Massive black hole science with eLISA and pulsar timing

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In collaboration with EPTA, IPTA and the eLISA consortium

EPTA

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

Gravitational Wave Astronomy in Space
eLISA/NGO

OUTLINE

>Introduction to the massive black hole (MBH) hierarchical assembly

>Detecting the MBH babies with a space based GW interferometer (eLISA)

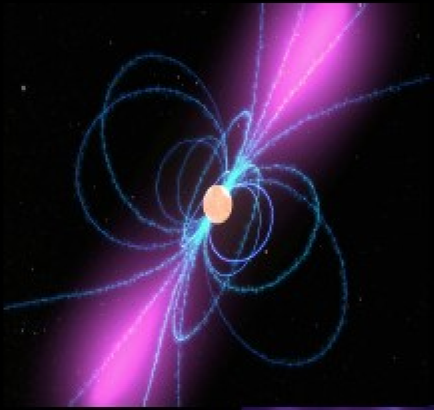
>Performance comparison for different eLISA designs

>Detecting the MBH beasts with precision timing of millisecond pulsars (PTA)

Gravitational wave sources

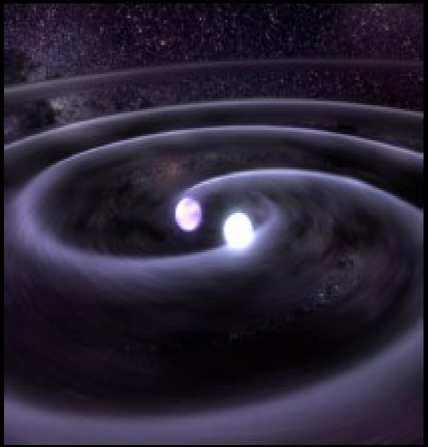
Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

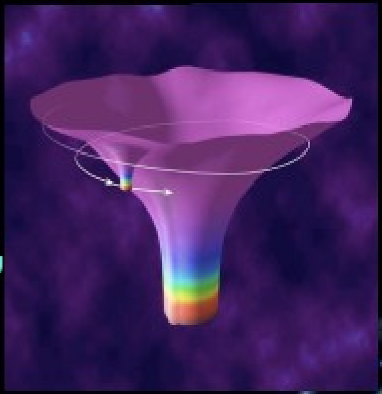


2-rotating asymmetric objects
(pulsars, MSPs)

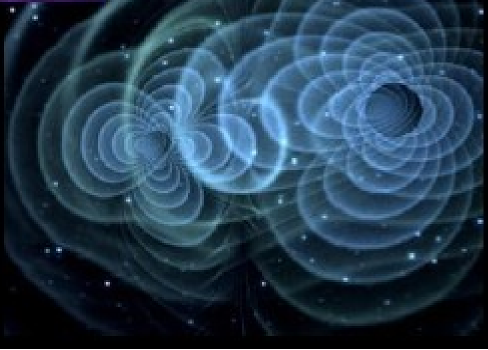
3-binary systems:



- a-stellar compact remnants
  (WD-WD, NS-NS, NS-BH, BH-BH)



- b-extreme mass ratio inspirals (EMRIs),
  CO falling into a massive black hole



- c-massive black hole binaries (MBHBs)
  forming following galaxy mergers

Heuristic scalings

We want compact accelerating systems
Consider a BH binary of mass M, and semimajor axis a

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

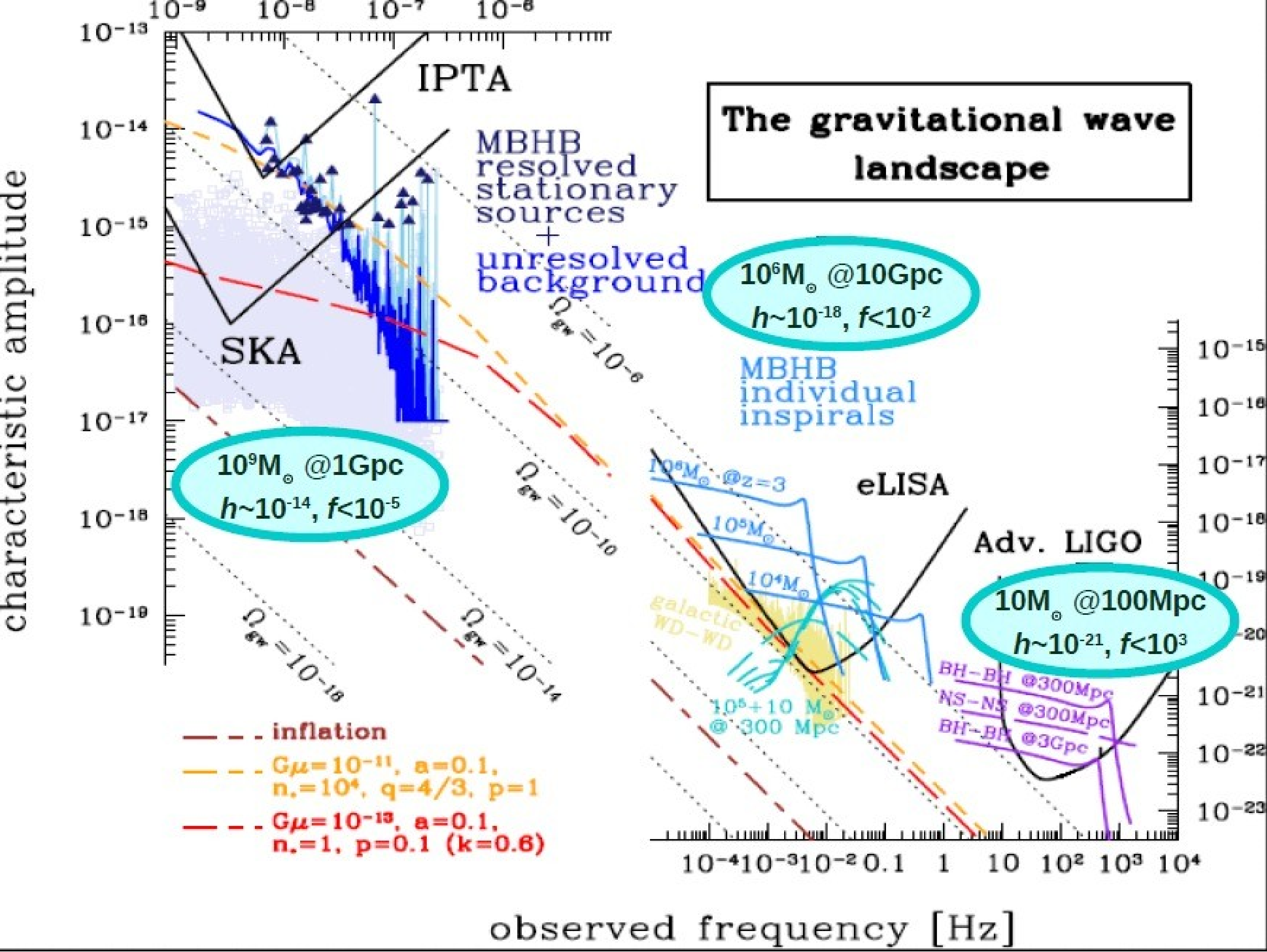
In astrophysical scales

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

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

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: $h \sim 10^{-14}$, $f < 10^{-5}$

The gravitational wave landscape

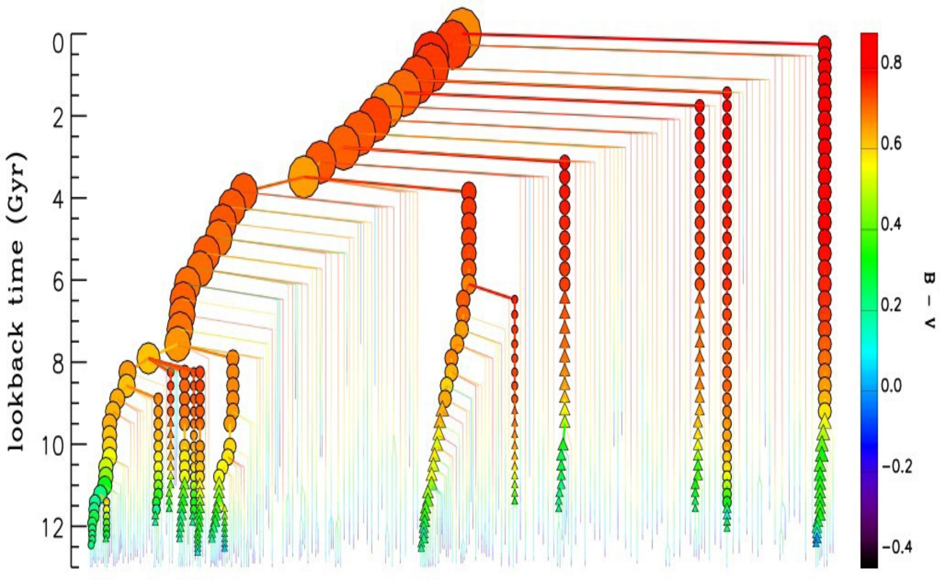


$10^6 M_\odot$ @10Gpc
$h \sim 10^{-18}$, $f < 10^{-2}$

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

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

Structure formation in a nutshell



(From de Lucia et al. 2006)

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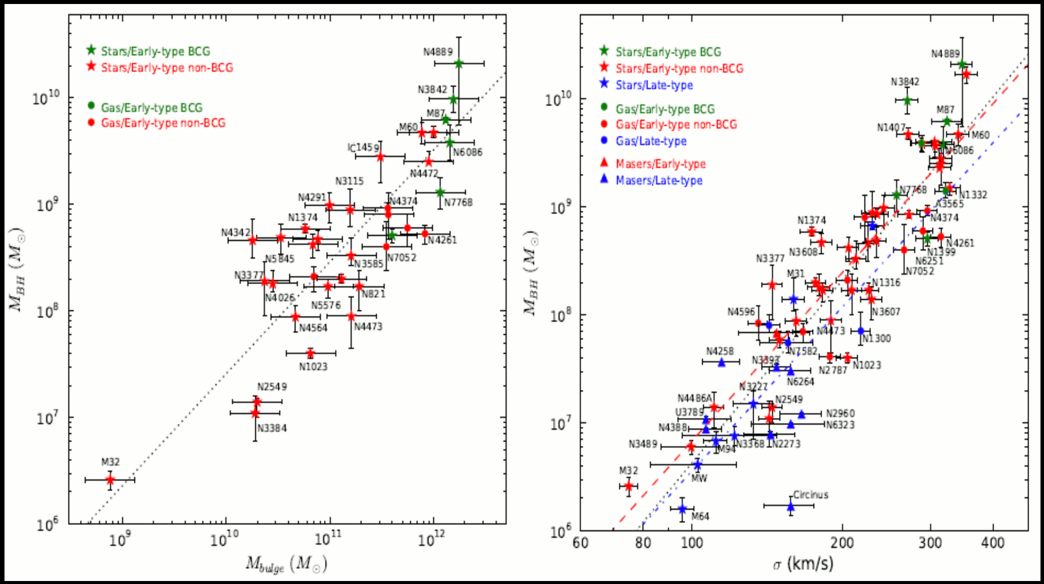

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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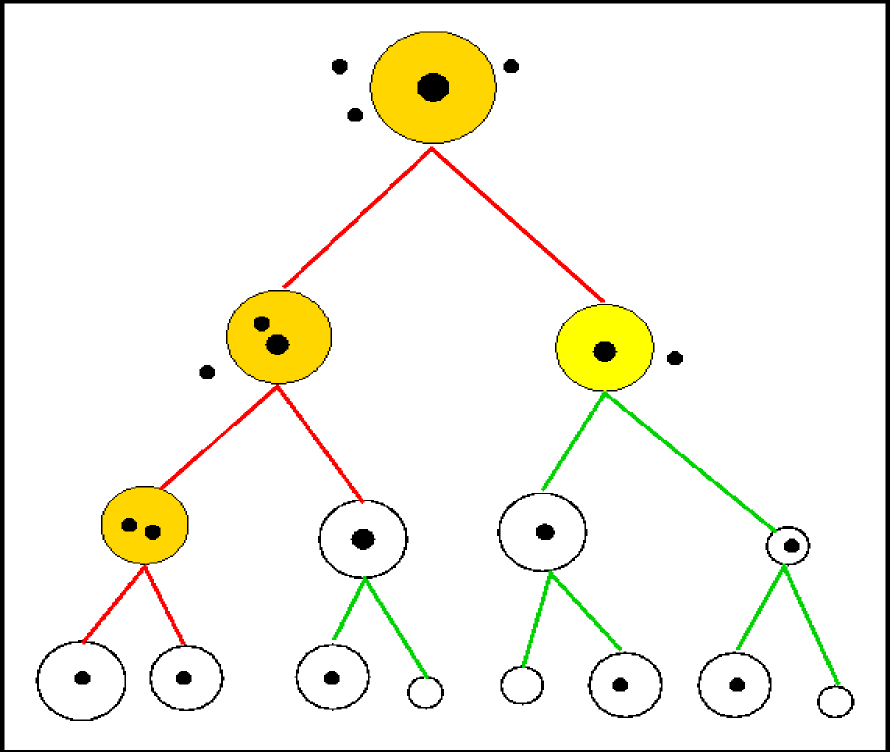
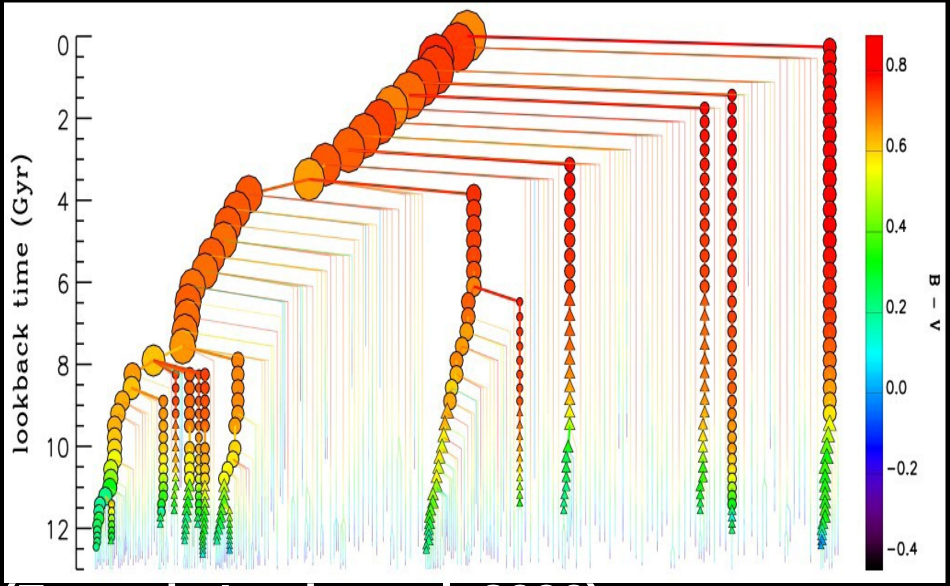


(Menou et al 2001, Volonteri et al. 2003)

Structure formation in a nutshell



(From de Lucia et al. 2006)

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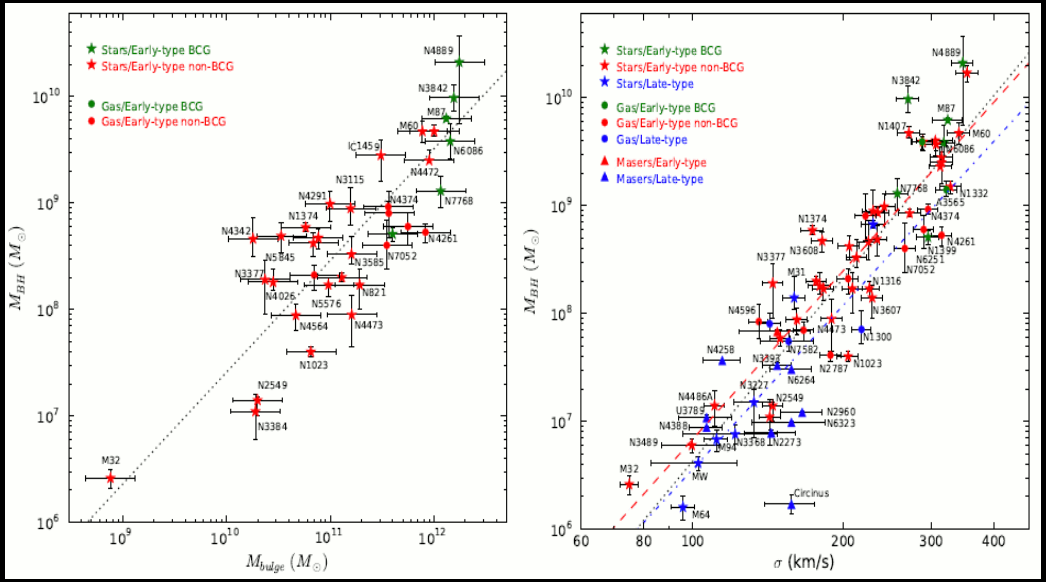

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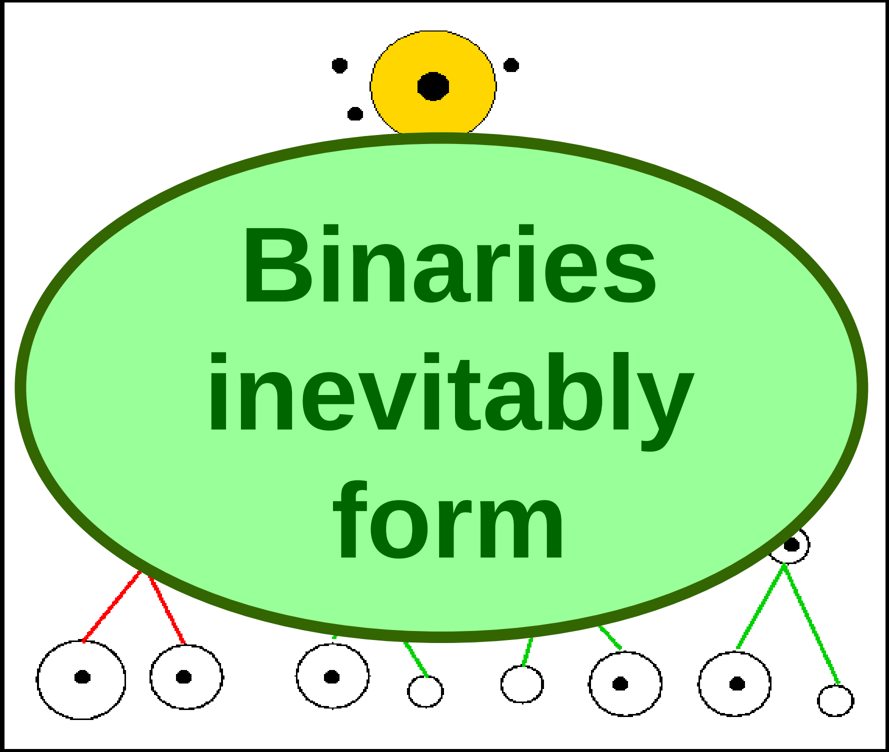


Binaries inevitably form

(Menou et al 2001, Volonteri et al. 2003)

*Where and when do the first MBH seeds form?

*How do they grow along the cosmic history?

*What is their role in galaxy evolution?

*What is their merger rate?

*How do they pair together and dynamically evolve?

Baby black hole science with space based laser interferometry (eLISA)

(The eLISA Consortium, arXiv:1305.5720)

Baby black hole science with space based laser interferometry (eLISA)

(The eLISA Consortium, arXiv:1305.5720)

Baby Black Hole Adoption Certificate

To:

From:

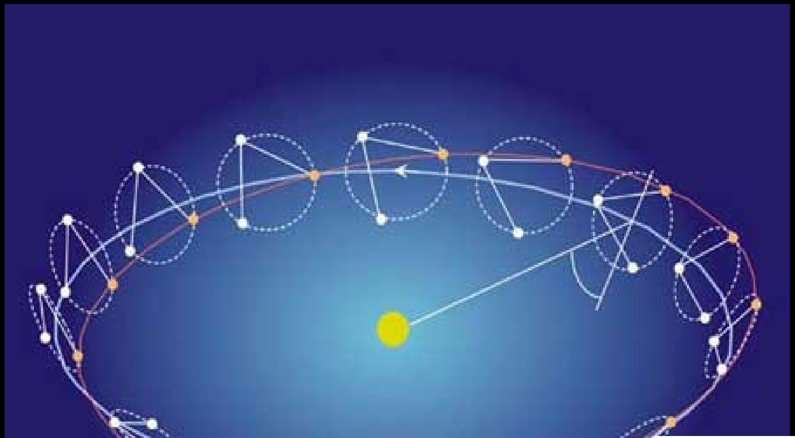
WARNING: Please wear the appropriate protective equipment whilst opening the transportation container. Do not place near any significant mass. Do not allow small children to approach its event horizon unsupervised.

www.ButterflyLove1.etsy.com

Baby black hole science with space based laser interferometry (eLISA)

(The eLISA Consortium, arXiv:1305.5720)

The evolving Laser Interferometer Space Antenna

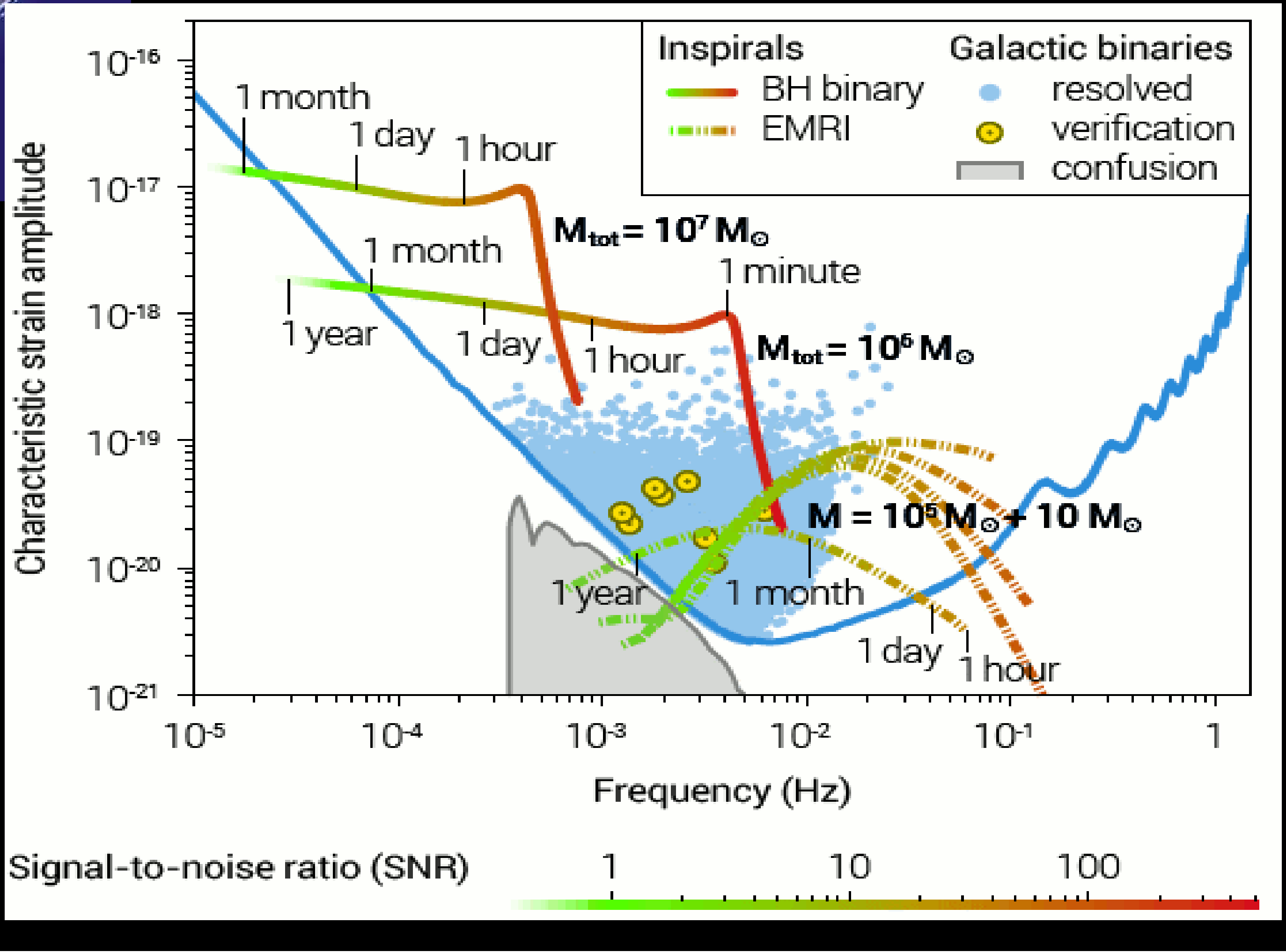


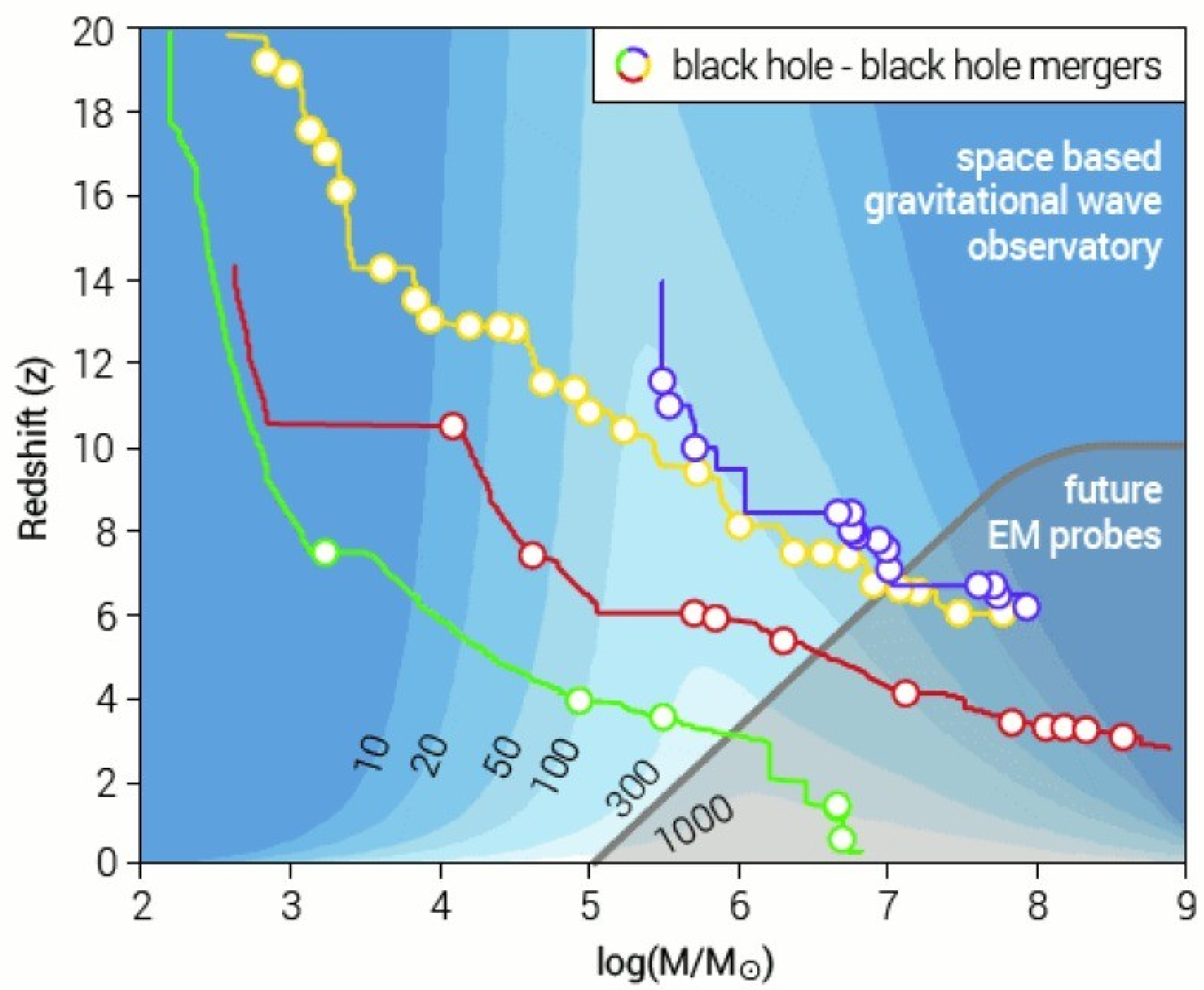
Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

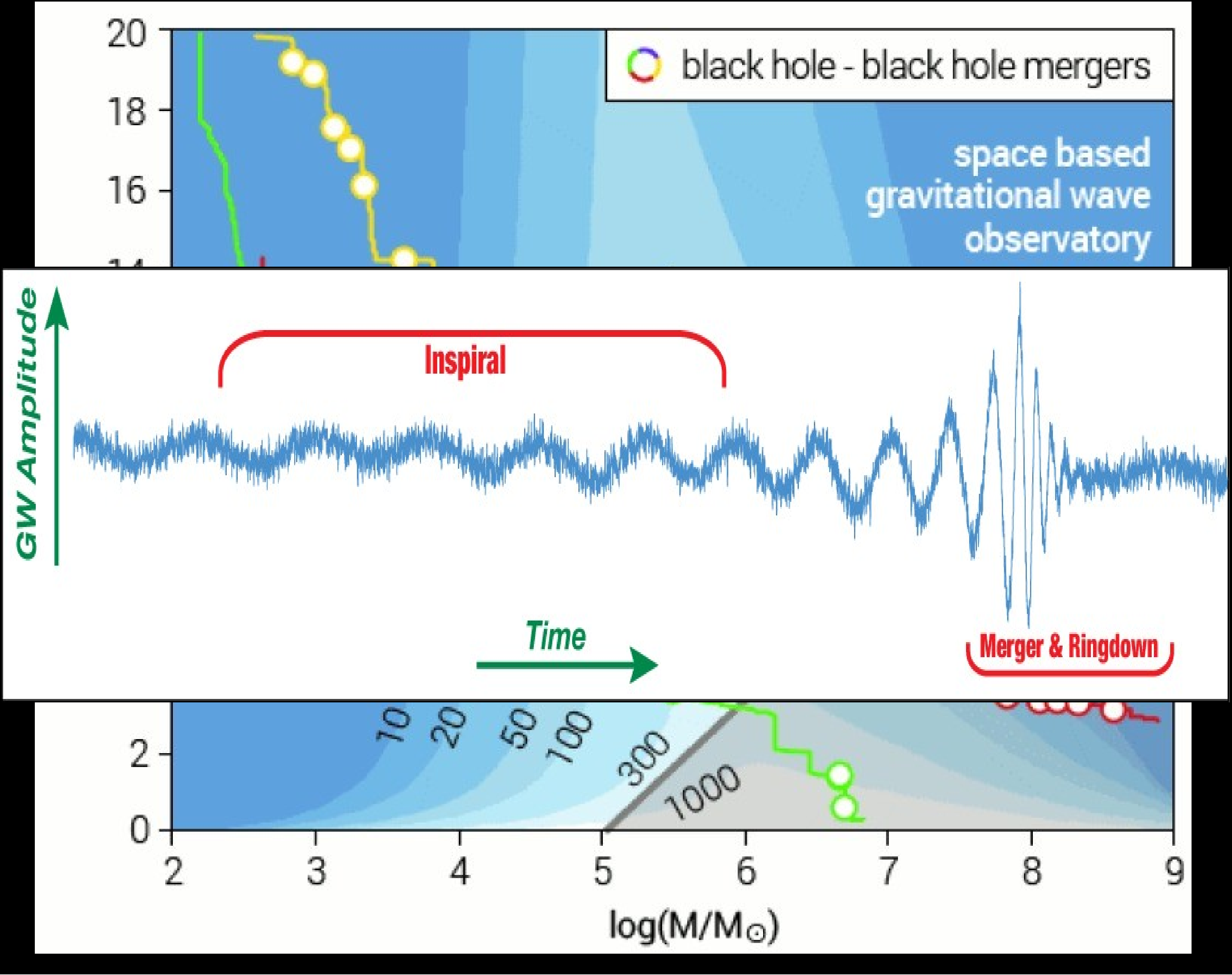
Observes the full inspiral/merger/ringdown

3 satellites trailing the Earth connected through laser links

Baseline not yet decided, currently under study




black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
0
2
4
6
8
10
12
14
16
18
20
log(M/M⊙)
2
3
4
5
6
7
8
9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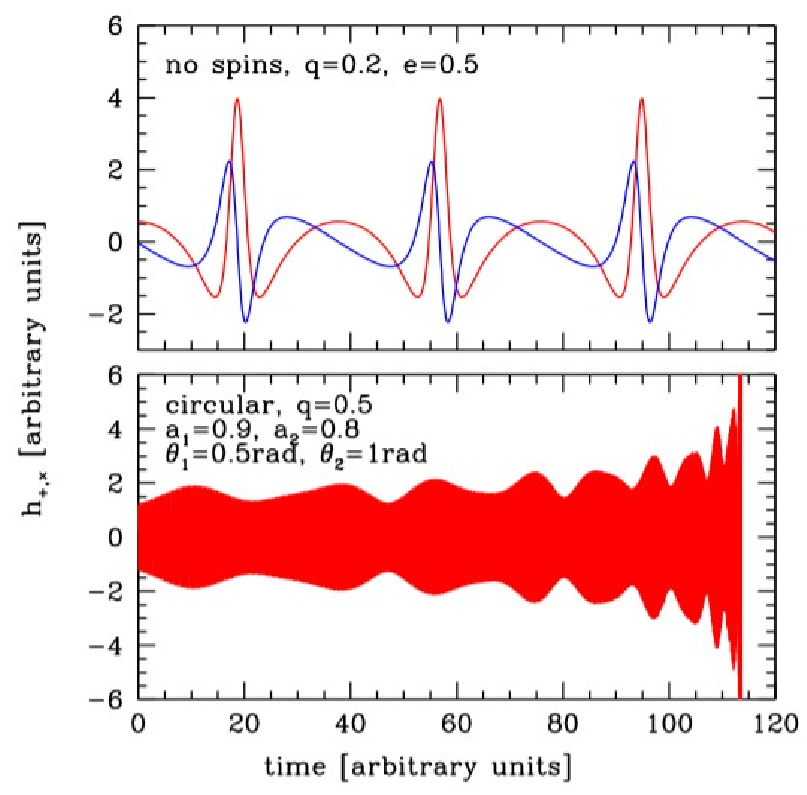
20
18
16
2
0
2
3
4
5
6
7
8
9
log(M/M⊙)
10
20
50
100
300
1000
GW Amplitude
Inspiral
Time
Merger & Ringdown

Extraction of information from the waveform



>Masses have the largest impact on the phase modulation

>Eccentricity impacts the waveform and the phase modulation

>Spins impact the waveform and the phase modulation (but weaker effect)

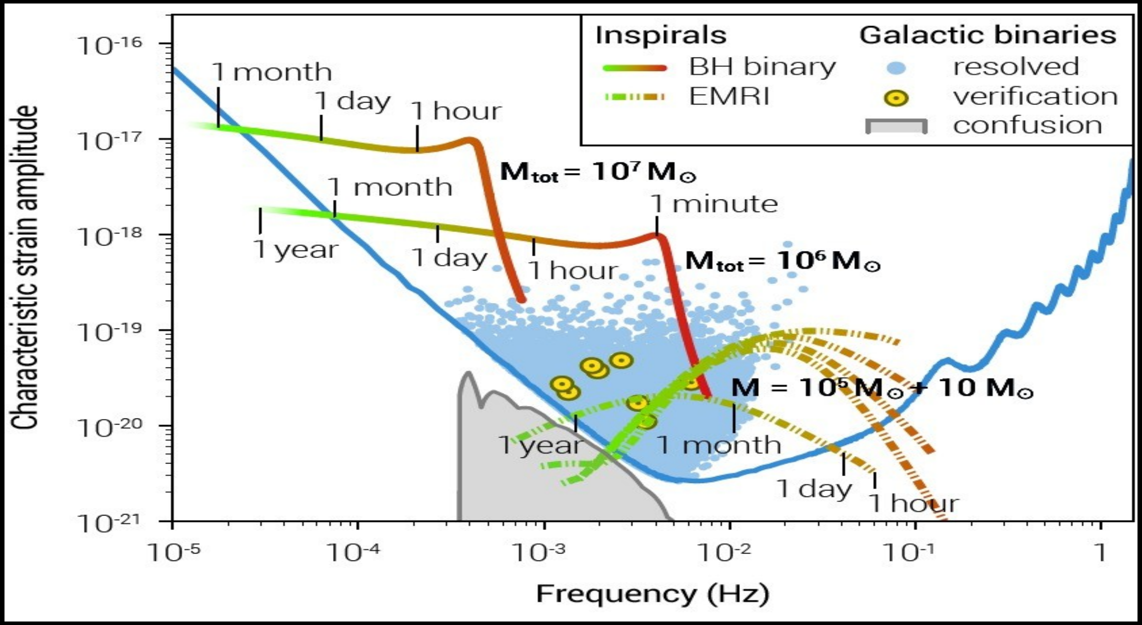
Depend on the number of cycles and SNR, can be easily measured with high precision

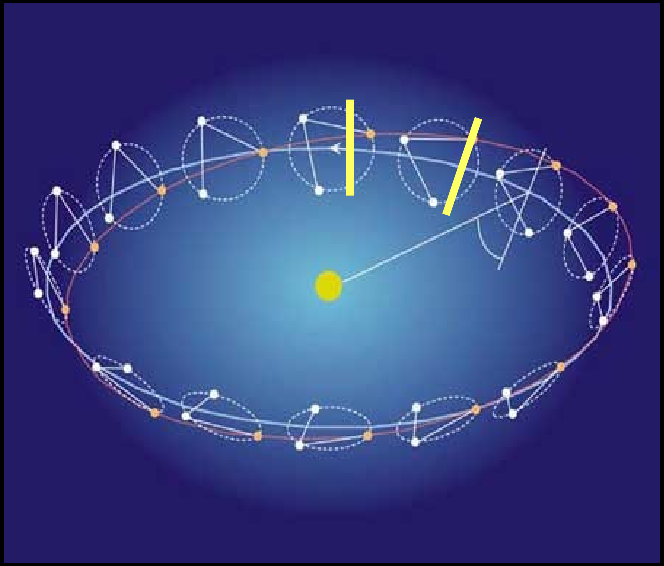
>Sky location impacts the waveform modulation over time through antenna beam pattern

>Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination)

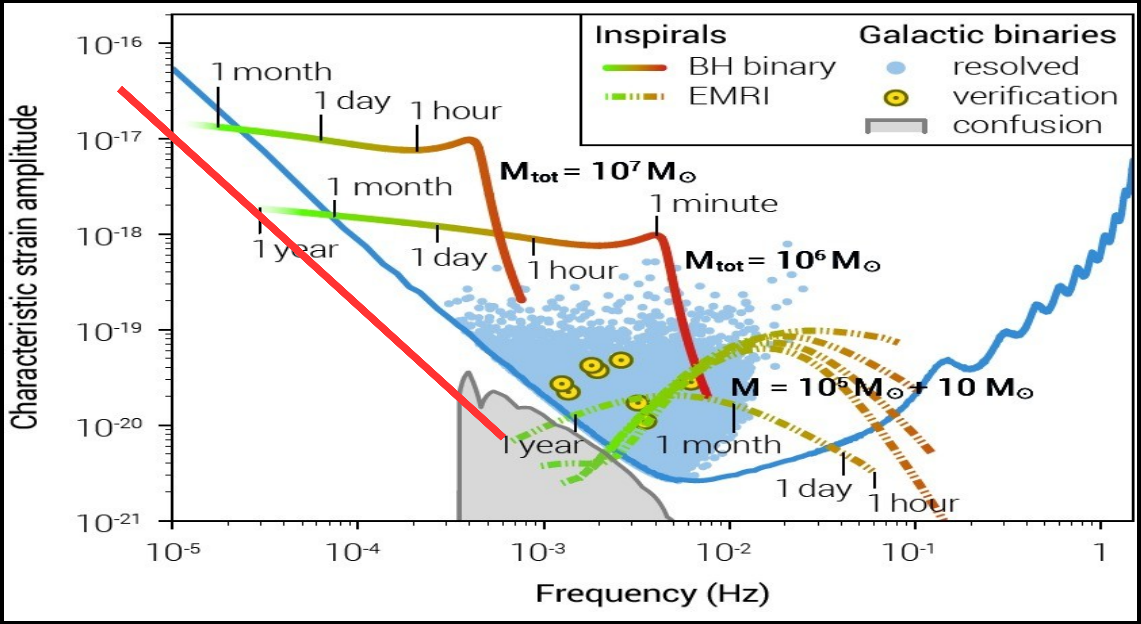
Depend on the time in band, polarization disentanglement, SNR.
Measurement is more difficult.
For MBH binaries, strong impact of having: 1) longer baseline
2) 6 laser links

Baseline


Inspirals
BH binary
EMRI
Galactic binaries
resolved
verification
confusion
1 month
1 day
1 hour
$M_{tot} = 10^7 M_\odot$
1 month
1 minute
1 year
1 day
1 hour
$M_{tot} = 10^6 M_\odot$
$M = 10^5 M_\odot + 10 M_\odot$
1 year
1 month
1 day
1 hour
Characteristic strain amplitude
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Frequency (Hz)



Baseline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$M_{tot} = 10^7 M_\odot$
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1 year
1 day
1 hour
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$M = 10^5 M_\odot + 10 M_\odot$
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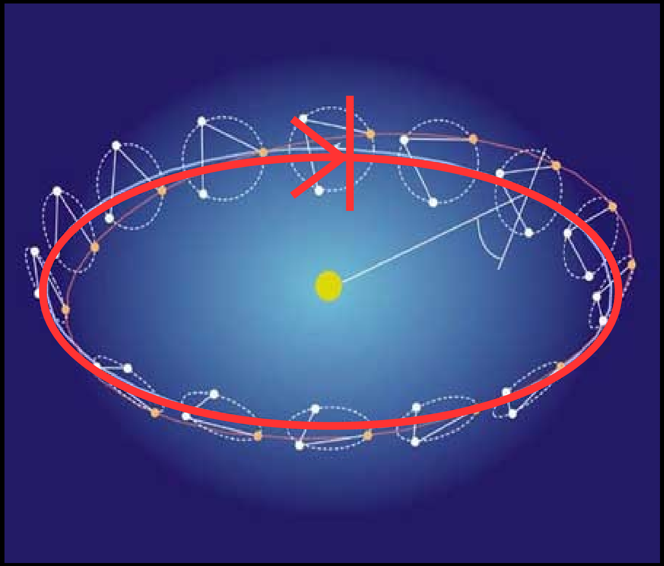
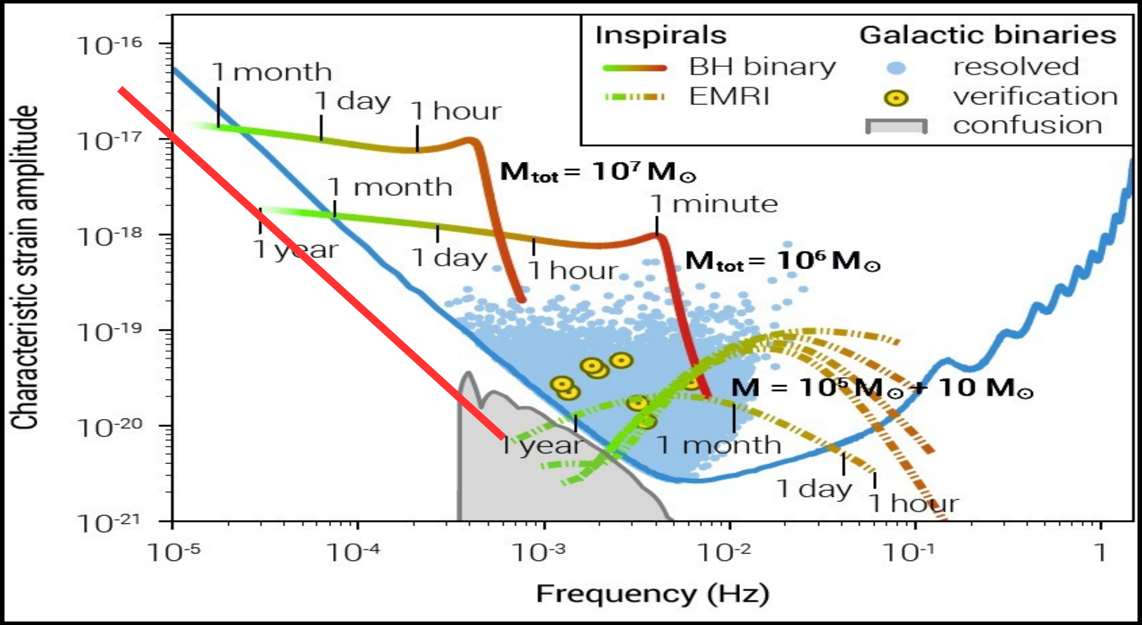
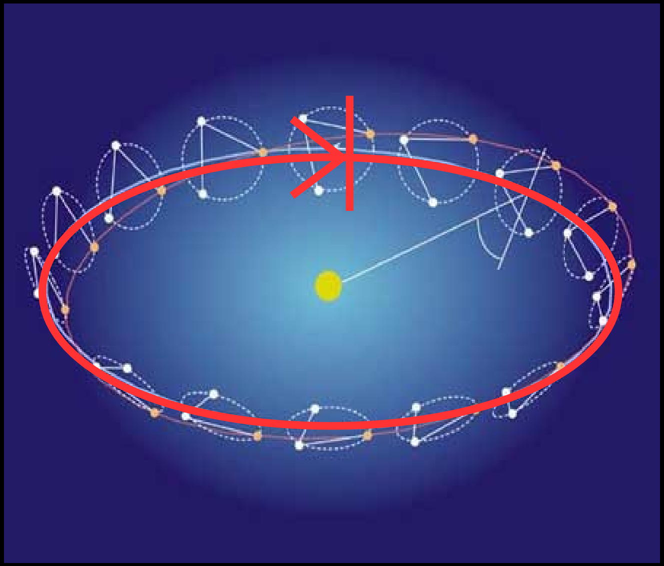
1 month
1 day
1 hour
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Frequency (Hz)

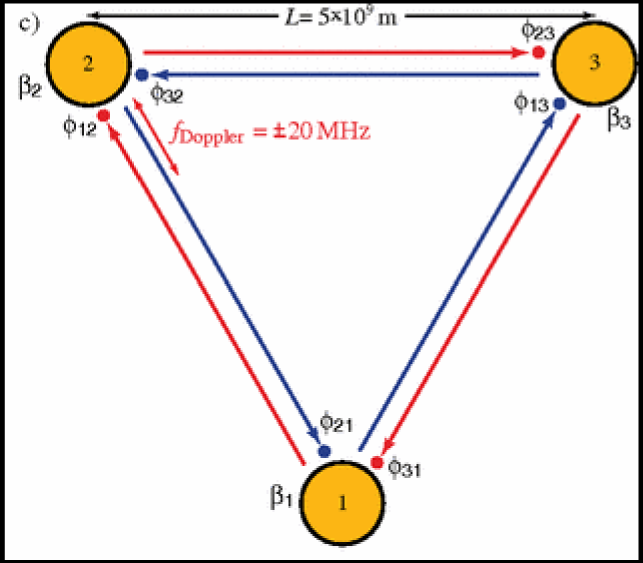


Baseline

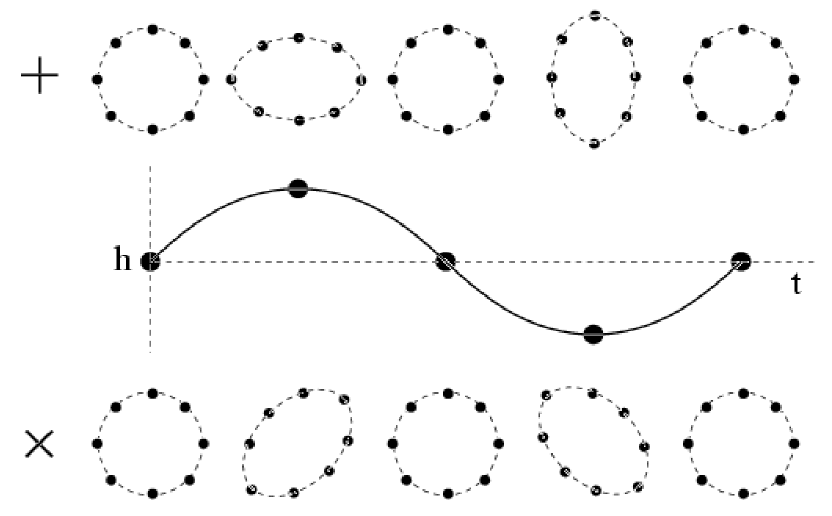




Number of laser links



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

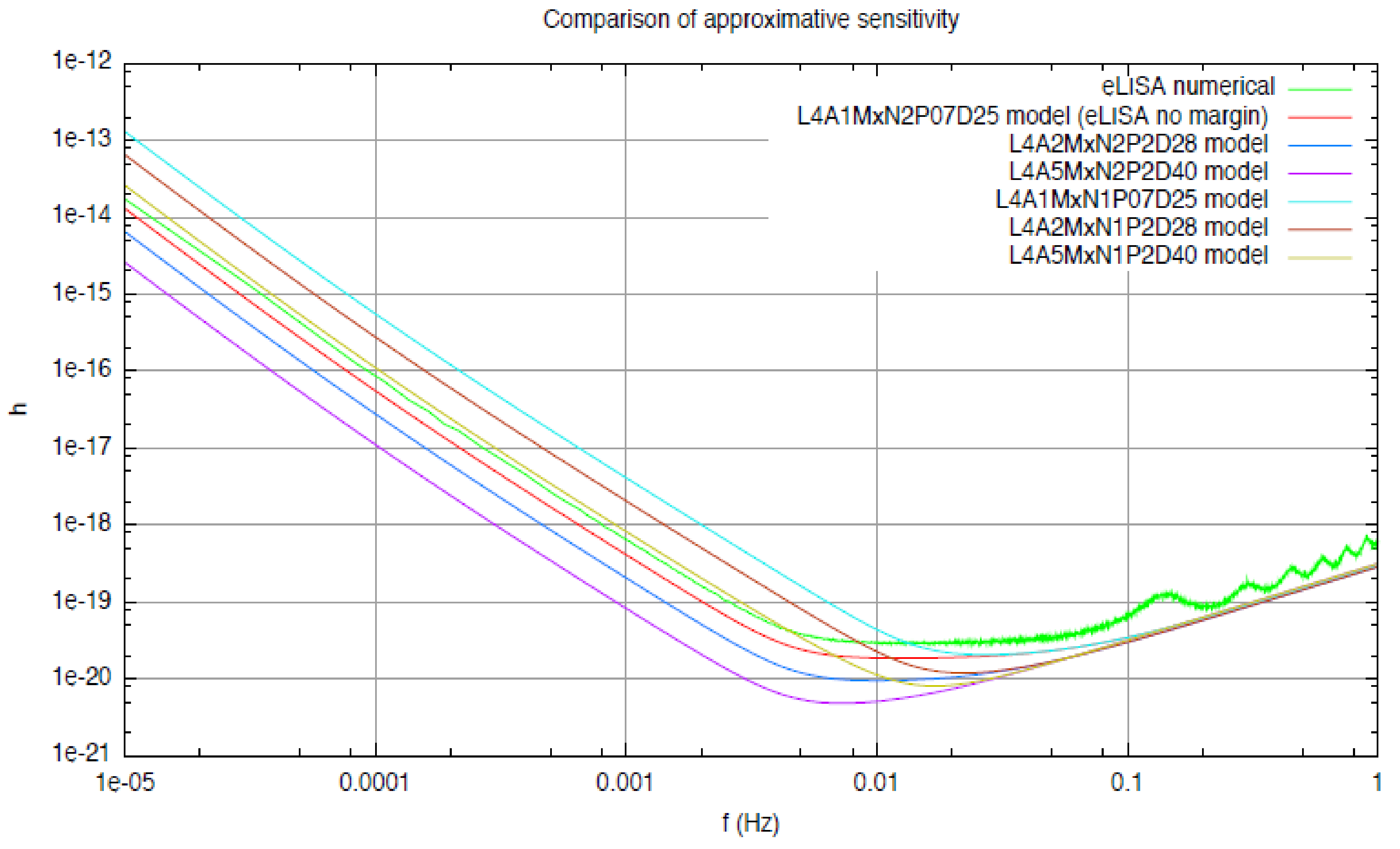


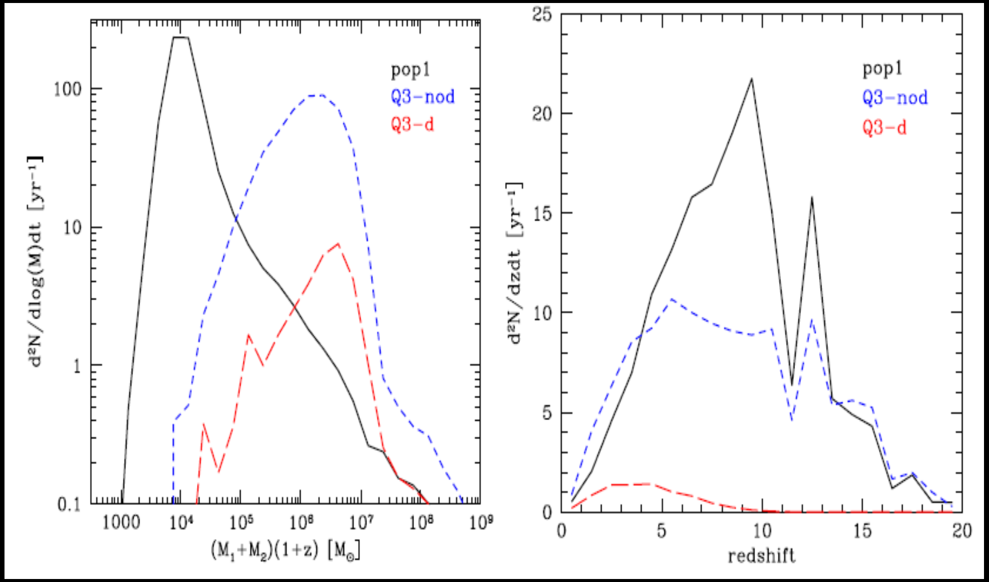
GOAT study

Performance comparison across mission designs

24 missions considered:

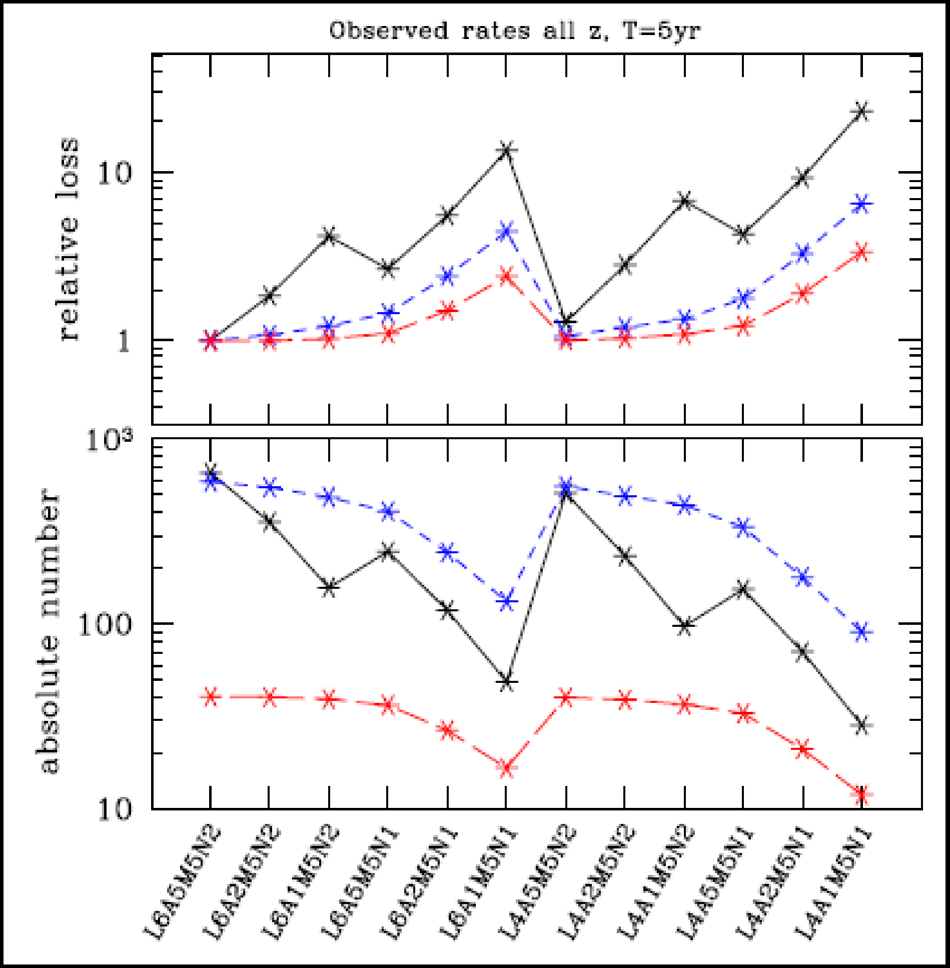
- **-Armlength: 1, 2, 5 Gm**
- **-Noise: LPF, LPFx10**
- **-Links: 4, 6**
- **-Lifetime: 2, 5 yrs**





We consider 3 selected MBH formation and evolution scenarios:

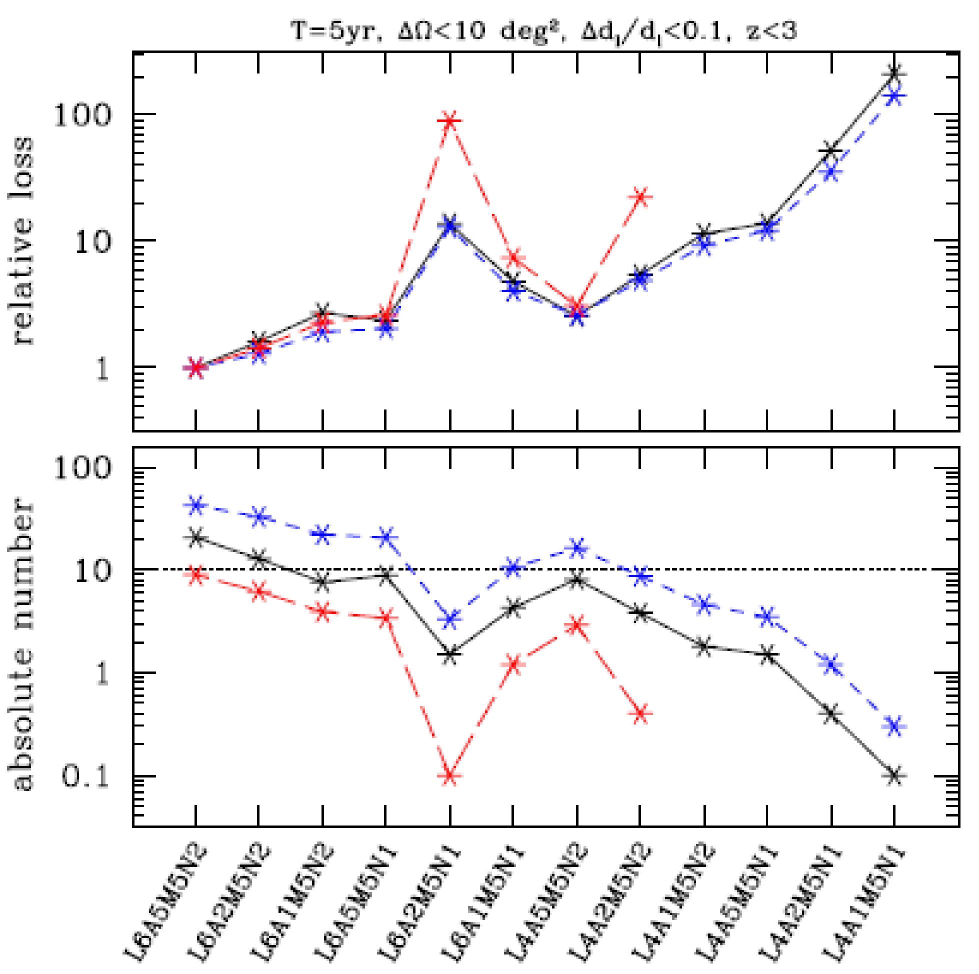
- -heavy seeds no-delays
- -heavy seeds delays
- -light seeds

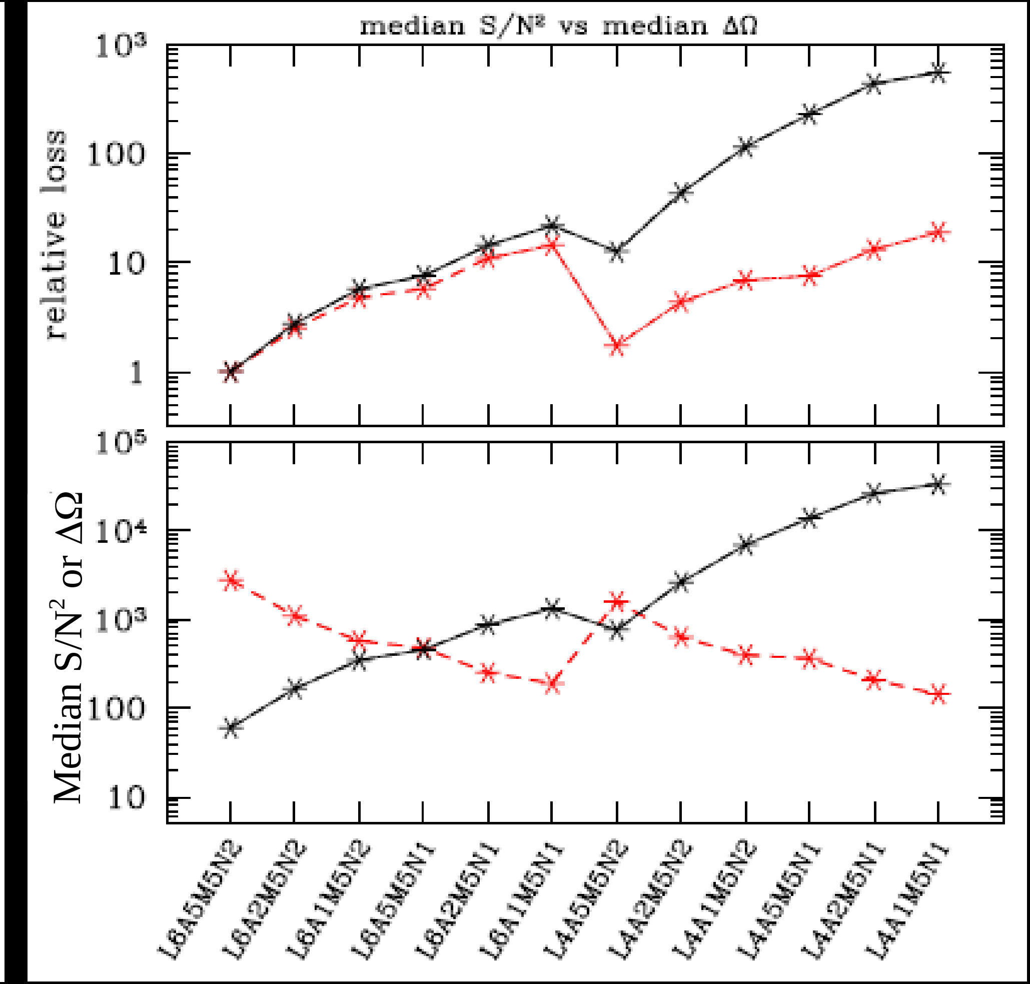


We quantify the performance of each design in terms of 'loss' with respect to Classic LISA.

Detection rates can vary by a factor of 30 across different designs

Example: sky localization





Design has a strong impact on sky localization:

-4 links do not allow istantaneous measurement of the 2 polarization

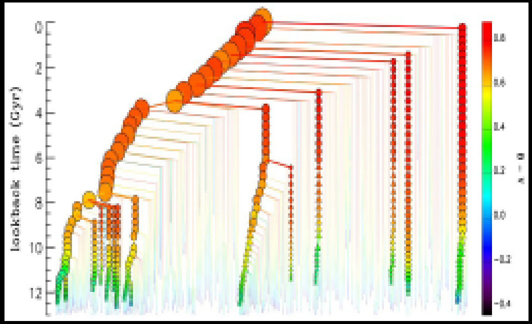
-short armlenght does not allow to disentangle polarization thanks to doppler modulation and detector response

Acc. noise wrt target	10× (N1)						1× (N2)					
Arm length (10^6 km)	1 (A1)		2 (A2)		5 (A5)		1 (A1)		2 (A2)		5 (A5)	
Configuration (arms/links)	2/4 (L4)	3/6 (L6)	2/4 (L4)	3/6 (L6)	2/4 (L4)	3/6 (L6)	2/4 (L4)	3/6 (L6)	2/4 (L4)	3/6 (L6)	2/4 (L4)	3/6 (L6)
Mission lifetime (yr)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	2 (M2)	
Acronym	L4A1M2N1	L6A1M2N1	L4A2M2N1	L6A2M2N1	L4A5M2N1	L6A5M2N1	L4A1M2N2	L6A1M2N2	L4A2M2N2	L6A2M2N2	L4A5M2N2	L6A5M2N2
Massive black hole binaries:												
total detected	5-36	7-54	15-165	16-197	8-72	11-98	16-197	16-222	13-133	15-165	16-222	16-266
detected at $z \geq 10$	0	0-1	0-37	0-54	0-3	0-8	0-56	0-72	0-21	0-34	0-73	0-84
both mass errors $\lesssim 1\%$	1-4	2-9	6-41	8-68	2-10	3-21	8-69	10-101	4-30	6-50	10-109	13-149
one spin error $\lesssim 1\%$	0-3	0-6	1-27	1-40	0-8	0-13	2-41	2-55	1-20	1-30	2-61	3-77
both spin errors $\lesssim 1\%$	0	0	0	0	0	0	0	0	0	0	0	0-1
distance error $\lesssim 3\%$	0	0-1	0-2	1-10	0	0-2	0-4	2-20	0-1	1-8	2-9	5-48
sky location $\lesssim 1\,\mathrm{deg}^2$	0	0	0	1-3	0	0	0-1	1-8	0	0-3	0-2	2-21
Others sources:												
total EMRIs detected	5-90	12-210	21-385	51-830	88-1205	184-2200	38-640	93-1330	176-2090	332-3270	543-4190	760-5010
CWD detected/resolved	569	952	1298	2043	3073	4987	5248	8805	9189	14757	13634	21744
CWD with 3D location	82	103	205	246	410	548	452	600	1001	1257	1816	2127
GWB sensitivity wrt LISA												
Qualitative capabilities:												
MBHB polarisation	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓
MBHB sky location	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓
MBHB luminosity distance	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓
EMRI/CWD polarisation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI/CWD position	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI/CWD luminosity distance	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓
stochastic background signal[a]	–	–	–	–	–	–	–	–	–	–	–	–
Science themes:												
CWD formation/evolution	–	–	–	–	–	–	–	–	–	–	–	–
fundamental tests of GR[b]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hubble constant (H_0) to few%[c]	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓
dark energy (w) to few%[d]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
cosmic web structure formation[e]	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓
multimessenger astronomy[f]	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓
Other:												
redundancy (spacecraft/arm failure)	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓

MBH astrophysics with GW observations

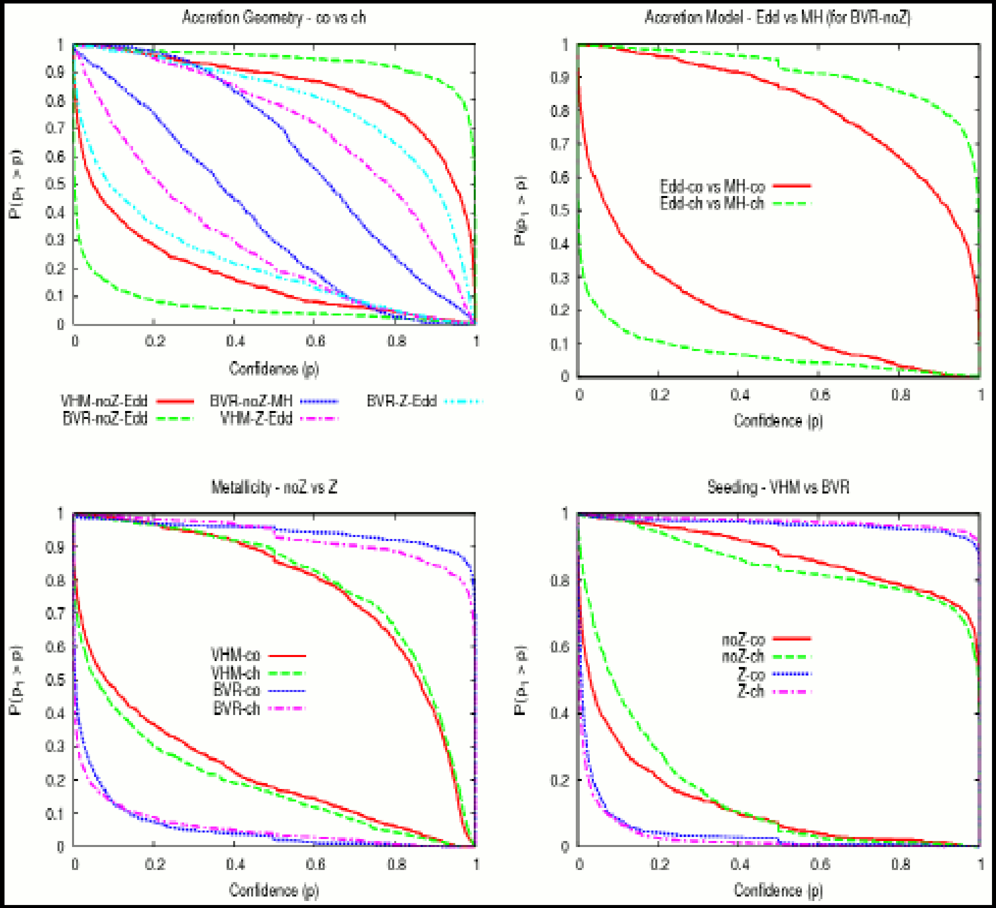
Astrophysical unknowns in MBH formation scenarios

1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metalliticies)
3- Accretion efficiency (Eddington?)
4- Accretion geometry (coherent vs. chaotic)



CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

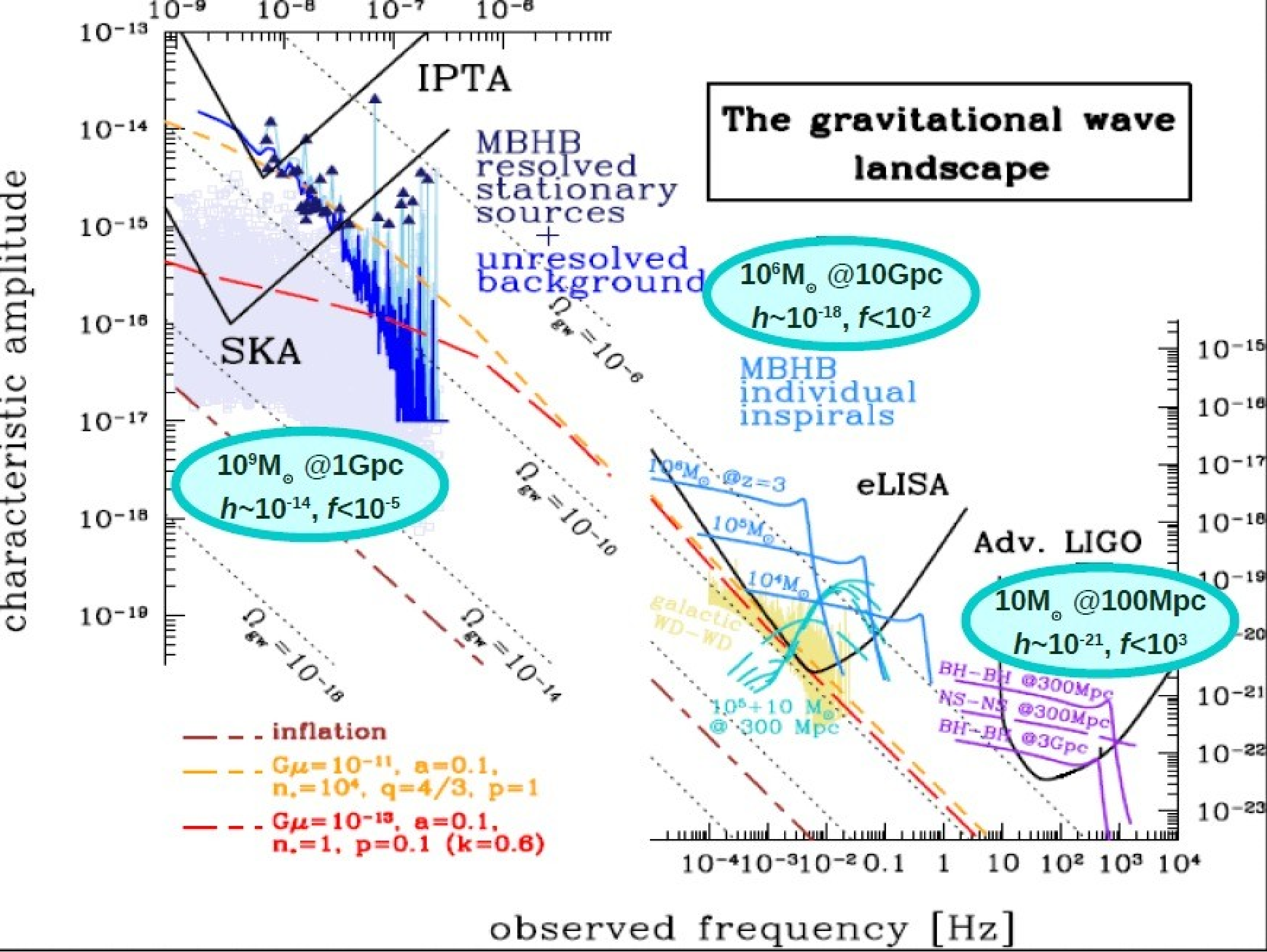
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models



AS et al. 2011, see also Plowman et al 2011

Detecting the real beasts with pulsar timing arrays

(IPTA, Hobbs et al. 2010)



The gravitational wave landscape

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

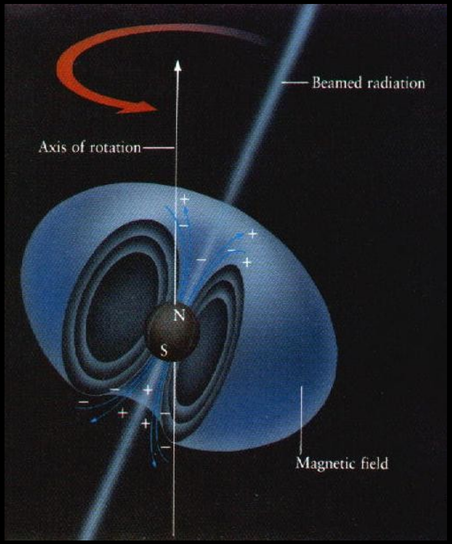
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-18}$, $f < 10^{-2}$

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

What is pulsar timing

Pulsars are neutron seen as regular radio pulsators in the sky

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system



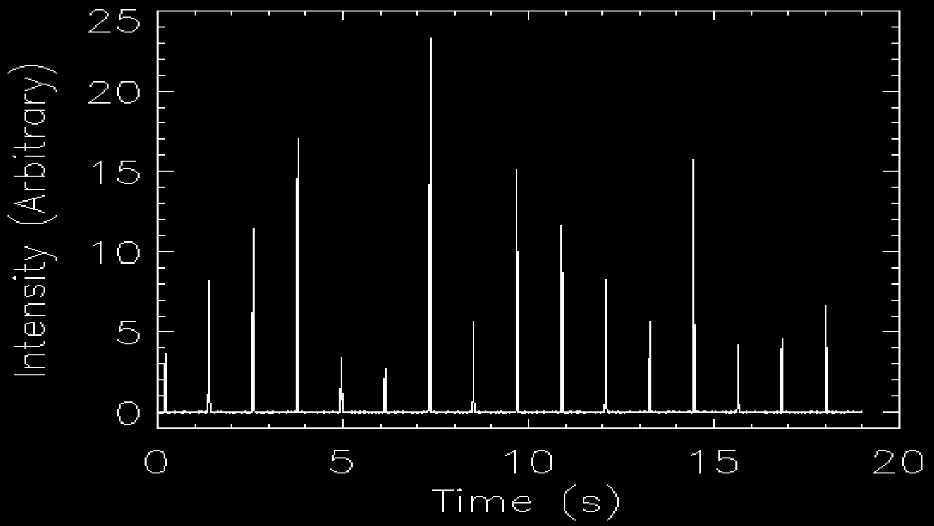
1-Observa a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

3-Compute the timing residual R

$$R=\mathrm{ToA}-\mathrm{ToA}_m$$

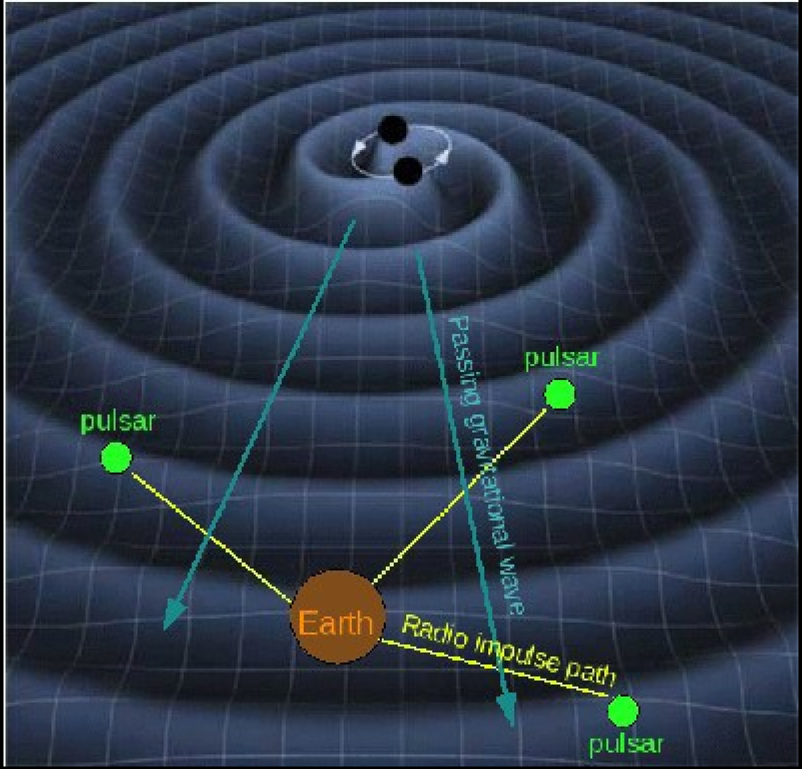
If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) *gravitational waves*



Effect of gravitational waves

The GW passage causes a modulation of the observed pulse 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 is the integral of this frequency modulation over the observation time (i.e. is a dephasing)

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

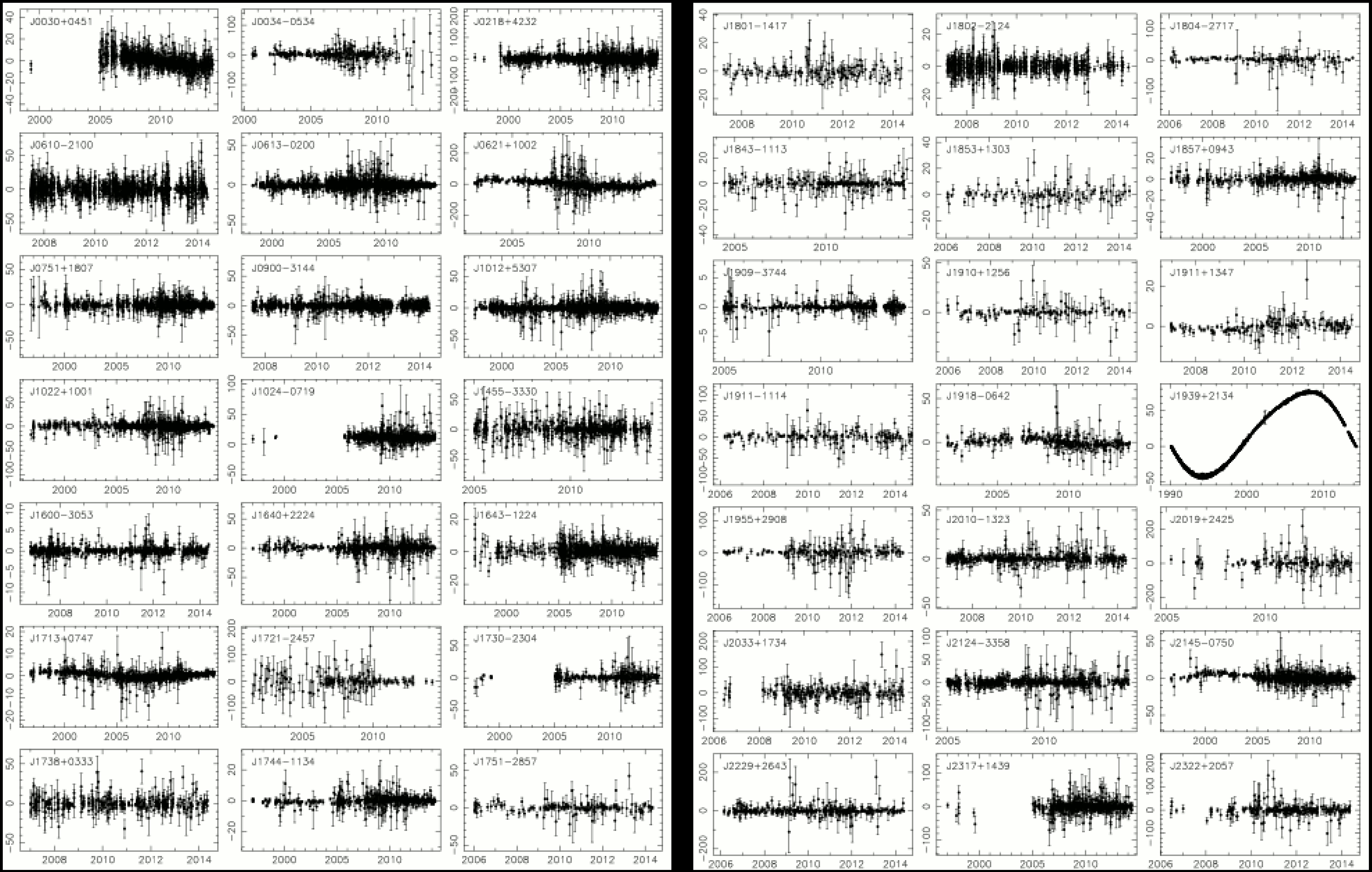
(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

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

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

The EPTA dataset

(Desvignes et al. In prep)



42 millisecond pulsars observed with 4 radio telescopes

Likelihood function

All search methods are based on the likelihood function, describing the probability that the residuals contain a signal of some sort described by certain parameters

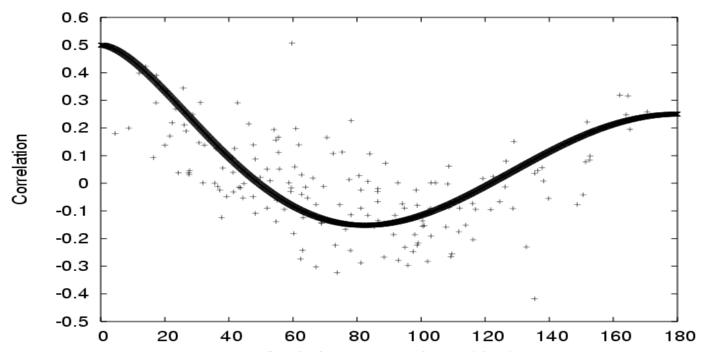
$$\mathcal{L}(\vec{\delta t}|\vec{\theta},\vec{\lambda}) = \frac{1}{\sqrt{(2\pi)^{n-m} det(G^T C G)}} \times$$
$$\exp\left(-\frac{1}{2}(\vec{\delta t}-\vec{r})^T G (G^T C G)^{-1} G^T (\vec{\delta t}-\vec{r})\right)$$

The signal is contained in the correlation matrix C which is a function of the signal power as a function of sky location and the 'antenna beam patterns'

$$\Gamma_{ab} = \frac{3}{8\pi}(1+\delta_{ab})\int_{S^2} d\hat{\Omega}\; P(\hat{\Omega}) \sum_{A} F_a^A(\hat{\Omega}) F_b^A(\hat{\Omega})$$

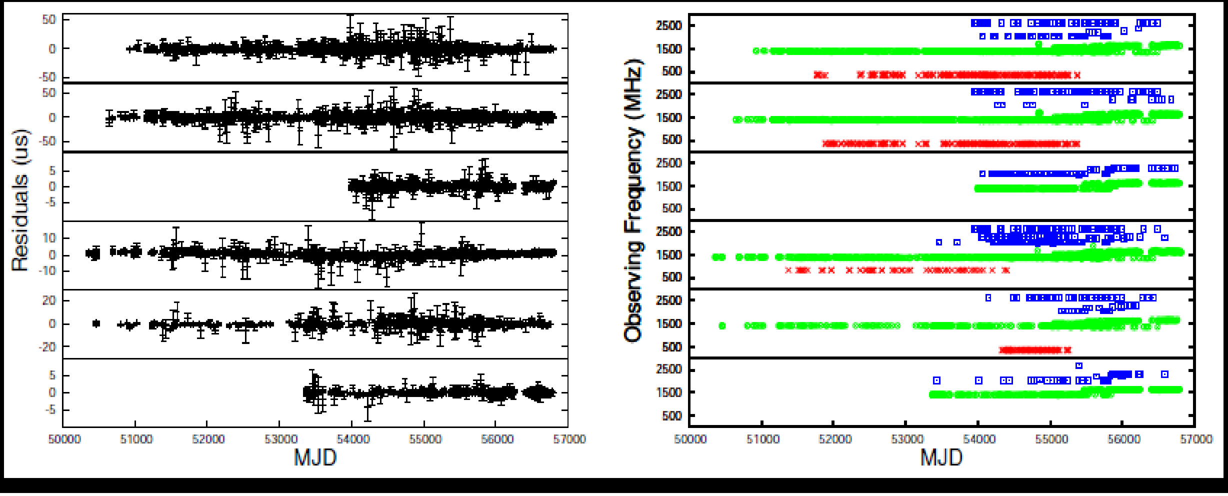
For an isotropic background this takes the form below, known as the 'Hellings & Downs ' curve:

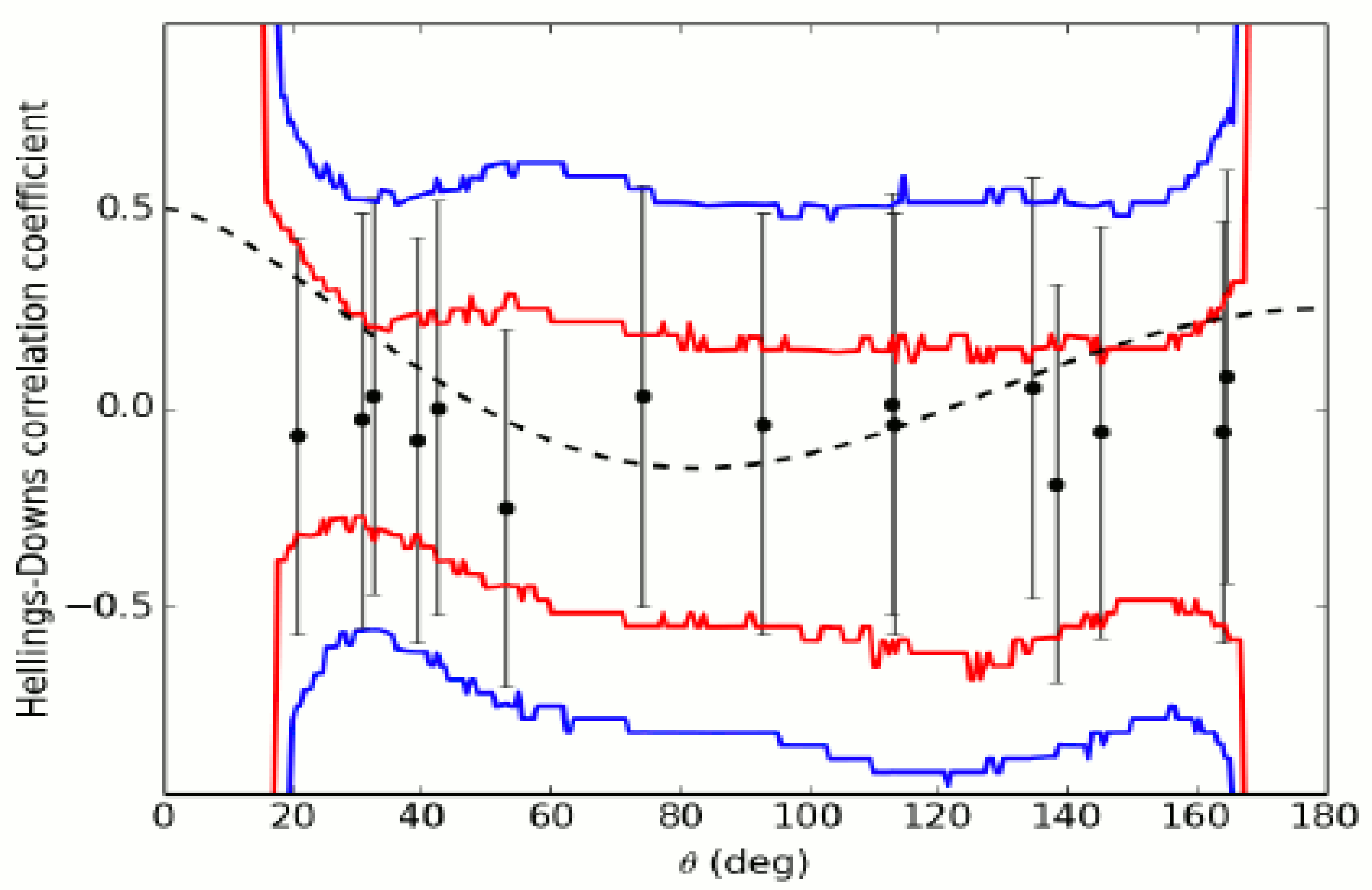
$$\Gamma(\theta_{mn}) = \frac{3}{8}\left[1 + \frac{\cos\theta_{mn}}{3} + 4(1-\cos\theta_{mn})\ln\left(\sin\frac{\theta_{mn}}{2}\right)\right](1+\delta_{mn})$$



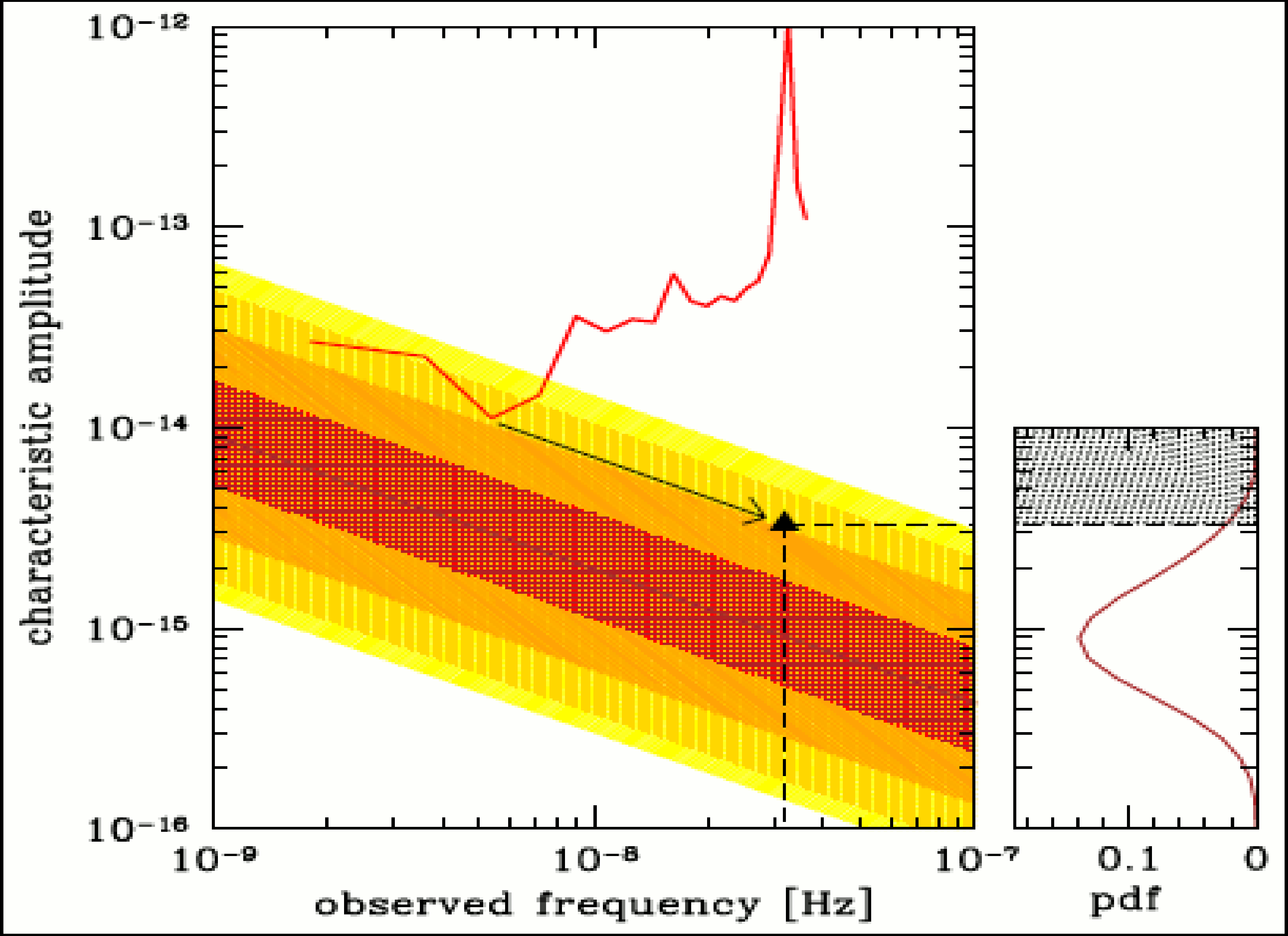
EPTA results: isotropic stochastic GWB

(Lentati et al. In arXiv:1504.03692)

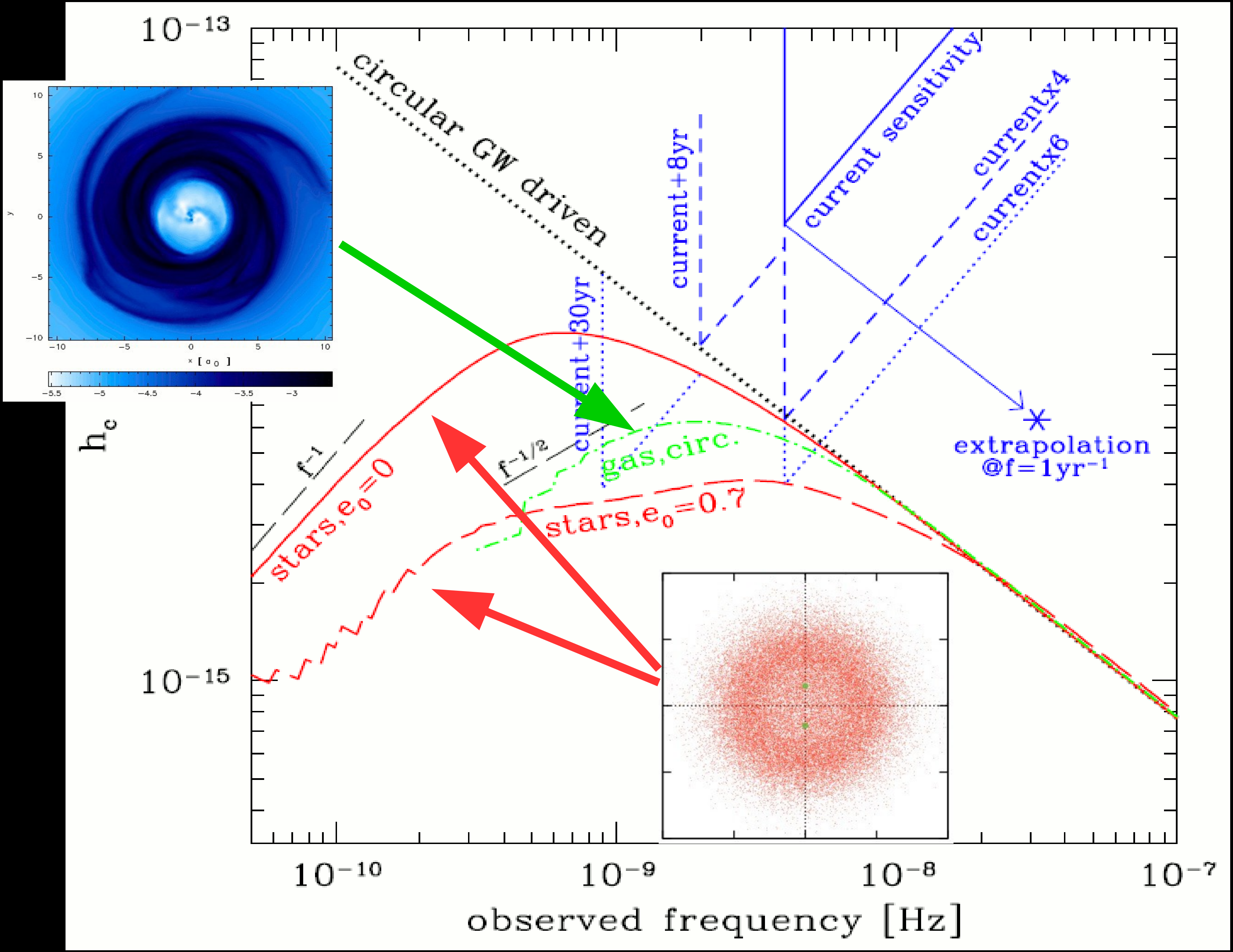




P(Ω) depends on the properties of the spectrum (index and amplitude for a single power law). Assuming $f^{-2/3}$ (appropriate for circular GW driven binaries), we can get a limit on the GWB amplitude:



Warning: the effect of the invironment



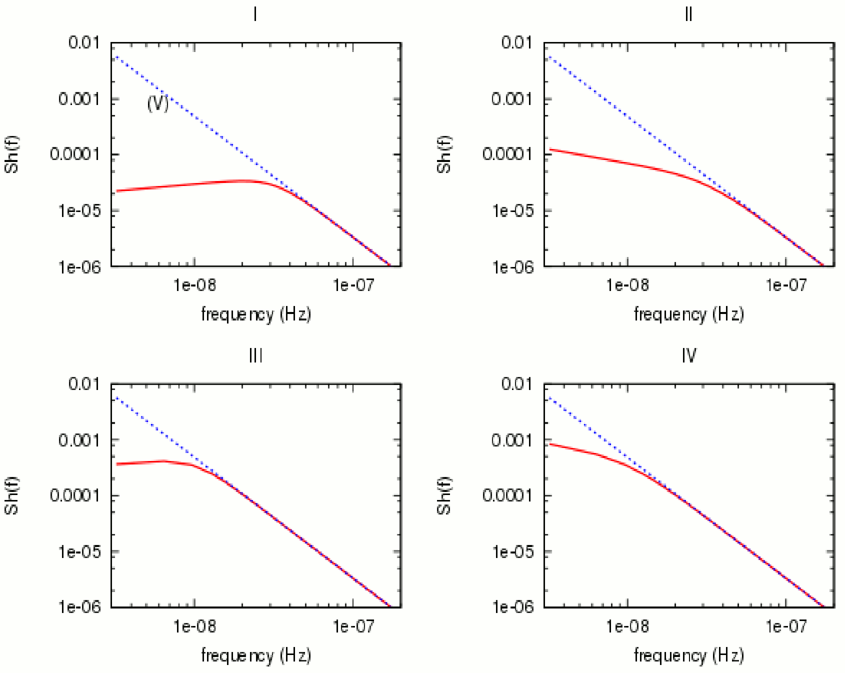
(Kocsis & AS 2011, AS 2013, Ravi et al. 2014)

Recovering the GW spectral shape

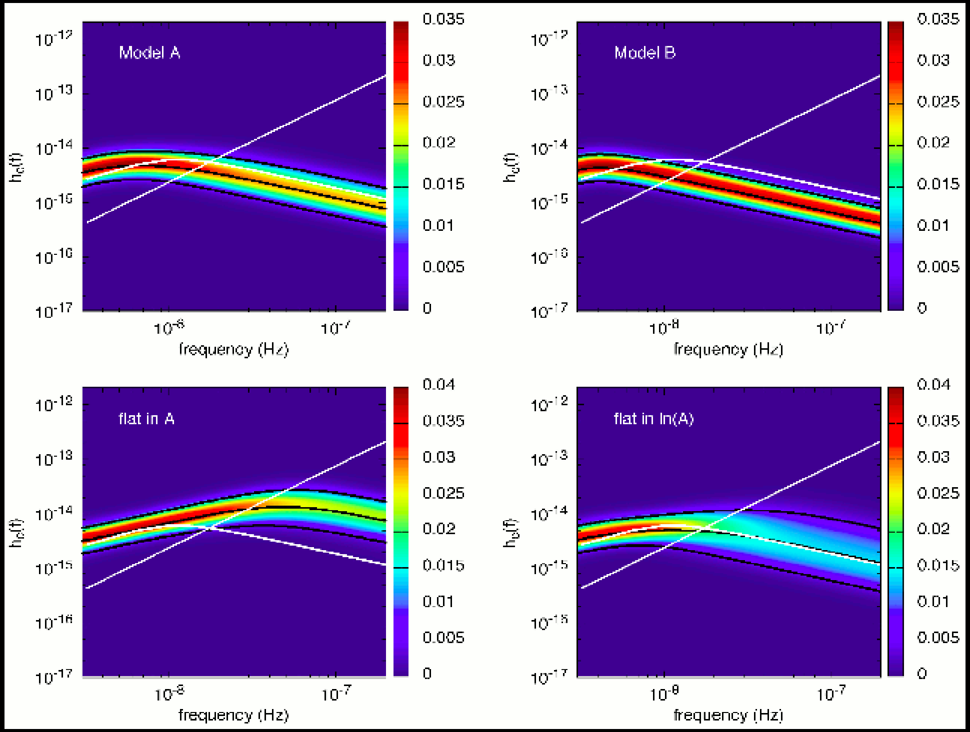
(Sampson et al. arXiv:1503.02662)

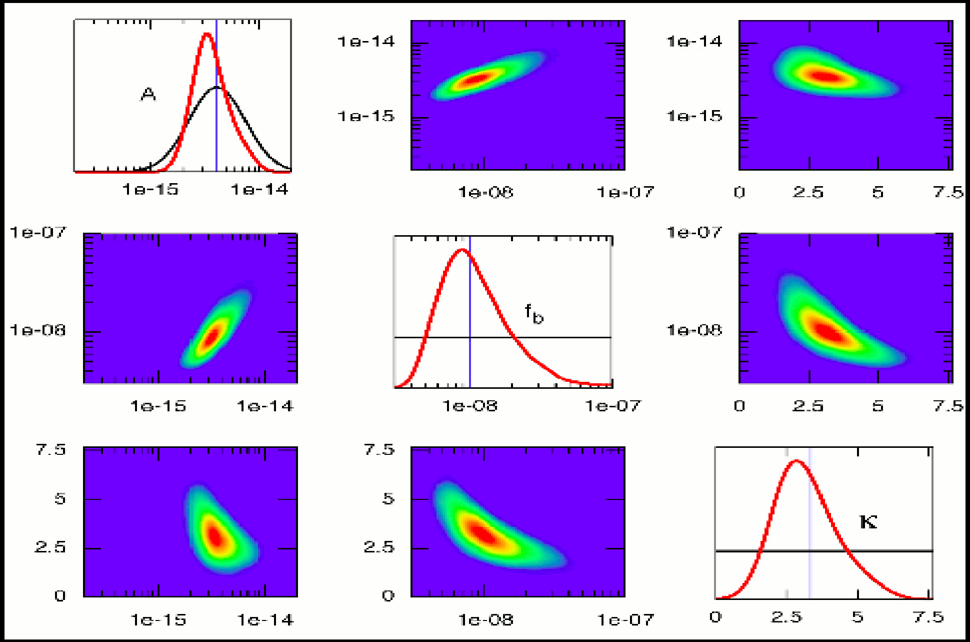
Simple broken-power law model mimicking possible environmental effects

$$h_c(f) = A\frac{(f/f_{\rm year})^{-2/3}}{(1+(f_b/f)^{\kappa})^{1/2}}$$

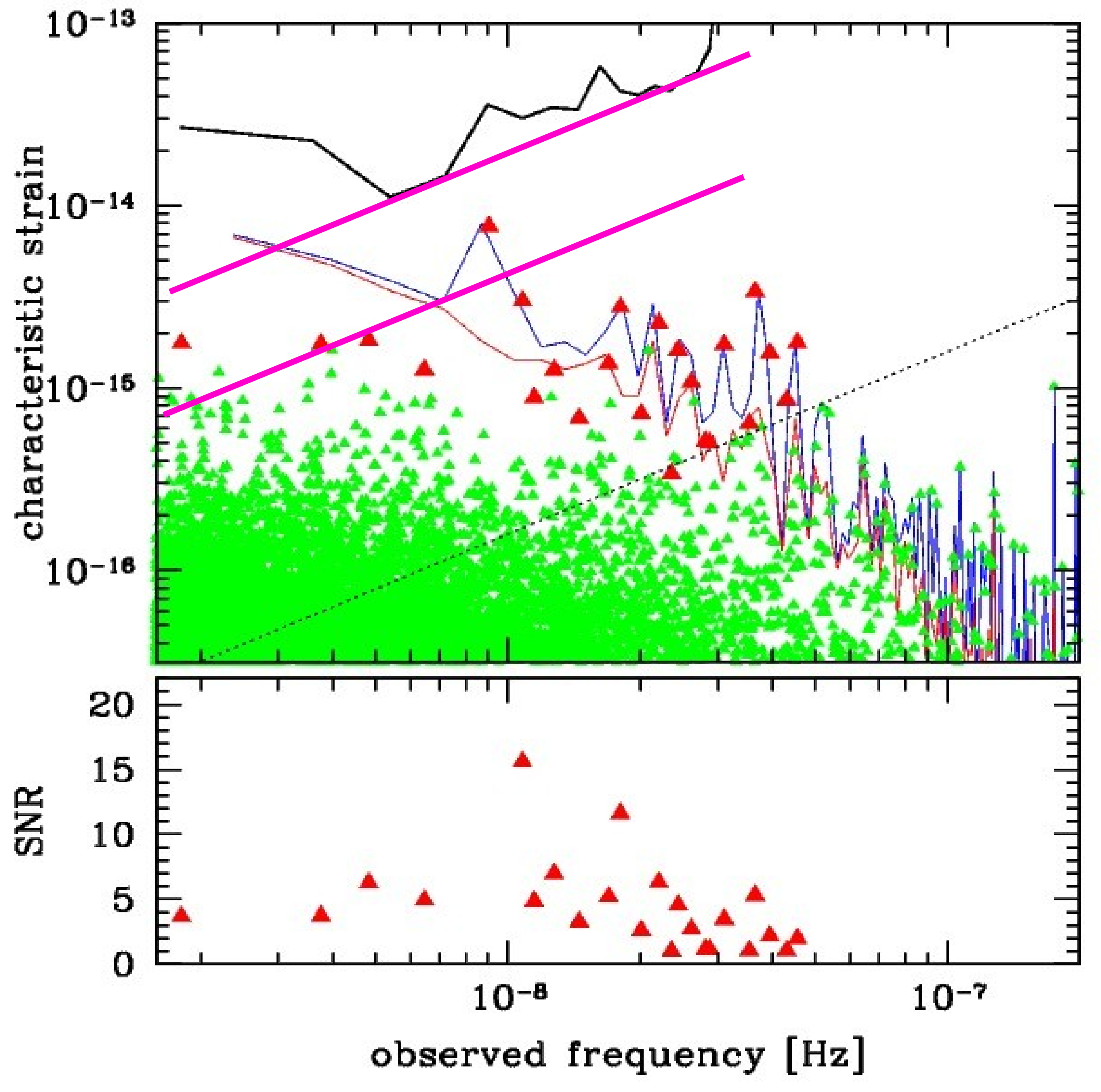


MCMC techniques to sample the posterior distribution of the signal parameters.





What prospects for individual sources?



*by simply monitoring for longer time, PTAs will eventually hit the GWB at low frequency

*TOA accuracy needs to be improved to get a better chance of resolving a single source

Summary:

>We are not yet in the golden age of GW astronomy but...

>Future space based interferometers will potentially detect tens of MBH binaries per year throughout the Universe

>The science return as a function of detector configuration is being extensively investigated

>Pulsar timing array is still in the race to make the very first GW detection