Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Pulsar Timing Arrays

Joris P.W. Verbiest

Max-Planck-Institut für Radioastronomie

GWPAW 2012, Hannover

Wednesday 06 June 2012

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Pulsar Timing Arrays

Joris P.W. Verbiest
Max-Planck-Institut für Radioastronomie

GWPAW 2012, Hannover

Wednesday 06 June 2012

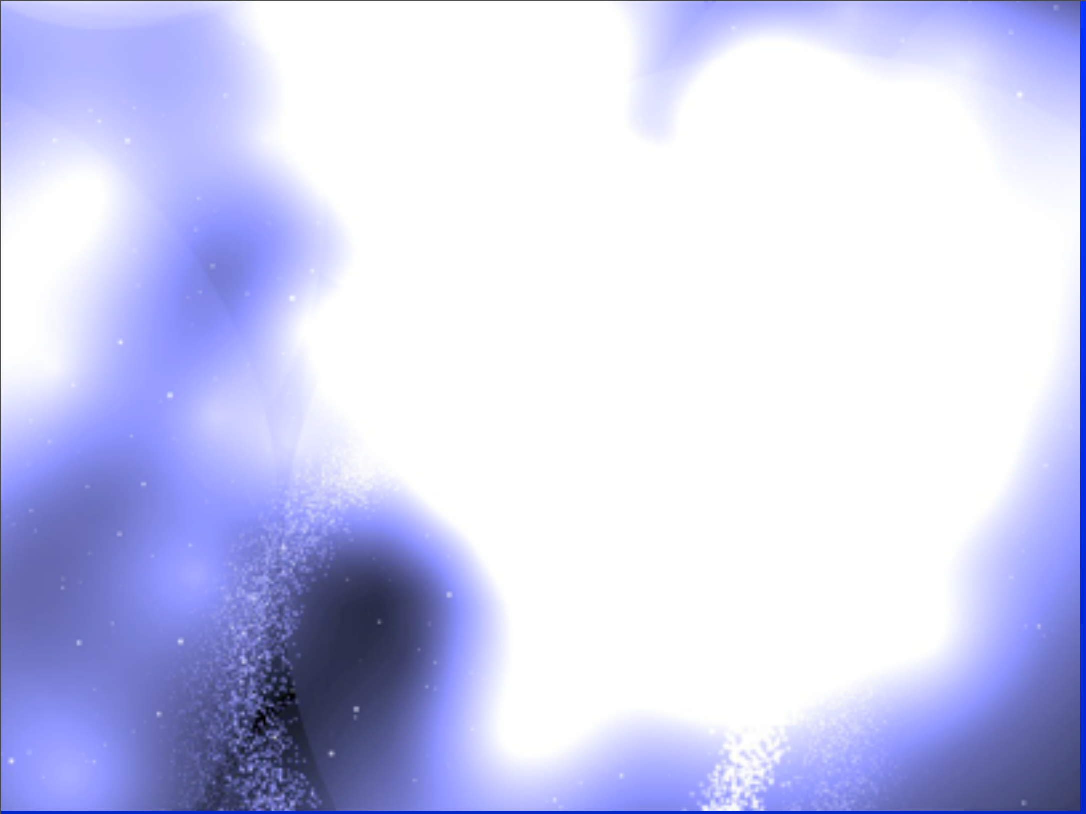
Outline

- Introduction:
  - Pulsars & Pulsar Timing (Arrays)
- Current PTA Sensitivity
- Simple Forecasts
- Ongoing Development
- GW Science
- Summary

Introduction: Pulsar Timing

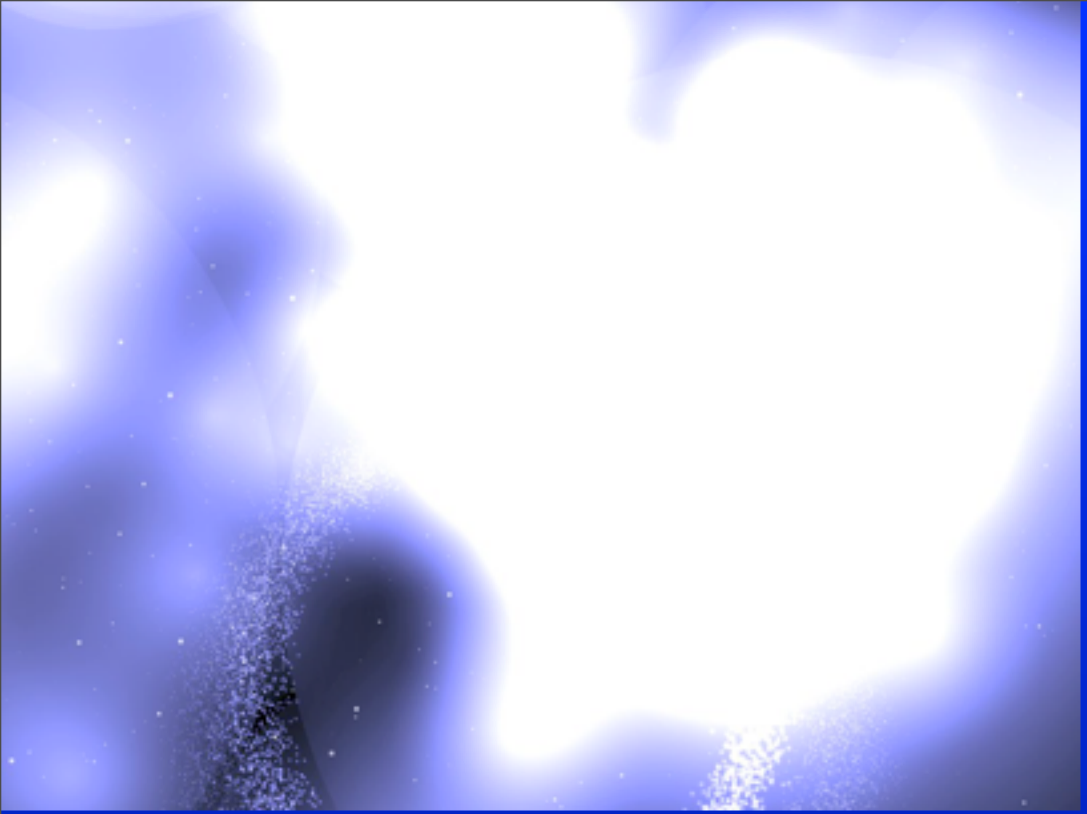
Courtesy Andrew Jameson (Swinburne)

Introduction: Pulsar Timing



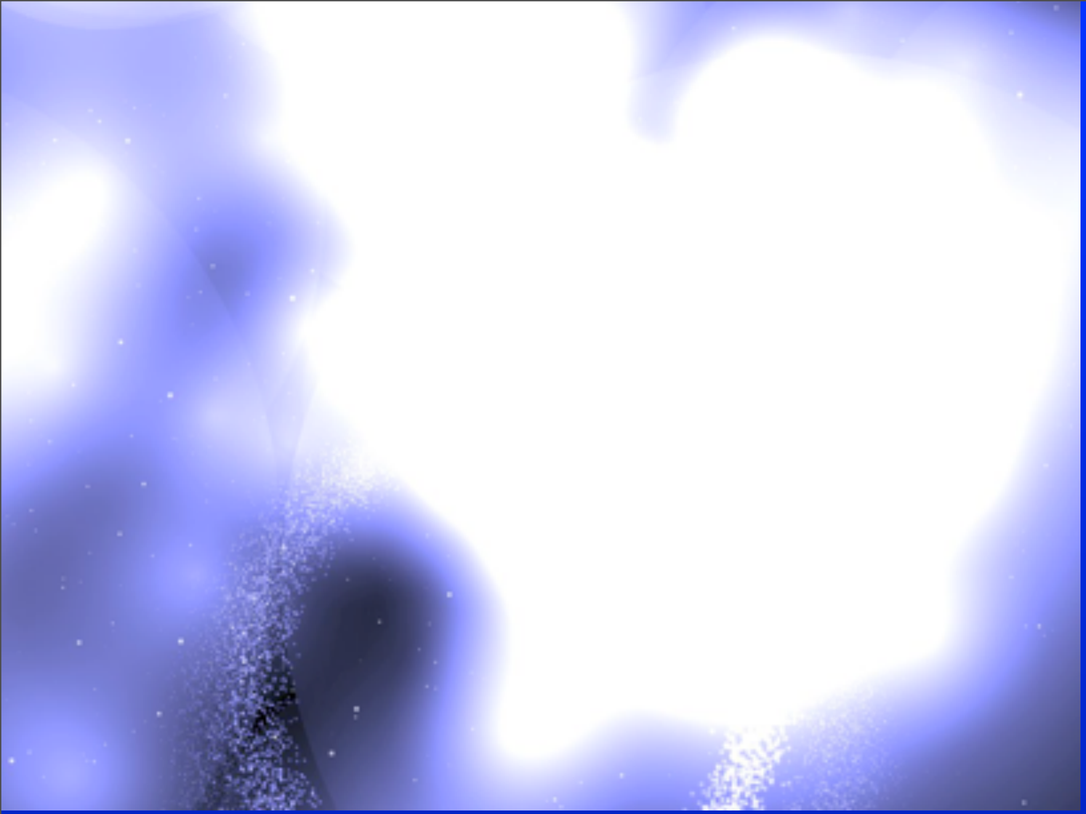
Courtesy Andrew Jameson (Swinburne)

Introduction: Pulsar Timing



Courtesy Andrew Jameson (Swinburne)

$$T_{\mathrm{th}} \propto \phi\left(\nu, \dot{\nu}, t\right) + D\frac{\int_0^d n_{\mathrm{e}} \mathrm{d}l}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\mathrm{T}}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$



Courtesy Andrew Jameson (Swinburne)

Introduction: Pulsar Timing

Basic Method:

Actual Pulse Arrival Time

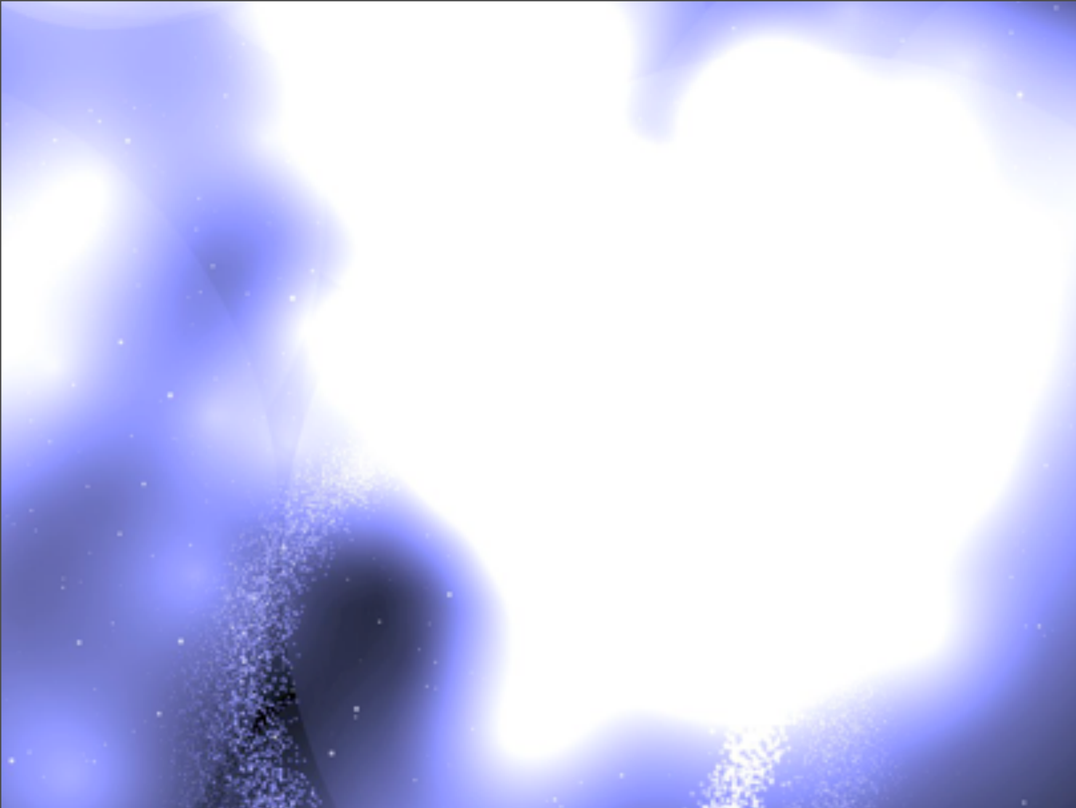
— Theoretical Model

= Timing Residual

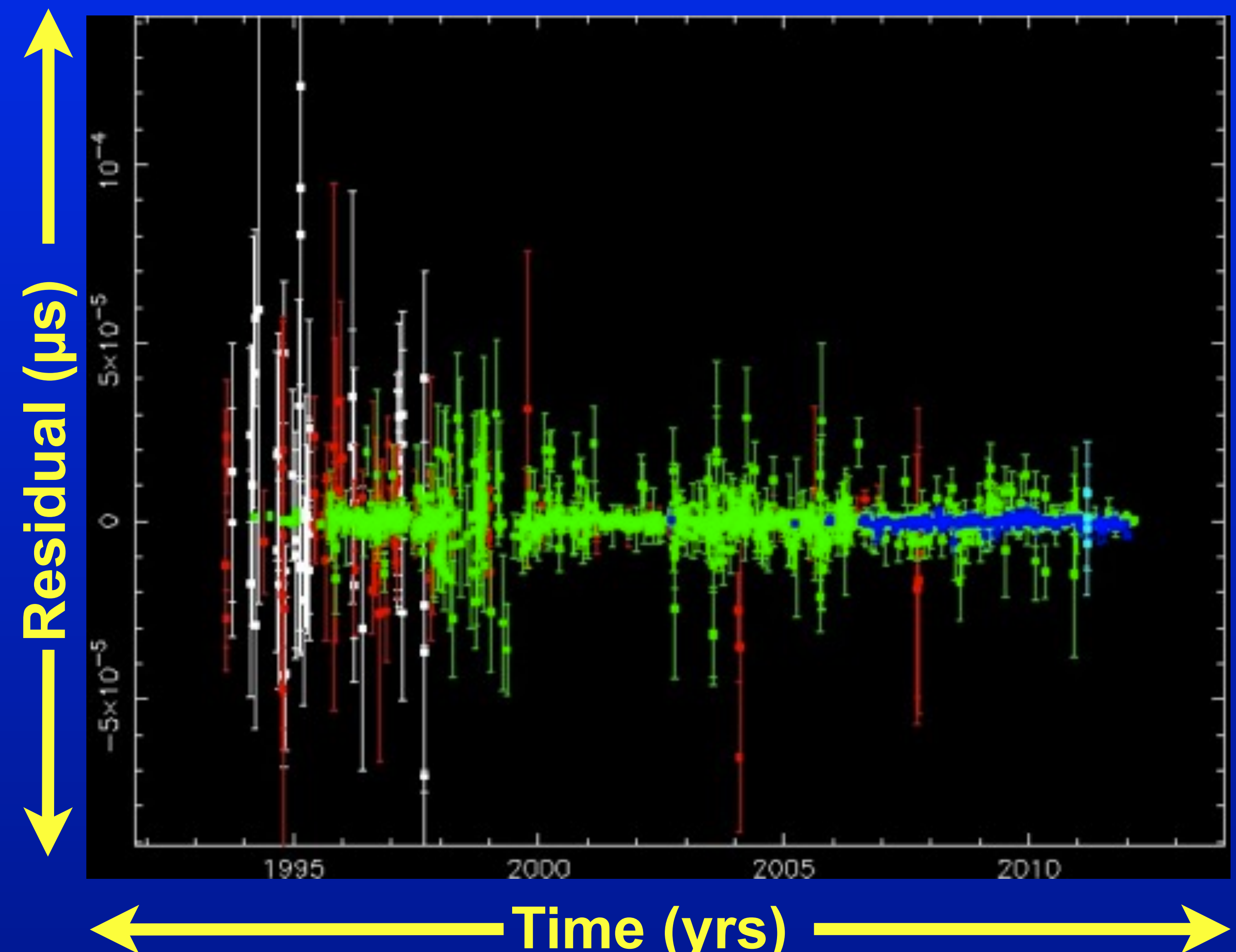
$$T_{\rm th} \propto \phi\left(\nu, \dot{\nu}, t\right) + D\frac{\int_0^d n_{\rm e} {\rm d}l}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\rm T}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$

Monday, June 11, 2012

Introduction: Pulsar Timing



Courtesy Andrew Jameson (Swinburne)



Basic Method:

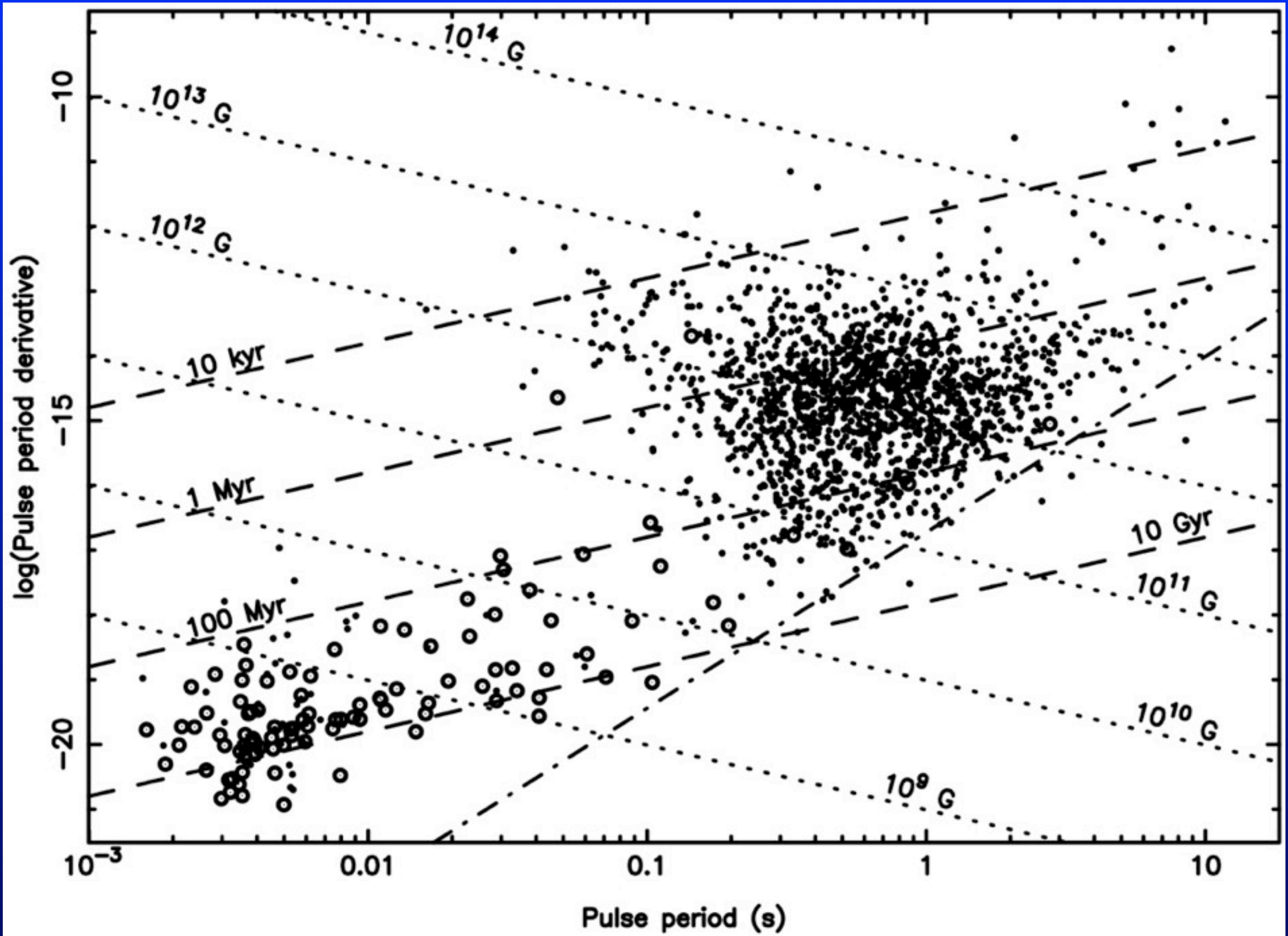
Actual Pulse Arrival Time

— Theoretical Model

= Timing Residual

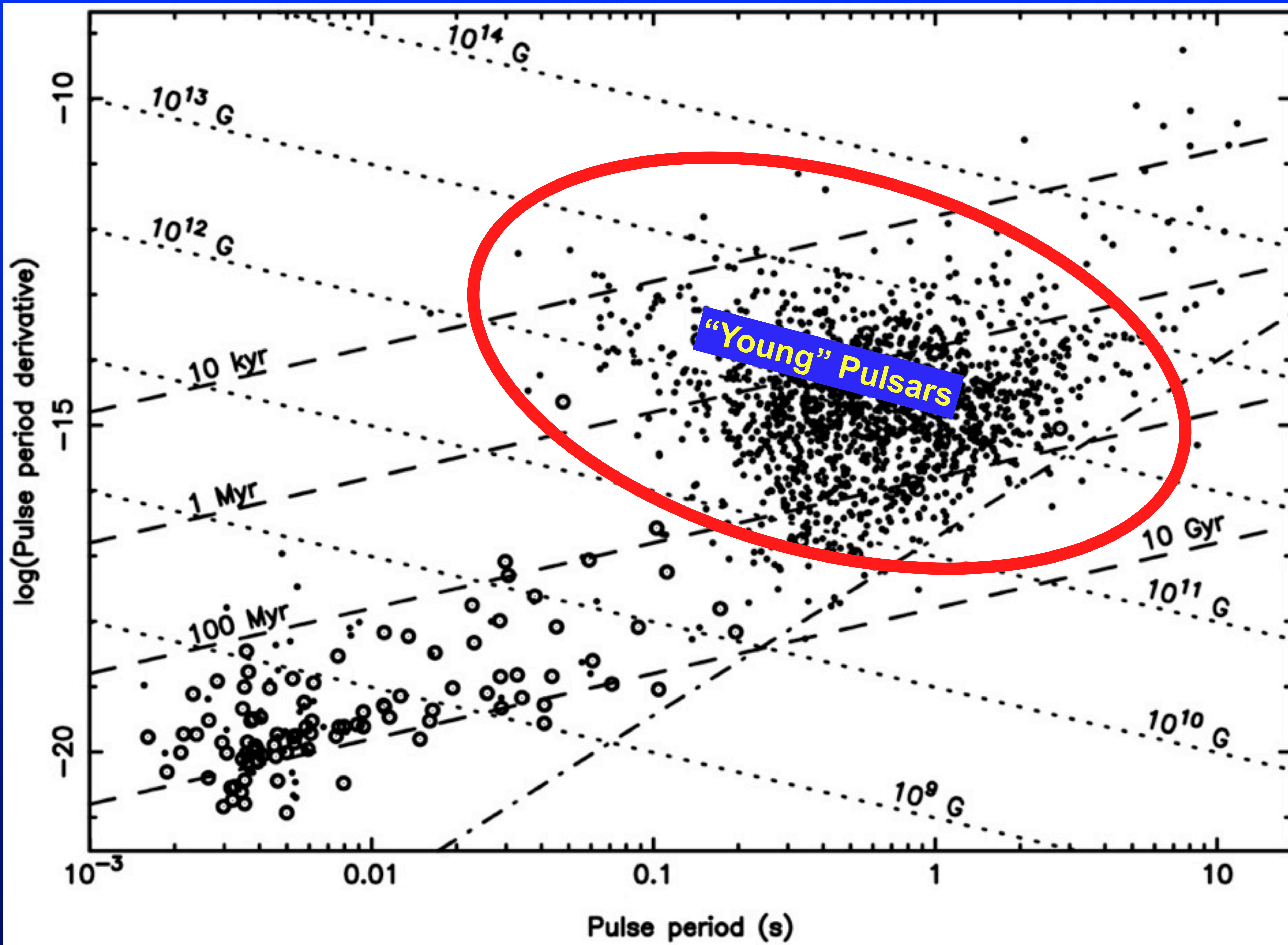
$$T_{\rm th} \propto \phi\left(\nu, \dot{\nu}, t\right) + D\frac{\int_0^d n_{\rm e} {\rm d}l}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\rm T}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$

Introduction: Pulsars

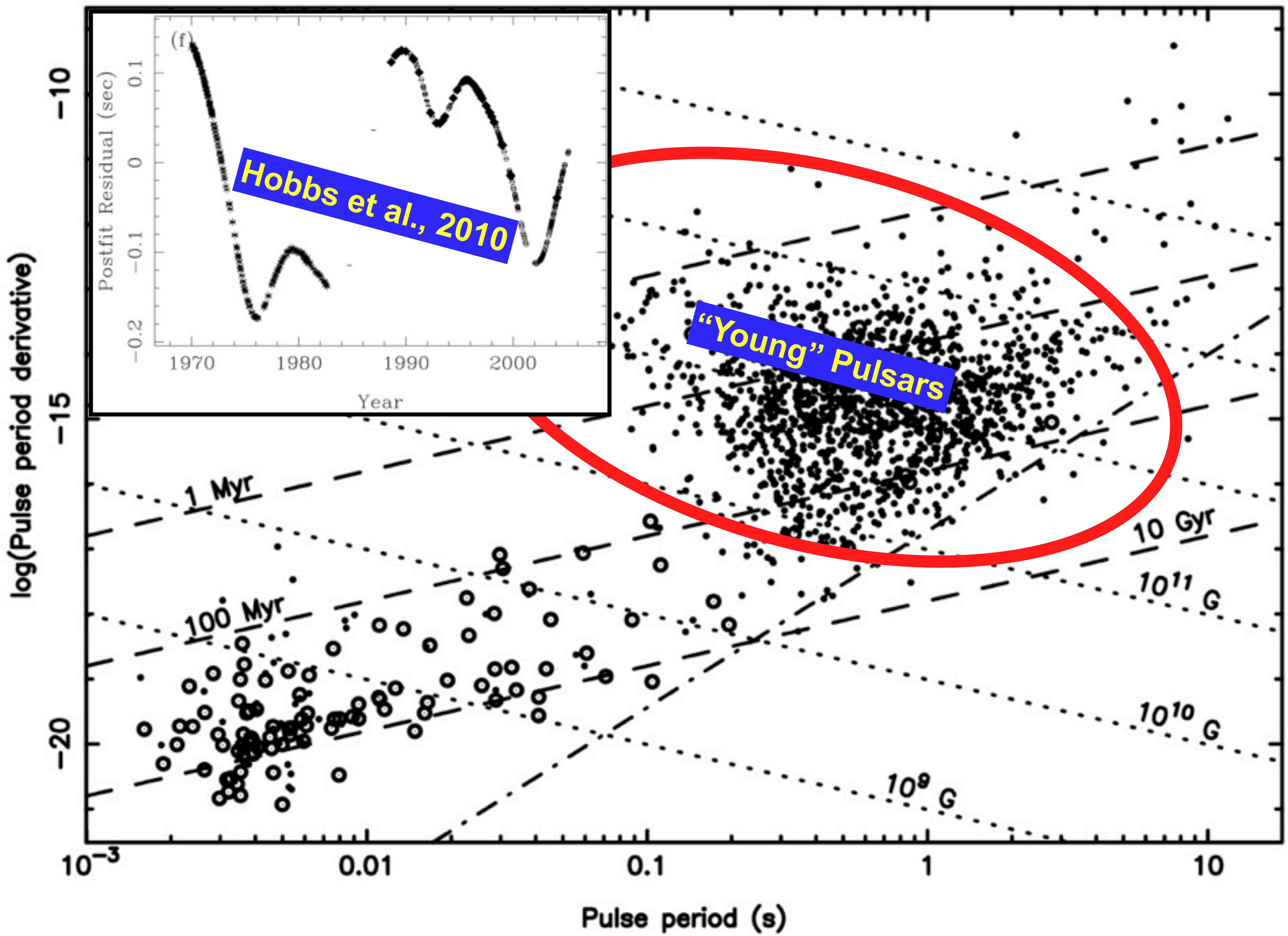


Monday, June 11, 2012

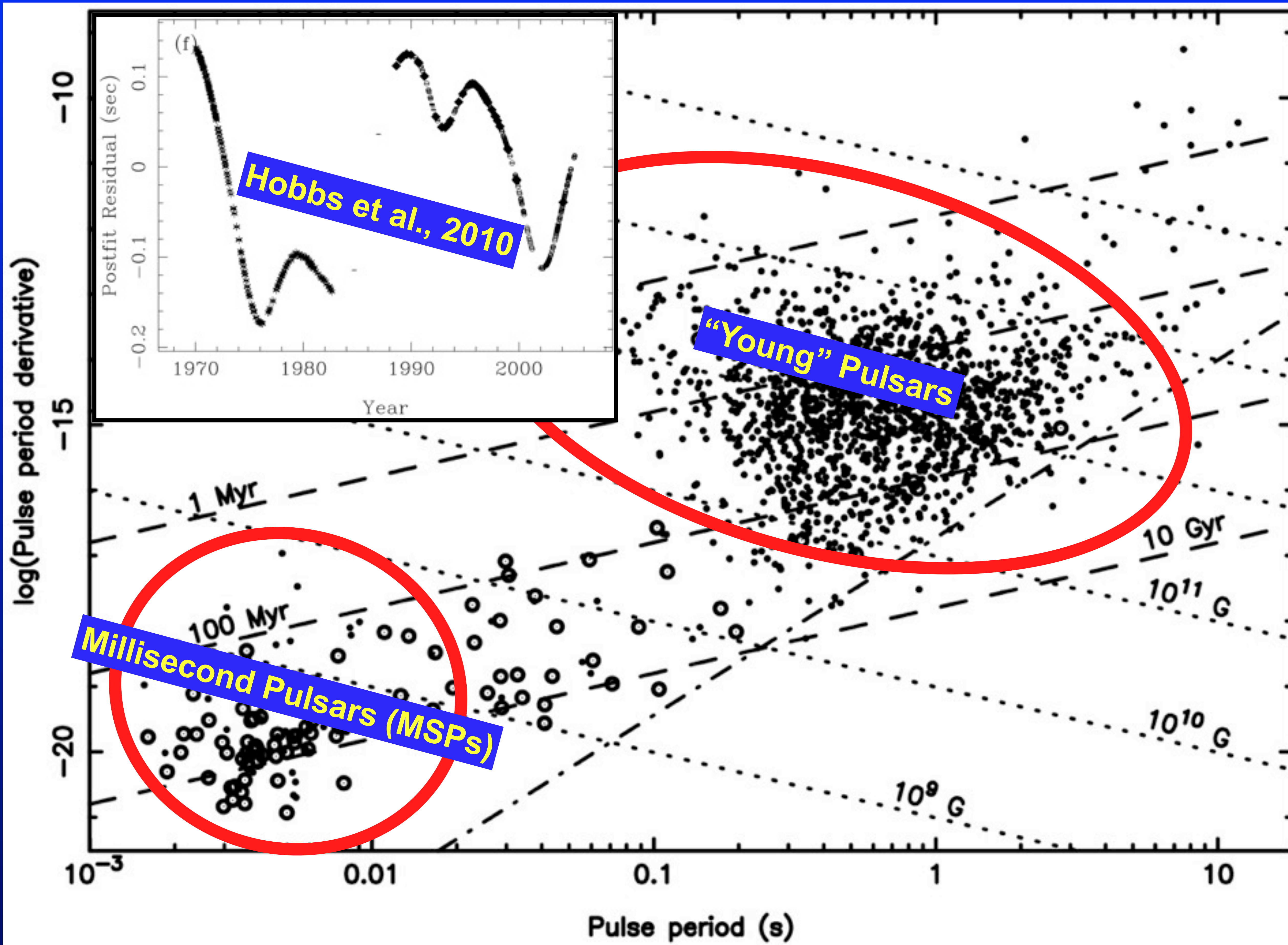
Introduction: Pulsars



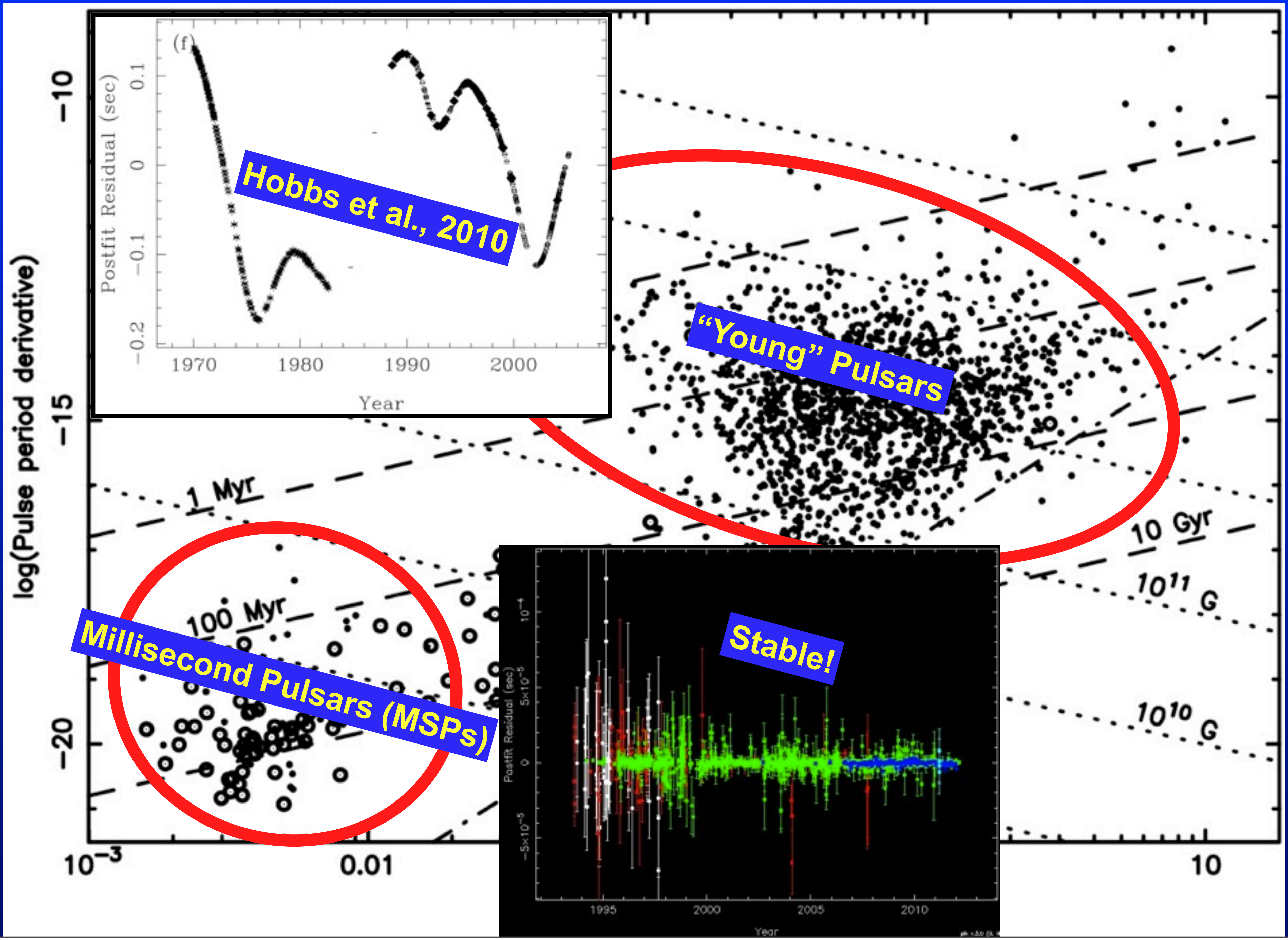
Introduction: Pulsars



Introduction: Pulsars



Introduction: Pulsars



Pulsar Timing Array (PTA) Concept

- Timing Residuals contain all unmodelled phenomena.
- Some phenomena are not (uniquely) identifiable in a single pulsar.
- Correlations between pulsars to the rescue!

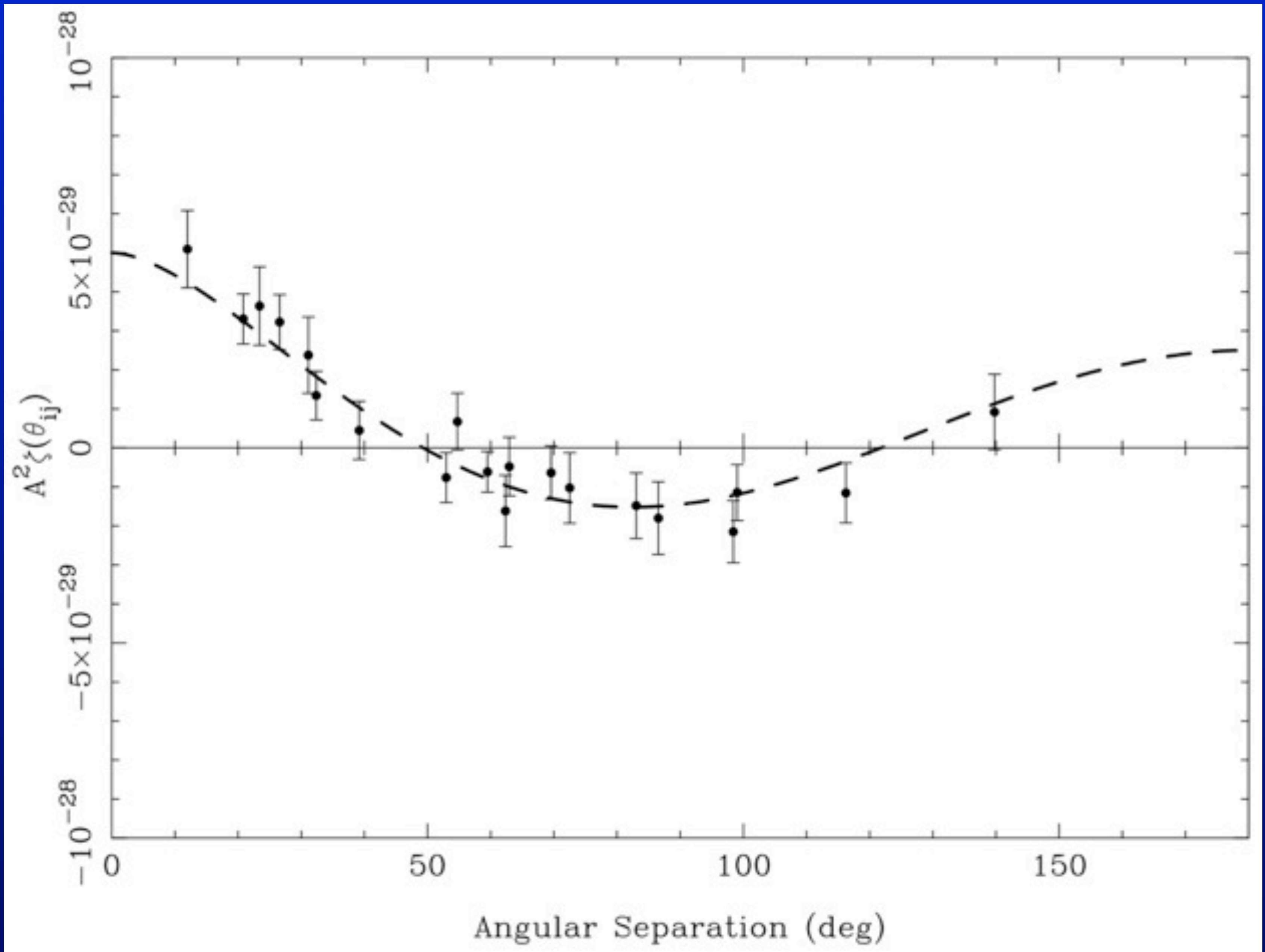
Correlations in PTA Data

- Monopole → Clock inaccuracies
- Dipole → Planetary Ephemerides
- Quadrupole → Gravitational Waves

Correlations in PTA Data

- Monopole → Clock inaccuracies
- Dipole → Planetary Ephemerides
- Quadrupole → Gravitational Waves

Theoretical work by:
Hellings & Downs, 1983

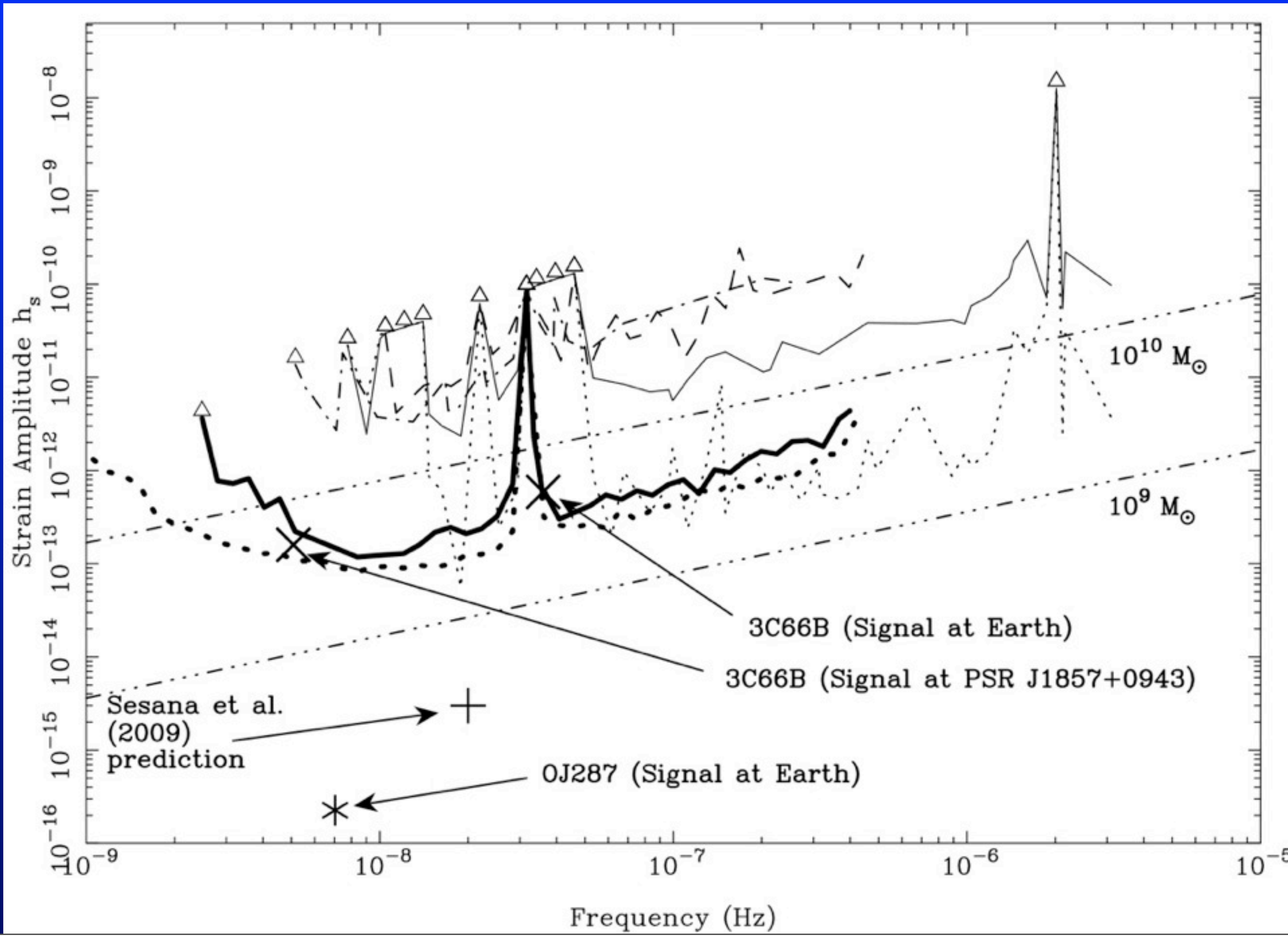


Graph: Yardley et al., MNRAS 2011

Current PTA Sensitivity

- Single SMBHBs
- GWBs

Single Source Limits



Yardley et al.; MNRAS; 2010

PTA GWB Sensitivity

- Current best limits
  - at 95% confidence
  - for a SMBHB GWB
  - with spectral index -2/3
  - Expected background: 10^{-15} Ğ10^{-14}

PTA GWB Sensitivity

- **Current best limits**
  - at 95% confidence
  - for a SMBHB GWB
  - with spectral index -2/3
  - Expected background: 10^{-15} Ğ10^{-14}

- PPTA: Jenet et al., 2006:

  $A < 11 \times 10^{-15}$

PTA GWB Sensitivity

- Current best limits
  - at 95% confidence
  - for a SMBHB GWB
  - with spectral index -2/3
  - Expected background: 10^{-15} Ğ10^{-14}

- PPTA: Jenet et al., 2006:

  $A < 11 \times 10^{-15}$

- EPTA: van Haasteren et al., 2011:

  $A < 6 \times 10^{-15}$

PTA GWB Sensitivity

- Current best limits
  - at 95% confidence
  - for a SMBHB GWB
  - with spectral index -2/3
  - Expected background: 10^{-15} Ğ10^{-14}

- PPTA: Jenet et al., 2006:

  $A < 11 \times 10^{-15}$

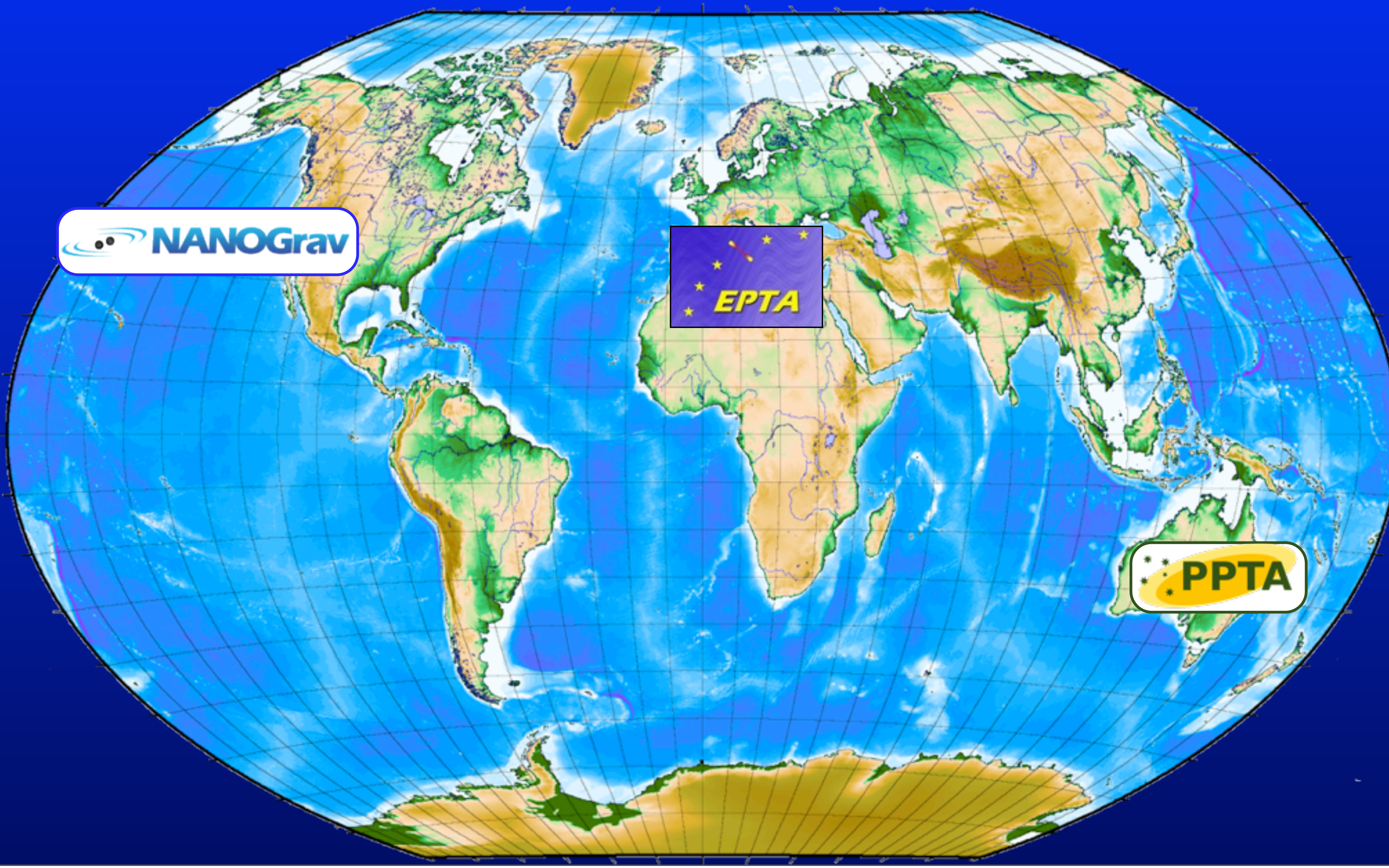
- EPTA: van Haasteren et al., 2011:

  $A < 6 \times 10^{-15}$

- NANOGrav: Demorest et al., 2012:

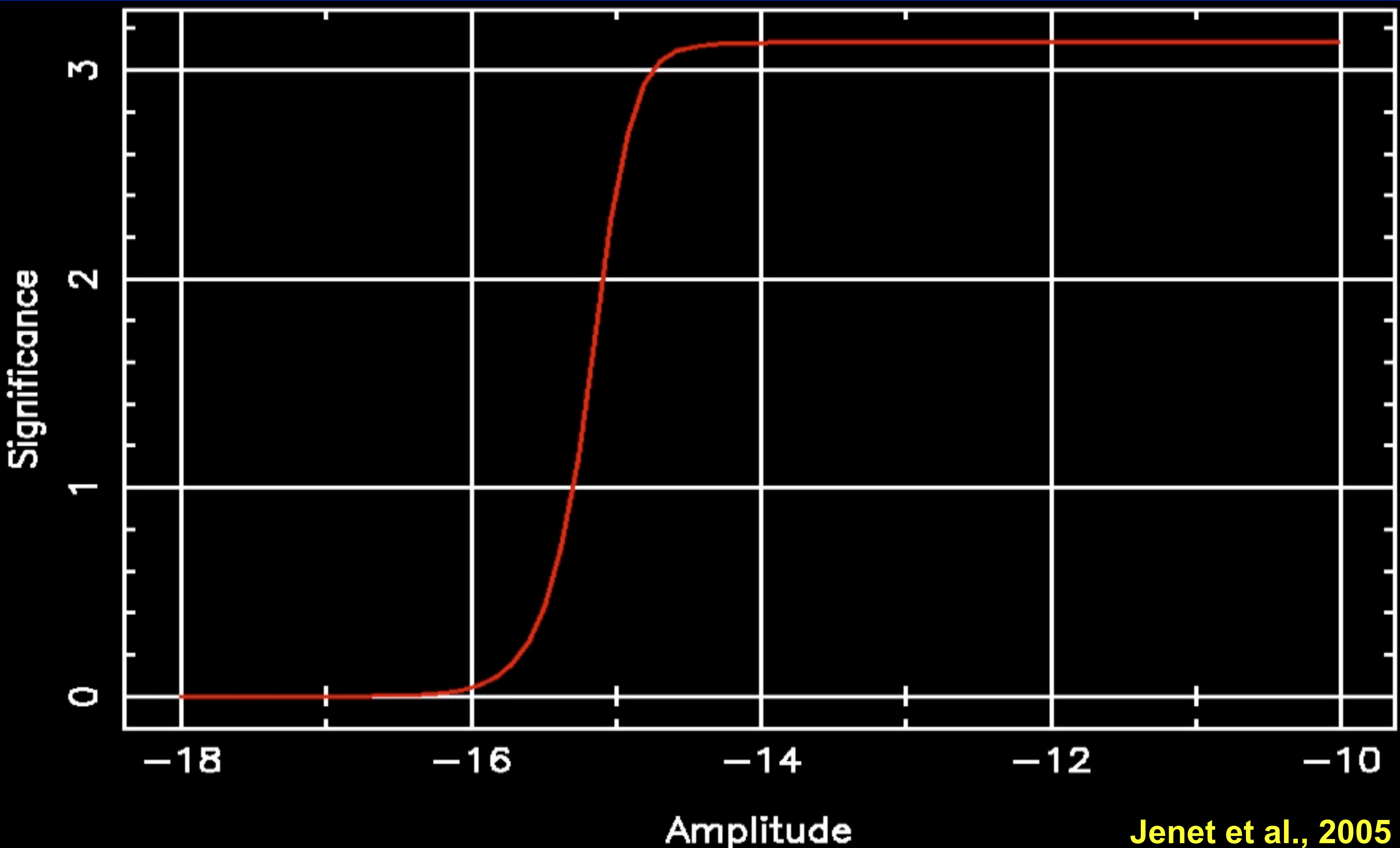
  $A < 7 \times 10^{-15}$

The International Pulsar Timing Array



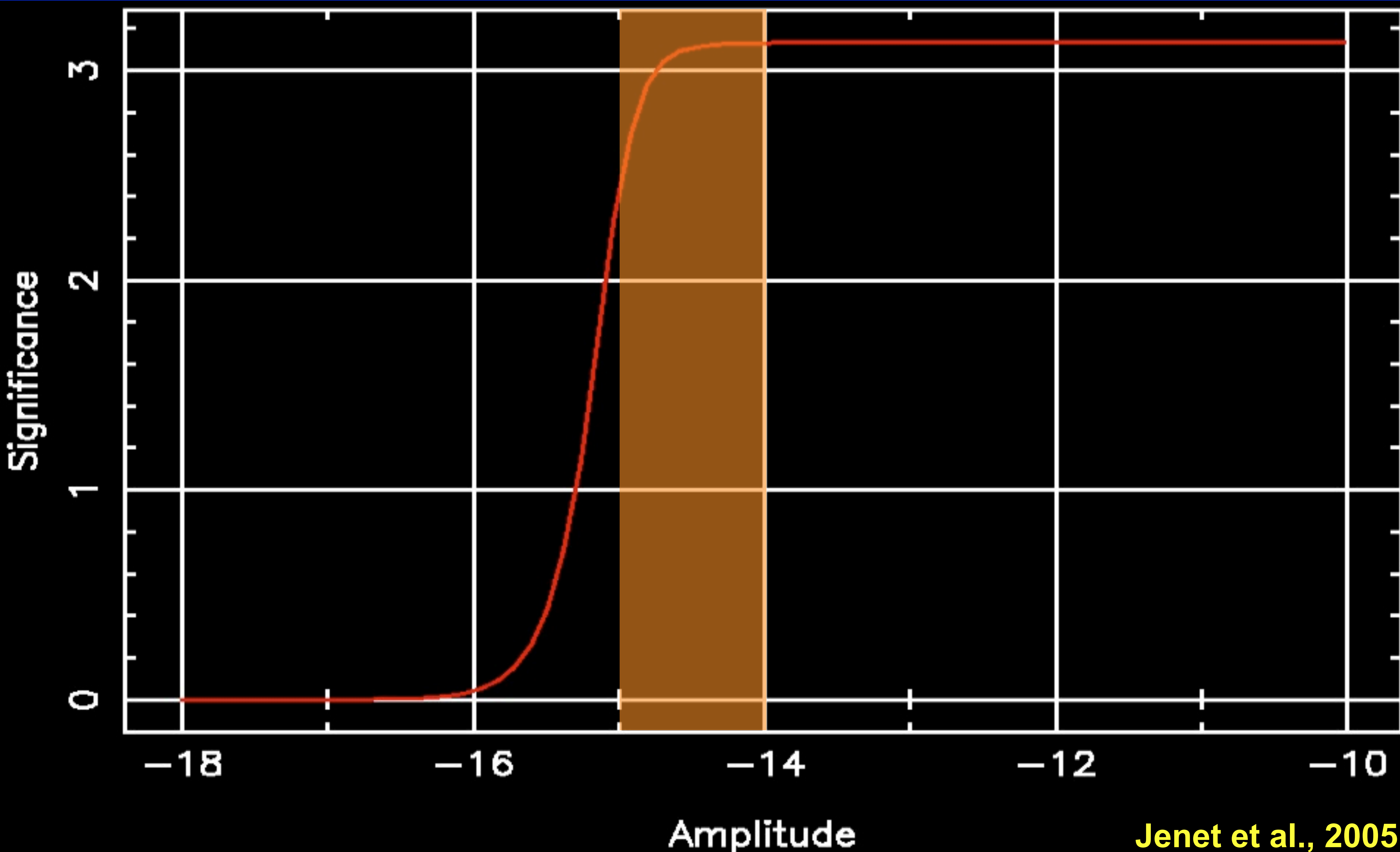
The International Pulsar Timing Array

Basic PTA Requirements



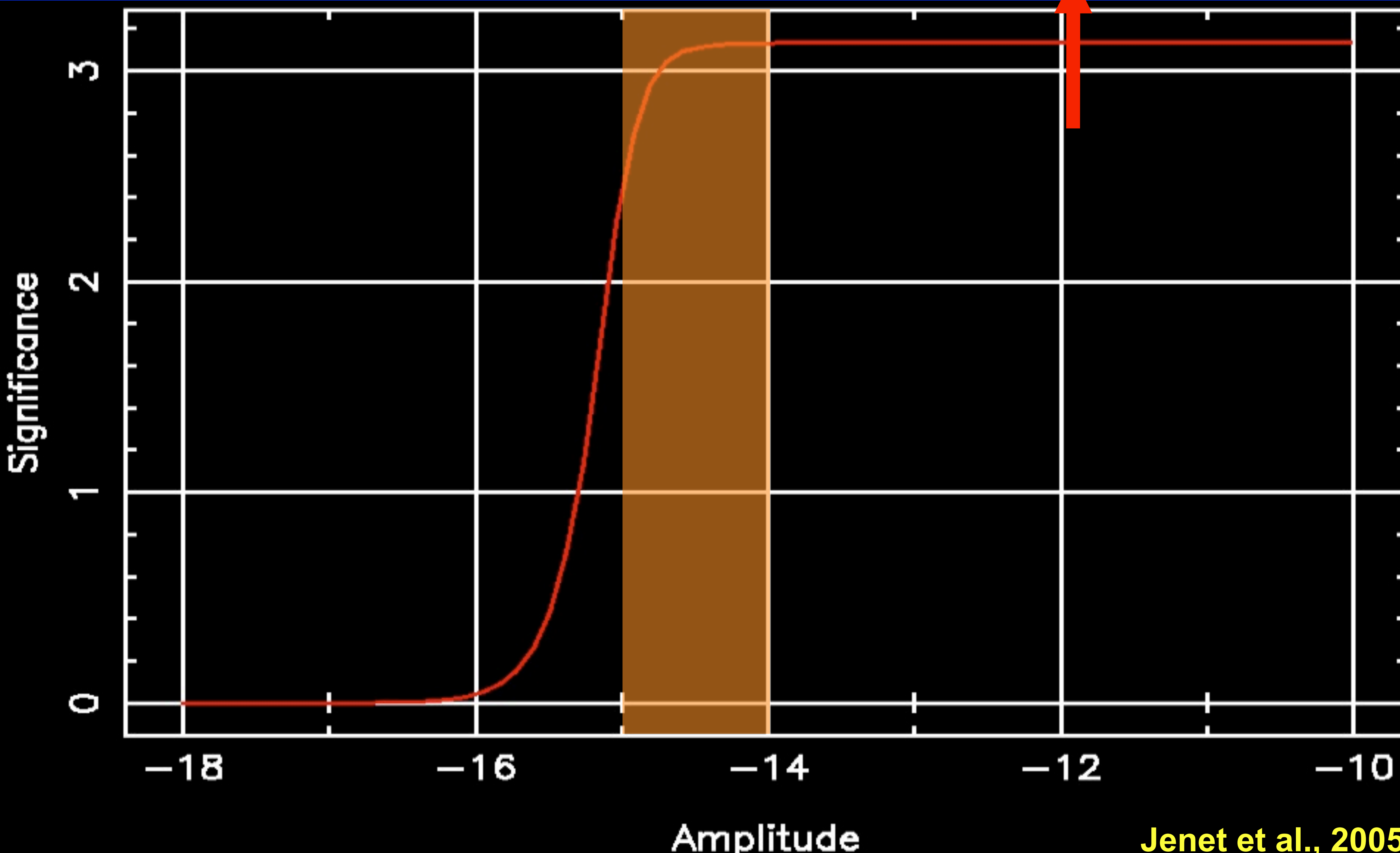
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



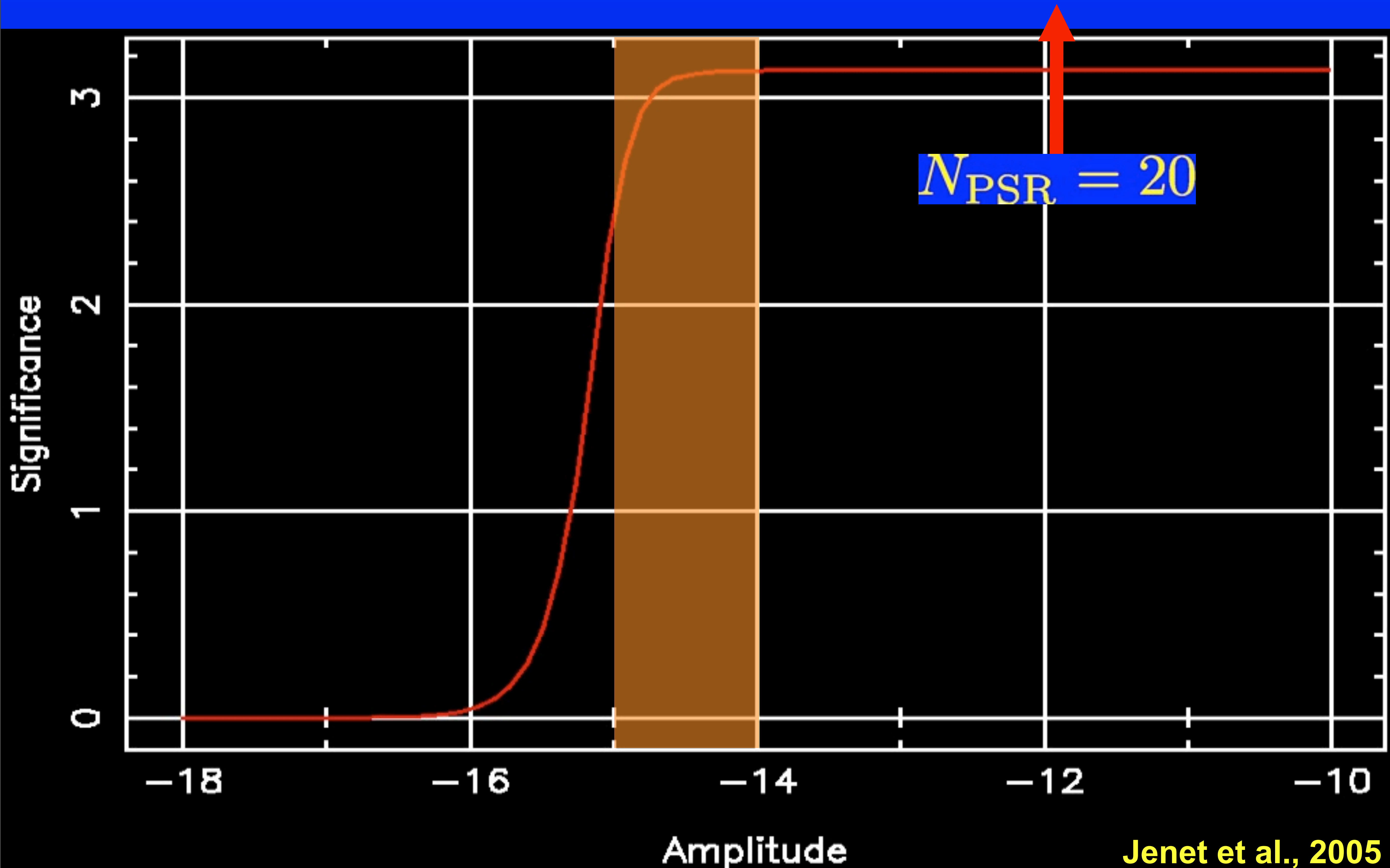
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



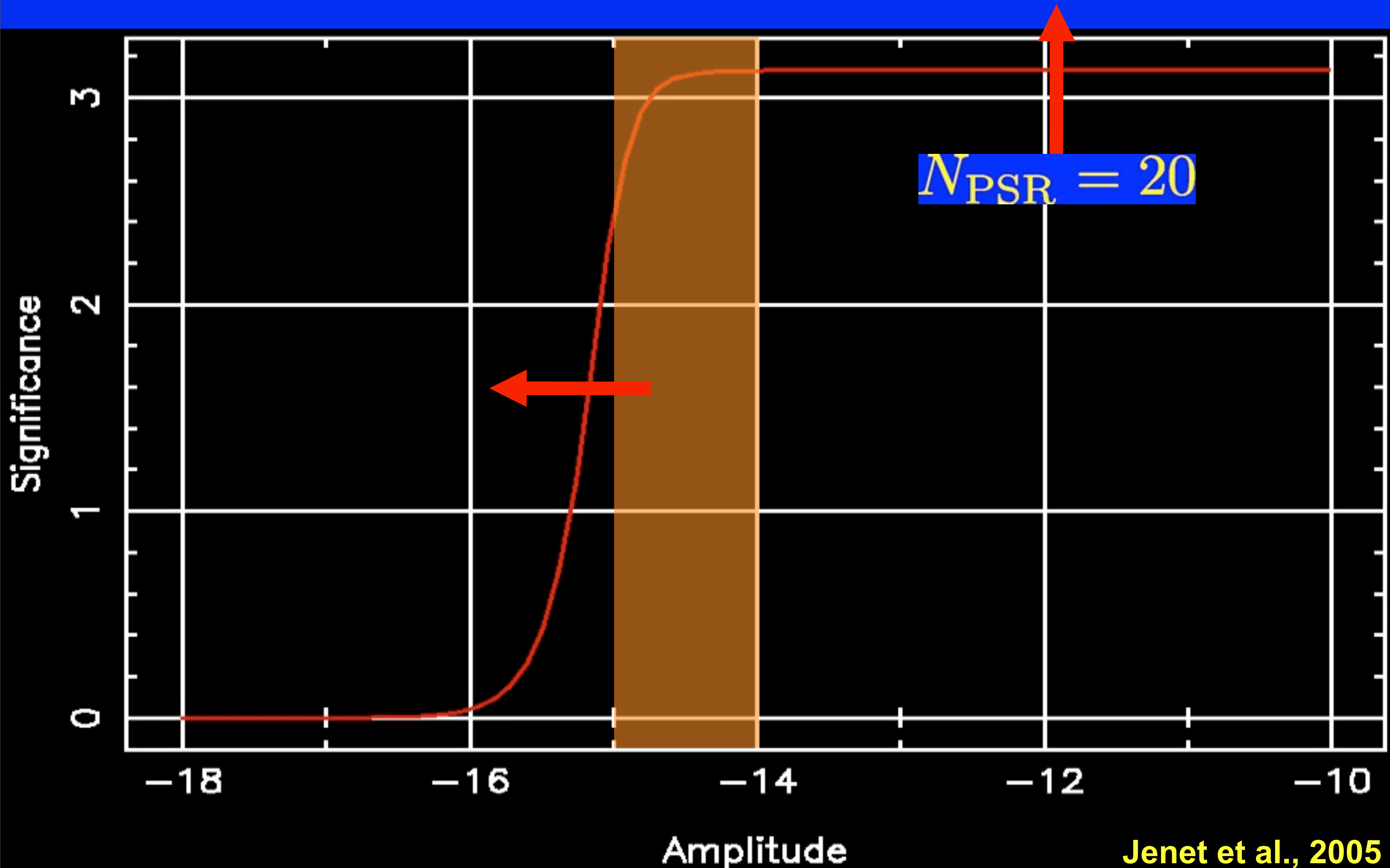
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



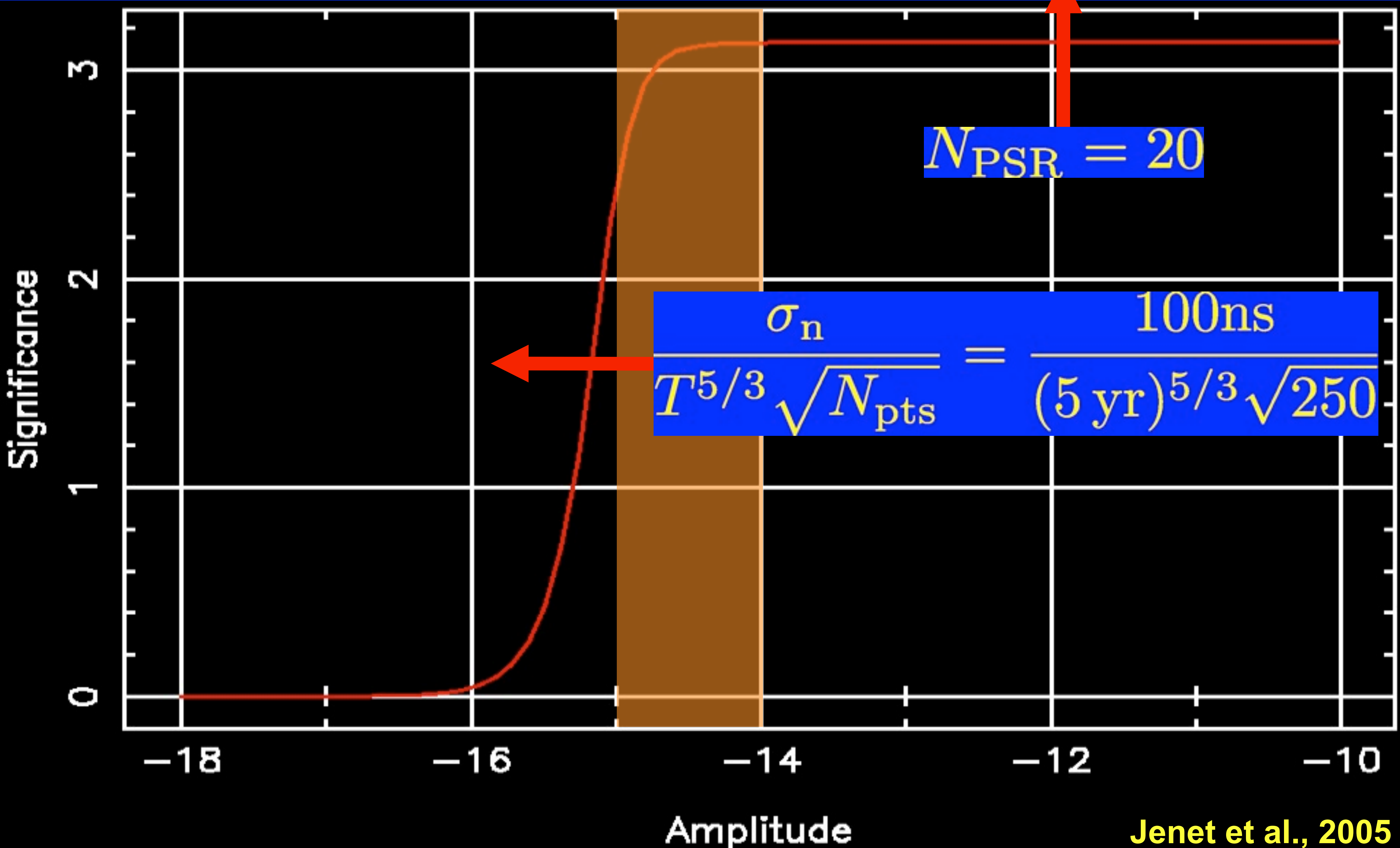
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



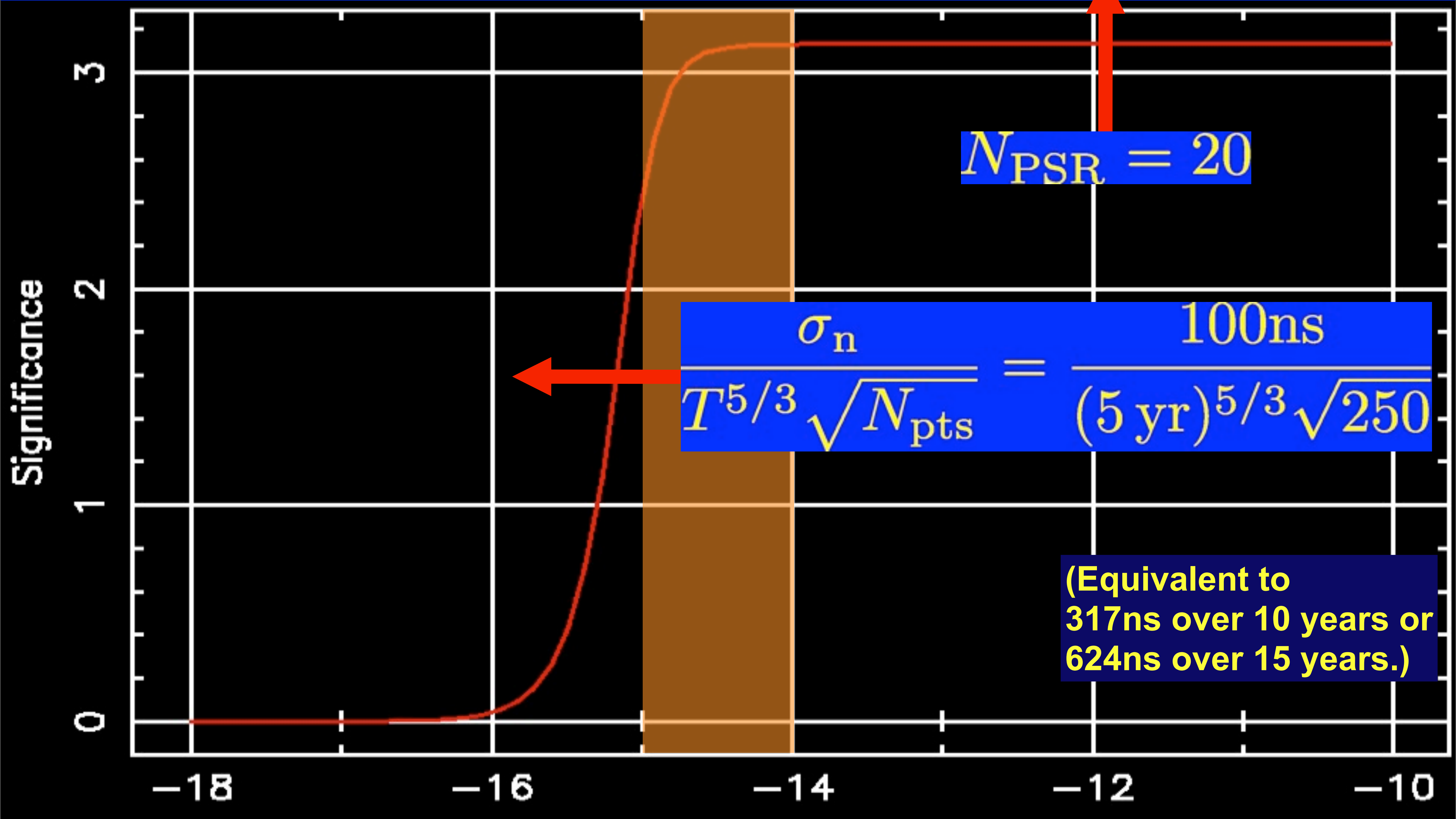
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



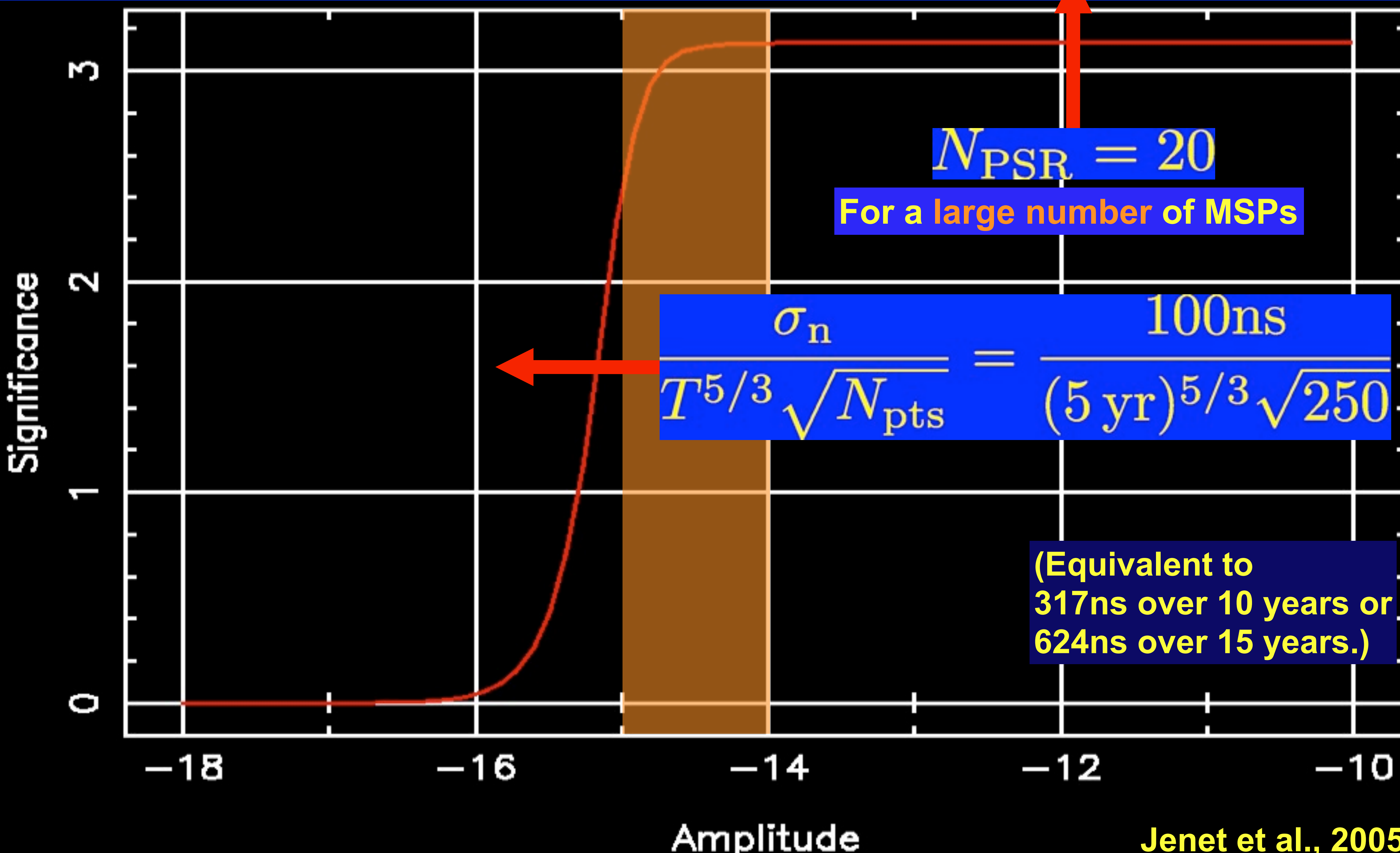
Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



$N_{\rm PSR} = 20$

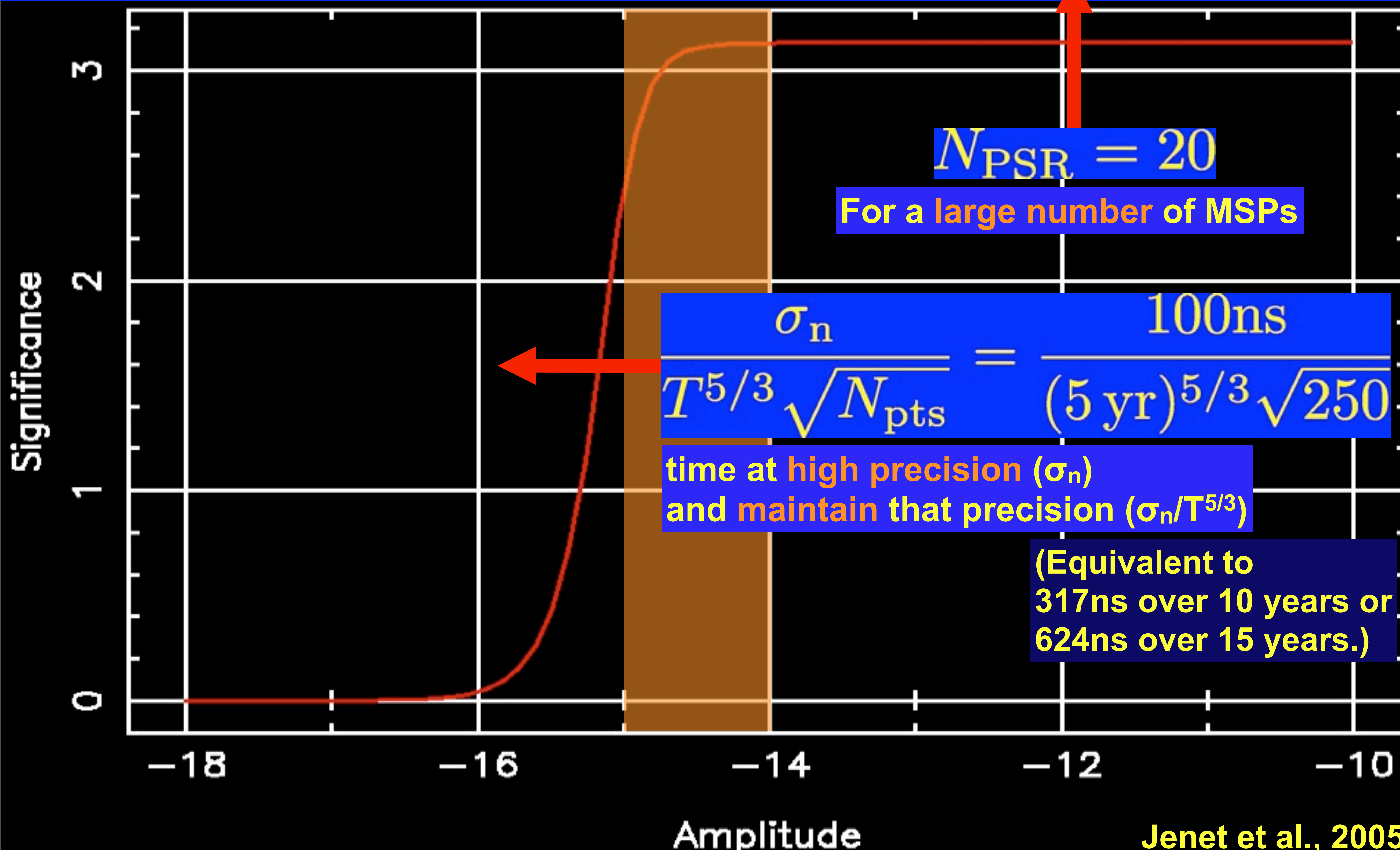
For a large number of MSPs

$$\frac{\sigma_{\rm n}}{T^{5/3}\sqrt{N_{\rm pts}}} = \frac{100{\rm ns}}{(5\,{\rm yr})^{5/3}\sqrt{250}}$$

(Equivalent to 317ns over 10 years or 624ns over 15 years.)

Jenet et al., 2005
Verbiest et al., 2009

Basic PTA Requirements



$N_{\rm PSR} = 20$

For a large number of MSPs

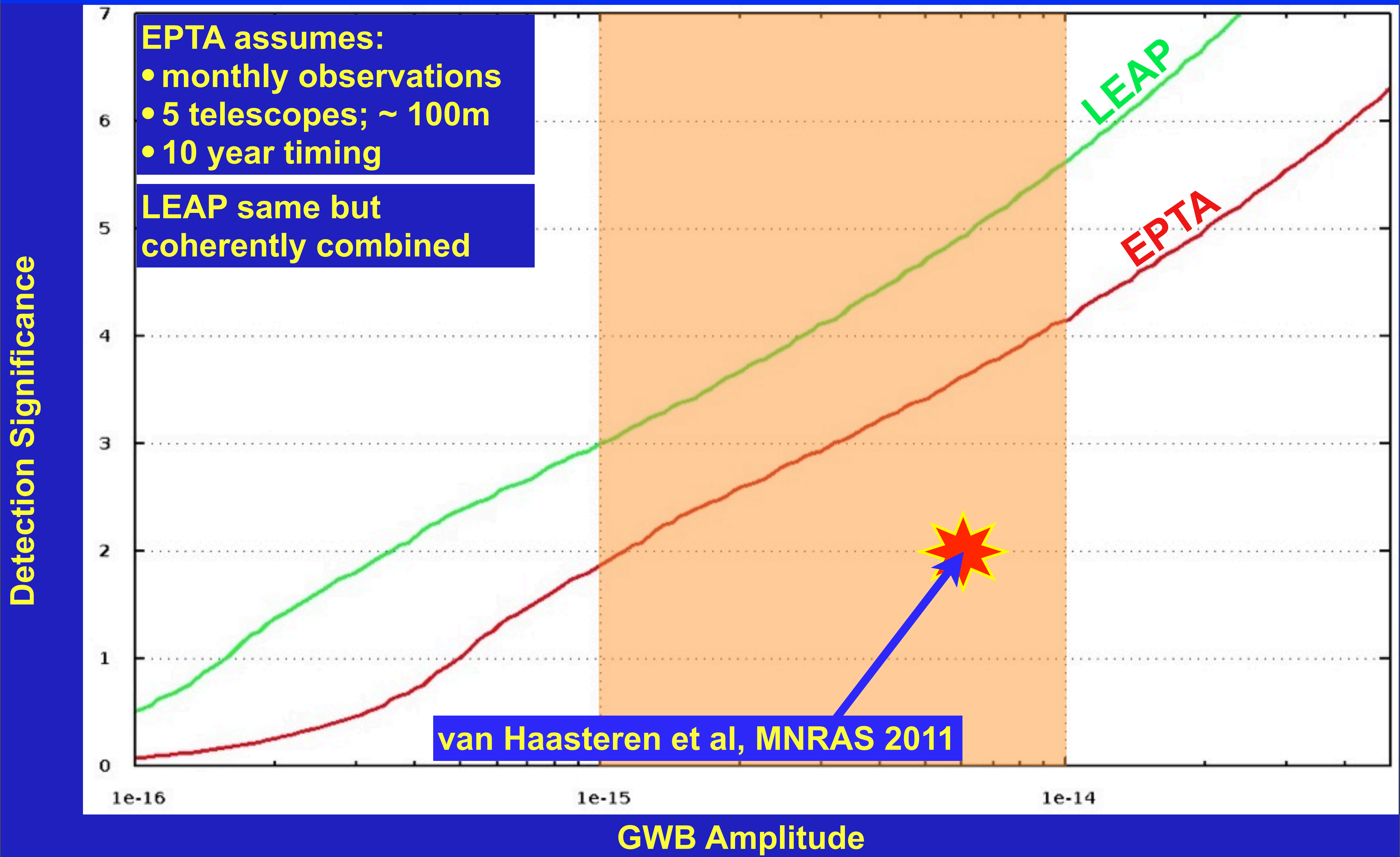
$$\frac{\sigma_{\rm n}}{T^{5/3}\sqrt{N_{\rm pts}}} = \frac{100{\rm ns}}{(5\,{\rm yr})^{5/3}\sqrt{250}}$$

time at high precision (σ_n)
and maintain that precision ($\sigma_n/T^{5/3}$)

(Equivalent to
317ns over 10 years or
624ns over 15 years.)

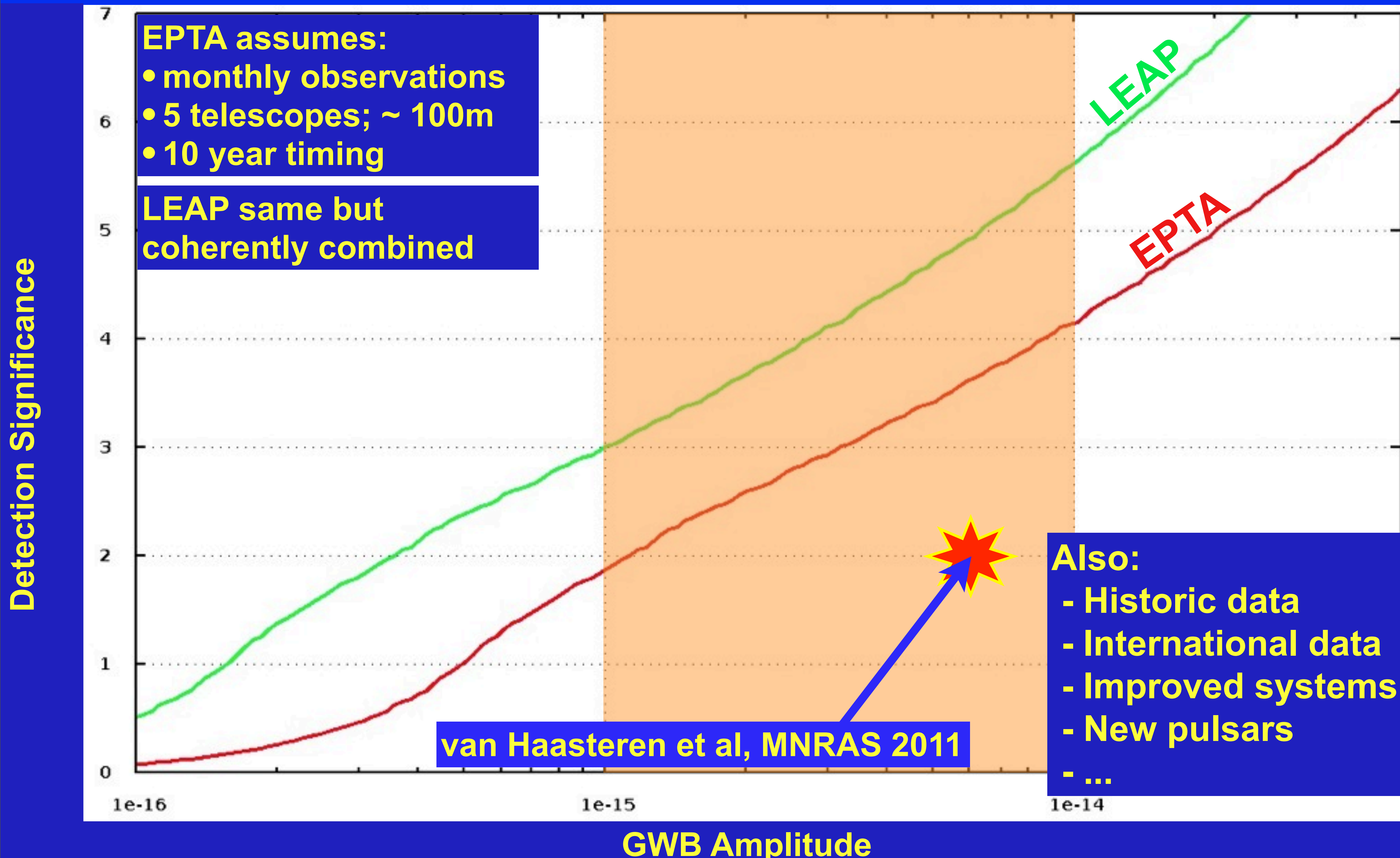
Jenet et al., 2005
Verbiest et al., 2009

Predicted Sensitivity

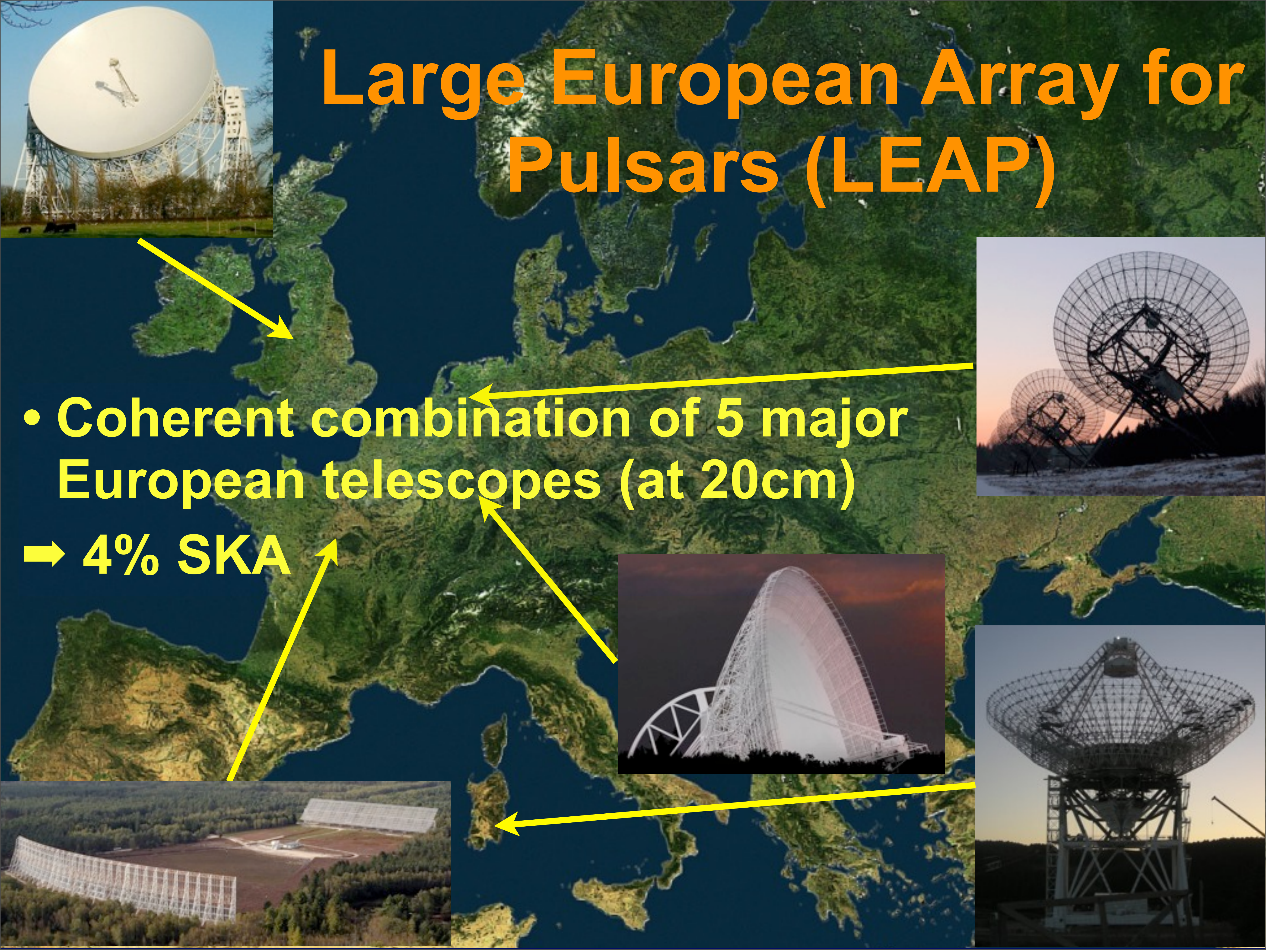


Based on Verbiest et al., 2009

Predicted Sensitivity



Based on Verbiest et al., 2009

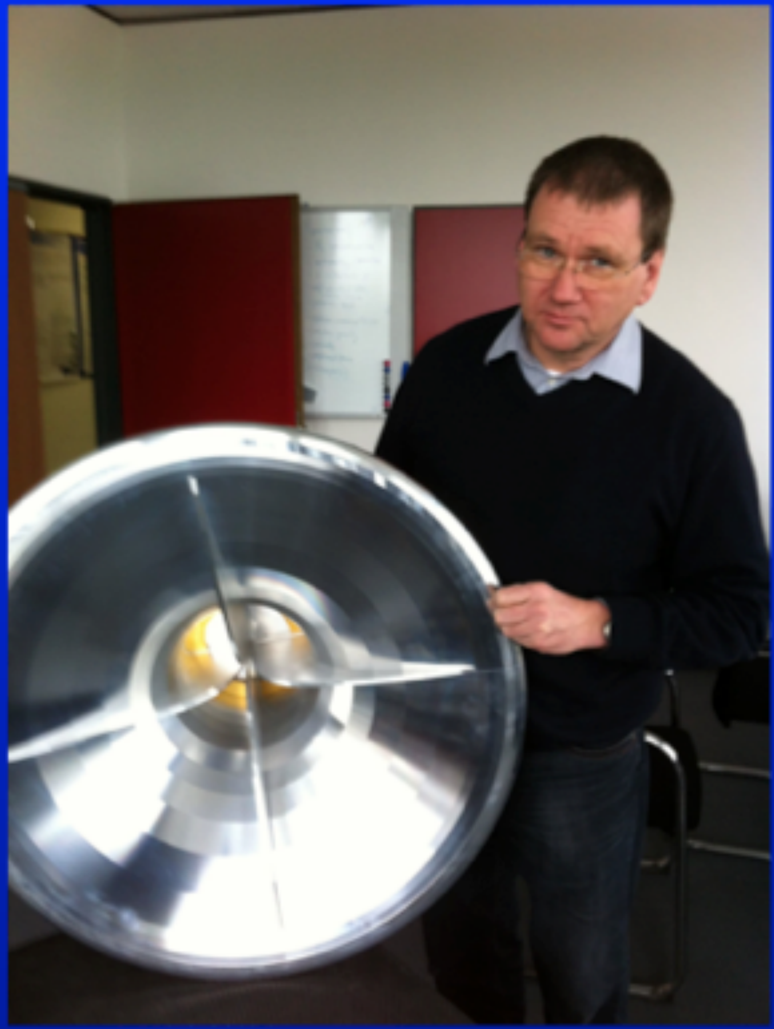

Large European Array for Pulsars (LEAP)
• Coherent combination of 5 major European telescopes (at 20cm)
➡ 4% SKA

Ongoing Development

- IPTA
- LEAP
- Ultra Broad-Band (UBB) Receivers
- LOFAR / LWA / MWA
- Optimal Scheduling
- Cyclic Spectroscopy/
  Scattering Mitigation

Ultra Broad-Band (UBB) Receiver

- Instantaneous 600-3000 MHz bandwidth
- 70% useable bandwidth (RFI blocks rest)
- Built for high-precision pulsar timing



Courtesy Michael Kramer (MPIfR)

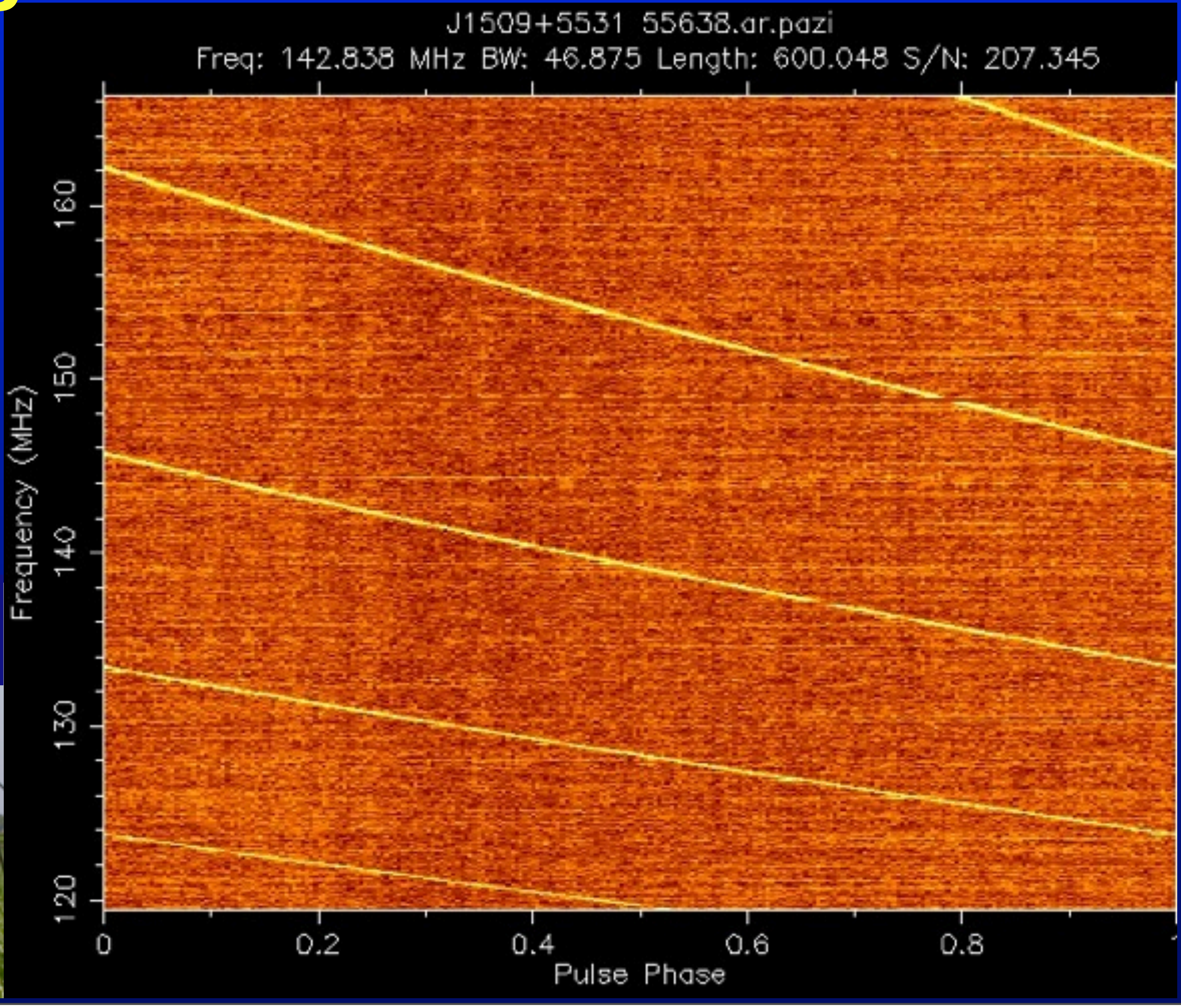
- On Effelsberg 100-m by July 2012 (PKS, GBT)
- T_{sys} < 49 K (Most sensitive receiver ever)
- Modified Lindgren feed (Sandy Weinreb, JPL)

LOFAR & ISM Effects

$D \frac{\int_0^d n_e dl}{f^2}$

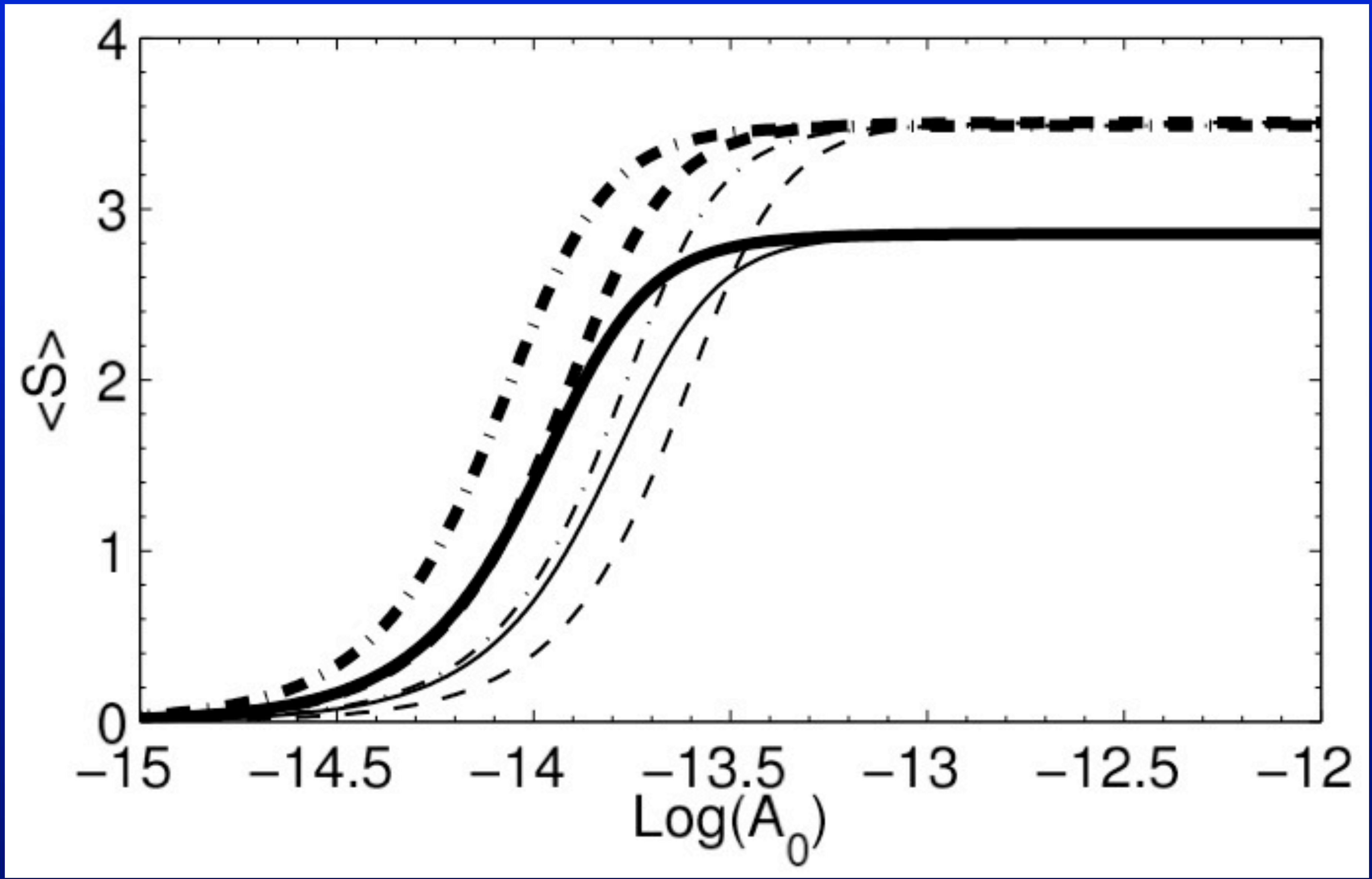
- **Interstellar Dispersion delays the pulse**
- **These delays *change* due to motion and turbulence**
- **Low-f observations can measure these changes precisely**

Stay Tuned...



Optimal Scheduling

See K.J. Lee et al., MNRAS 2012 (arXiv:1204.4321)



Lee, Bassa et al., MNRAS 2012

Cyclic Spectroscopy

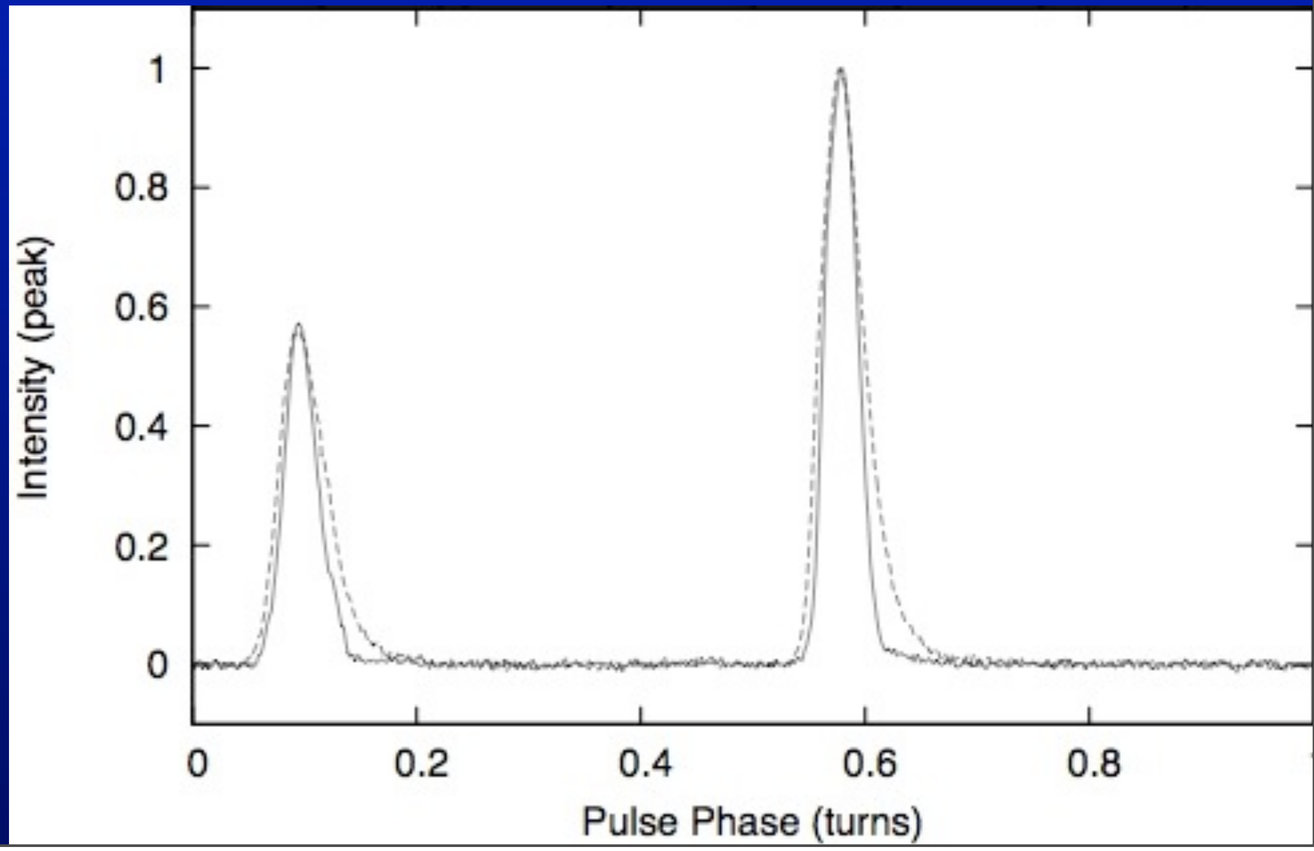
- See Demorest, MNRAS 2011 (arXiv:1106.3345)

- New method to de-scatter pulses

- Corrects for variations in scattering

- Sharpens pulses!

Demorest, MNRAS 2011

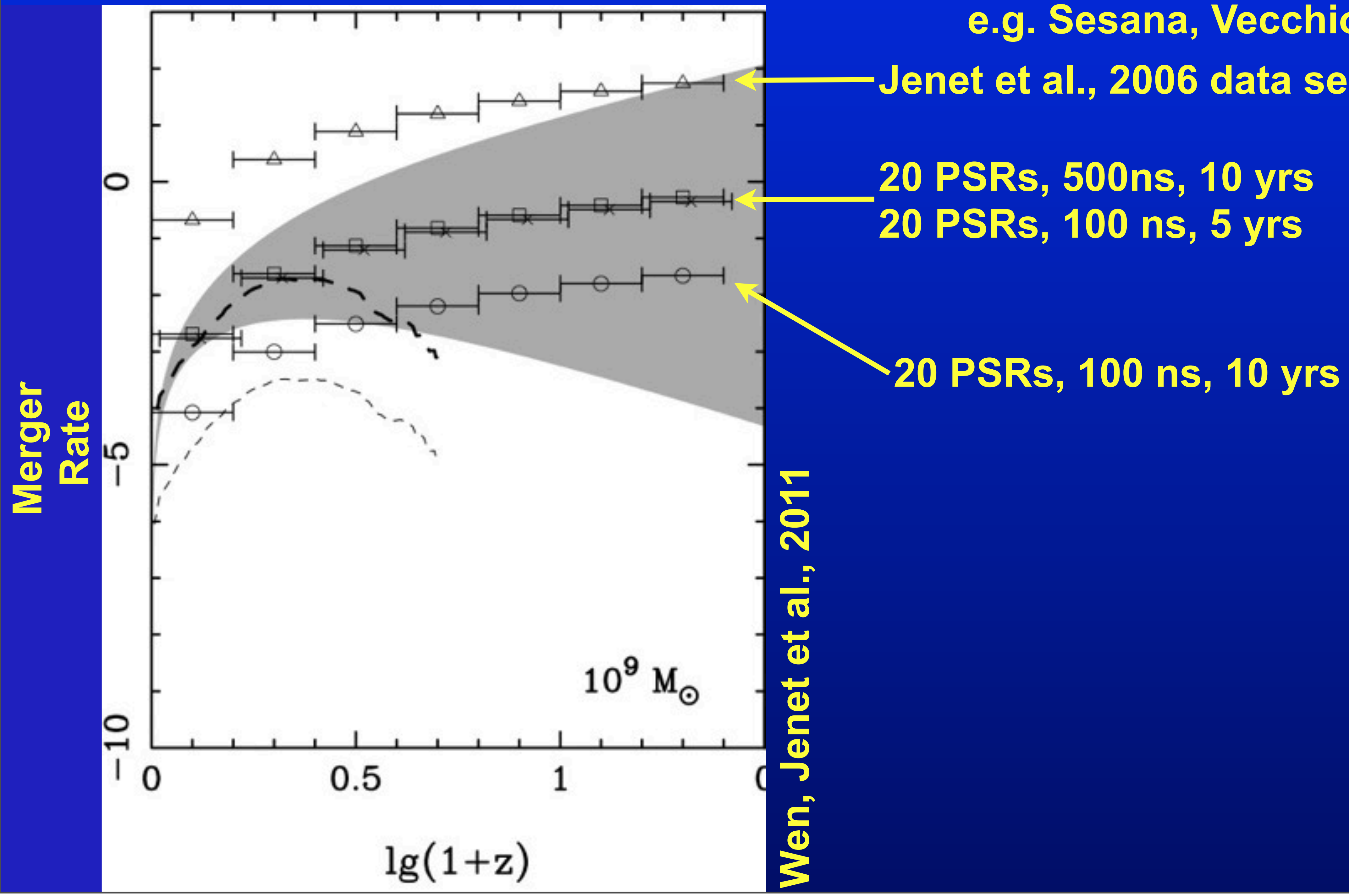


GW Science

GW Science

- **Amplitude & Spectrum**
  - SMBHB population & Galaxy evolution

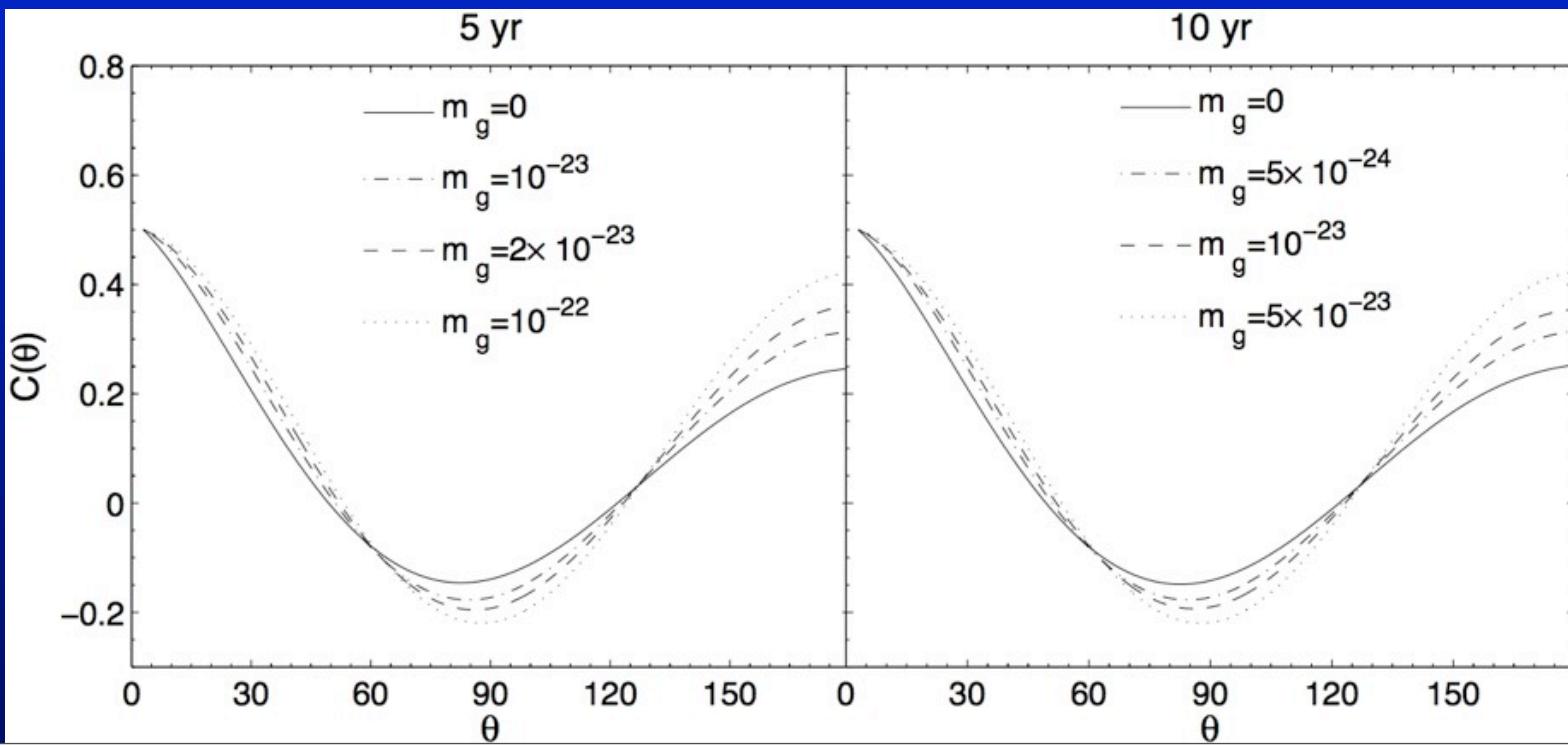
e.g. Sesana, Vecchio & Colacino, 2008



Wen, Jenet et al., 2011

GW Science

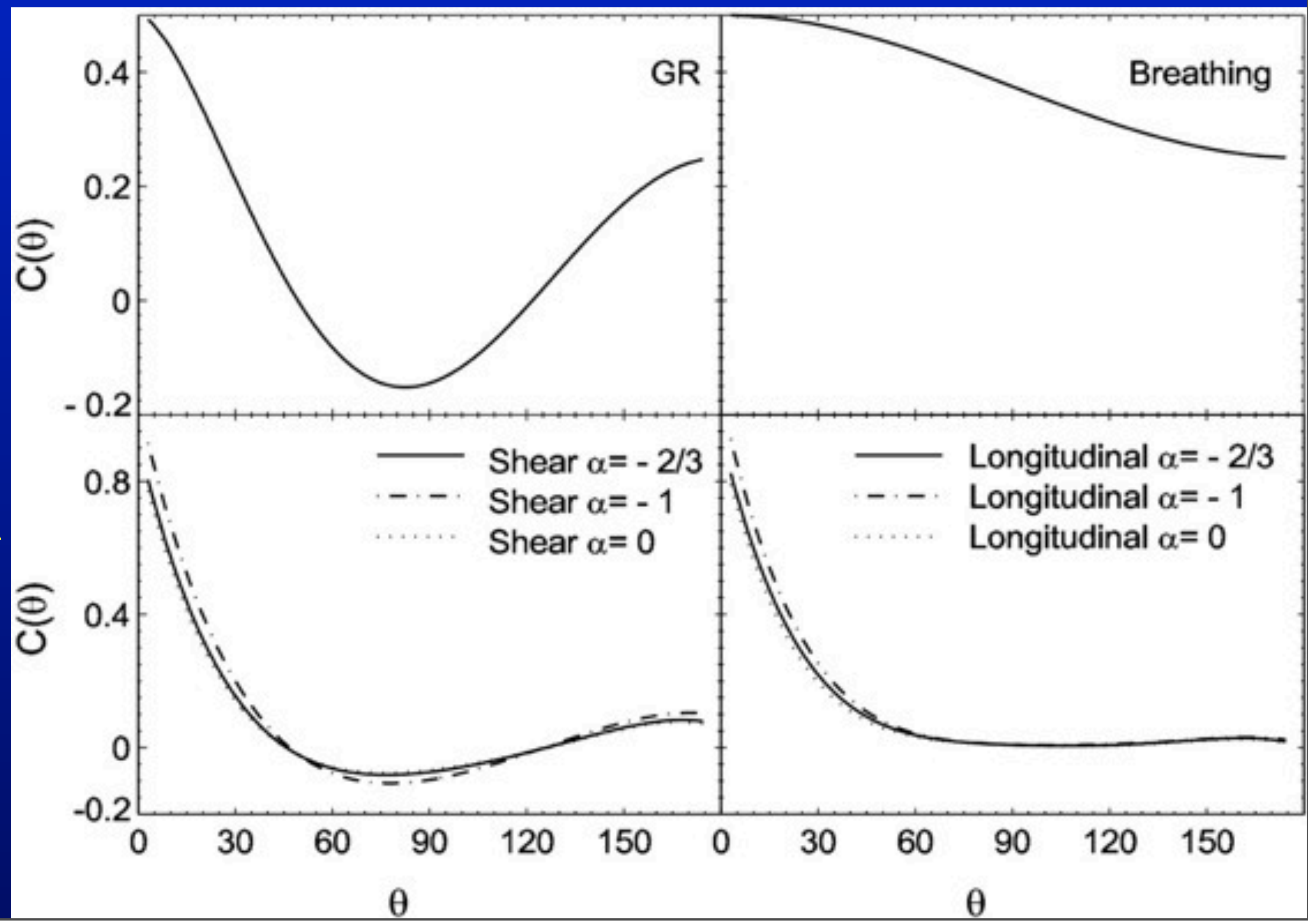
- **Amplitude & Spectrum**
  - SMBHB population & Galaxy evolution
- **Shape of correlation**
  - Graviton mass



Kejia Lee et al., 2010

GW Science

- Amplitude & Spectrum
  - SMBHB population & Galaxy evolution
- Shape of correlation
  - Graviton mass
  - Polarisation of GW

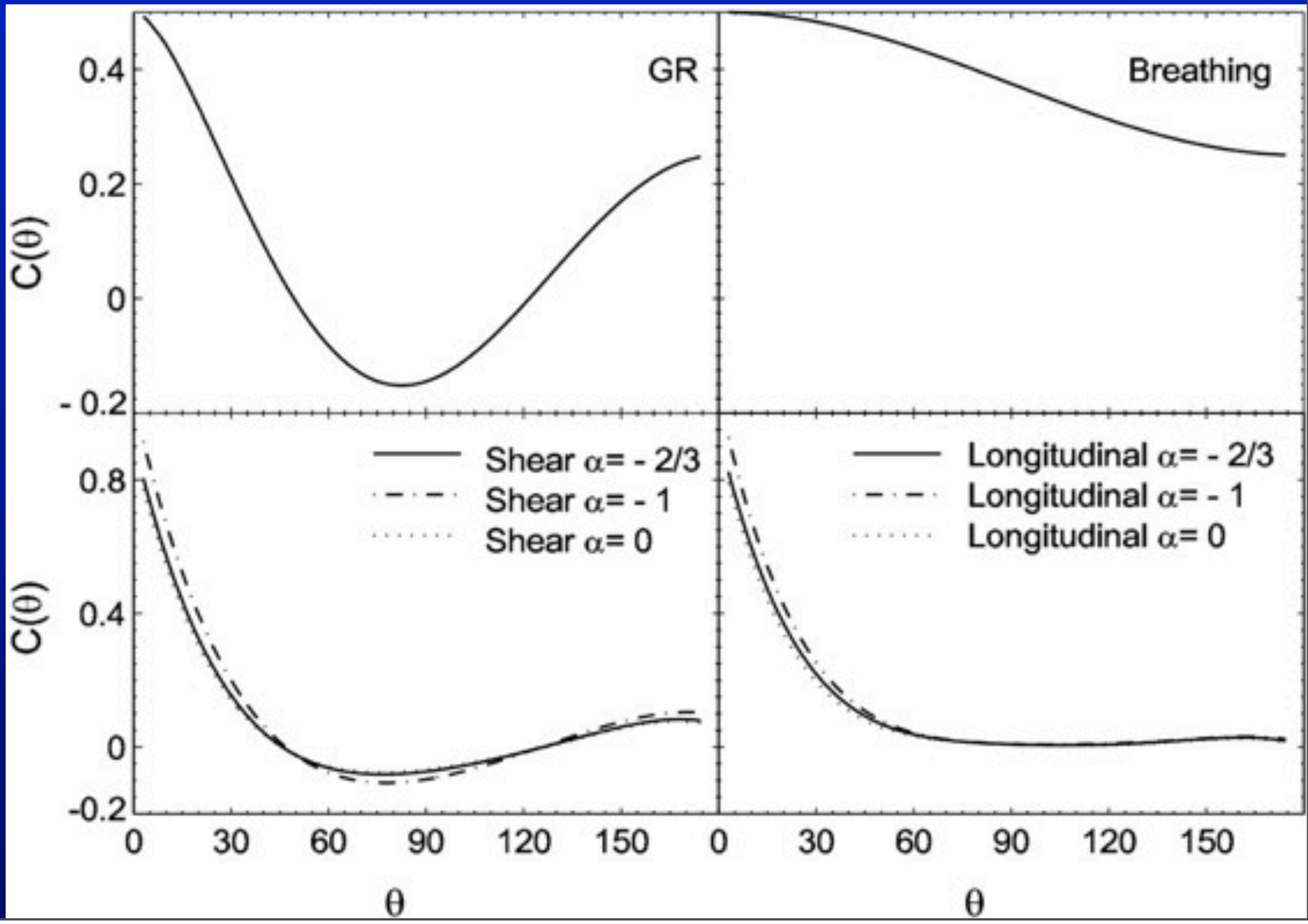


K. J. Lee et al., 2008

GW Science

- **Amplitude & Spectrum**
  - SMBHB population & Galaxy evolution
- **Shape of correlation**
  - Graviton mass
  - Polarisation of GW
- **Single source detections... (see next talk by Sesana)**

K. J. Lee et al., 2008



Summary

- PTAs are sensitive to a GWB of SMBHBs.
- Already probing the expected range halfway
- Many technical and algorithmic developments ongoing
- Should probe entire range (detection?!) by the end of the decade