Probing Massive black hole binaries with space based interferometry and pulsar timing

Alberto Sesana

Albert Einstein Institute, Golm

EPTA

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

Gravitational Wave Astronomy in Space

eLISA/NGO

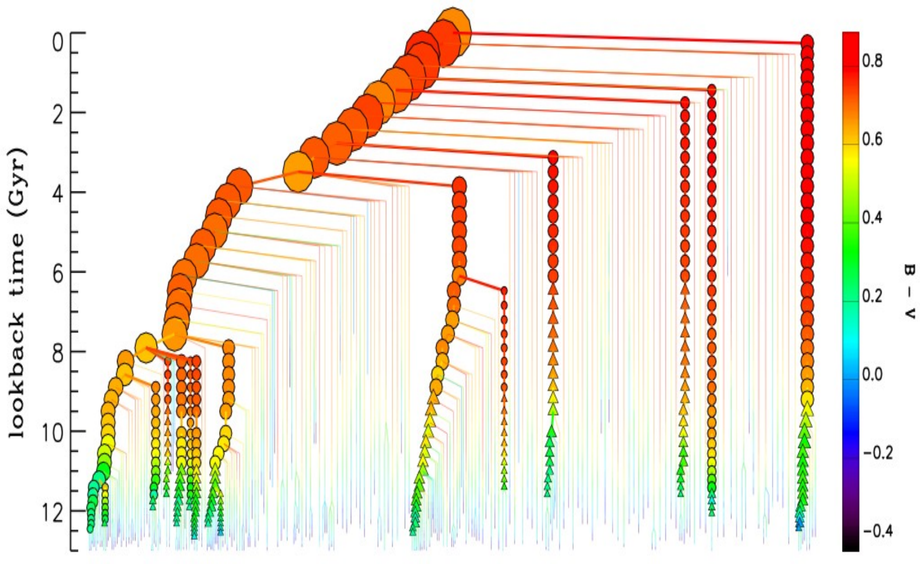
OUTLINE

1- The hierarchical model: MBH assembly and growth

2- Gravitational waves

3- Probing the Babies with eLISA and the Beasts with PTAs

Structure formation in a nutshell



From De Lucia et al 2006

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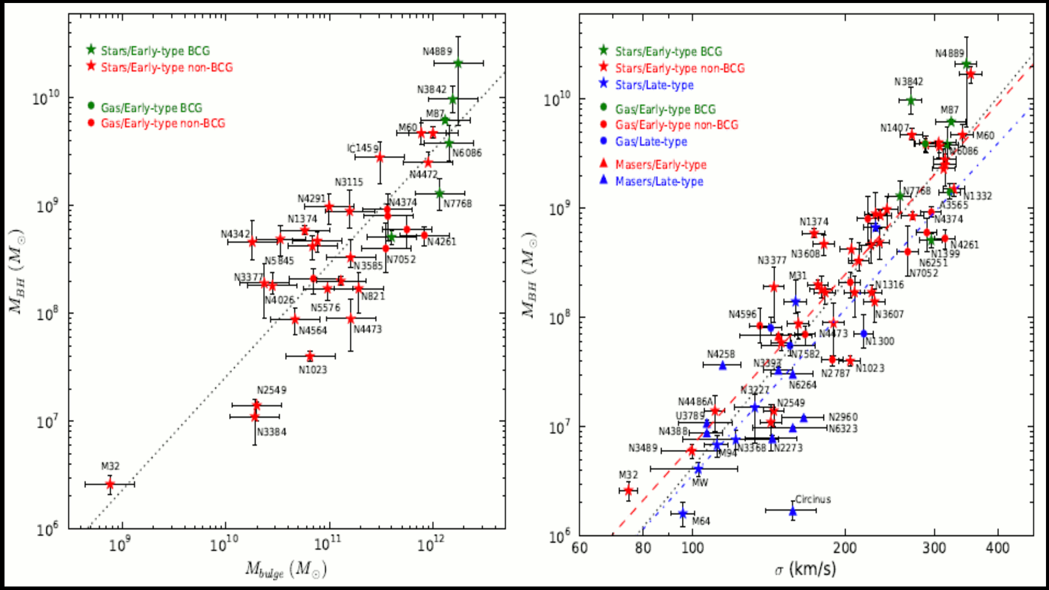

Ferrarese & Merritt 2000, Gebhardt et al. 2000

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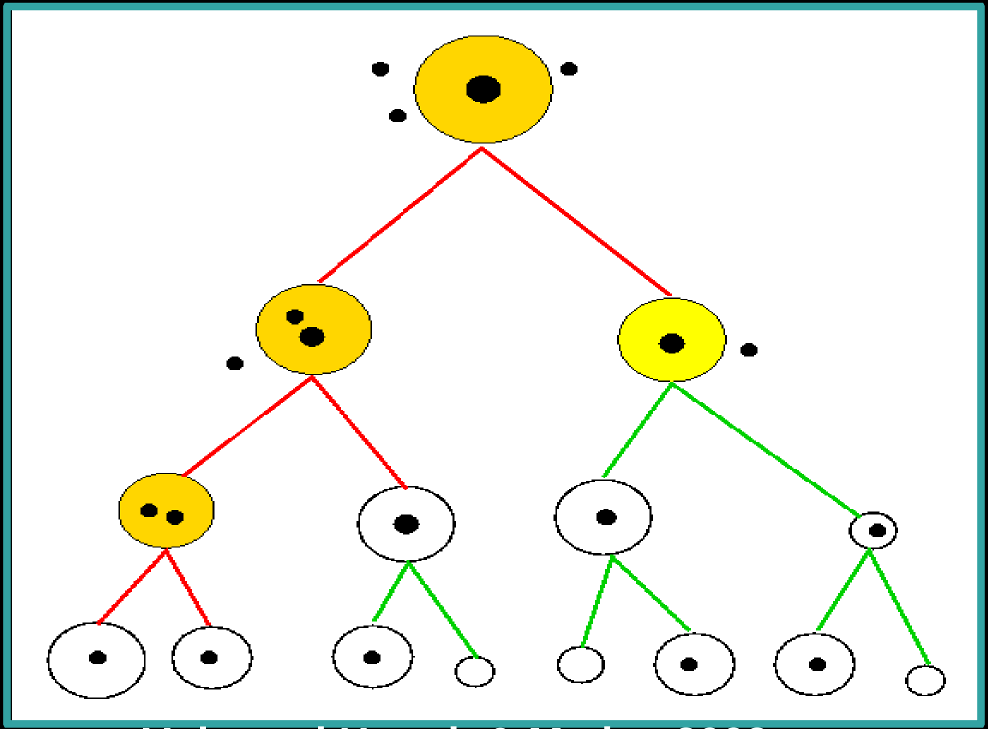
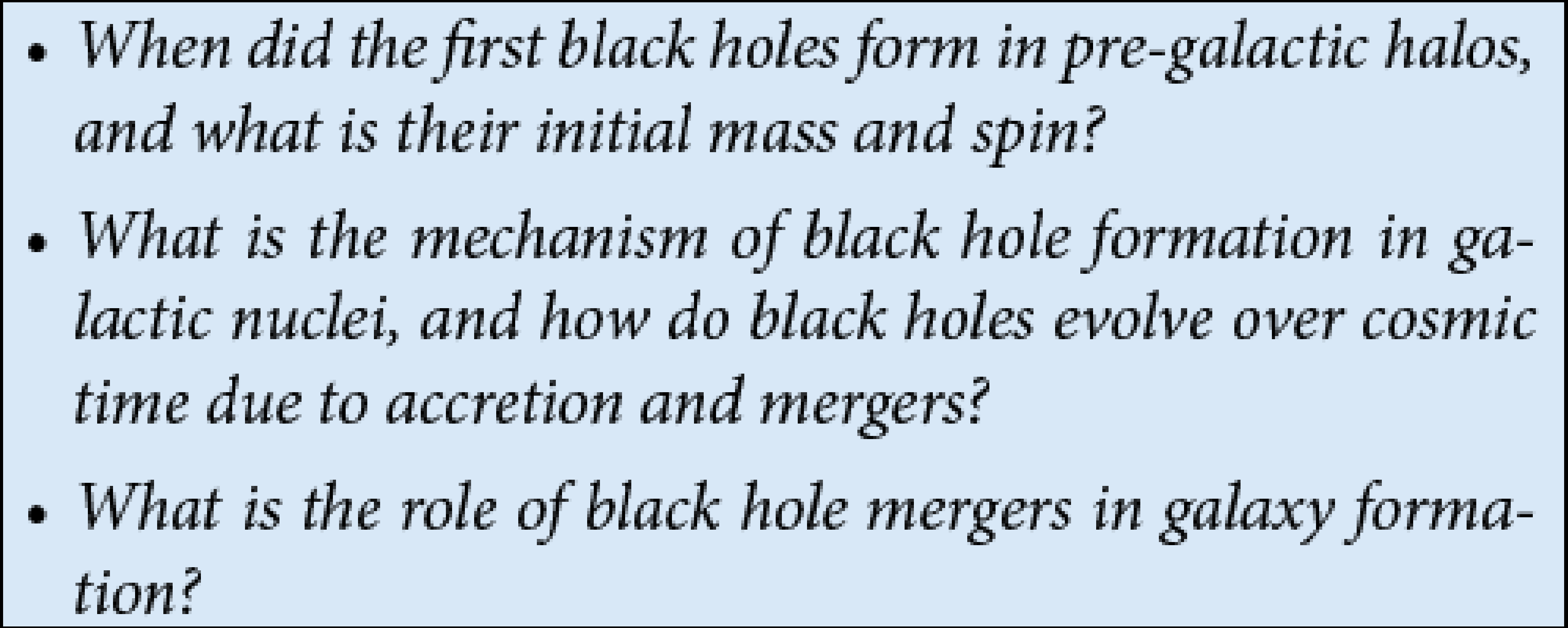
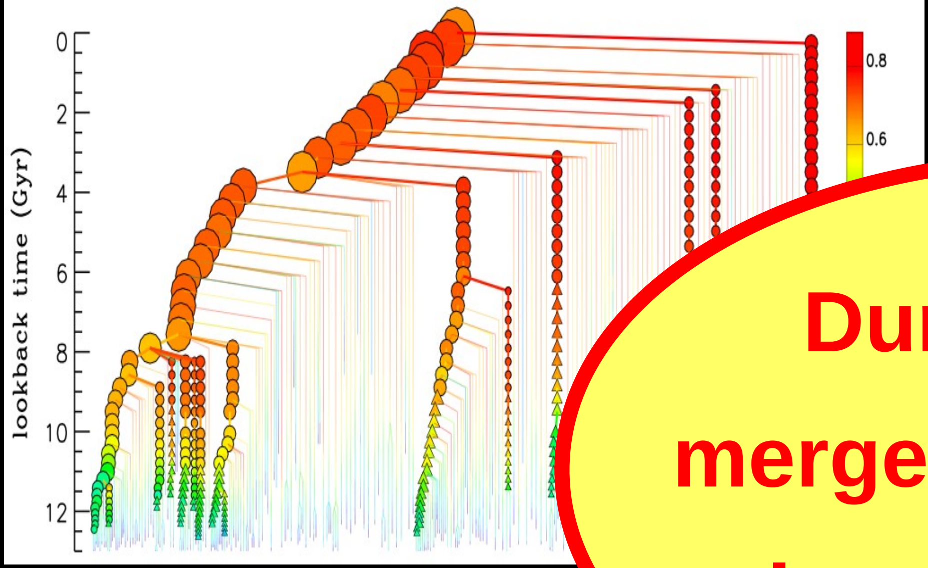


Volonteri Haardt & Madau 2003



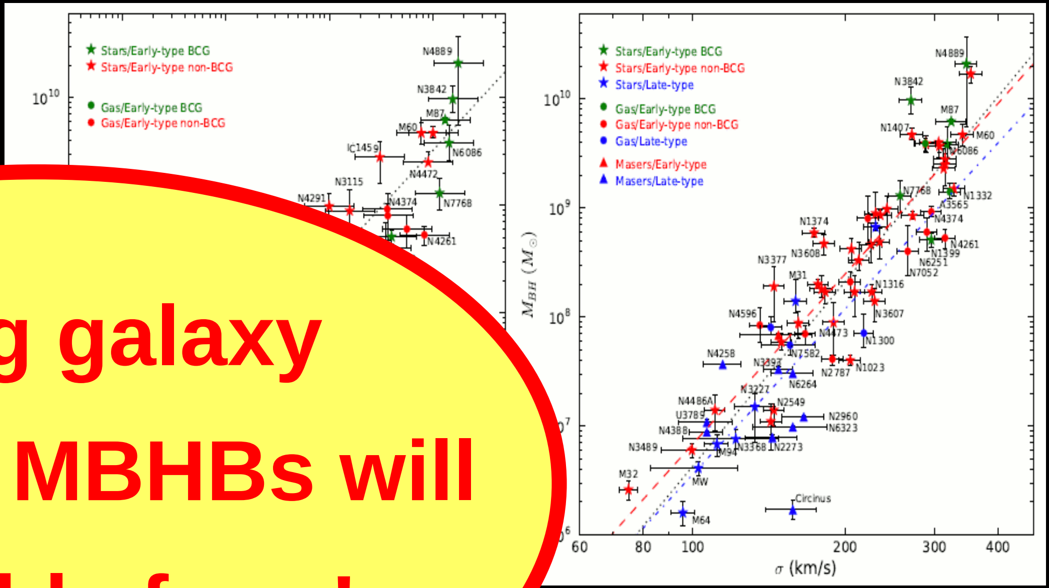
- *When did the first black holes form in pre-galactic halos, and what is their initial mass and spin?*
- *What is the mechanism of black hole formation in galactic nuclei, and how do black holes evolve over cosmic time due to accretion and mergers?*
- *What is the role of black hole mergers in galaxy formation?*

Structure formation in a nutshell



From De Lucia et al 2006

During galaxy mergers, MBHBs will Inevitably form!



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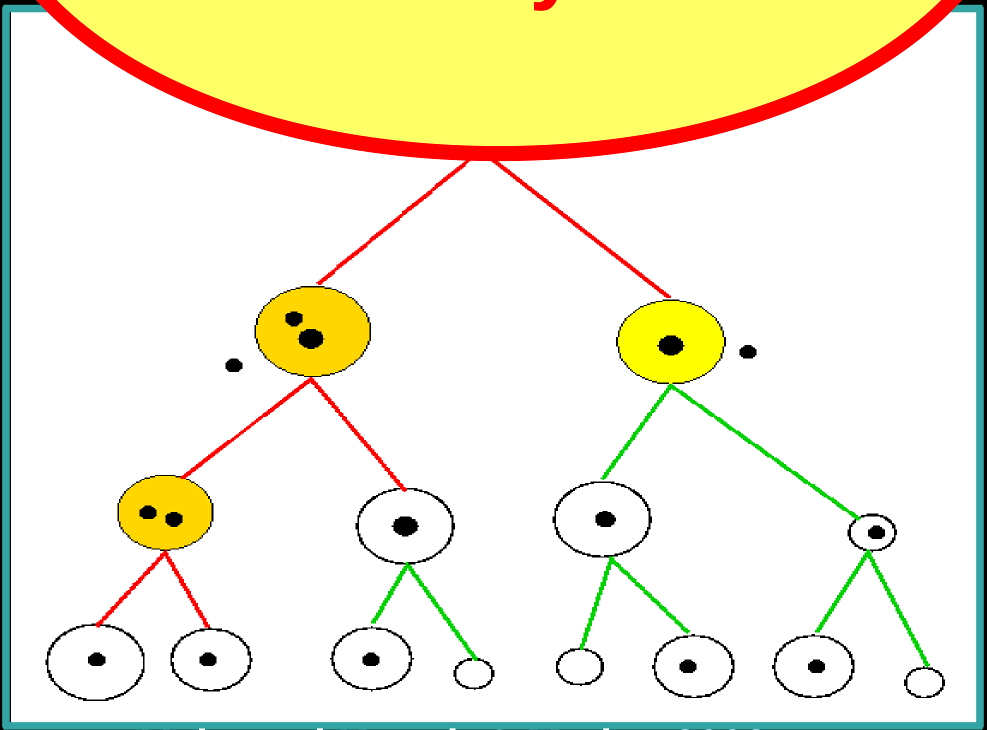


Volonteri Haardt & Madau 2003

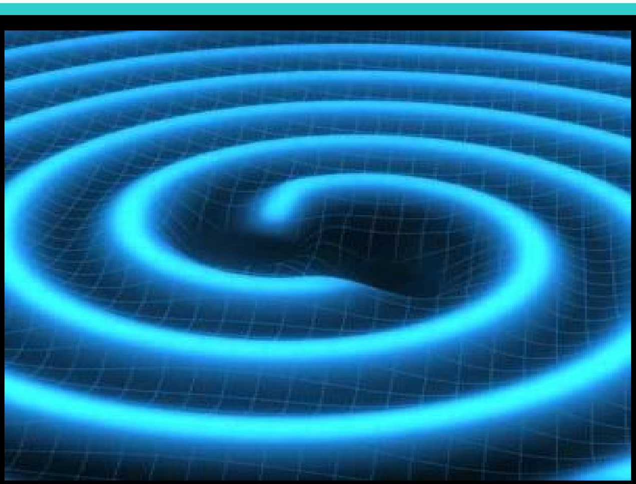
Directly from general relativity

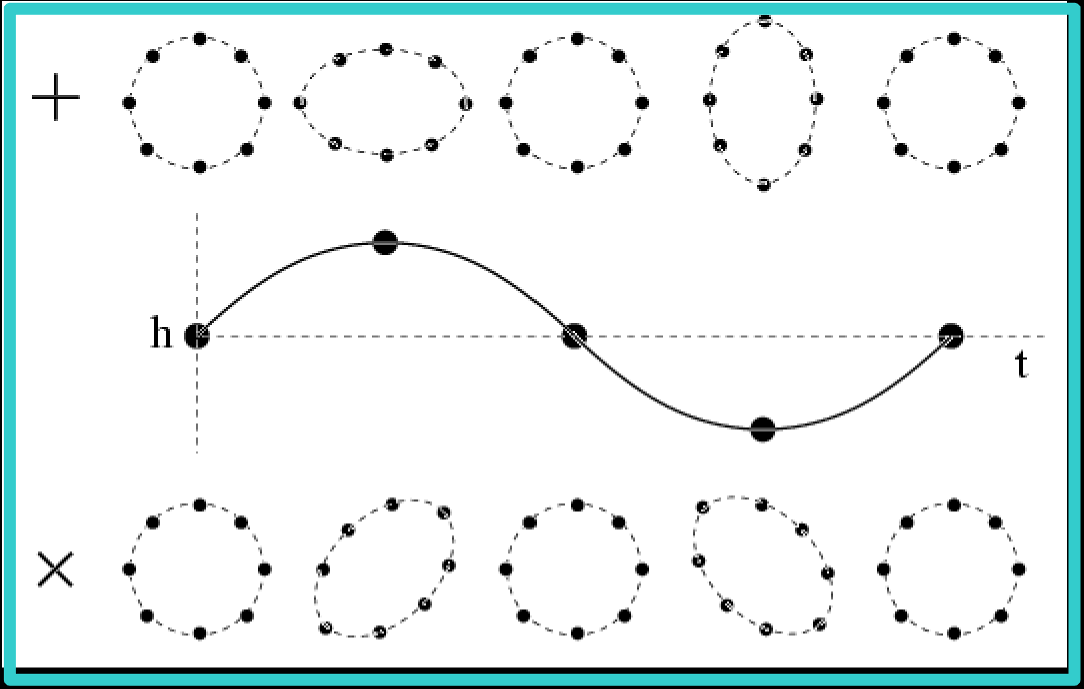
Every accelereting mass distribution with non-zero quadrupole momentum emits GWs!

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad h_{\mu\nu} \ll 1$$

Perturbed Minkowski metric tensor :

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 + h_+^{TT} & h_\times^{TT} \\ 0 & 0 & h_\times^{TT} & 1 - h_+^{TT} \end{pmatrix}$$





Perturbation perpendicular to the wave propagation direction

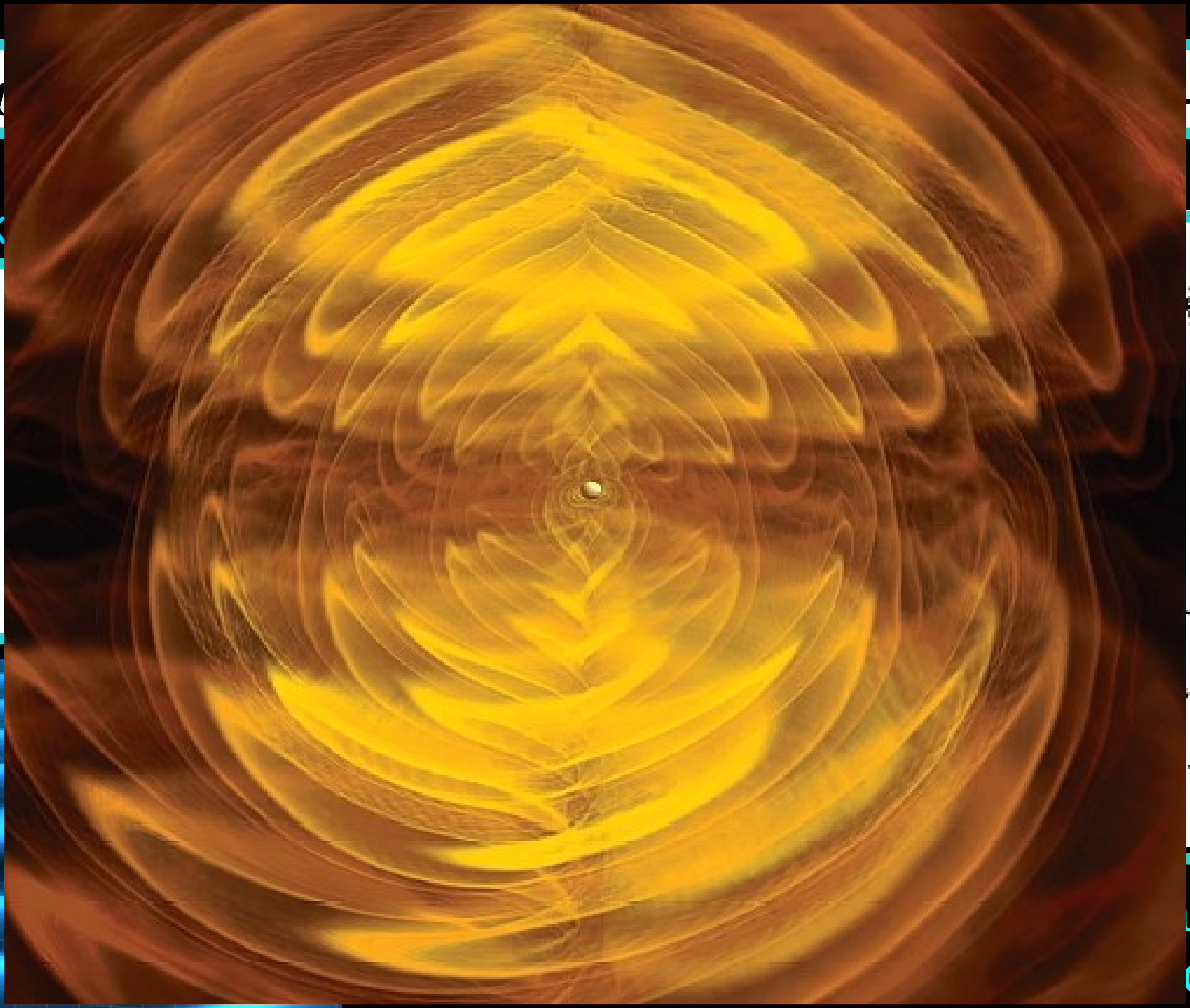
Directly from general relativity

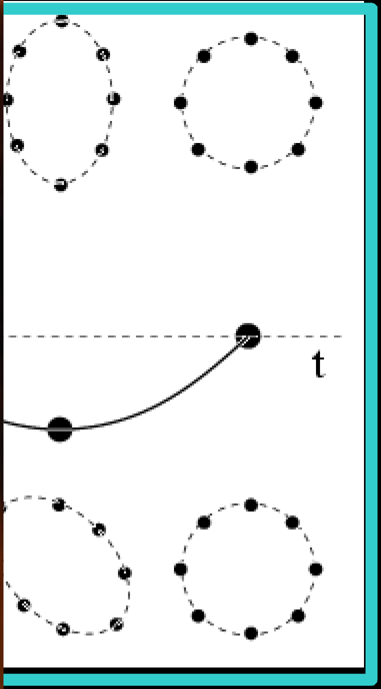
Every accelereting mass distribution with non-zero quadrupole momentum emits GWs!

g_μ

Perturbed Mink

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$





r to the wave
ction

Massive black hole binaries are the loudest gravitational wave sources in the Universe!

Heuristic scalings

We want compact accelerating systems

Consider a BH binary of mass M, and semimajor axis a

$$h \sim \frac{R_S}{a}\frac{R_S}{r} \sim \frac{(GM)^{5/3}(\pi f)^{2/3}}{c^4 r}$$

In astrophysical scales

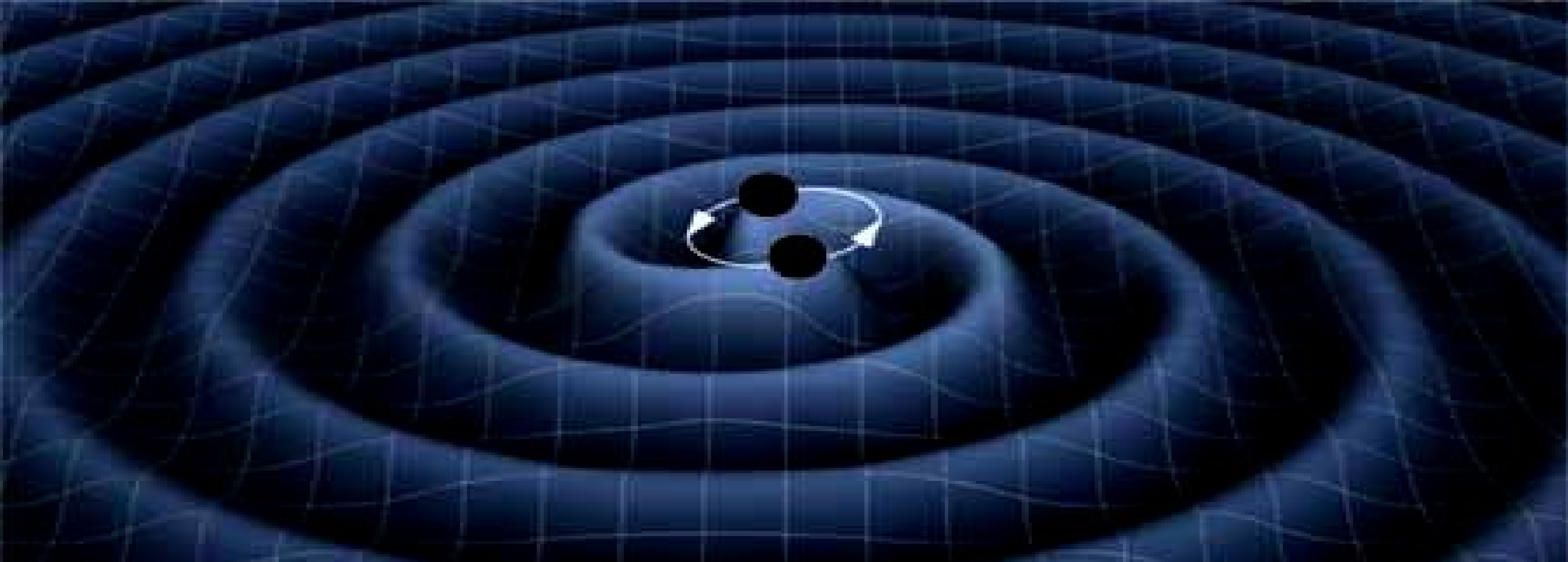
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

$$f \sim \frac{c}{2\pi R_s} \sim 10^4\mathrm{Hz}\frac{M_\odot}{M}$$

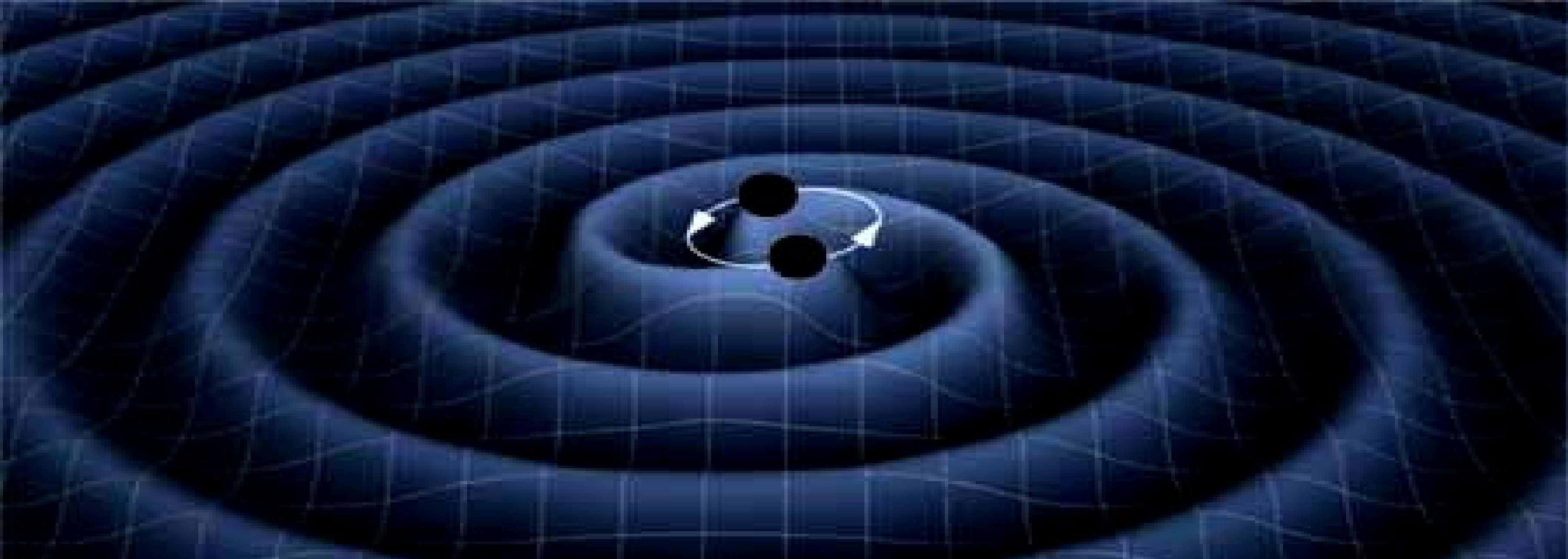
10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f<10^{3}$

10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f<10^{-2}$

10^9 $M_\odot$ binary at 1Gpc: $h \sim 10^{-14}$, $f<10^{-5}$



Baby black holes: eLISA



Baby black holes: eLISA

Baby Black Hole Adoption Certificate

To:

From:

WARNING: Please wear the appropriate protective equipment whilst opening the transportation container. Do not place near any significant mass. Do not allow small children to approach its event horizon unsupervised.

www.ButterflyLove1.etsy.com

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

The eLISA Consortium, arXiv:1305.5720

Baby black holes: eLISA

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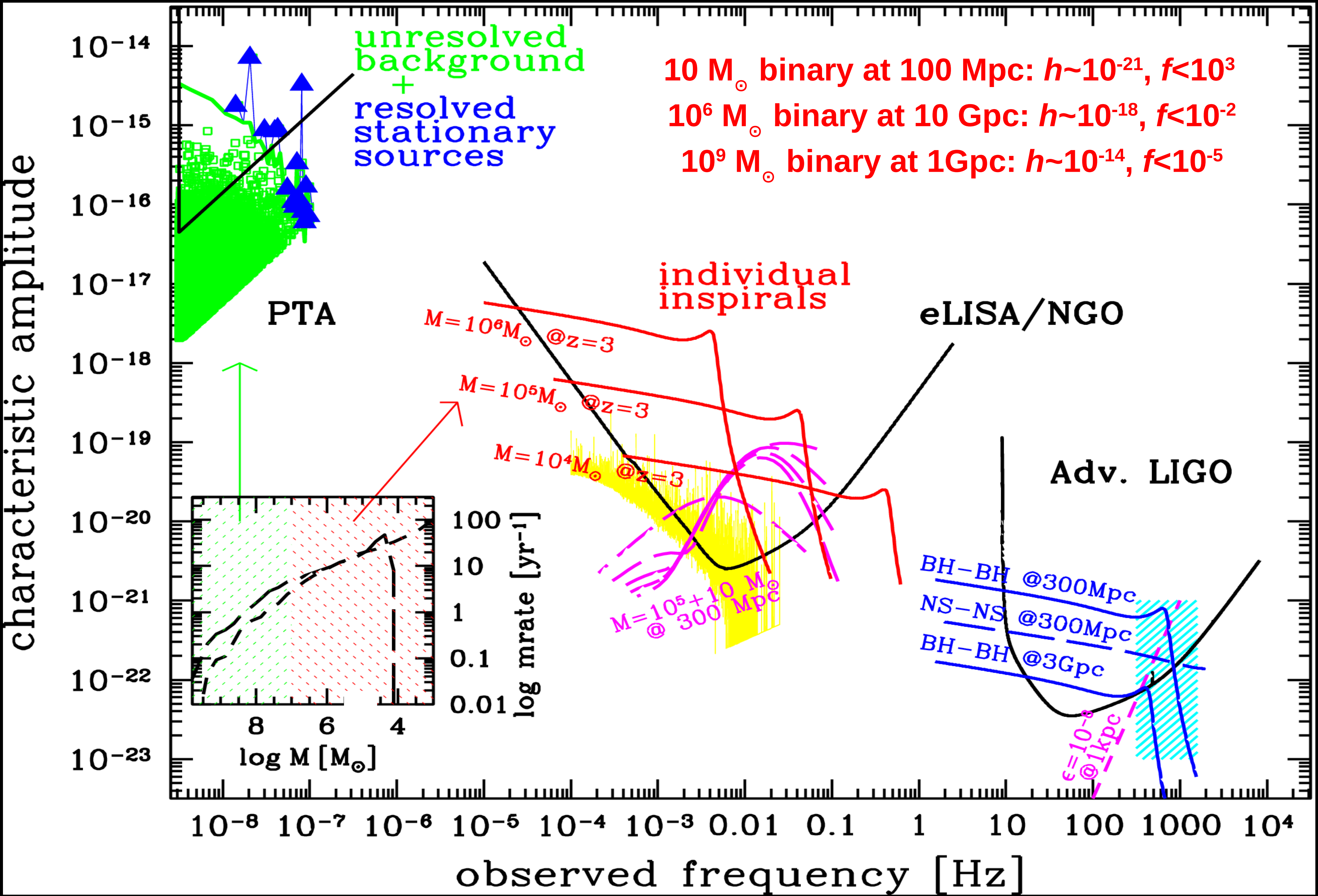
Coverage of the GW spectrum



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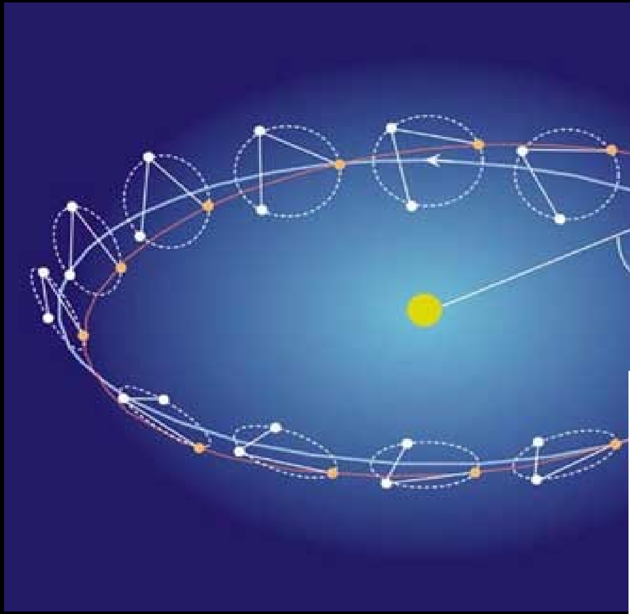
AS 2013

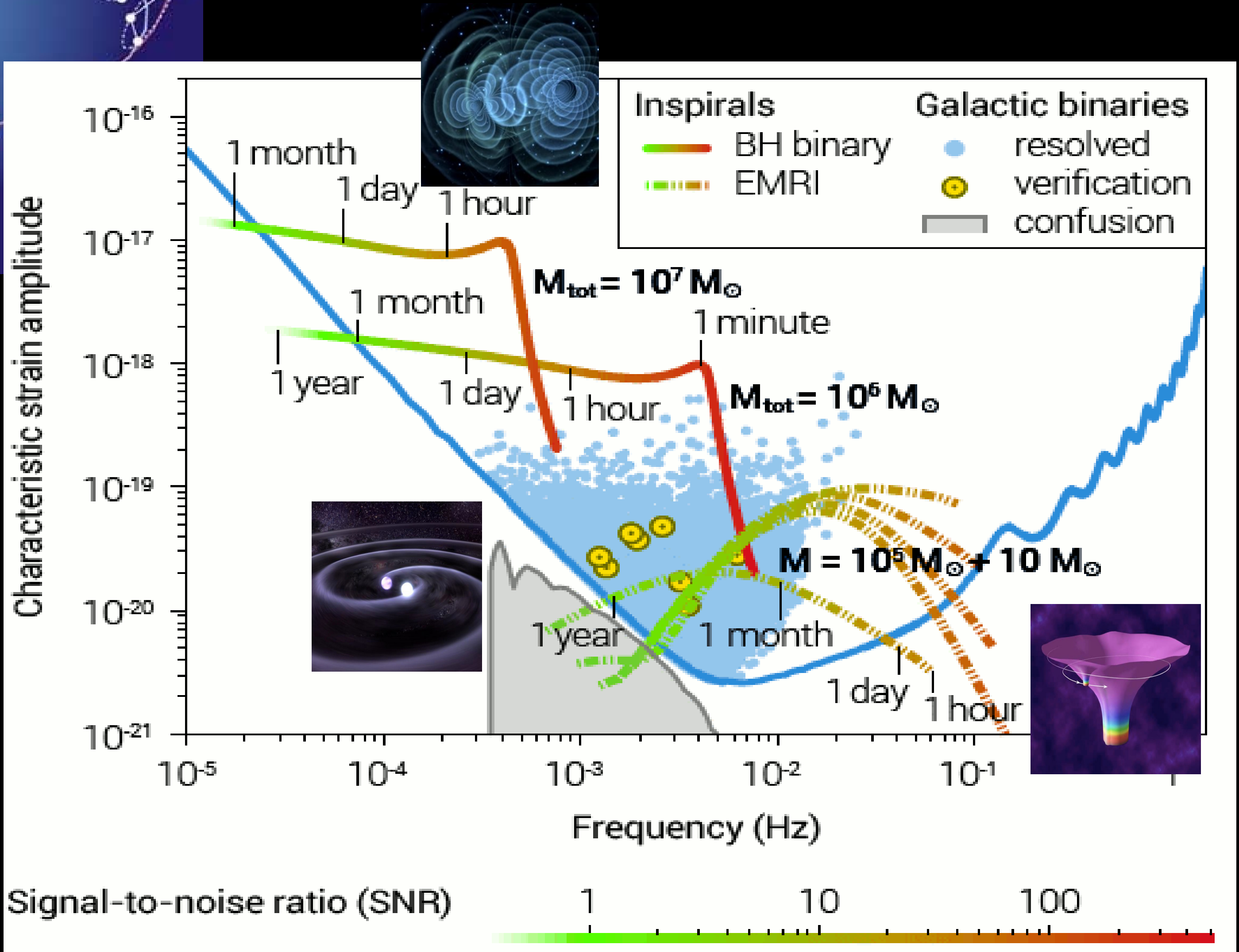
Interferometry in space:
evolved Laser Interferometer Space Antenna



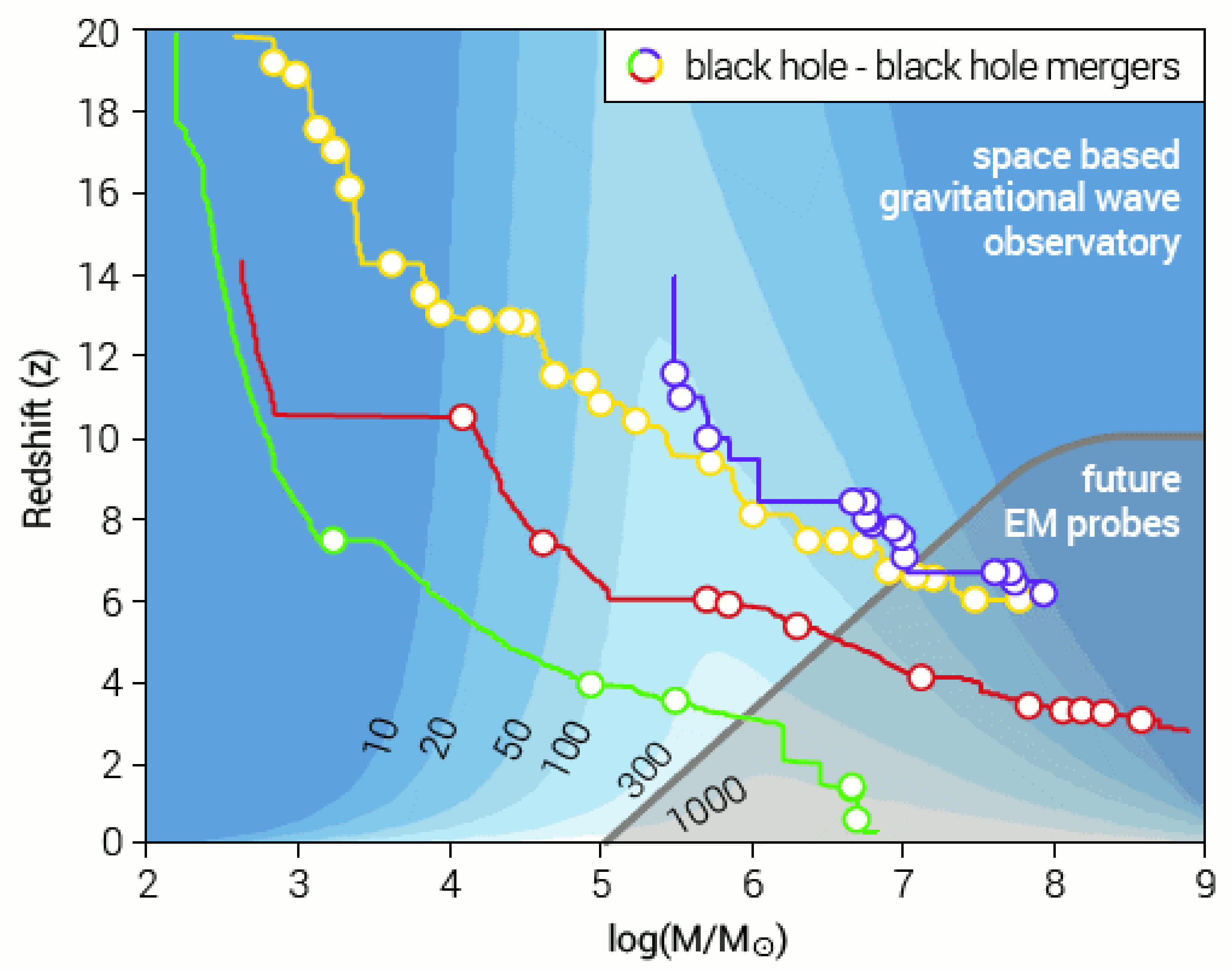
***eLISA* is sensitive at mHz frequency, where the evolution of MBH binaries is fast.**

***eLISA* will detect MBH binary inspirals and mergers.**

- **same orbit as *LISA***
- **1Gm armlength**
- **four laser links**
- **max 6 year lifetime**



eLISA coverage of the Universe



Detection rates

We consider 4 different formation models differing in:

1- MBH seeding mechanism (small vs large seeds)

2- Accretion geometry (efficient vs chaotic)

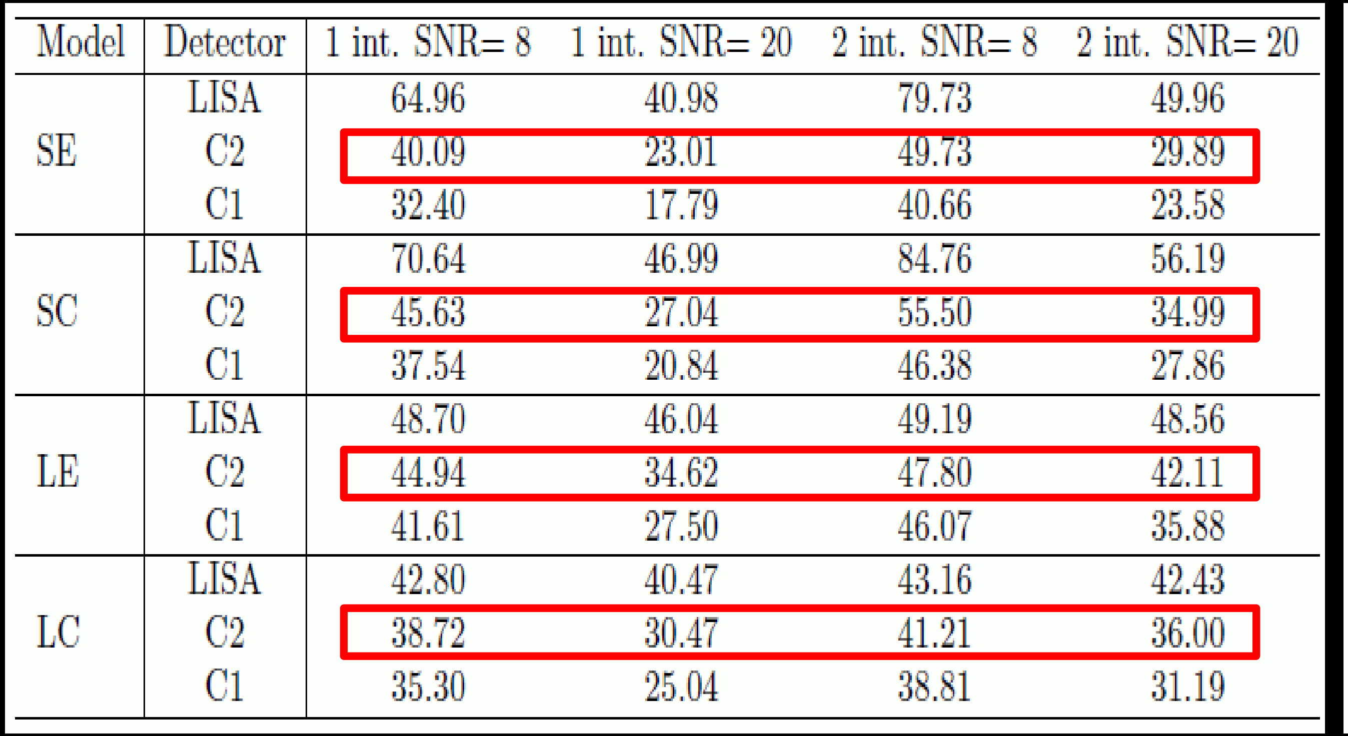
Models are named after the LISA PE taskforce paper:

1-SE: small seeds+efficient accretion

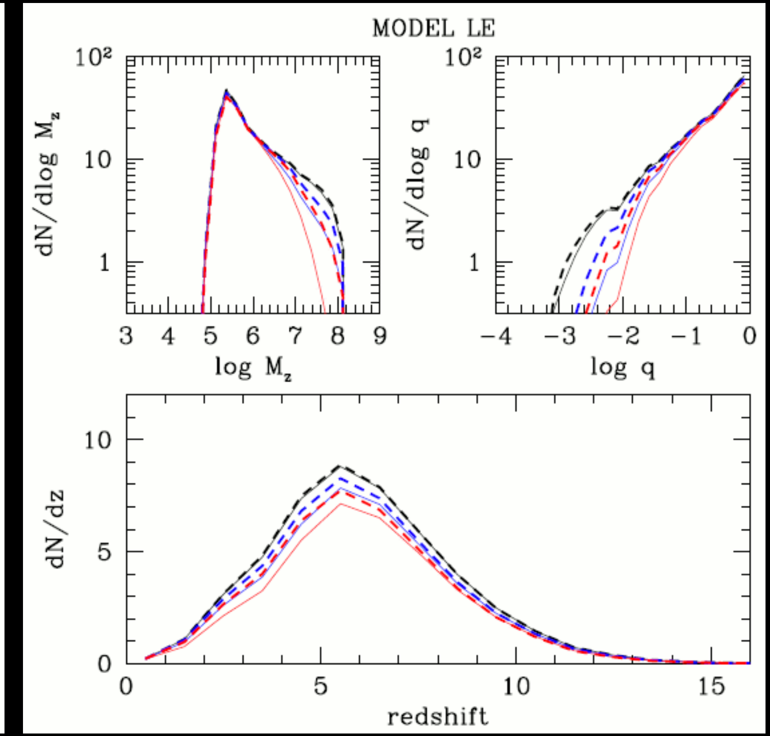
2-SC: small seeds+chaotic accretion

3-LE: large seeds+efficient accretion

4-LC: large seeds+chaotic accretion

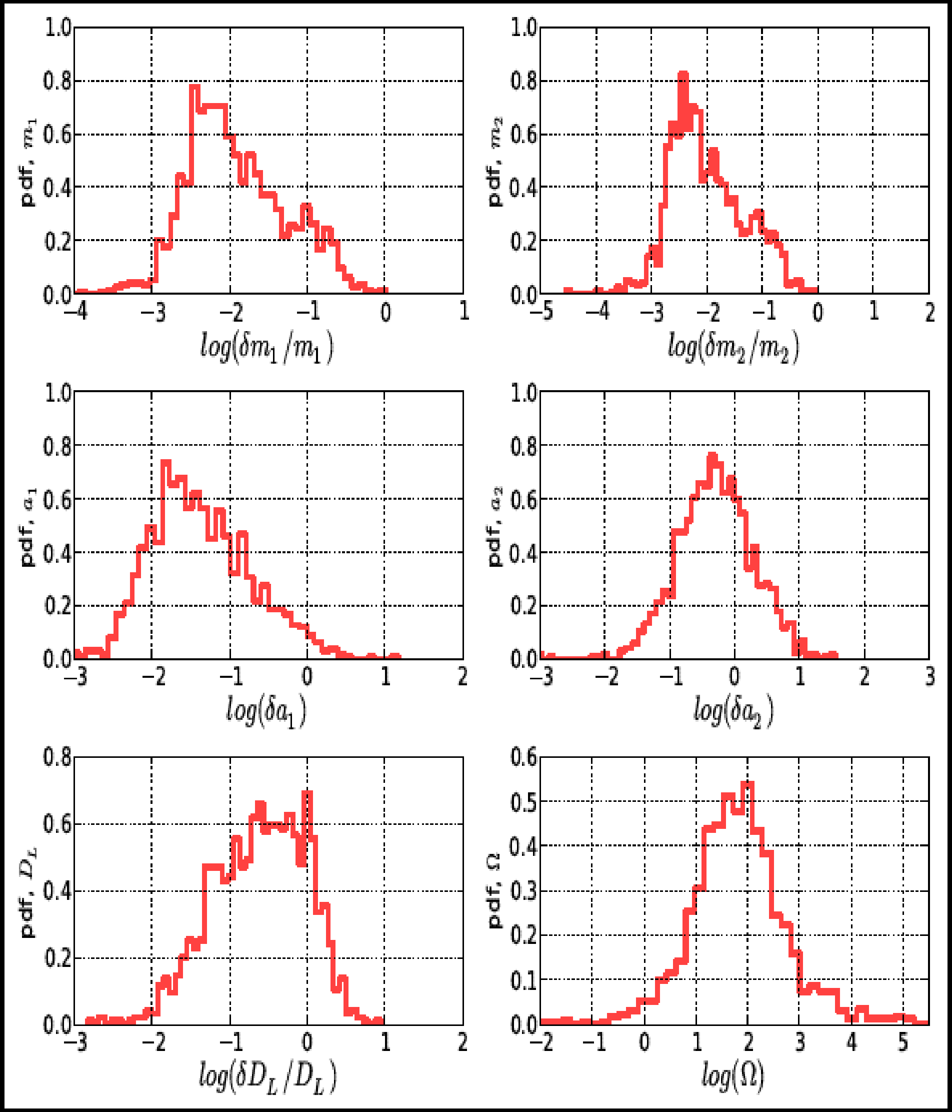


Model	Detector	1 int. SNR= 8	1 int. SNR= 20	2 int. SNR= 8	2 int. SNR= 20
SE	LISA	64.96	40.98	79.73	49.96
	C2	40.09	23.01	49.73	29.89
	C1	32.40	17.79	40.66	23.58
SC	LISA	70.64	46.99	84.76	56.19
	C2	45.63	27.04	55.50	34.99
	C1	37.54	20.84	46.38	27.86
LE	LISA	48.70	46.04	49.19	48.56
	C2	44.94	34.62	47.80	42.11
	C1	41.61	27.50	46.07	35.88
LC	LISA	42.80	40.47	43.16	42.43
	C2	38.72	30.47	41.21	36.00
	C1	35.30	25.04	38.81	31.19



Big uncertainties, see Koushiappas et al. 2005, AS et al. 2007, 2011

Parameter estimation: FIM results



**(Results by N. Cornish,
using spinning full IMR waveforms)**

eLISA will give us:

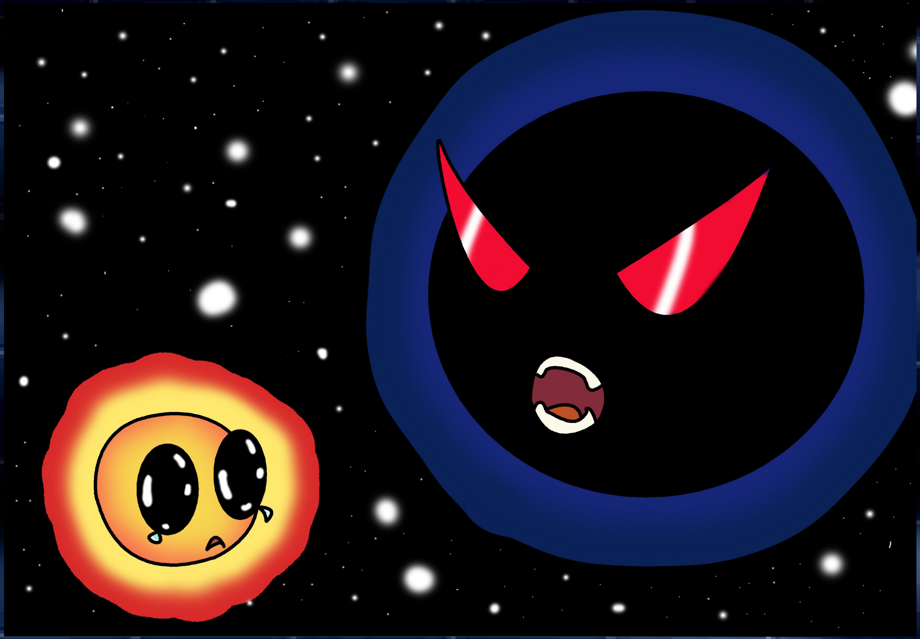
-Individual (redshifted) masses to <1% relative accuracy

-spin of the primary hole to <0.1 (in many cases to <0.01)

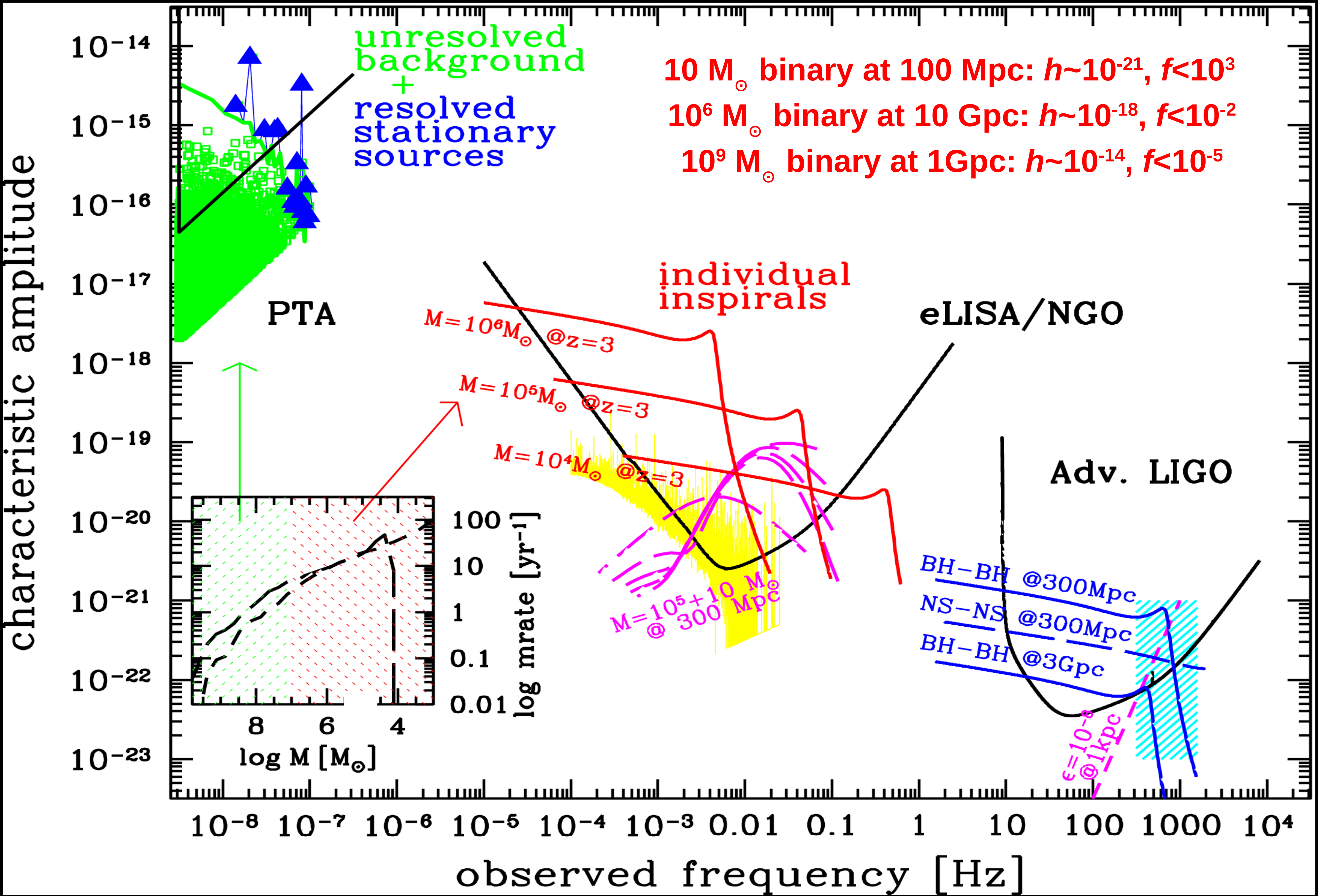
-sky location to 10-100 deg

-luminosity distance to <10% in many cases

Black hole beasts: PTA



Coverage of the GW spectrum



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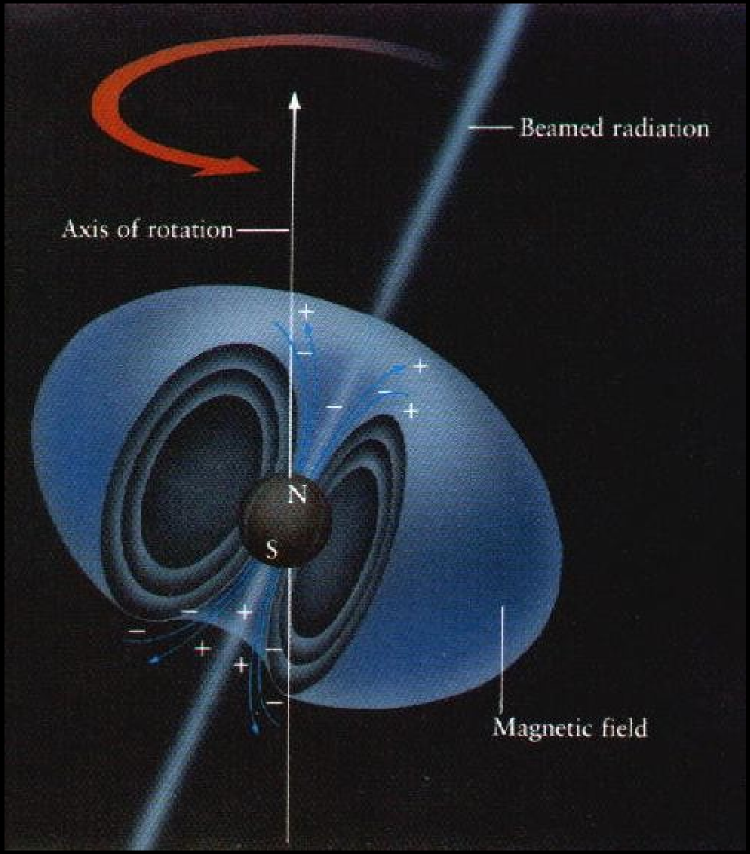
AS 2013

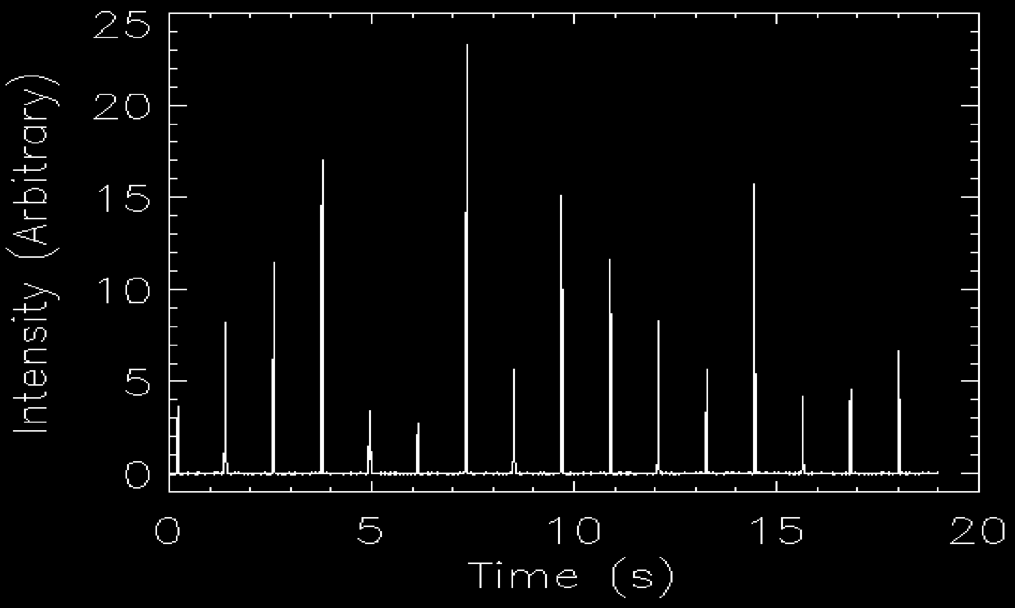
What is pulsar timing?

Pulsars are neutron stars that emit regular burst of radio radiation

Pulsar timing is the process of measuring the time of arrival (TOA) of each individual pulse and then subtracting off the expected time of arrival given a physical model for the system.

1- Observe a pulsar and measure the TOA of each pulse





2-Determine the model which best fits the TOA data

$$t_{\mathrm{e}}^{\mathrm{psr}} = t_{\mathrm{a}}^{\mathrm{obs}} - \Delta_{\odot} - \Delta_{\mathrm{IS}} - \Delta_{\mathrm{B}}.$$

The emission time at the pulsar is converted to the observed time at the Earth modelling several time delays due to:

- **-coordinate transformations**
- **-GR effects (e.g. Shapiro delay, PN binary dynamics)**
- **-Propagation uncertainties (e.g. Atmospheric delay, ISM dispersion)**

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3-Calculate the timing residual *R*

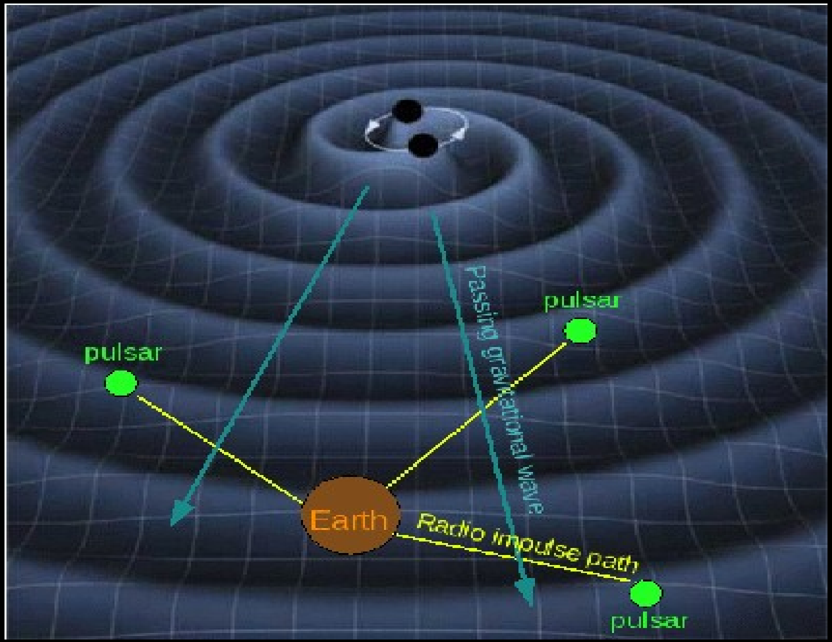
$$R = \mathrm{TOA} - \mathrm{TOA}_{\mathrm{m}}$$

If your model is perfect, then *R*=0. *R* contains all the uncertainties related to the signal propagation and detection plus the effect of unmodelled physics, like -possibly- *gravitational waves*

Timing residual from MBH binaries

The GW passage cause a modulation of the MSP frequency

$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p}, \hat{\Omega}) - h_{ab}(t_{\rm ssb}, \hat{\Omega})$$



The *residual* in the time of arrival of the pulse is the integral of the frequency modulation over time

$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0}\, dt$$

(Sazhin 1979, Helling & Downs 1983, Jenet et al. 2005, AS Vecchio & Volonteri 2009)

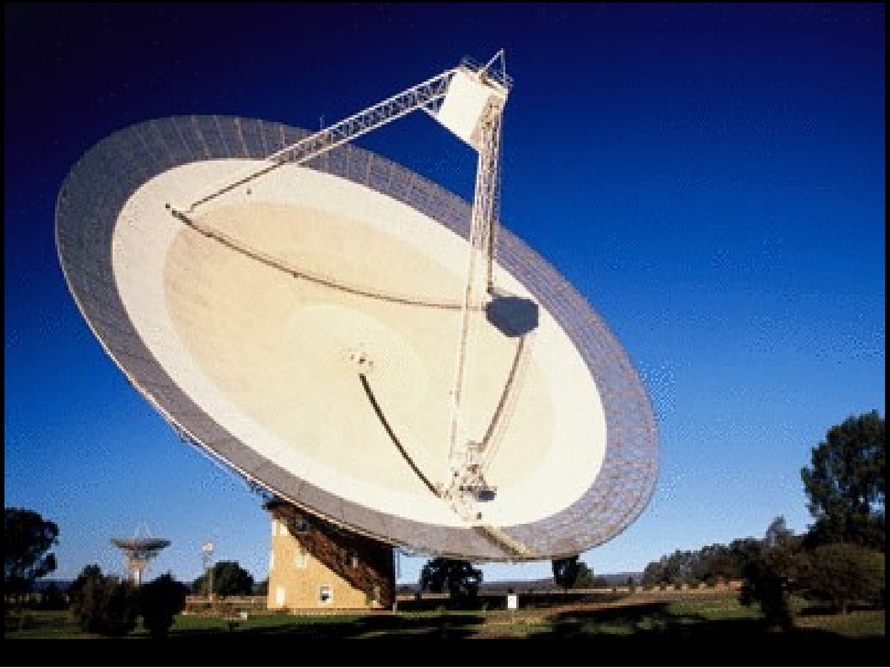
$$\begin{aligned} &= \frac{\mathcal{M}^{5/3}}{D} \left[\pi f(t)\right]^{-1/3} \\ &\simeq 25.7 \left(\frac{\mathcal{M}}{10^9\ M_\odot}\right)^{5/3} \left(\frac{D}{100\ \mathrm{Mpc}}\right)^{-1} \\ &\quad \times \left(\frac{f}{5\times 10^{-8}\ \mathrm{Hz}}\right)^{-1/3} \mathrm{ns} \end{aligned}$$

$R \sim h/(2\pi f)$

The pulsar timing arrays network

EPTA/LEAP (large European array for pulsars)

NanoGrav (north American nHz observatory for gravitational waves)



PPTA (Parkes pulsar timing array)

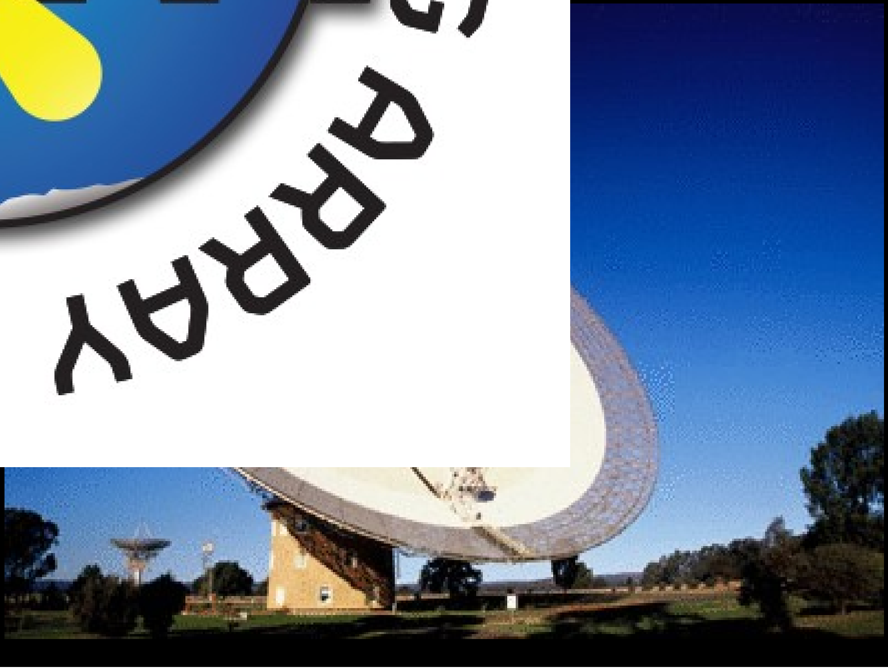
The pulsar timing arrays network

EPTA/LEAP (large European

INTERNATIONAL PULSAR TIMING ARRAY

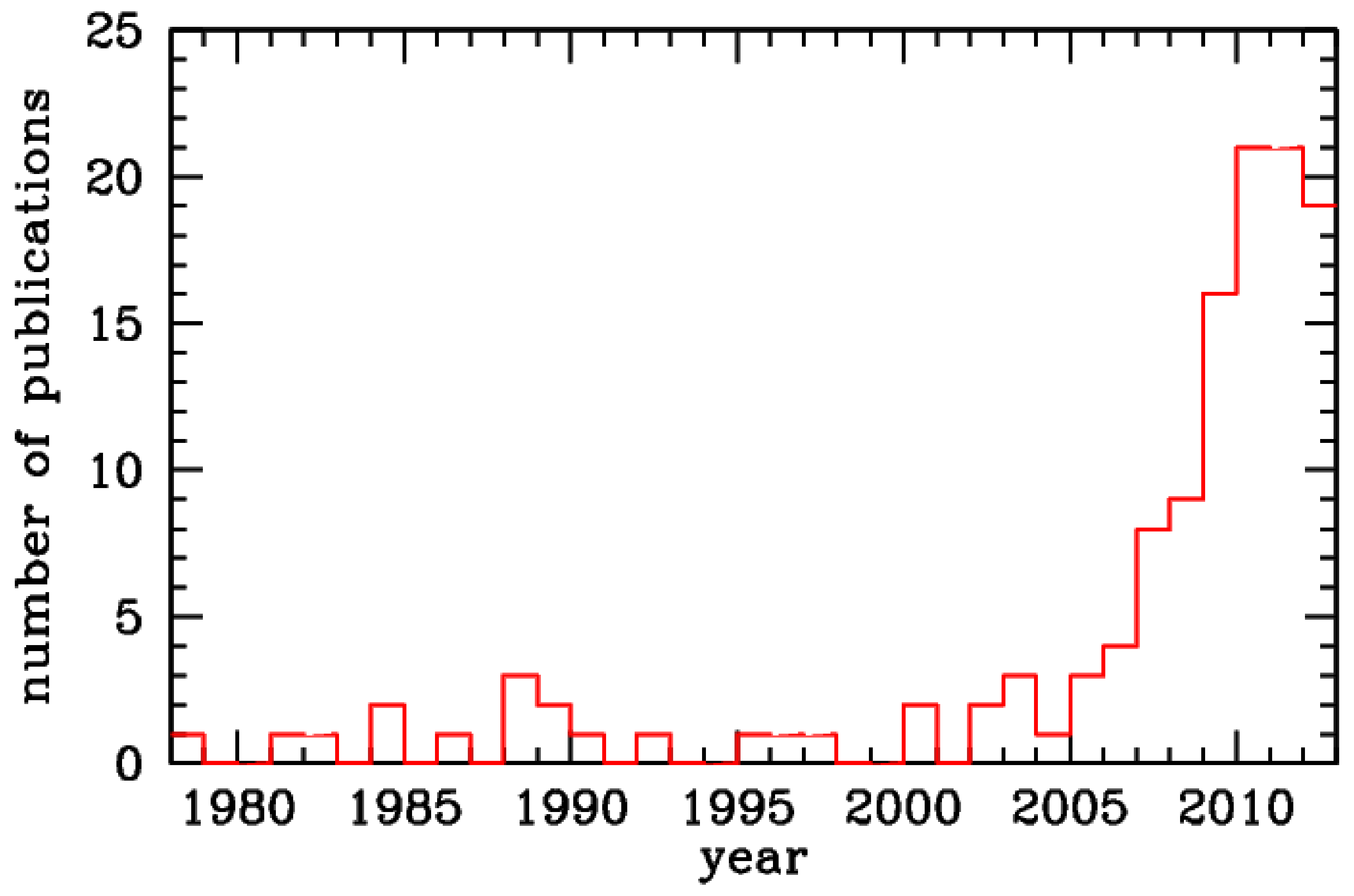
IPTA

rican nHz
onal waves)



PPTA (Parke

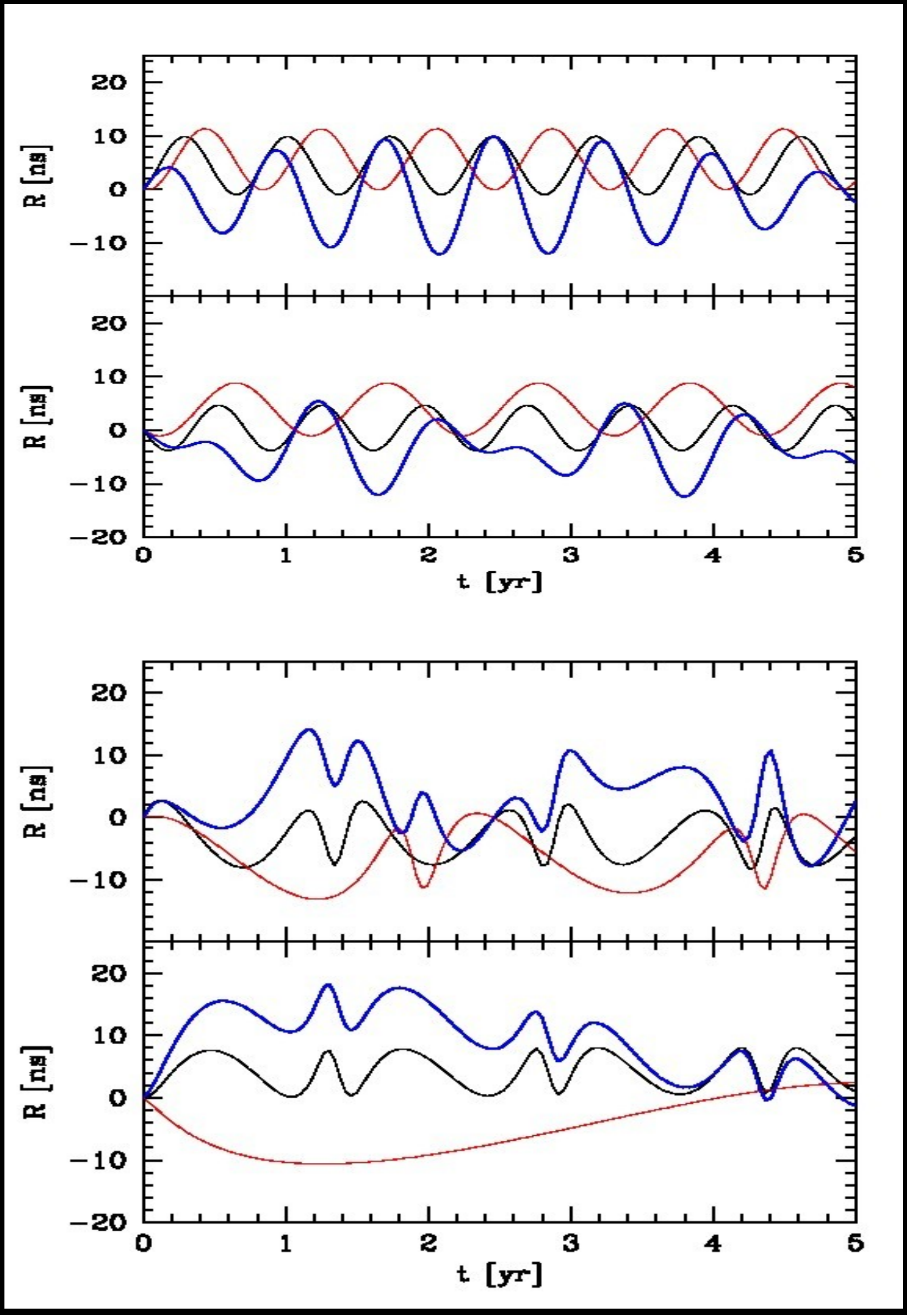
of papers found on the ADS containing both "pulsar timinng array" and "gravitational wave" in the title.



Numbers multiply by a factor of 10 if you consider the abstracts

Examples of signals

$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p},\hat{\Omega}) - h_{ab}(t_{\rm ssb},\hat{\Omega})$$



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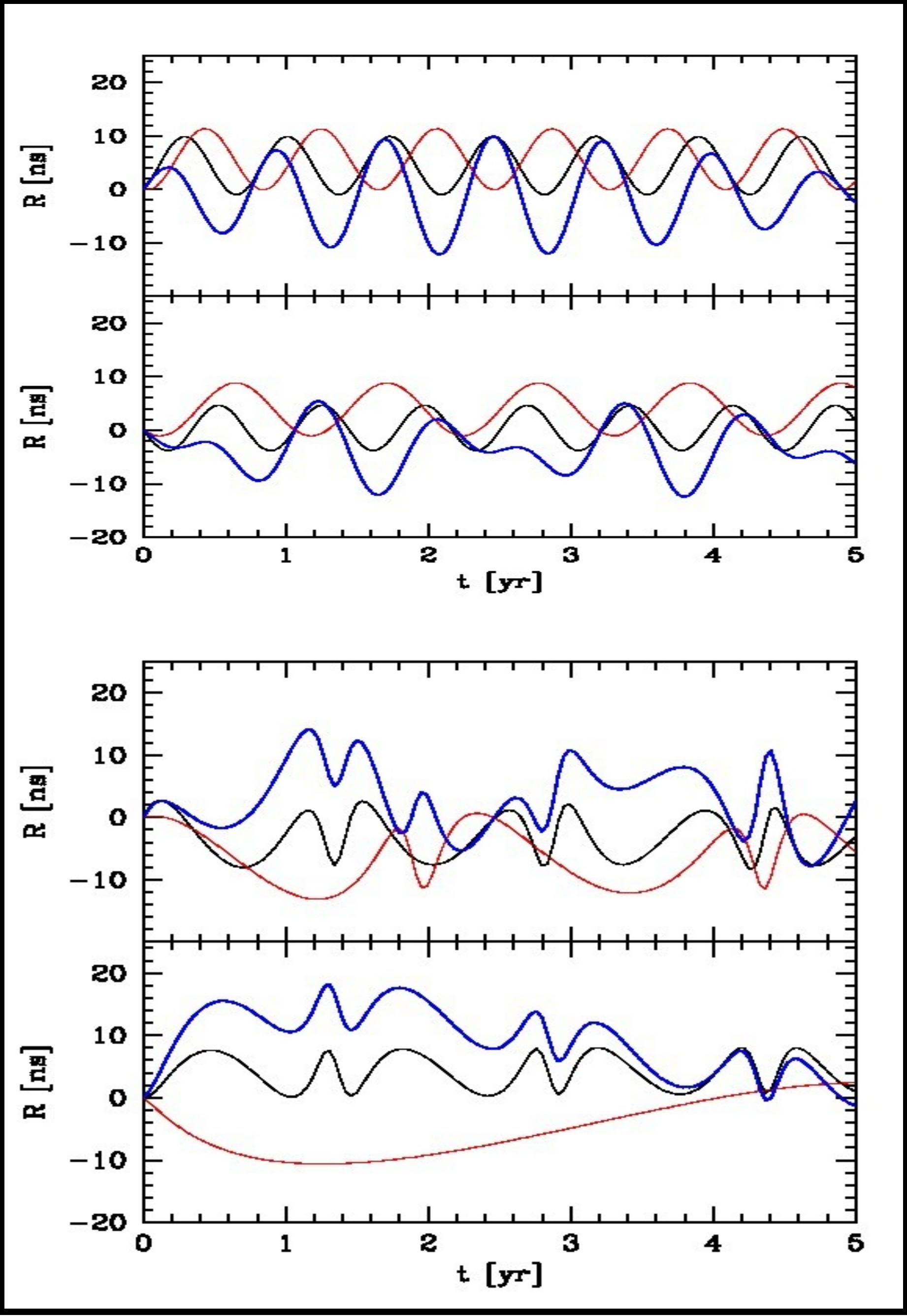
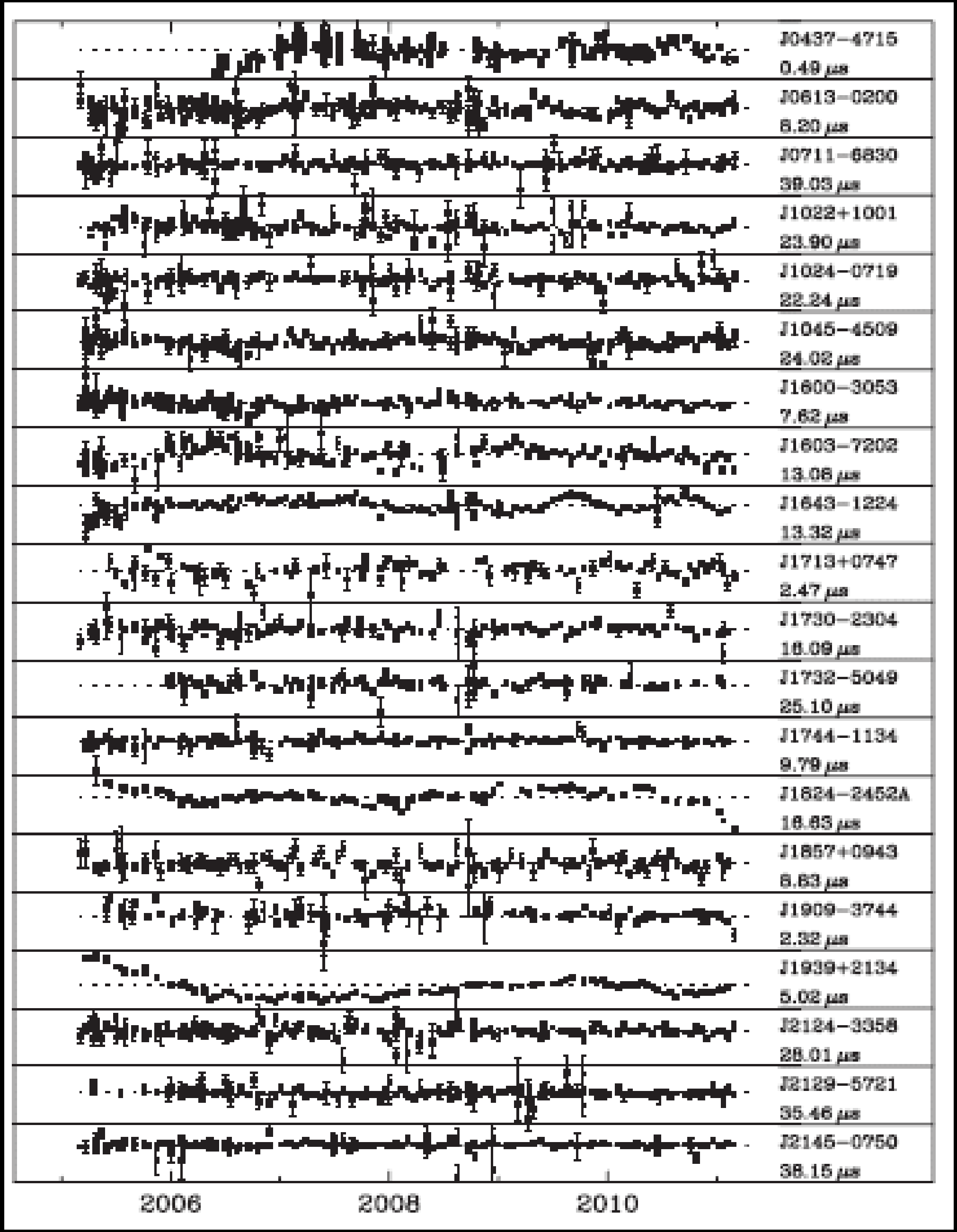


The cruel reality



Manchester et al. 2013

GW signal from a MBHB population

Characteristic amplitude of a GW signal coming from a certain source population

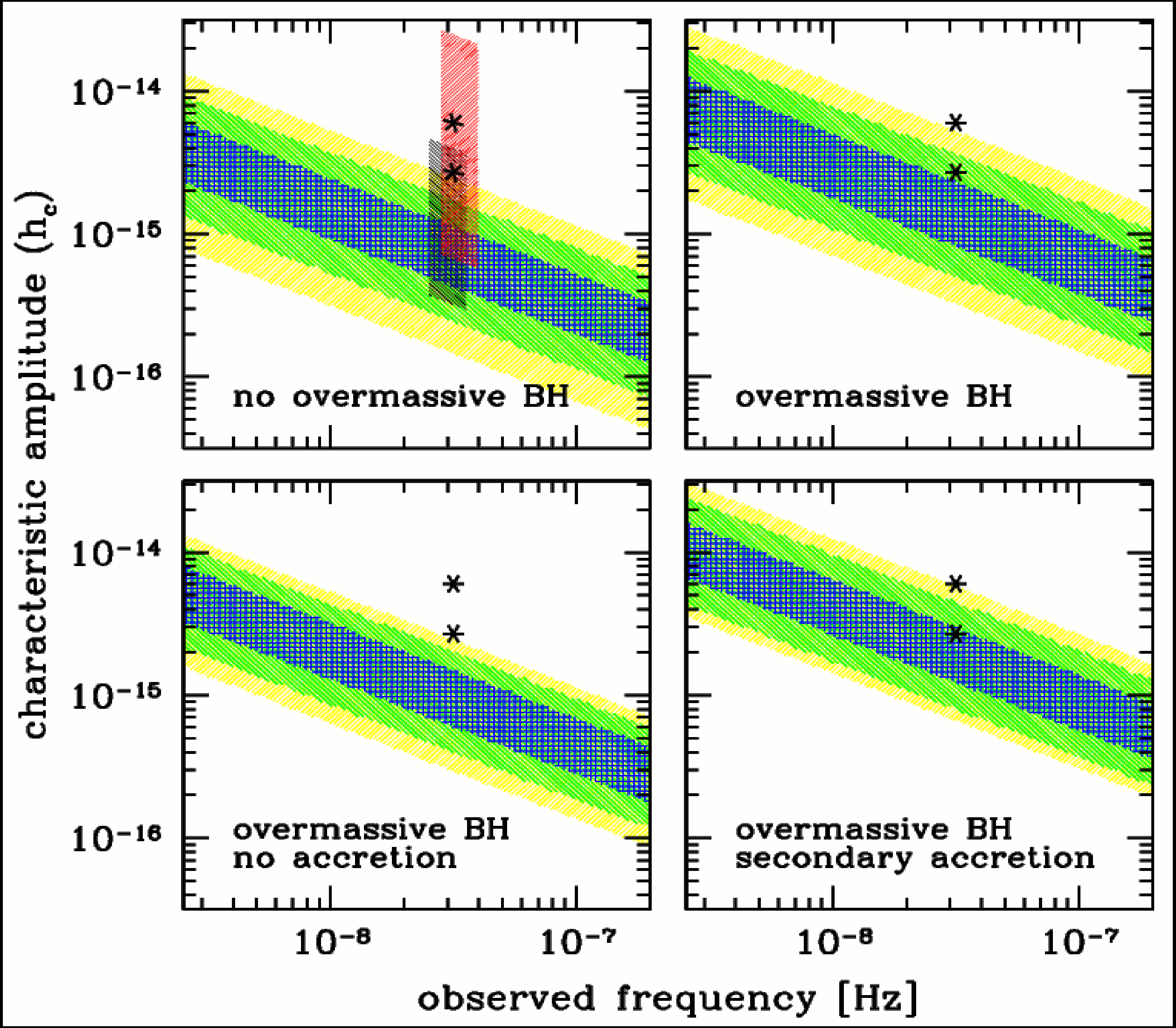
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

For circular GW driven MBHBs $dN/d\ln f \propto f^{-8/3}$

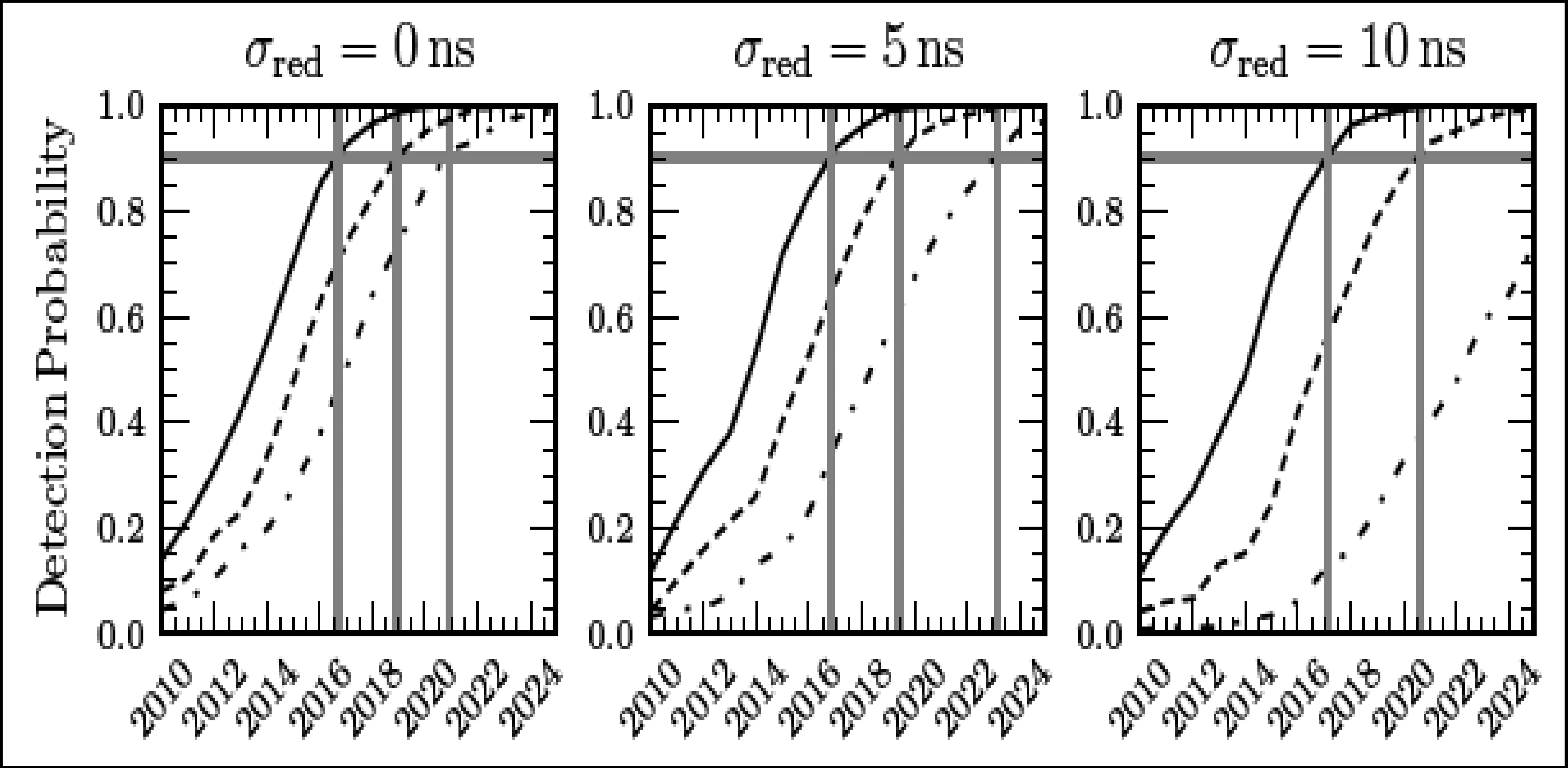
$$h_c(f) = A \left(\frac{f}{{\rm yr}^{-1}}\right)^{-2/3}$$

Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, AS et al. 2004, Enoki et al. 2004, Jenet et al 2005, 2006


characteristic amplitude (h_c)
10^{-14}
10^{-15}
10^{-16}
no overmassive BH
overmassive BH
overmassive BH
no accretion
overmassive BH
secondary accretion
10^{-8}
10^{-7}
observed frequency [Hz]

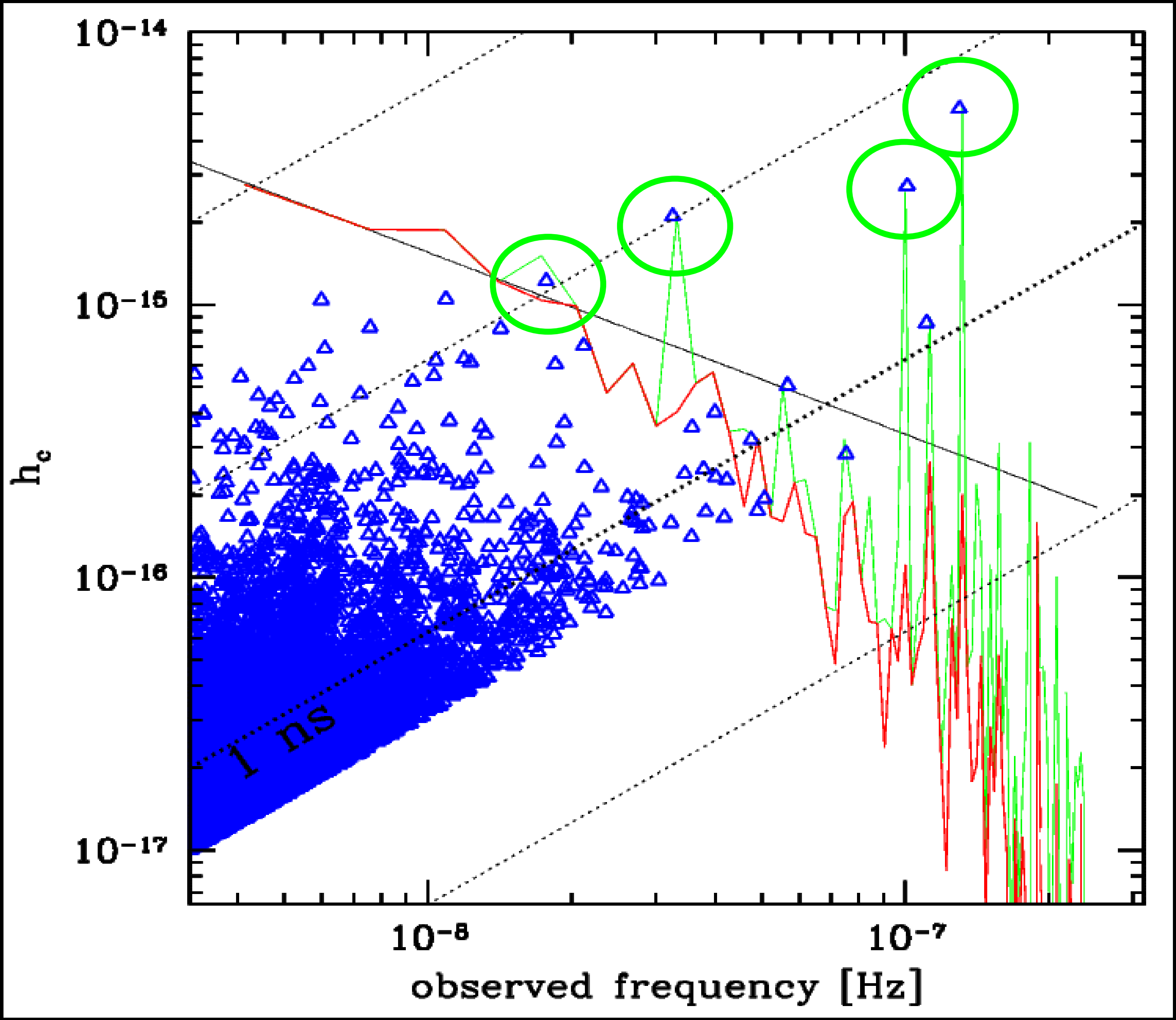
AS 2013

Plausible timescale for detection



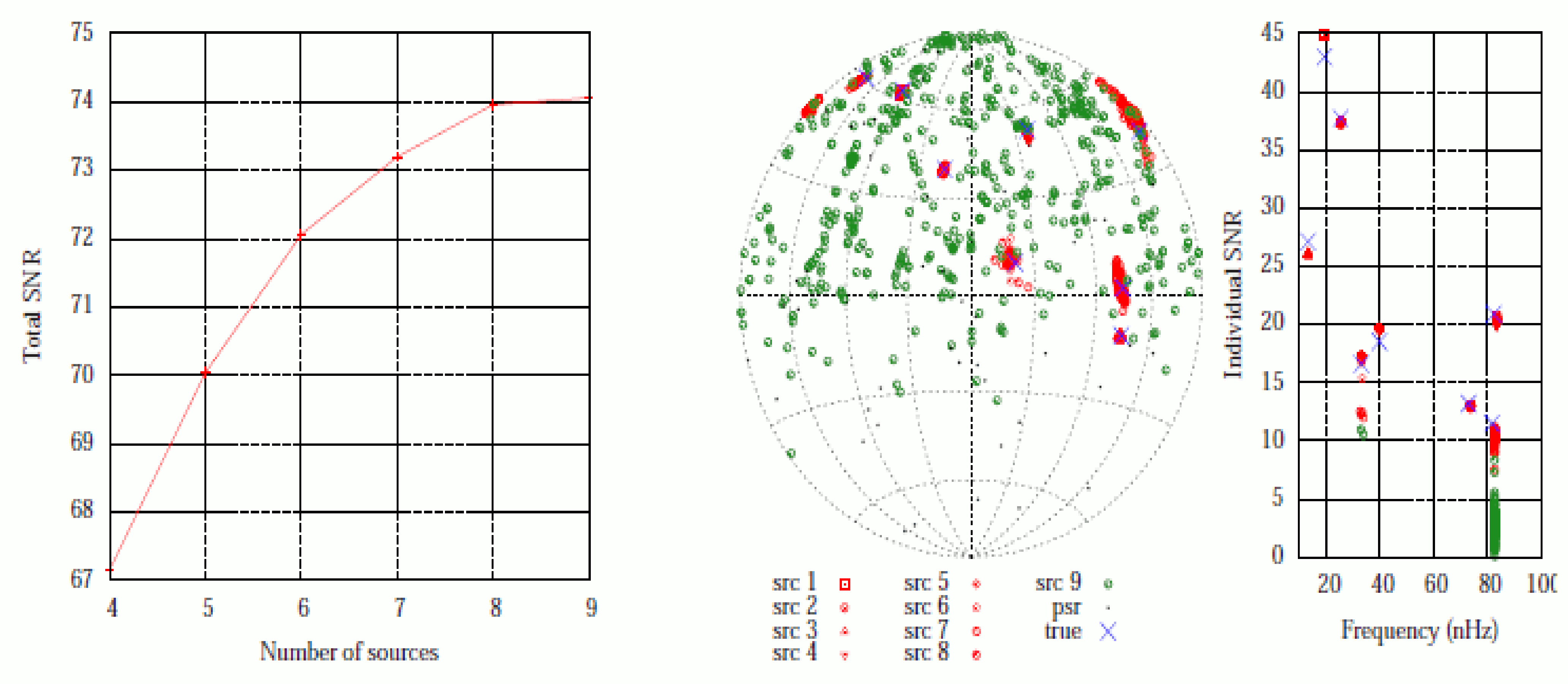
Siemens et al. 2013

Resolvable sources



Particularly bright sources might stand above the 'confusion noise' level generated by other sources

Babak & AS 2012, Petiteau et al. 2013, Ellis et al. 2012



-We recover the correct number of sources (no false positive)

-We can determine the source parameters with high accuracy:

> SNR within few%

> sky location within few deg offset

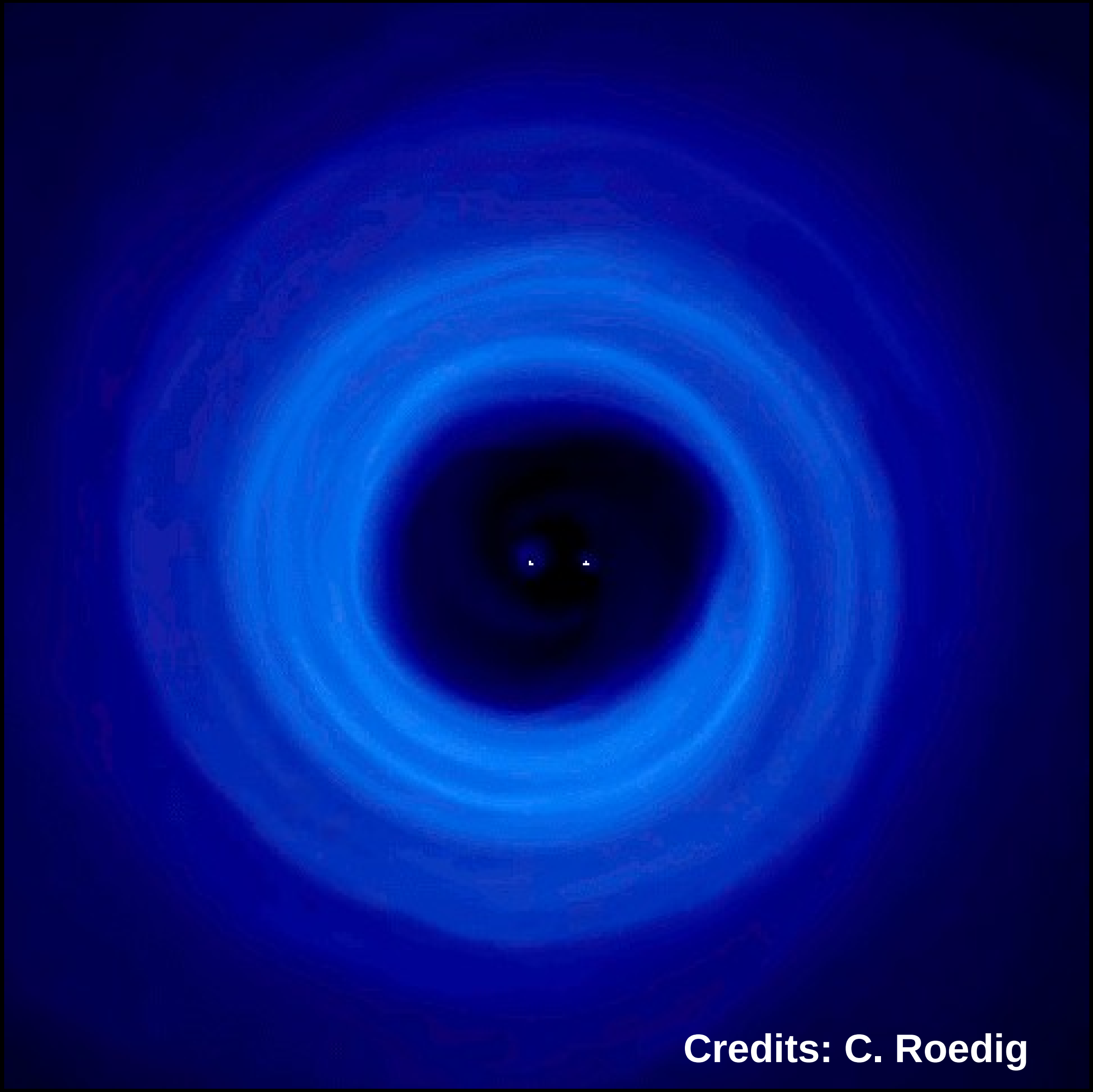
> frequency at sub-bin level

-Extremely promising, needs test on more realistic situations

ELECTROMAGNETIC COUNTERPARTS

Tanaka et al. 2012, AS et al. 2012

MBHB+circumbinary disk



Credits: C. Roedig

-Opt/IR dominated by the outer disk. Steady?

-UV generated by the Inner disks. Periodic variability.

-X ray corona. Periodic variability

-Variable broad emission lines (in response to the UV/X ionizing continuum)

-Double fluorescence 6.4keV $K\alpha$ iron lines

Summary

> We are *not yet* in a new era (nor in a golden age) of gravitational wave astronomy. But.....

(> Advanced ground based interferometer are expected to open the high frequency window, possibly detecting dozens of compact binaries per year.)

> Future space based interferometers (LISA like) will detect MBH binaries throughout the Universe.

> In the meantime PTAs might have a chance to make the very first GW detection (almost certainly the first low frequency one).