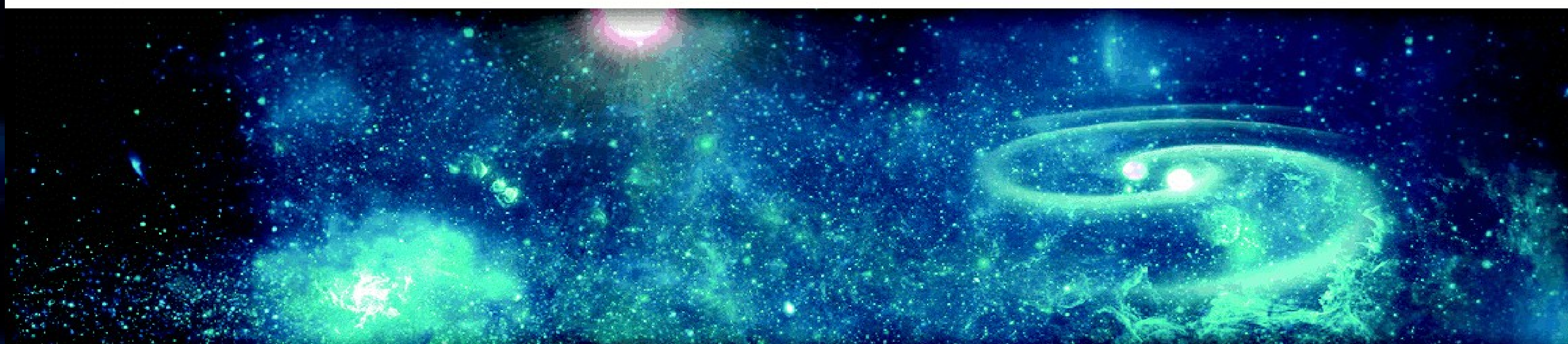
eLISA science

THE GRAVITATIONAL UNIVERSE

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



The eLISA Consortium, arXiv:1305.5720

www.elisascience.org

Alberto Sesana
Albert Einstein Institute, Golm

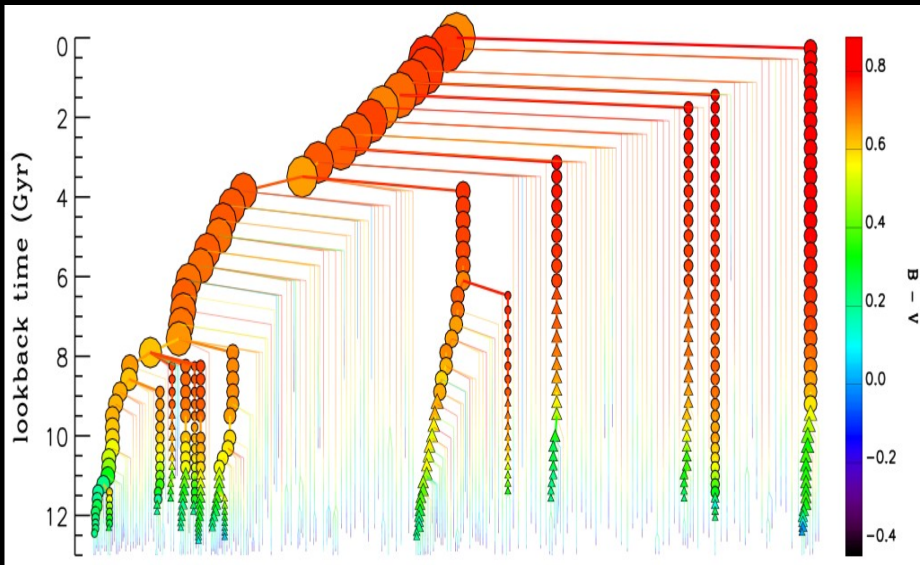
OUTLINE

1- General considerations:
massive black hole binaries (MBHBs) and gravitational waves (GWs)

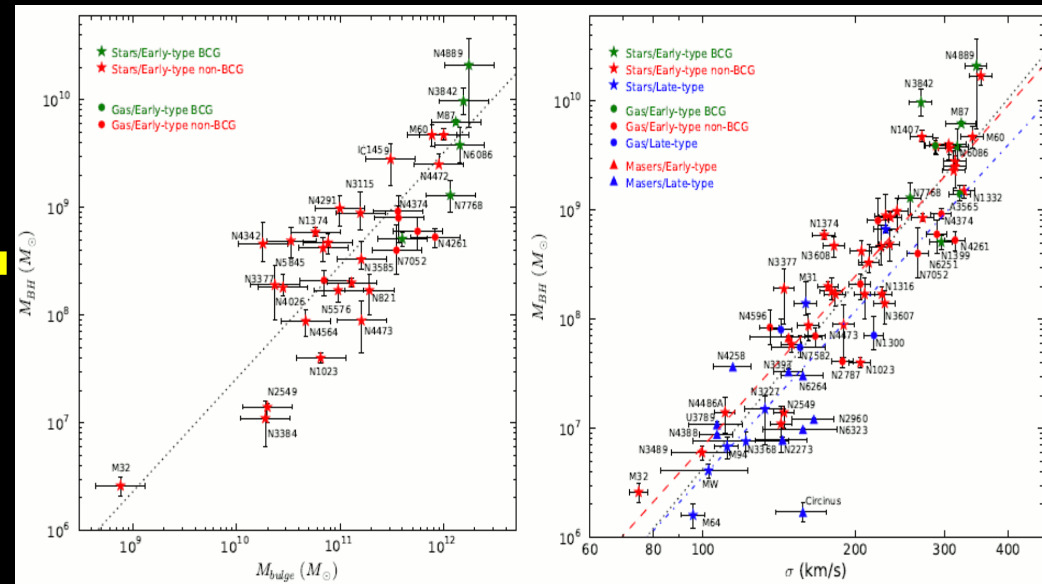
2- Science with the eLISA mission

3- Bonus: pulsar timing arrays (PTAs)

Structure formation in a nutshell



From De Lucia et al 2006



Ferrarese & Merritt 2000, Gebhardt et al. 2000

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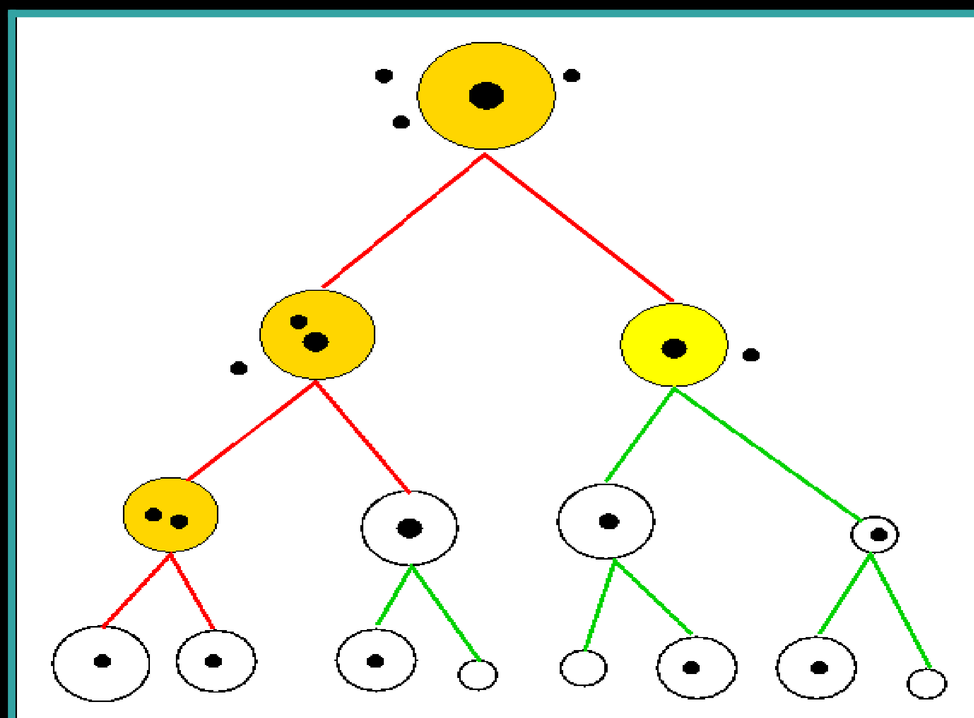
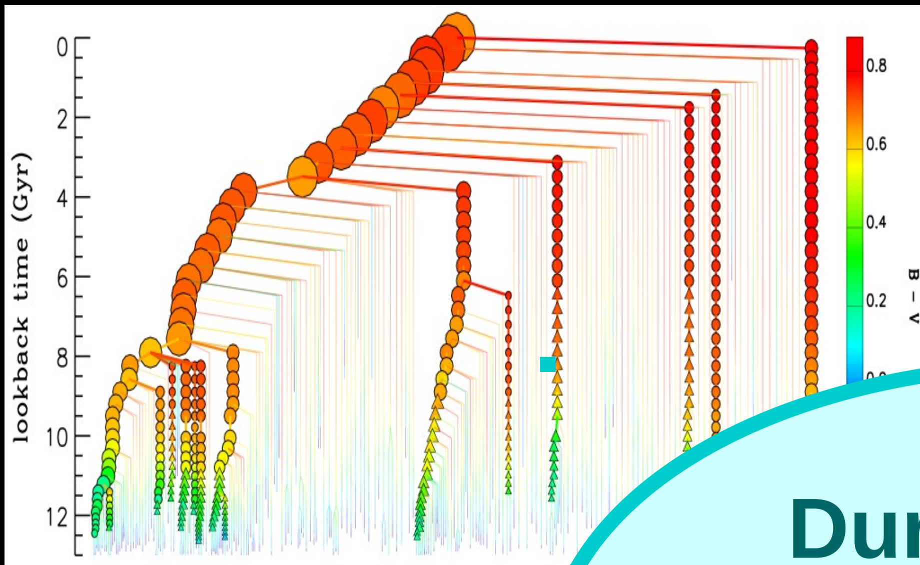


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



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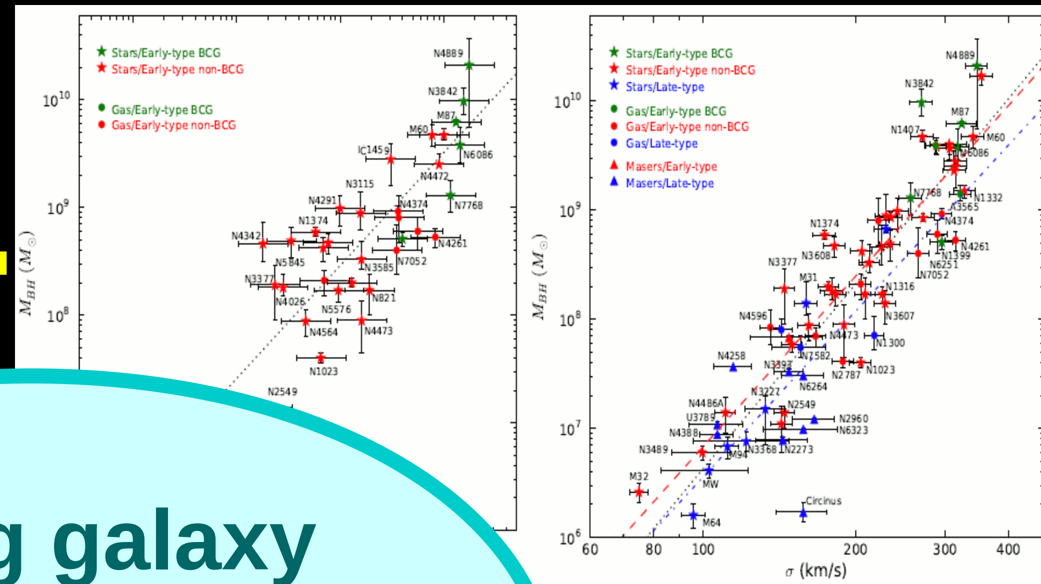
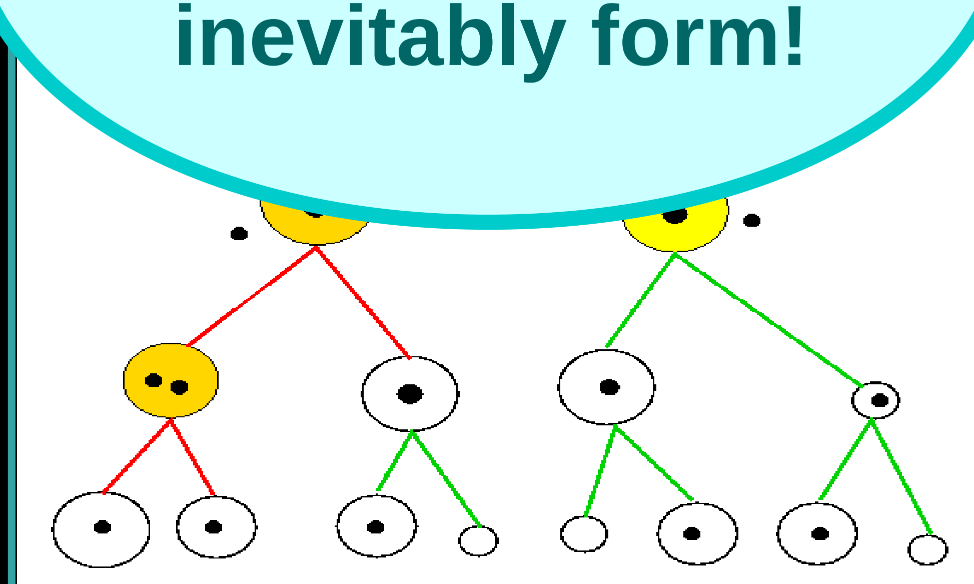


0, Gebhardt et al. 2000

During galaxy mergers, MBHBs will inevitably form!



Volonteri Haardt & Madau 2003

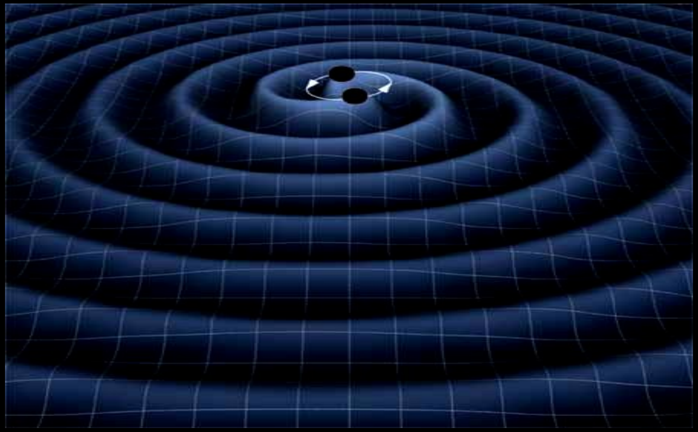
Directly from general relativity

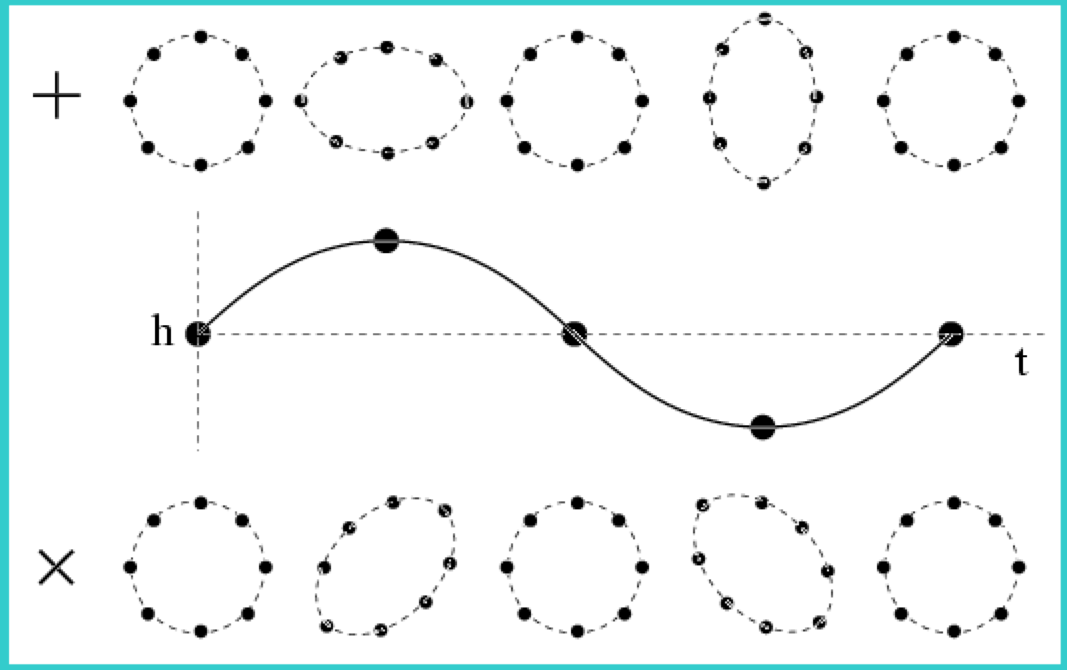
Every accelerating mass distribution with non-zero quadrupole moment emits GWs!

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

Perturbed Minkowski metric tensor :

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





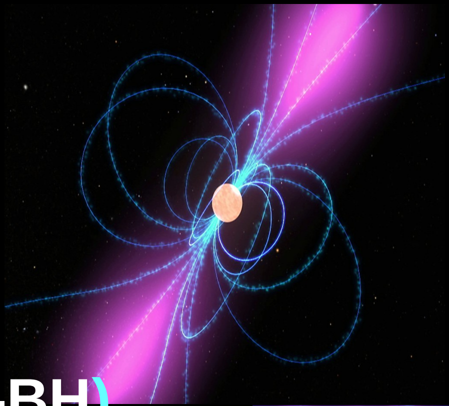
Perturbation perpendicular to the wave propagation direction

Gravitational wave sources

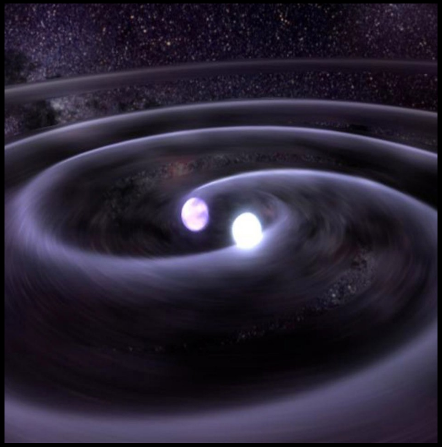
Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

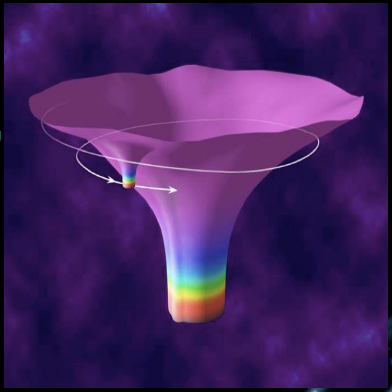
2-rotating asymmetric objects
(pulsars, MSPs)



3-binary systems:



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

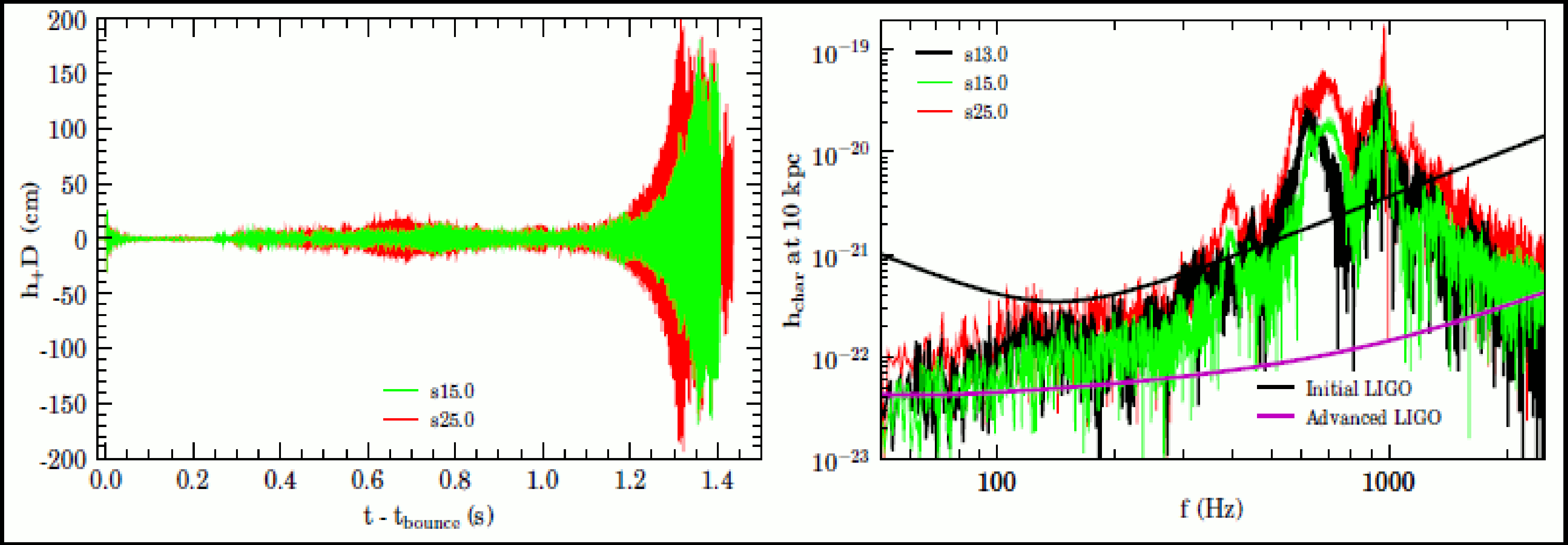


b-extreme mass ratio inspirals (EMRIs),
CO falling into a massive black hole

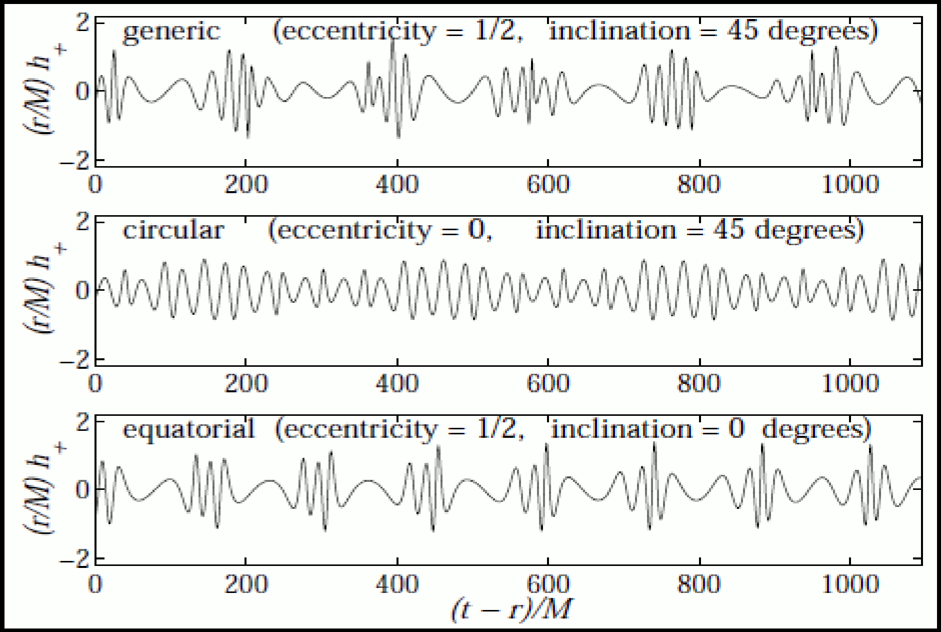
c-massive black hole binaries (MBHBs)
forming following galaxy mergers

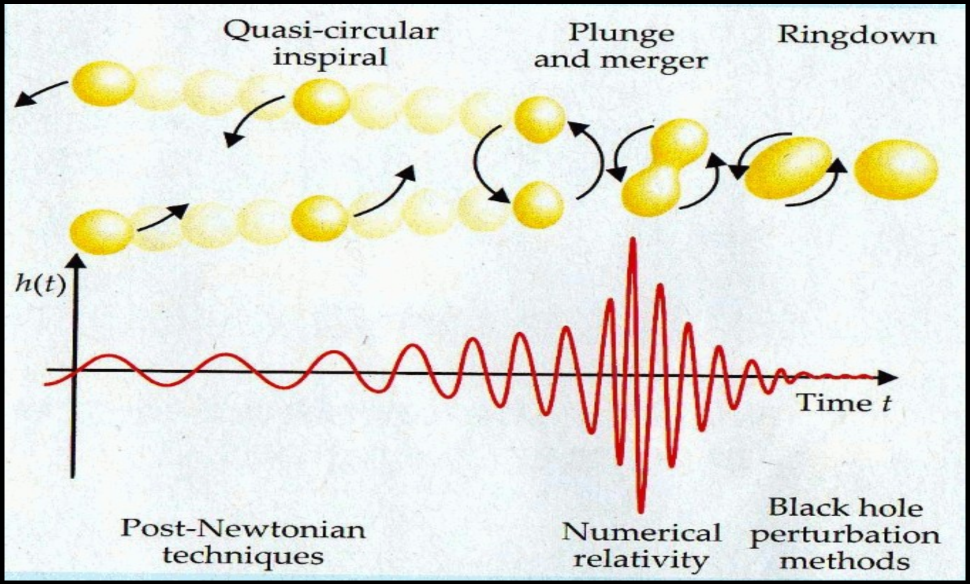
Example of gravitational waveforms

Supernova explosion (credits C. Ott)



EMRIs (credits Drasco & Hughes)





Black hole binaries

WHY GRAVITATIONAL WAVES

1-It is a completely new window on the Cosmo. 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 will 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.

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

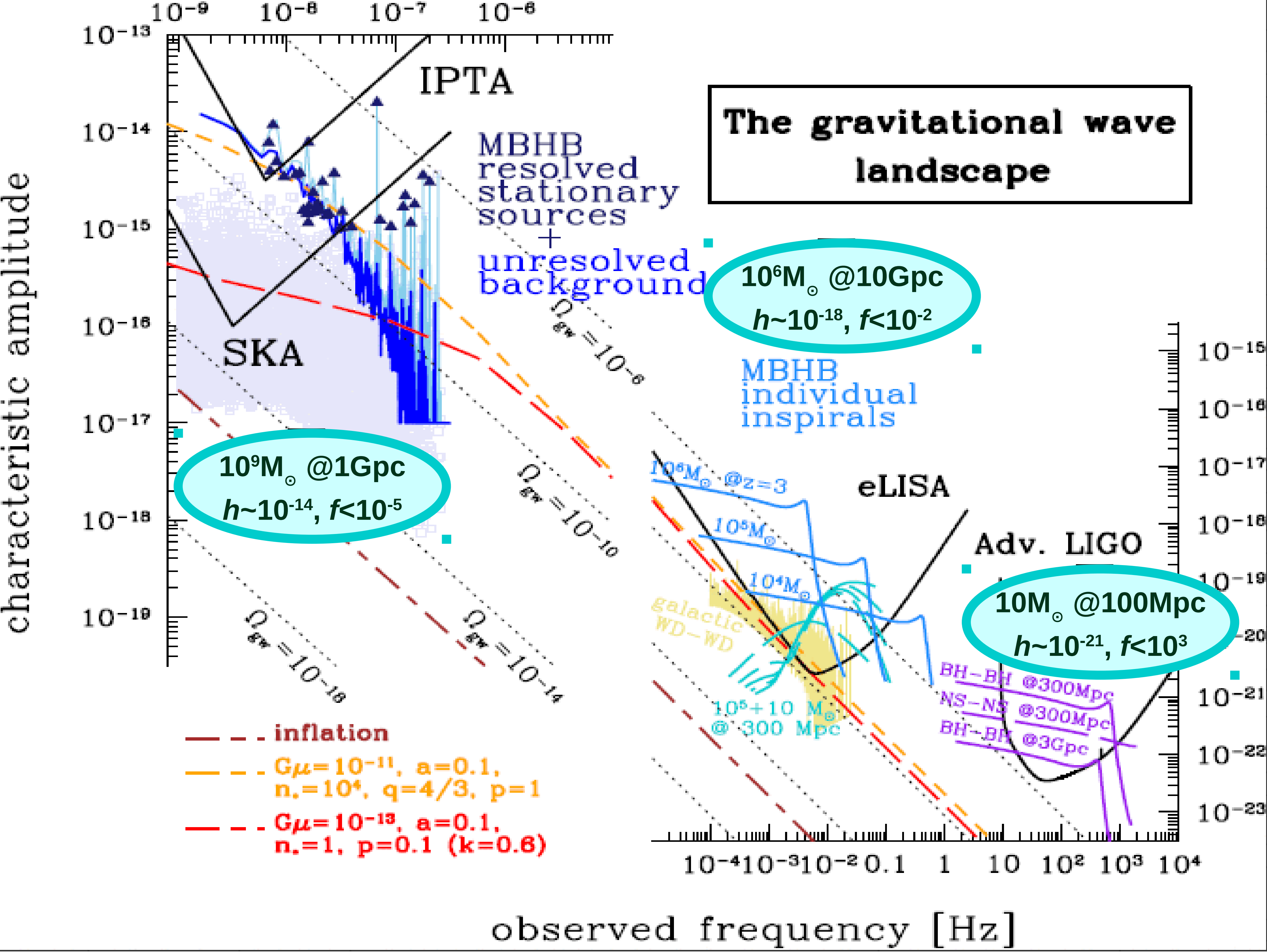
$$h \sim 10^{-20}\frac{M}{M_\odot}\frac{\mathrm{Mpc}}{D}$$

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

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: $h \sim 10^{-14}$, $f < 10^{-5}$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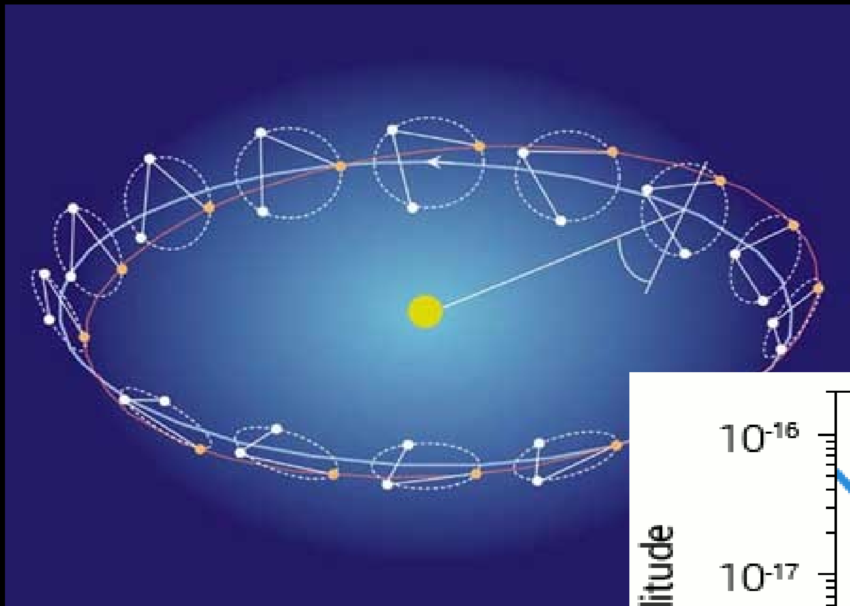
Adv. LIGO
10M⊙ @100Mpc
h~10^-21, f<10^3
10^6M⊙ @z=3
10^5M⊙
10^4M⊙
galactic WD−WD
10^5+10 M⊙ @ 300 Mpc
BH−BH @300Mpc
NS−NS @300Mpc
BH−BH @3Gpc
Ωgw=10^-6
Ωgw=10^-10
Ωgw=10^-14
Ωgw=10^-18
inflation
Gμ=10^-11, a=0.1, n.=10^4, q=4/3, p=1
Gμ=10^-13, a=0.1, n.=1, p=0.1 (k=0.6)

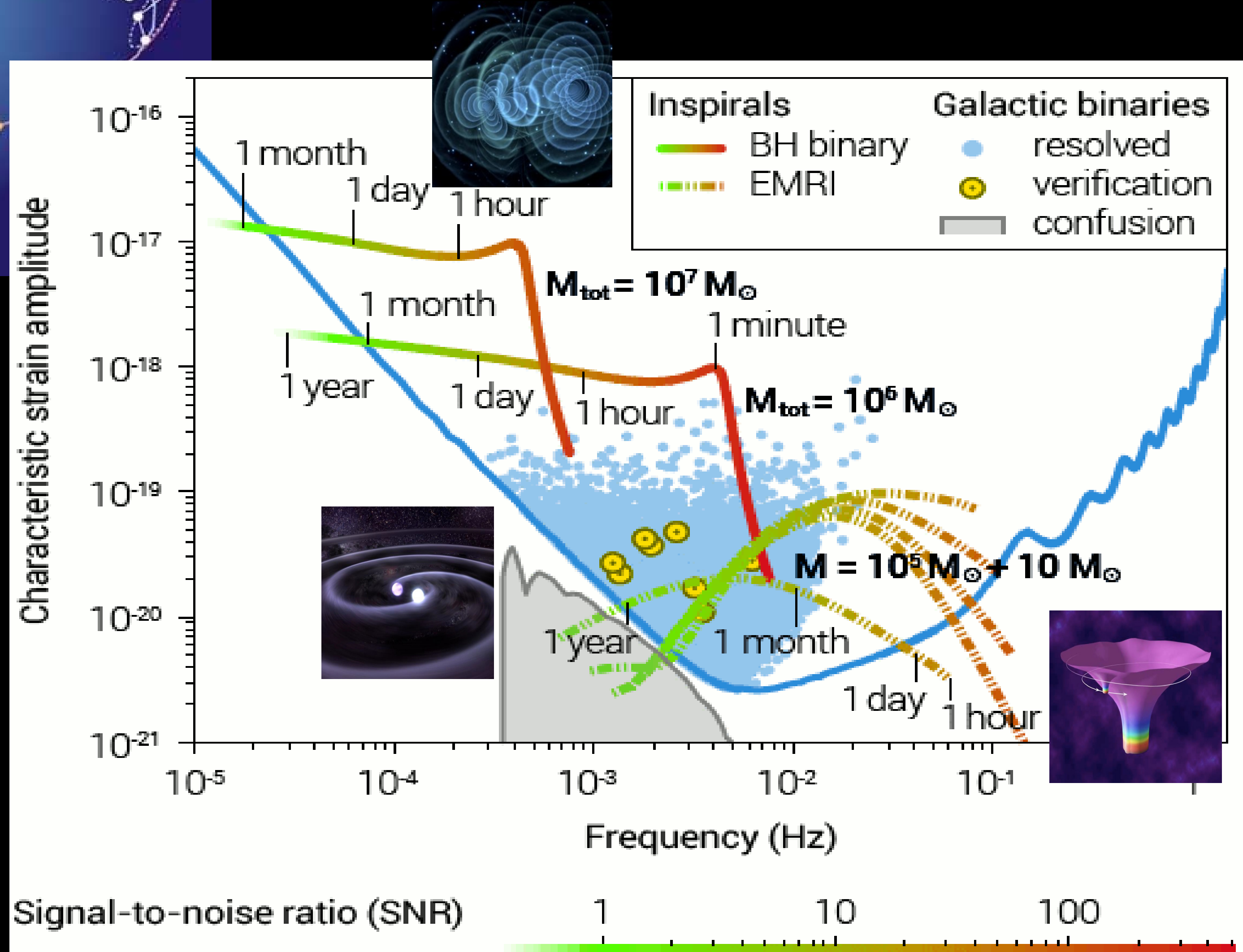
Interferometry in space:
evolved Laser Interferometer Space Antenna



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

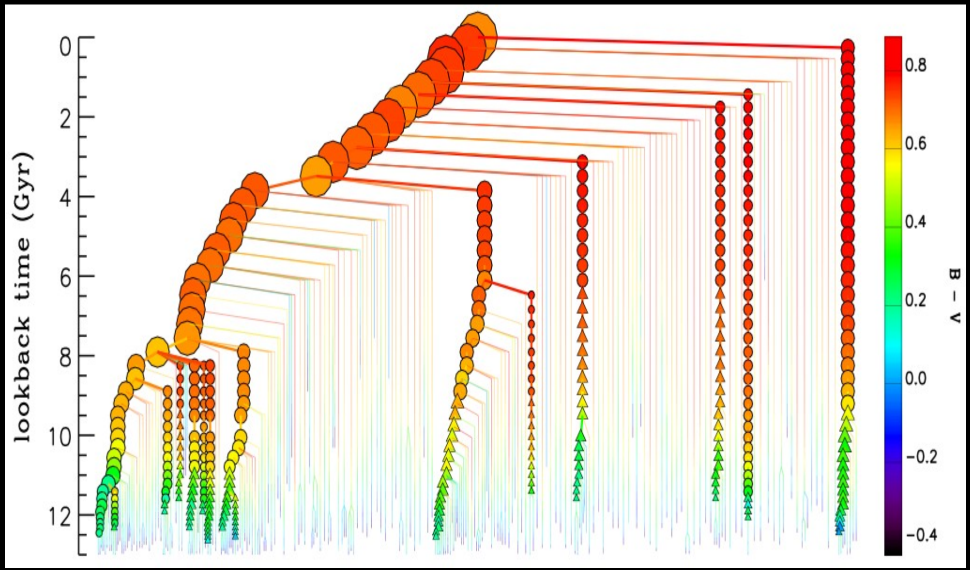
eLISA **will detect MBH binary inspirals and mergers.**

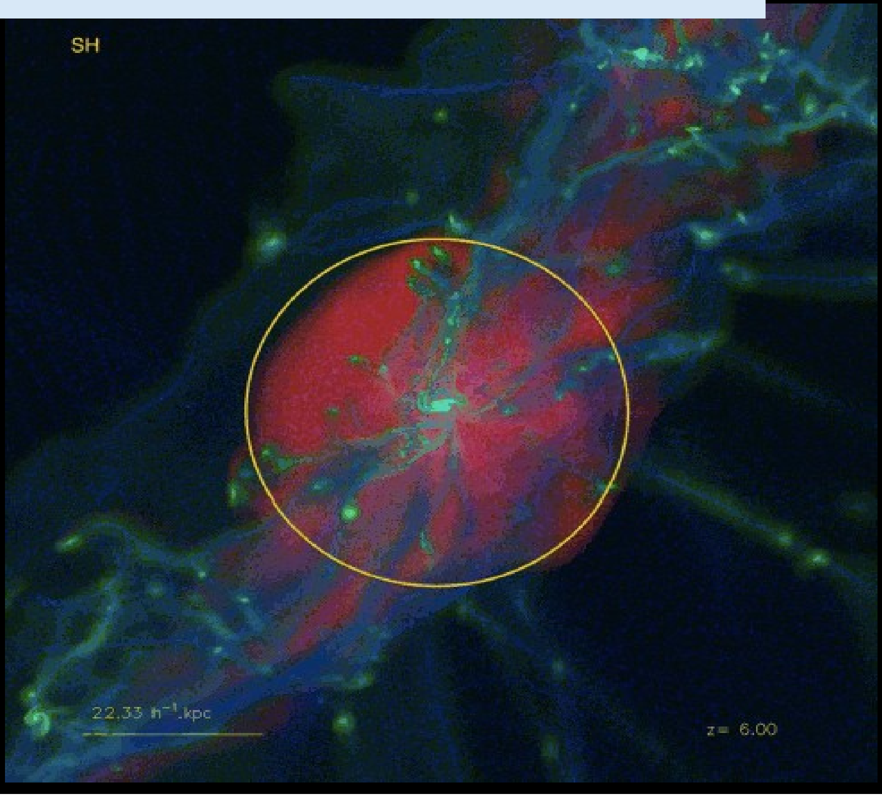
- **same orbit as *LISA***
- **1Gm armlength**
- **four laser links**
- **max 6 year lifetime**



Baby massive black hole binaries

- *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?*





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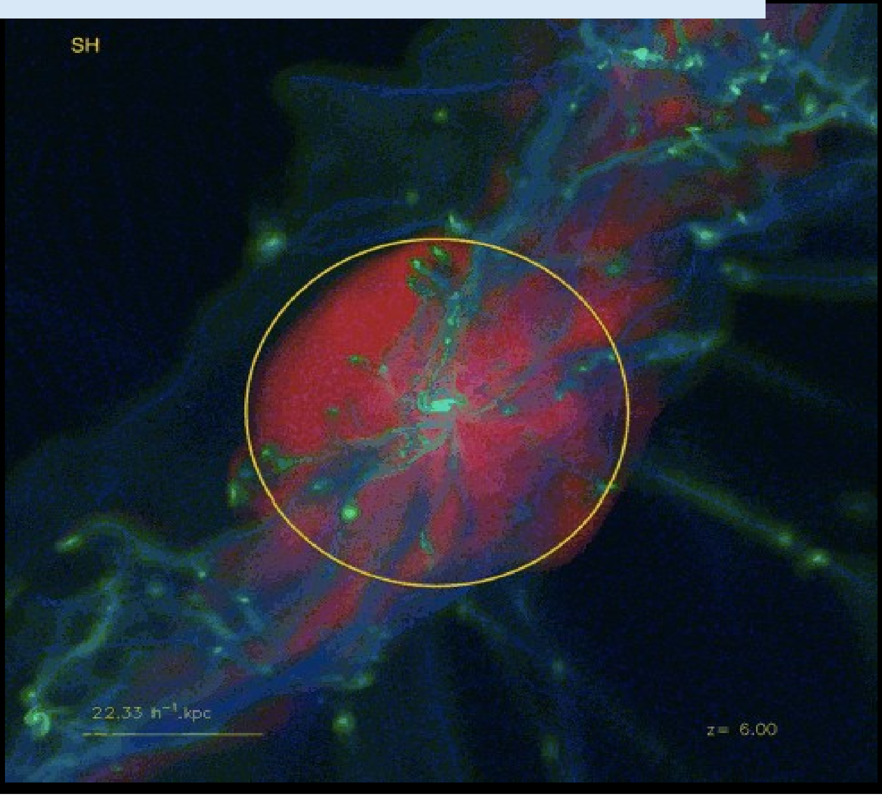

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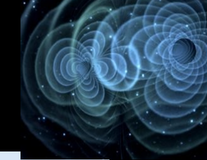

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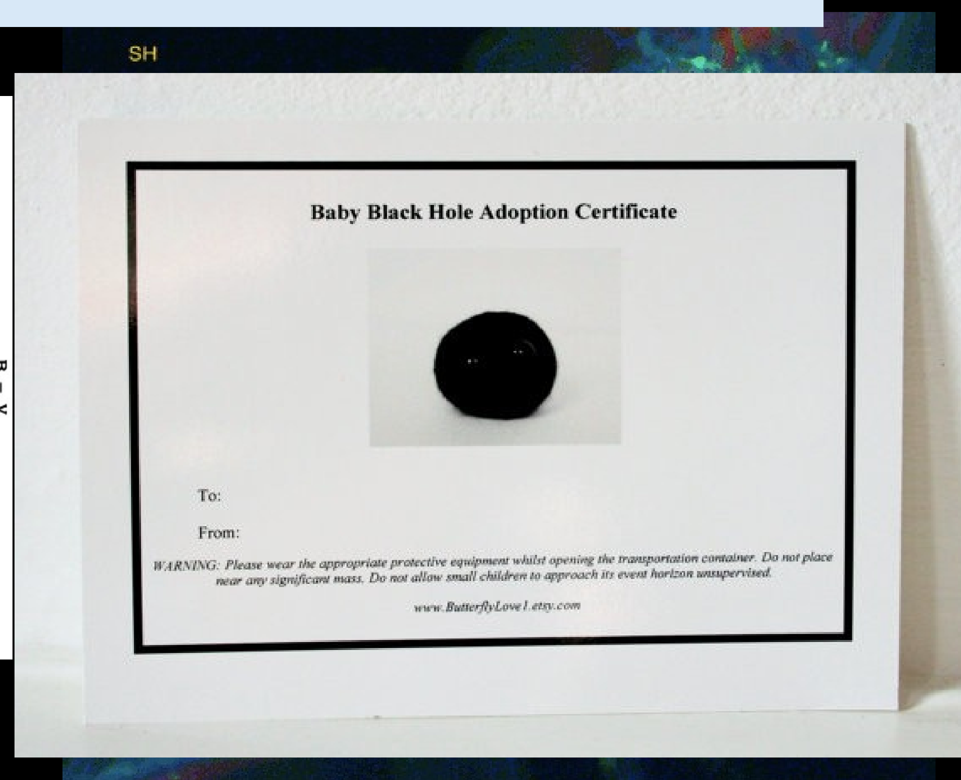
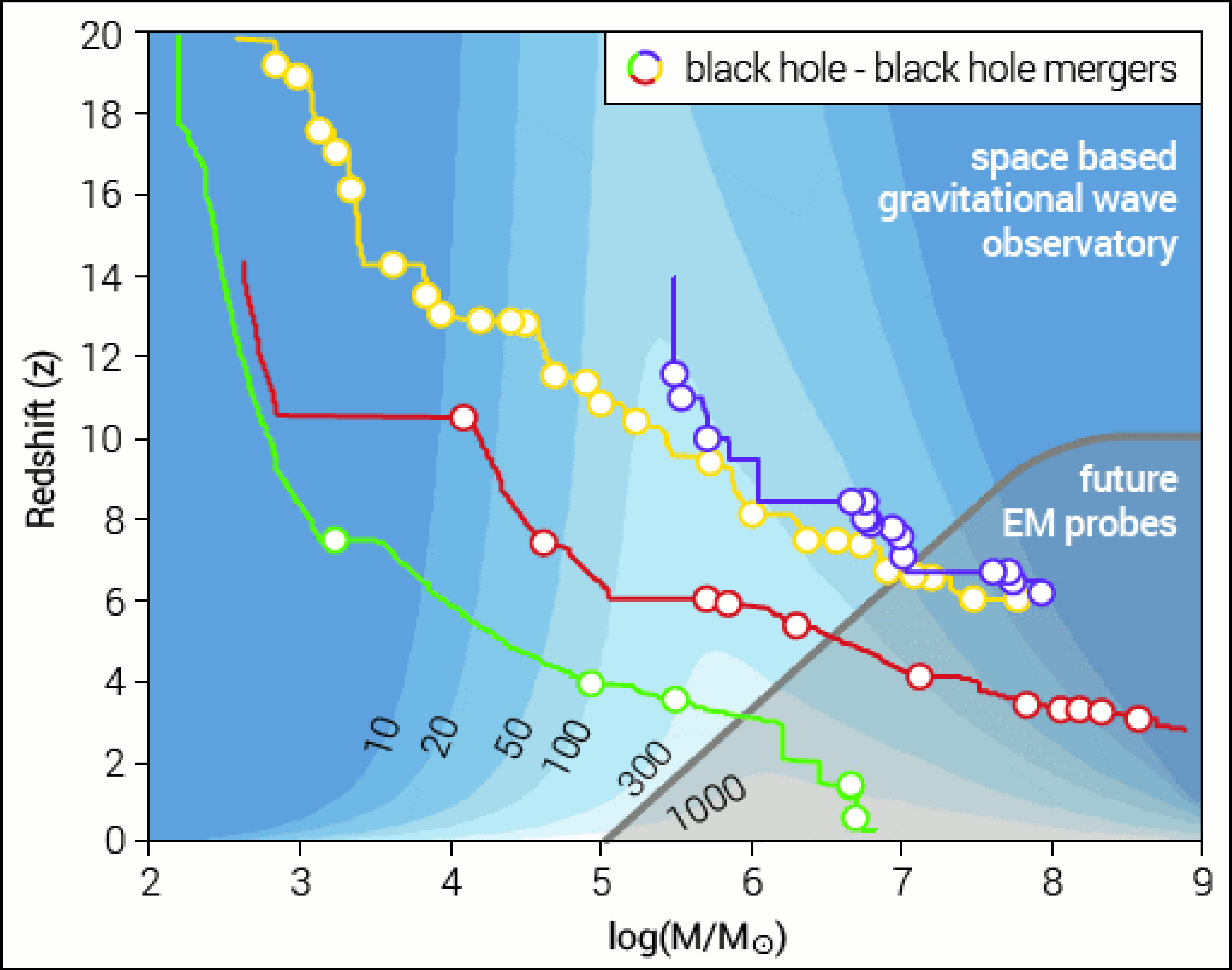


eLISA coverage of the Universe



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:

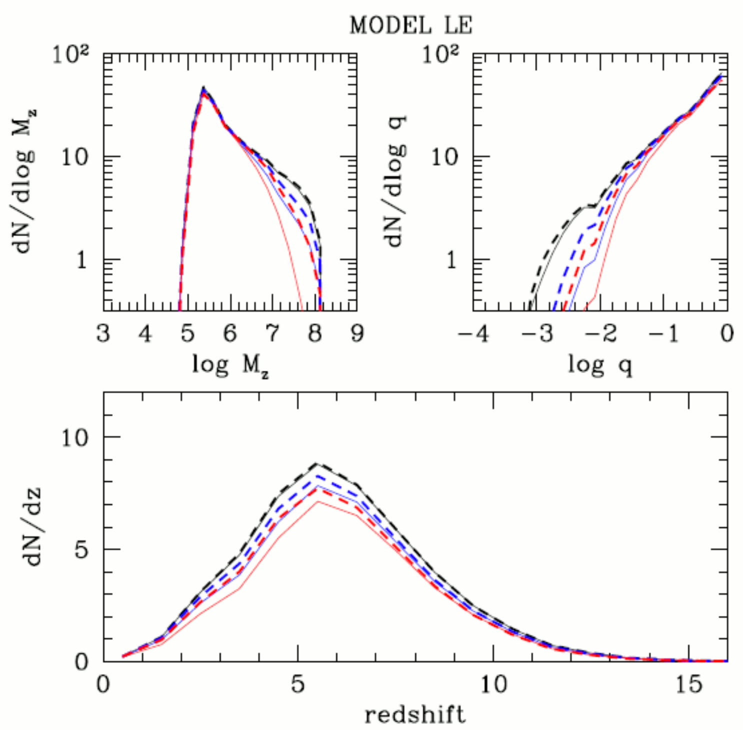
1-SE: small seeds+efficient accretion

2-SC: small seeds+chaotic accretion

3-LE: large seeds+efficient accretion

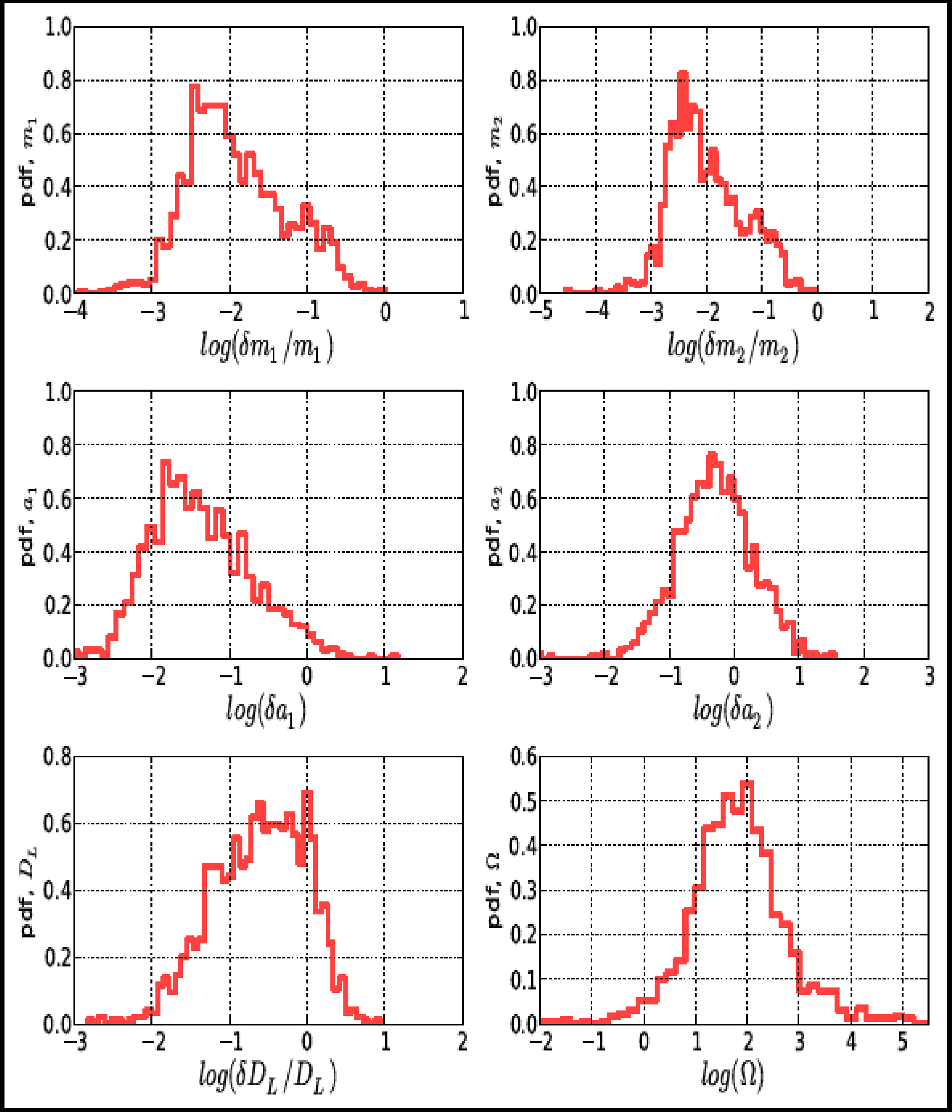
4-LC: large seeds+chaotic accretion

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)

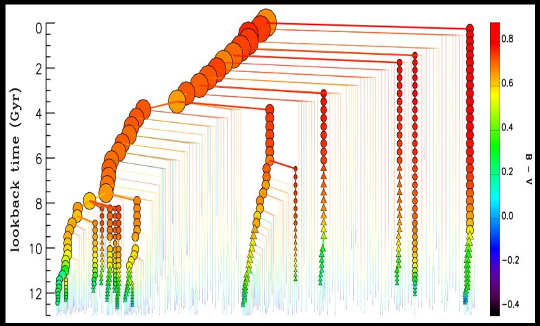
-sky location to 10-1000 deg

-luminosity distance to <10% in many cases

MBH astrophysics with GW observations

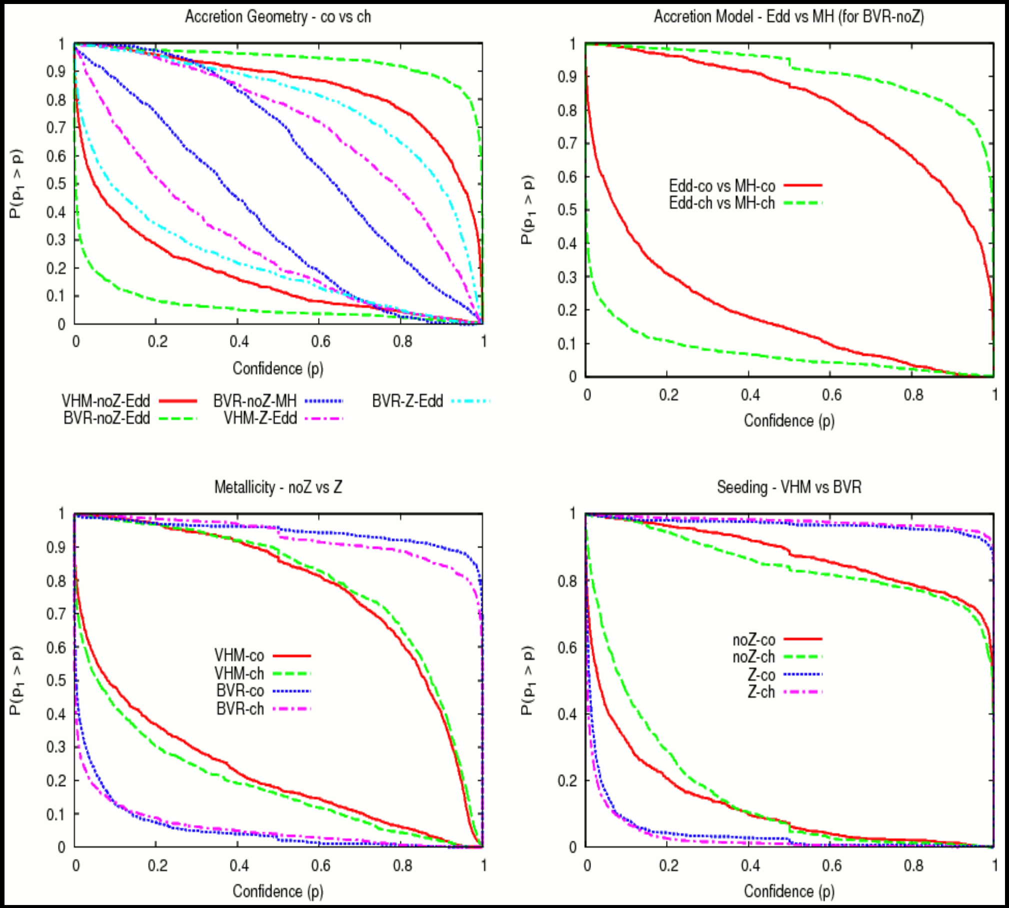
Astrophysical unknowns in MBH formation scenarios

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

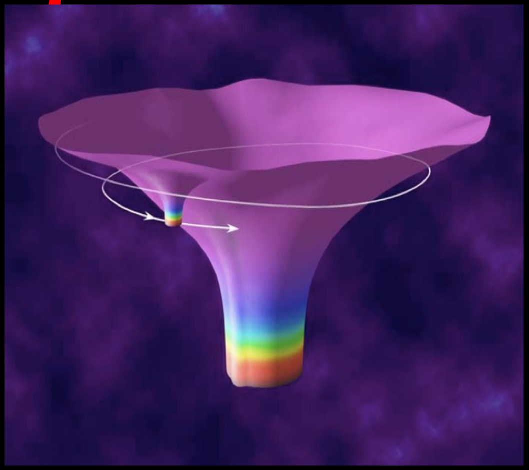


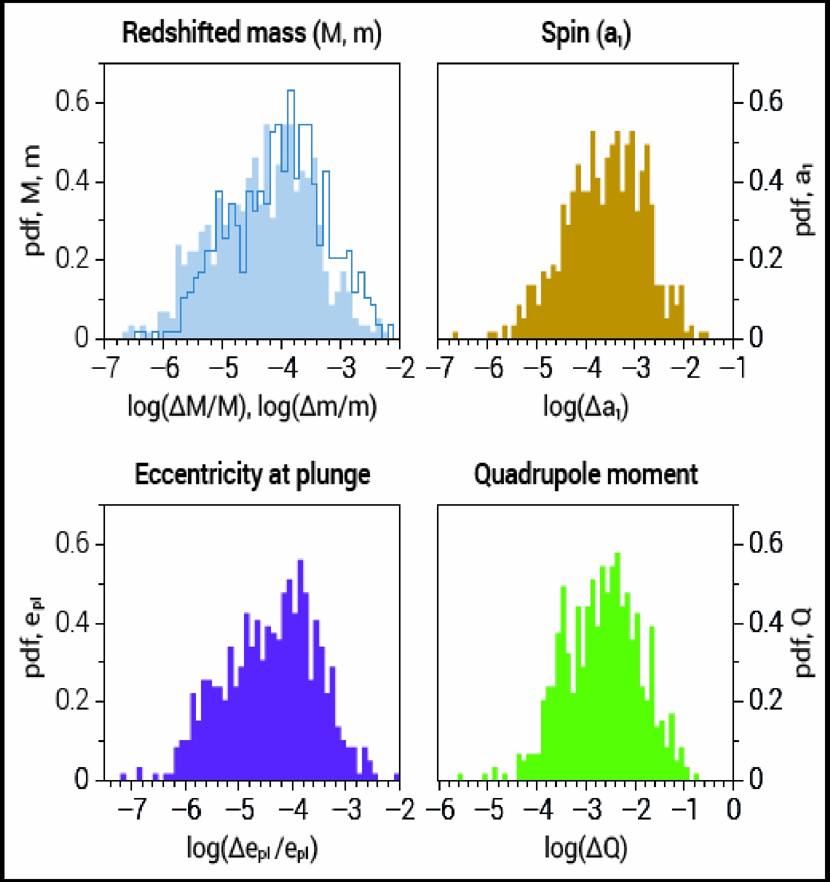
AS et al. 2011, see also Plowman et al 2011

Credits: J. Gair

Extreme mass ratio inspirals

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

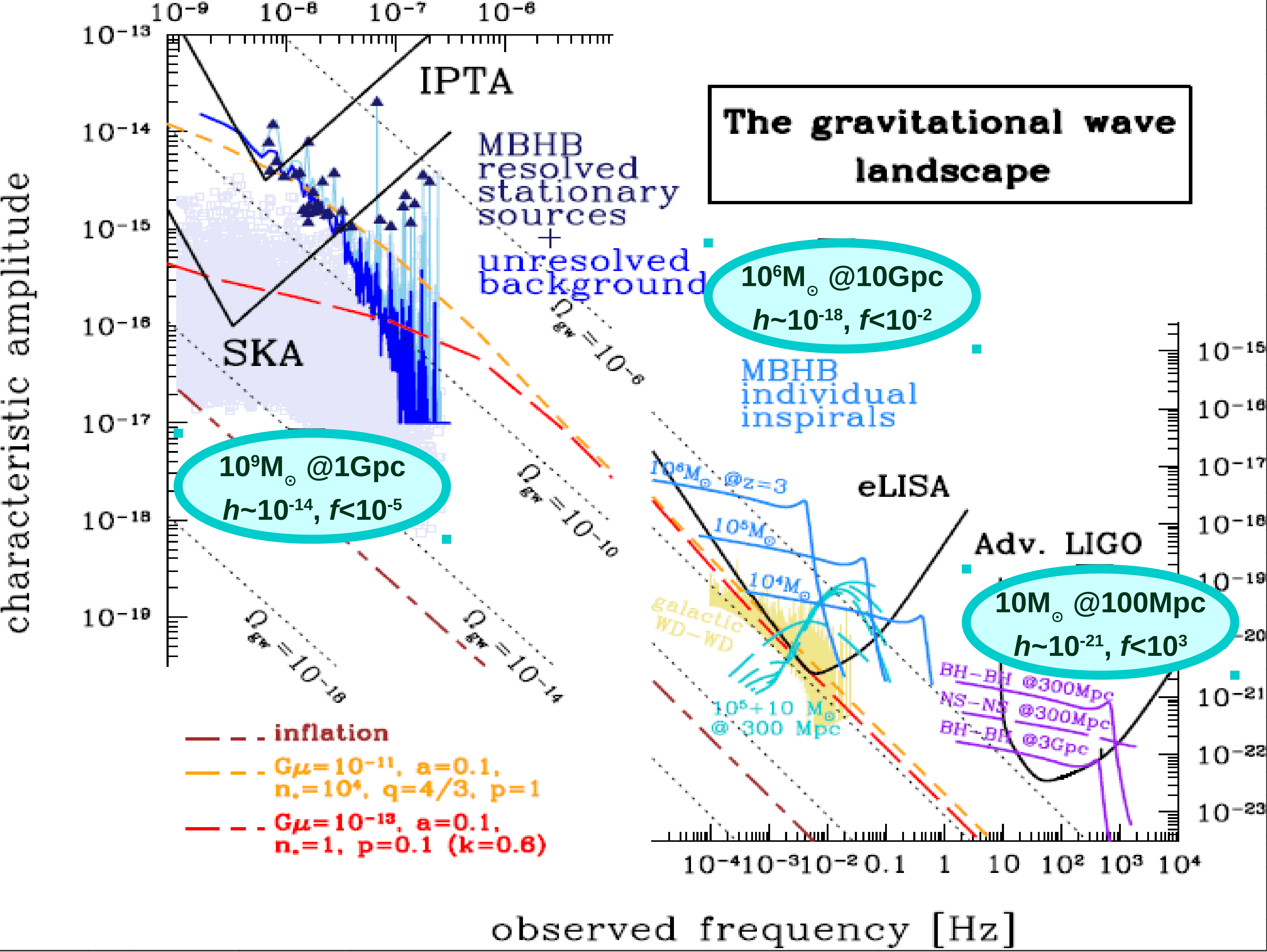




eLISA will give us:

- MBH mass to <0.1%
- 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)



The gravitational wave landscape
characteristic amplitude
observed frequency [Hz]
IPTA
SKA
MBHB resolved stationary sources + unresolved background
10⁶M⊙ @10Gpc
h~10⁻¹⁸, f<10⁻²
MBHB individual inspirals
10⁹M⊙ @1Gpc
h~10⁻¹⁴, f<10⁻⁵
eLISA
Adv. LIGO
10M⊙ @100Mpc
h~10⁻²¹, f<10³
10⁶M⊙ @z=3
10⁵M⊙
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10⁵+10 M⊙ @ 300 Mpc
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Ωgw=10⁻⁶
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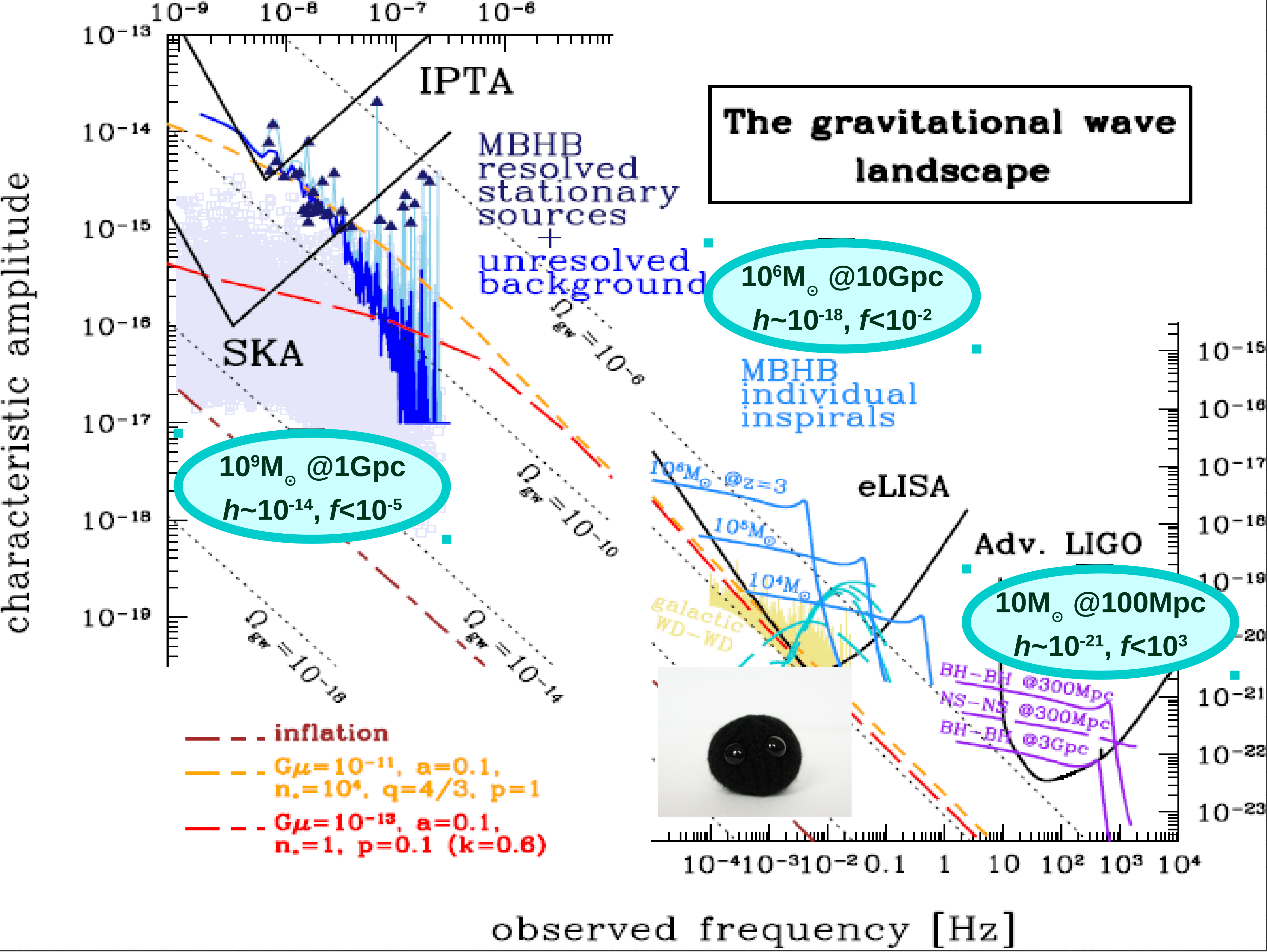
Ωgw=10⁻¹⁸
inflation
Gμ=10⁻¹¹, a=0.1, n.=10⁴, q=4/3, p=1
Gμ=10⁻¹³, a=0.1, n.=1, p=0.1 (k=0.6)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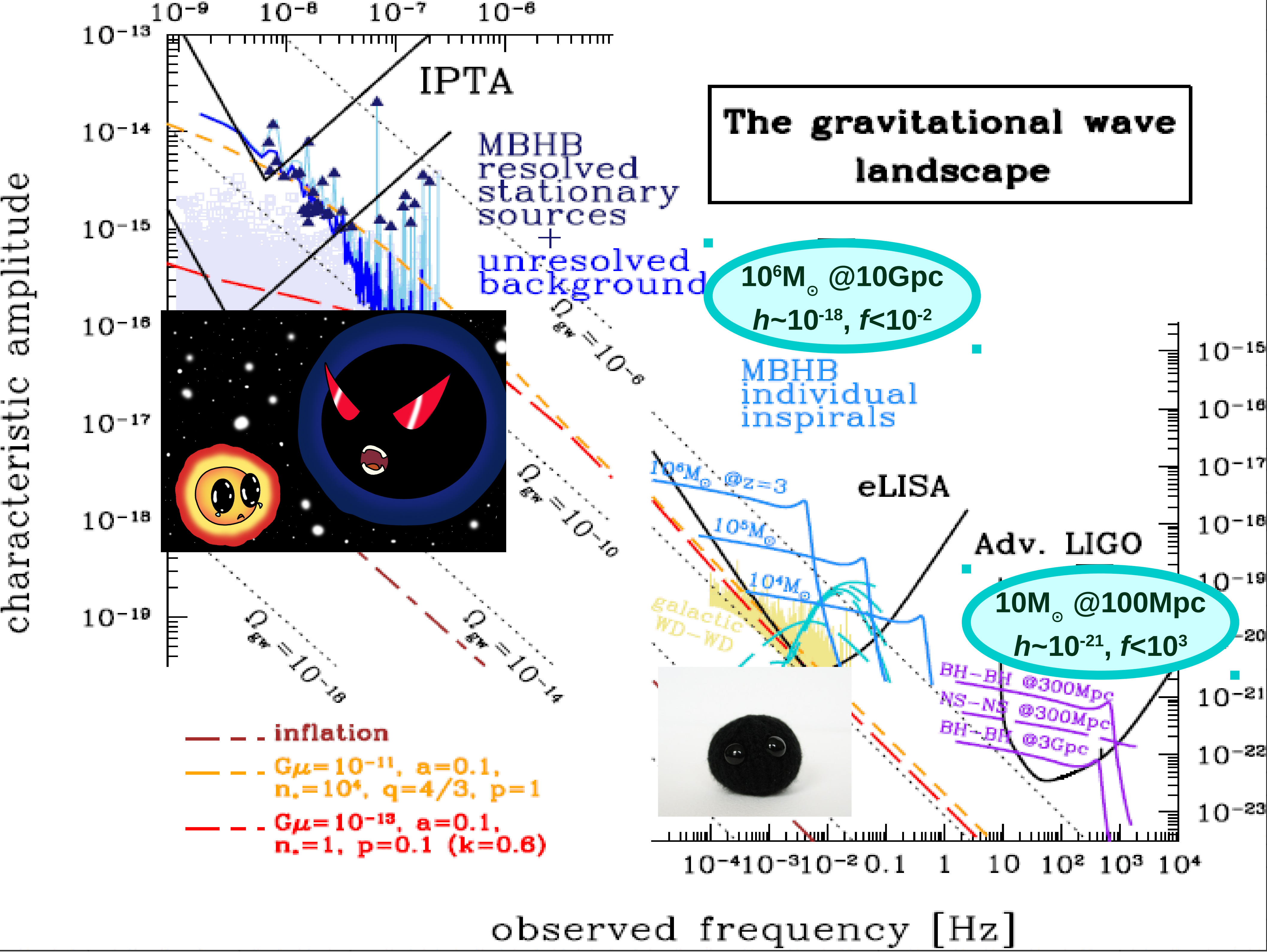
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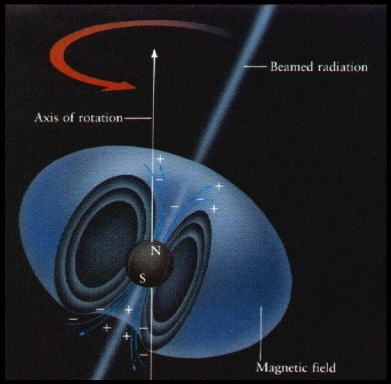
$\Omega_{gw} = 10^{-6}$
$\Omega_{gw} = 10^{-10}$
$\Omega_{gw} = 10^{-14}$
$\Omega_{gw} = 10^{-18}$
inflation
$G\mu = 10^{-11}$, a=0.1, $n_s = 10^4$, q=4/3, p=1
$G\mu = 10^{-13}$, a=0.1, $n_s = 1$, p=0.1 (k=0.6)
characteristic amplitude
observed frequency [Hz]
10^{-9} 10^{-8} 10^{-7} 10^{-6}
10^{-4} 10^{-3} 10^{-2} 0.1 1 10 10^2 10^3 10^4
10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19}
10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23}

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.

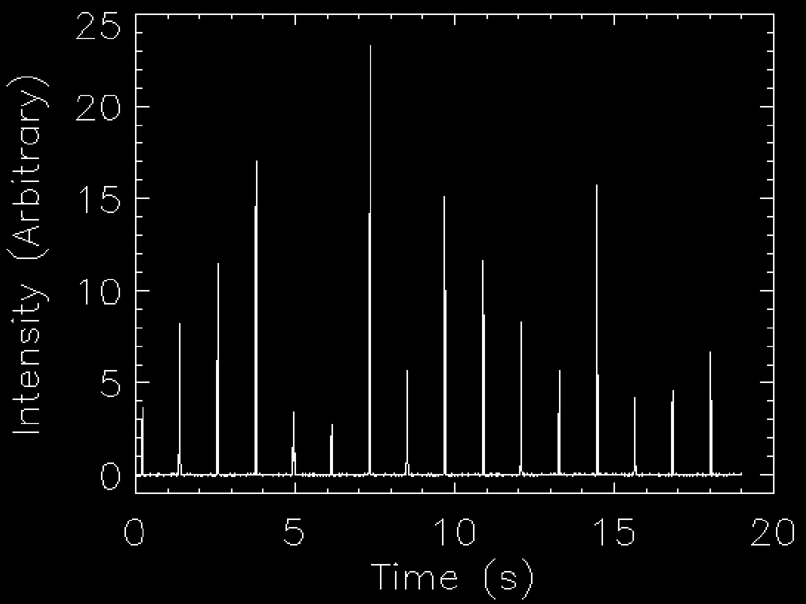


1- Observe a pulsar and measure the TOA of each pulse

2-Determine the model which best fits the TOA data

3-Calculate the timing residual *R*

$$R = TOA - TOA_m$$

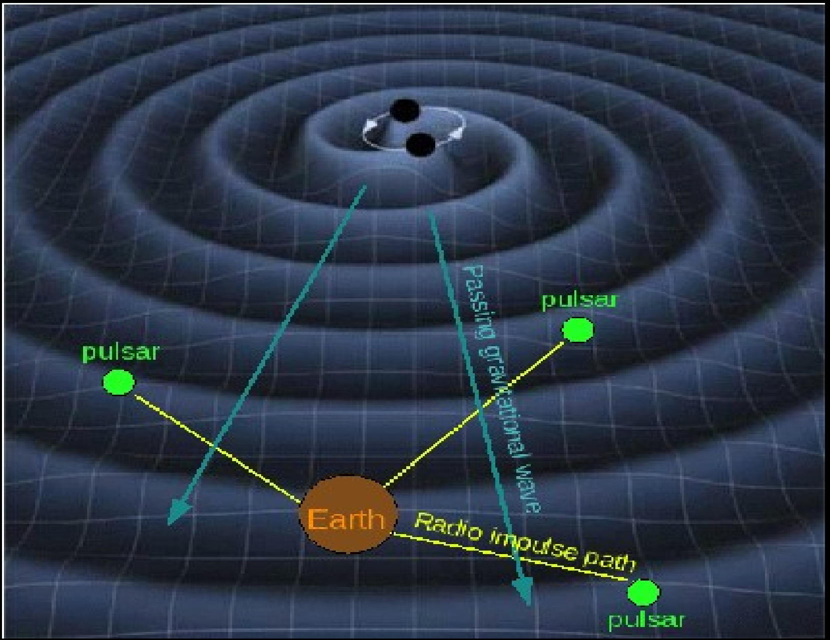


If your model is perfect, then *R*=0. *R* contains all the uncertainties related to the signal propagation and detection plus the effect of unmodelled physics, like -possibly- *gravitational waves*

Timing residual from MBH binaries

The GW passage cause a modulation of the MSP frequency

$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv \sum_A F^A(\hat{\Omega})\Delta h_A(t;\hat{\Omega})$$



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)

10^9 $M_\odot$ binary at 1Gpc: h~10^{-15}, f~10^{-8}

Implies a residual ~100ns

100ns is the accuracy at which we can time the most stable millisecond pulsars today!

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

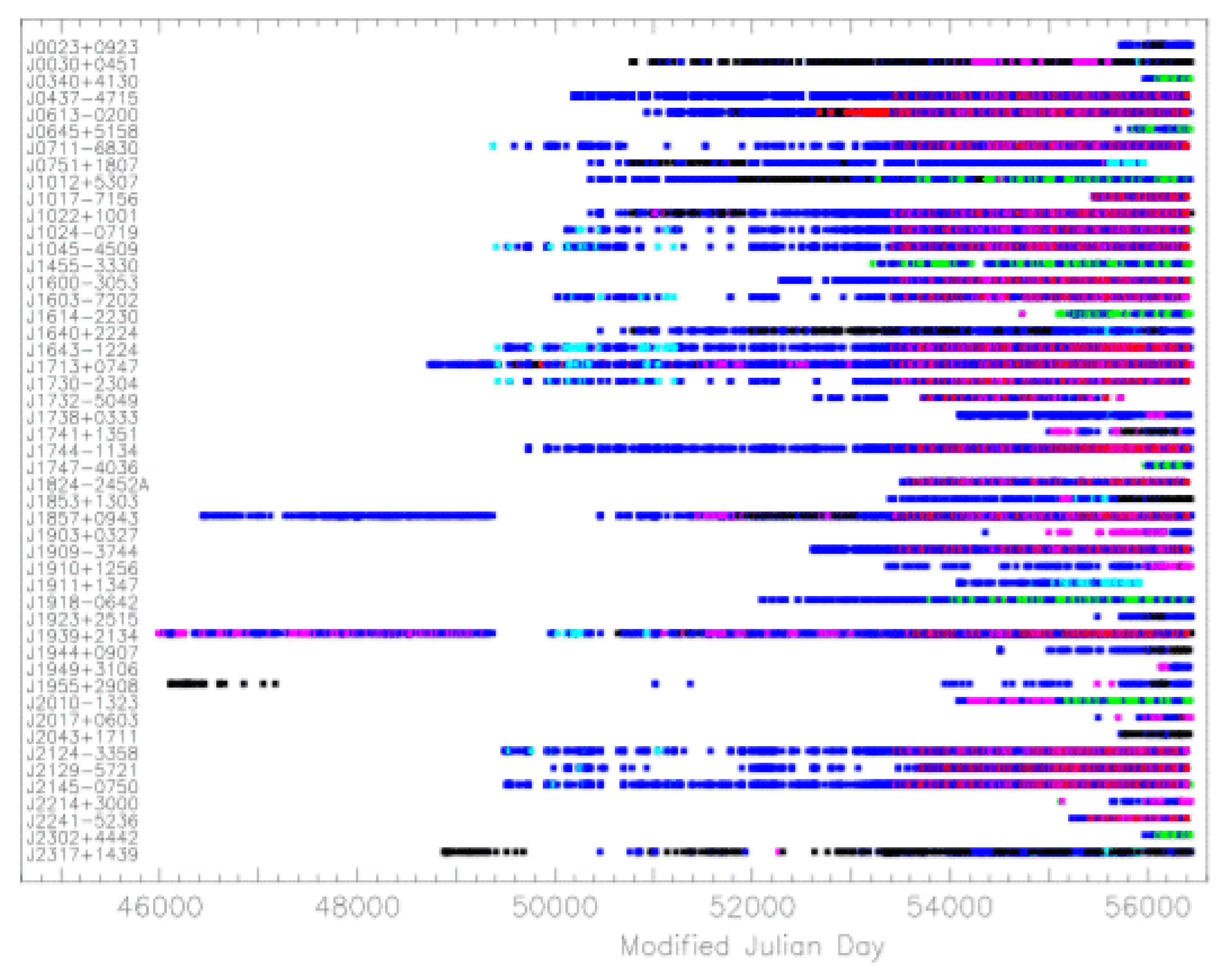
EPTA/LEAP (large European

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

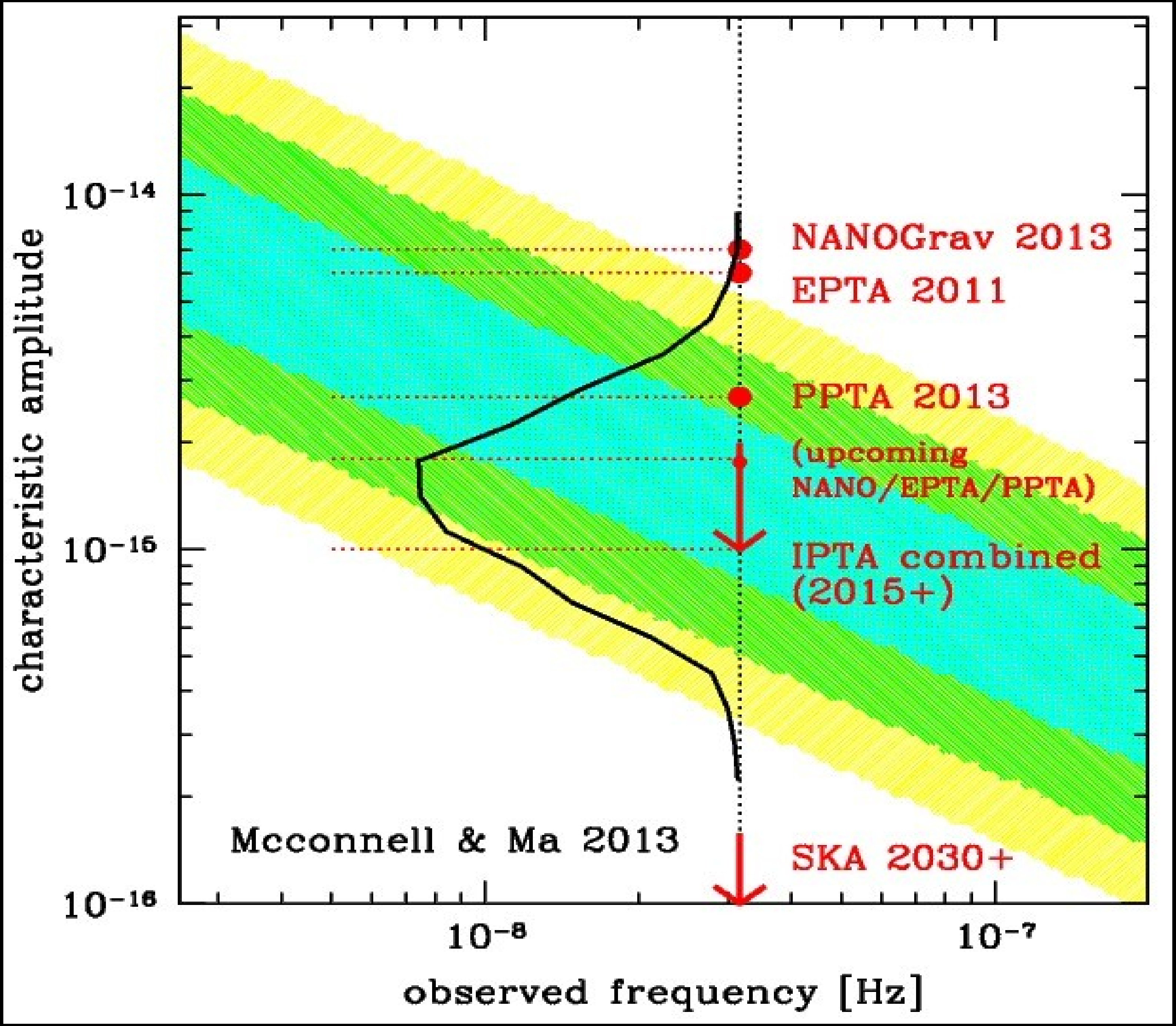
nHz
aves)

PPTA (Park



J0023+0923
J0030+0451
J0340+4130
J0437−4715
J0613−0200
J0645+5158
J0711−6830
J0751+1807
J1012+5307
J1017−7156
J1022+1001
J1024−0719
J1045−4509
J1455−3330
J1600−3053
J1603−7202
J1614−2230
J1640+2224
J1643−1224
J1713+0747
J1730−2304
J1732−5049
J1738+0333
J1741+1351
J1744−1134
J1747−4036
J1824−2452A
J1853+1303
J1857+0943
J1903+0327
J1909−3744
J1910+1256
J1911+1347
J1918−0642
J1923+2515
J1939+2134
J1944+0907
J1949+3106
J1955+2908
J2010−1323
J2017+0603
J2043+1711
J2124−3358
J2129−5721
J2145−0750
J2214+3000
J2241−5236
J2302+4442
J2317+1439
46000
48000
50000
52000
54000
56000
Modified Julian Day

Current limits are getting interesting!



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.)

> eLISA will detect MBH binaries throughout the Universe.

> eLISA will allow to test GR by observing compact objects inspiralling into SMBHs (EMRIs)

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