Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Detecting SMBH binaries with Pulsar Timing Arrays

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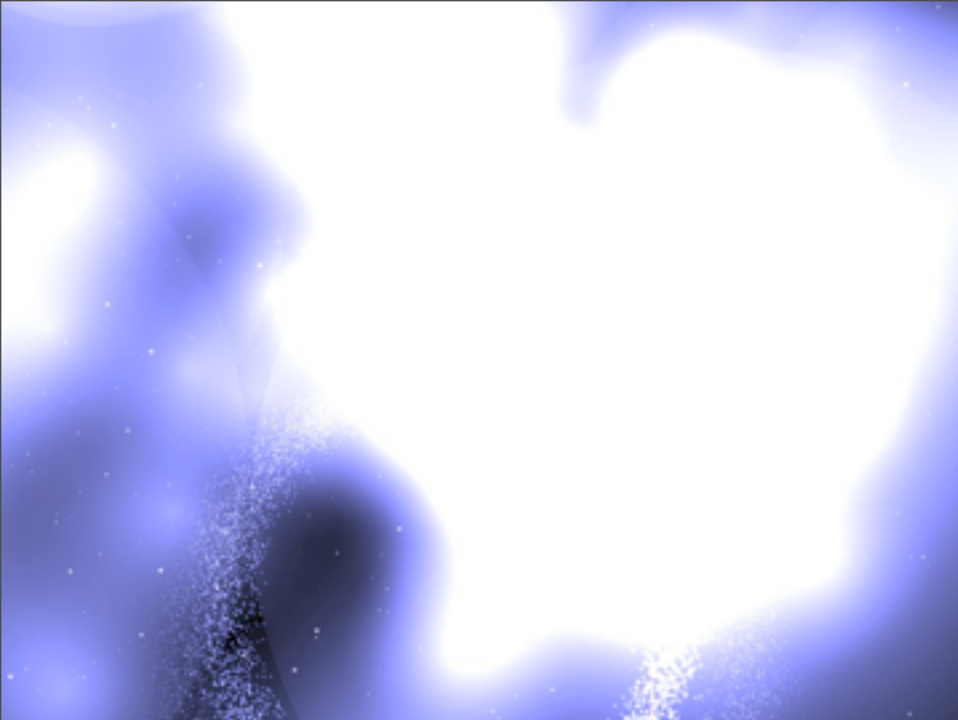
COST Meeting, Monday 15 Nov 2010

Outline

- Introduction:
  - Pulsar Timing (Arrays)
  - Gravitational Wave Detection
- Gravitational Wave sources
  - Individual SMBHB systems
    - Mass, Distance, counterparts.
    - Current sensitivity
  - Stochastic Background of MBHBs
- Conclusions

Introduction: Pulsar Timing

Courtesy Andrew Jameson (Swinburne)



Courtesy Andrew Jameson (Swinburne)

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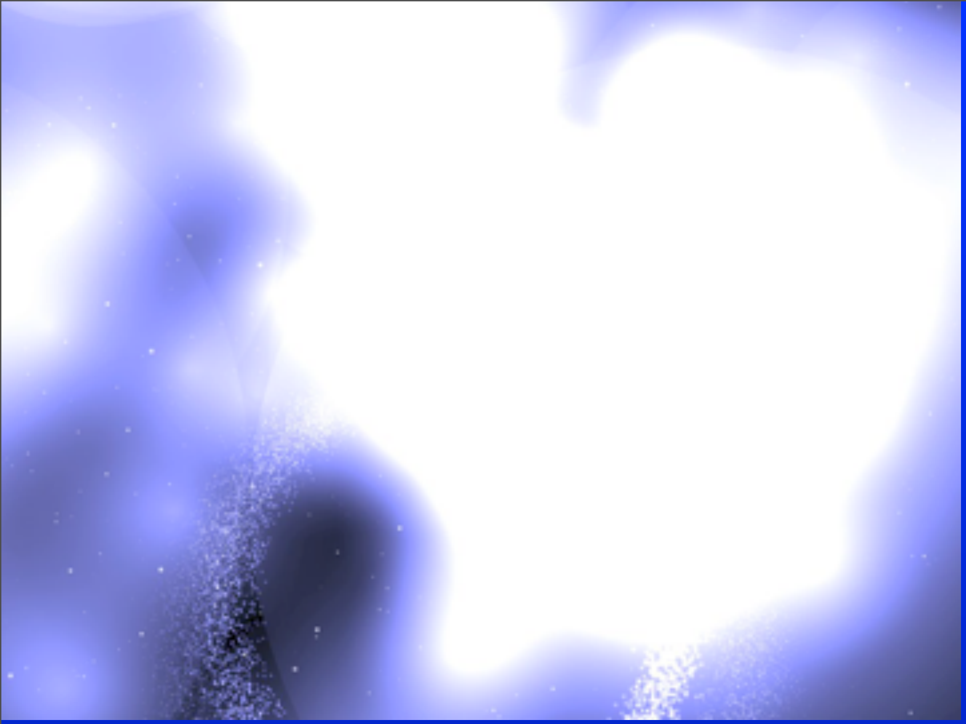
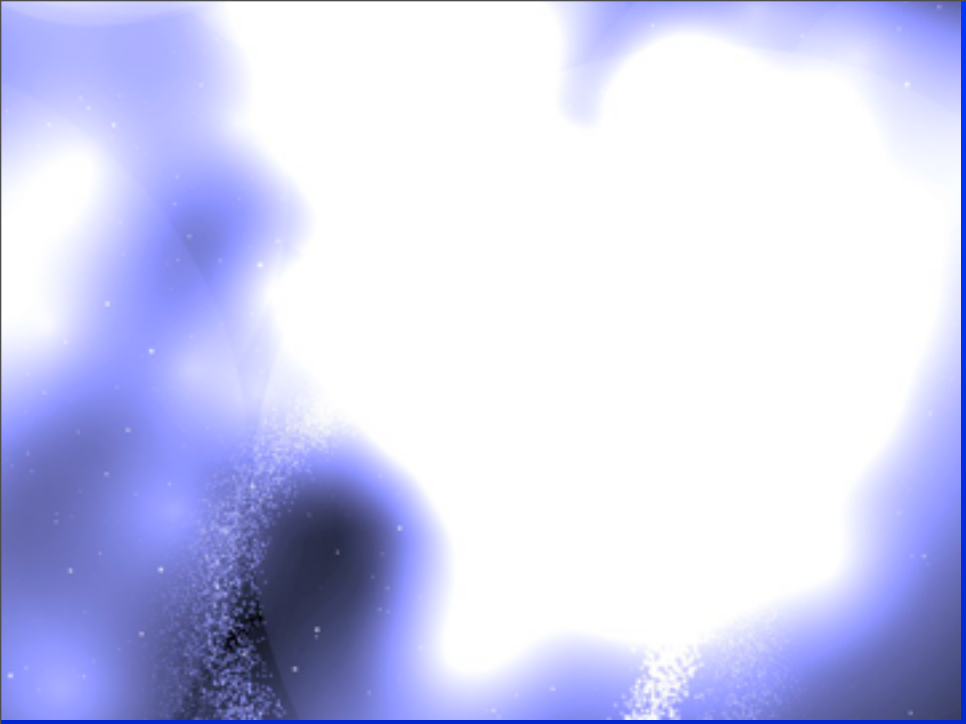

Courtesy Andrew Jameson (Swinburne)

Introduction: Pulsar Timing

$$T_{\rm th} = \nu t + \frac{1}{2}\dot{\nu}t^2 + D\frac{\int_0^d n_e dl}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\rm T}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$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Introduction: Pulsar Timing

Basic Method:

Actual Pulse Arrival Time

— Theoretical Model

= Timing Residual

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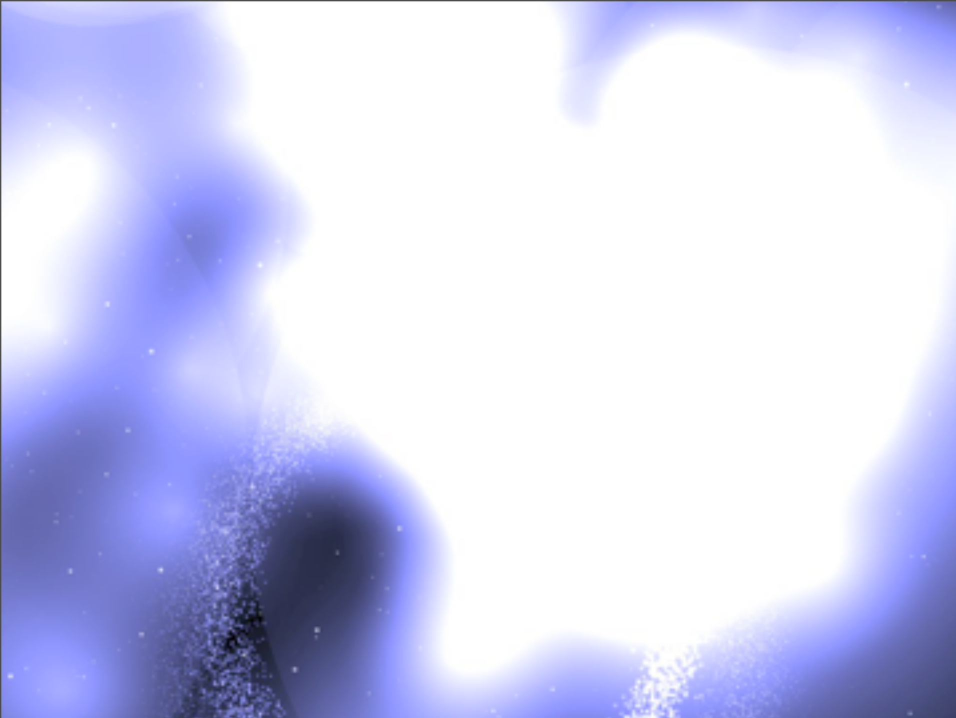

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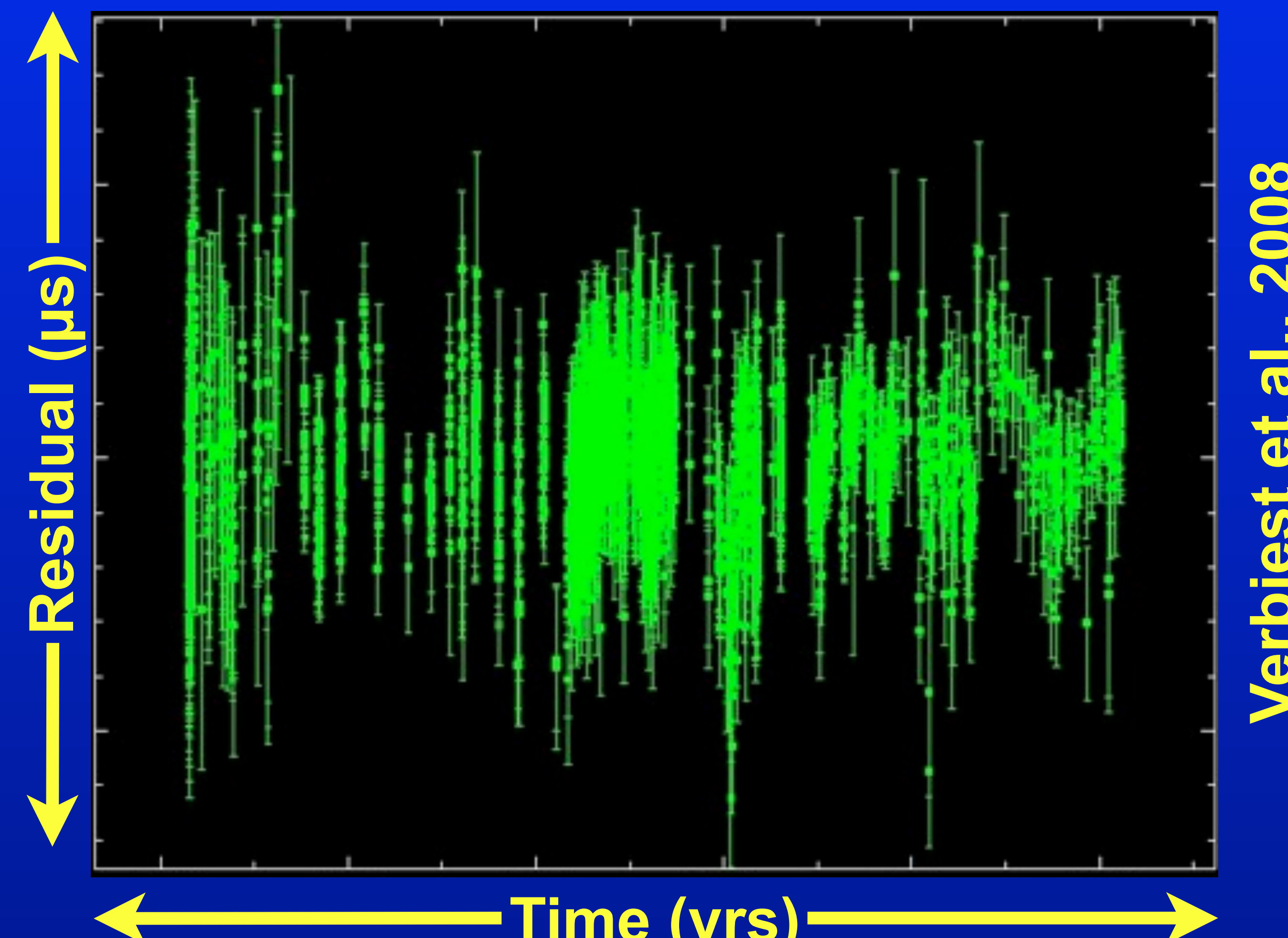

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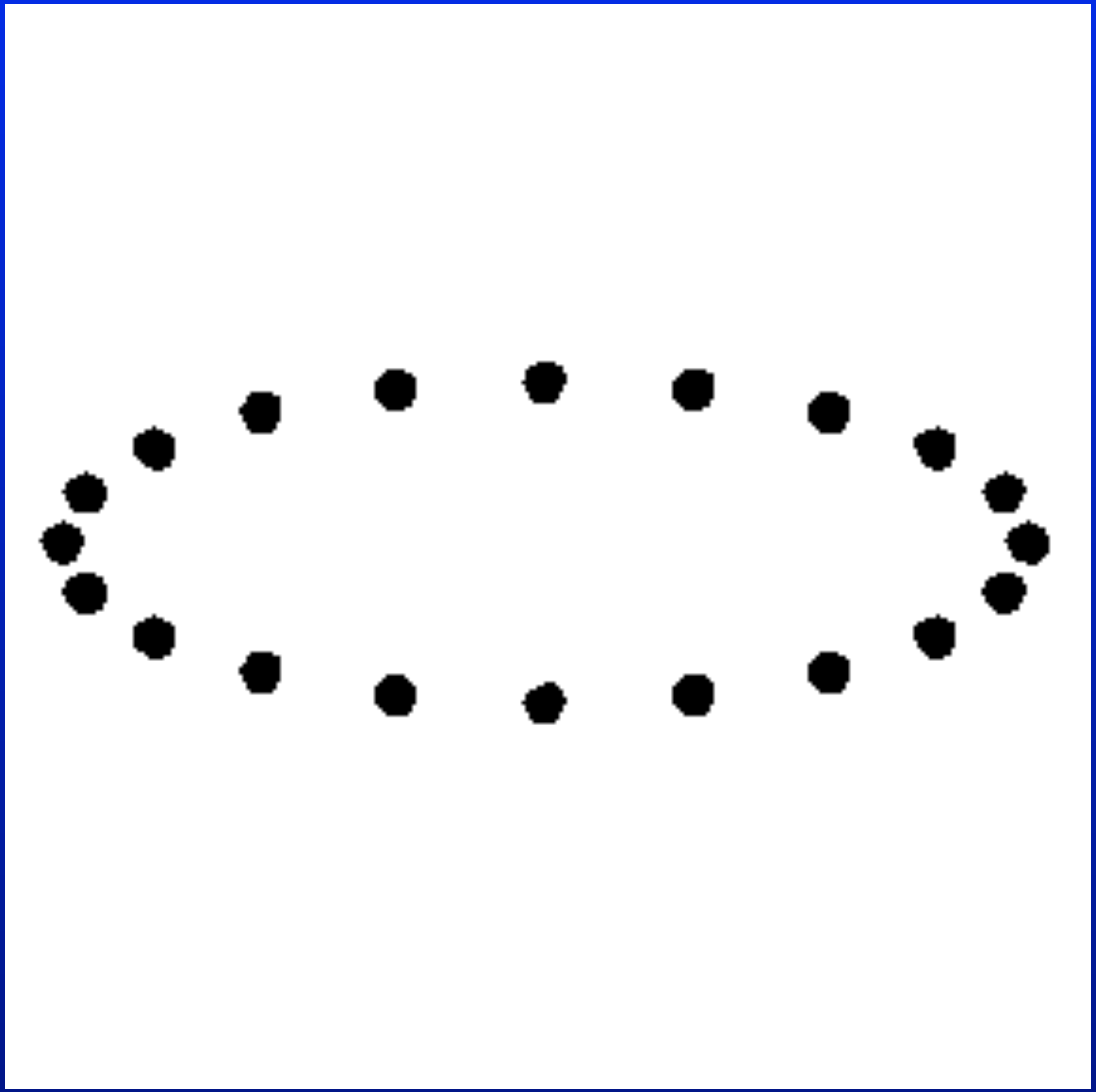
Pulsar Timing Array Concept

Source: Wikipedia

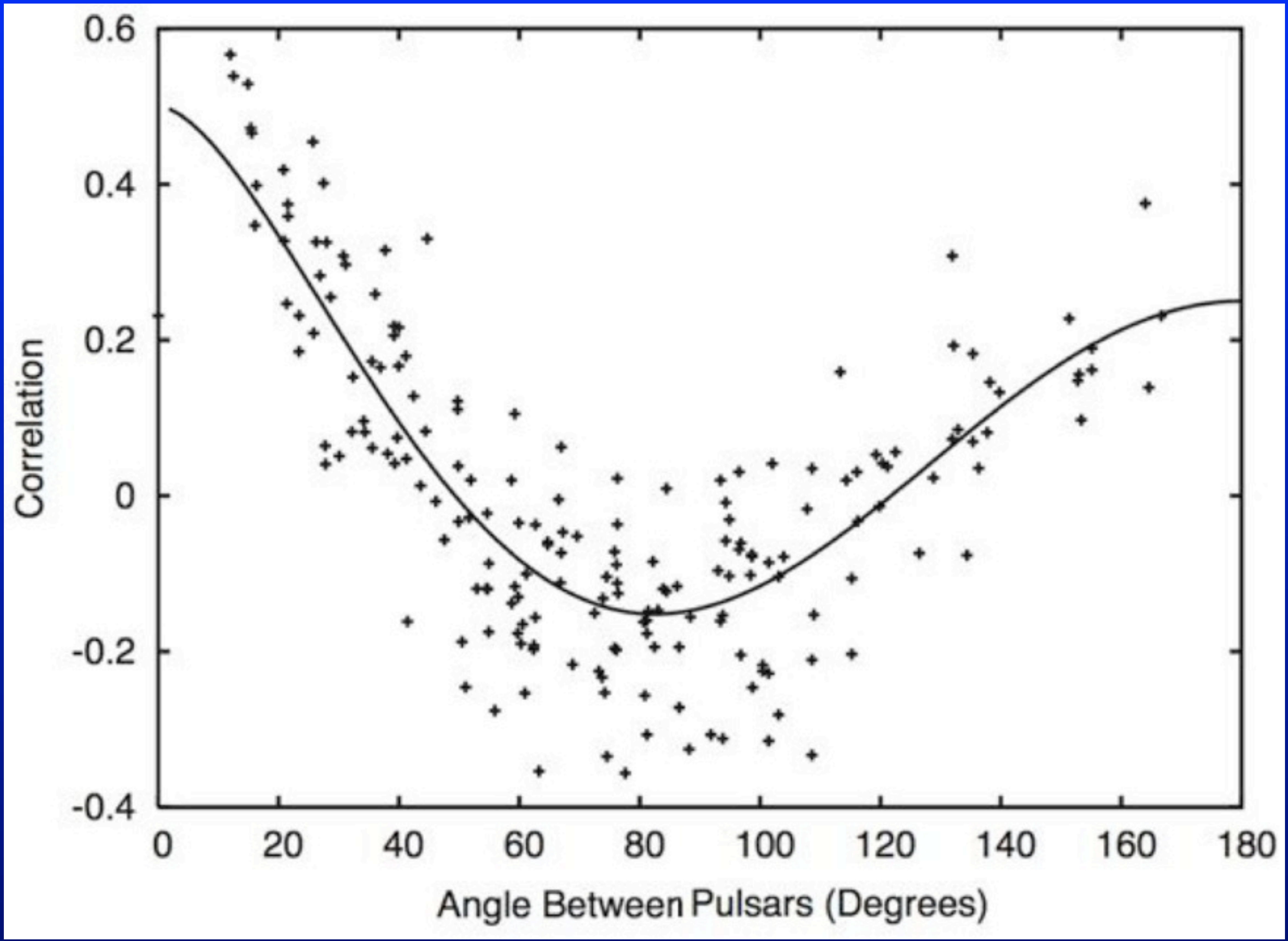
Pulsar Timing Array Concept



Source: Wikipedia

Pulsar Timing Array Concept

Hellings & Downs, 1983



Graph courtesy of Daniel Yardley (USyd)

The GW Spectrum

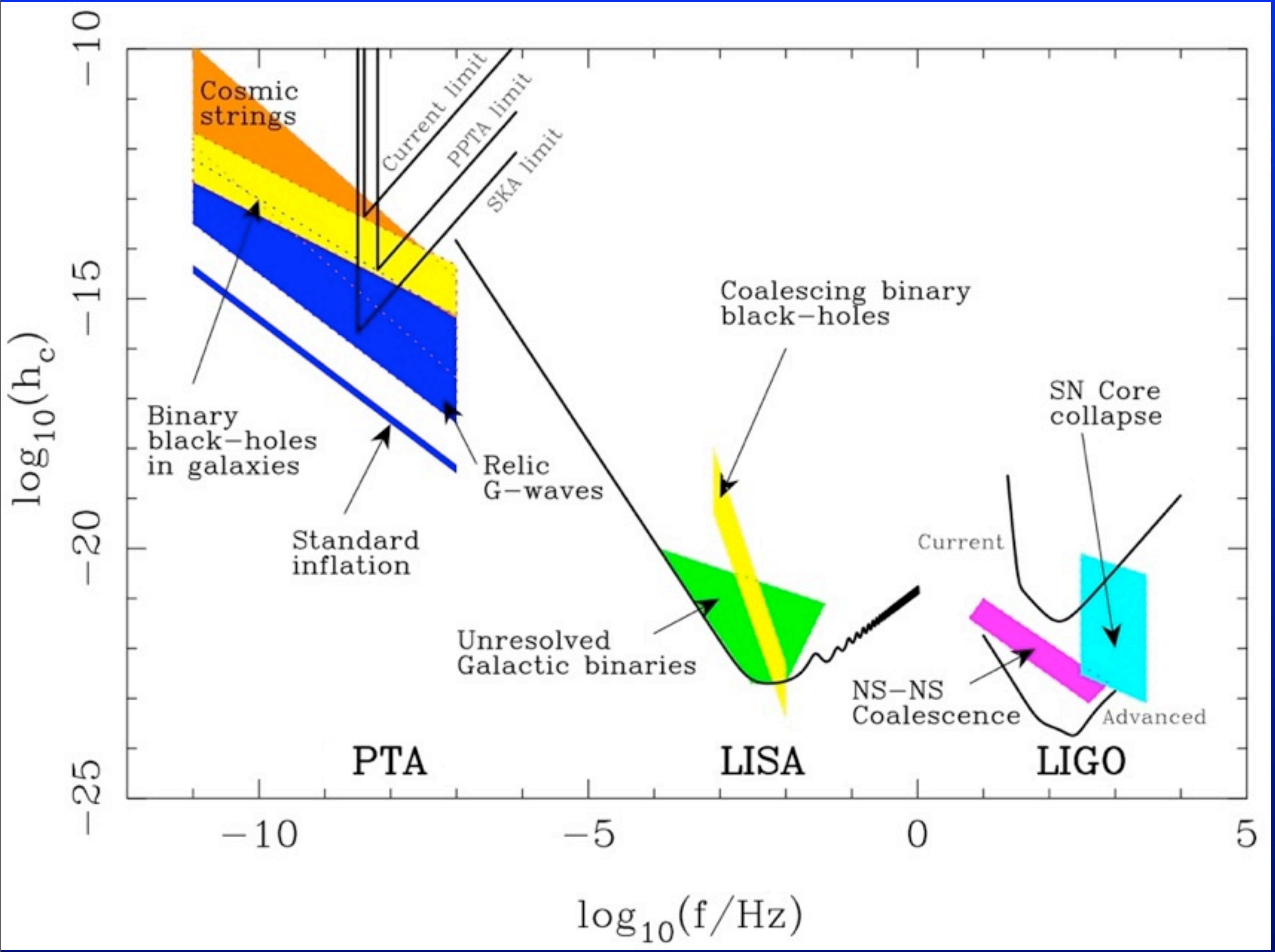


Figure courtesy George Hobbs (ATNF)

The GW Spectrum

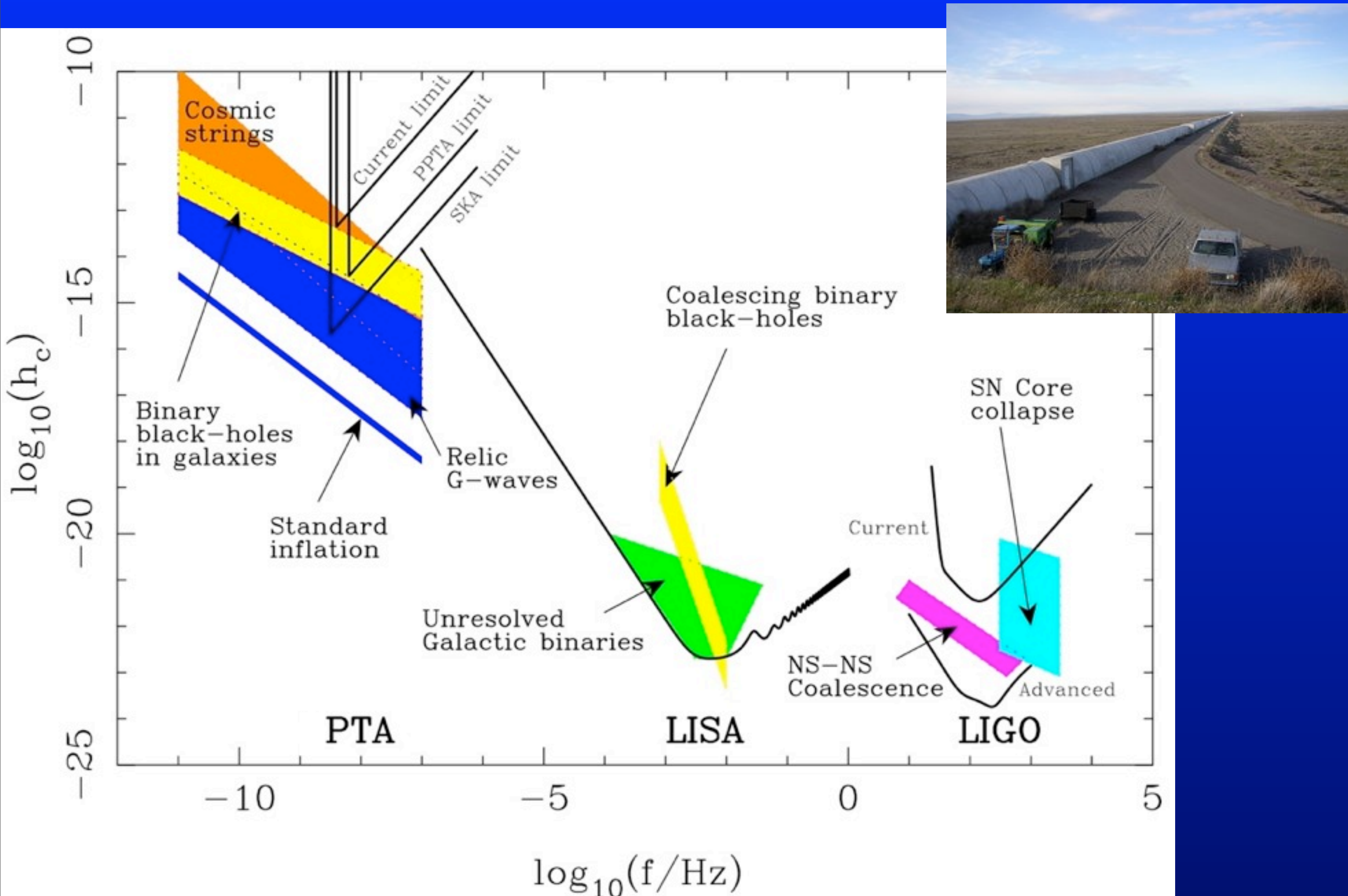


Figure courtesy George Hobbs (ATNF)

The GW Spectrum

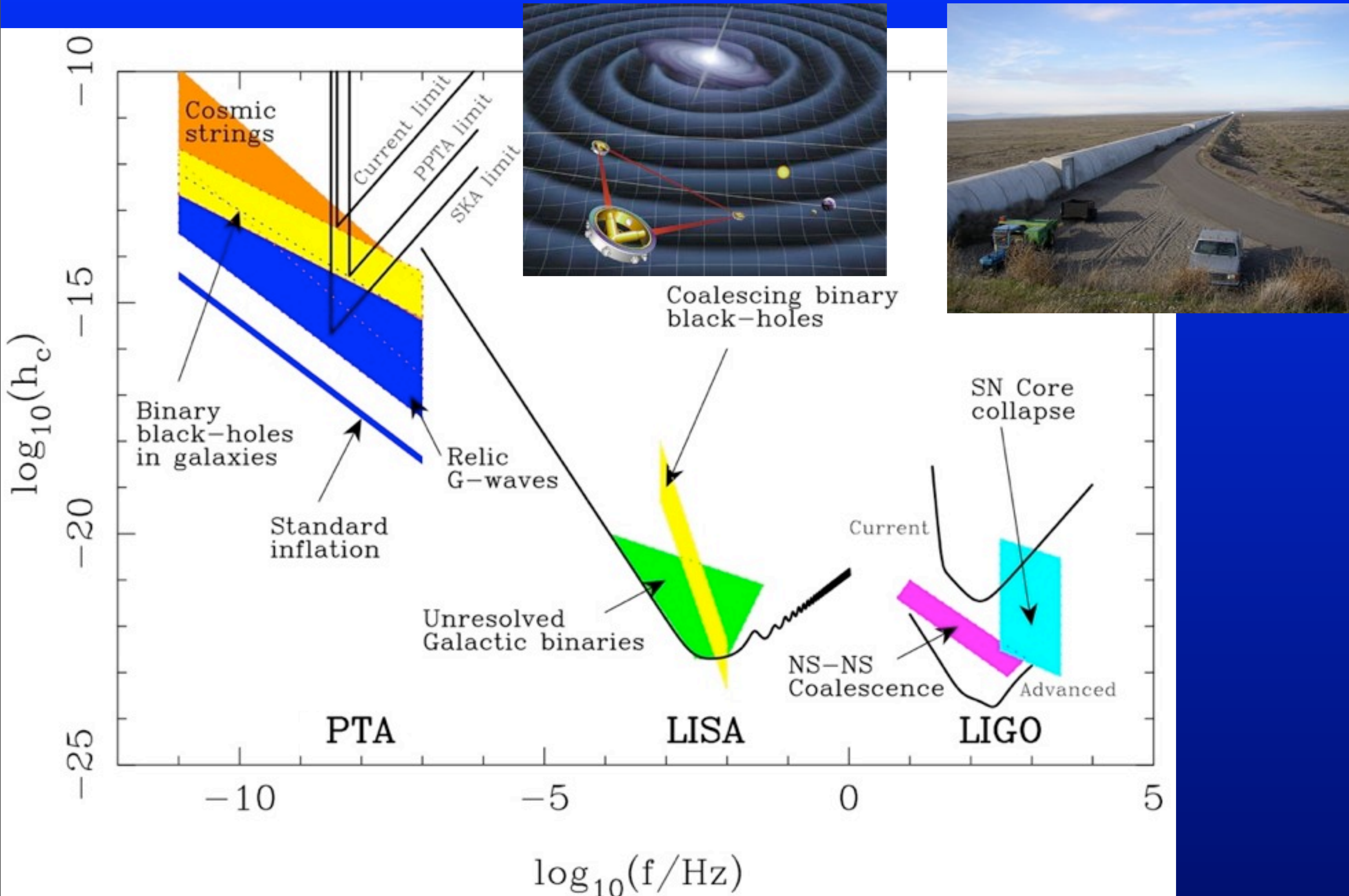
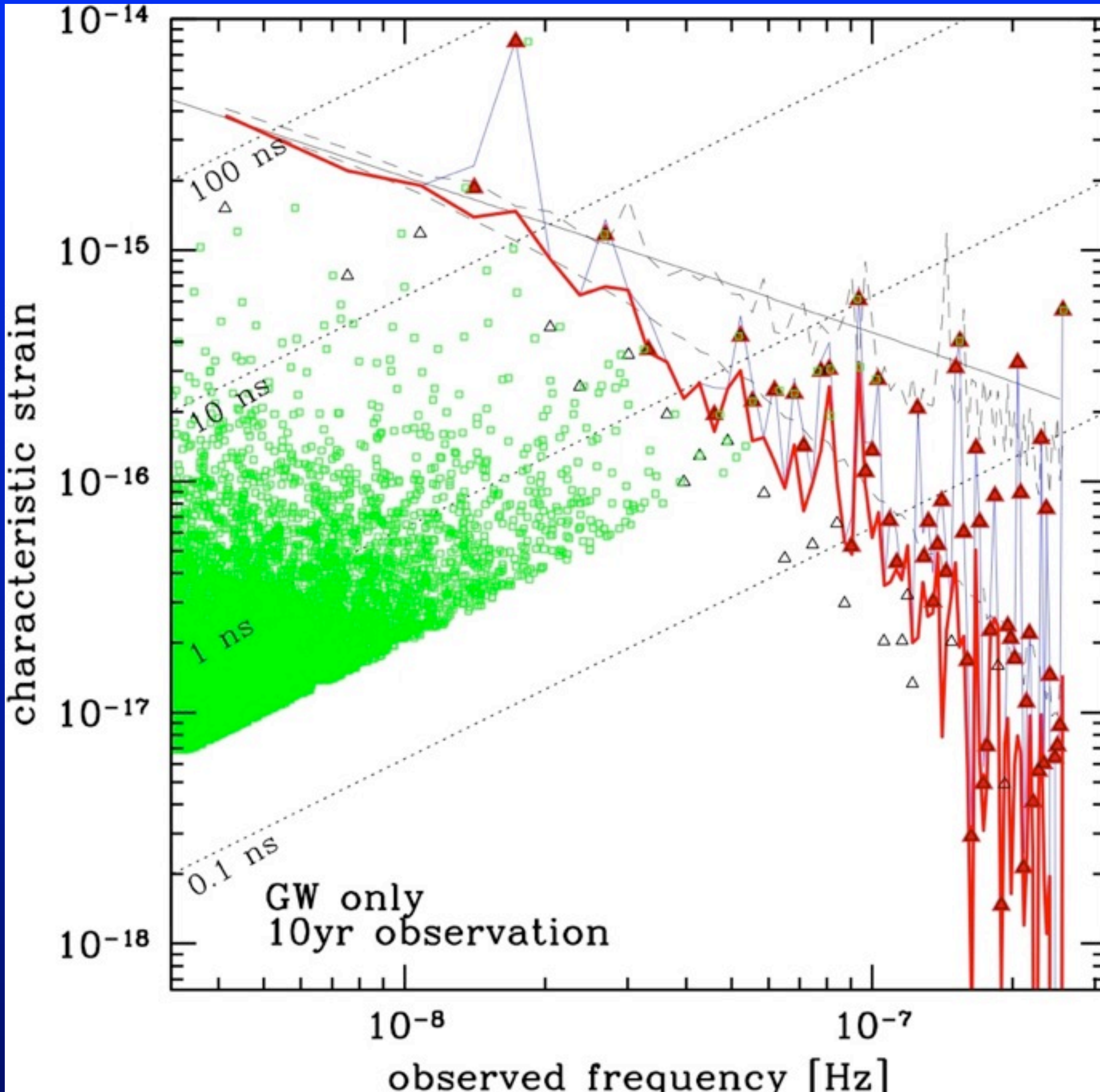


Figure courtesy George Hobbs (ATNF)

GW sources for PTAs



Kocsis & Sesana, MNRAS, 2010

Single SMBHBs

Expected timing residuals (Jenet et al., ApJ, 2004):

PSR — GW source angle (as seen from Earth)

$$\mathbf{R(t)} = \frac{1}{2}\left(1 + \cos\mu\right)\left[\mathbf{r}_{+}(\mathbf{t})\cos\left(2\psi\right) + \mathbf{r}_{\times}(\mathbf{t})\sin\left(2\psi\right)\right]$$

GW polarisation angle

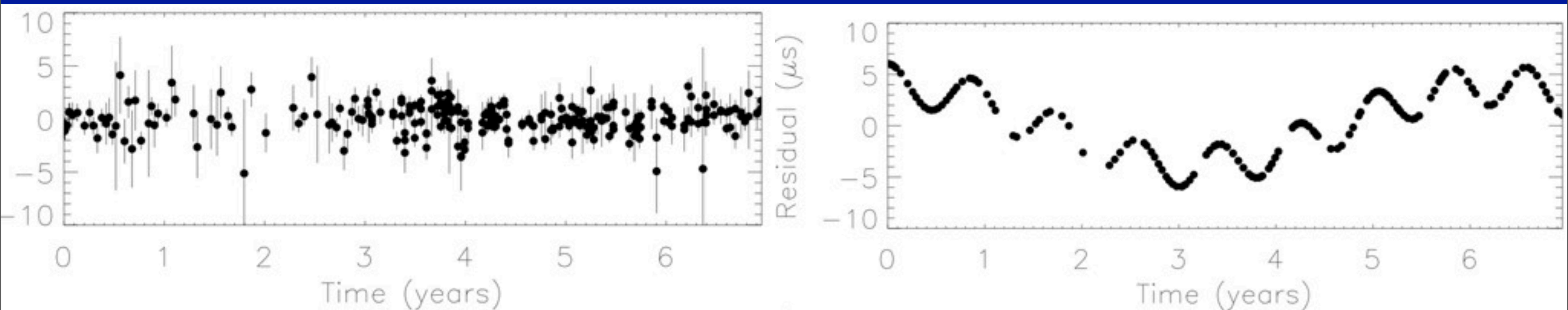
$$\mathbf{r}_{+,\times}(\mathbf{t}) = \mathbf{r}^{\mathbf{Earth}}_{+,\times}(\mathbf{t}) - \mathbf{r}^{\mathbf{PSR}}_{+,\times}(\mathbf{t})$$

Integrated GW strain (at Earth and pulsar)

3C 66B, e.g.: (Sudou et al., 2003)

$$\mathbf{M_{Tot}} = \mathbf{5.4 \times 10^{10}\, M_\odot}$$

$$\mathbf{z = 0.02}$$



Single SMBHBs — Earth term

- Sesana & Vecchio (Phys.Rev.D; 2010)
  - $M \geq 10^8\ M_{Sun}$; $z \leq 1.5$ detectable
  - $R \propto \mathcal{M}^{5/3} / \left(D_L f^{1/3} \right)$ degeneracy
  - $\Delta\Omega \sim 40\ deg^2$ — identification of counterpart difficult.
  - Only considered circular, monochromatic sources!

Single SMBHBs — PSR term

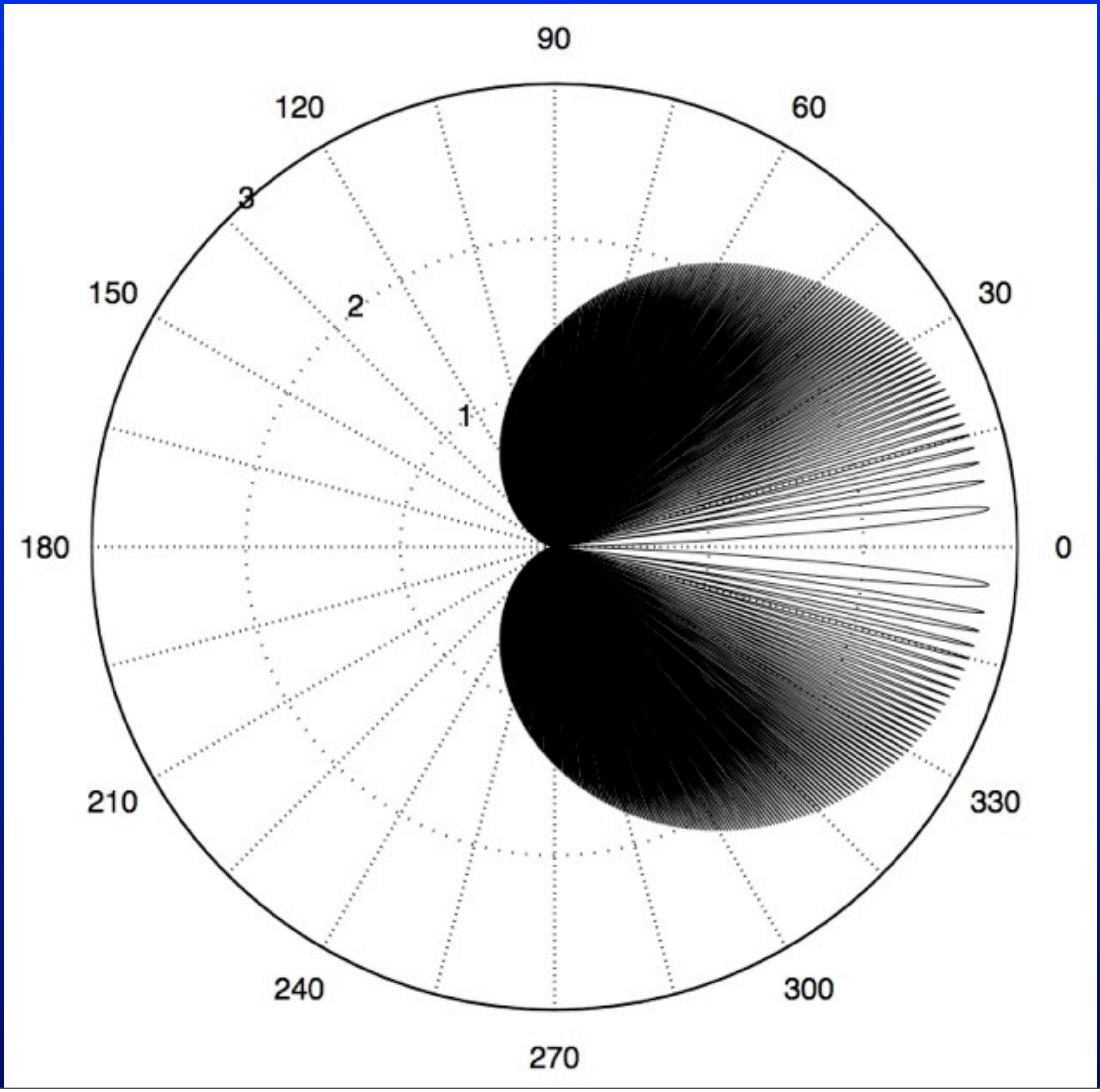
- Corbin & Cornish (ApJ; 2010)
  - Use PSR term by marginalising over PSR distance in a Bayesian analysis.
  - Consider circular, evolving GW sources
  - Evolution $\longrightarrow$ SMBHB mass $\longrightarrow$ GW source Distance
  - $\Delta\Omega \sim 3$ deg^2
  - Require high S/N (~20)

Single SMBHBs — PSR term

- K.J. Lee et al. (MNRAS; 2010)
  - Use PSR term from timing parallax.
  - Consider circular, monochromatic GW sources
  - Interference pattern between PSR and Earth term interferometer-like localisation of GW source.
  - $\Delta\Omega \ll 1$ deg^2
    $\longrightarrow$ counterpart identification
    $\longrightarrow$ GW source distance
    $\longrightarrow$ SMBHB mass
  - Require high timing precision (~15 ns)

Single SMBHBs — PSR term

K.J. Lee et al. (MNRAS; 2010)



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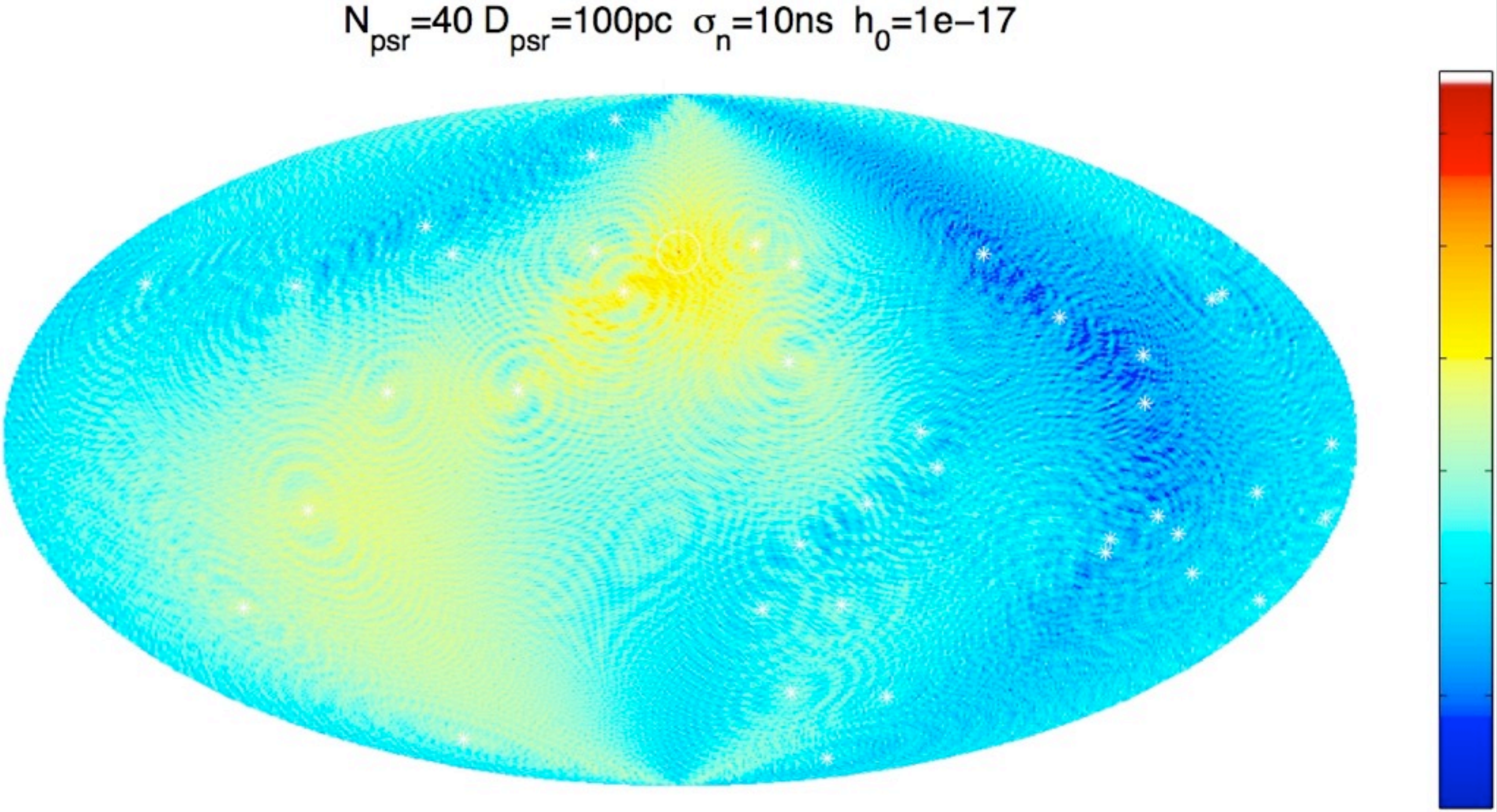

Single SMBHBs — PSR term

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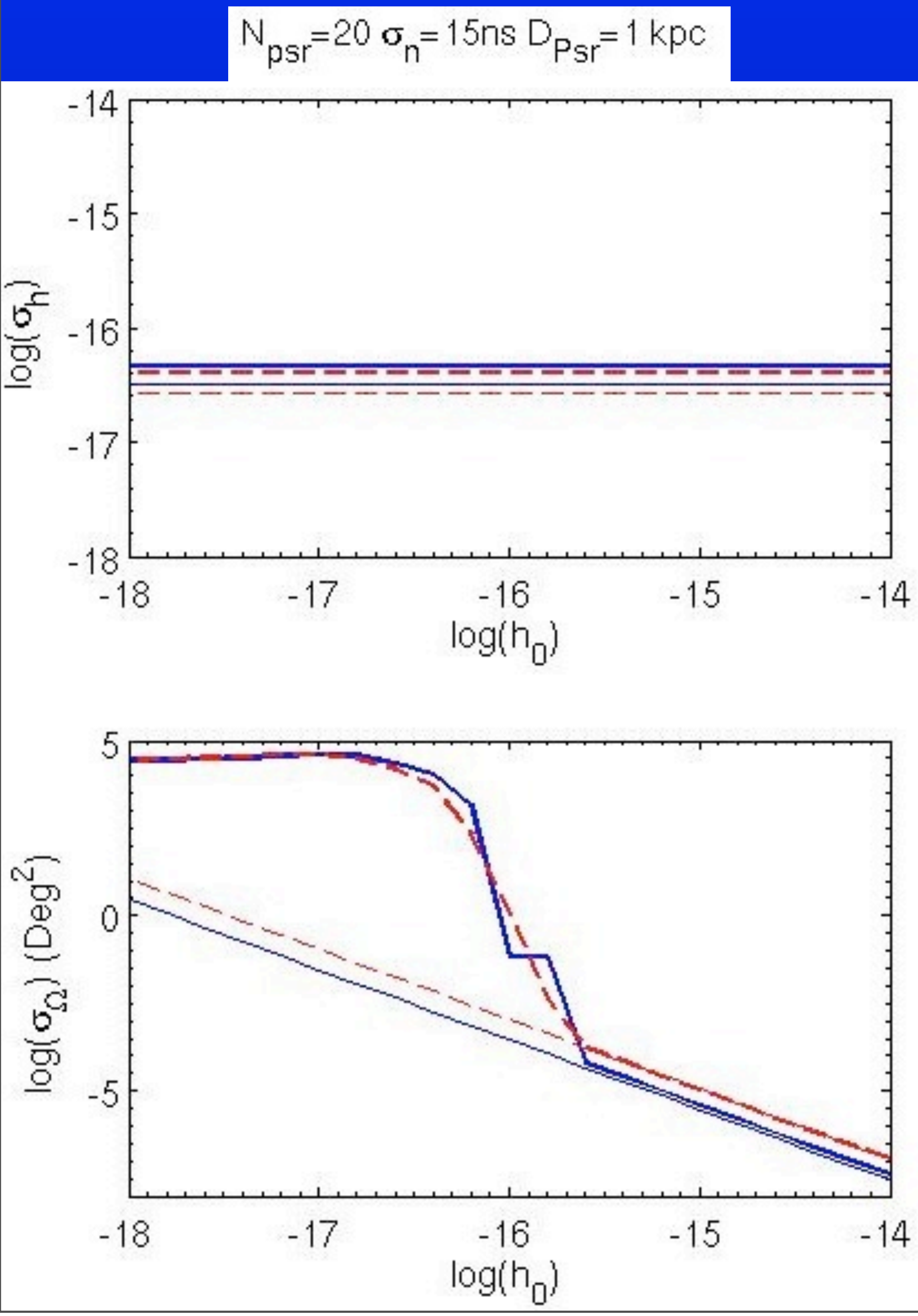
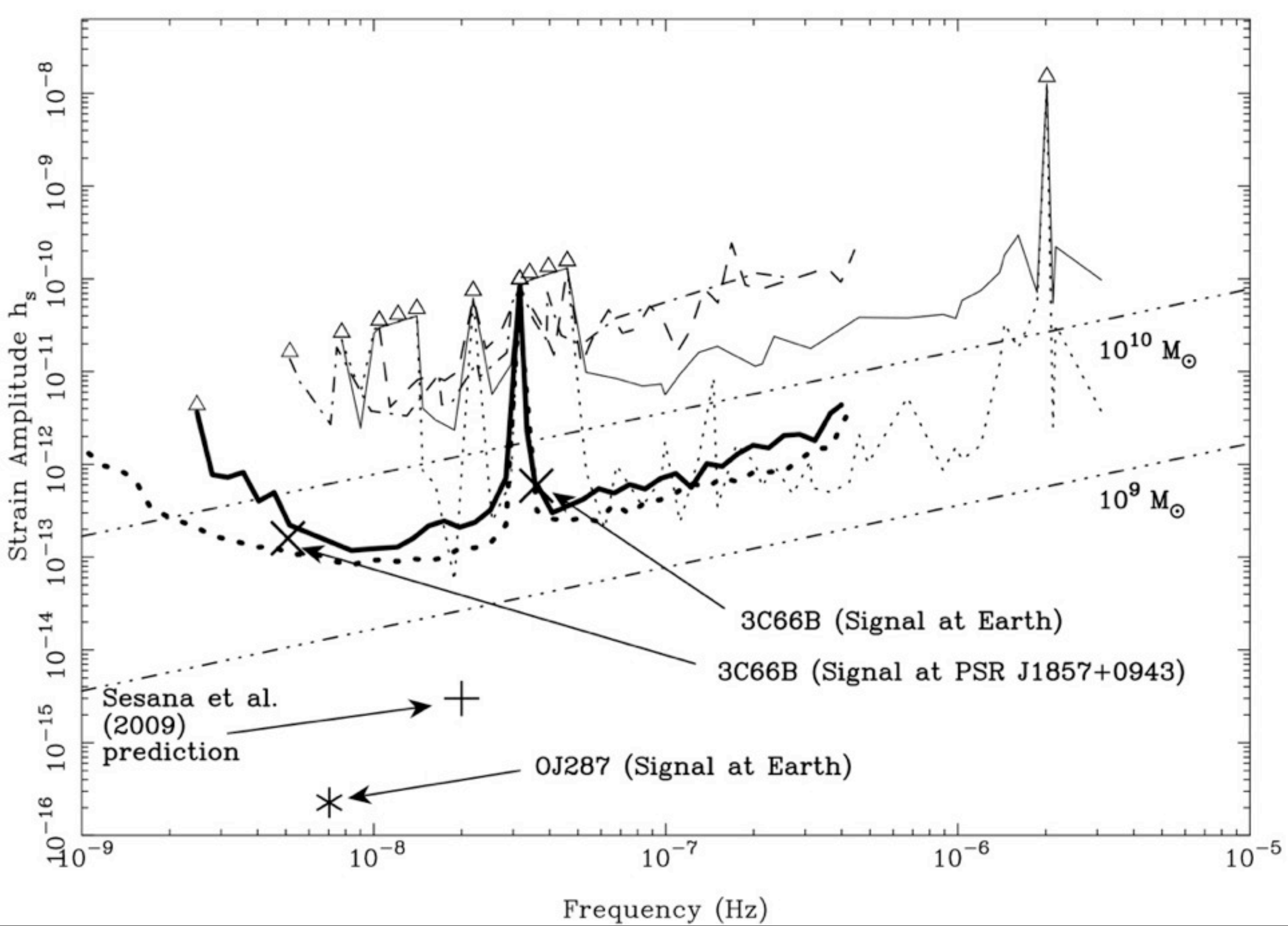


$$h_0 \propto \frac{\mathcal{M}^{5/3}}{D} \omega_g^{2/3} (1+z)^{2/3}$$

$h_0 = 10^{-16}$
equivalent to
$D \approx 2$ Mpc; $M \approx 2 \times 10^7 M_{Sun}$

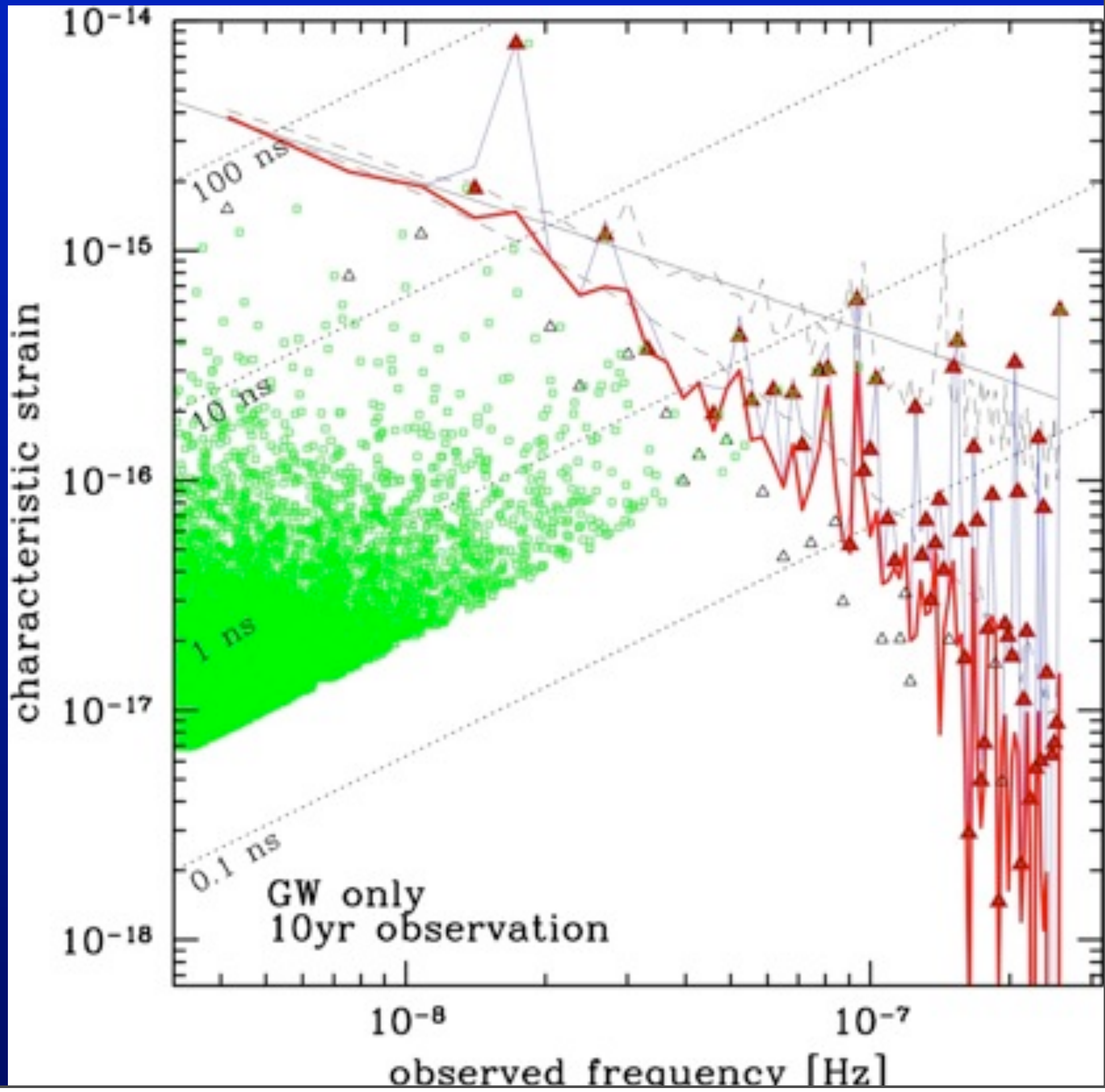
Single Source Limits



Yardley et al.; MNRAS; 2010

Stochastic Background

- **Generation of predicted sources:**
  (Sesana & Vecchio, CQG, 2010)
  - Millennium Run catalogue of merging galaxies
  - Assign BHs to galaxies based on various models
  - Assume BH accretion models
  - ➡ BH coalescence rates

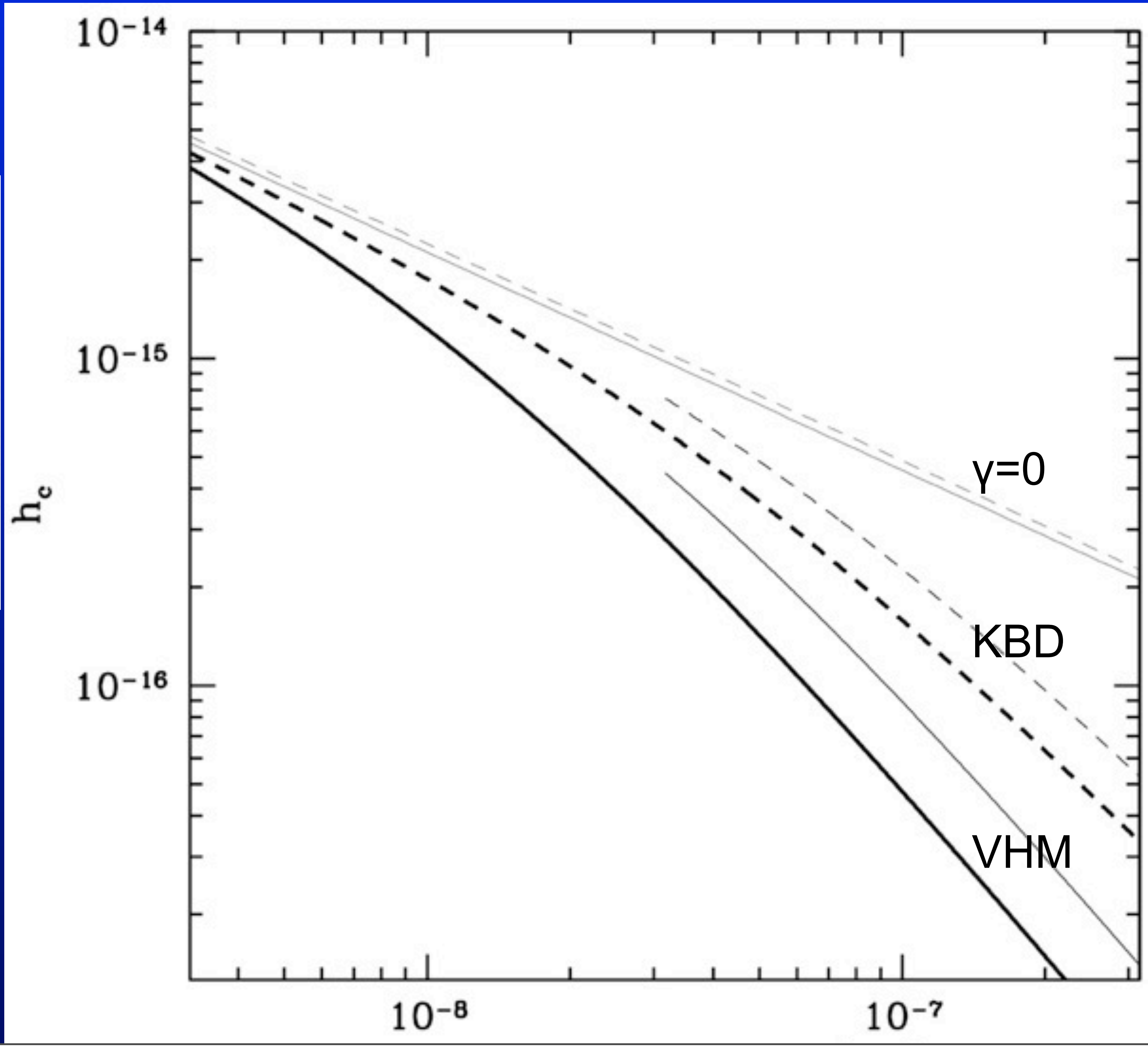


Impact of BH formation & evolution models

Sesana, Vecchio & Colacino, MNRAS, 2008

$$h_c(f) = h_0 \left(\frac{f}{f_0}\right)^{-2/3} \left(1 + \frac{f}{f_0}\right)^{\gamma}$$

Model	h_0 $(\times 10^{-15})$	f_0 $(\times 10^{-8}$ Hz)	γ
VHM	2.15	1.42	−1.09
VHMhopk	0.69	4.27	−1.08
KBD	0.67	5.24	−1.04
BVRhf	0.89	3.95	−1.11



Volonteri, Haardt & Madau (2003)
Volonteri, Salvaterra & Haardt (2006)
Koushiappas, Bullock & Dekel (2004)
Begelman, Volonteri & Rees (2006)

Impact of BH formation & evolution models

- f_0 and γ define the spectrum
  - Measureable with SKA, but (probably) not now

- $h_0 \propto \sqrt{N}\mathcal{M}^{5/3}$ defines the amplitude
  - Dependent on:
    - MBH mass function
    - galactic halo merger rate
    - M_{BH} - σ and M_{BH} - M_{bulge} relations

- See Sesana, Vecchio & Colacino, MNRAS 2008

Conclusions

- Pulsar timing:
  expected to detect GWs from SMBHBs

- Single-source detection
  @ $z < 2$; $M > 10^7\, M_{Sun}$ possible
  - counterpart identification hard w/o SKA
  - M-D degeneracy problematic w/o SKA

- Stochastic background
  depends on BH formation & evolution models, but accurate predictions not made yet.