Gravitational wave detection using laser interferometers and pulsar timing arrays

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OUTLINE

1- Sources and waveforms

2- Ground based interferometers

3- Science with space based interferometers

4- Pulsar timing arrays

WHY INVEST IN GRAVITATIONAL WAVES

1-It is a completely new window on the Cosmos. New windows always brought new unexpected exciting discoveries in the past.

2-MBH formation and evolution in the young Universe is a puzzle, GW astronomy will provide neat detections to $z>10$, telling us mass and spin properties of the MBHs with unprecedented precision.

3-GW detection of MBH binaries will provide direct measurement of the luminosity distance of the source, no electromagnetic observation can provide that.

4-combination of GW and electromagnetic observations may allow us to do cosmography in a 'calibration free' way.

5-GW detection of an accreting system might become the Rosetta stone for accretion physics.

6-Tests of fundamental physics

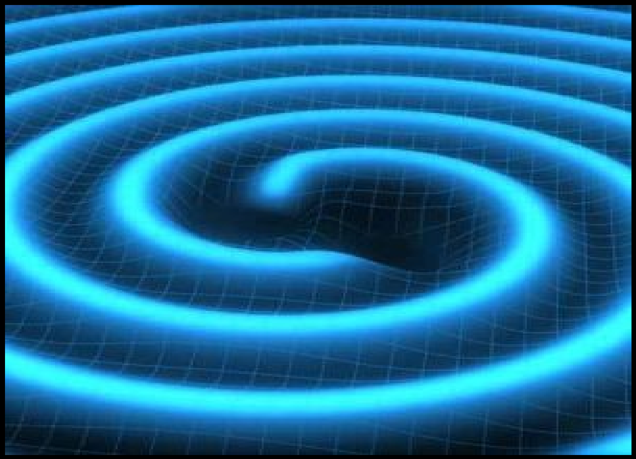
What is a gravitational wave

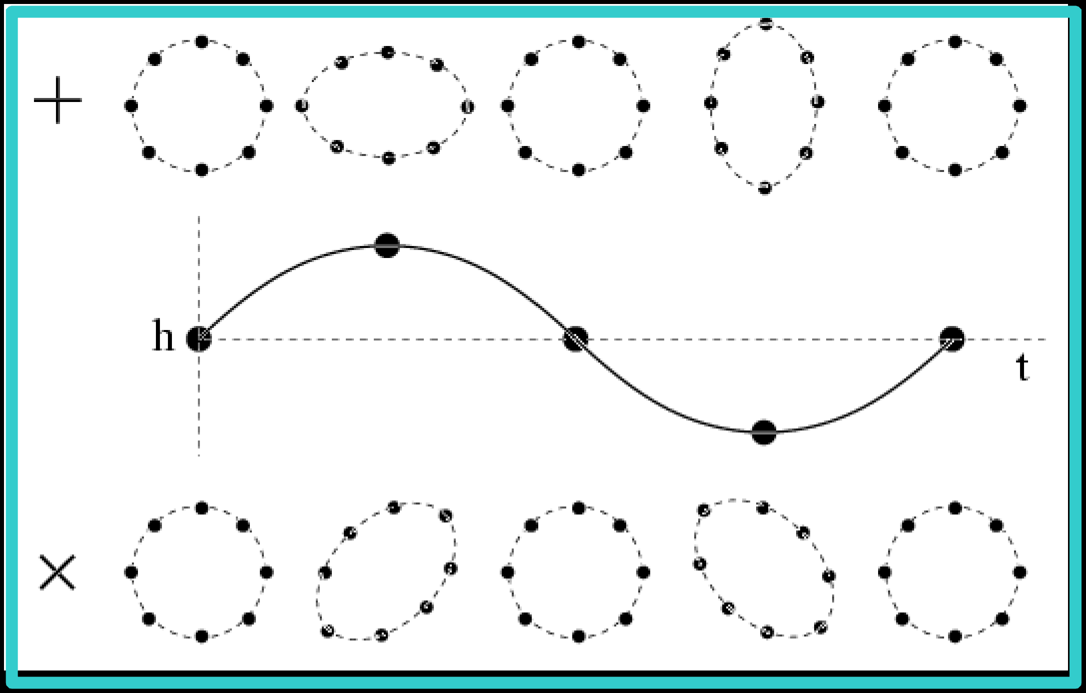
Every accelereting mass distribution with non-zero quadrupole momentum emits GWs!

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

Perturbed Minkowski metric tensor :

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



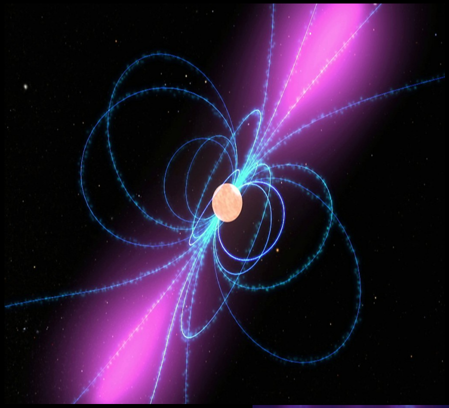


Perturbation perpendicular to the wave propagation direction

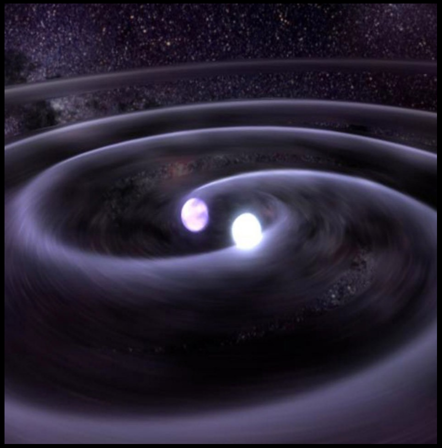
Gravitational wave sources

Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

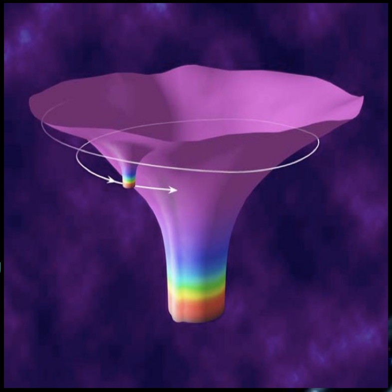


2-rotating asymmetric objects
(pulsars, MSPs)



3-binary systems:

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

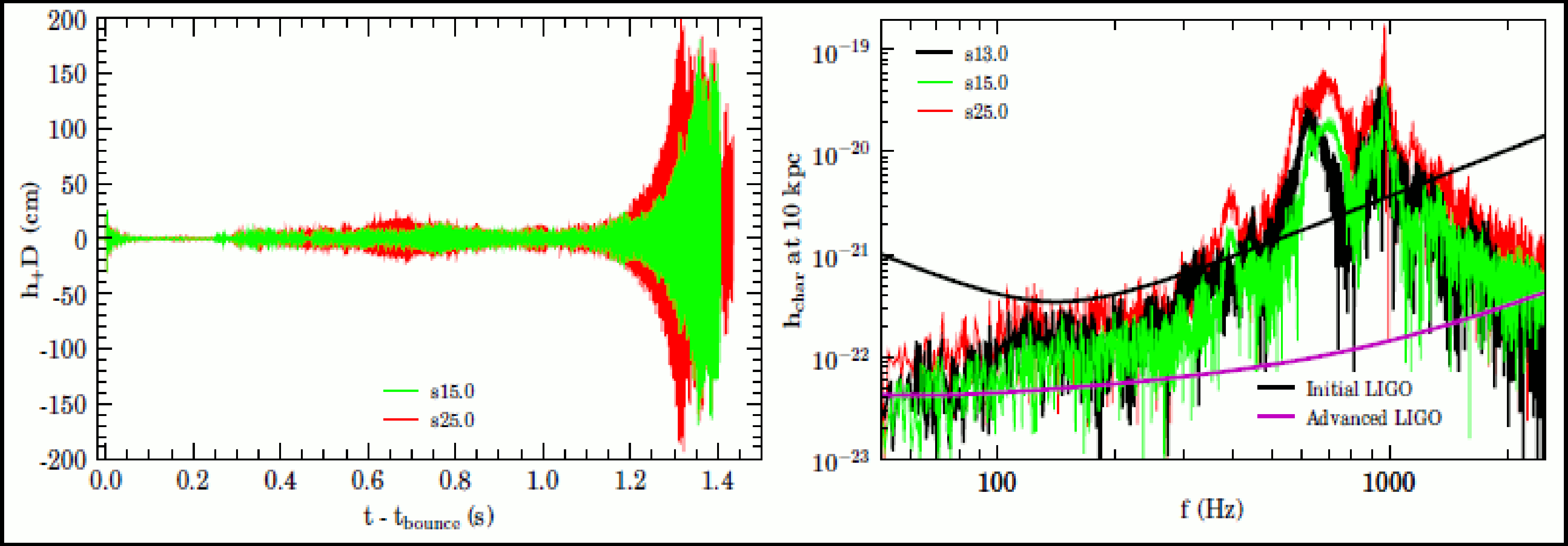


b-extreme mass ratio inspirals (EMRIs),
CO falling into a massive black hole

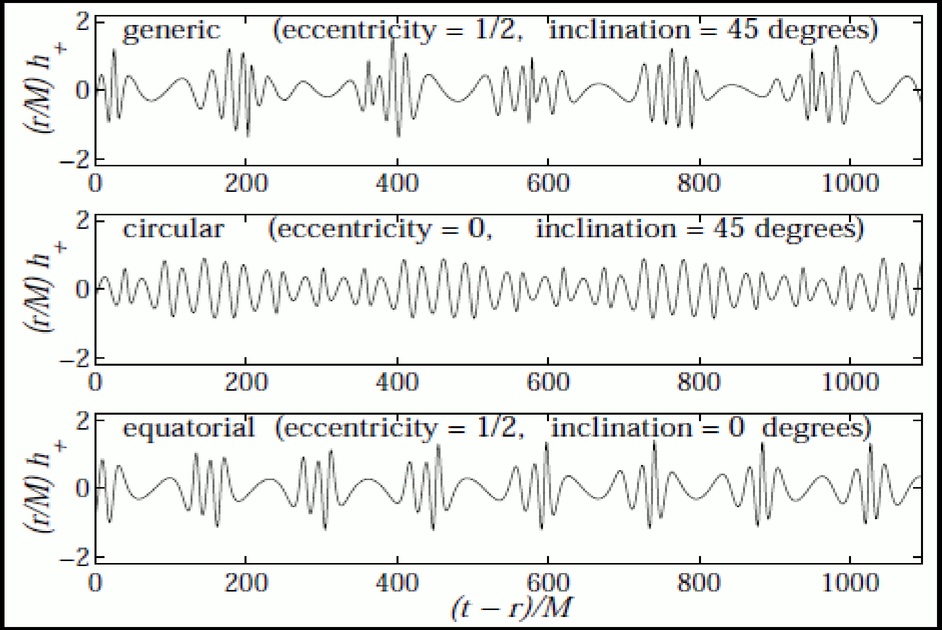
c-massive black hole binaries (MBHBs)
forming following galaxy mergers

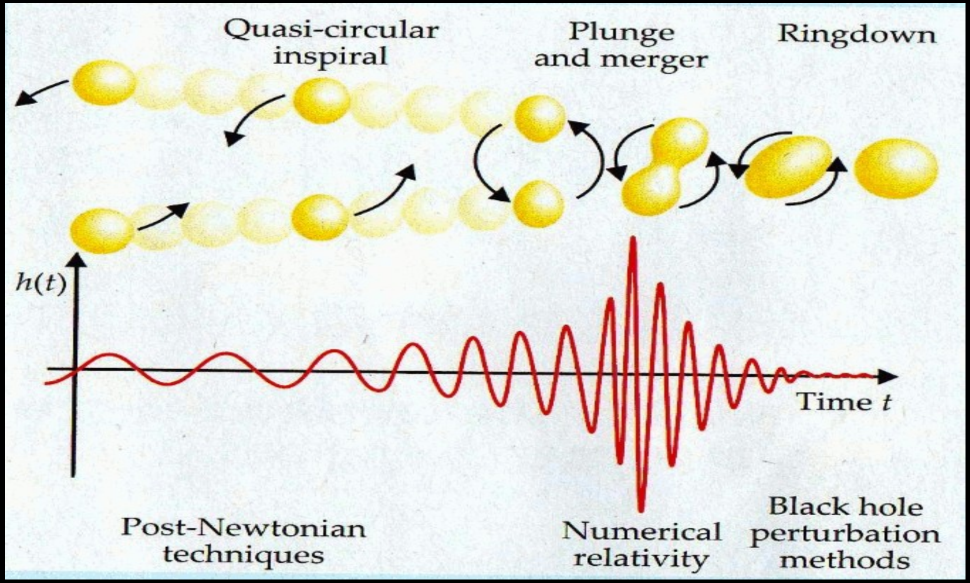
Example of gravitational waveforms

Supernova explosion (credits C. Ott)



EMRIs (credits Drasco & Hughes)





Black hole binaries

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

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

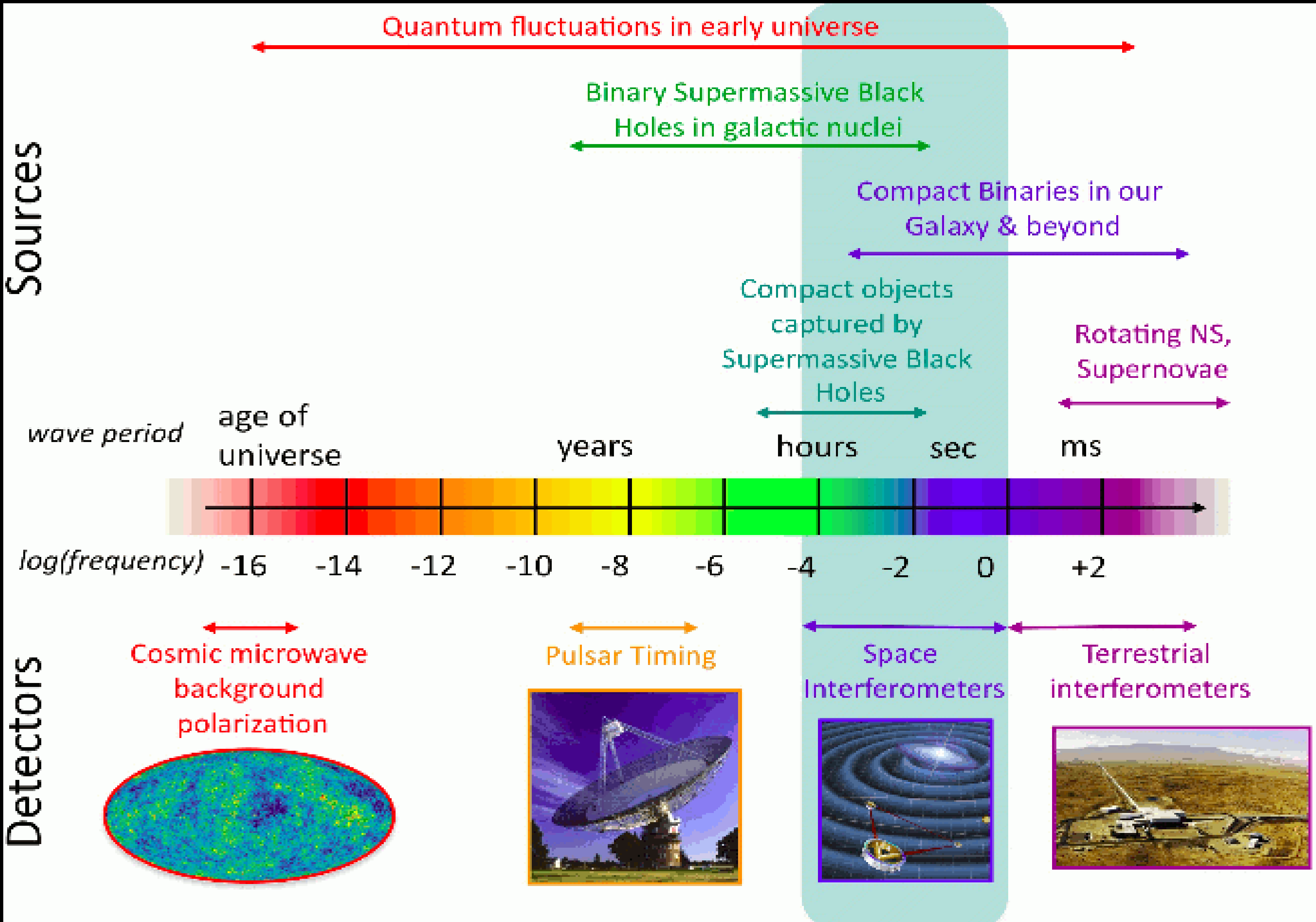
$$f \sim \frac{c}{2\pi R_s} \sim 10^4\,\mathrm{Hz}\,\frac{M_\odot}{M}$$

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

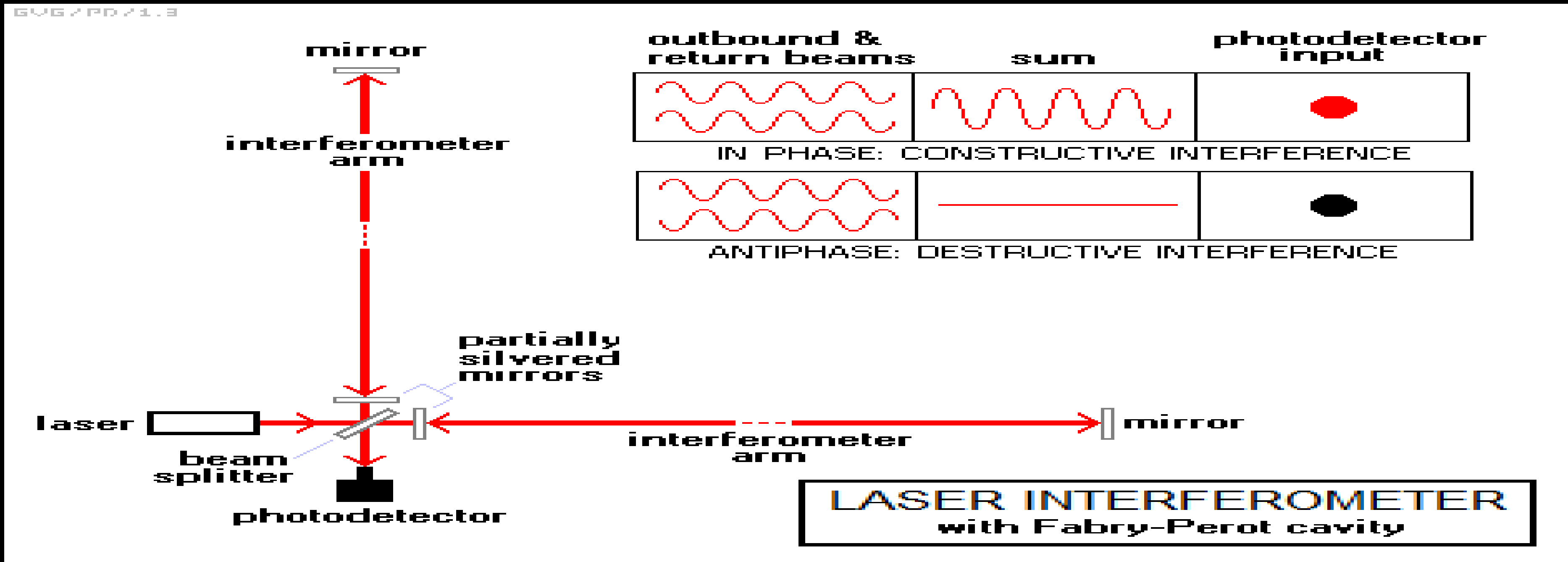
10^6 $M_\odot$ binary at 10 Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$

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

The gravitational wave spectrum



Detection technique: laser interferometry



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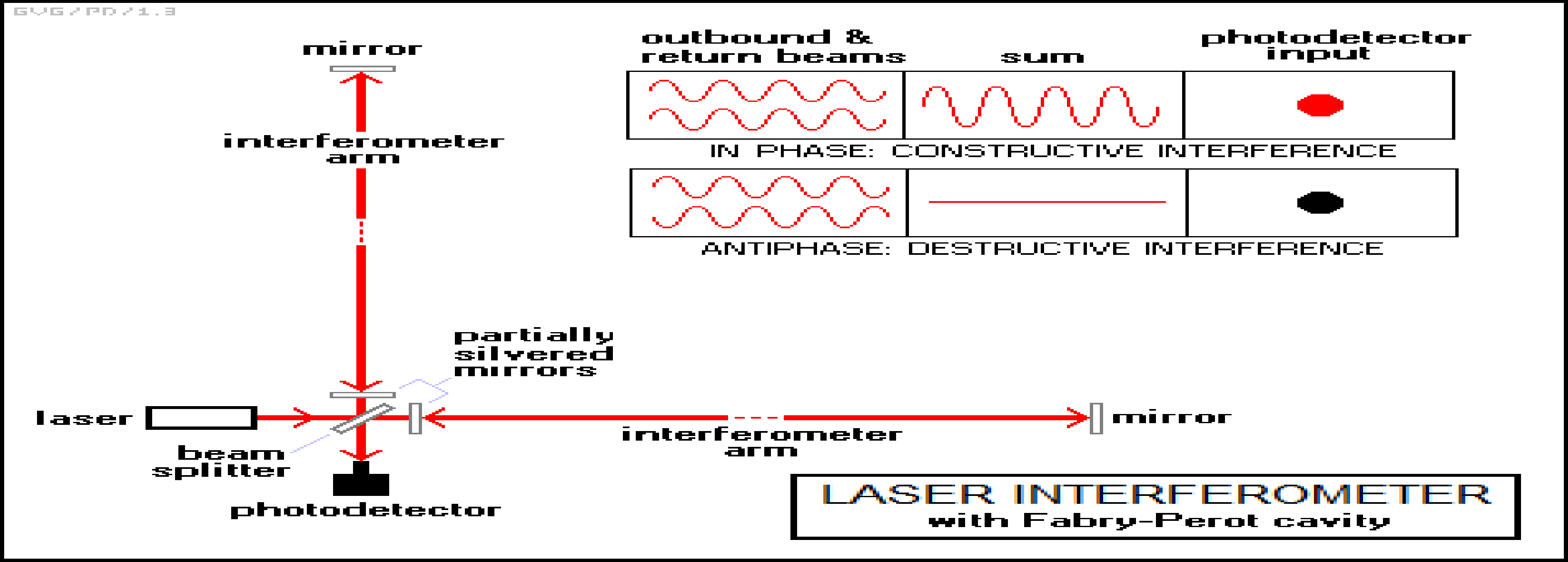
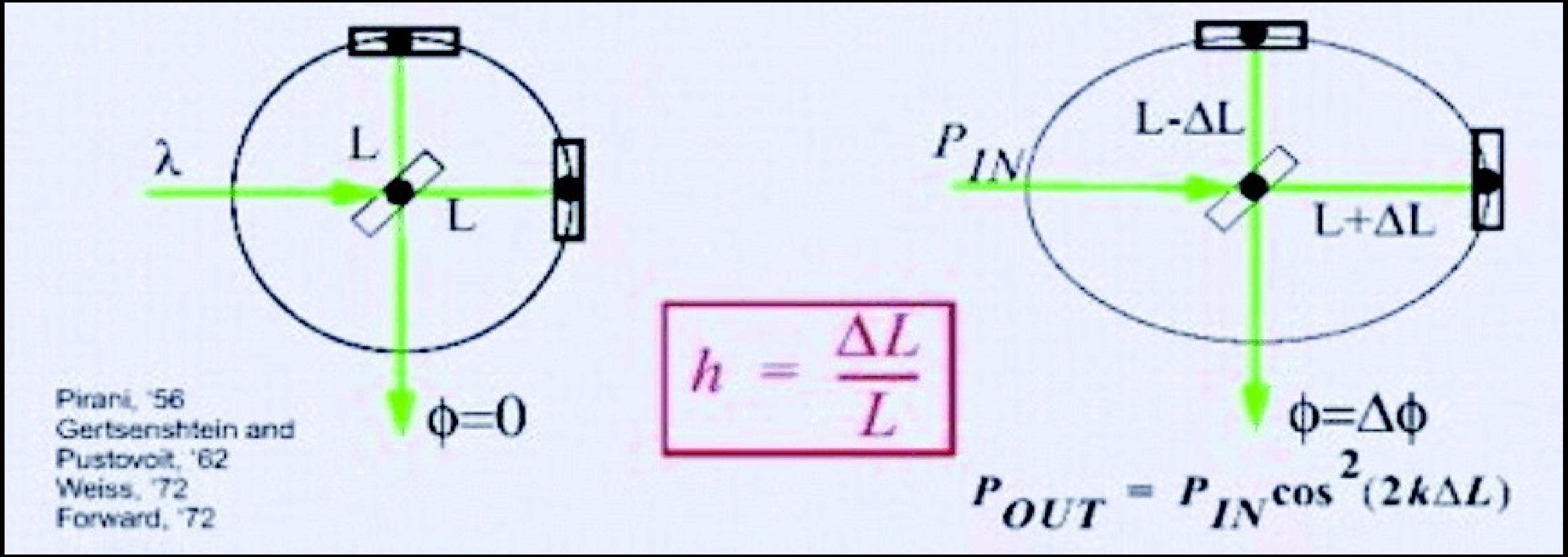
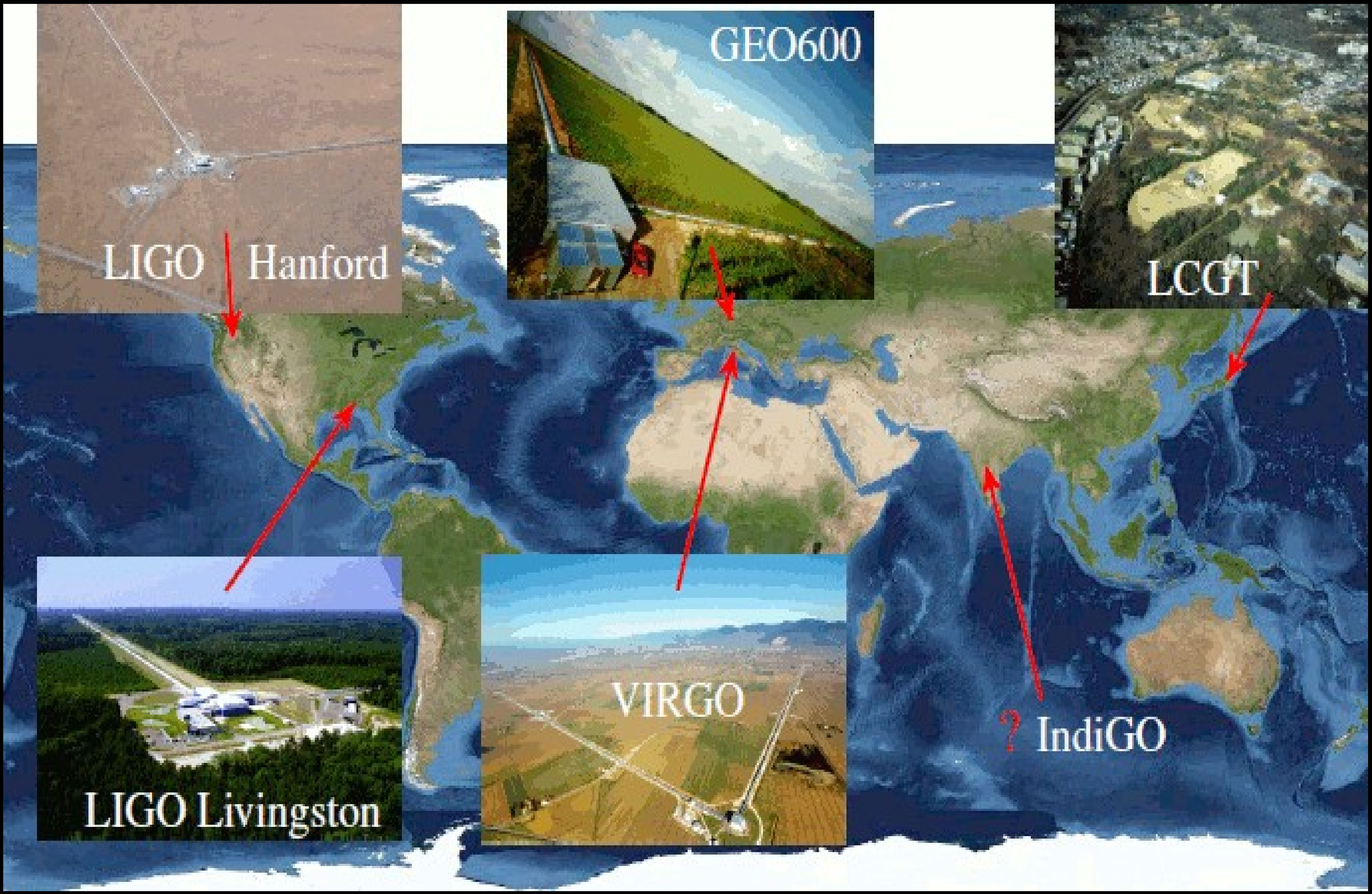




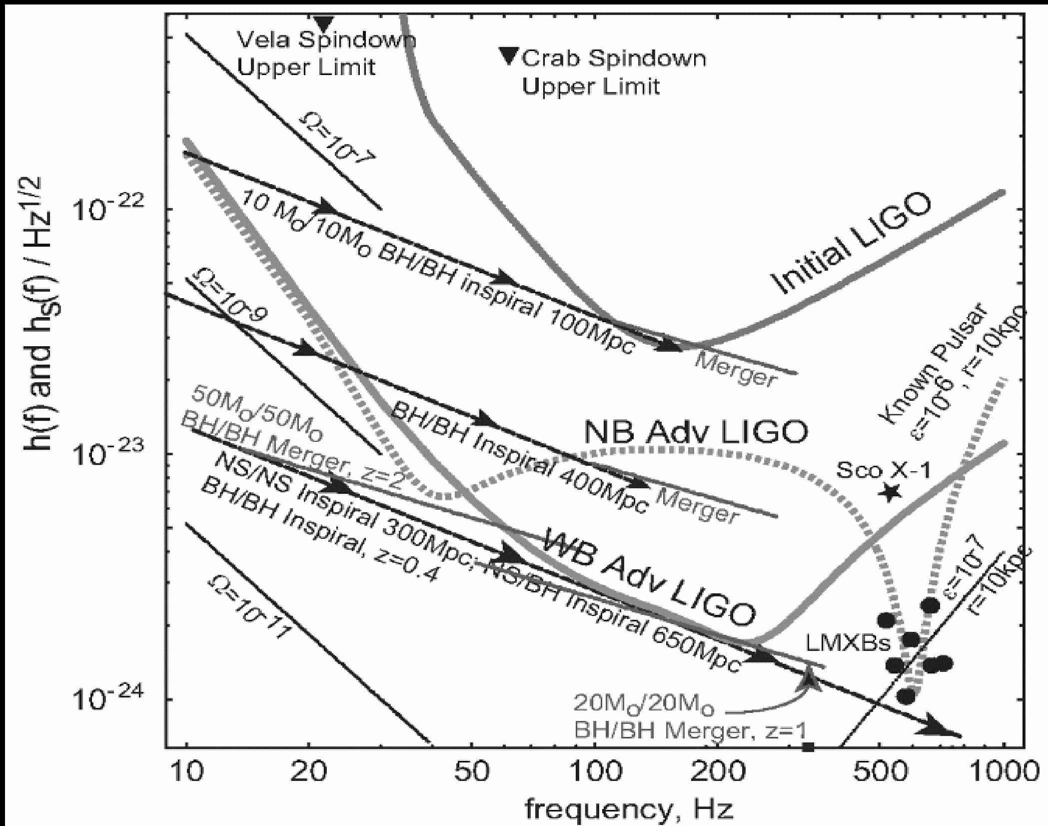
The passing wave changes the relative path of the photons in the two arms. This translates in a dephasing of the two laser beams that can be measured.

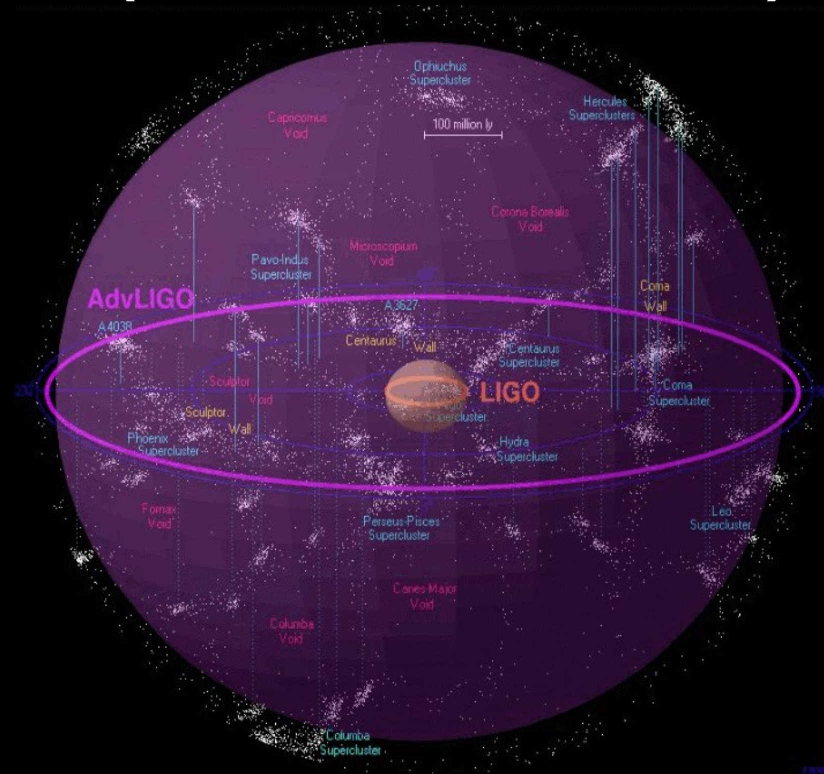
The ground-based interferometer network



Ground based detectors reach

(See next talk for more!)

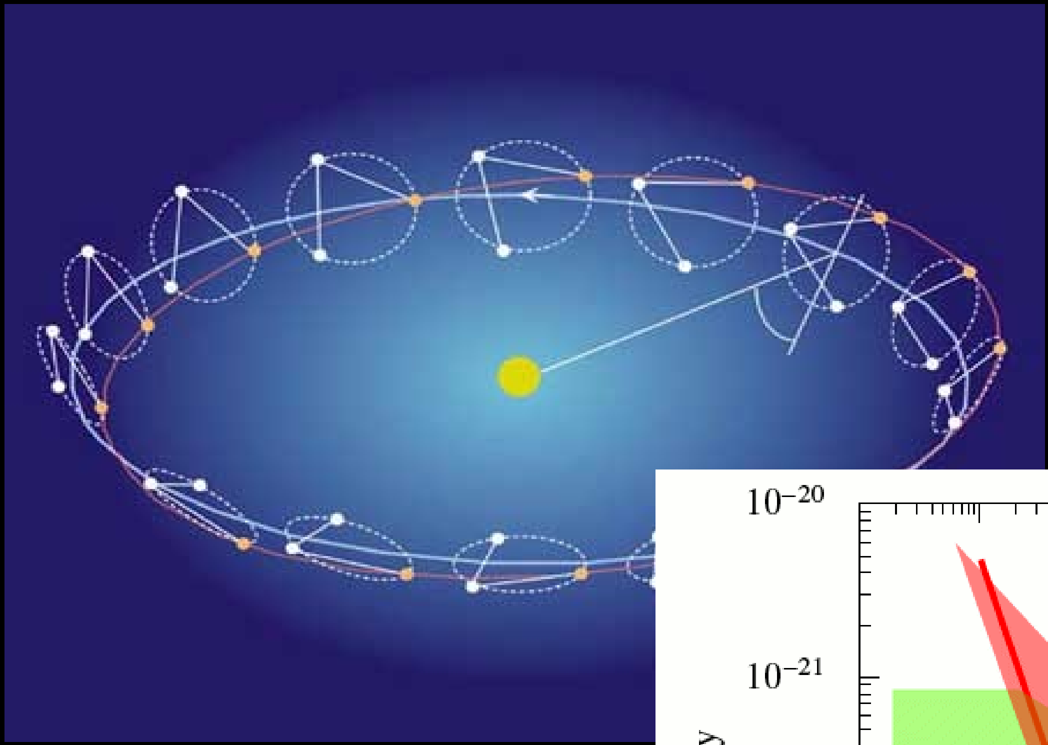




IFO	Source^a	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

LIGO scientific collaboration 2010

Interferometry in space:
***e**volved **L**aser **I**nterferometer **S**pace **A**ntenna*

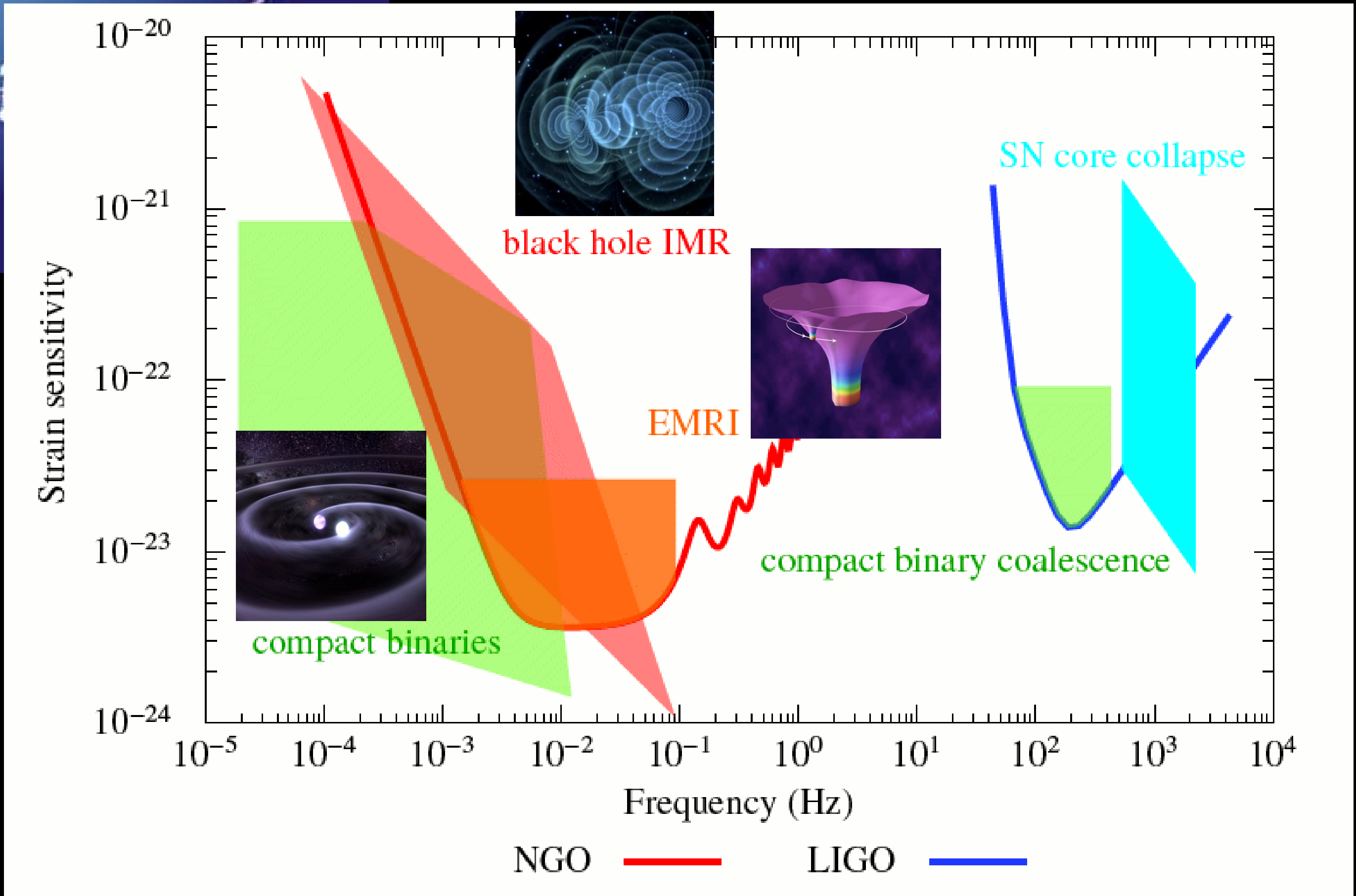


NGO/eLISA **is sensitive at mHz frequency, where the evolution of MBH binaries is fast.**

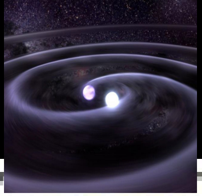
NGO/eLISA **will detect MBH binary inspirals and mergers.**

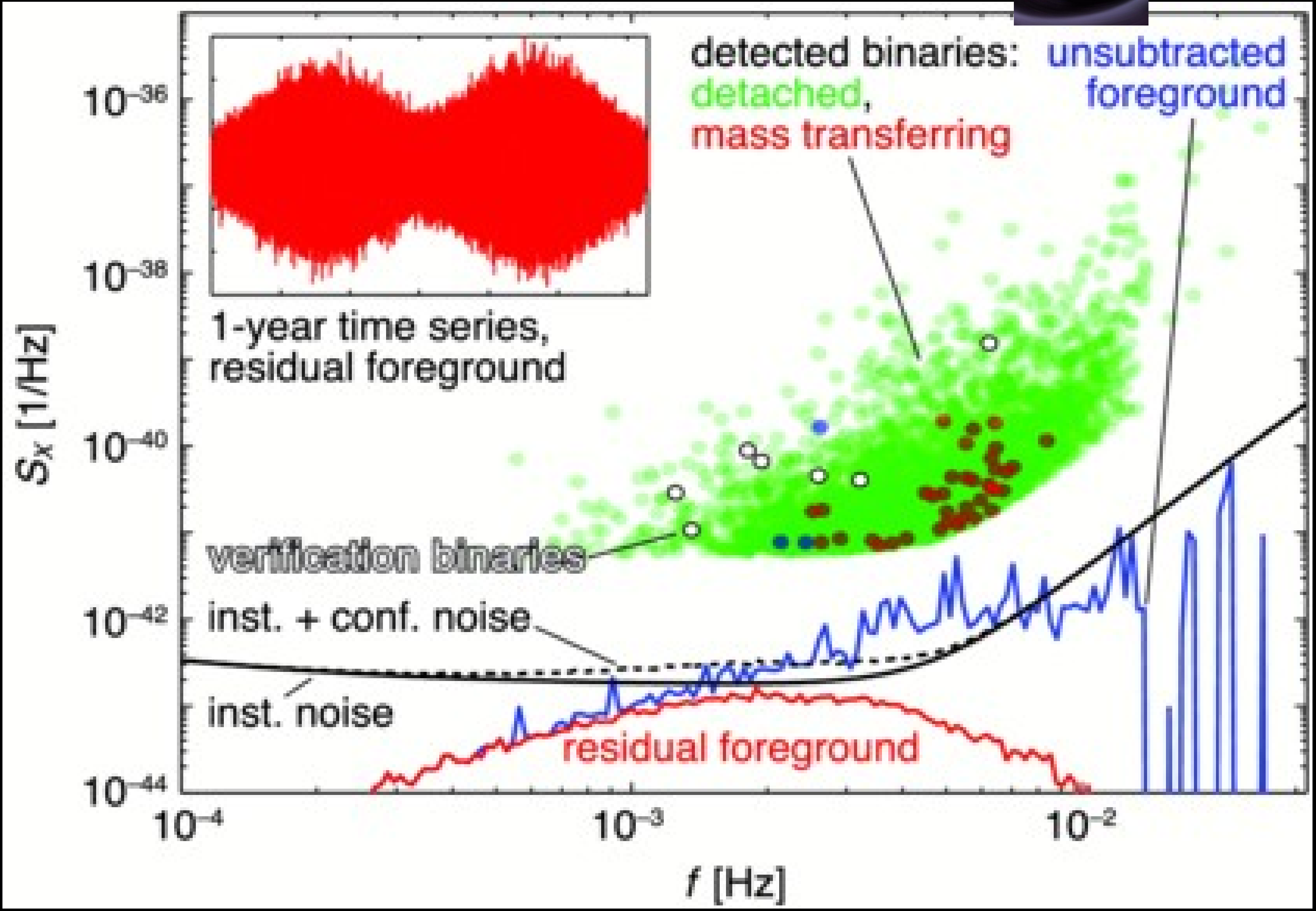
NGO/eLISA

- **-same orbit as *LISA***
- **-1Gm armlength**
- **-four laser links**
- **->2 year lifetime**
- **-launch >2025**



White dwarf binaries





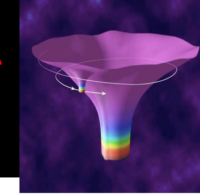
eLISA science team, Amaro-Seoane et al. 2012

	C3 - 4 links new baseline	C3 - 6 links new baseline	C1 - 4 links worst	C2 - 6 links best
SNR > 7	3367	5733	909	6211
df/dt < 20%	1148	1476	286	1657
df^2/dt^2 < 20%	1	2	0	3

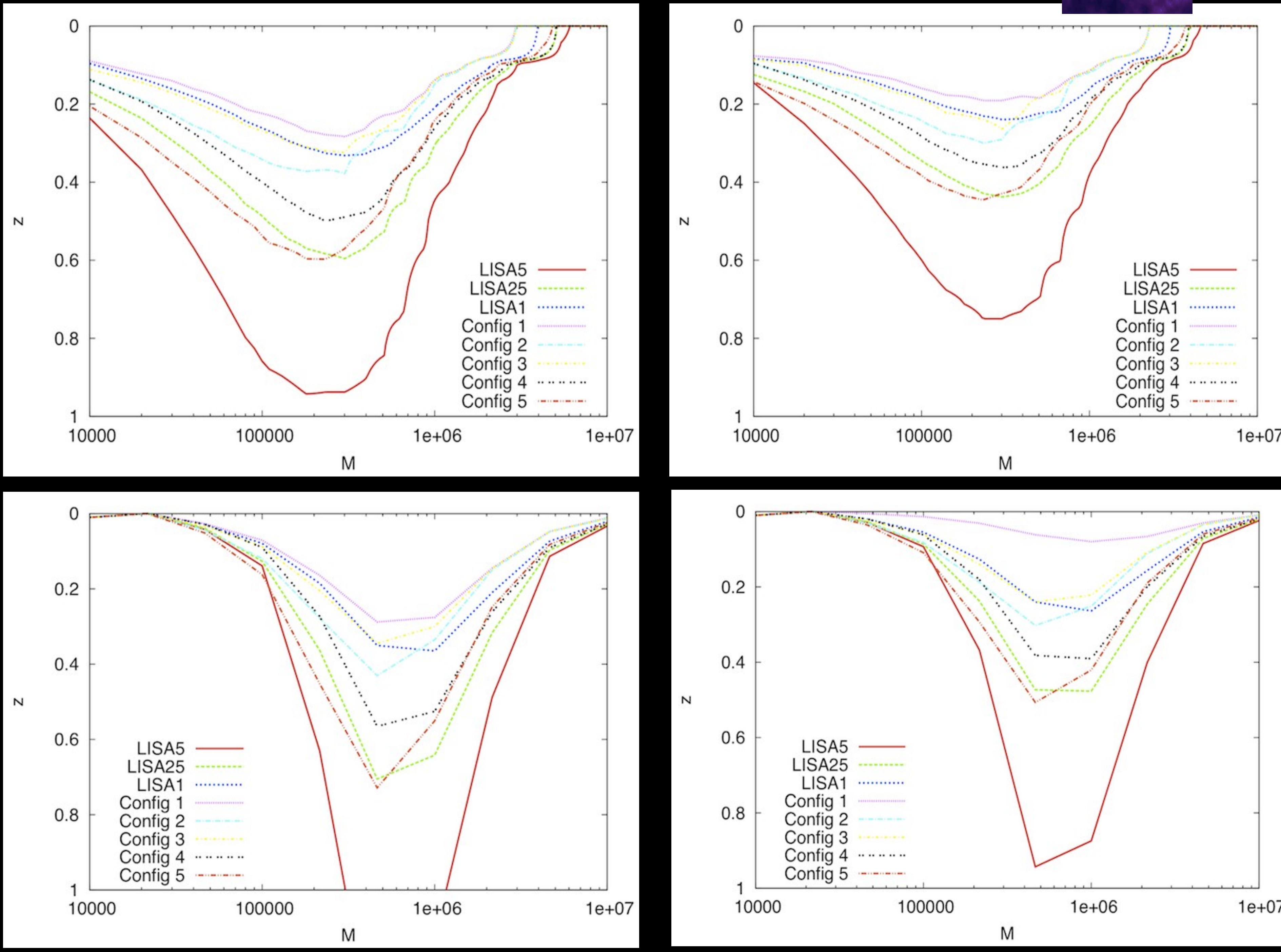
Credits: A. Petiteau

+ sky location to few deg^2 for several sources

Extreme mass ratio inspirals



6 Links **4 Links**



Credits: J. Gair

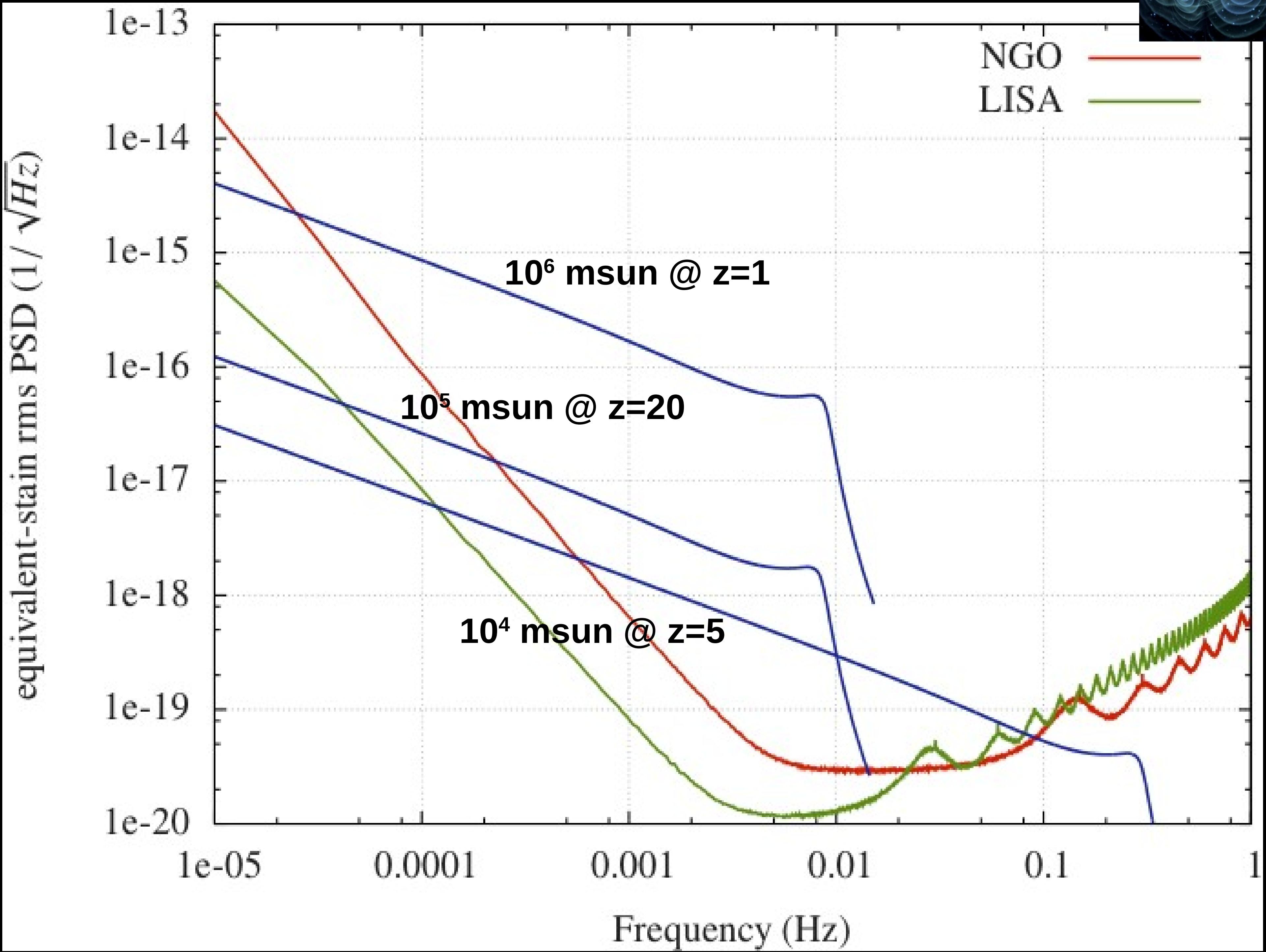
Configuration	Two Michelson Streams			One Michelson Stream		
	Black hole spin			Black hole spin		
	0	0.5	0.9	0	0.5	0.9
LISA5	1000	1100	1200	550	600	700
LISA25	300	350	500	135	150	235
LISA1	70	80	130	30	35	60
Config 1	40	45	75	15	20	30
Config 2	90	110	175	45	50	90
Config 3	60	65	105	25	30	50
Config 4	185	210	320	80	90	145
Config 5	310	335	465	140	155	235

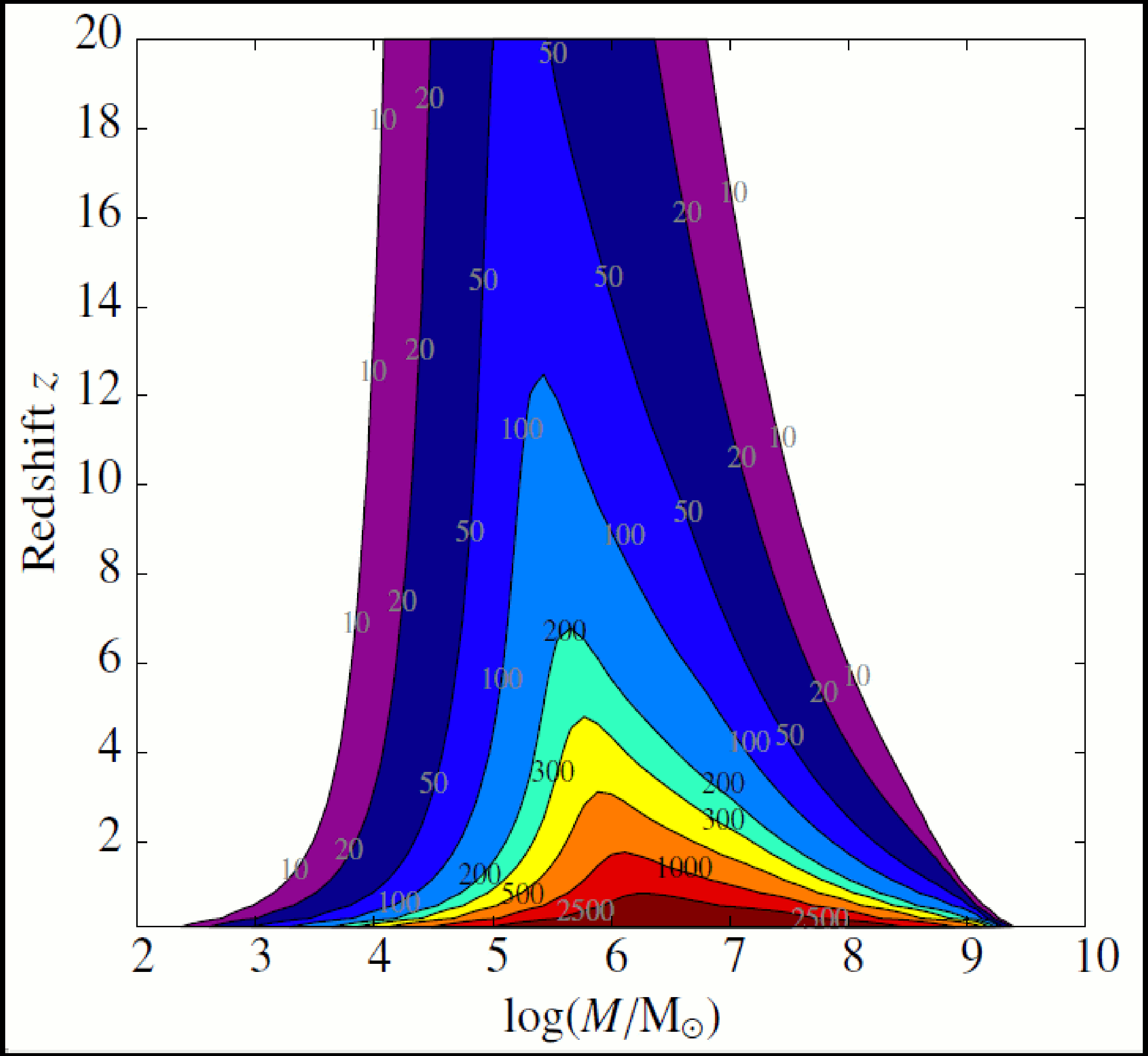
eLISA will give us:

- MBH mass to <0.1% relative accuracy
- spin of the primary hole to <0.01
- sky location to few deg^2
- luminosity distance to few%

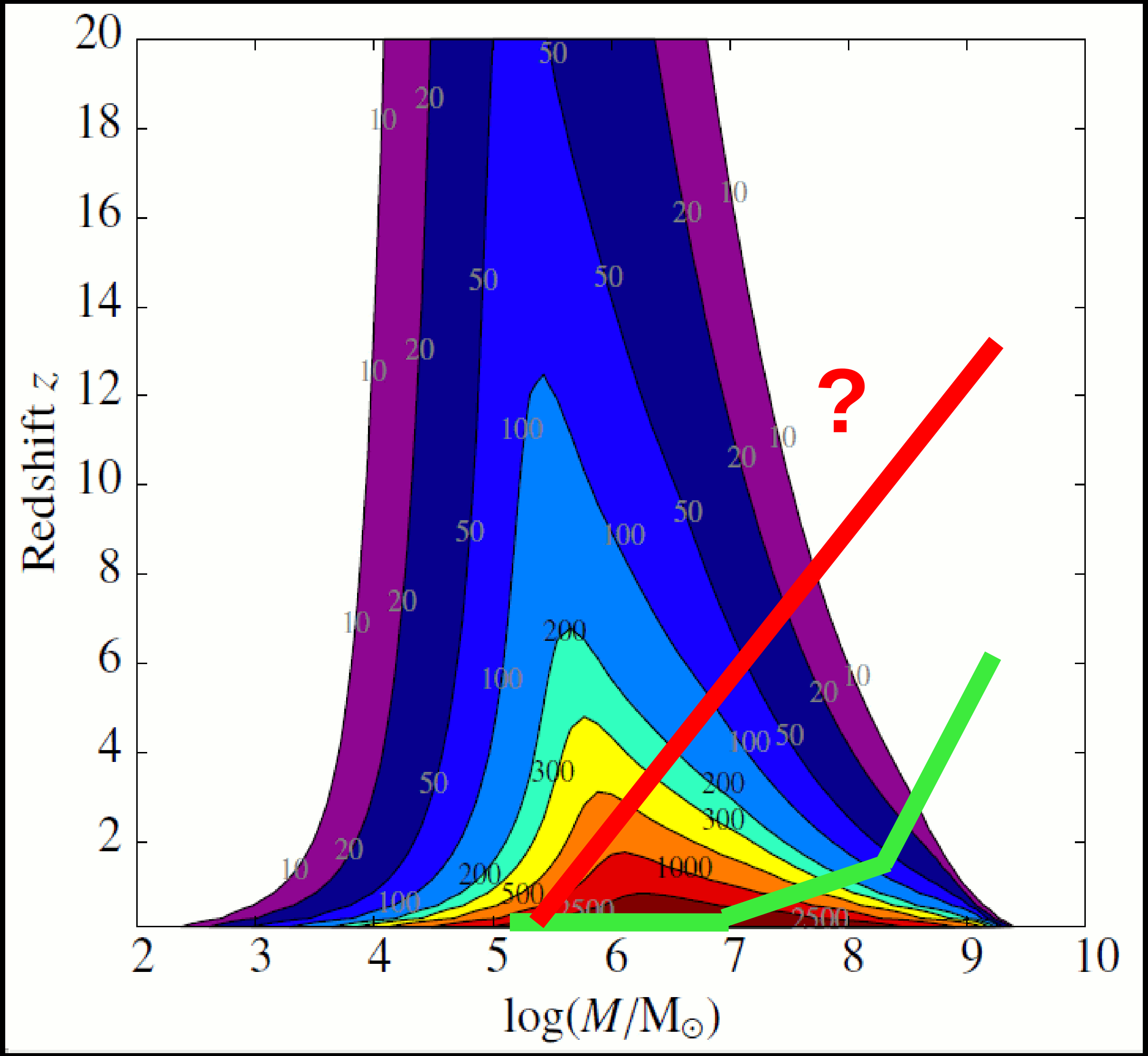
(Barack & Cutler 2004, eLISA science team, Amaro-Seoane et al. 2012)

Baby massive black hole binaries



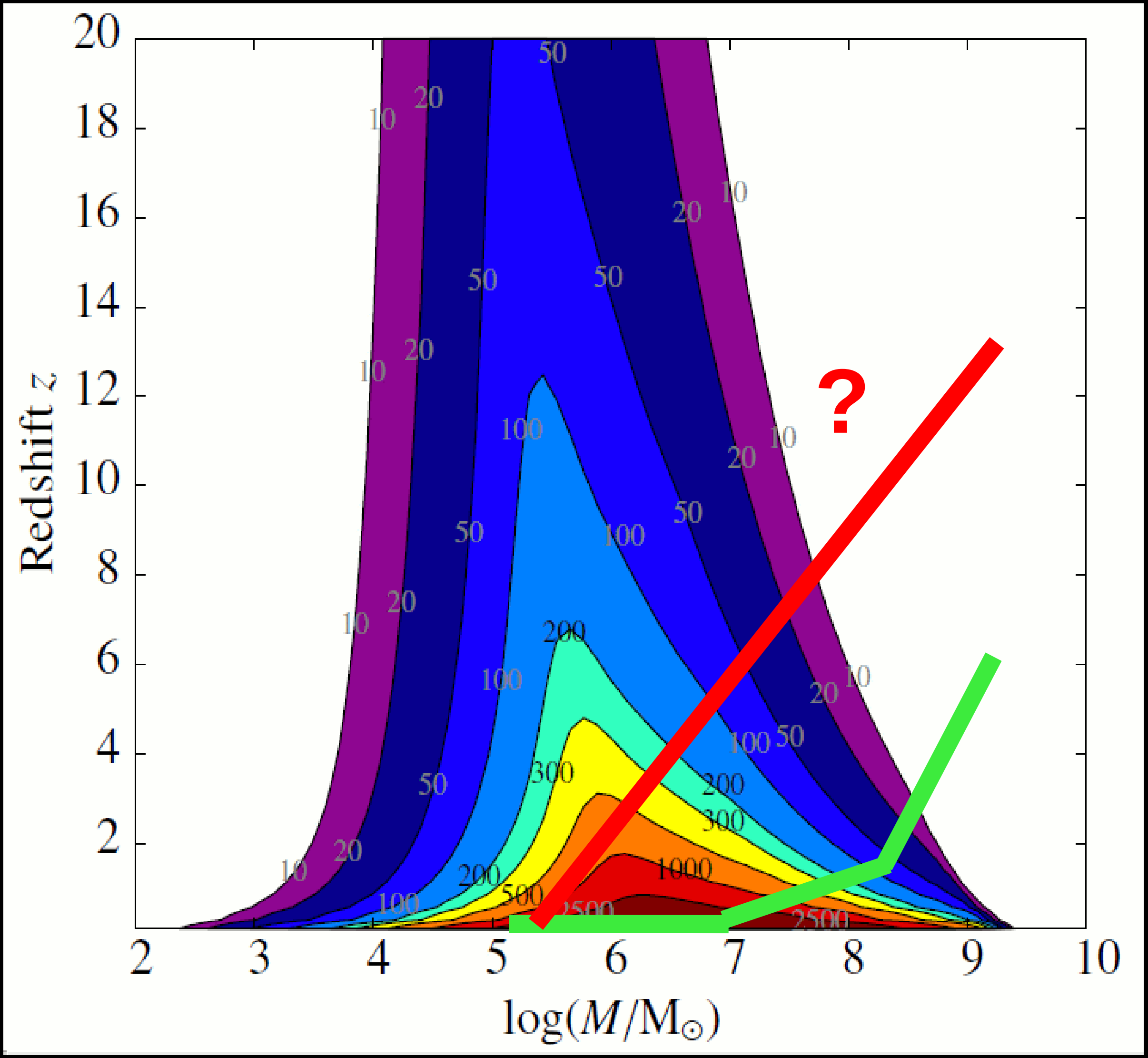


Credits: E. Berti

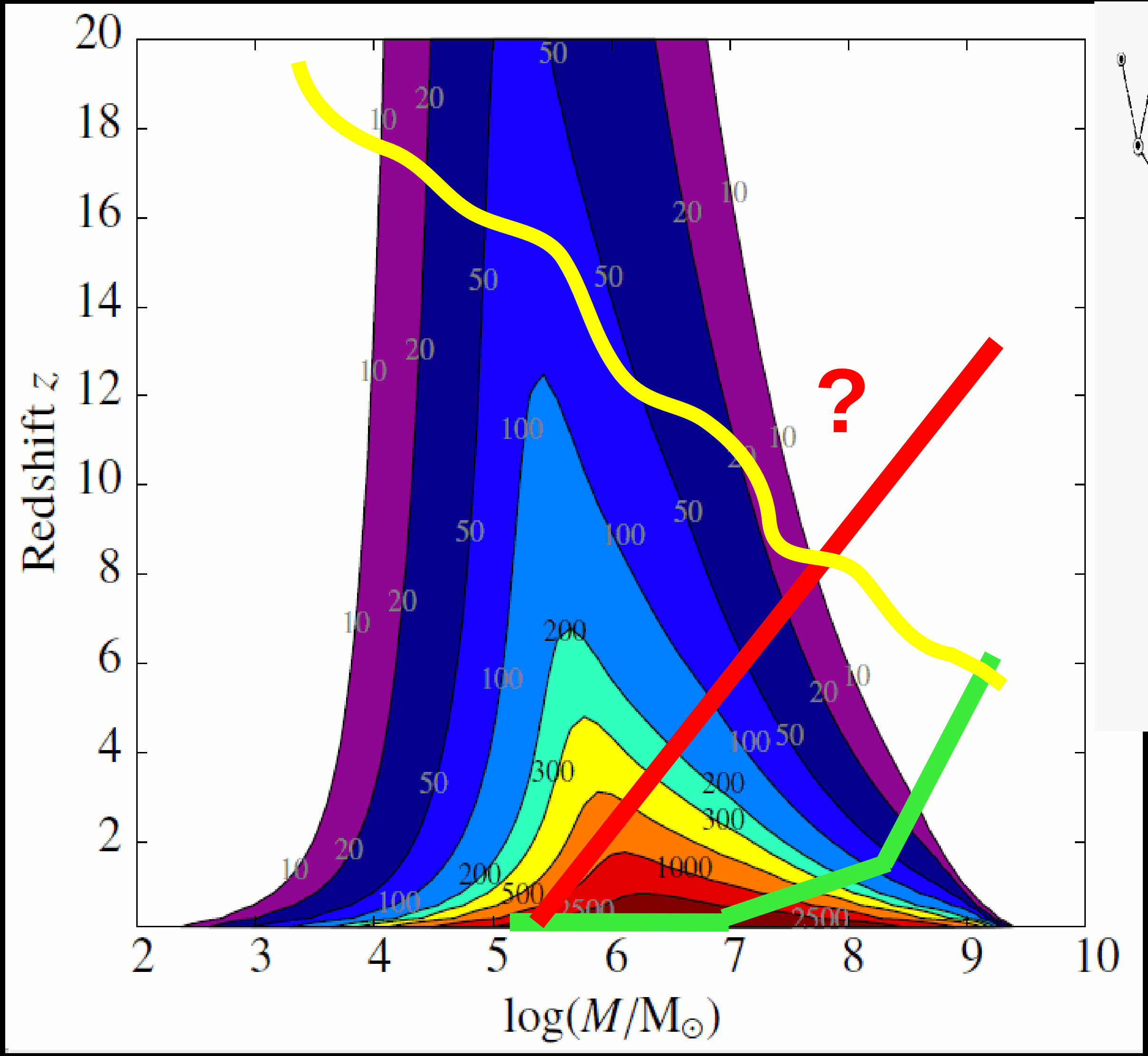


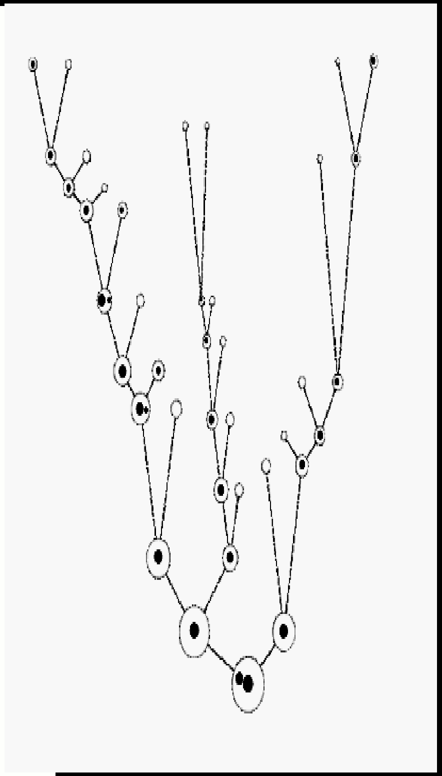
Redshift z
log(M/M⊙)
?
10
20
50
100
200
300
500
1000
2500

eLISA is a completely new window on the Universe covering most of the relevant parameter space for astrophysical massive black holes



eLISA is a completely new window on the Universe covering most of the relevant parameter space for astrophysical massive black holes





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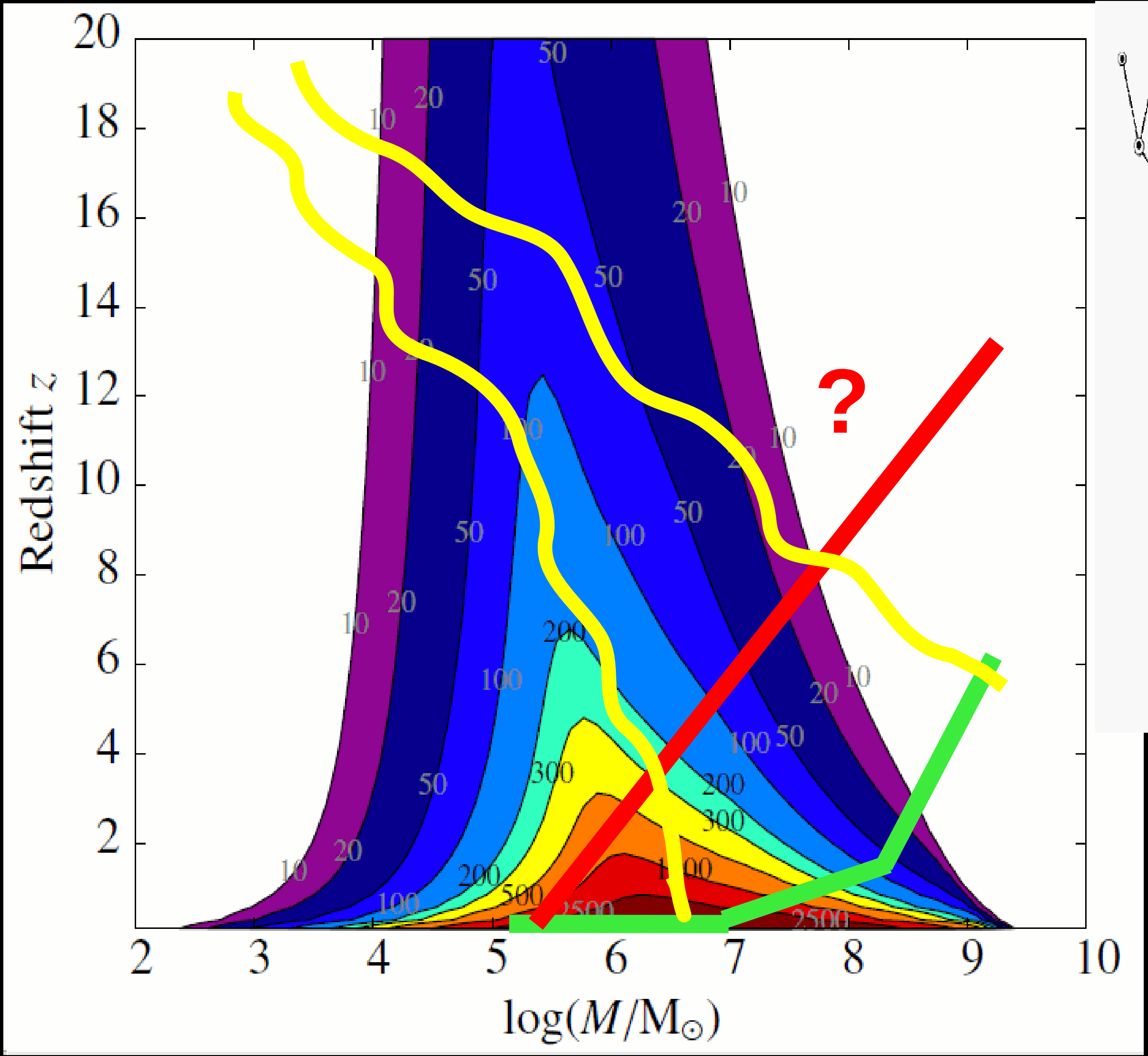

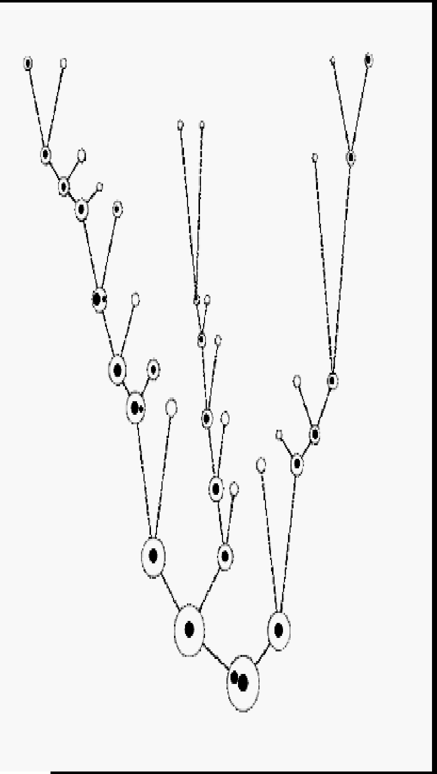

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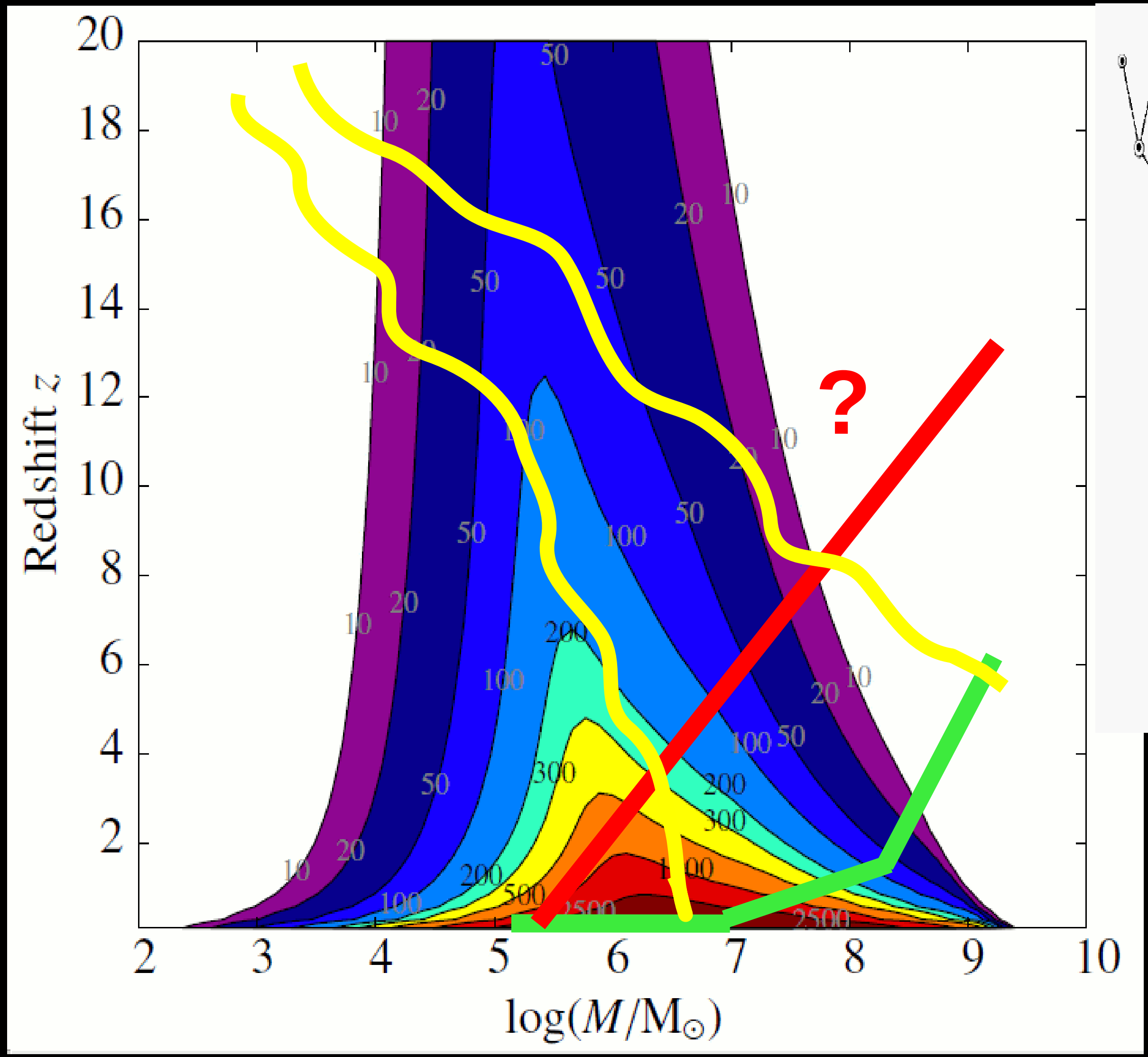
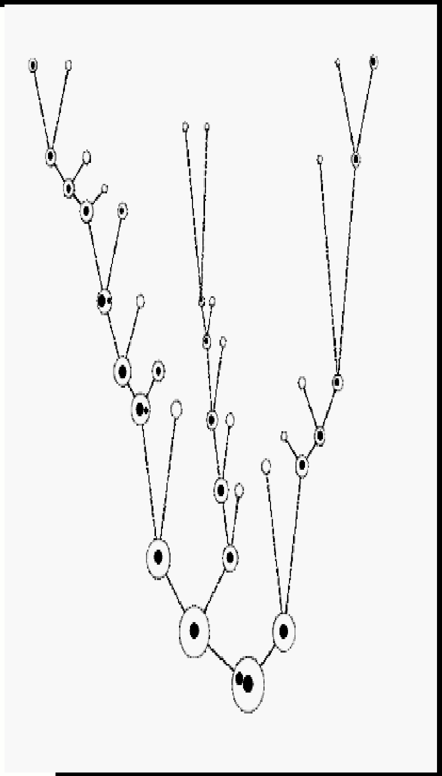




Possibly all massive black holes we see in galaxy today crossed the eLISA sensitivity domain in their history!

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

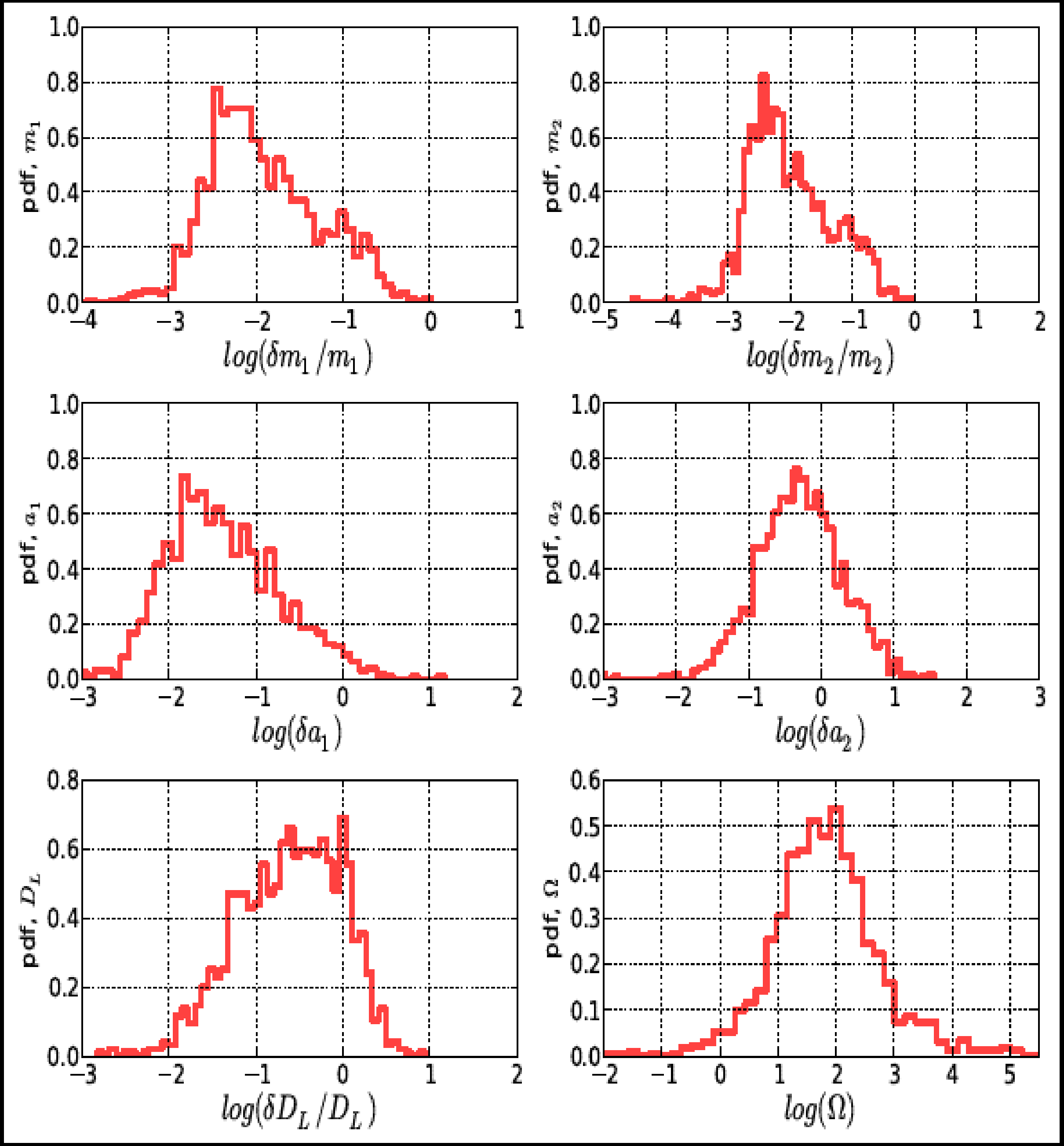
3-LE: large seeds+efficient accretion

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)

We can measure:

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

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

-sky location to 10-1000 deg
-luminosity distance to 10-100%

(See Vecchio 2004; Lang et al. 2006, 2008; Arun et al. 2009...+++)

We cannot measure redshift.
Redshift can be extracted by D_L or via an EM counterpart

Potential problem: D_L accuracy degrades a lot for distant sources

eLISA will give us:

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

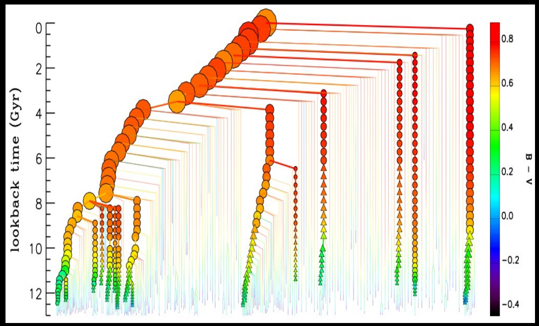
-spin of the primary hole to <0.1 (in many cases to <0.01)

-sky location to 10-1000 deg

-luminosity distance to <10% in most cases

MBH astrophysics with GW observations

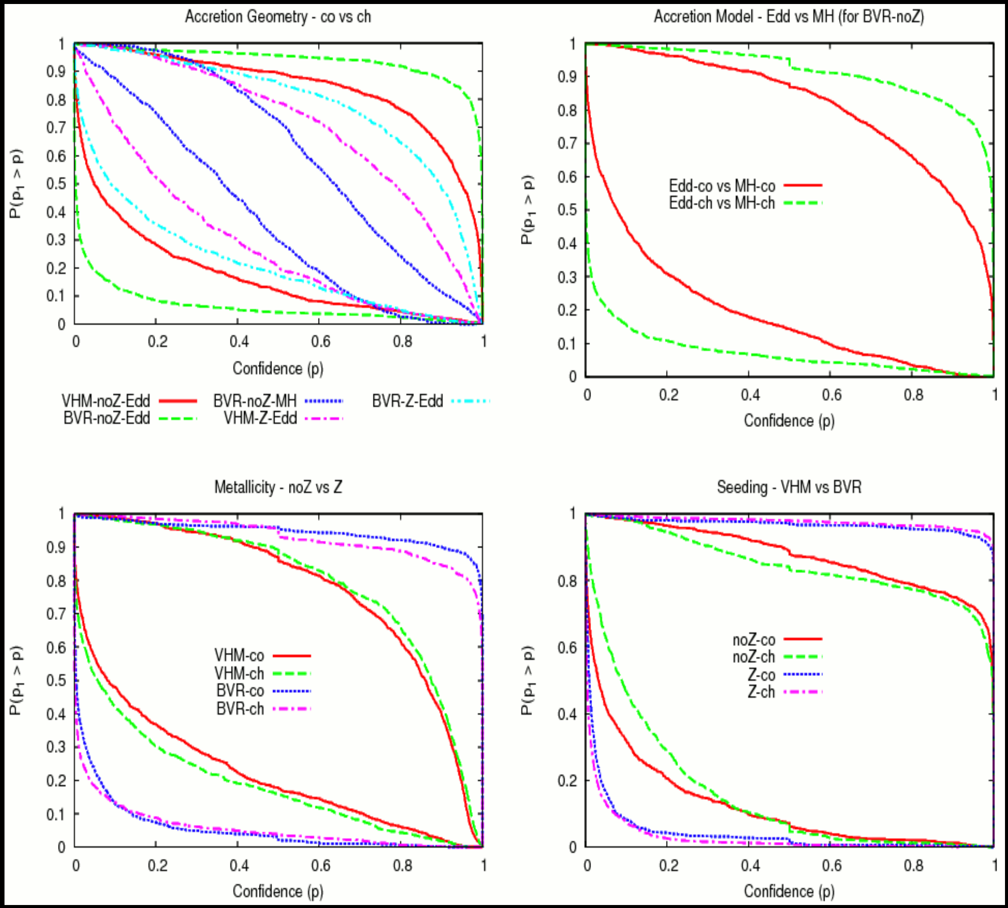
Astrophysical unknowns in MBH formation scenarios



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



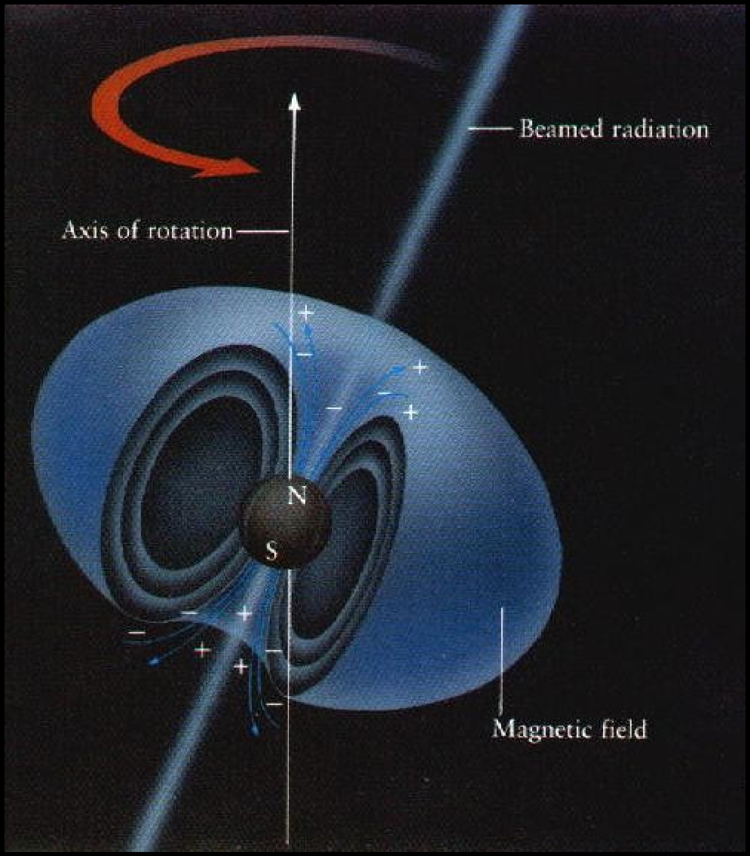
AS et al. 2011, see also Plowman et al 2011

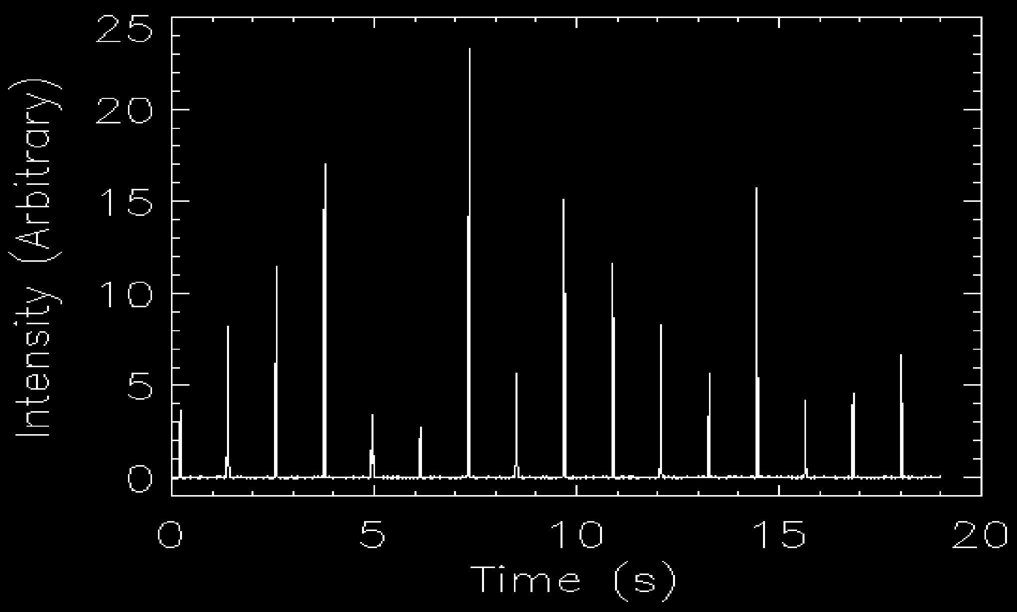
What is pulsar timing?

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

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

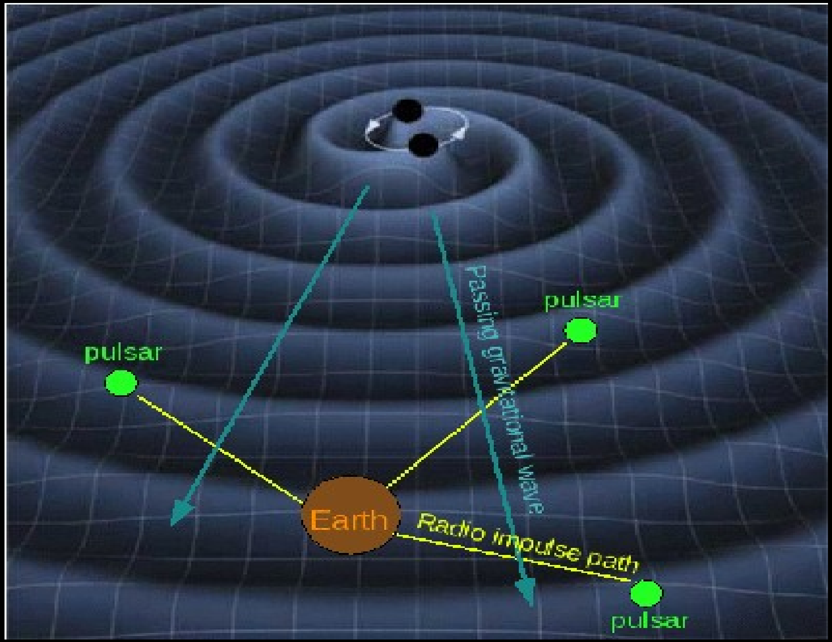
3-Calculate the timing residual *R*

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

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*

The Beasts: Pulsar Timing, a natural complement to eLISA

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)

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

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

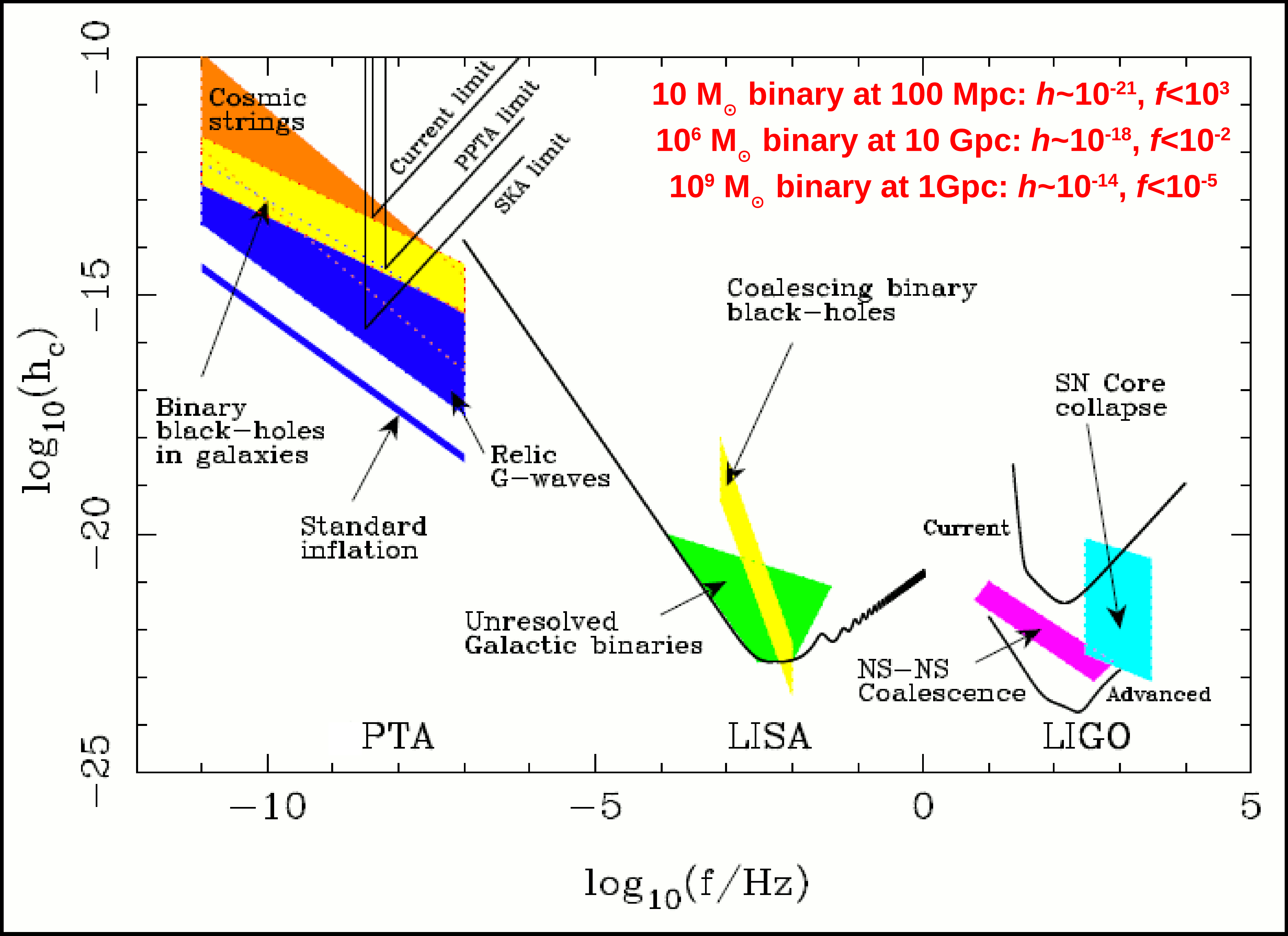
The pulsar timing arrays network

PPTA (Parkes pulsar timing array)

NanoGrav (north American nHz observatory for gravitational waves)

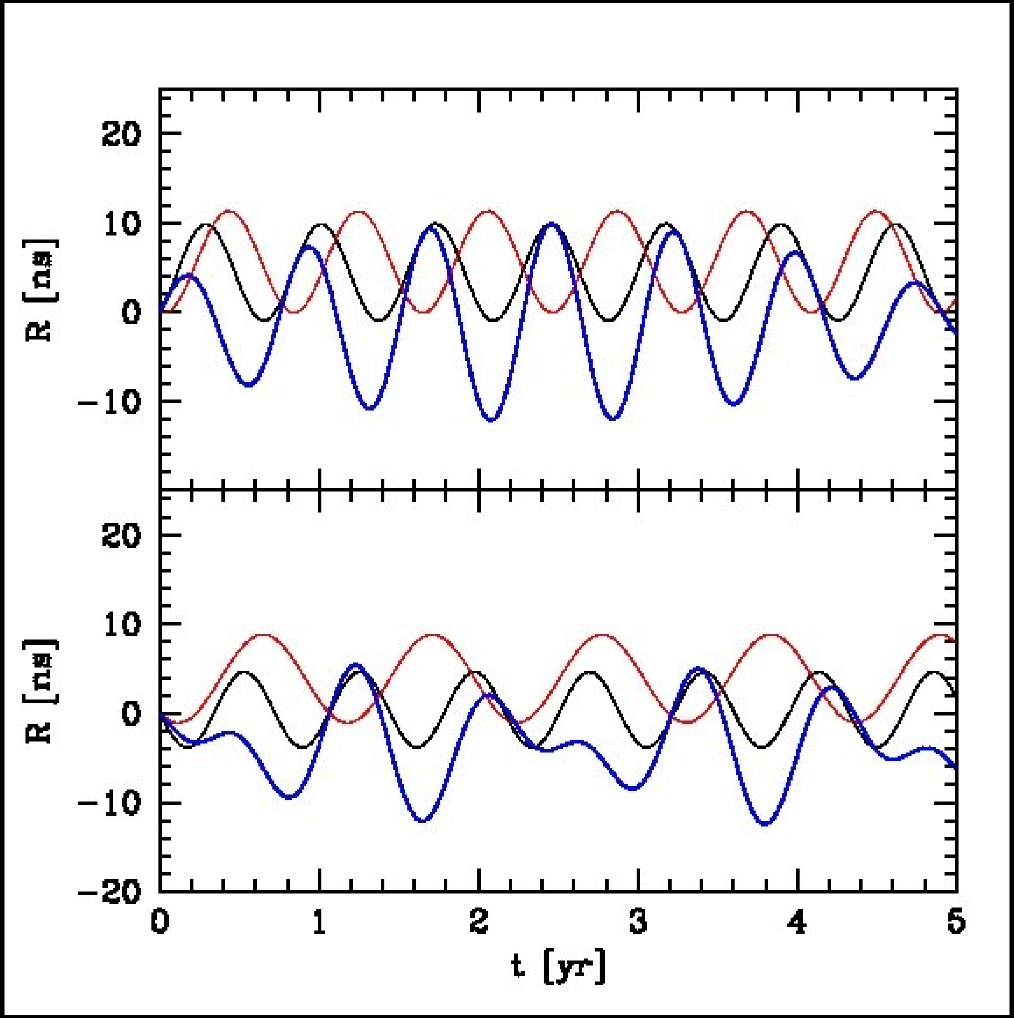
EPTA/LEAP (large European array for pulsars)

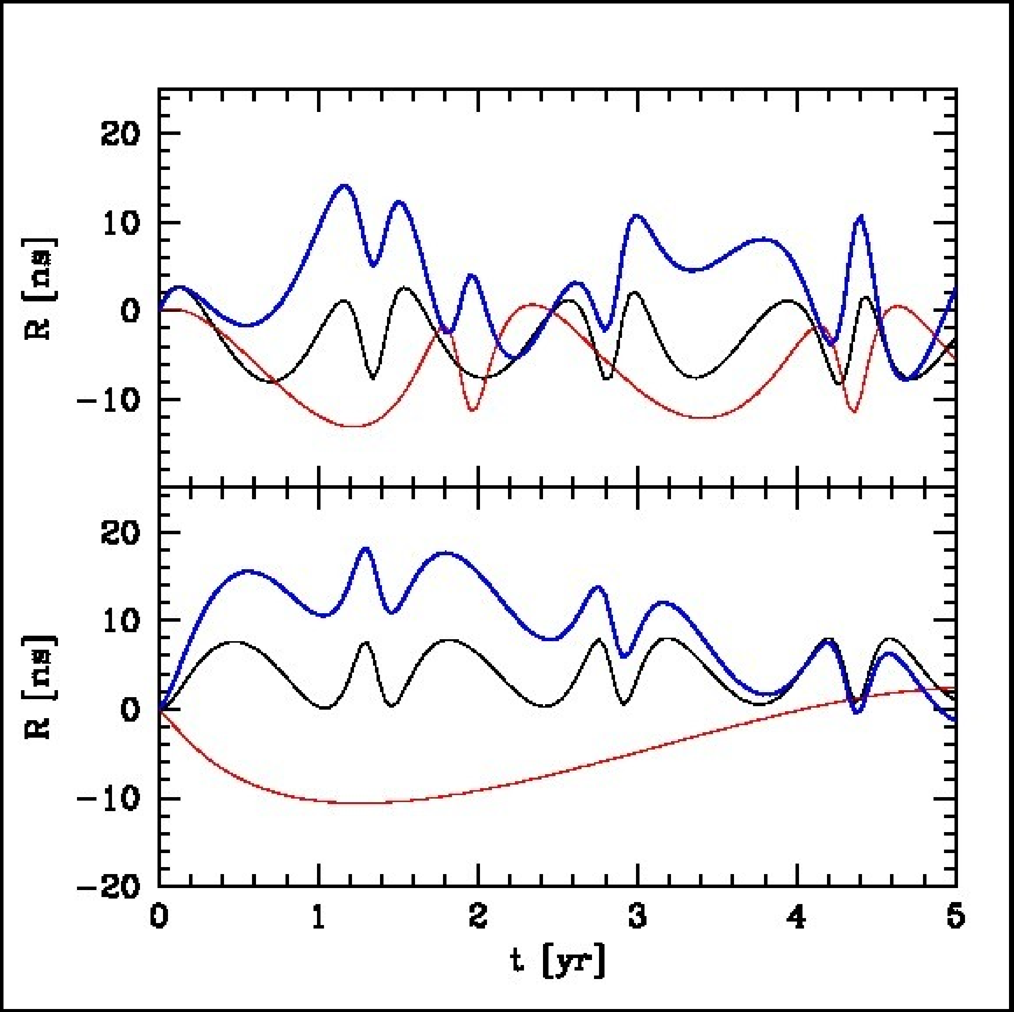
Coverage of the whole GW spectrum



Examples of individual source signals

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





Verbiest et al. 2009

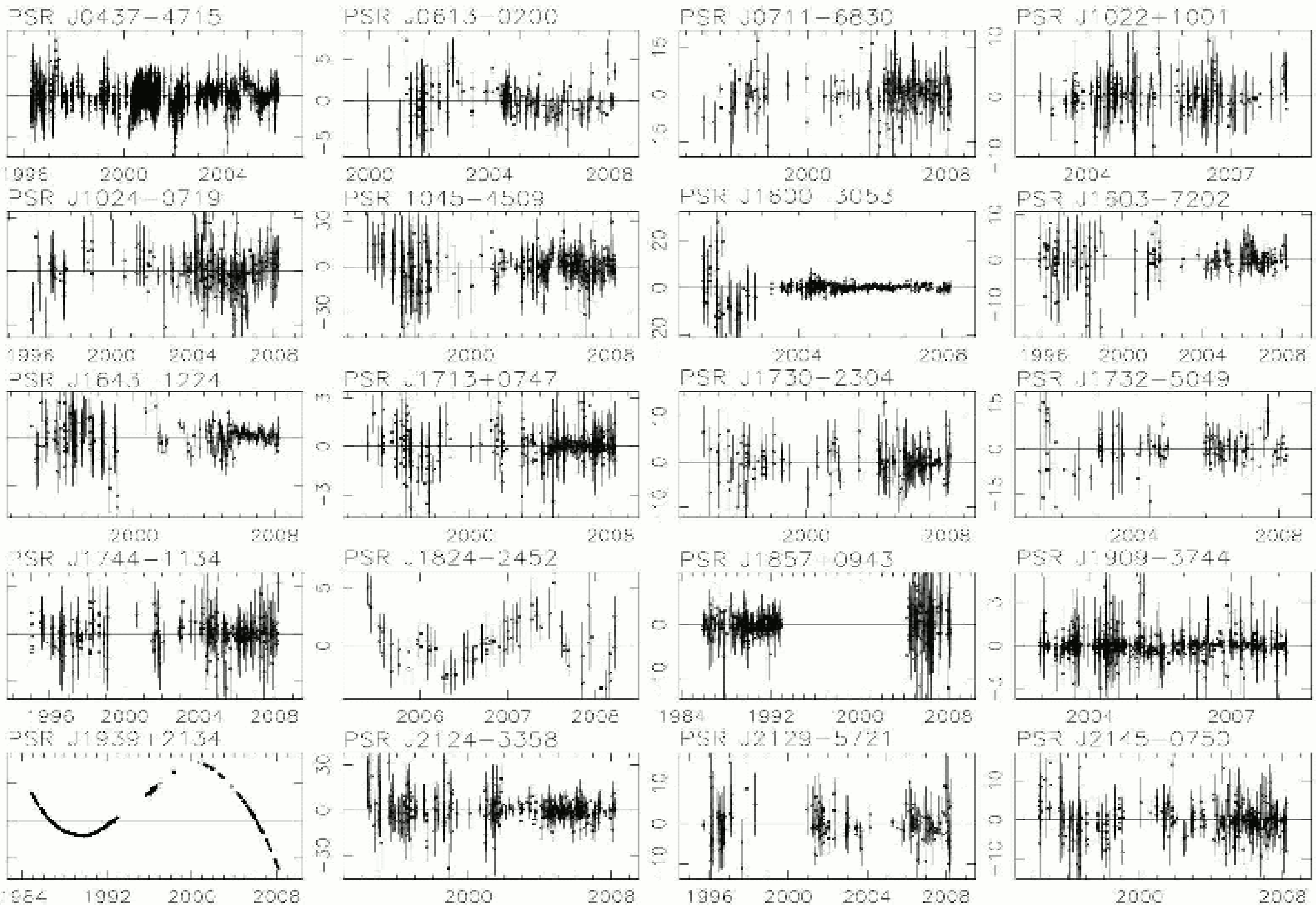


Figure 1. Timing residuals of the 20 pulsars in our sample. Scaling on the x-axis is in years and on the y-axis in μs. For PSRs J1857+0943 and J1939+2134, these plots include the Arecibo data made publically available by Kaspi et al. (1994); all other data are from the Parkes telescope, as described in §2. Sudden changes in white noise levels are due to changes in pulsar backend set-up - see §2 for more details.

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 MBHBs $dN/d\ln f \propto f^{-8/3}$

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

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

OBSERVATIONAL APPROACH:

> *Galaxy mass functions*

> *Galaxy pair counts*

> *Pair coalescence time*

$$\frac{d^3 n_G}{dz dM dq} = \frac{\phi(M,z)}{M \ln 10} \frac{\mathcal{F}(z,M,q)}{\tau(z,M,q)} \frac{dt_r}{dz}$$

> *MBH-host relations*

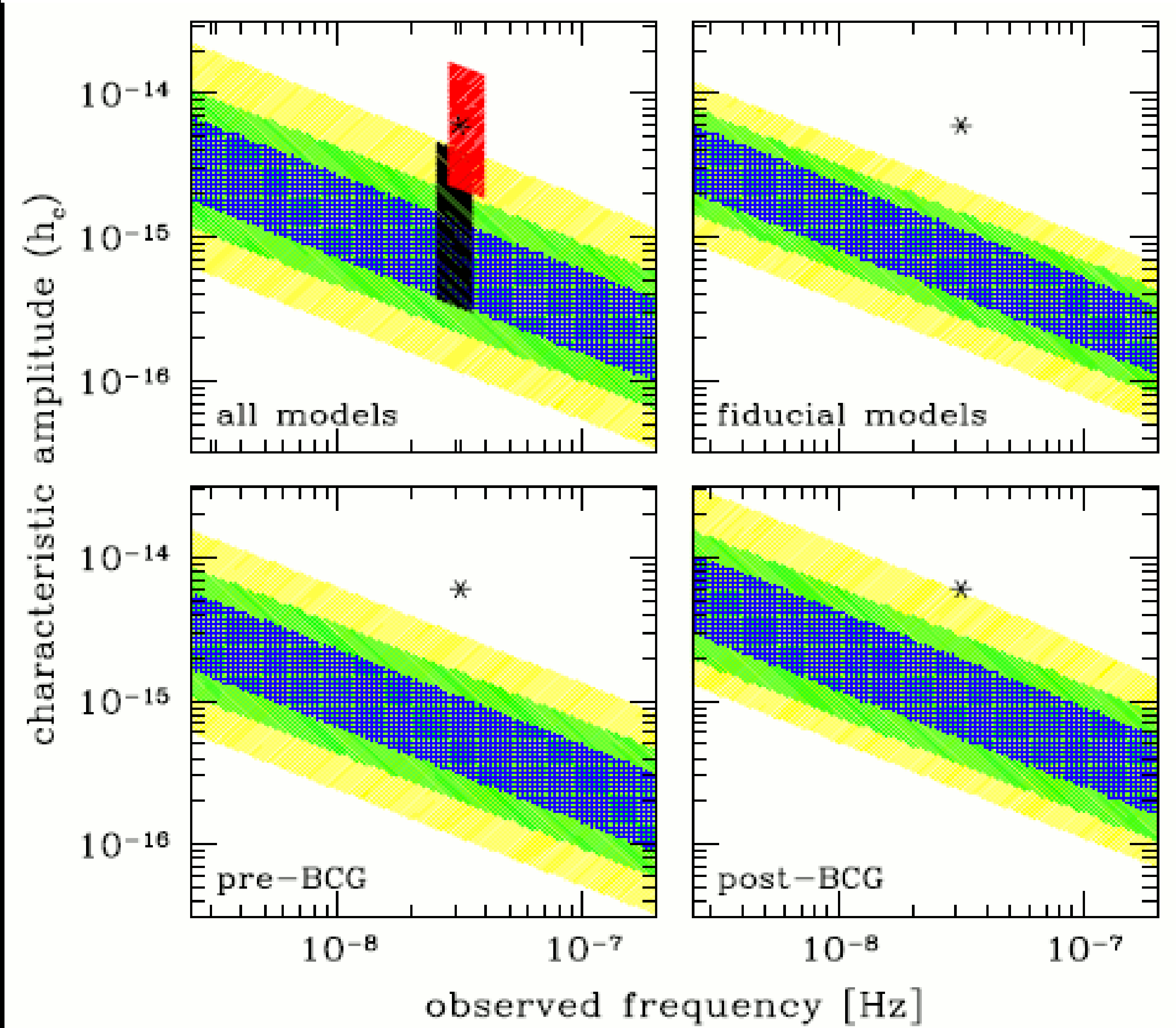
> *Accretion prescriptions*

Merger rate of MBHBs throughout the Universe per unit mass, mass ratio and redshift.

(Alternatively, the rate can be extracted by merger trees or N-body simulation-based models for galaxy formation
AS et al. 2008, 2009, Ravi et al. 2012)

Expected background level

$$A \approx 8 \times 10^{-16} \frac{\delta t_{\rm rms}}{100\,{\rm ns}} \left(\frac{N_r}{100}\right)^{-1/4} \left(\frac{N_p}{20}\right)^{-1/2} \left(\frac{T_{\rm obs}}{5\,{\rm yr}}\right)^{-5/3}$$



68% confidence interval around 10^{-15}.

But large spread due to huge uncertainties.

Forthcoming IPTA limits could test the upper end of plausible scenarios within a year.

Astrophysics with PTA!

AS 2012, see also McWilliams et al. 2012

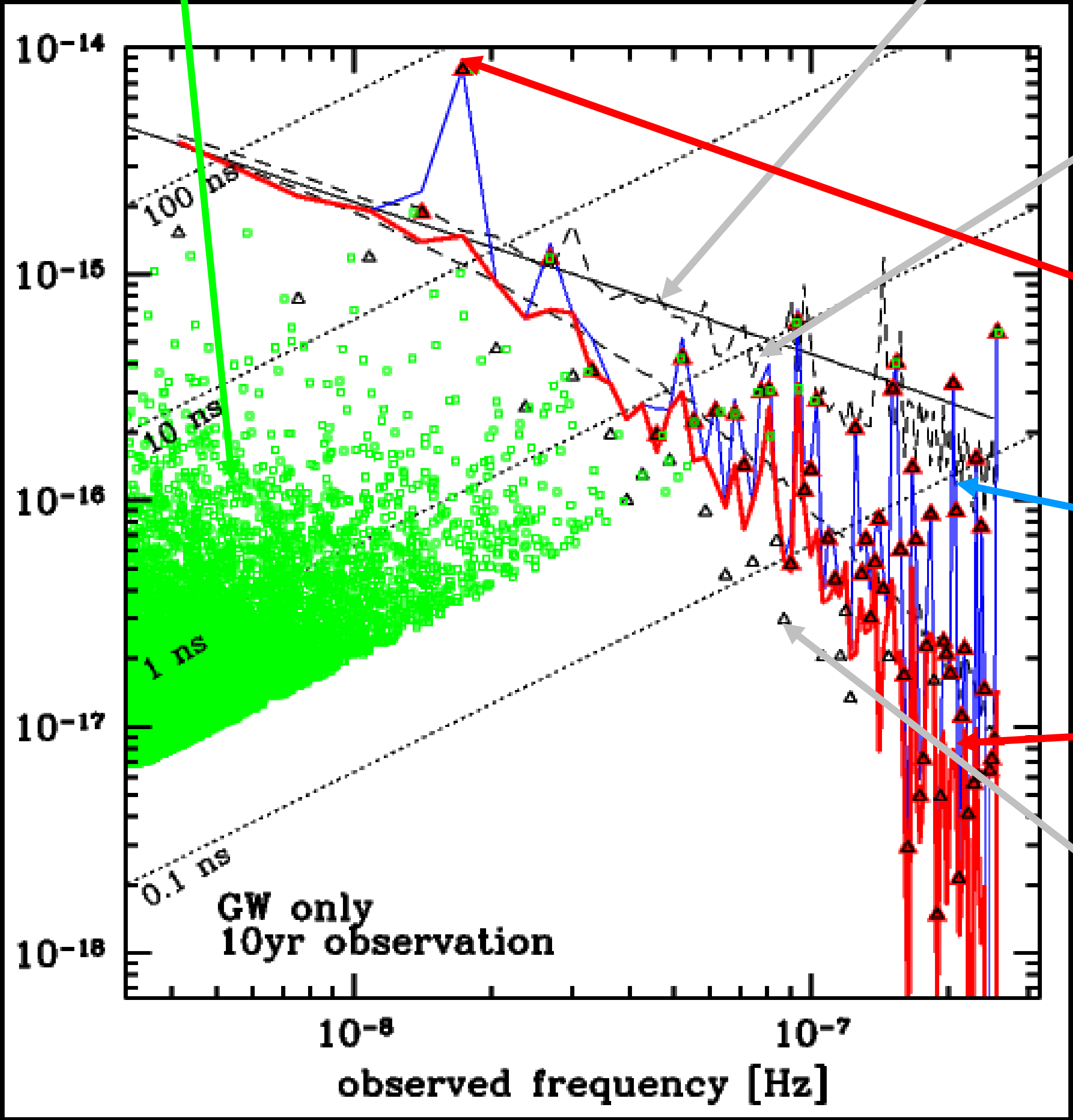
Signal from a MBHB population

Theoretical 'average' spectrum

Contribution of individual sources

Spectrum averaged over 1000 Monte Carlo realizations

Resolvable systems: i.e. *systems whose signal is larger than the sum of all the other signals falling in their frequency bin*



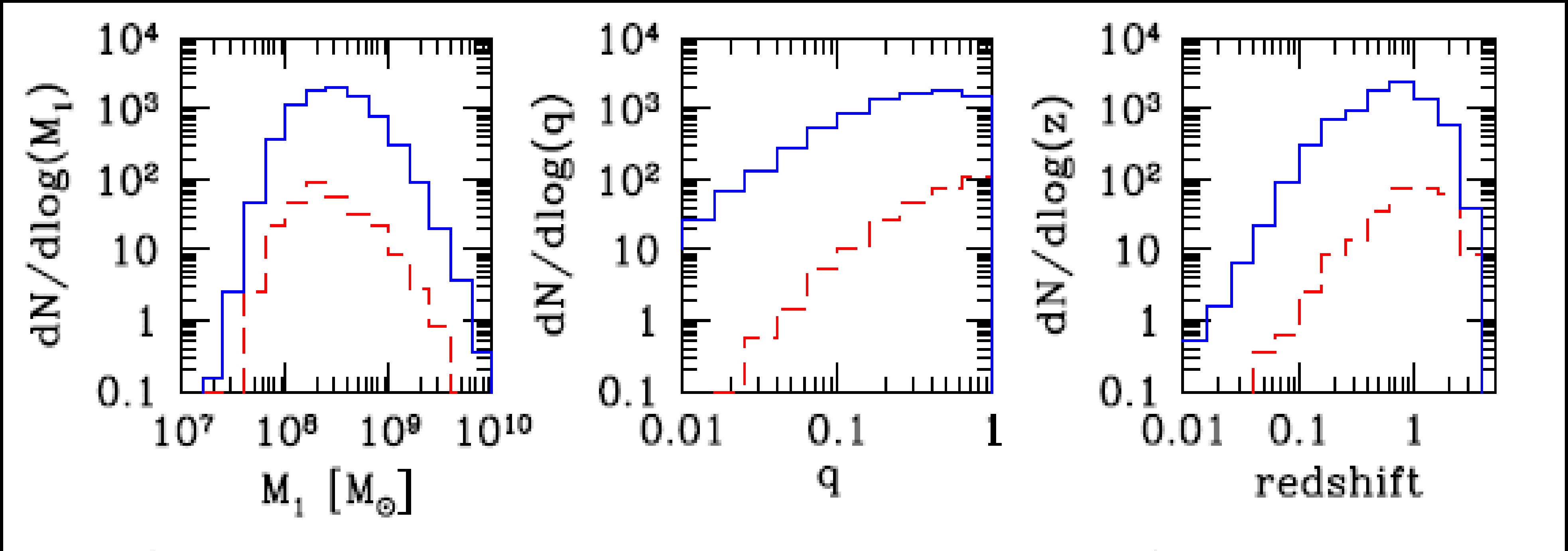
Total signal

Unresolved background

Brightest sources in each frequency bin

Kocsis & AS 2011

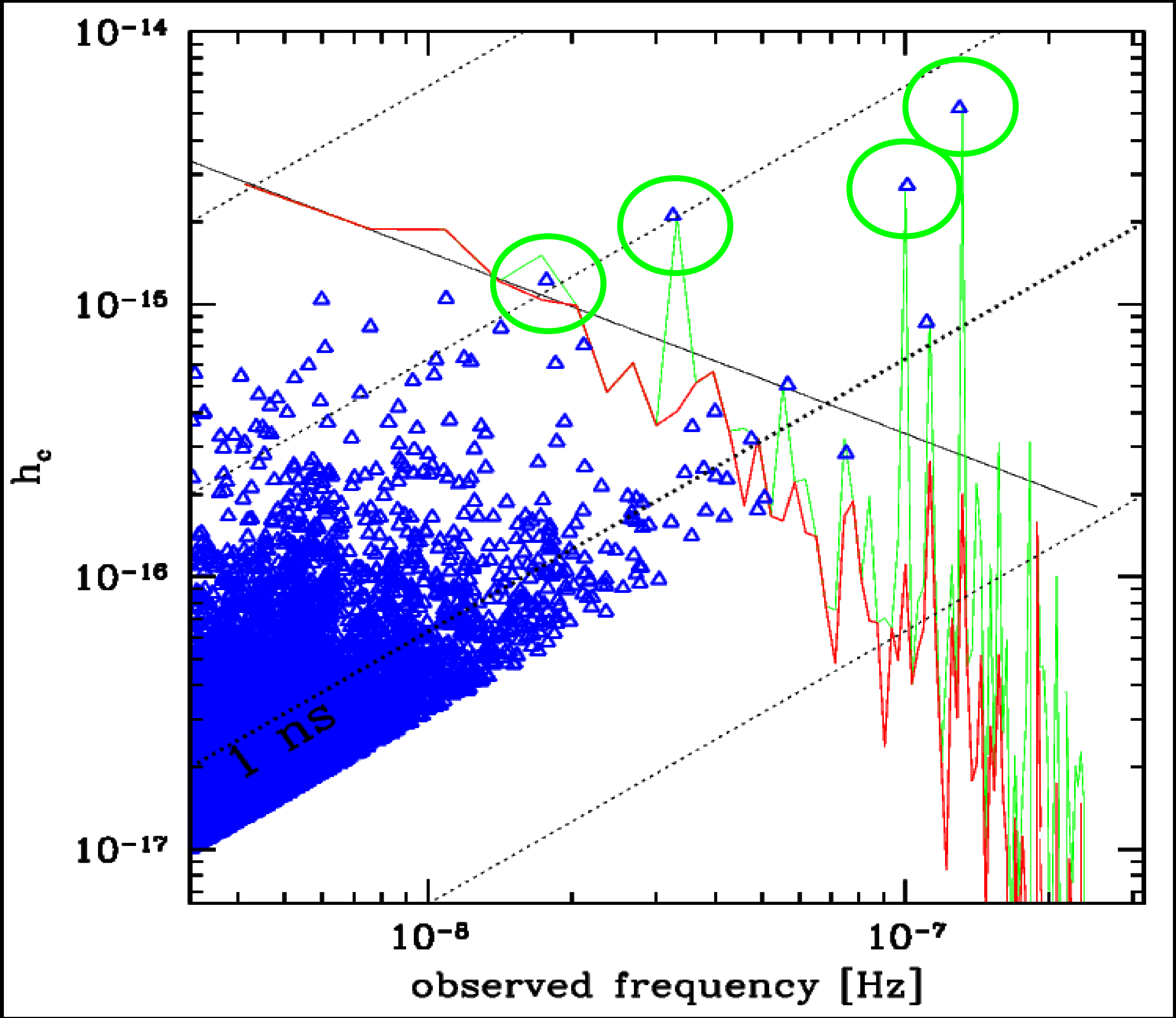
Detail of the contributing population



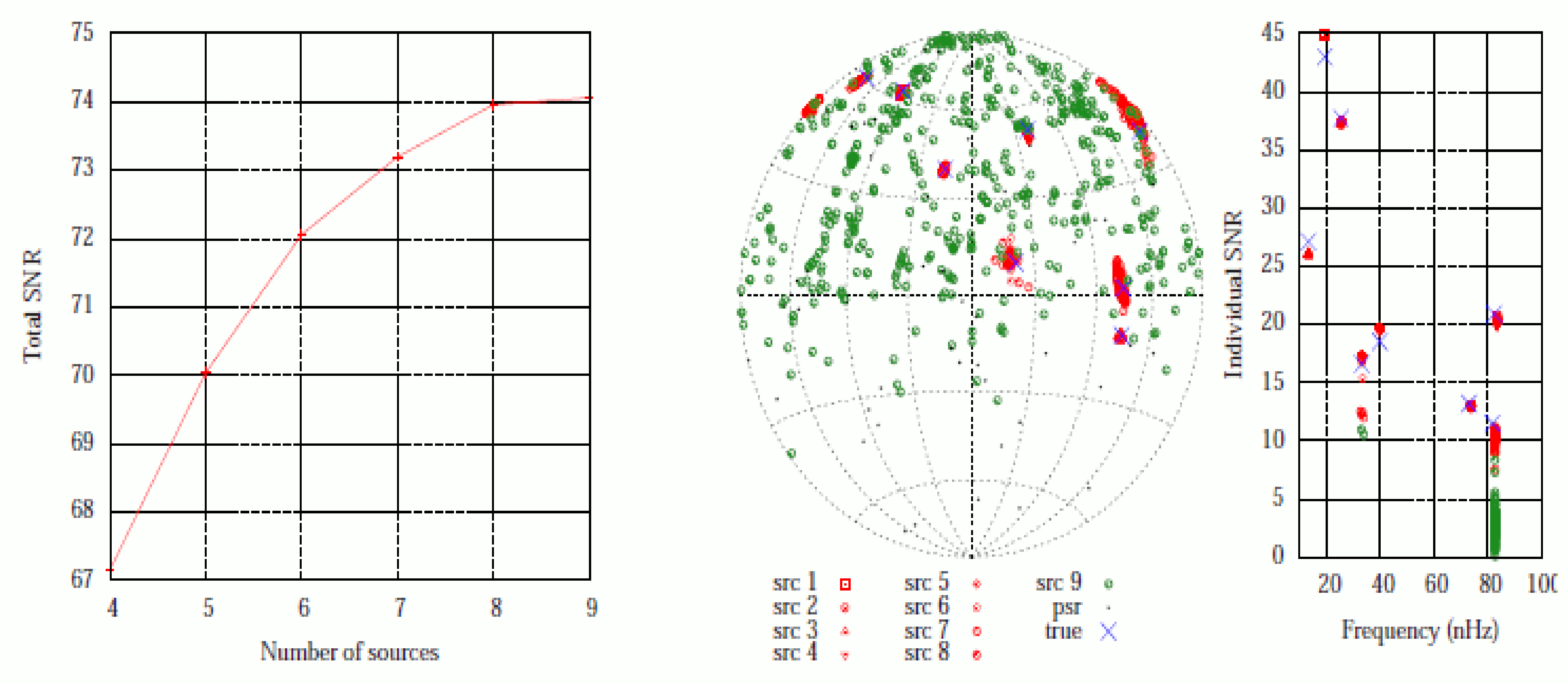
-sensitive to massive ($>10^8 M_\odot$), cosmologically nearby ($z<2$) binaries: complementary to the LISA range (AS et al. 2008, 2009).

-if a source can be individually resolved, its sky position can be pinned down to ~1-50deg^2 accuracy (AS & Vecchio 2010, Cornish et al. 2010, Lee et al. 2011, Ellis et al. 2012). Promising prospects for multimessenger astronomy (massive+nearby---> bright counterparts)

RESOLVABLE SOURCES



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



-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

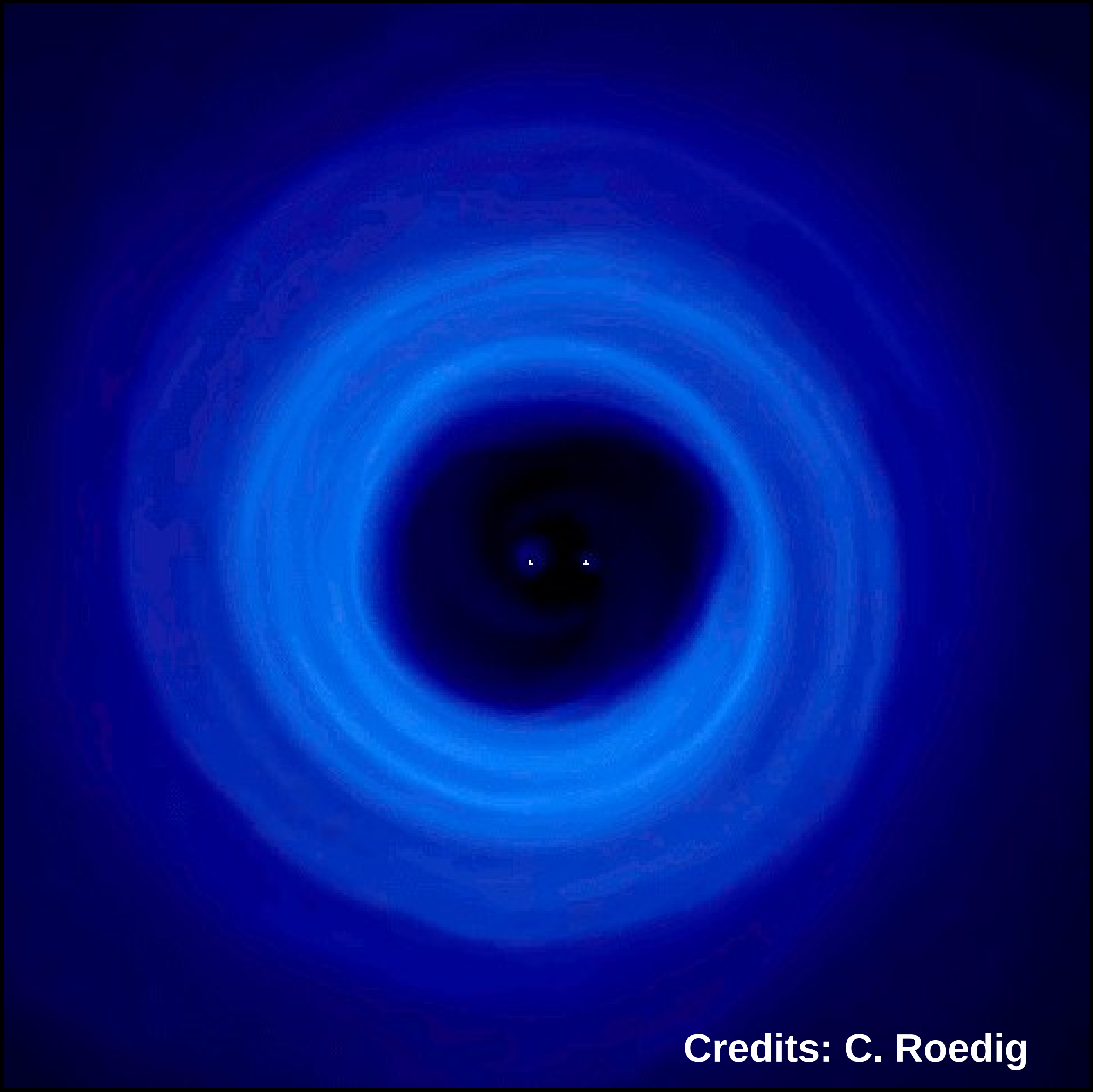
> frequency at sub-bin level

-Extremely promising, needs test on more realistic situations

ELECTROMAGNETIC COUNTERPARTS

Tanaka et al. 2012, AS et al. 2012

MBHB+circumbinary disk



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

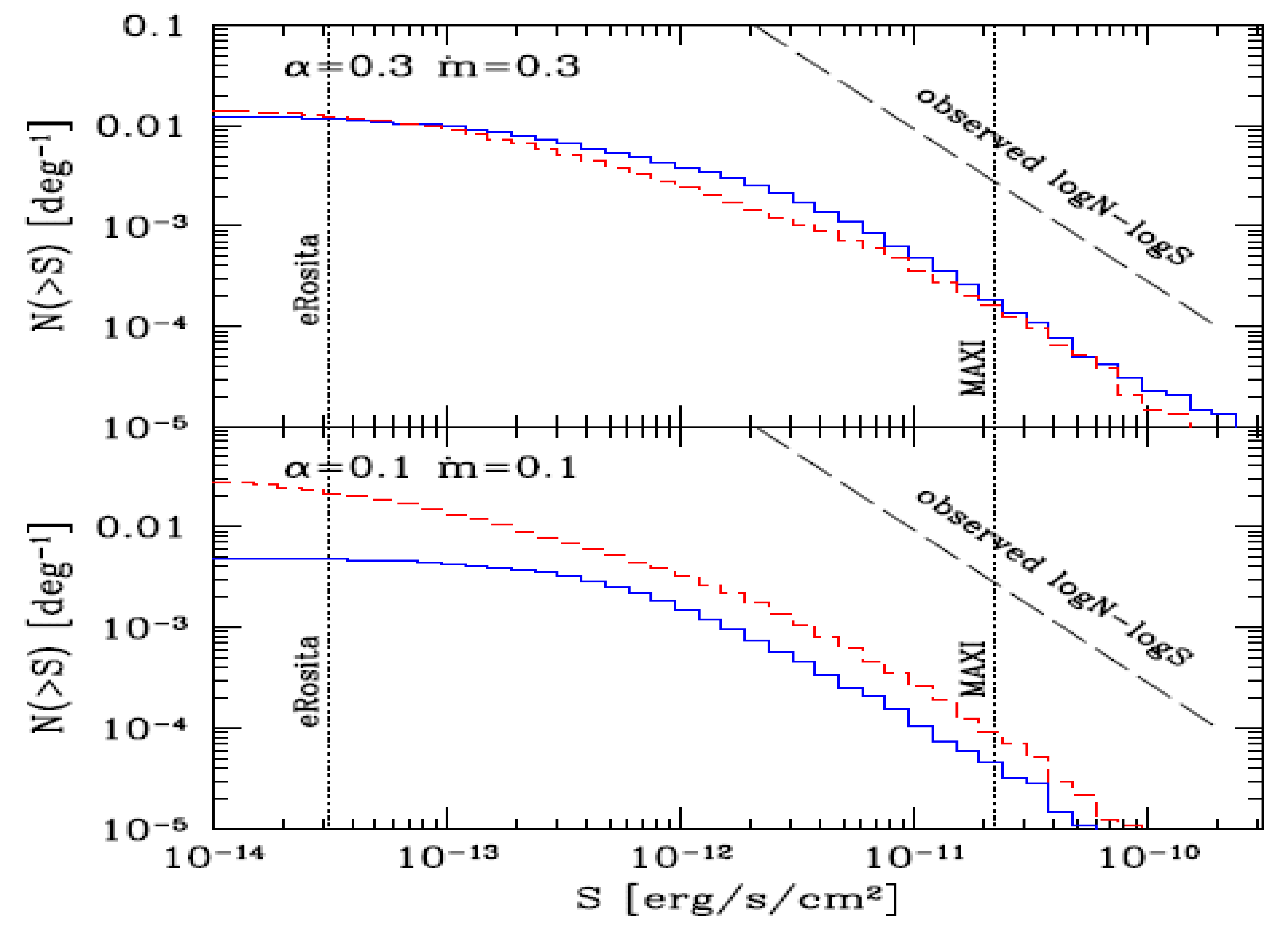
-UV generated by the Inner disks. Periodic variability.

-X ray corona. Periodic variability

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

-Double fluorescence 6.4keV Kα iron lines

AS et al 2012



Sensitivity more than sufficient, *more than 100 sources* might be detected at the eROSITA sensitivity limit!

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: thousands of WD-WD binaries (NS-NS? NS-BH?); dozens of EMRIS to $z>0.5$; 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).