QuickTime?and a
TIFF (LZW) decompressor
are needed to see this picture.

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Gravitational Wave Detection using Pulsar Timing

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QuickTime?and a
TIFF (LZW) decompressor
are needed to see this picture.

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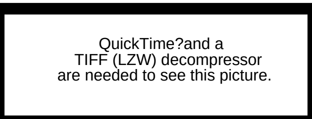
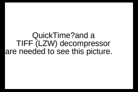
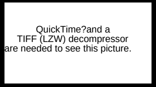
(Franklin & Marshall)

Pulsar Timing Array Consortia

- Parkes Pulsar Timing Array
  - ATNF, Swinburne, CGWA
- European Pulsar Timing Array
  - Jodrell Bank, Effelsberg, SRT
- NANOGrav (North American Nano-Hertz GRAVitational wave observatory)
  - Arecibo, Greenbank, + 11 research institutions
- China Pulsar Timing Array



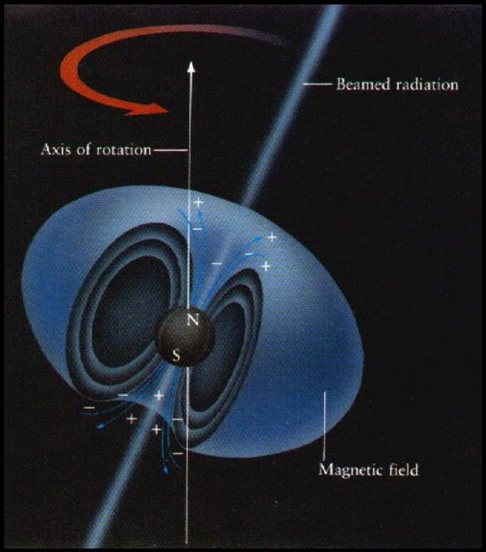


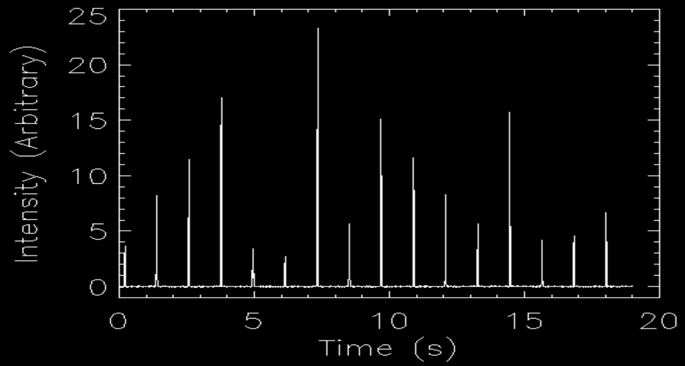


International Pulsar Timing Array Workshop

- Held at the Arecibo Radio Observatory on August 1st-2nd 2008.
- Primary Goal: To organize the efforts of researchers working in the field.
- Details to be announced soon.

Radio Pulsars





Gravitational Waves

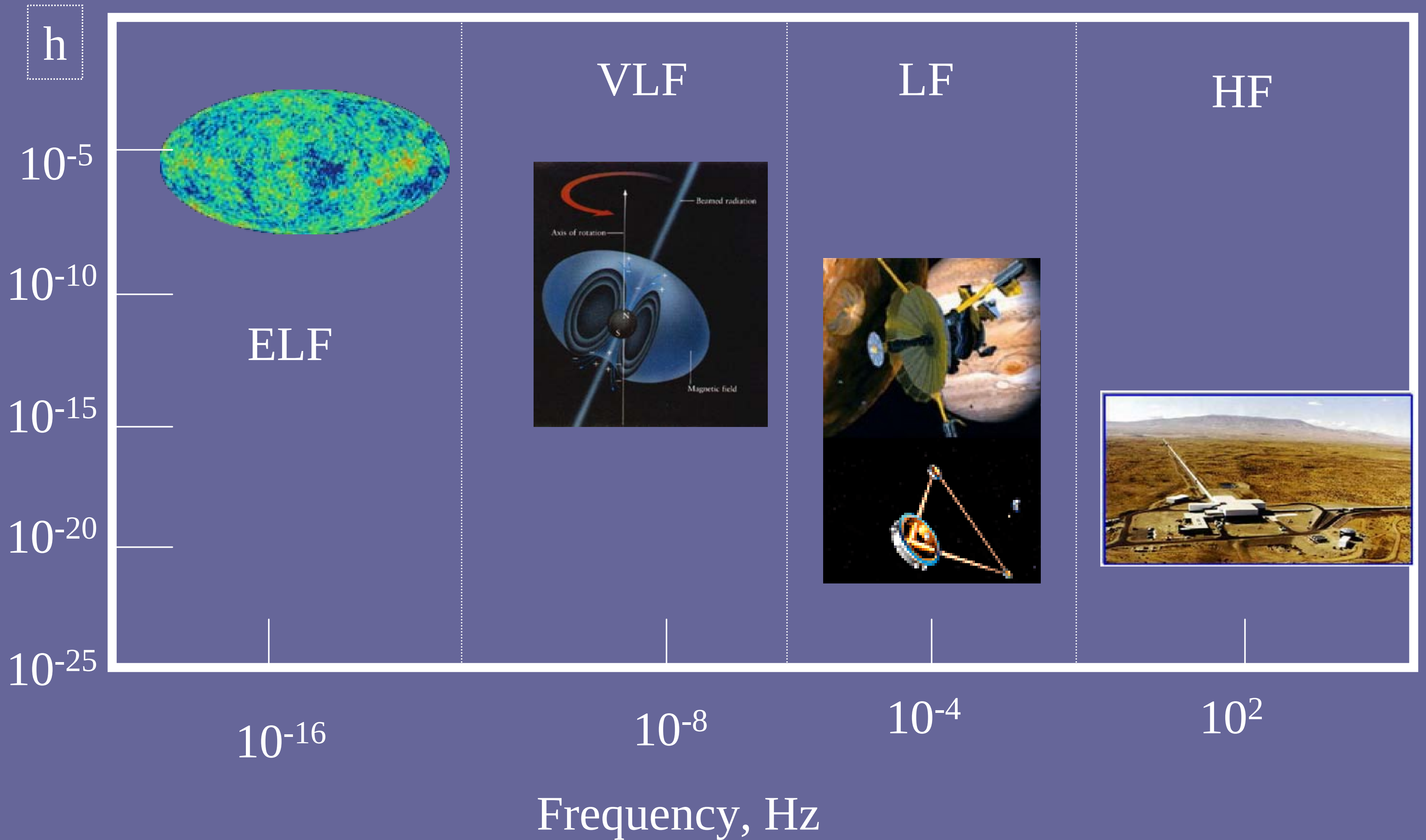
"Ripples in the fabric of space-time itself"

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$G_{\mu\nu}(g) = 8\,\pi\, T_{\mu\nu}$$

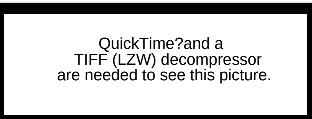
$$-\,\partial^2 h_{\mu\nu} / \partial^2 t + \nabla^2 h_{\mu\nu} = 4\pi\, T_{\mu\nu}$$

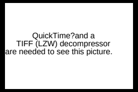
The Big Picture of G-wave Detection

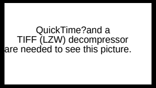


Science in the Nano-Hz Gravitational Wave Band

- Binary Supermassive Black Hole formation and Evolution
- Equation of State of the Early Universe (Quintessence)
- Study of Cosmic Strings
- Testing GR by measuring the polarization properties of GWs.







How do we detect/limit GW using radio pulsars?

Consider small perturbations from a flat space-time:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}(t, x^i)$$

The slight change in the rate at which pulsar pulses arrive at Earth is given by:

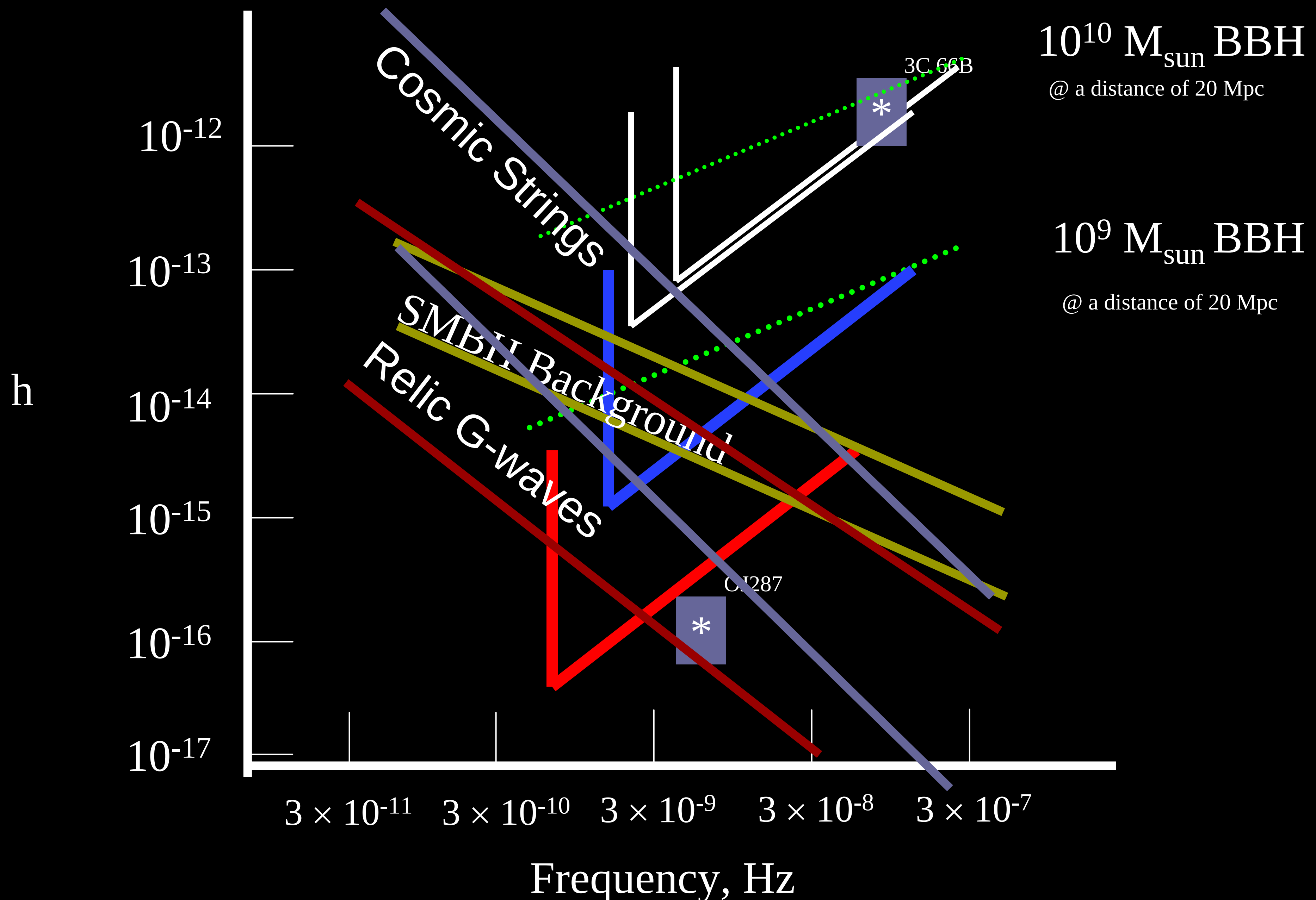
$$\frac{\delta\nu}{\nu} = -\mathcal{H}^{ij}(h_{ij}(t_e, x_e^i) - h_{ij}(t_e - d, x_p^i))$$

Pulsar timing observations measure the timing residuals:

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$

$$R \approx \frac{h}{\Omega}$$

Sensitivity of pulsar timing to GWs



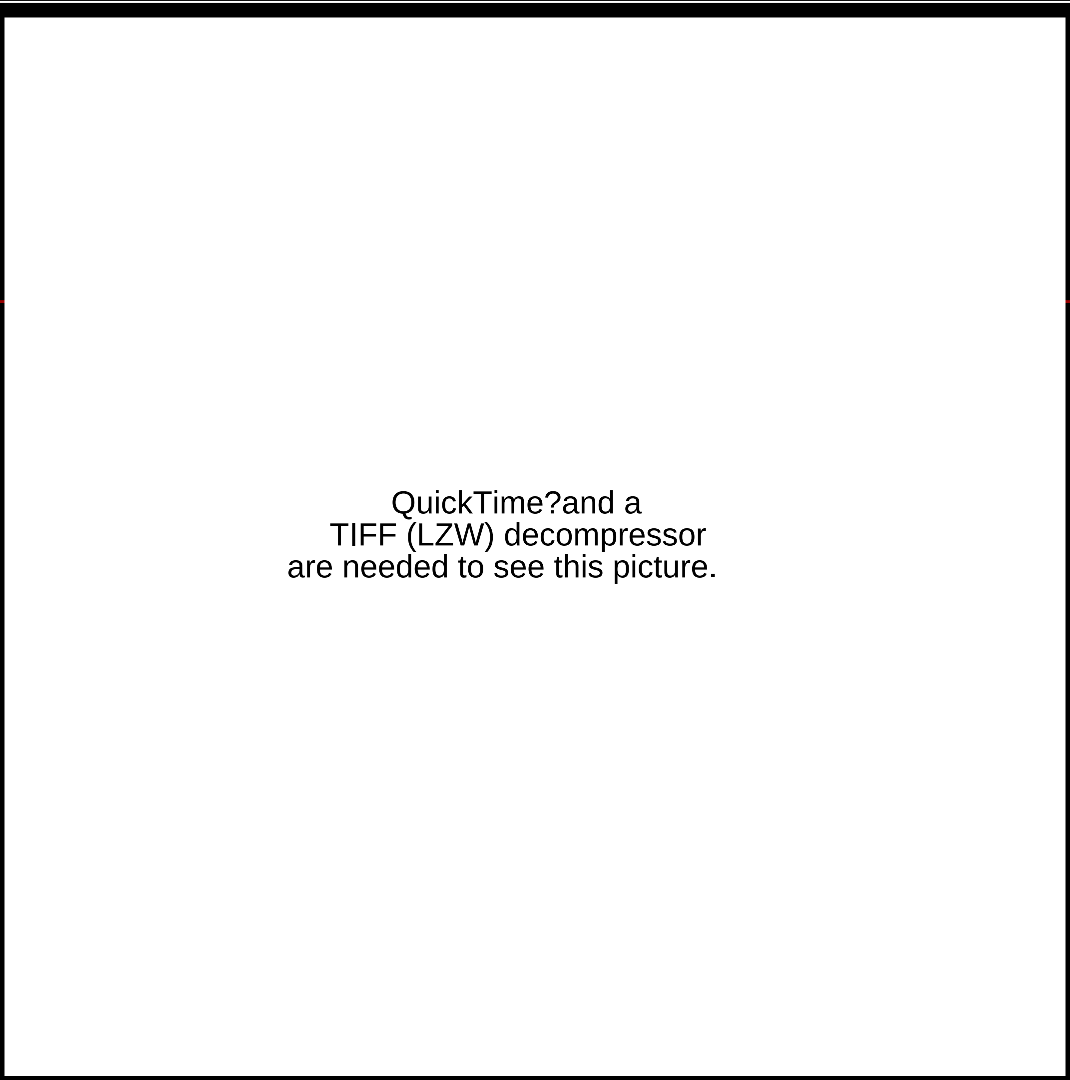
Detecting a single supermassive black hole binary

The amplitude of a gravitational wave strain produced by a SMBH binary is given by:

$$h = \frac{M_c^{5/3}\omega^{2/3}}{r} \quad \Rightarrow \quad R = \frac{M_c^{5/3}}{\omega^{1/3} r}$$

Now, include the effects of cosmology:

$$h = \frac{M_c^{5/3}\omega^{2/3}(1+z)^{2/3}}{D(z)} \quad \Rightarrow \quad R = \frac{M_c^{5/3}(1+z)^{2/3}}{\omega^{1/3}D(z)}$$



文中略 (Zhonglue Wen)

Individual Supermassive Black Hole Binaries

Probability of detecting individual sources:

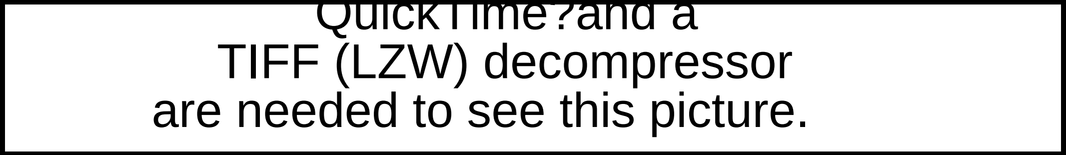
20 Pulsars, 100 ns: < 2%

5 Pulsars, 10 ns: > 90%

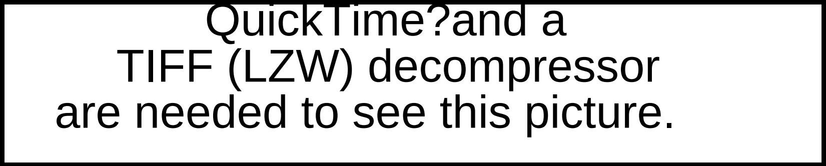
(Preliminary results by 文中略 (Zhonglue Wen))

Limits on the rate

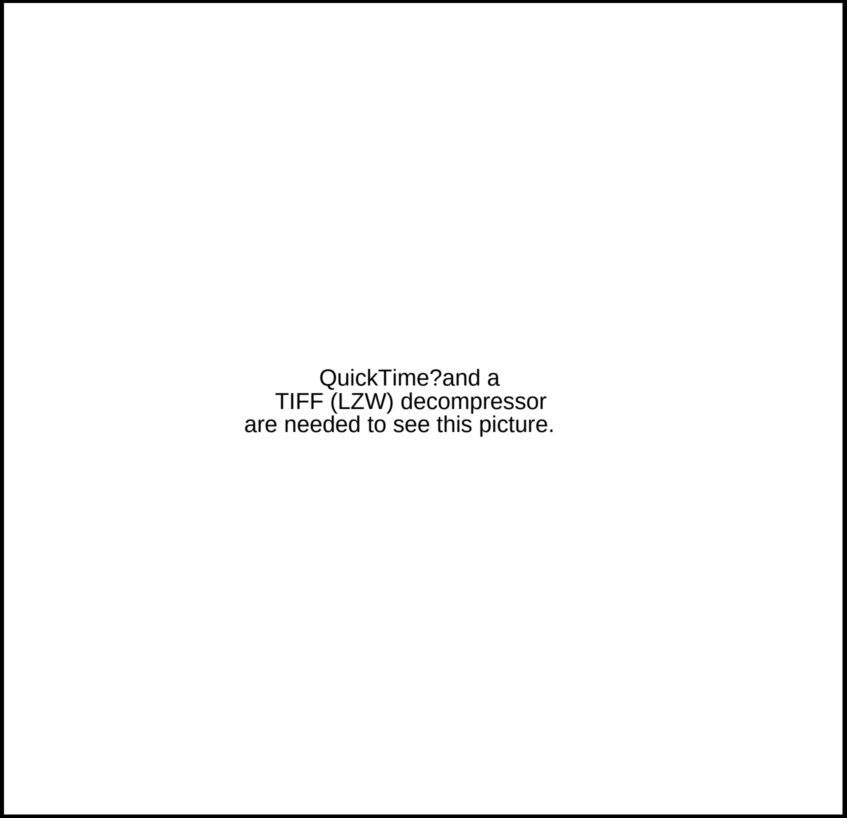
- In the context of Supermassive black hole binaries, these upper bounds may be cast in terms of the coalescence rate.
- Stochastic Constraint:



- Poission Constraint:



Stochastic SMBH Coalescence Rate Constraint



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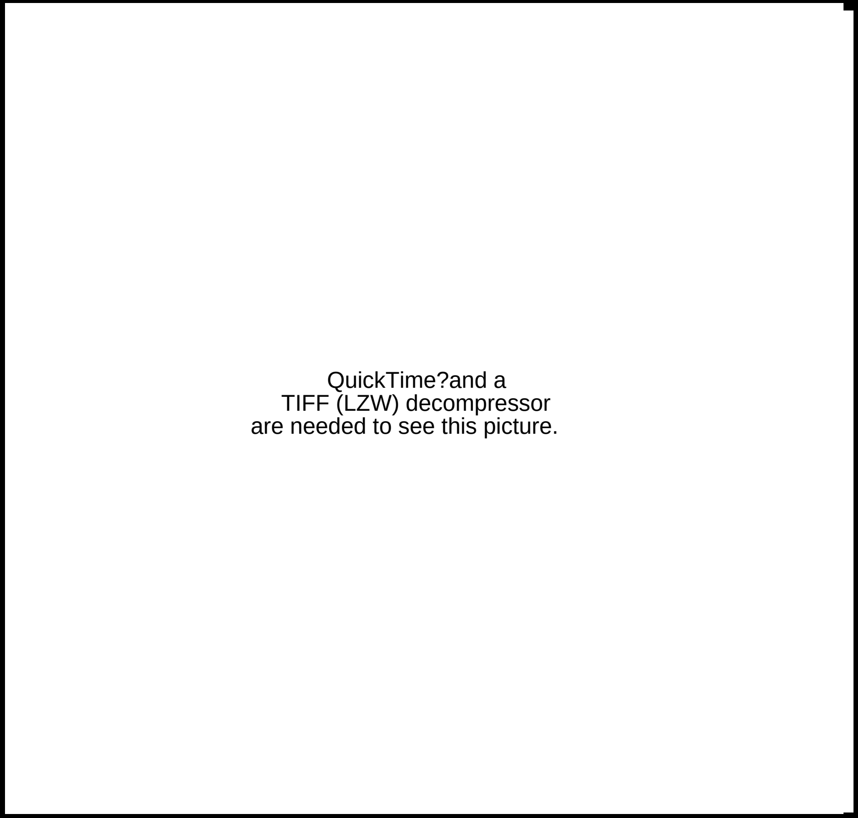
Poisson SMBH Coalescence Rate Constraint



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The Stochastic Background (Definitions of various quantities)

$$h_{\mu\nu} = \mathrm{Re}\left[\sum_j A_{\mu\nu_j} e^{i\vec{k}_j\cdot\vec{x} - i\omega_j t}\right]$$

The stochastic background is made up of a sum of a large number of plane gravitational waves. The power spectrum of h is given by $S_h(f)$ and satisfies:

$$\int_0^\infty S_h(f)df \;=\; \frac{1}{2} < h_{\mu\nu}(t)h^{\mu\nu}(t) >$$

$$h_c(f) \;=\; \sqrt{f S_h(f)}.$$

$h_c(f)$ is the 'characteristic strain' spectrum and is defined by the above equation.

The Stochastic Background

Characterized by its "Characteristic Strain" Spectrum:

$$h_c(f) = A\left(\frac{f}{f_{1\mathrm{yr}}}\right)^{\alpha}$$

$$\Omega_{gw}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c(f)^2 = \frac{2\pi^2}{3H_0^2} A^2 \left(\frac{f}{f_{1\mathrm{yr}}}\right)^{2\alpha+2}$$

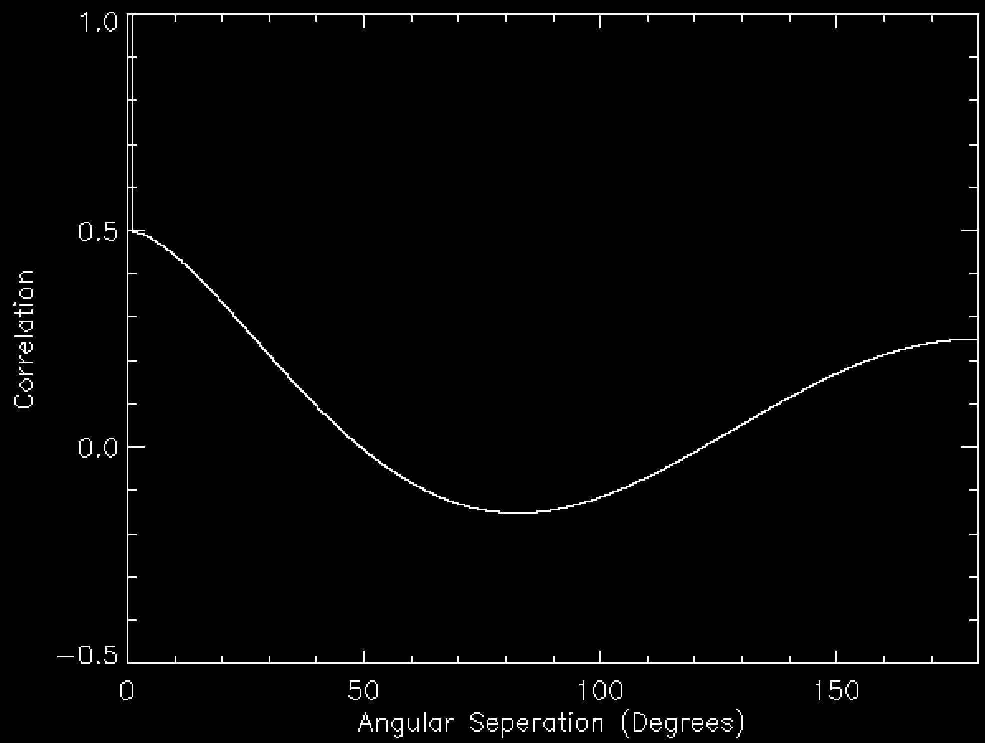
Table 1: The expected parameters for predicted stochastic backgrounds

Model	A	α	References
Supermassive black holes	$10^{-15} - 10^{-14}$	$-2/3$	Jaffe & Backer (2003)
			Wyithe & Loeb (2003)
			Enoki et al. (2004)
Relic GWs	$10^{-17} - 10^{-15}$	$-1 - -0.8$	Grishchuk (2005)
Cosmic String	$10^{-16} - 10^{-14}$	$-7/6$	Maggiore (2000)

Detecting a Stochastic Background of GWs

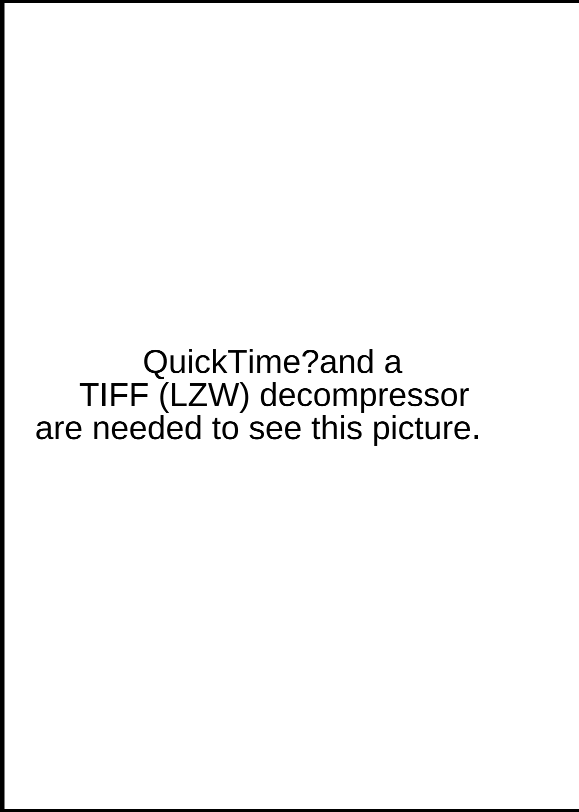
Pulse arrival time fluctuations from different pulsars will be correlated:

$$C(\theta_{ij}) = \langle R_I \, R_j \rangle$$



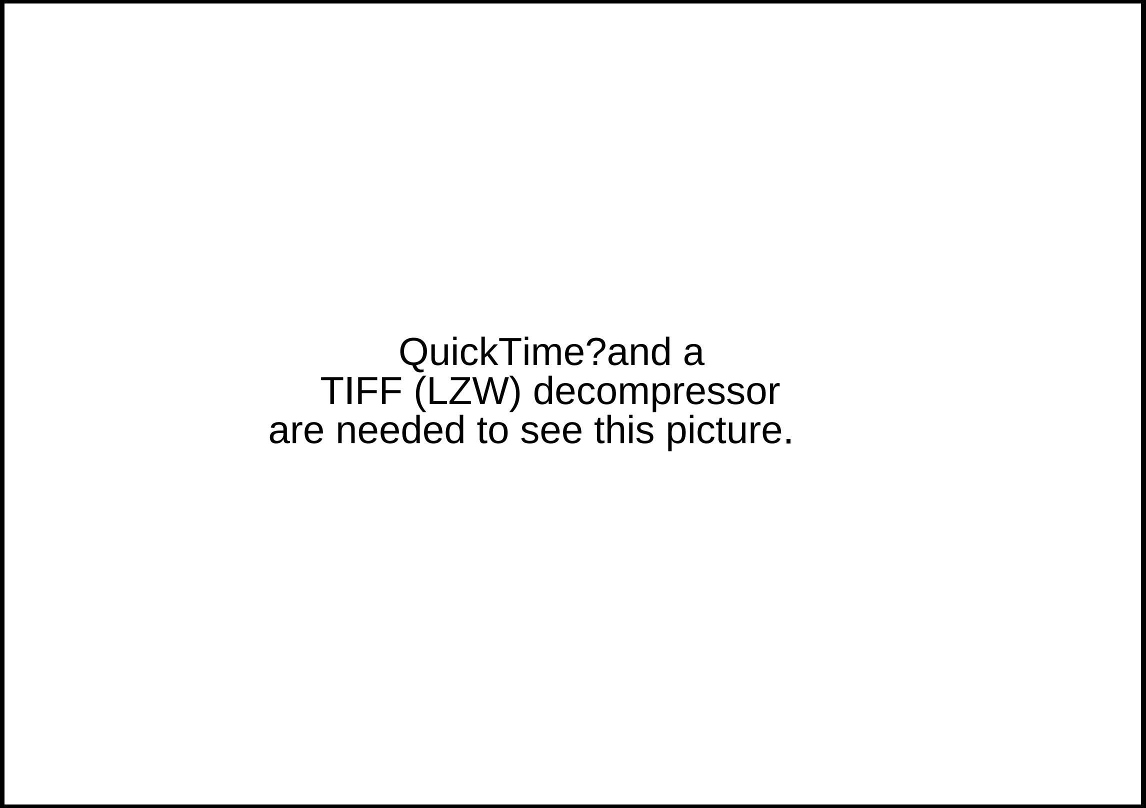
Polarization Properties of GWs

- GR predicts only two polarization modes.
- A general metric theory has 4 more.
- Pulsar timing is better suited to determine the polarization structure of a GW than LIGO.

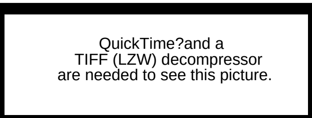


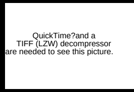
Testing GR with the stochastic background

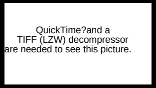
- Different polarization modes will have different curves.
- The actual correlation curve will be a weighted sum of these curves.



李柯伽
KJ Lee







How many pulsar do we need to detect the background?

- Assuming 100 nanosecond precision with 5 years of observing, one needs at least 20 pulsars.

How many pulsars do we need to discriminate the different modes?

- Assuming 100ns RMS, 10 years, about 100 pulsars will needed.
  - Results from work by 李柯伽 (KJ Lee)

Summary

- Nature has created its own gravitational wave observatory in the form of Radio pulsars.
  - We can use the properties of radio pulsars to directly detect gravitational waves.
    - $R \approx h / \omega$
  - Researchers are currently working to improve the sensitivity of such a detector.
    - The Parkes pulsar timing array project (20 pulsar, 100 ns accuracy, 5 years)
- Upper bounds may be placed using a small number of pulsars
    - Place limits on the existence of the proposed supermassive binary black hole in 3C 66B
    - Limits may be placed on a Stochastic background:
    - $h_c(f=1/yr) < 1.4 \times 10^{-14}$ $\Omega_g w\{f=1/20yr\}h^2 < 10^{-8}$
- Observations of Multiple pulsars are need to definitively detect gravitational waves
    - Look for correlations in the pulsar timing residuals to detect the presence of a stochastic background
    - A minimum of 20 pulsars, 5 years, 100 nano-second precision.