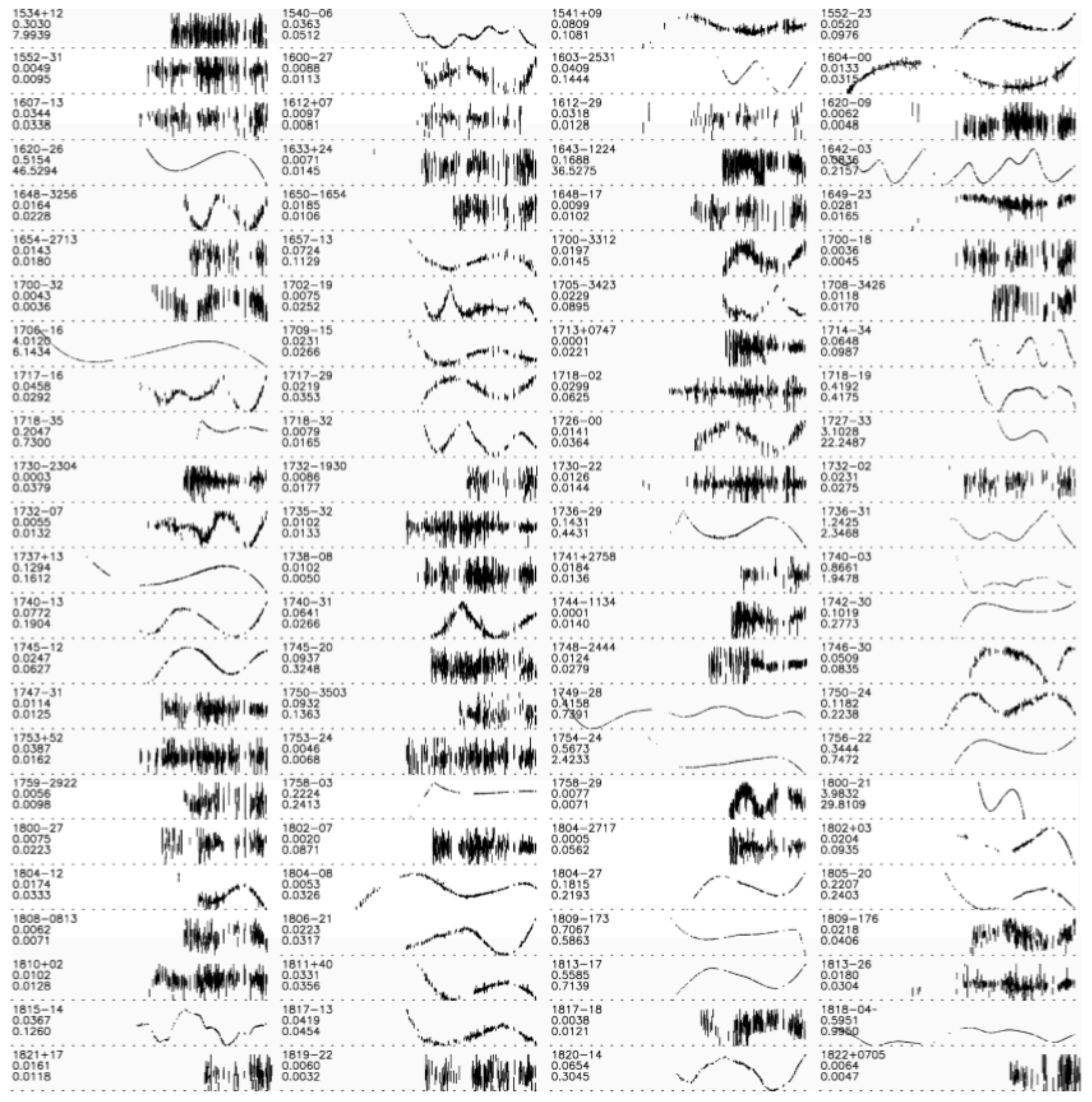
Pulsar radiation is highly **polarized**

van Straten (2013)

Time-variable instrumental errors can result in systematic correlations between pulsar timing measurements



Pulsars exhibit intrinsic “red” **timing noise** Hobbs et al. (2010)



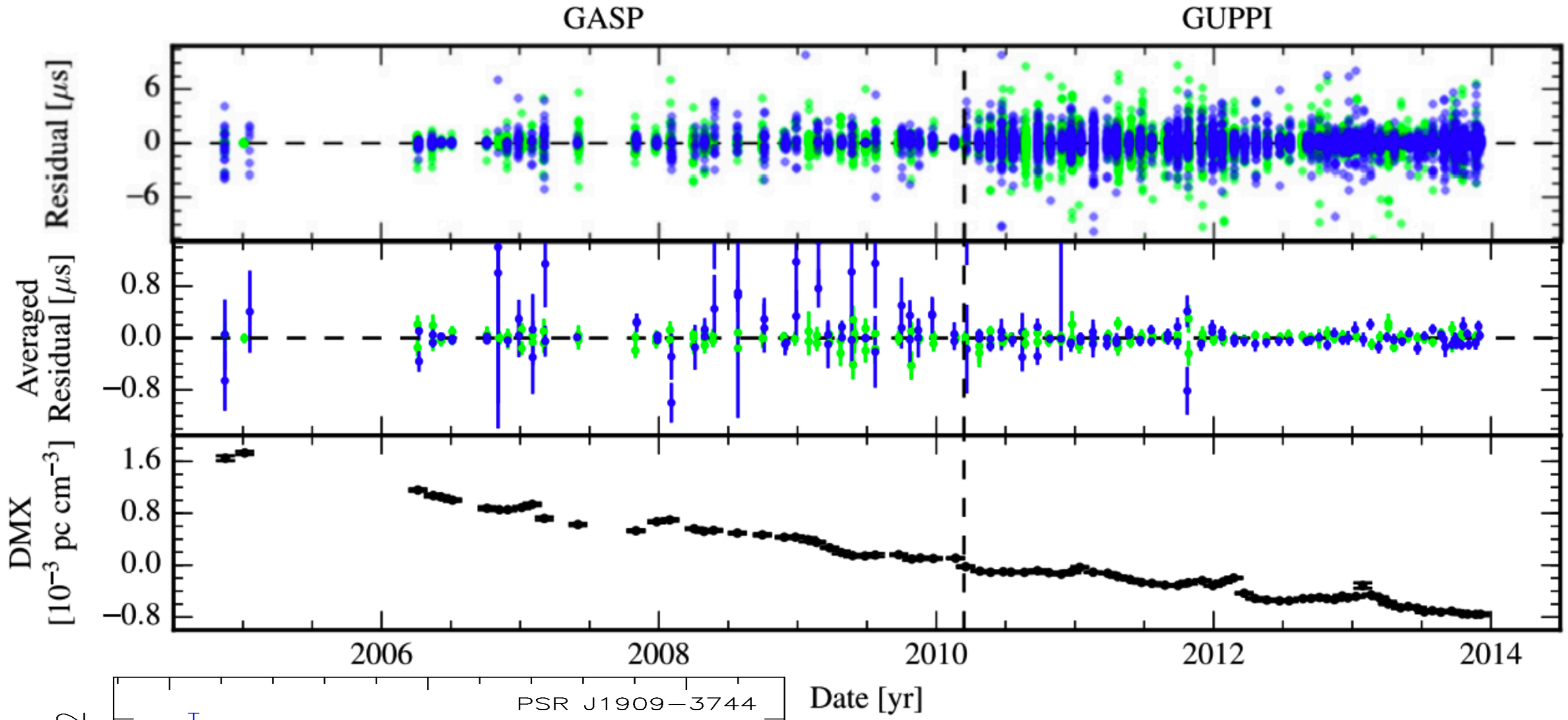
Noise processes affecting pulsar measurements

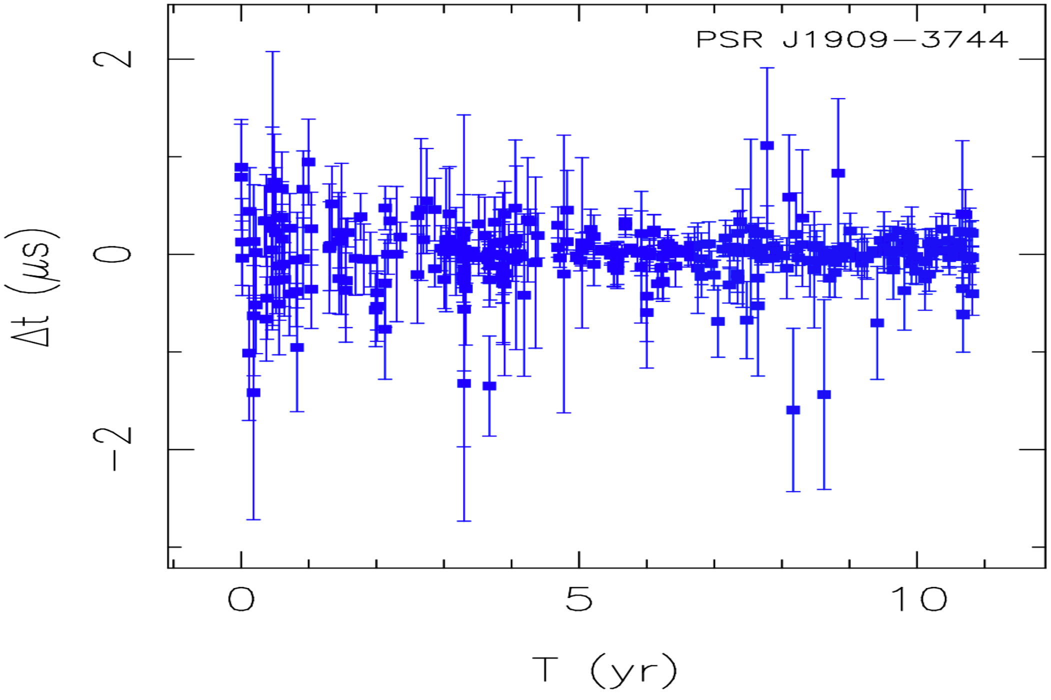
- Radio telescope radiometer (measurement) noise. Mitigated by using bigger, more sensitive telescopes e.g., wideband receivers, larger apertures, phased arrays.
- "Pulse jitter" - the stochasticity of individual pulses. Can be mitigated by looking for correlates with individual pulses.

  e.g., Shannon & Cordes (2012), Oslowski et al. (2013), Lam et al. (2017)
- Scattering - causes different frequencies to light up at different times. Mitigated by frequency-dependent pulse profile templates.

  e.g., Pennucci et al. (2014), Liu et al. (2014), Coles et al. (2015), Lentati et al. (2017a, b)
- Calibration errors - cause sky-position dependency in measurements. Can be mitigated by estimating calibration parameters self-consistently with pulsar measurements. e.g., van Straten (2013)
- Dispersion variations - cause chromatic wander in pulse arrival times. Mitigated by multi-frequency analyses and high-frequency observations. e.g., Keith et al. (2012), Lam et al. (2016)
- Intrinsic timing noise. Mitigated by careful selection of pulsars, and potentially by looking for a deterministic component.

  e.g., Lyne et al. (2010), Coles et al. (2011), van Haasteren & Levin (2013)



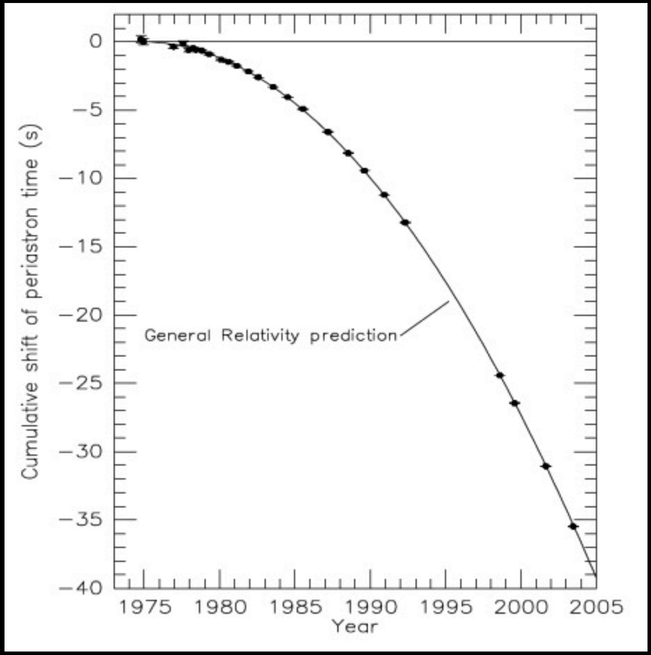


And yet it works!

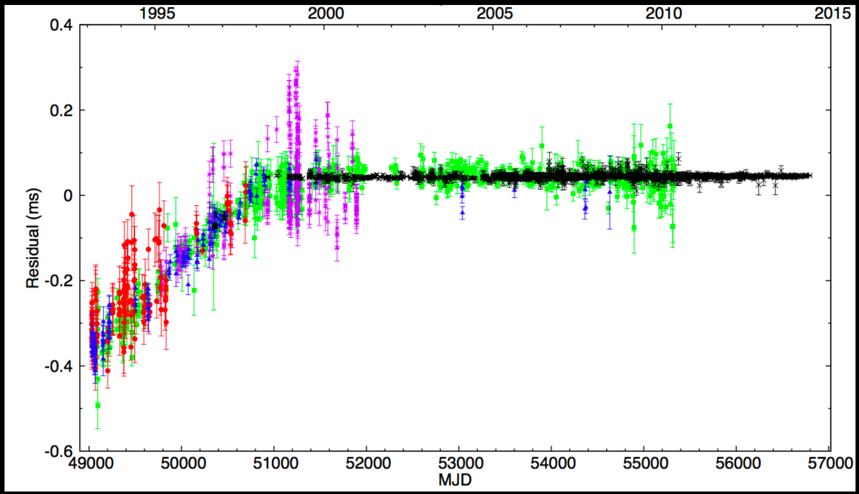
Top: NANOGrav 9-yr release (Arzoumanian et al. 2015)
Left: PPTA 10-cm data (Shannon et al. 2015)

The (astro)physics is in the residuals

- Gravitational radiation and tests of GR in binary neutron star systems.
- The neutron star equation of state as probed through pulsar mass measurements and rotation glitch dynamics.
- Exotic low-mass and sub-stellar pulsar companions.
- Pulsar proper motions -> supernova asymmetries and Galactic dynamics.



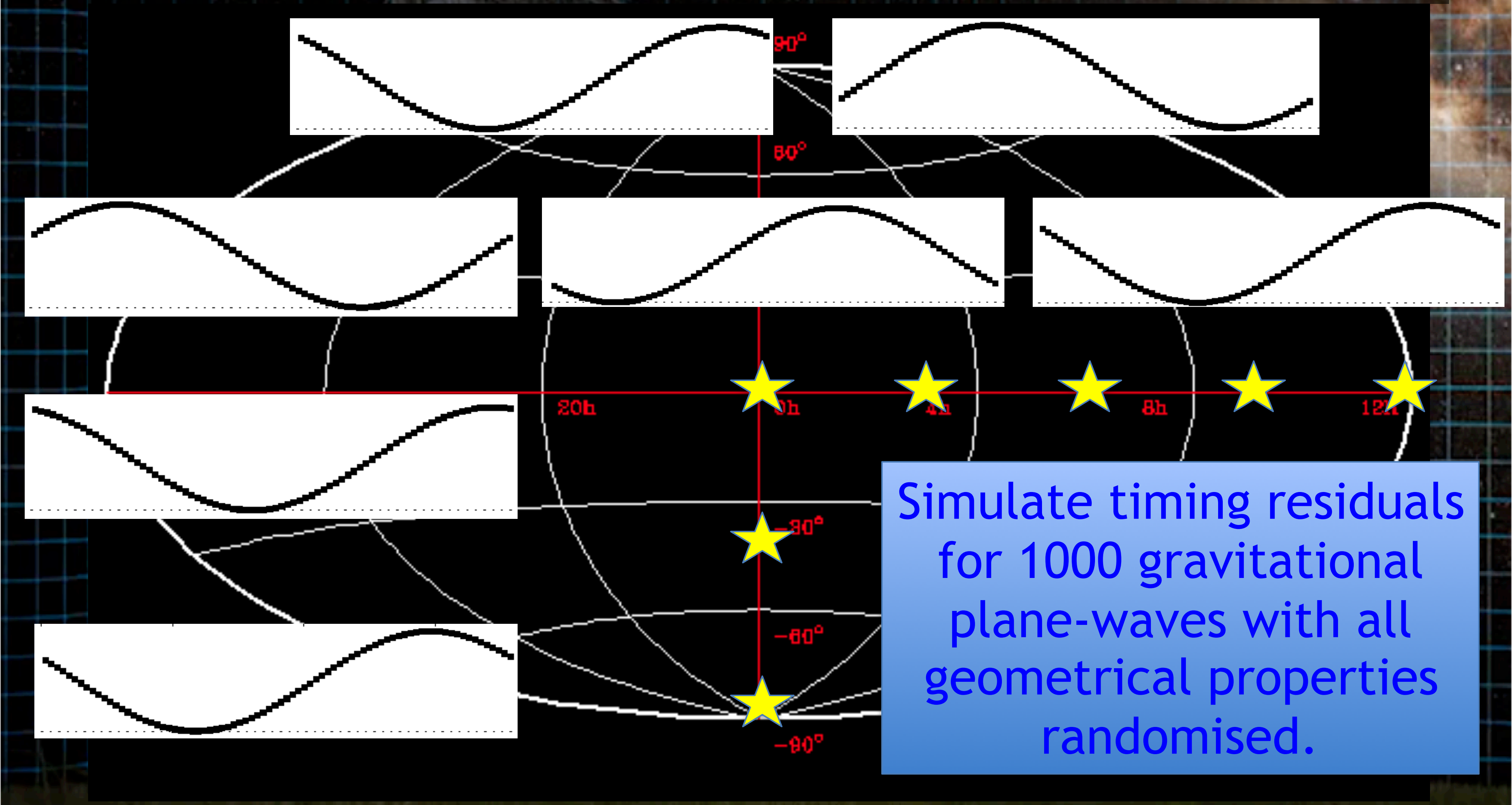
Weisberg & Taylor (2004)



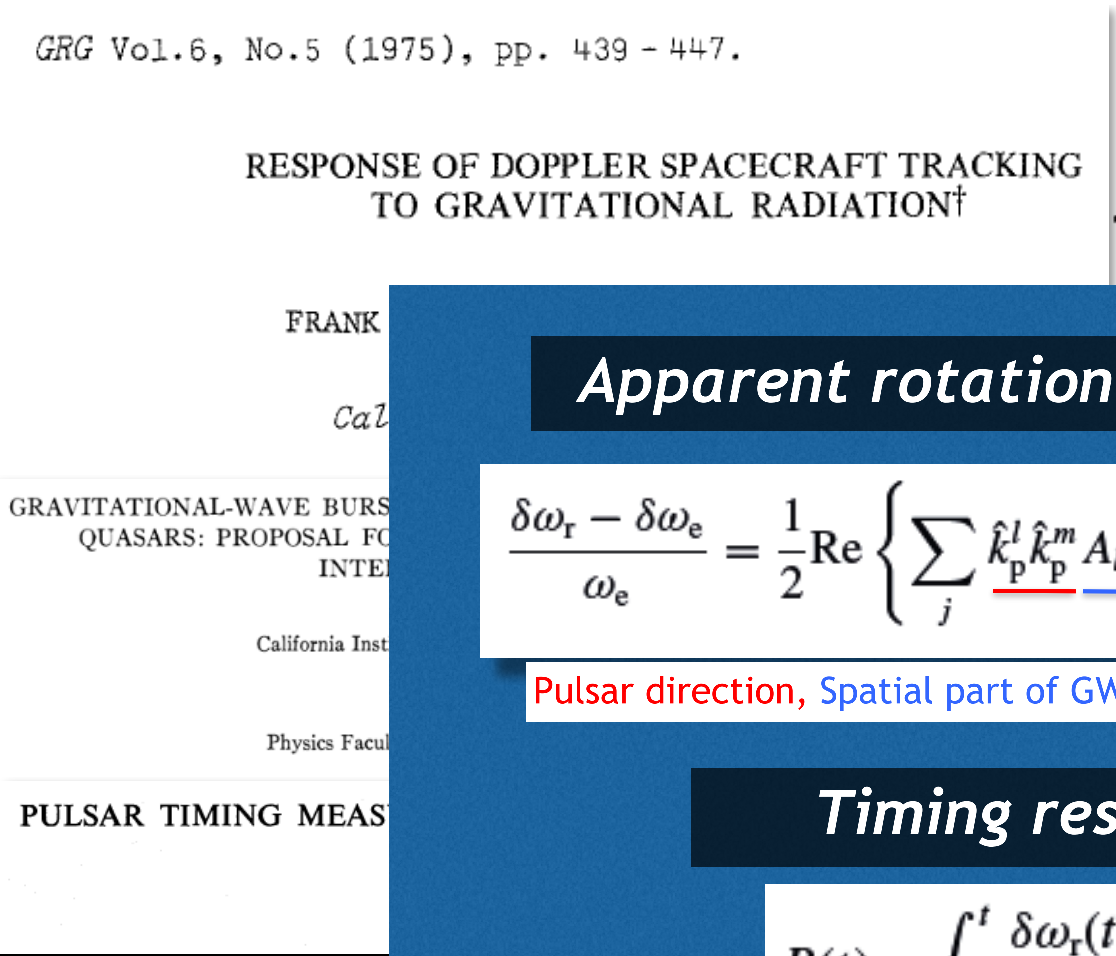
McKee et al. (2016)

Pulsar timing arrays: contemporaneous observations of many pulsars to search for *correlated* timing behaviour

***Monopole**: clock errors. **Dipole**: Solar System ephemerides errors.*
***Quadrupole**: gravitational waves.*



Simulate timing residuals for 1000 gravitational plane-waves with all geometrical properties randomised.



GRG Vol.6, No.5 (1975), pp. 439 - 447.

RESPONSE OF DOPPLER SPACECRAFT TRACKING
TO GRAVITATIONAL RADIATION†

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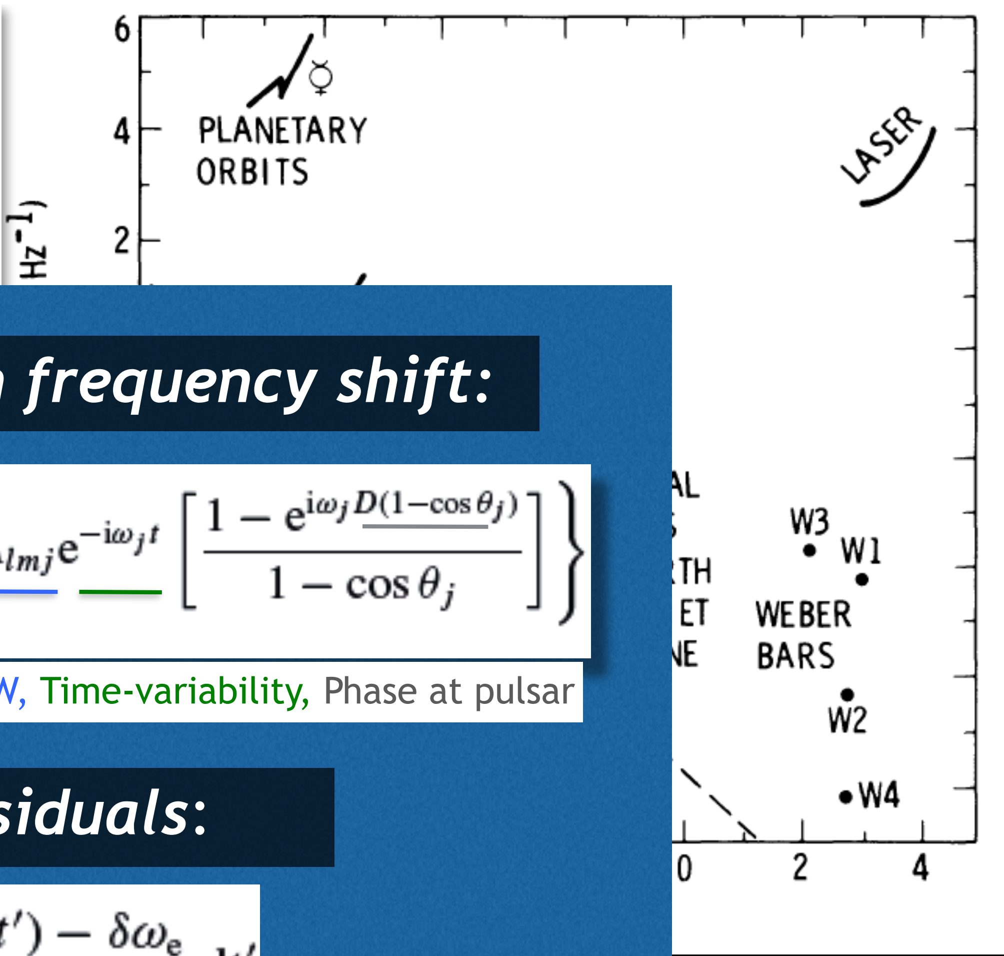
GRAVITATIONAL-WAVE BURS
QUASARS: PROPOSAL FO
INTE

California Inst

Physics Facul

PULSAR TIMING MEAS



Apparent rotation frequency shift:

$$\frac{\delta\omega_{\rm r}-\delta\omega_{\rm e}}{\omega_{\rm e}}=\frac{1}{2}{\rm Re}\left\{\sum_j \underline{\hat{k}_{\rm p}^l\hat{k}_{\rm p}^m}\,\underline{A_{lmj}}\,\underline{{\rm e}^{-i\omega_j t}}\left[\frac{1-{\rm e}^{i\omega_j \underline{D(1-\cos\theta_j)}}}{1-\cos\theta_j}\right]\right\}$$

Pulsar direction, Spatial part of GW, Time-variability, Phase at pulsar

Timing residuals:

$$R(t)=\int_0^t \frac{\delta\omega_{\rm r}(t')-\delta\omega_{\rm e}}{\omega_{\rm e}}\,{\rm d}t'$$

Pulsar timing arrays:

Hellings & Downs (1983)
Foster & Backer (1990)
Stinebring et al. (1990)
Kaspi, Taylor & Ryba (1994)

1. Rich physics and astrophysics is revealed through the pulsar timing technique.

2. Despite this, the arrival times of pulses from some millisecond pulsars can be modeled with few-hundred nanosecond accuracy over decade-long timescales.

3. The search for signals (e.g., GWs) in pulsar timing data requires understanding / measurement of deterministic and stochastic processes in the data **derived in a quasi-simultaneous analysis.**

Lambda-CDM predicts hierarchical galaxy merging

Binary SMBHs form in galaxy mergers, and radiate GWs

GWs from all binary SMBHs form a cosmological background

The GW background causes stochastic variations in pulse arrival times from radio pulsars

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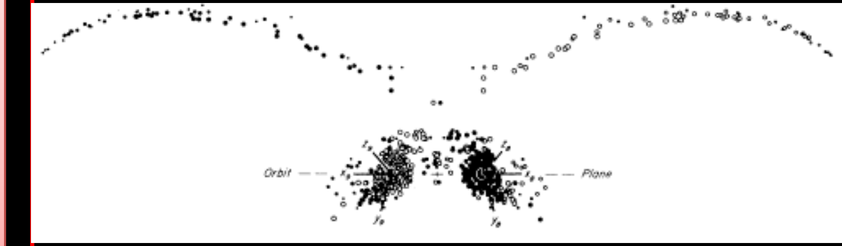
SMBH: super-massive black hole, 10^6 to 10^{11} solar masses
Gravitational waves (GWs): propagating spatial metric perturbations
PTA: Pulsar Timing Array – timing observations of pulsars to detect effects of gravitational waves

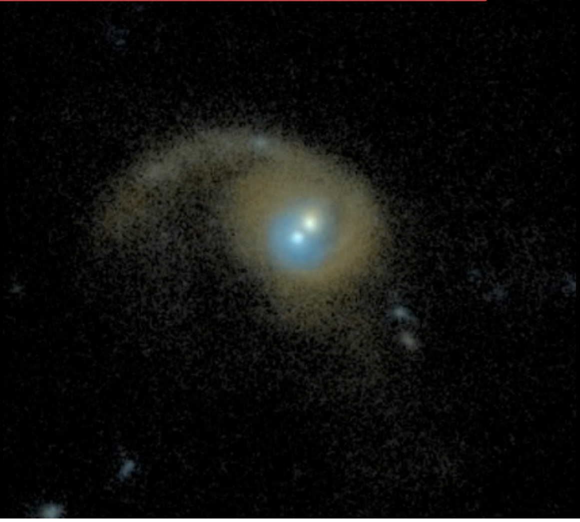
A population of binary SMBHs?

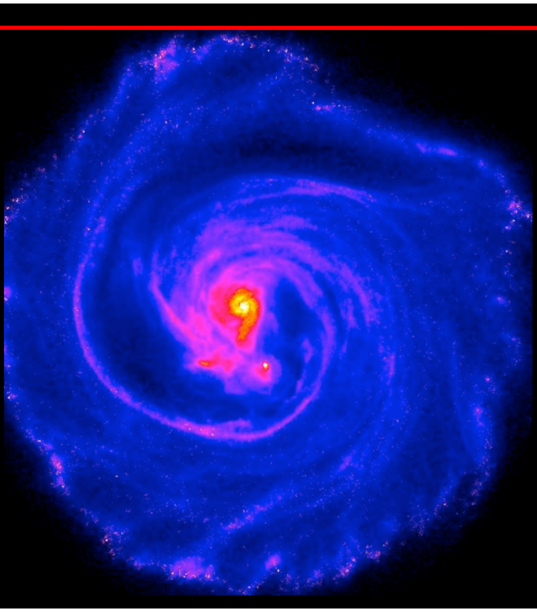
Mergers should be integral to the histories of local galaxies, given the cold dark matter paradigm

We see evidence of galaxies in the process of merging, backed up by simulations

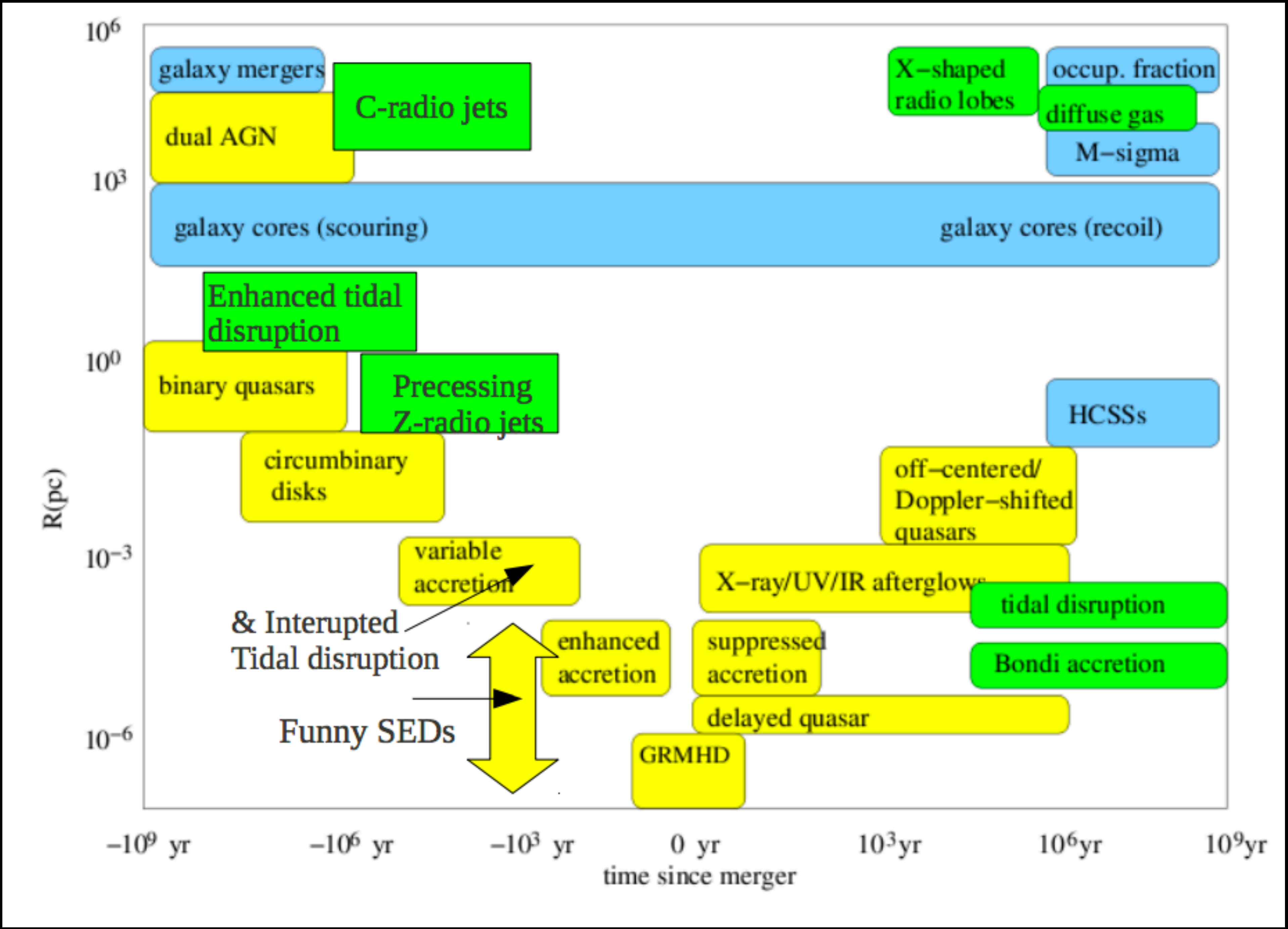
Simulations, with some observational evidence, show SMBHs can form binaries in merging galaxies.







heritage.stsci.edu
Toomre & Toomre (1972)
www.mpa-garching.mpg.de



J. Schnittman, S. Phinney

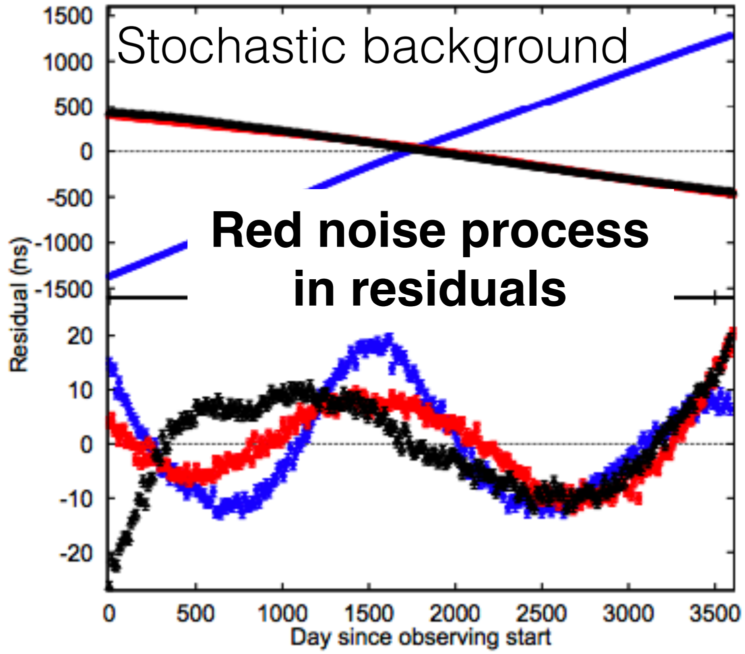
Modeling the population of binary supermassive black holes

1. (Demographics of DM haloes) -> demographics of galaxies -> demographics of SMBHs.

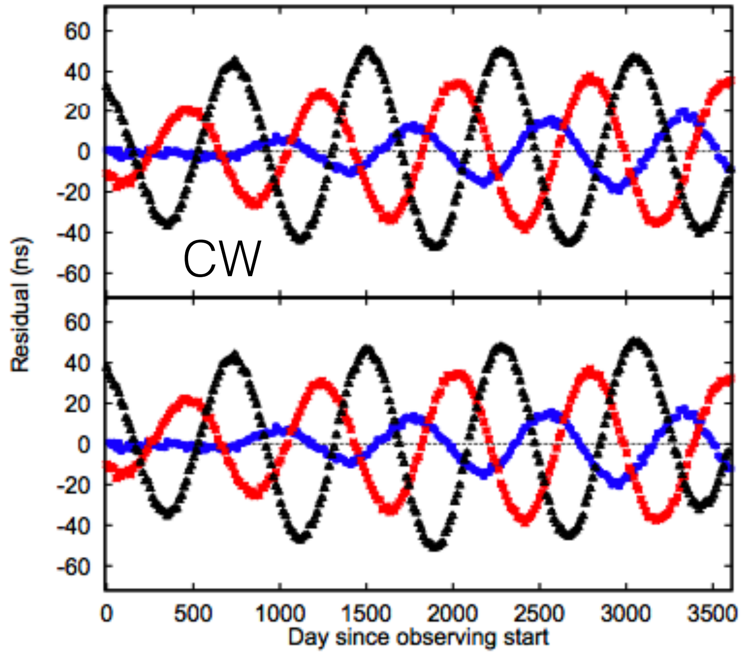
2. (DM Halo merger rate) -> galaxy merger rate -> SMBH coalescence rate.

3. SMBH coalescence rate + evolution of binary SMBH orbits -> # of binary SMBHs at different separations -> total GW emission.

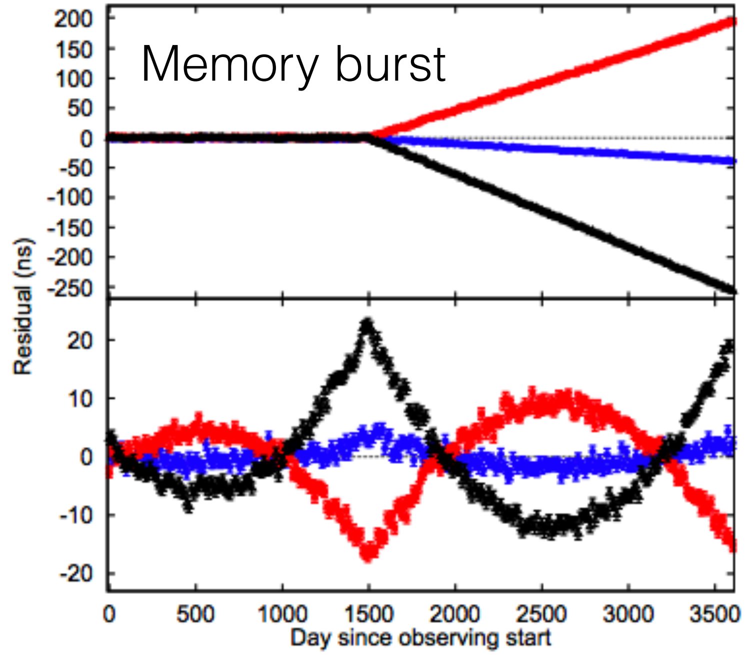
Rajagopal & Romani (1995), Jaffe & Backer (2003), Wyithe & Loeb (2003), Sesana et al. (2004, 2008, 2013, 2016, 2017), Ravi et al. (2012, 2014, 2015), Shannon/Ravi et al. (2013), McWilliams et al. (2015), Robber et al. (2016), Kelley et al. (2017a, b), Middleton et al. (2016)



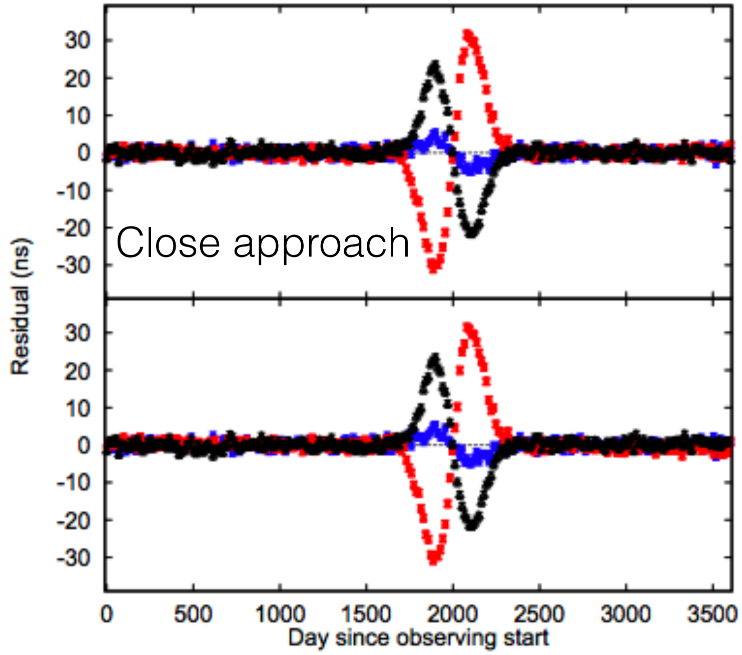
(a) Gravitational Wave Background



(b) Continuous Wave

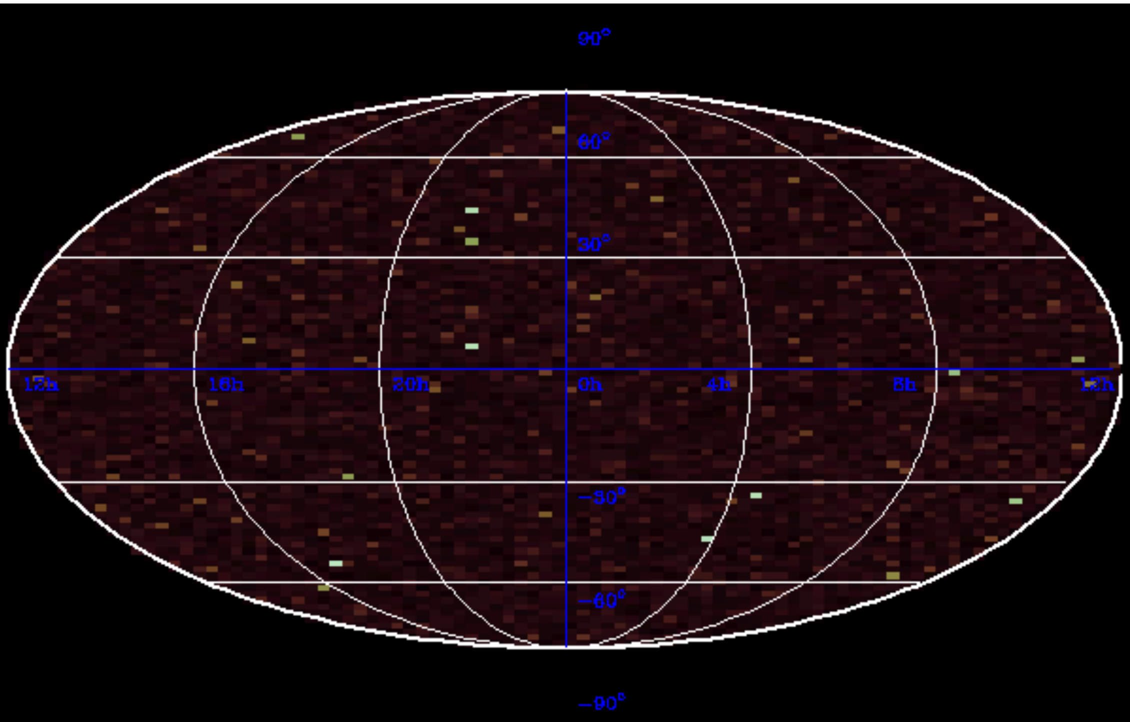


(c) Memory

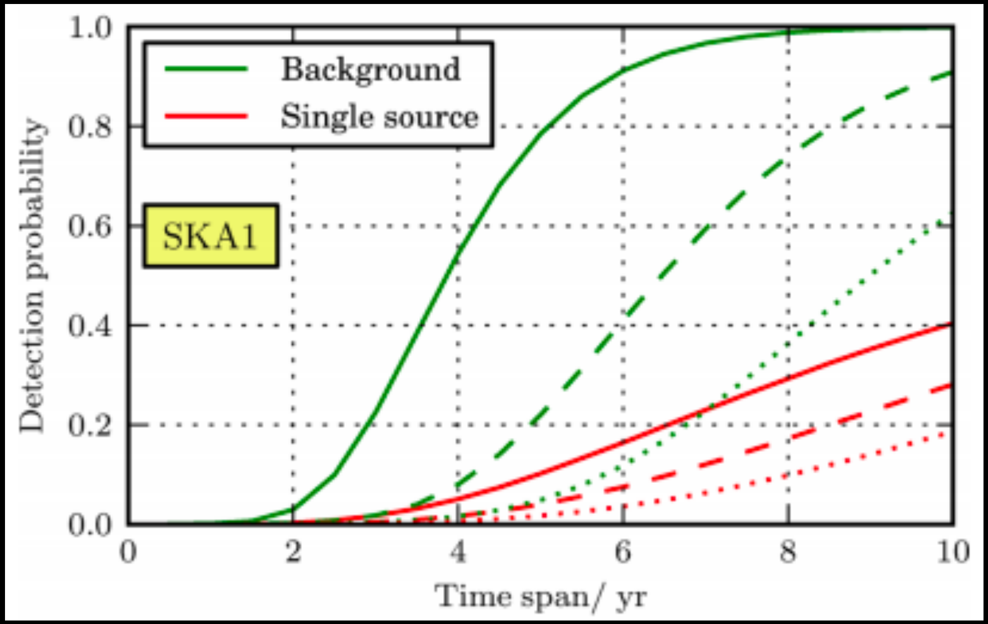


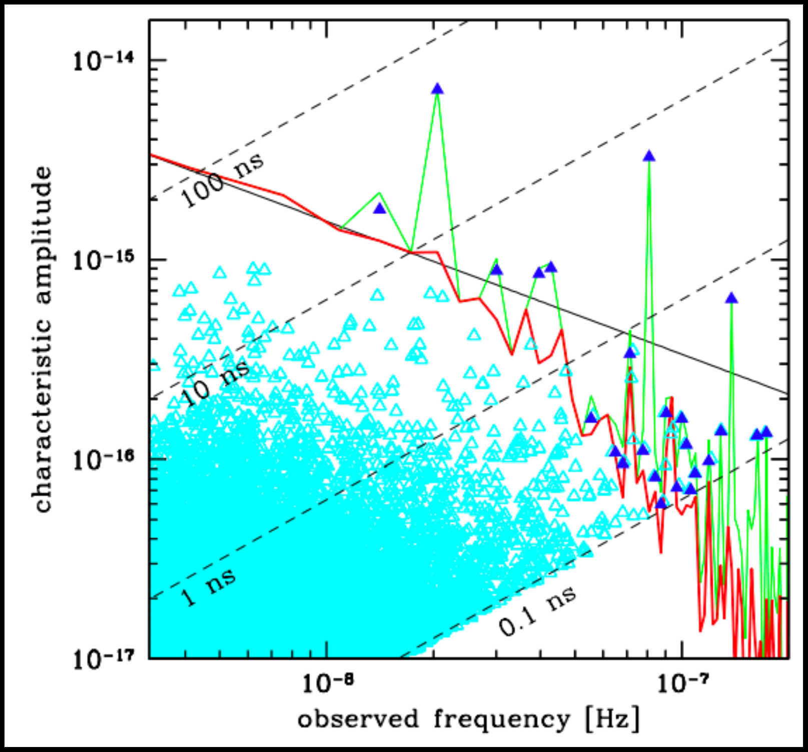
(d) Burst

Burke-Spolaor (2015)



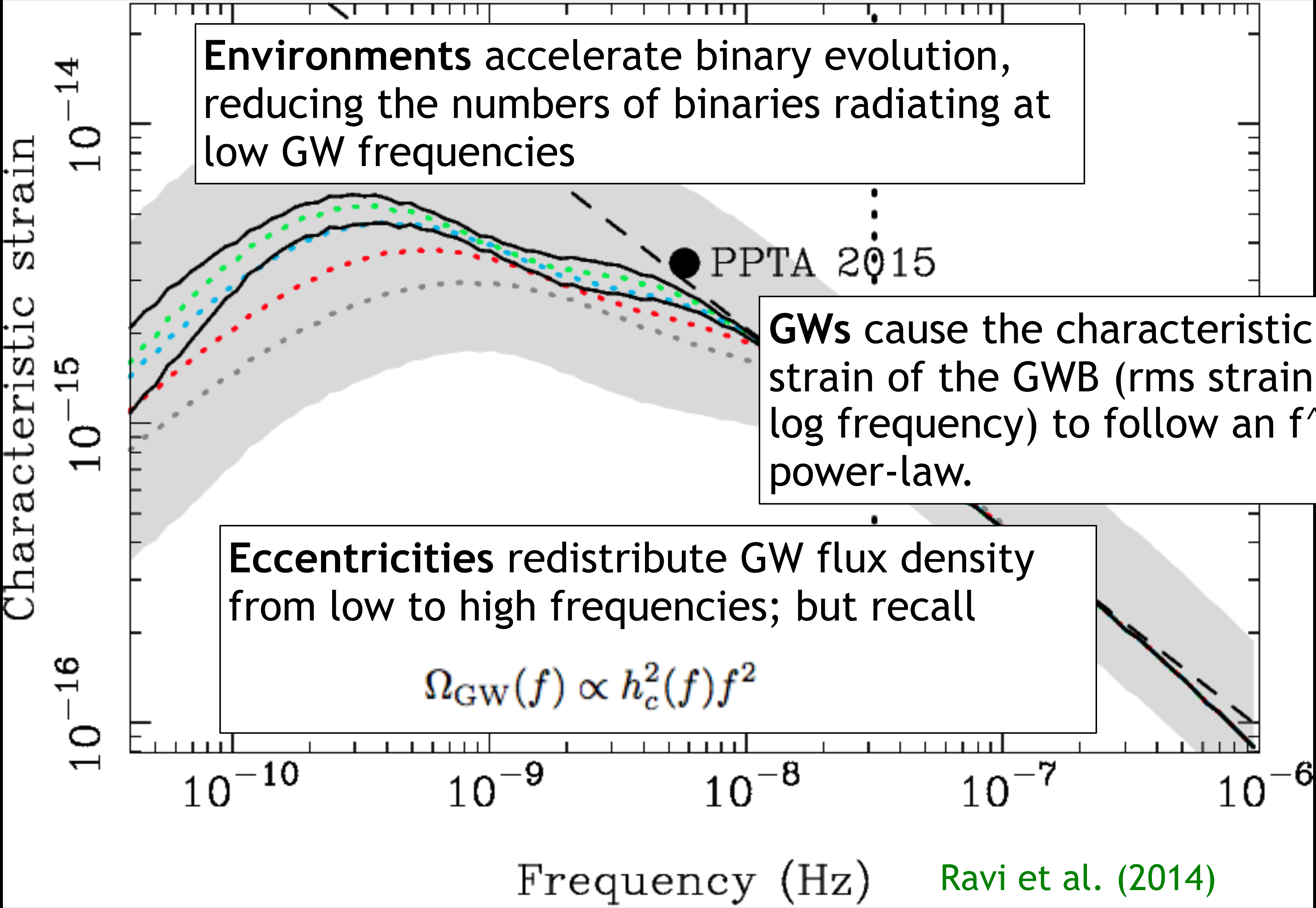
The GW sky corresponding to binary SMBHs is expected to be a superposition of individual bright sources on a stochastic background (e.g., Sesana et al. 2008, Ravi et al. 2012, Roebber et al. 2016).





However, population synthesis models (e.g., Rosado et al. 2014, 2016; Ravi et al. 2015) suggest that a stochastic GWB will be detected first.

Super-efficient binary SMBH coalescence, driven by interactions with full loss-cone of stars.



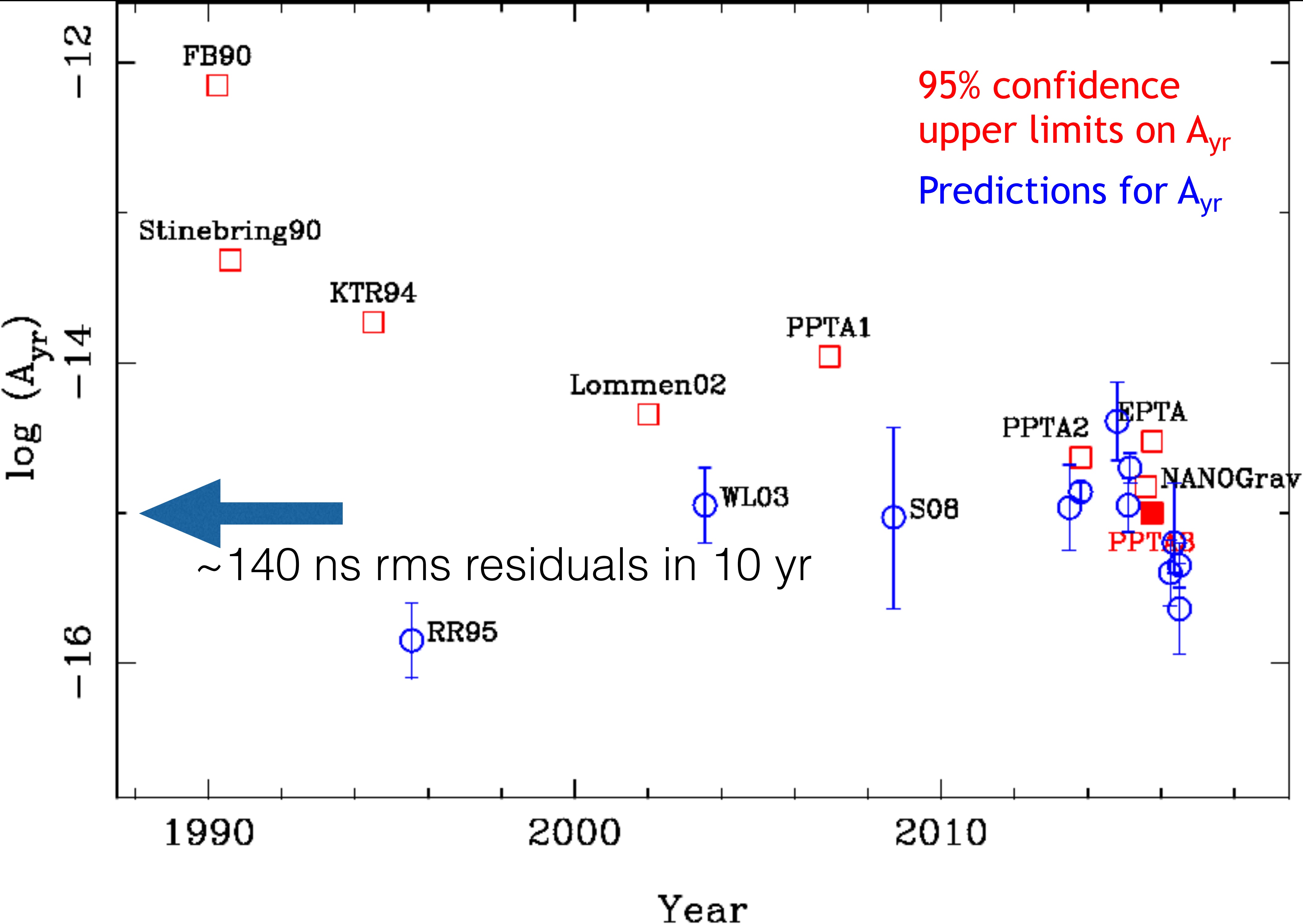
Environments accelerate binary evolution, reducing the numbers of binaries radiating at low GW frequencies

GWs cause the characteristic strain of the GWB (rms strain per log frequency) to follow an f^-2/3 power-law.

Eccentricities redistribute GW flux density from low to high frequencies; but recall

$$\Omega_{\rm GW}(f) \propto h_c^2(f) f^2$$

Ravi et al. (2014)



95% confidence upper limits on A_{yr}

Predictions for A_{yr}

~140 ns rms residuals in 10 yr

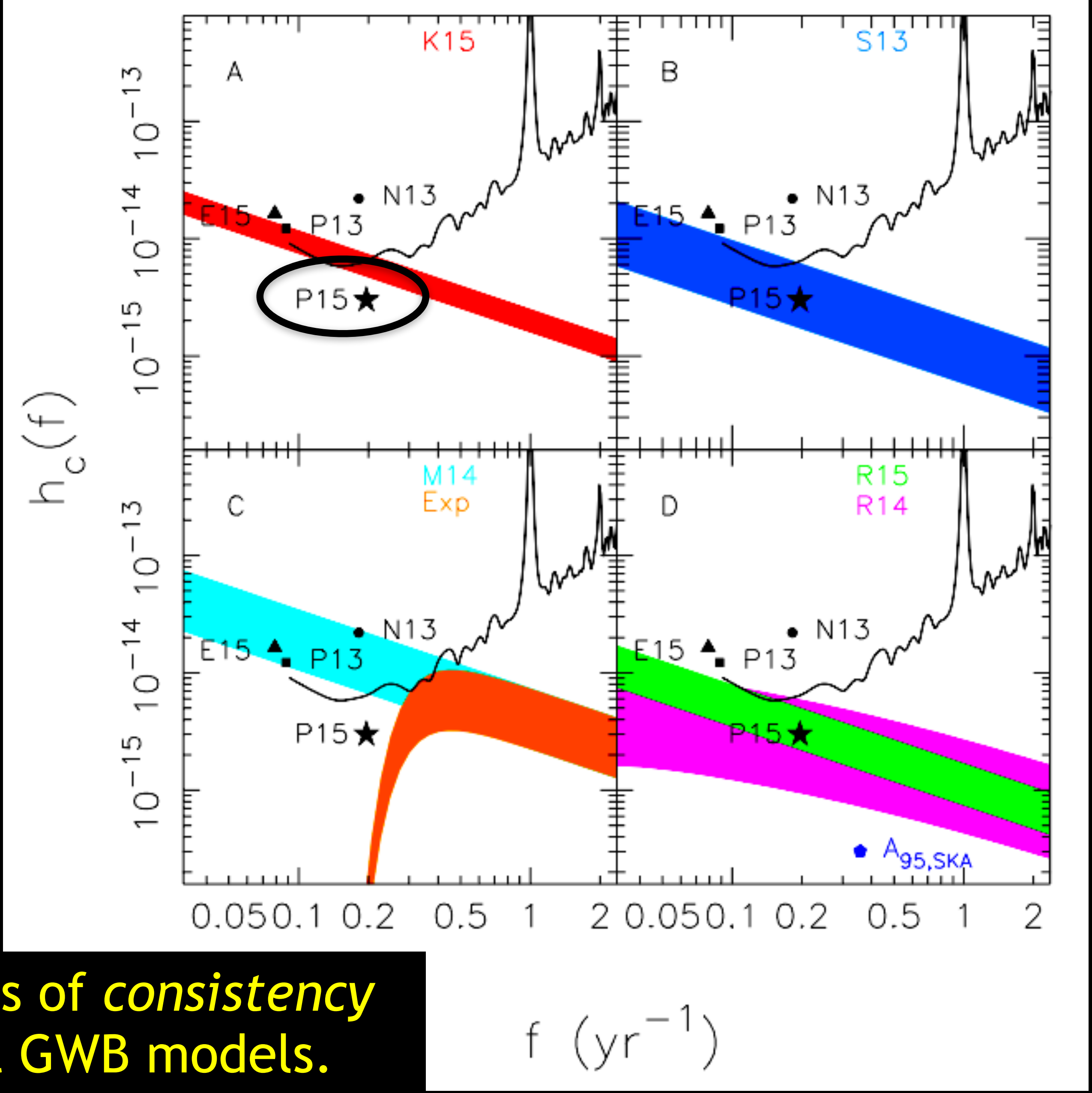
Shannon et al. (2015) constraints

0.5%

9%

0.5%
(6%)

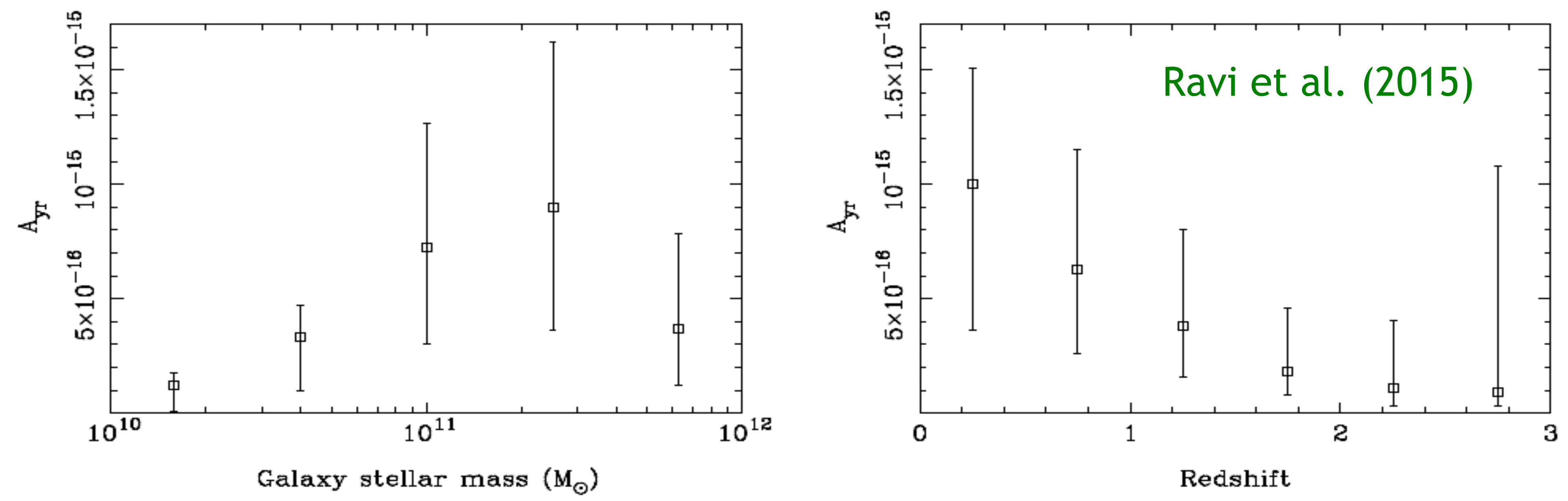
5%
(20%)

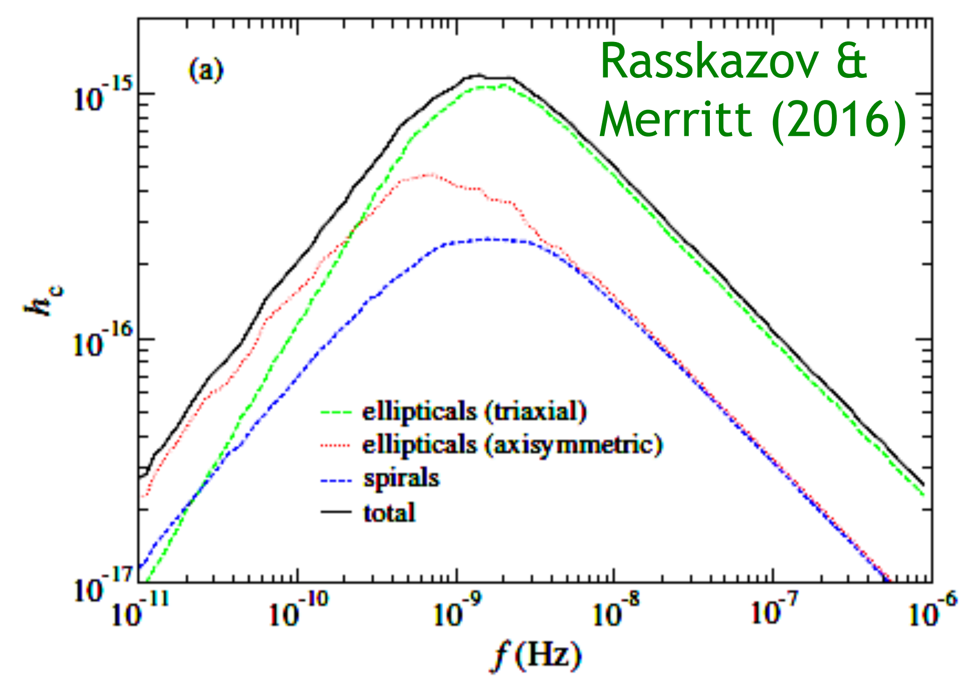


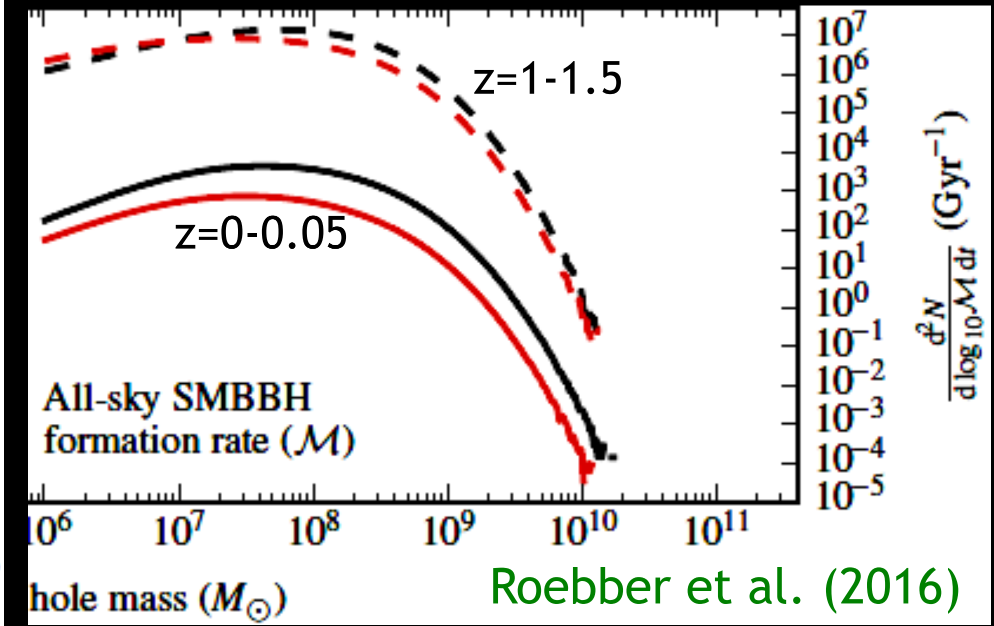
Probabilities of *consistency* of different GWB models.

Uncertainty 1: Massive early-type galaxies dominate

A_yr (all) = 1.2e-15   A_yr (early-type only) = 1.0e-15   A_yr (with late-type) = 5e-16

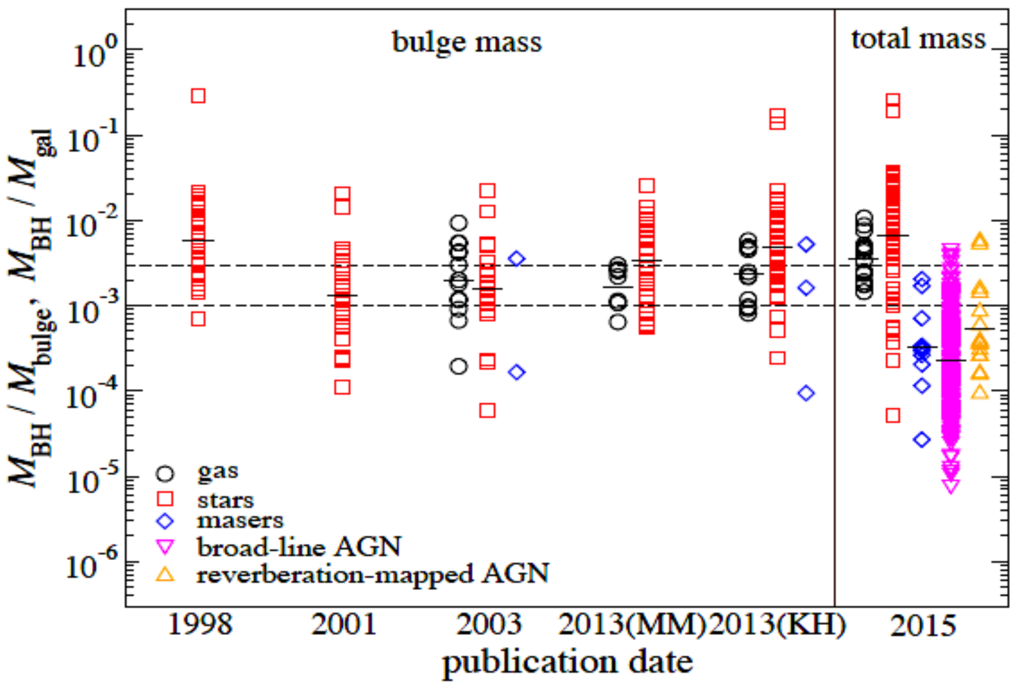

Ravi et al. (2015)


Rasskazov & Merritt (2016)


Roebber et al. (2016)

Uncertainty 2: SMBH masses

SMBH and bulge mass measurements



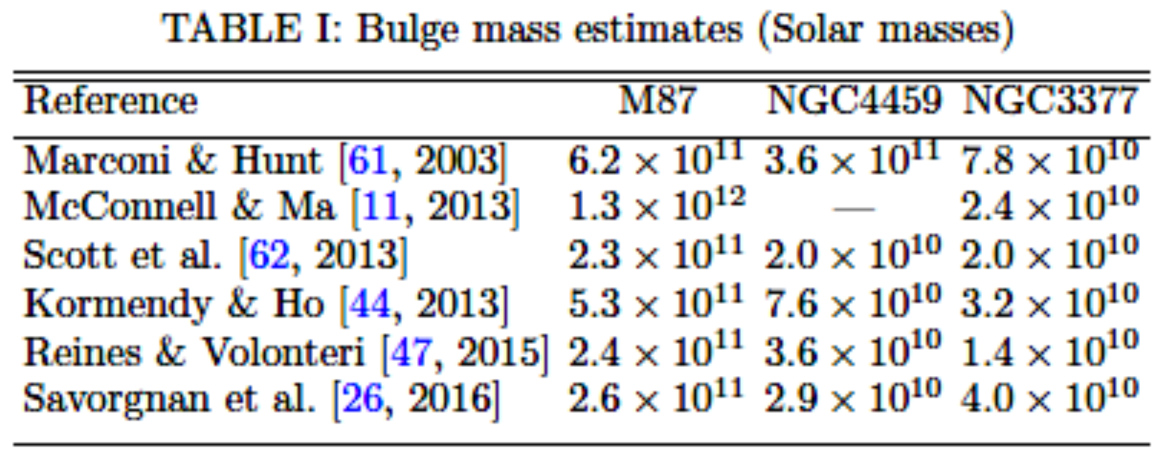
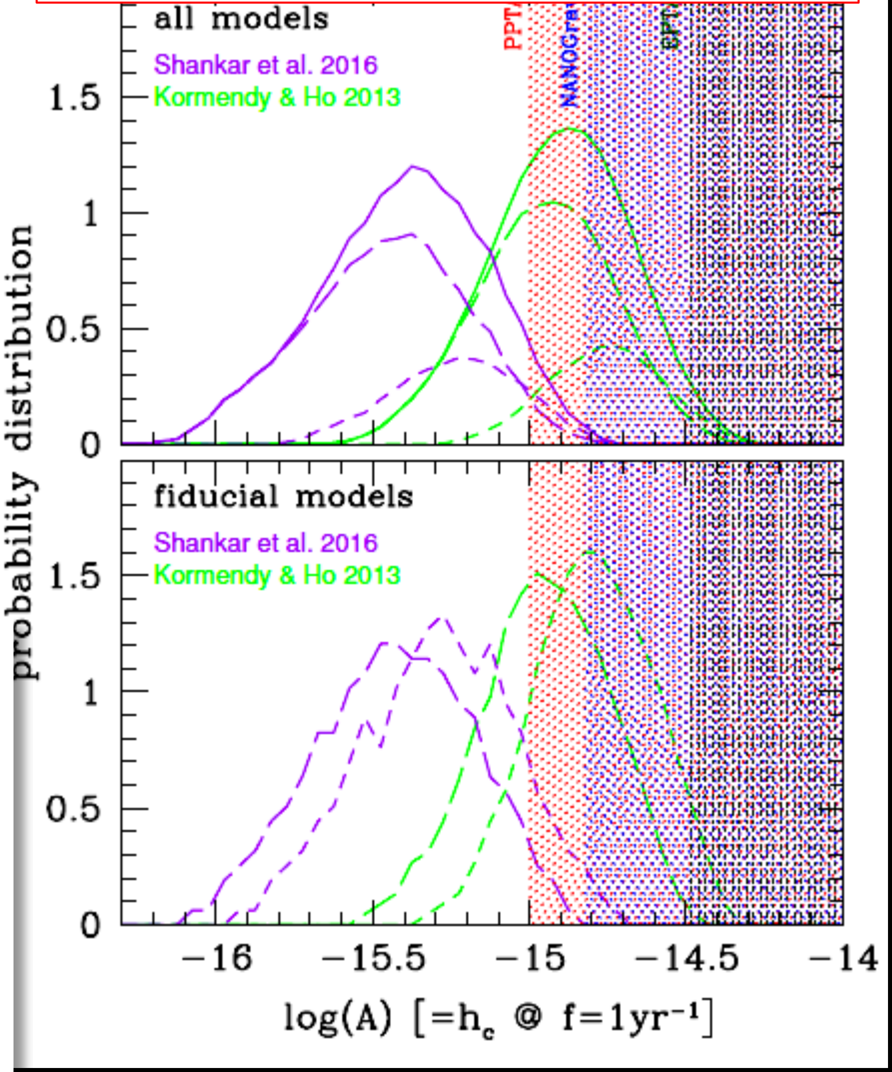


TABLE I: Bulge mass estimates (Solar masses)

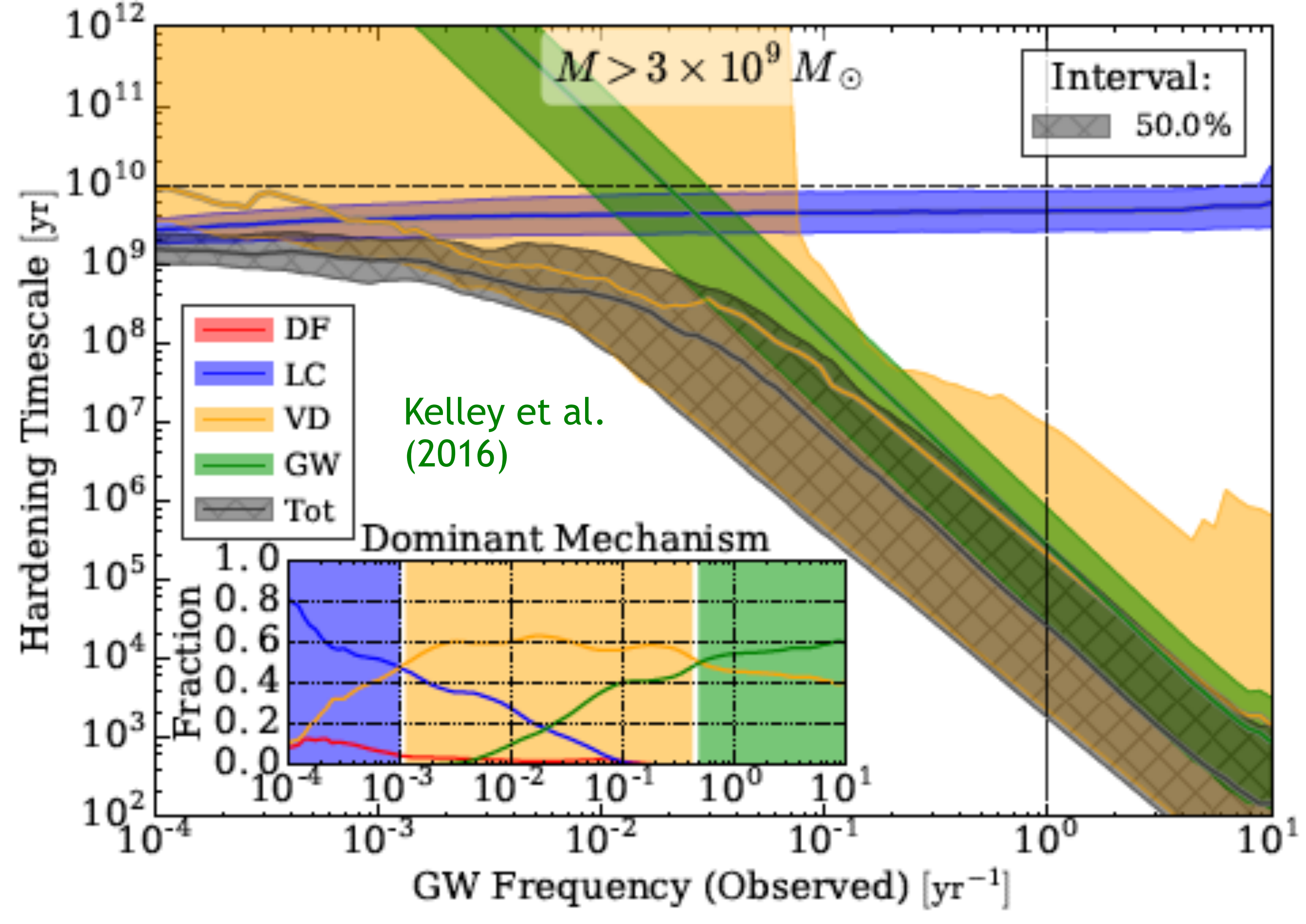
Reference	M87	NGC4459	NGC3377
Marconi & Hunt [61, 2003]	6.2×10^{11}	3.6×10^{11}	7.8×10^{10}
McConnell & Ma [11, 2013]	1.3×10^{12}	—	2.4×10^{10}
Scott et al. [62, 2013]	2.3×10^{11}	2.0×10^{10}	2.0×10^{10}
Kormendy & Ho [44, 2013]	5.3×10^{11}	7.6×10^{10}	3.2×10^{10}
Reines & Volonteri [47, 2015]	2.4×10^{11}	3.6×10^{10}	1.4×10^{10}
Savorgnan et al. [26, 2016]	2.6×10^{11}	2.9×10^{10}	4.0×10^{10}

Bias in local sample of galaxies with SMBH mass measurements



Shankar et al. (2016), Sesana et al. (2016), Rasskazov & Merritt (2016)

Uncertainty 3: SMBH environments



Kelley et al. (2016)

Hardening timescales for different mechanisms.

DF: dynamical friction. LC: loss cone. VD: viscous disk.

1. There is circumstantial evidence for the coalescence of supermassive black holes in galaxy mergers.

2. Pulsar timing measurements are currently sensitive to optimistic predictions for the stochastic gravitational-wave background from binary supermassive black holes.

3. The large uncertainties in characterizing the stochastic GWB are indicative of the breadth of astrophysics accessible to pulsar timing arrays.

NANOGrav

Uses the Arecibo and Green Bank telescopes.

http://nanograv.org/

EPTA

Five telescopes: Jodrell Bank, Westerbork, Nancay, Effelsberg, Sardinia. Also coherently phases all five.

http://www.epta.eu.org/

PPTA

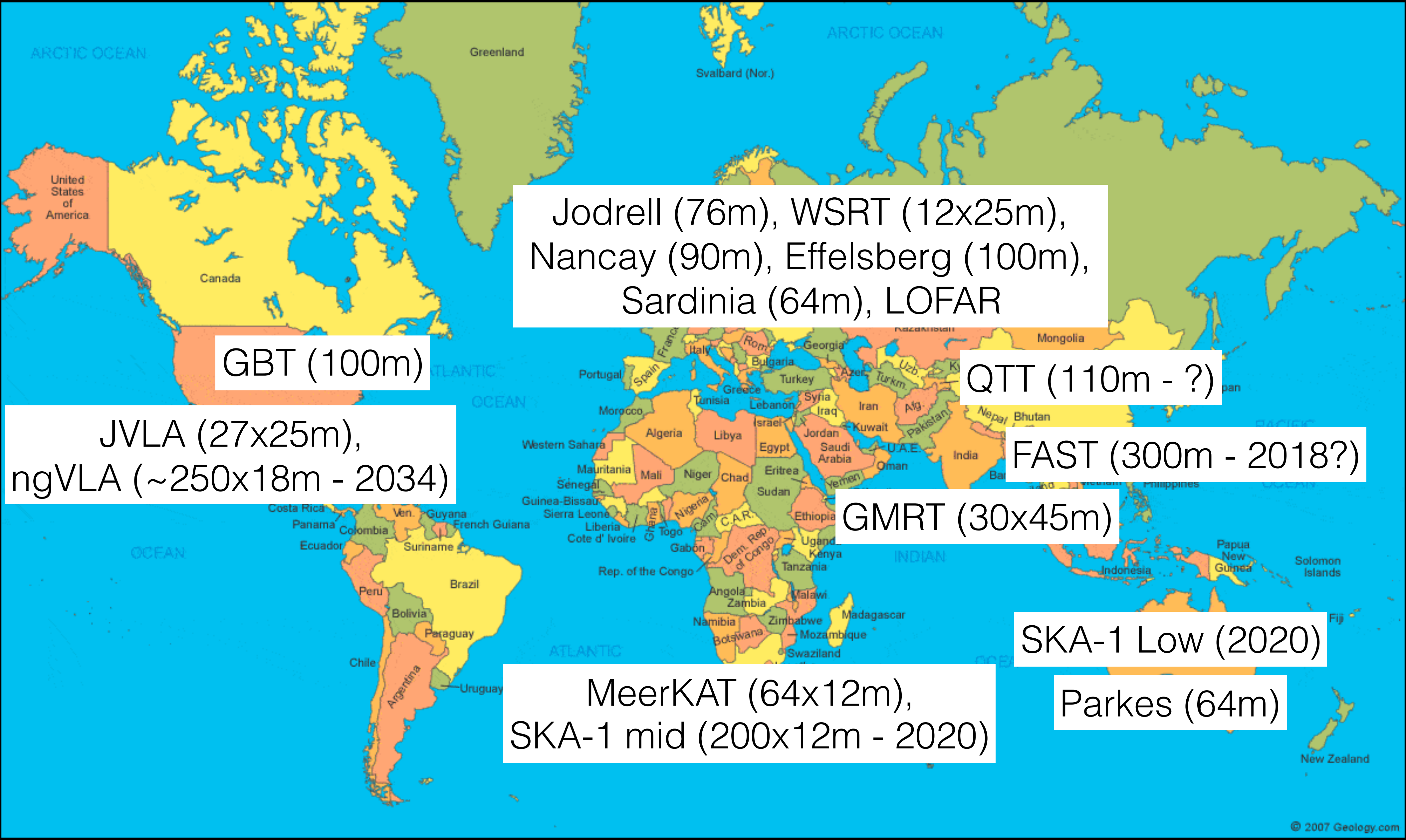
Uses the Parkes telescope.

https://www.atnf.csiro.au/research/pulsar/ppta/

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

A collaboration of collaborations, to combine data from all telescopes.

http://www.ipta4gw.org/



Jodrell (76m), WSRT (12x25m),
Nancay (90m), Effelsberg (100m),
Sardinia (64m), LOFAR

GBT (100m)

JVLA (27x25m),
ngVLA (~250x18m - 2034)

QTT (110m - ?)

FAST (300m - 2018?)

GMRT (30x45m)

MeerKAT (64x12m),
SKA-1 mid (200x12m - 2020)

SKA-1 Low (2020)

Parkes (64m)

The continuity of pulsar timing arrays

- The future of radio astronomy is in large arrays of small dishes (SKA - 2020+, ngVLA - 2034+). Pulsar searching and timing will (nonetheless) be key to their science returns.

- The increase in GW signal strengths with longer wave periods implies that **contiguous observations are crucial**. For a stochastic background, until the self-noise limit is reached, the signal-to-noise ratio can increase as rapidly as $t^{13/3}$

1. Pulsars are ridiculously awesome objects!
2. Gravitational-wave detection in pulsar timing measurements is practicable
3. Pulsar-timing constraints on GWs from binary supermassive black holes are currently of astrophysical interest