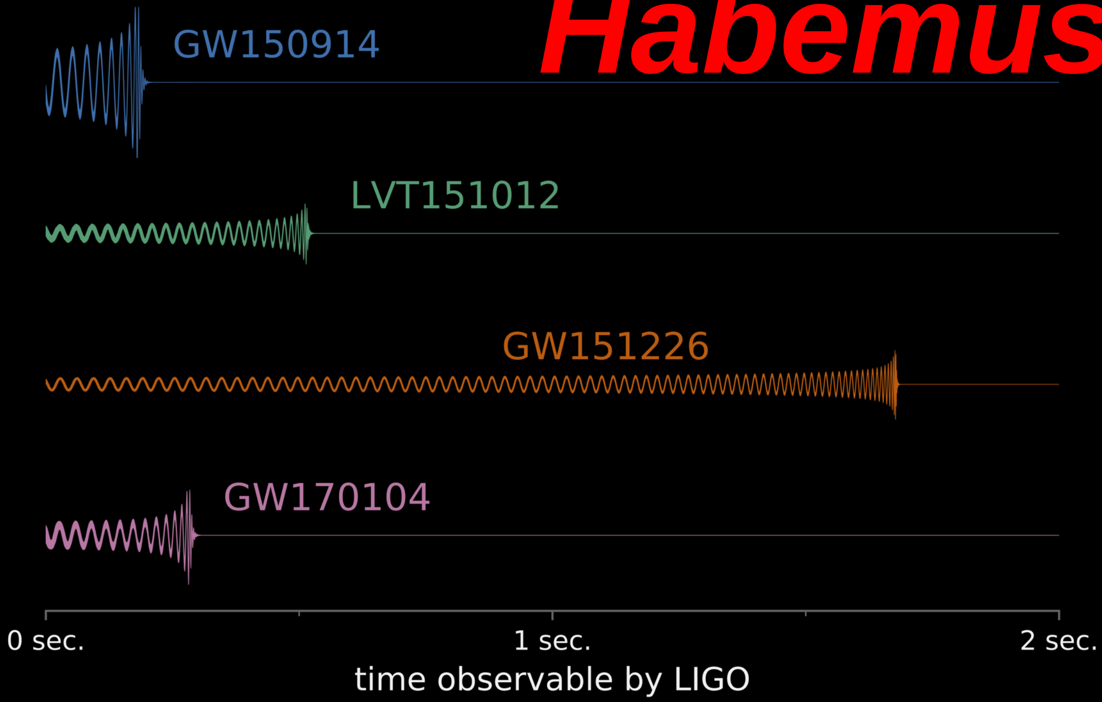
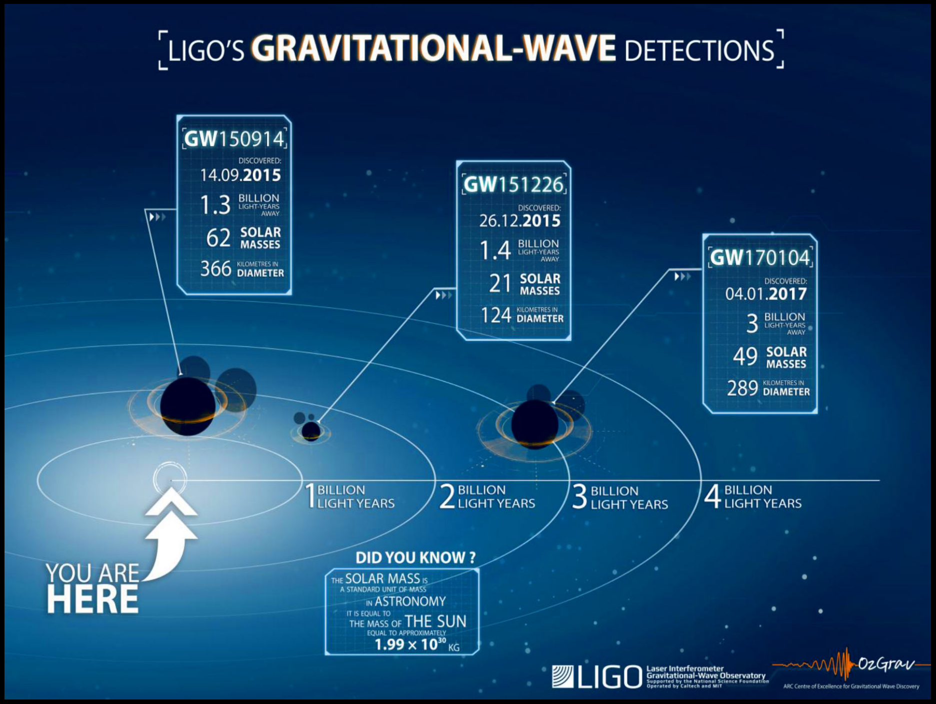
The future of gravitational wave detection: the low frequency band

Alberto Sesana
(University of Birmingham)

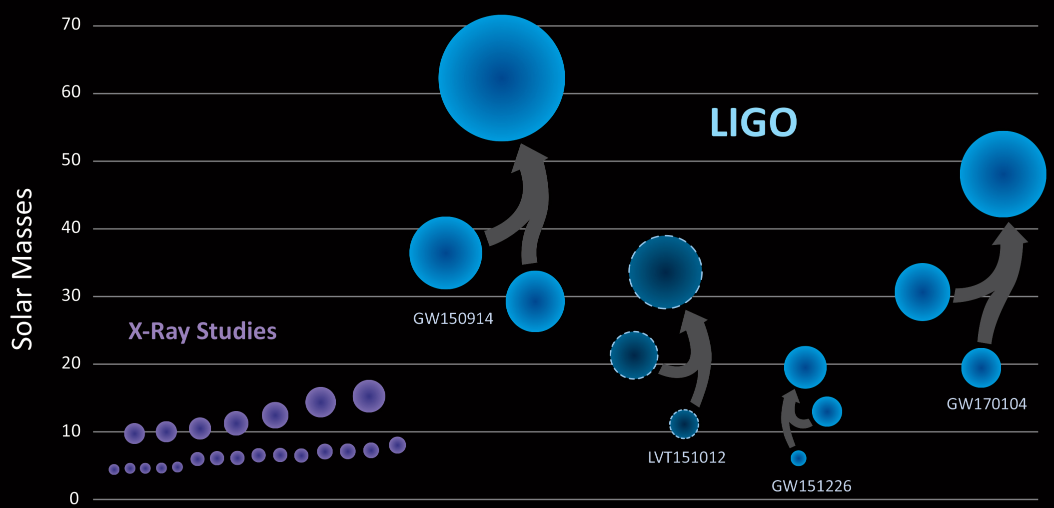
Habemus GWs!





We see BHB coalescing for the first time (several Abbott+ 2016 2017)

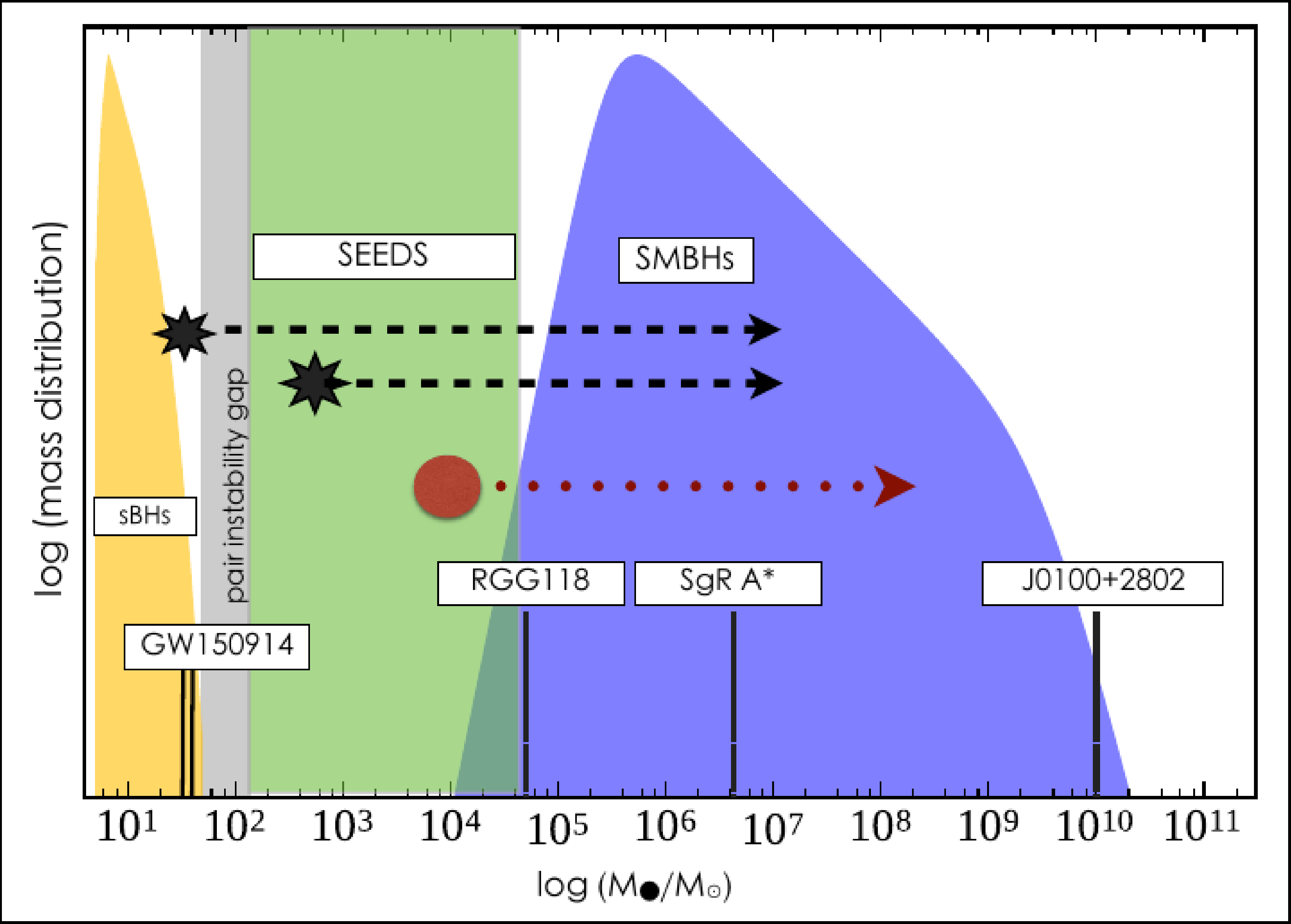
Black Holes of Known Mass



First tests of GR in the strong field regime

Interesting astrophysical information (masses, spins)

Formation scenario?



SEEDS
SMBHs
sBHs
pair instability gap
RGG118
SgR A*
J0100+2802
GW150914
log (mass distribution)
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11
log (M●/M☉)

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

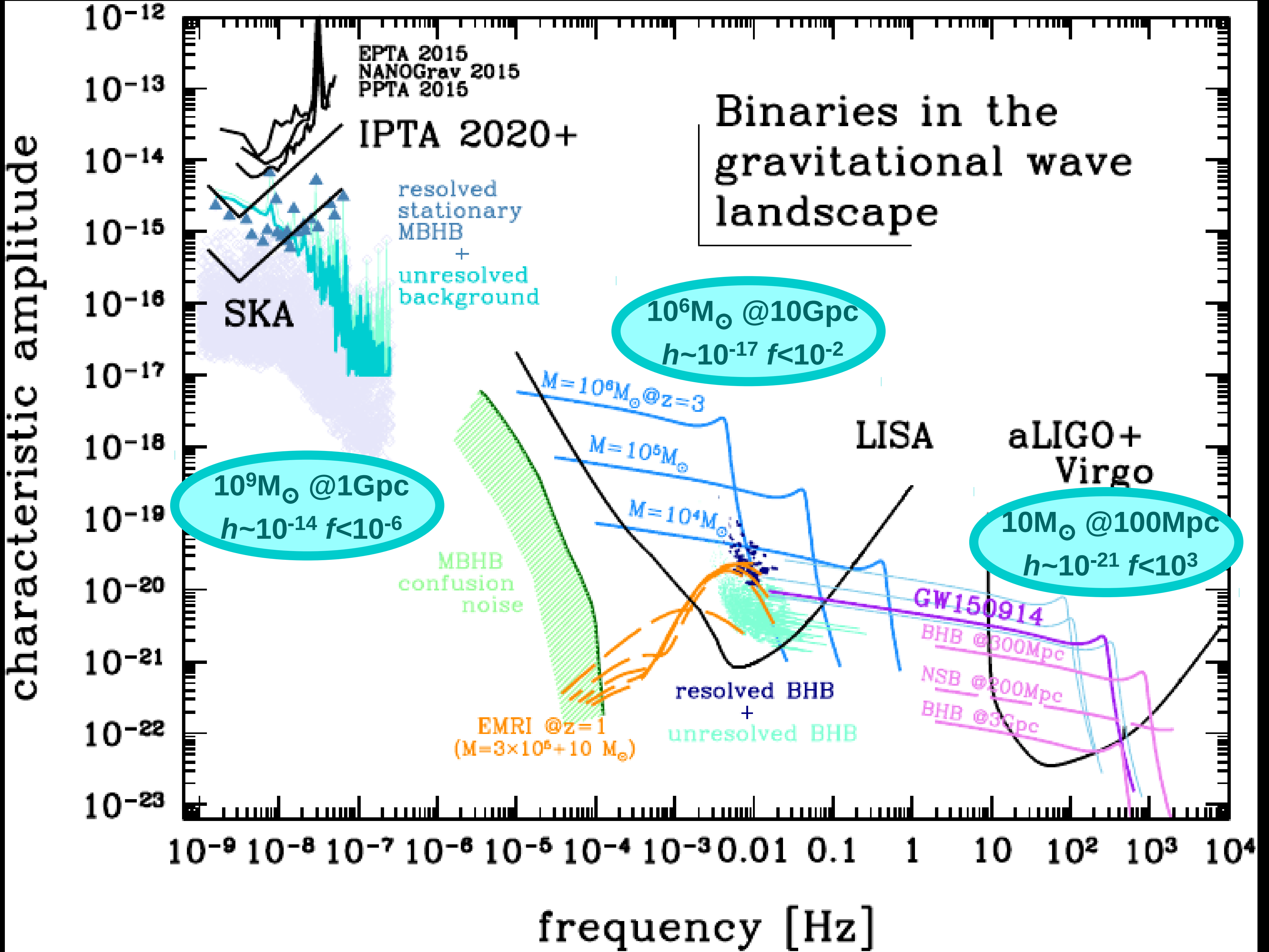
$$h \sim 10^{-20}\,\frac{M}{M_\odot}\,\frac{\mathrm{Mpc}}{D}$$

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

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

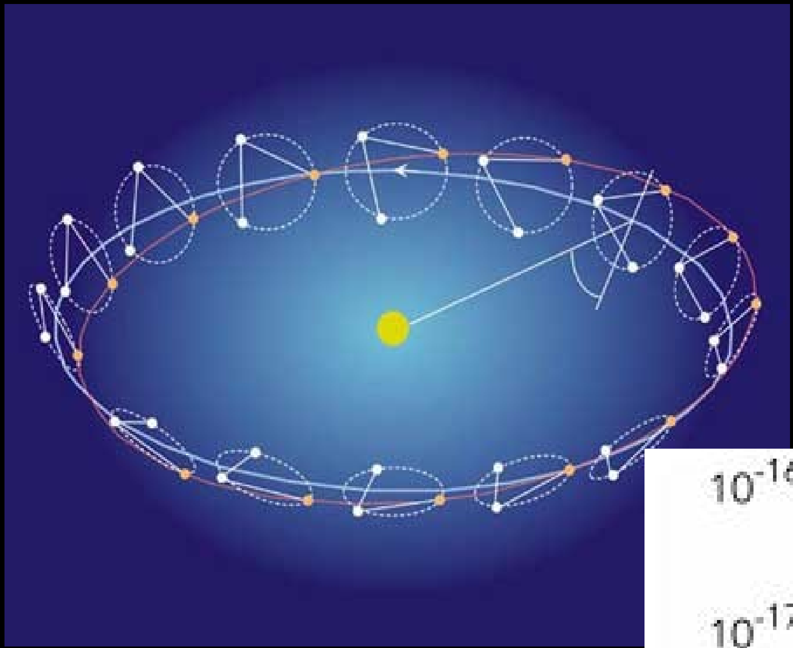
10^6 $M_\odot$ binary at 10 Gpc: h~10^{-18}, f<10^{-2}

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



Binaries in the gravitational wave landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
10⁶M⊙ @10Gpc
h~10⁻¹⁷ f<10⁻²
10⁹M⊙ @1Gpc
h~10⁻¹⁴ f<10⁻⁶
10M⊙ @100Mpc
h~10⁻²¹ f<10³
M=10⁶M⊙@z=3
M=10⁵M⊙
M=10⁴M⊙
LISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
EMRI @z=1
(M=3×10⁵+10 M⊙)
resolved BHB
+
unresolved BHB
characteristic amplitude
frequency [Hz]

The Laser Interferometer Space Antenna

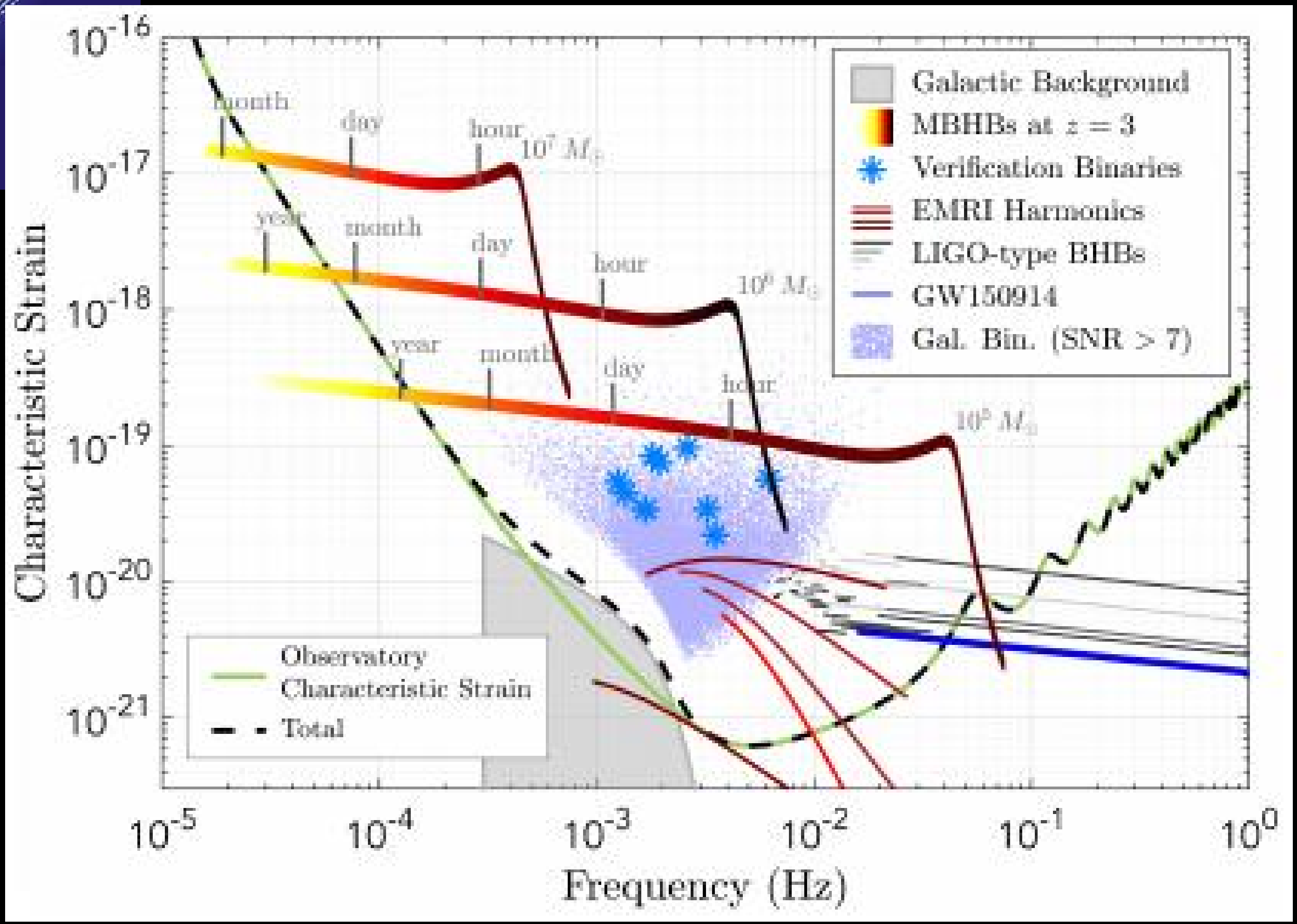


Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)



Observational facts

1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

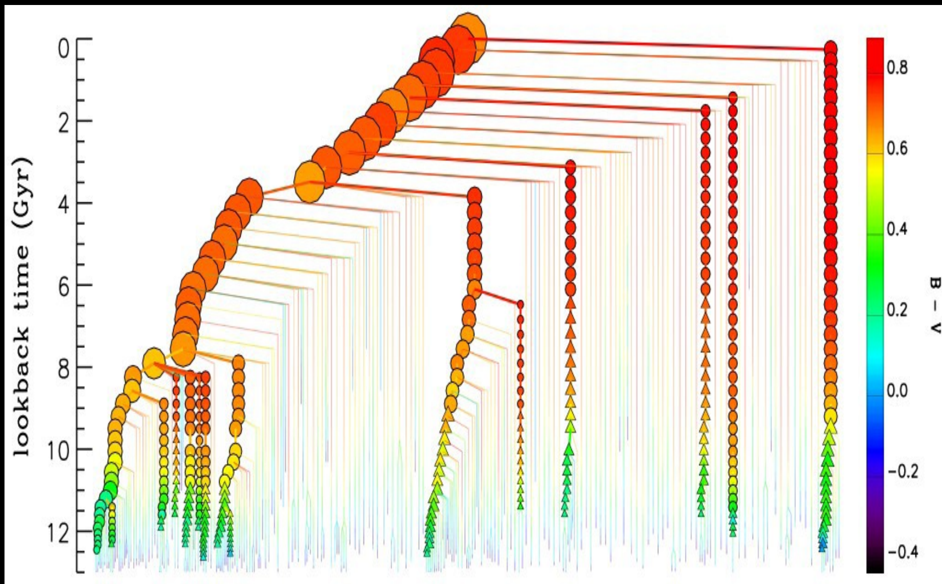
2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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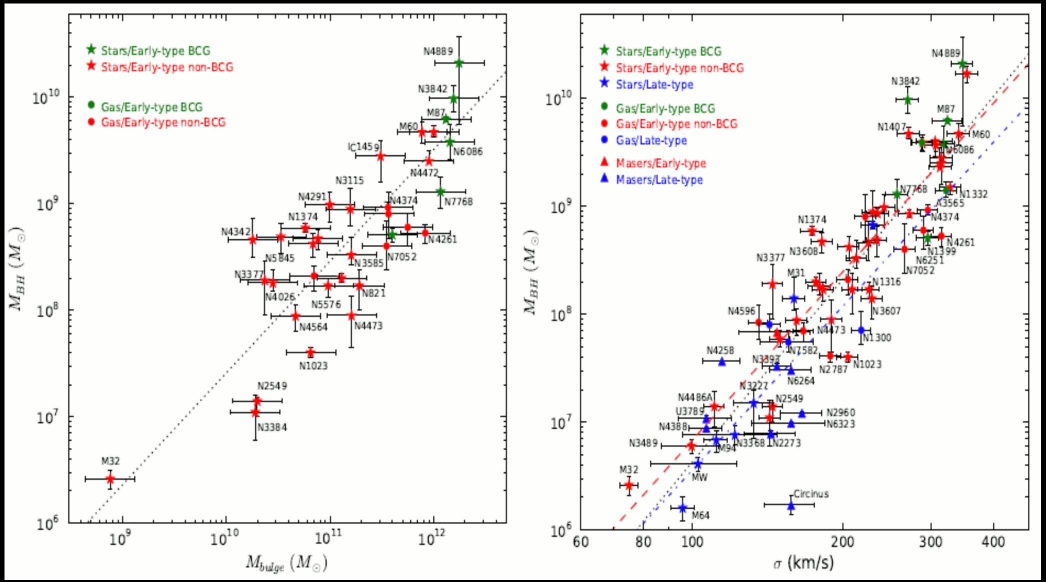

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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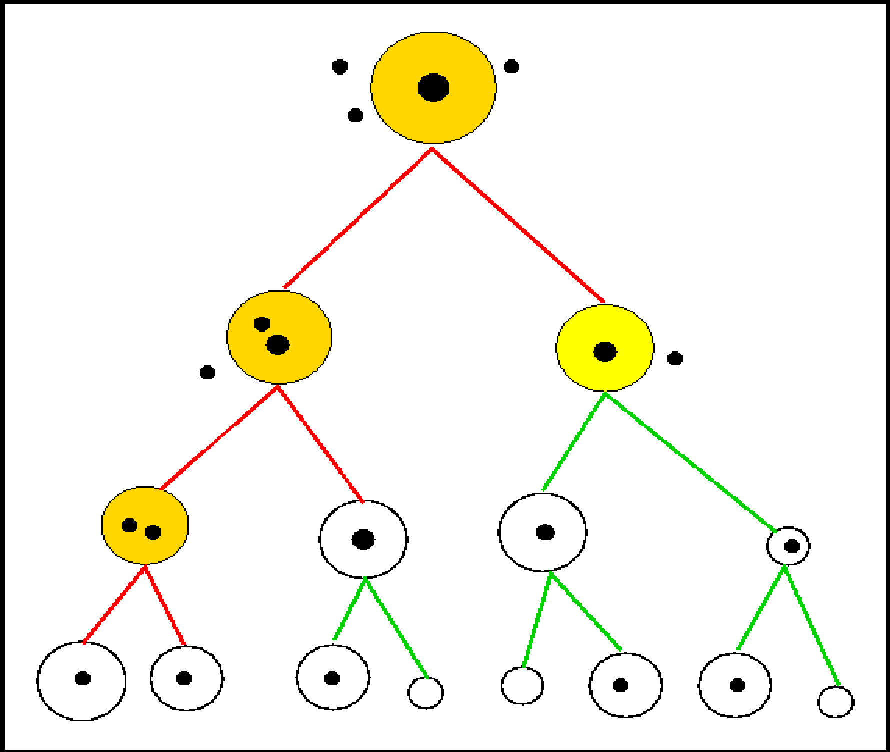
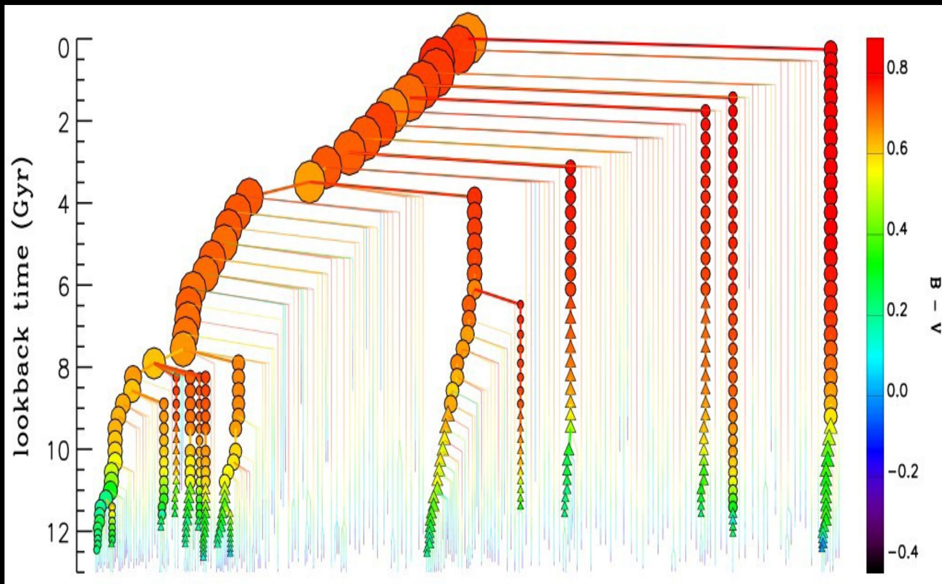


(Menou et al 2001, Volonteri et al. 2003)

MBH evolution in a nutshell



(From de Lucia et al. 2006)

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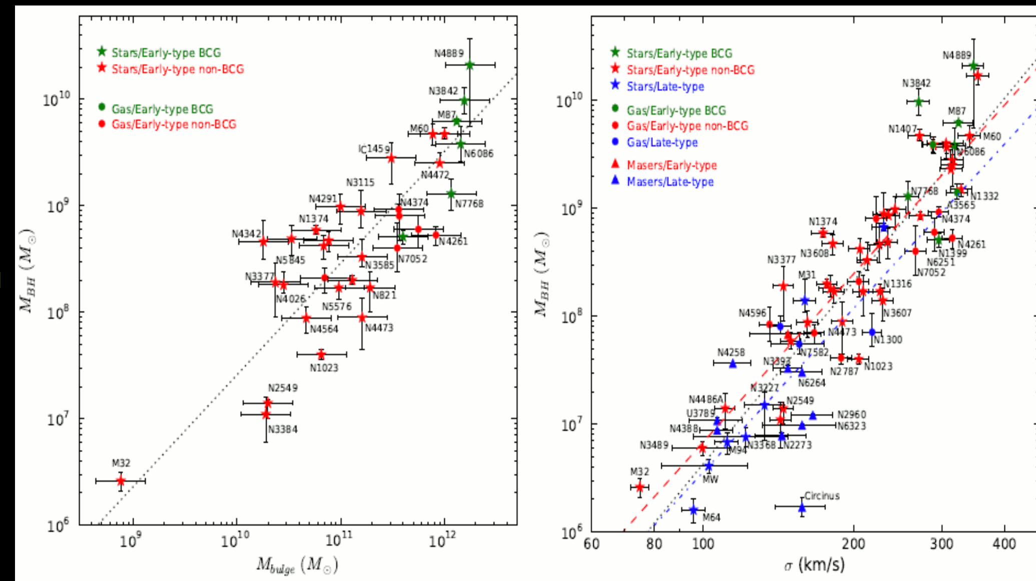

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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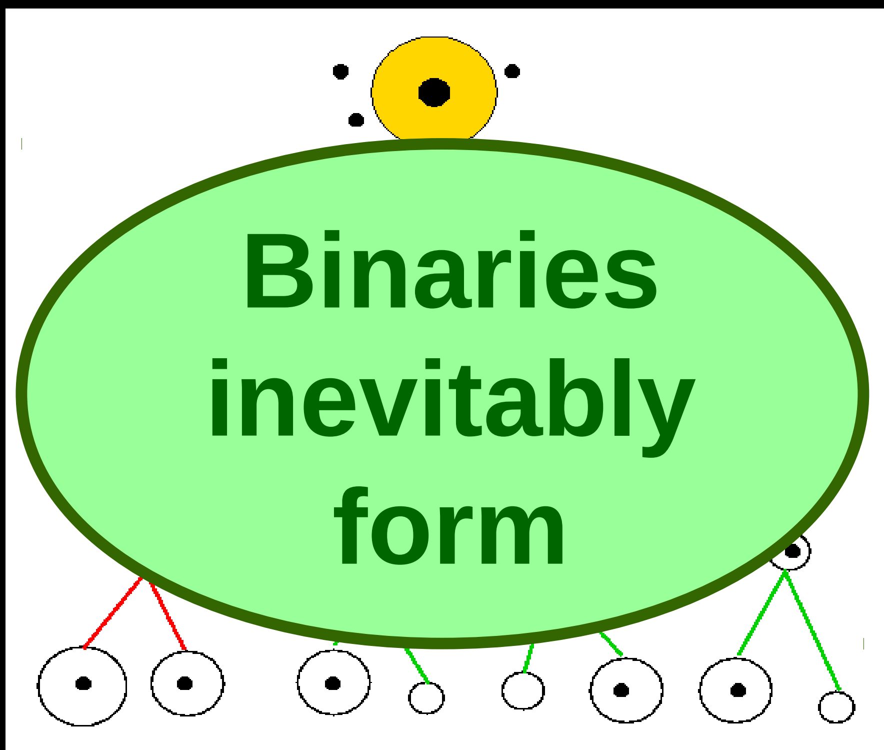
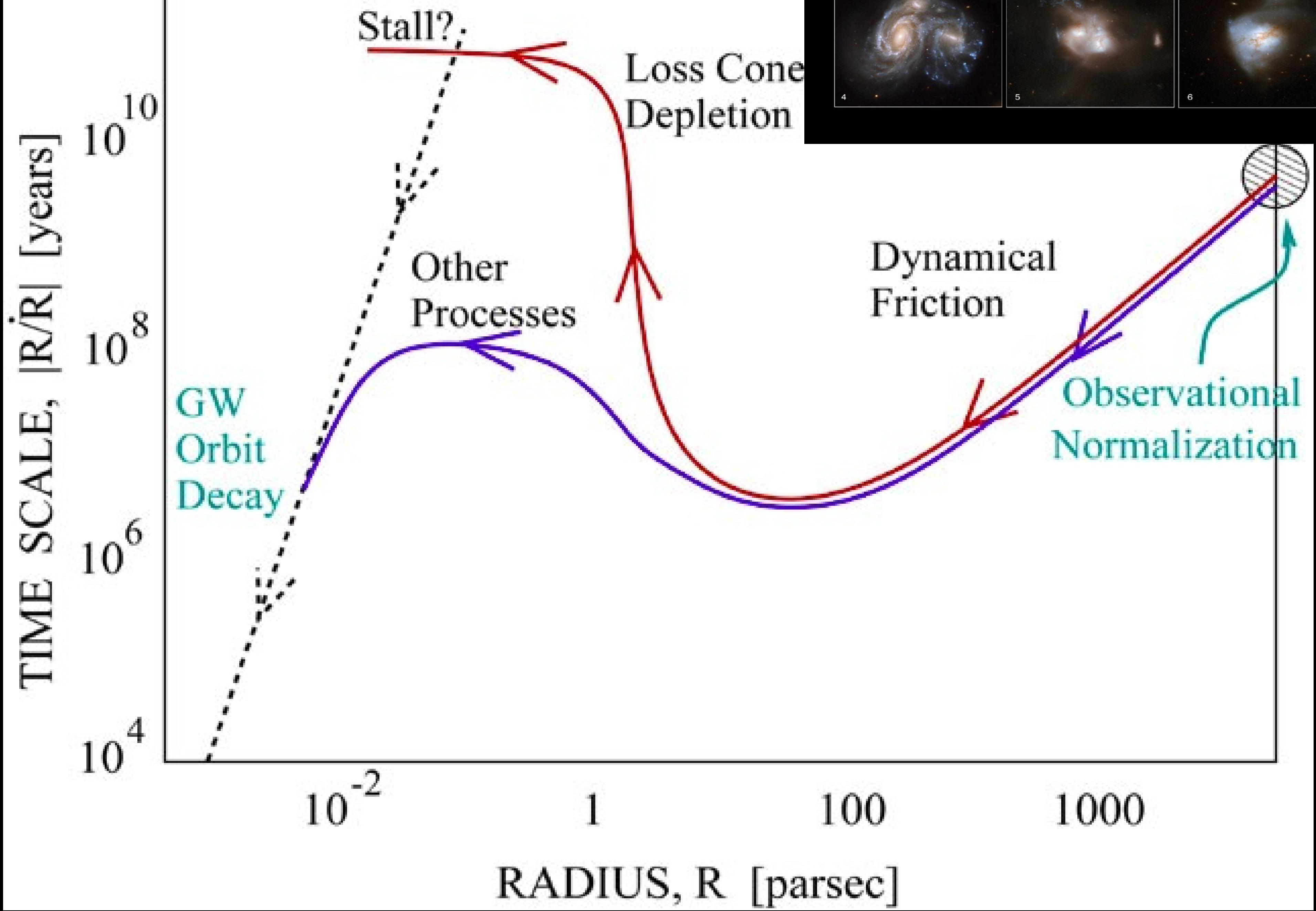
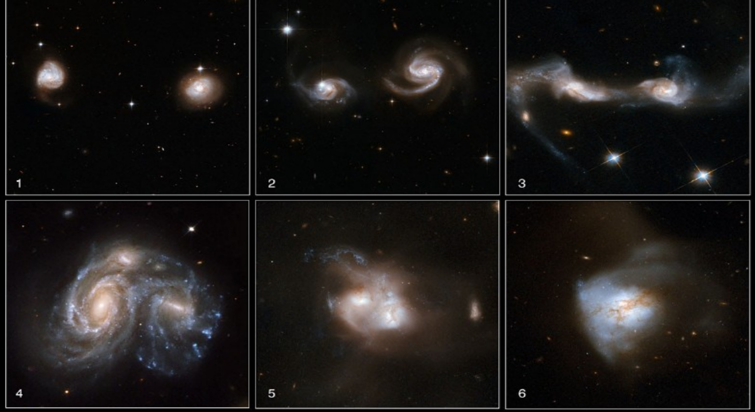


(Menou et al 2001, Volonteri et al. 2003)

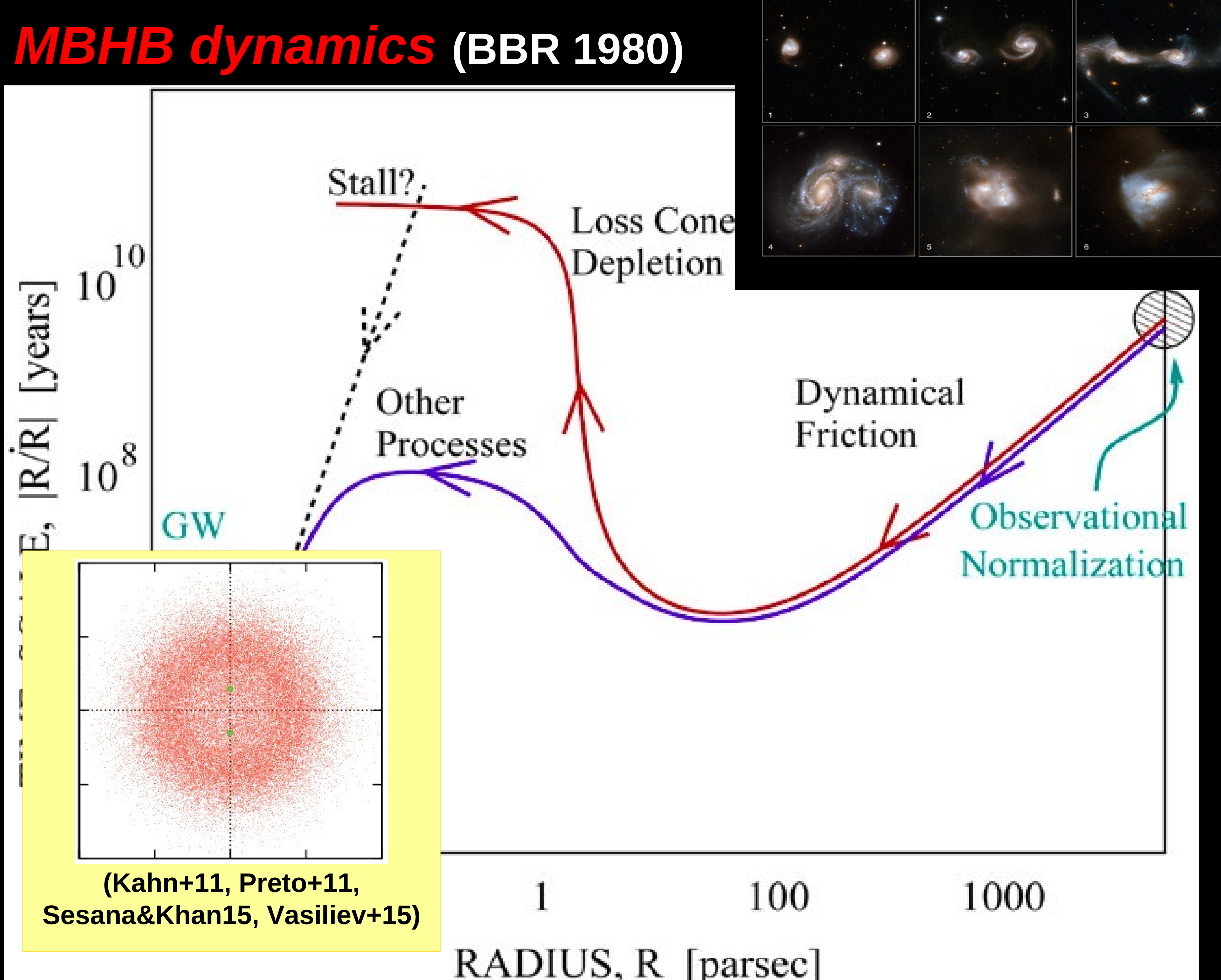
*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?

MBHB dynamics (BBR 1980)



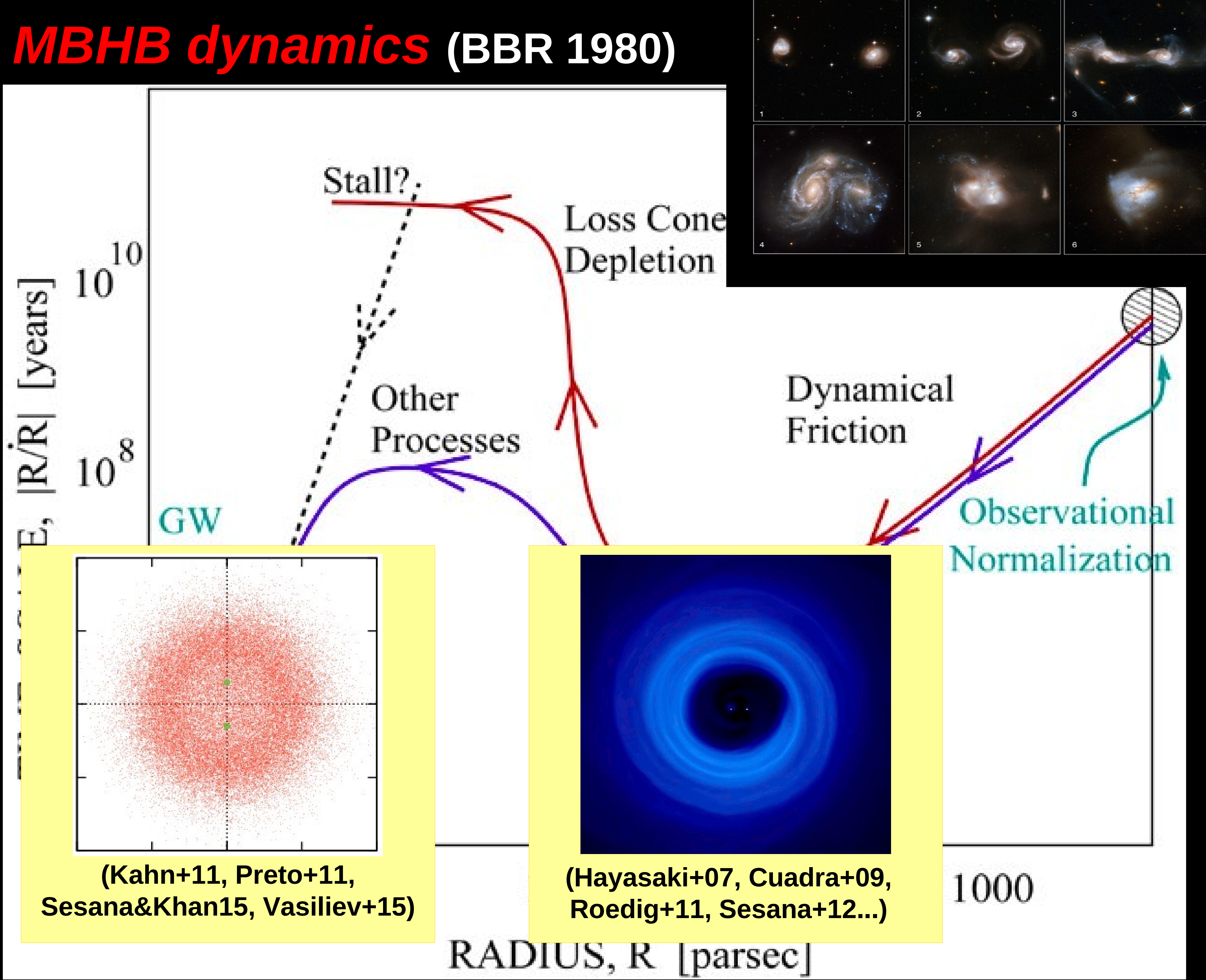


MBHB dynamics (BBR 1980)

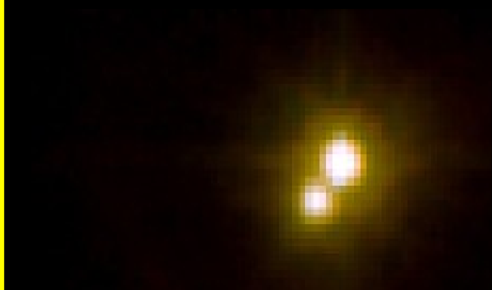
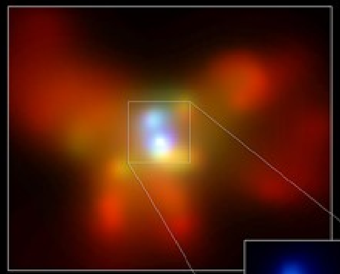
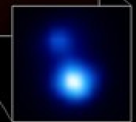


(Kahn+11, Preto+11, Sesana&Khan15, Vasiliev+15)

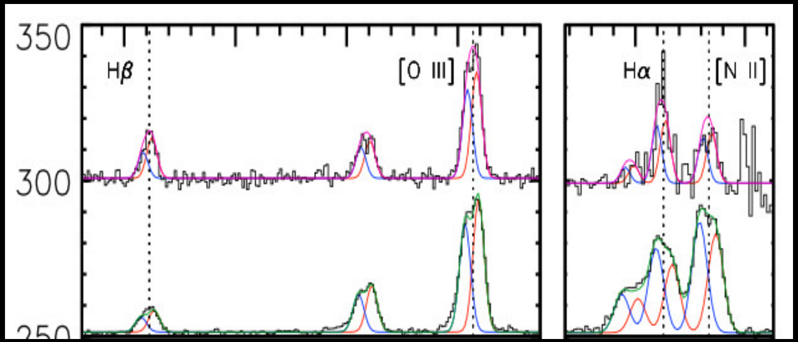
MBHB dynamics (BBR 1980)



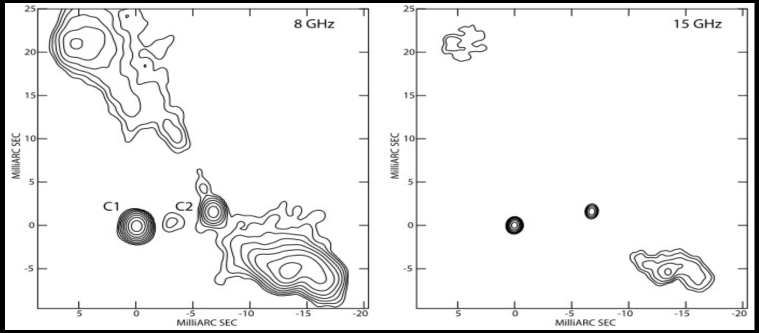
But do we see them?

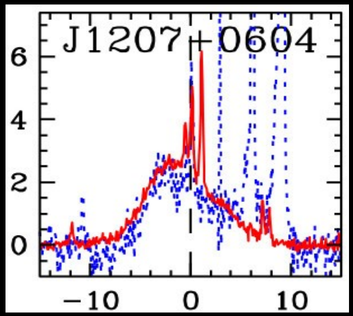
10 kpc: double quasars
(Komossa 2003)

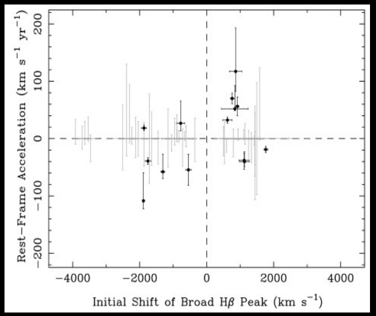


1 kpc: double peaked NL
(Comerford 2013)

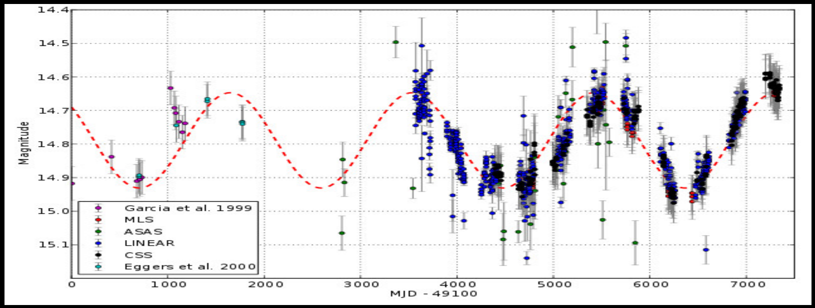


10 pc: double radio cores
(Rodriguez 2006)

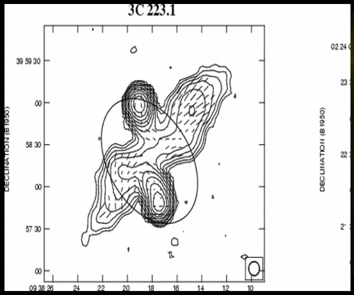




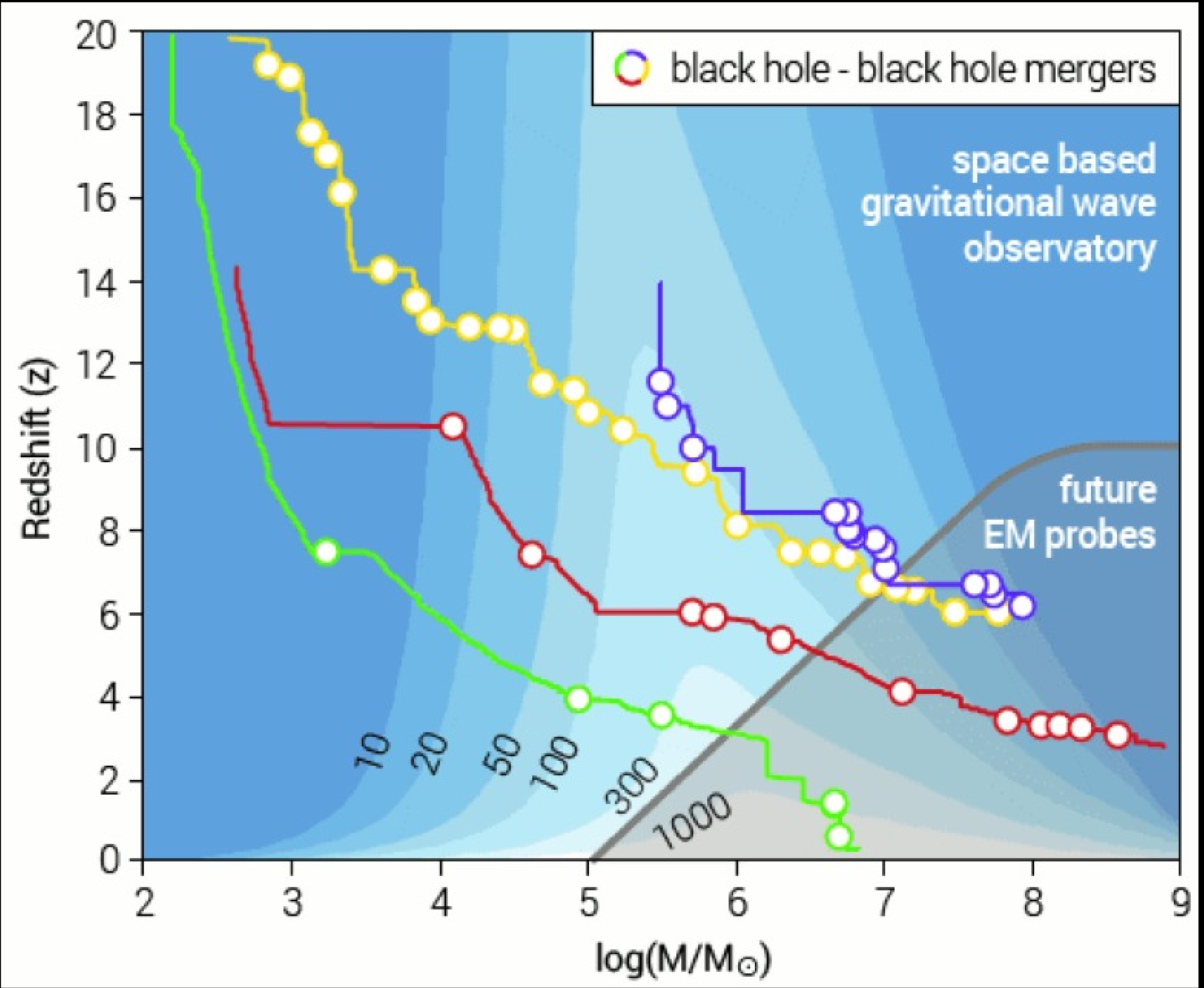
1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



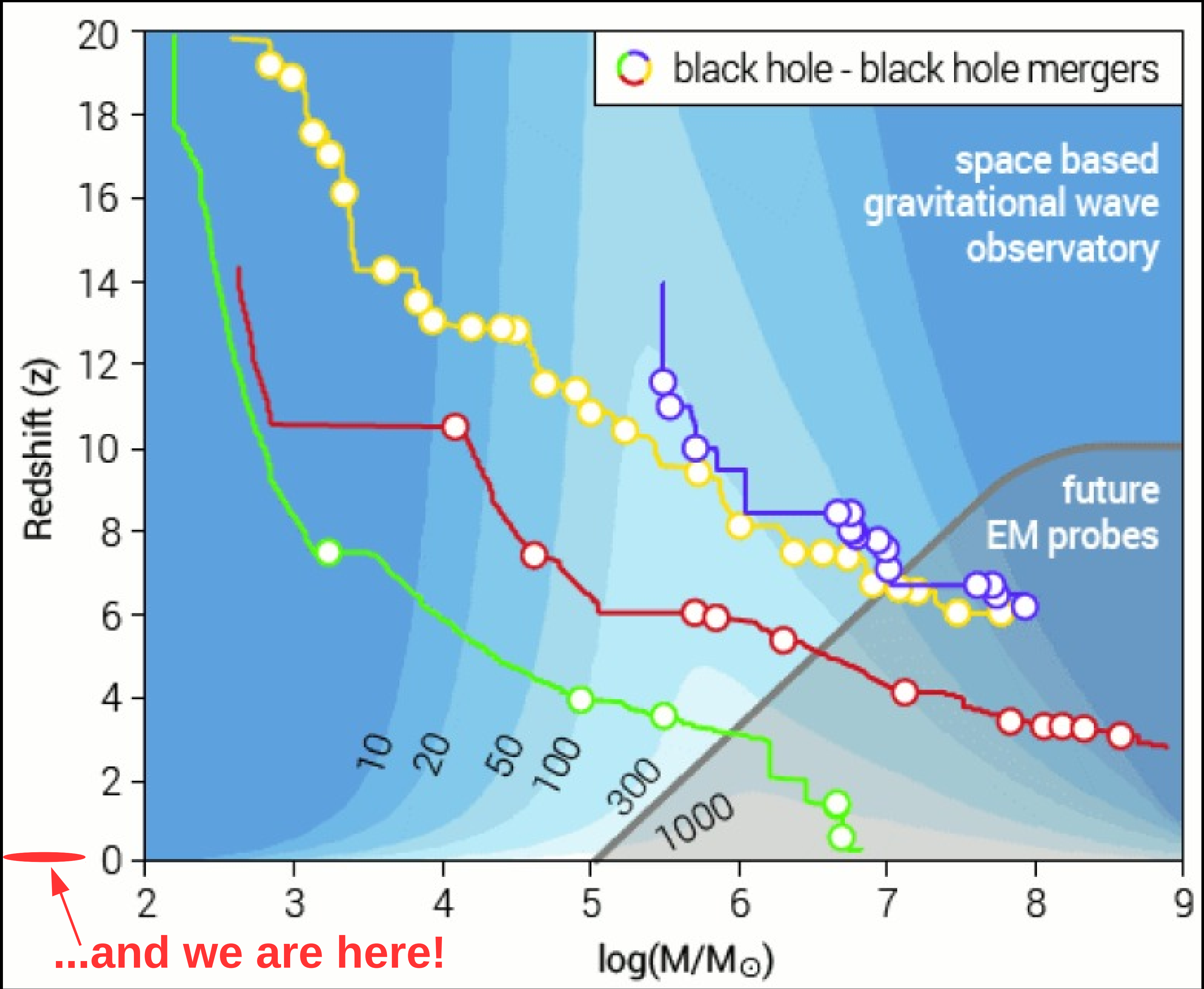
0.01 pc: periodicity (Graham 2015)

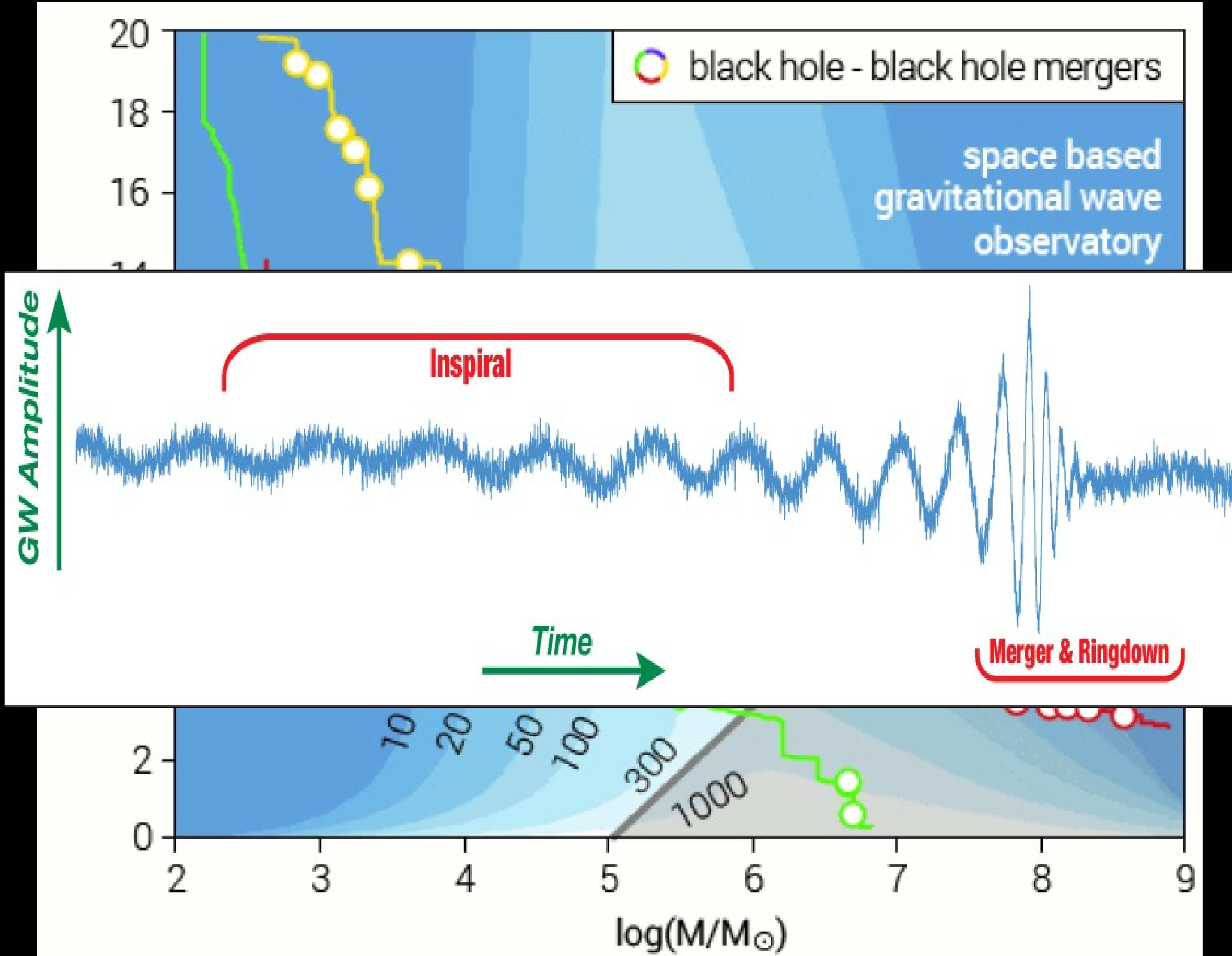


0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)



black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M$_\odot$)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9


black hole - black hole mergers
space based gravitational wave observatory
future EM probes
Redshift (z)
log(M/M⊙)
10
20
50
100
300
1000
...and we are here!



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

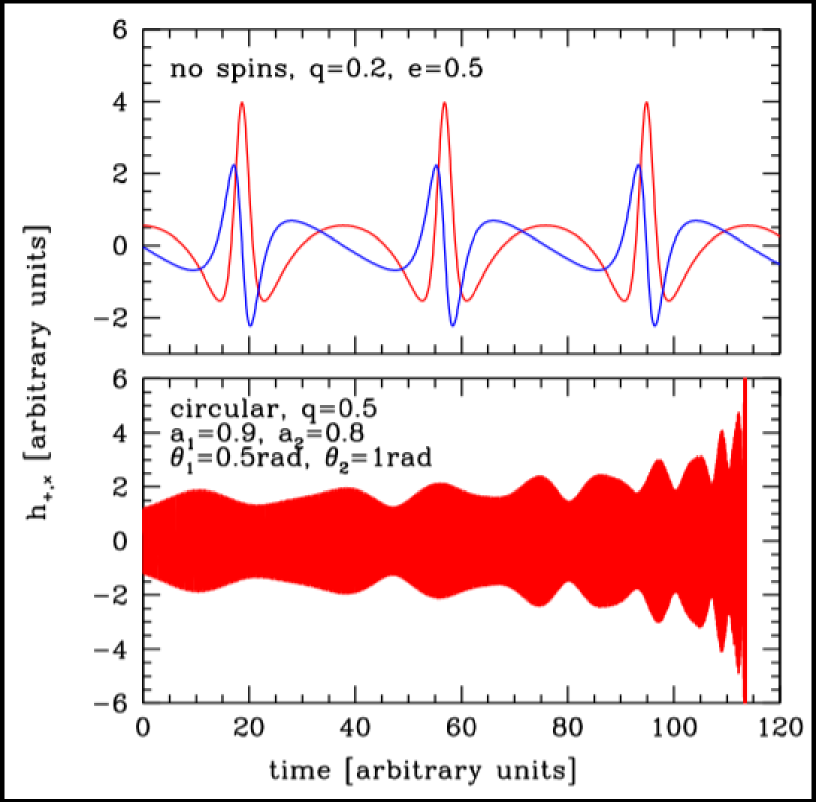
Extraction of information from the waveform

>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

Extraction of information from the waveform

>Masses have the largest impact on the phase modulation

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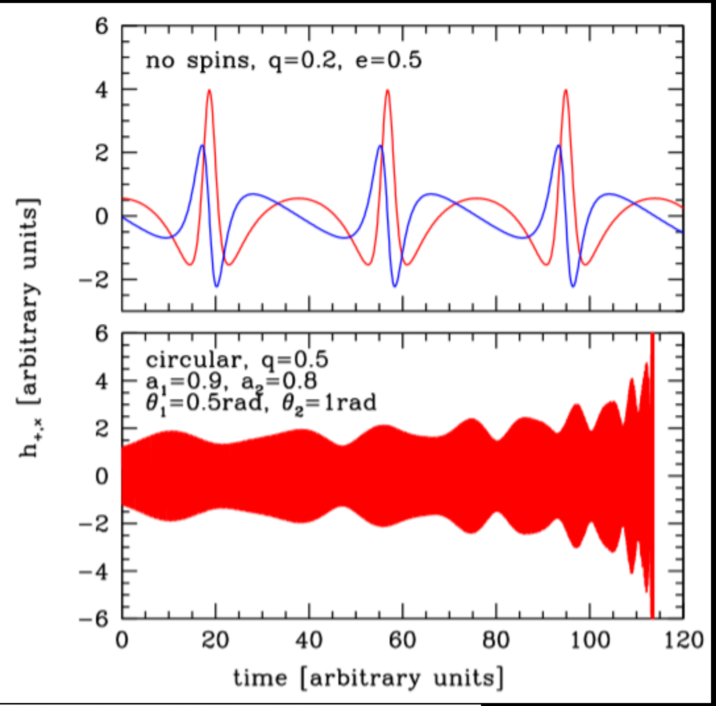
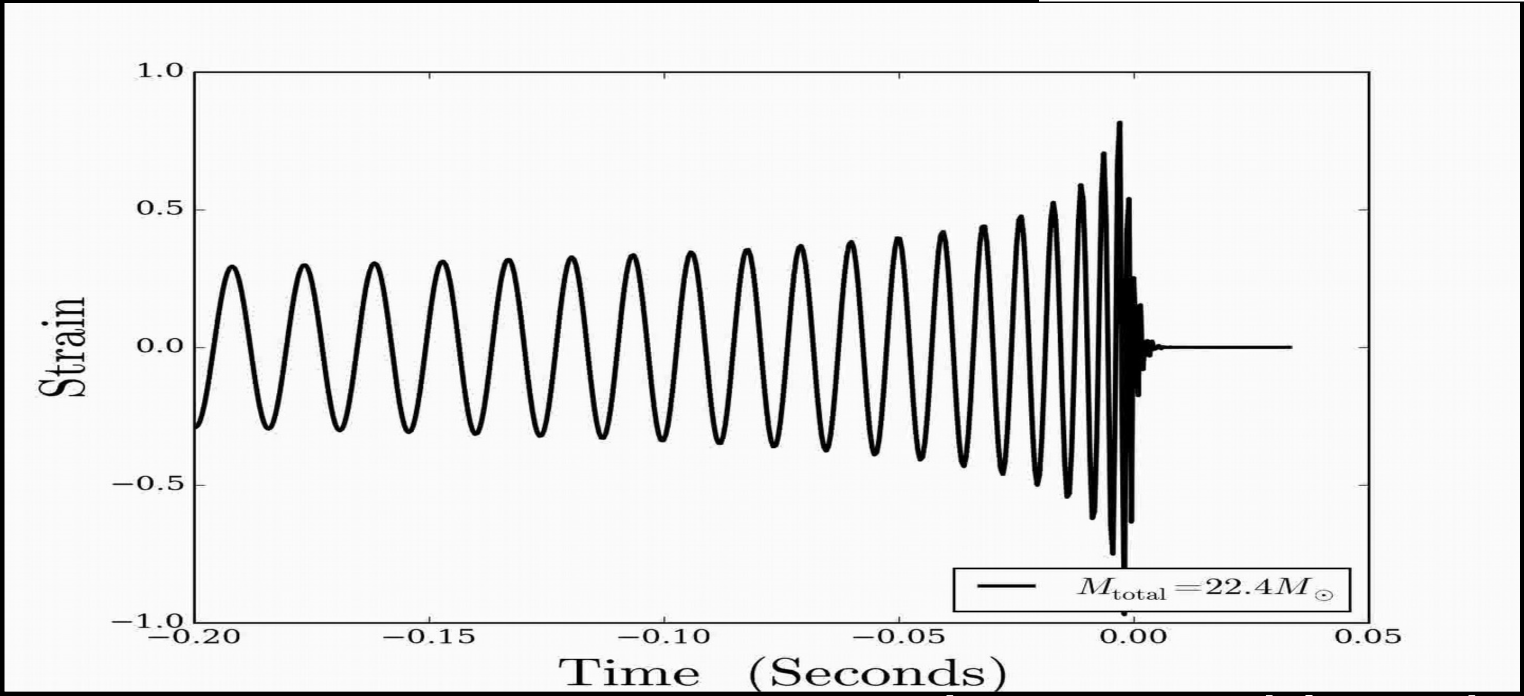
Depend on the number of cycles and SNR, can be easily measured with high precision





(Courtesy W. del Pozzo)

Summary of LISA parameter estimation

Assuming 4 years of operation and 6 links:

~100+ detections

~100+ systems with sky localization to 10 deg2

~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

~50 systems with secondary spin determined to 0.1

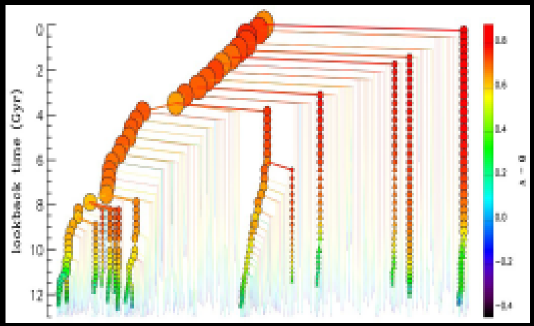
~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

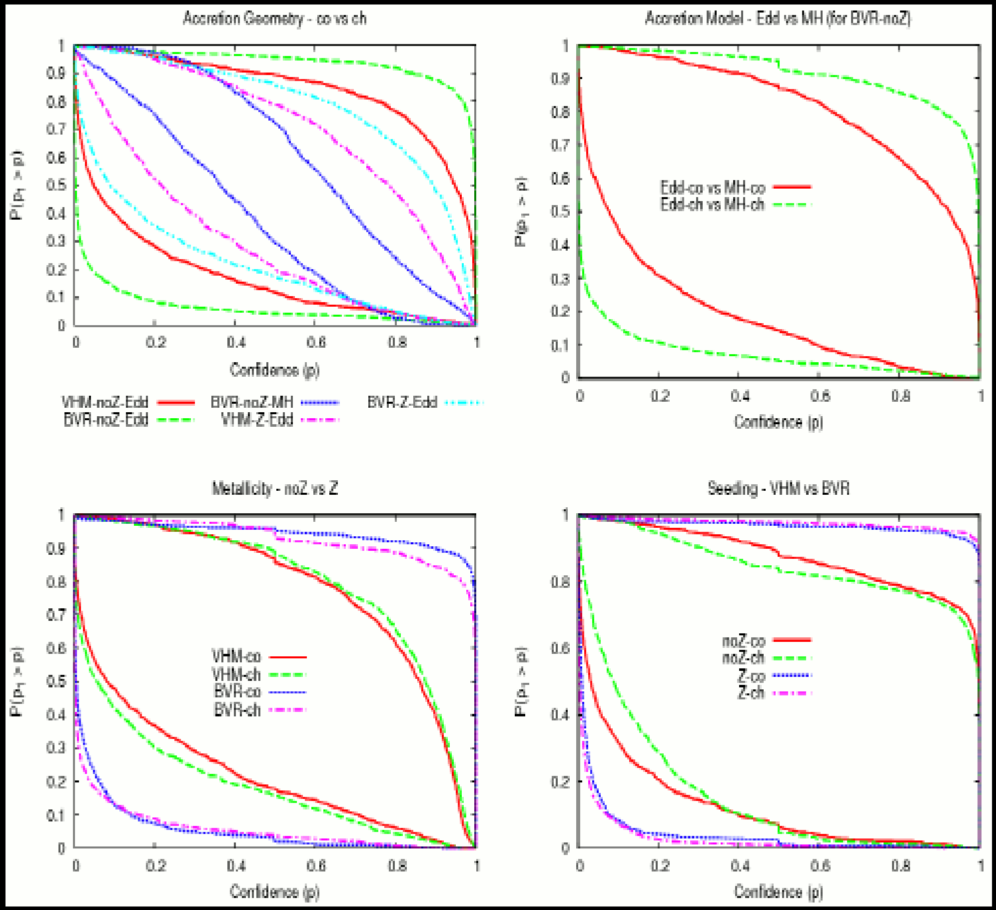
MBH astrophysics with GW observations

Astrophysical unknowns in MBH formation scenarios

1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metallicities)
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?

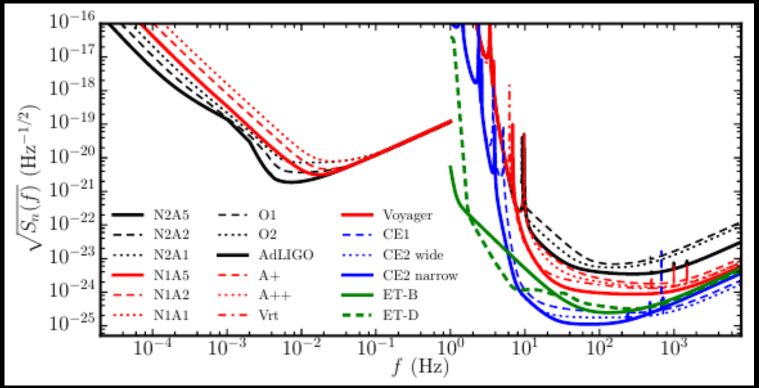


Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

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

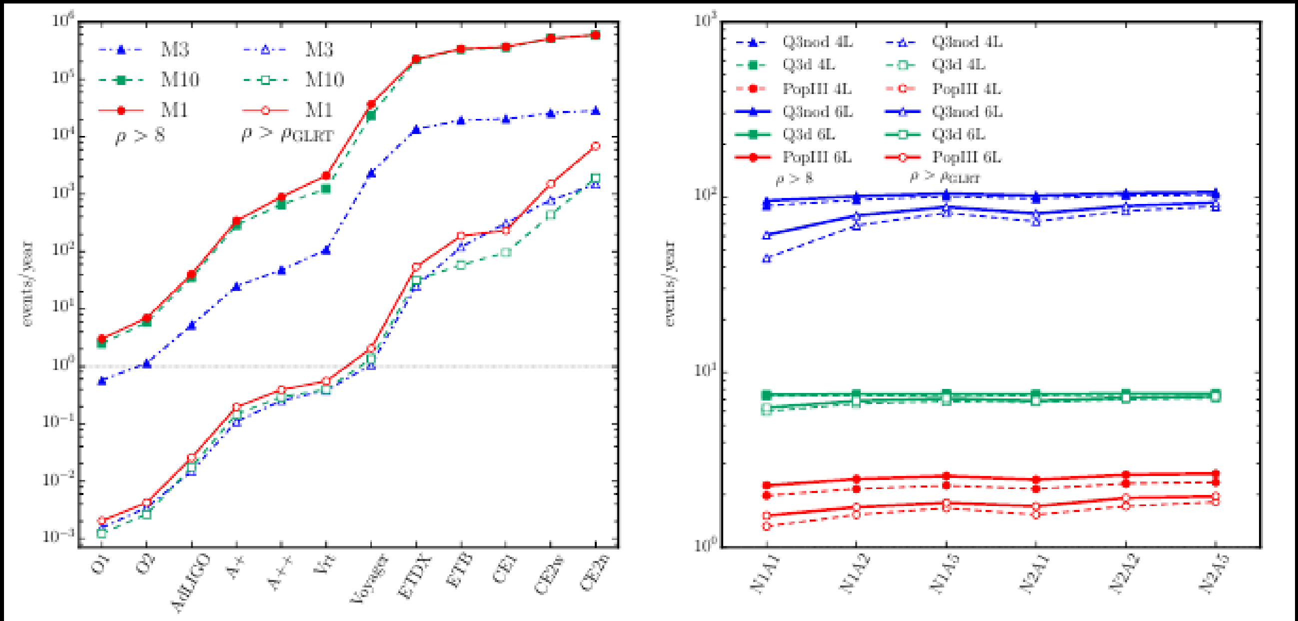
Resolving ringdown modes: BH spectroscopy

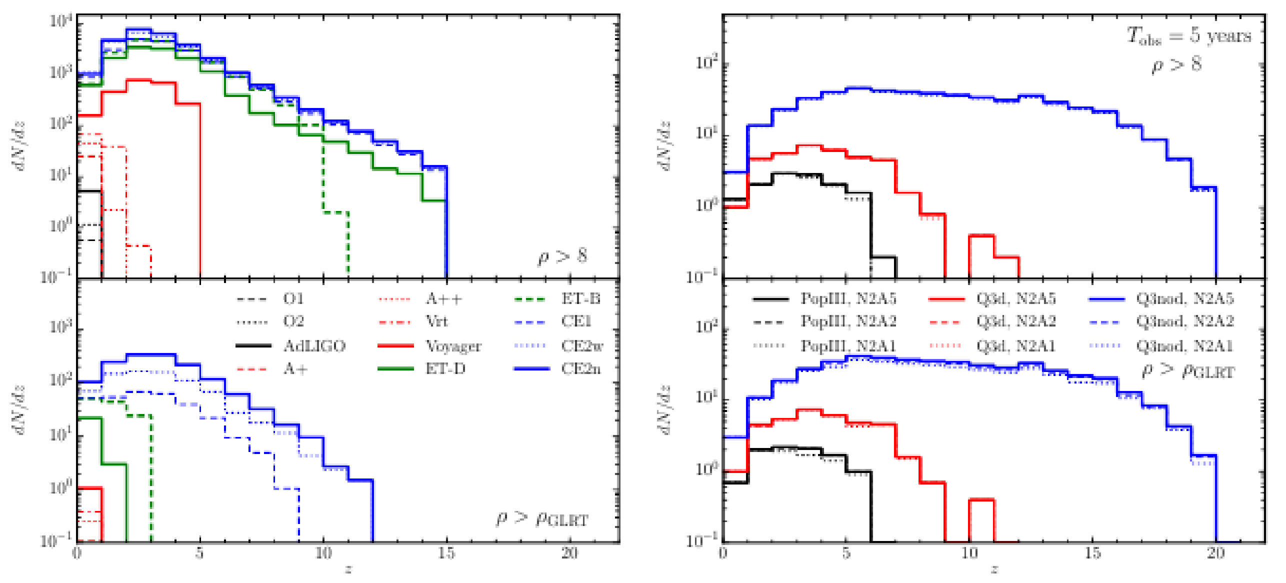
(Berti et al. 2016)



$$\rho^{2,3}_{\rm GLRT} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q},$$

$$\rho^{2,4}_{\rm GLRT} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}$$





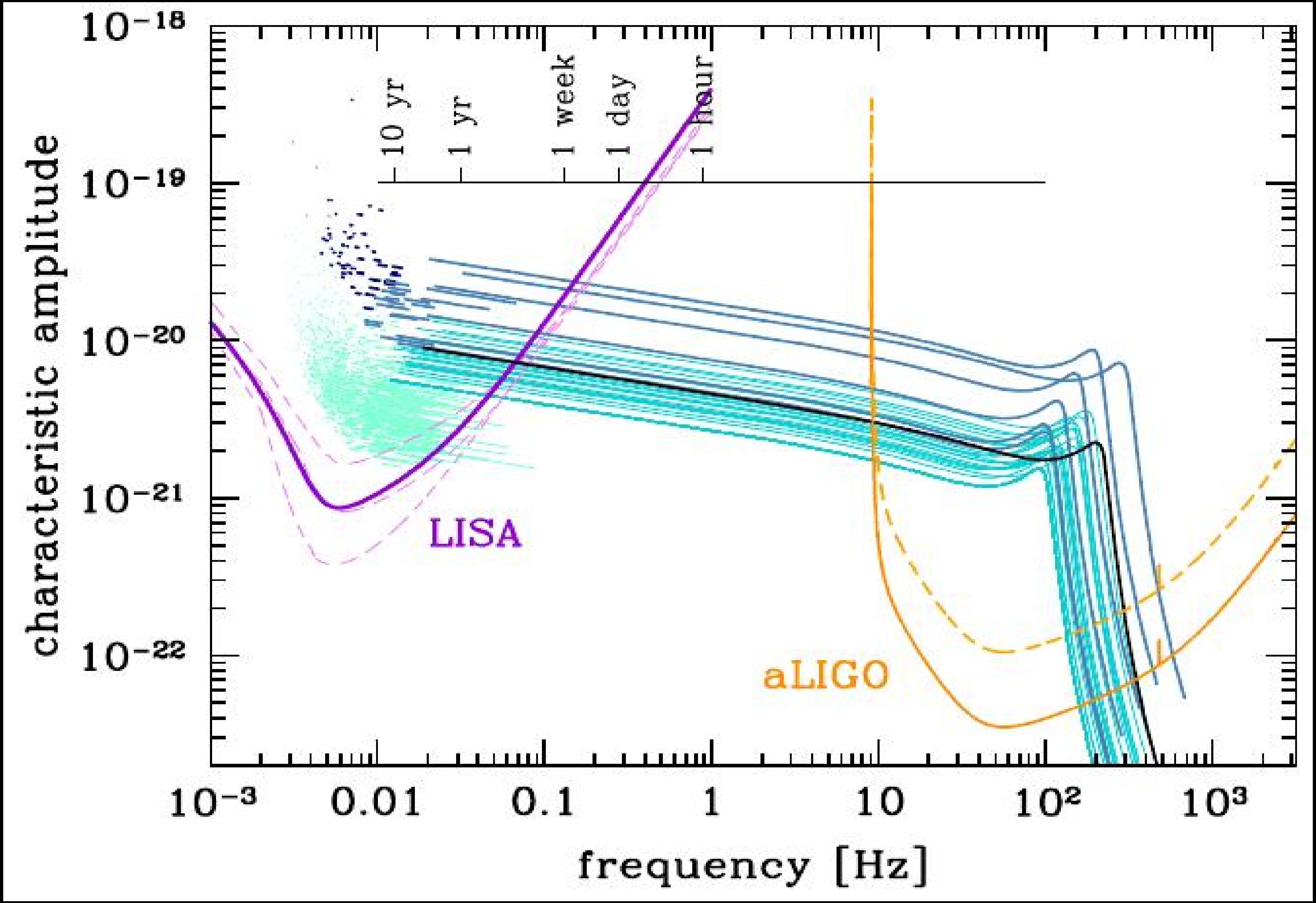
LIGO will not enable BH spectroscopy on individual BHB mergers

Voyager/ET type detectors are needed

eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

Implications of GW150914: multi-band GW astronomy

(AS 2016, PRL 116, 1102)



BHB will be detected by LISA and cross to the LIGO band, assuming a 5 year operation of LISA.

What do we do with them?

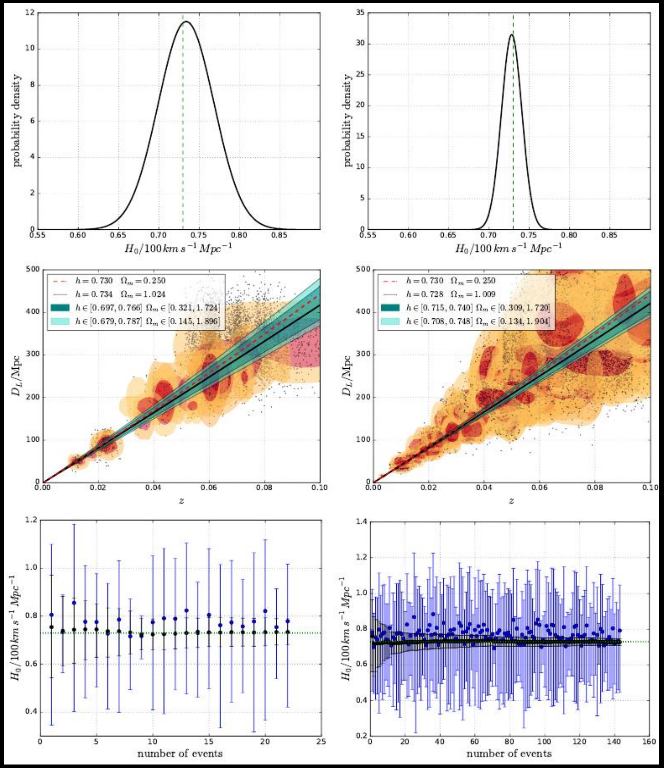
>Detector cross-band calibration and validation (LISA aLIGO)

>Multiband GW astronomy:
- -alert aLIGO to ensure multiple GW detectors are on
- -inform aLIGO with source parameters: makes detection easier

>Multimessenger astronomy:
- -point EM probes at the right location before the merger

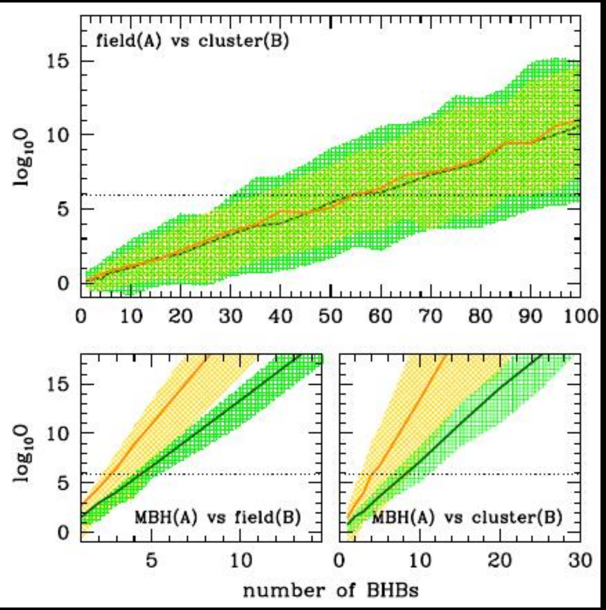
>Enhanced tests of GR: e.g. strongest limits on deviations from GR

(Barausse et al 2016)



>Astrophysics:
- -independent measure of spins
- -measure of eccentricity

(Nishizawa, AS, Berti, Klein 2017, Breivik et al 2017)



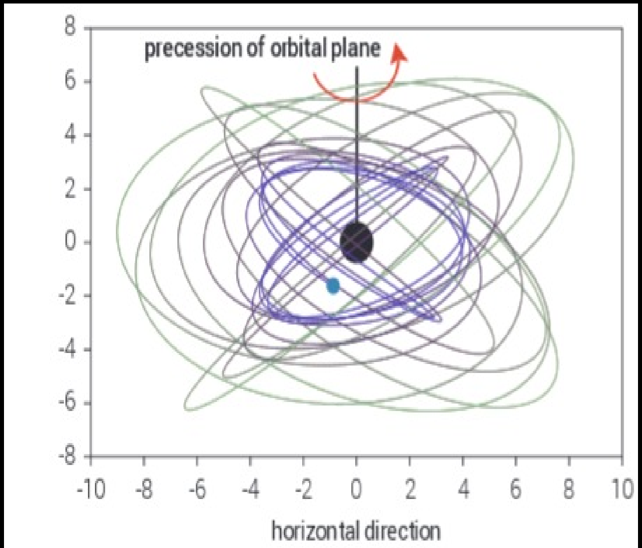
>Cosmology:
- -new population of standard sirens?

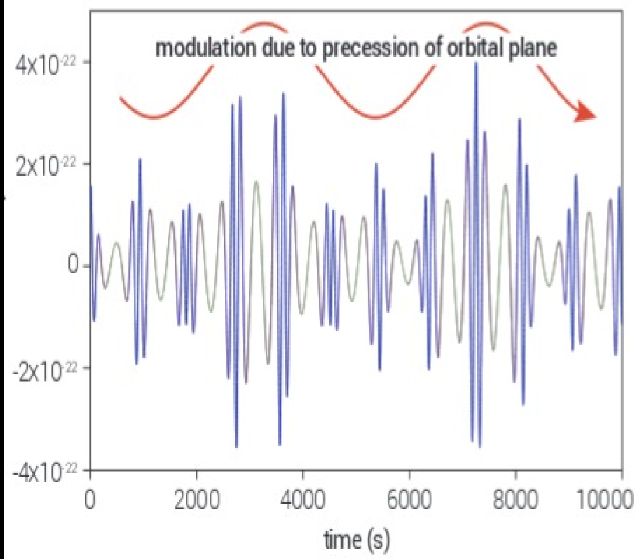
(Del Pozzo, AS, Klein 2017)

Extreme mass ratio inspirals (EMRIs)

- What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?
- Are massive black holes as light as $\sim 10^5 M_\odot$ inhabiting the cores of low mass galaxies? Are they seed black hole relics? What are their properties?

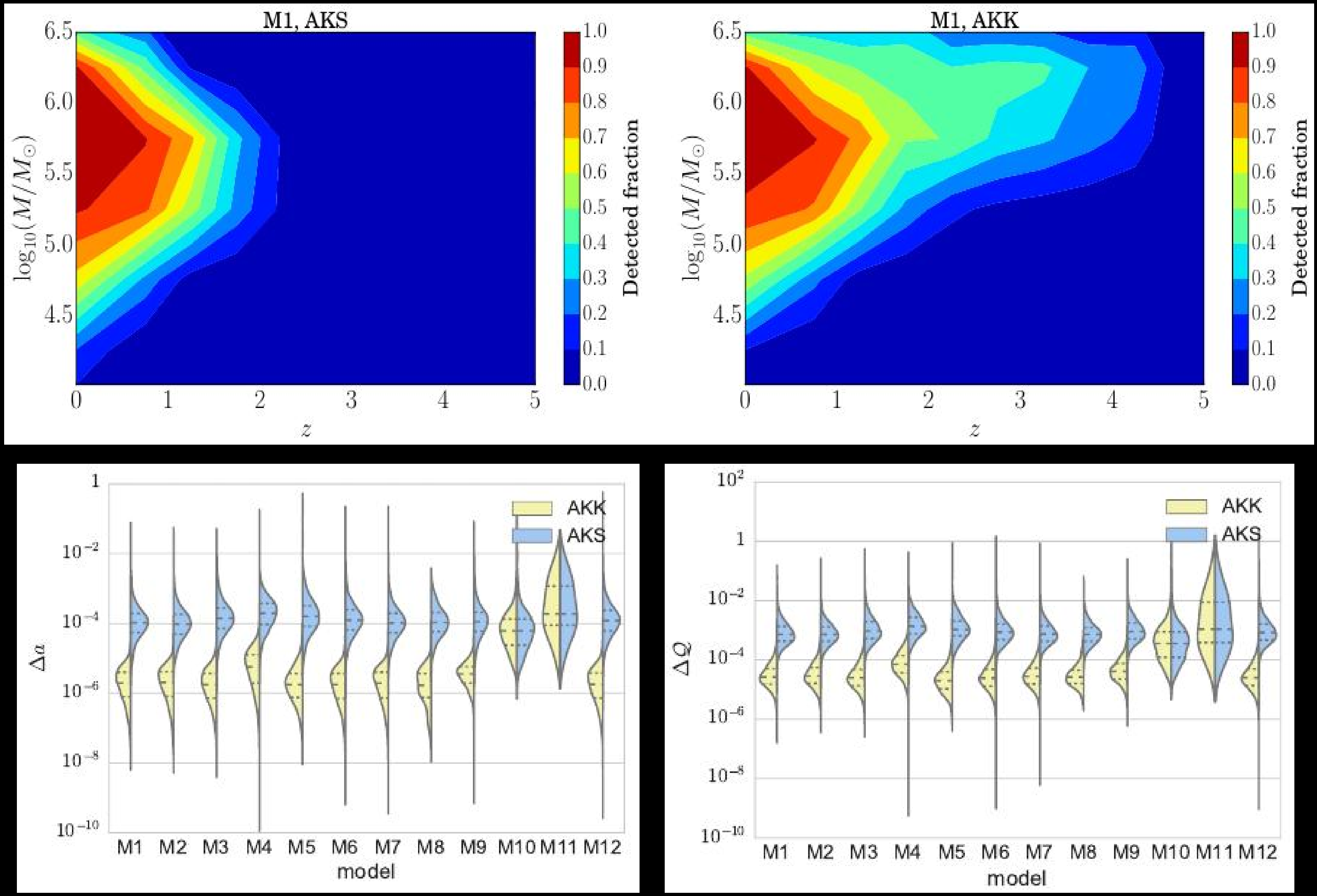
- Does gravity travel at the speed of light ?
- Does the graviton have mass?
- How does gravitational information propagate: Are there more than two transverse modes of propagation?
- Does gravity couple to other dynamical fields, such as, massless or massive scalars?
- What is the structure of spacetime just outside astro-physical black holes? Do their spacetimes have horizons?
- Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?





Selected results: LISA reach and parameter estimation

(Babak et al, almost submitted...finally!)



Summary of EMRI parameter estimation

~1-1000 detections/yr

~typical sky localization better than 10 deg2

~distance to better than 10%

~MBH mass to better than 0.01%

~CO mass to better than 0.01%

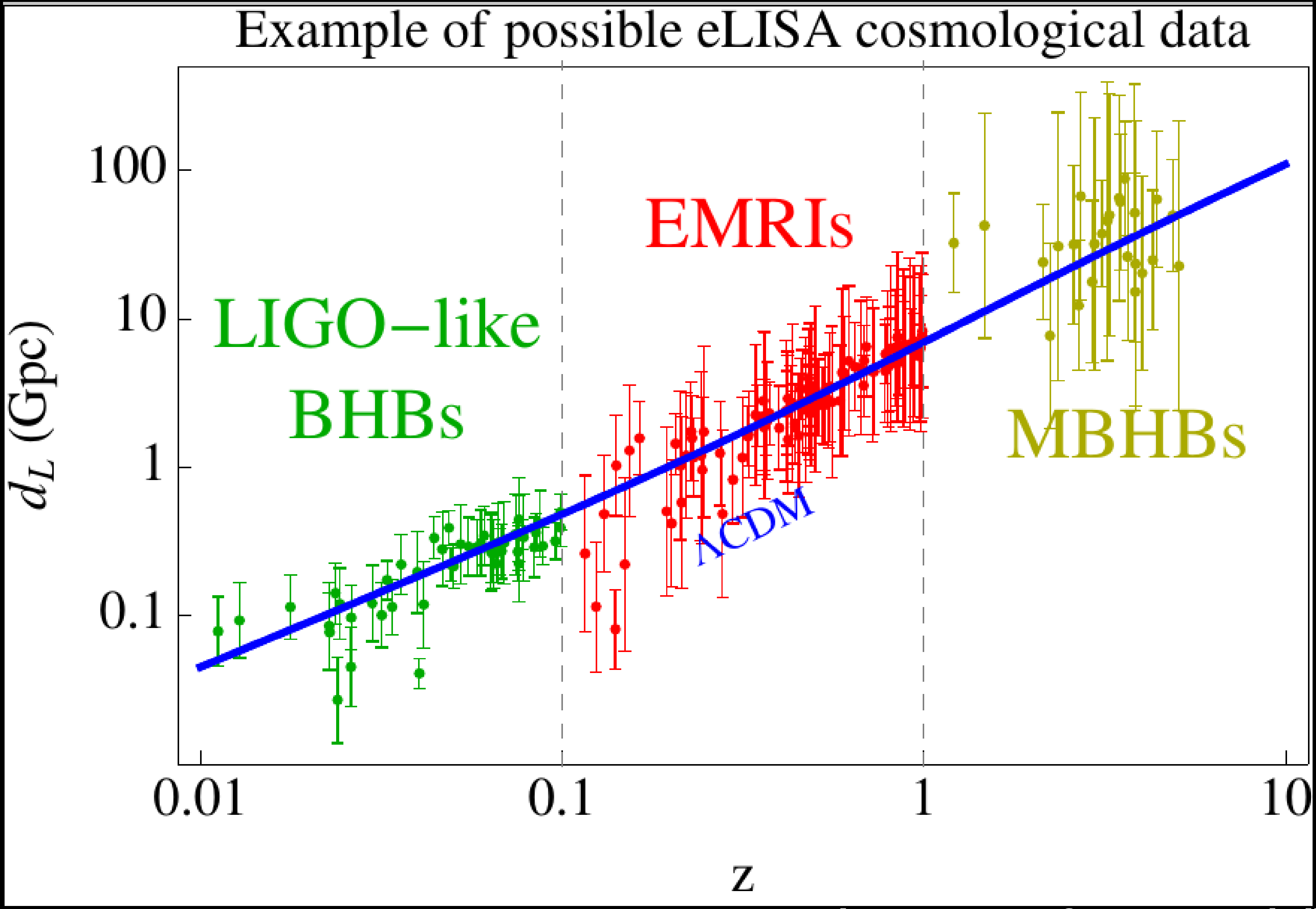
~MBH spin to better than 0.001

~plunge eccentricity to better than 0.0001

~deviation from Kerr quadrupole moment to <0.001

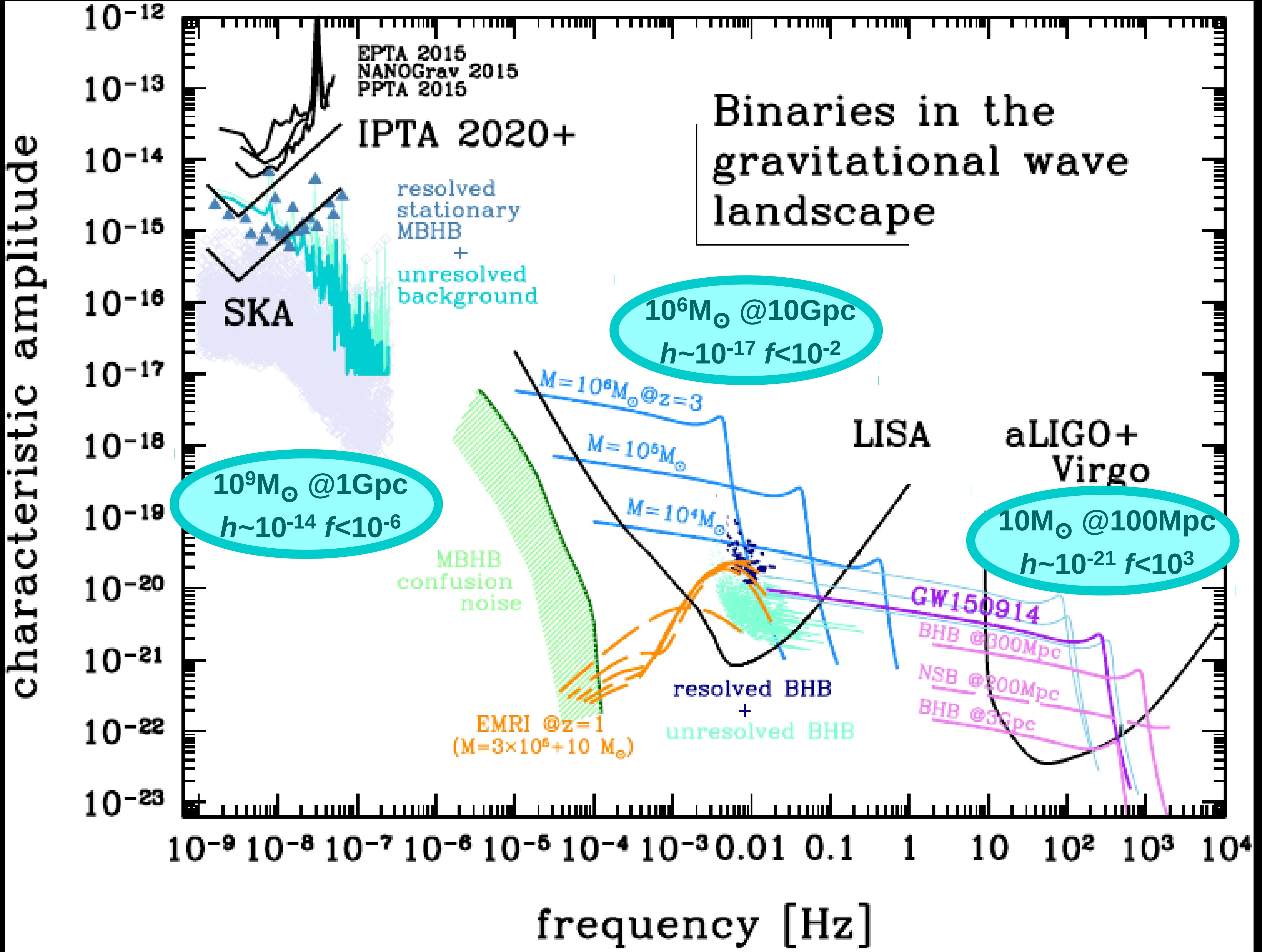
New tool for astrophysics (Gair et al 2010) cosmology (McLeod & Hogan 2008), and fundamental physics (Gair et al 2013) … to be further explored

Cosmology with gravitational waves



(Courtesy of N. Tamanini)

Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts.

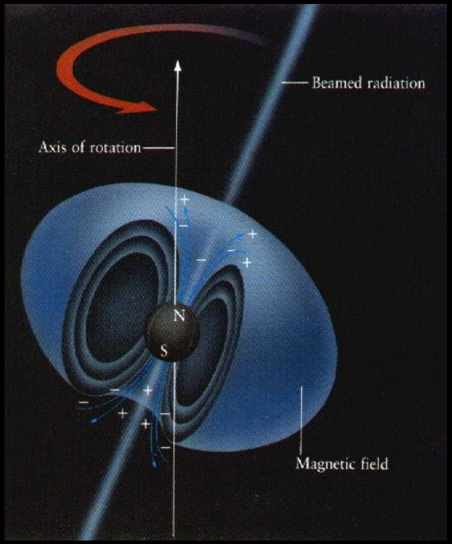


EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
$10^6 M_\odot$ @10Gpc
$h\sim10^{-17}$ $f<10^{-2}$
$10^9 M_\odot$ @1Gpc
$h\sim10^{-14}$ $f<10^{-6}$
$10 M_\odot$ @100Mpc
$h\sim10^{-21}$ $f<10^{3}$
$M=10^6 M_\odot$@z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
LISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB + unresolved BHB
EMRI @z=1
($M=3\times10^5+10\ M_\odot$)
characteristic amplitude
frequency [Hz]

What is pulsar timing

Pulsars are neutron seen through their regular radio pulses

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



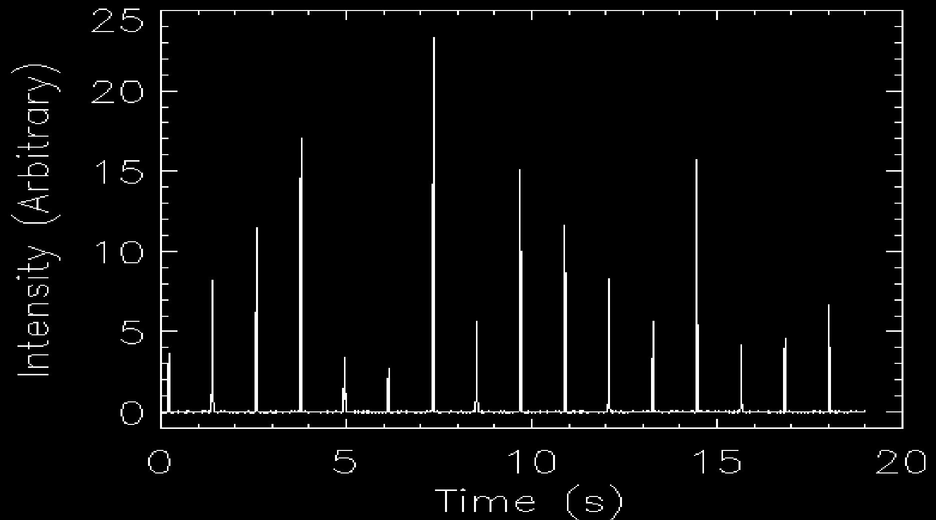
1-Observe a pulsar and measure the ToAs

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*



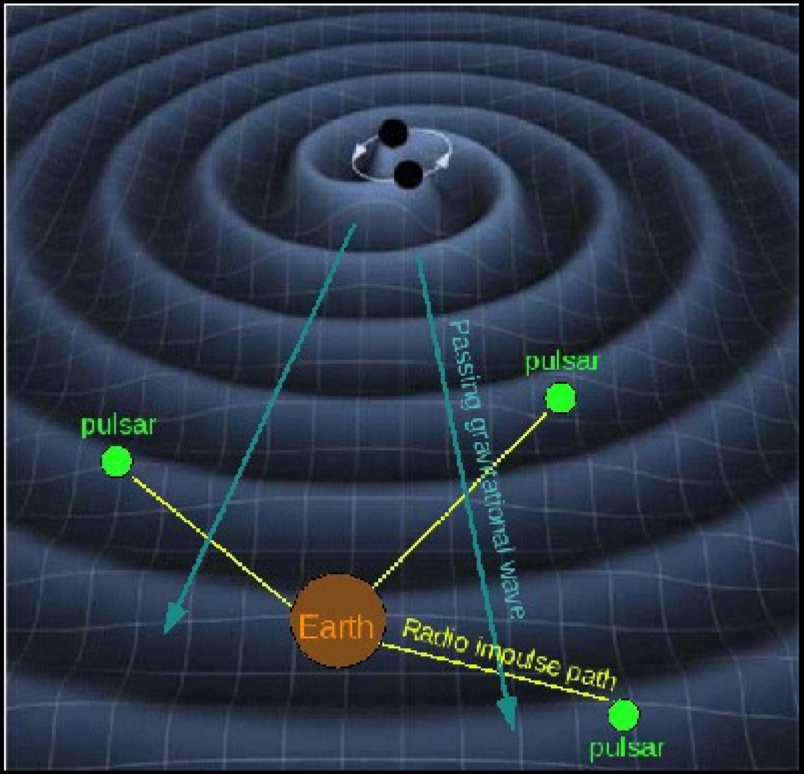
Effect of gravitational waves

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 de-phasing)

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



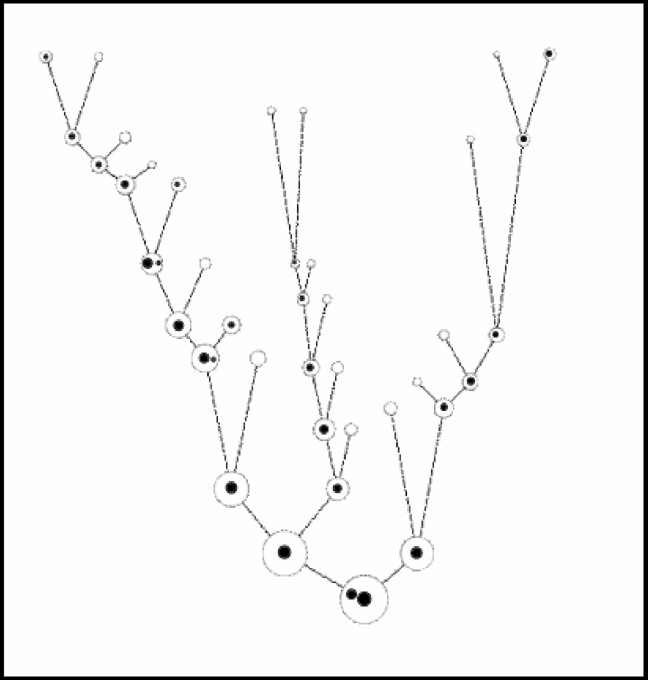
(Sazhin 1979, Hellings & Downs 1983, Jenet et al. 2005, AS et al. 2008, 2009)

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 expected GW signal in the PTA band



The GW characteristic amplitude coming from a population of circular MBH binaries

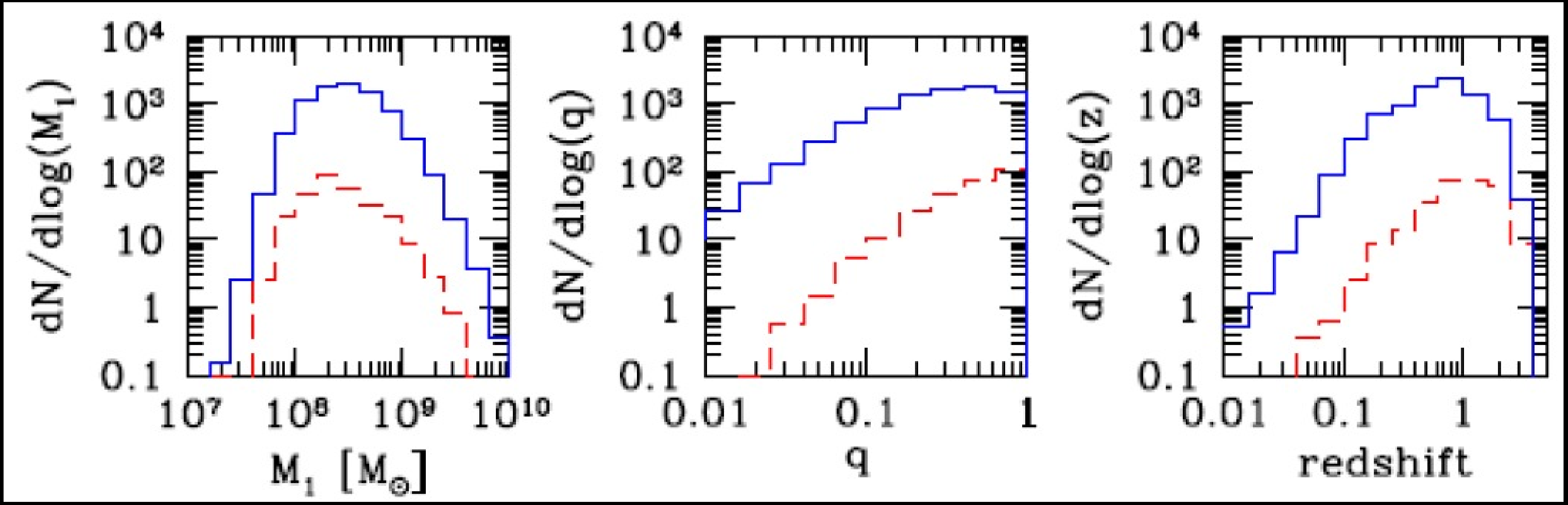
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

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

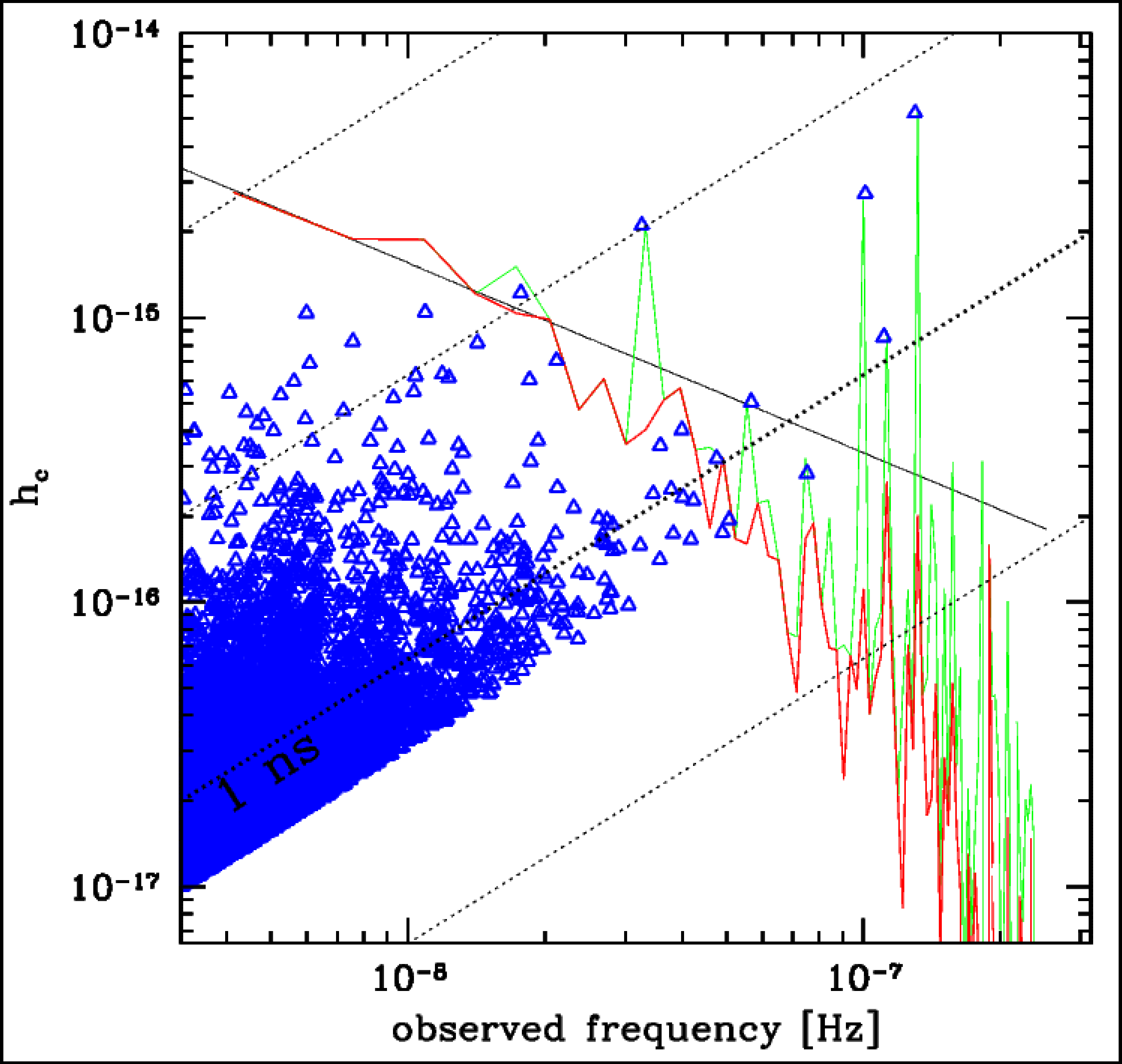
Theoretical spectrum: simple power law

(Phinney 2001)

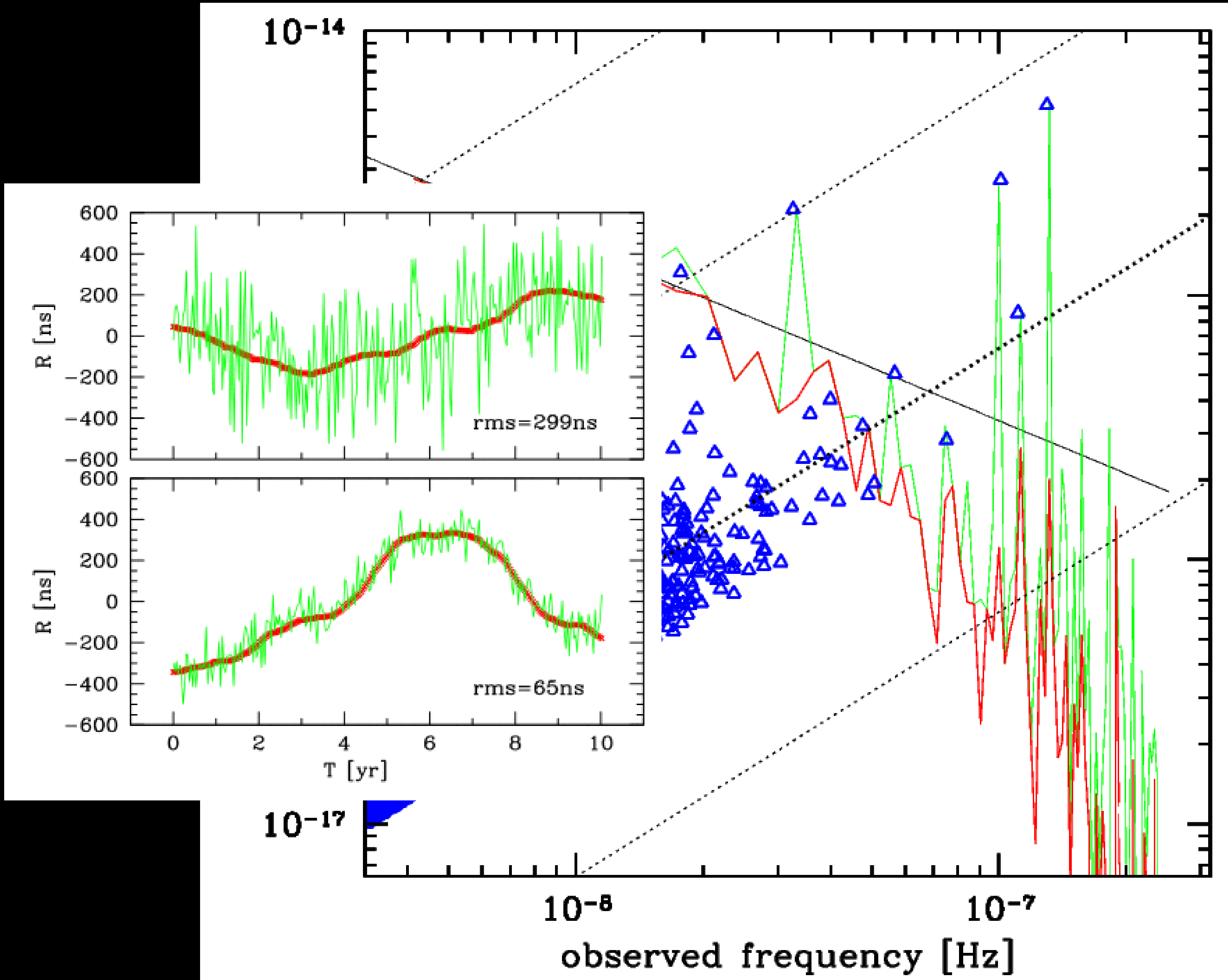
$$h_c(f) = A \left(\frac{f}{\rm yr^{-1}} \right)^{-2/3}$$



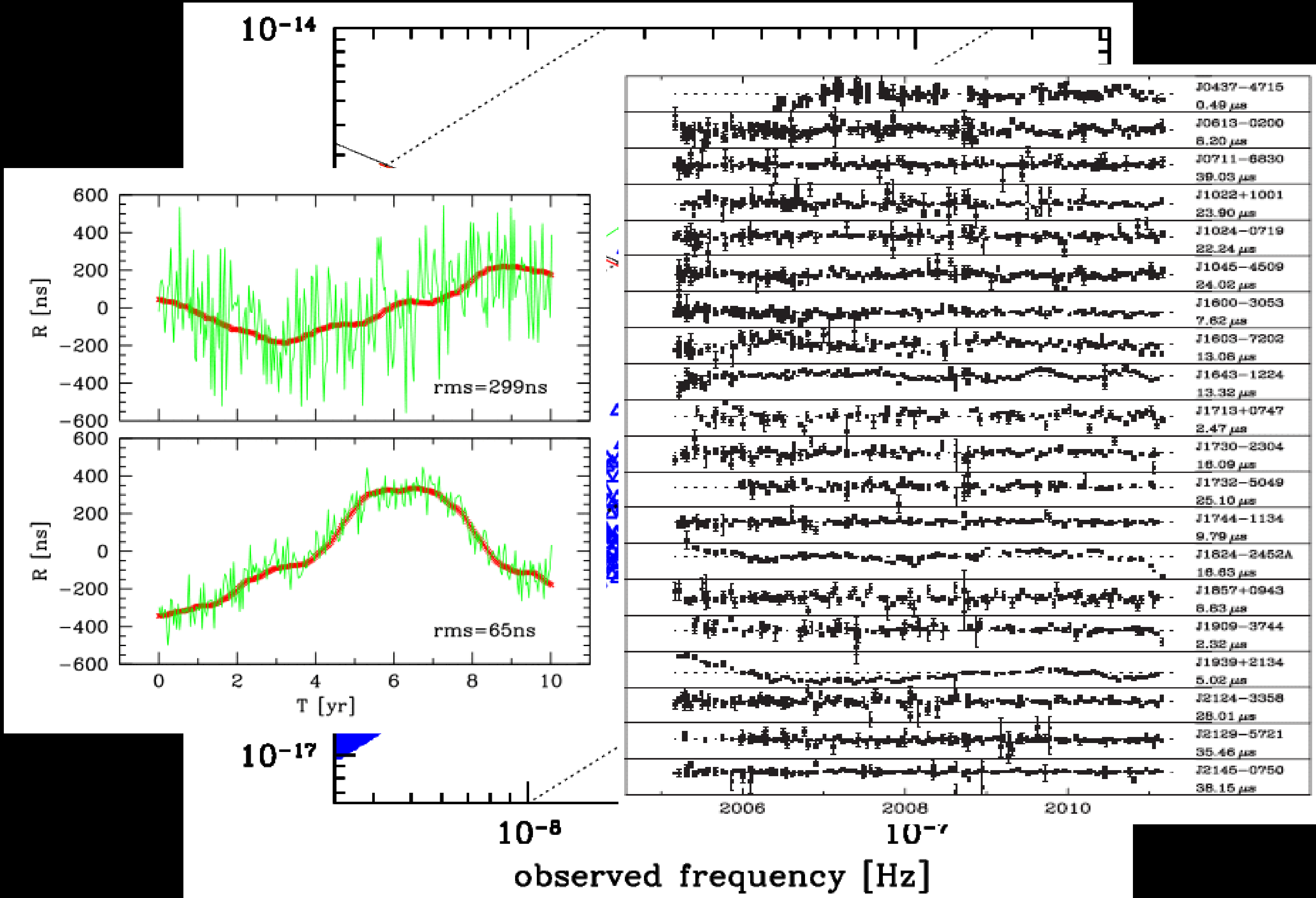
The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries **(AS et al. 2008, 2012)**



10^{-14}
10^{-15}
10^{-16}
10^{-17}
h_c
1 ns
10^{-8}
10^{-7}
observed frequency [Hz]

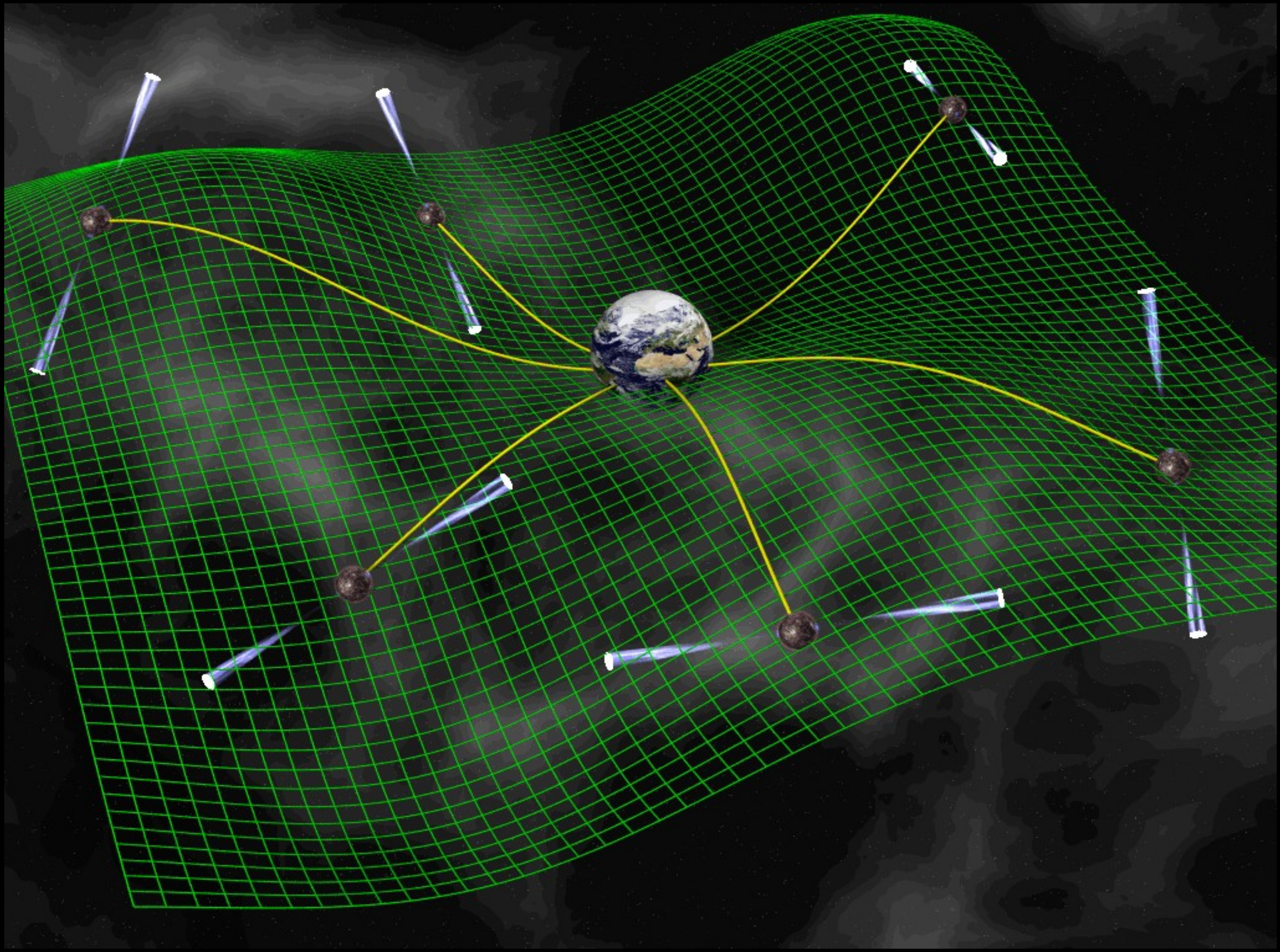


10⁻¹⁴
10⁻¹⁷
10⁻⁸
10⁻⁷
observed frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]

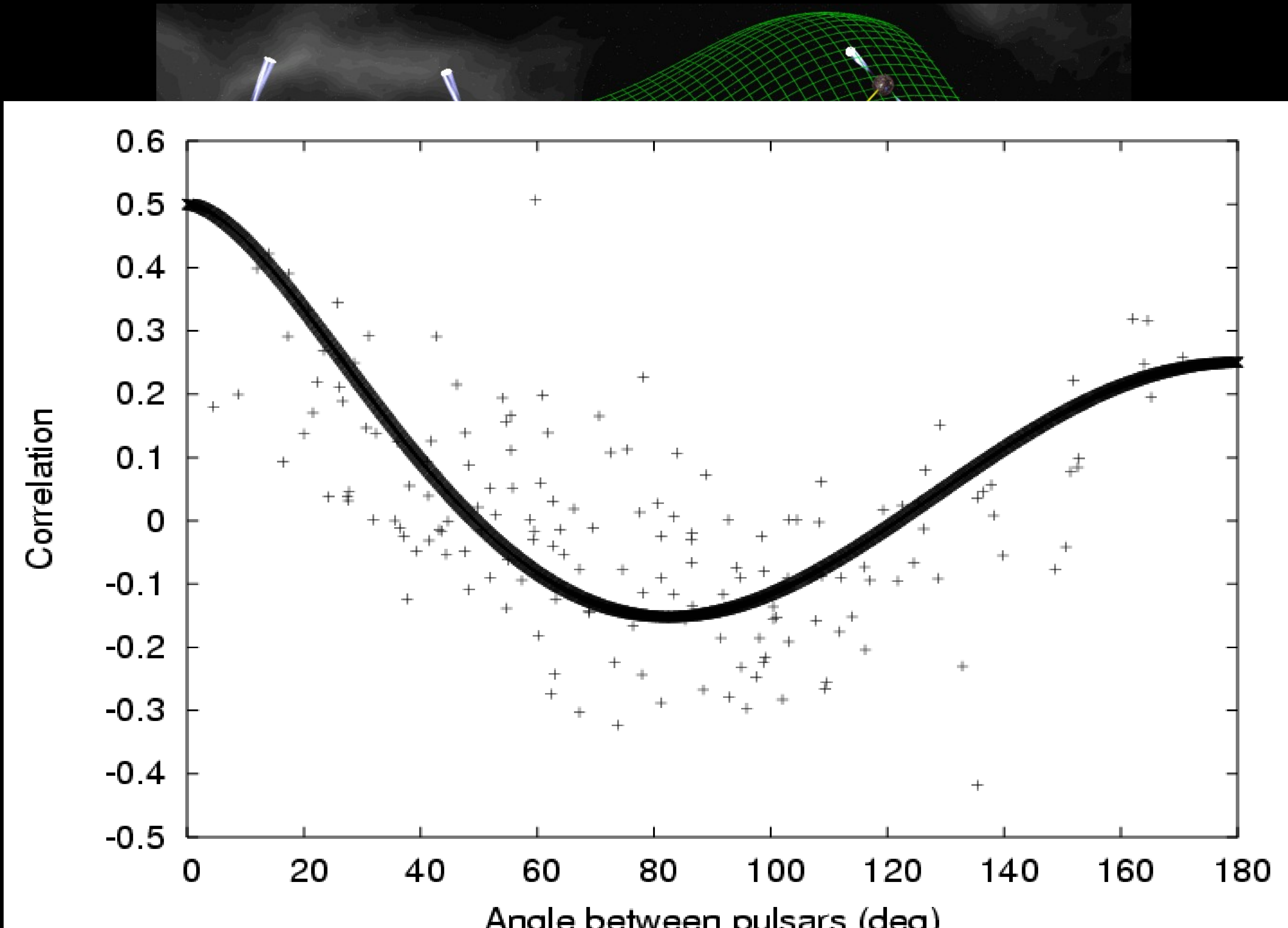


10^{-14}
10^{-17}
10^{-8}
10^{-7}
observed frequency [Hz]
R [ns]
rms=299ns
rms=65ns
T [yr]
J0437−4715 0.49 μs
J0613−0200 8.20 μs
J0711−6830 39.03 μs
J1022+1001 23.90 μs
J1024−0719 22.24 μs
J1045−4509 24.02 μs
J1600−3053 7.62 μs
J1603−7202 13.06 μs
J1643−1224 13.32 μs
J1713+0747 2.47 μs
J1730−2304 16.09 μs
J1732−5049 25.10 μs
J1744−1134 9.79 μs
J1824−2452A 18.63 μs
J1857+0943 6.63 μs
J1909−3744 2.32 μs
J1939+2134 5.02 μs
J2124−3358 28.01 μs
J2129−5721 35.46 μs
J2145−0750 38.15 μs
2006
2008
2010

We are looking for a correlated signal



We are looking for a correlated signal



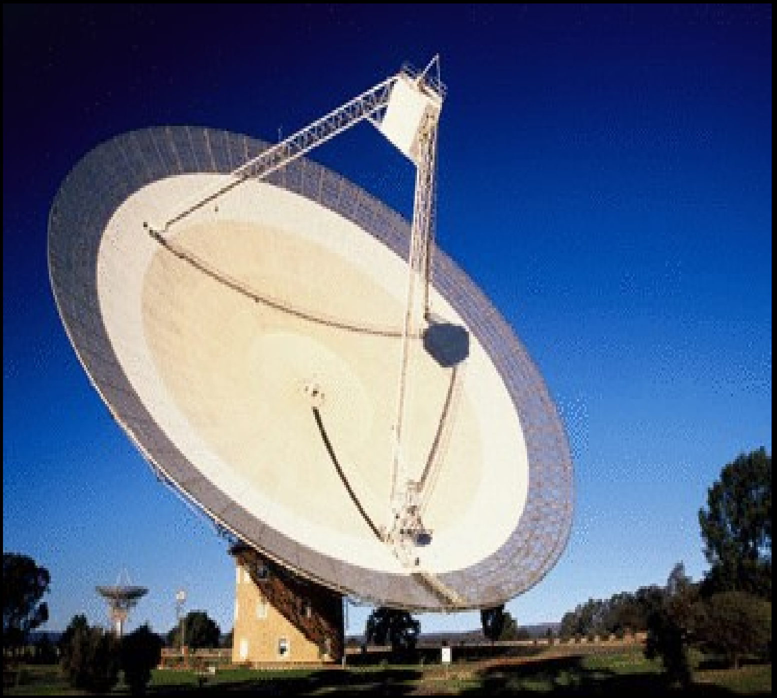
(Hellings & Downs 1983)

A worldwide observational effort

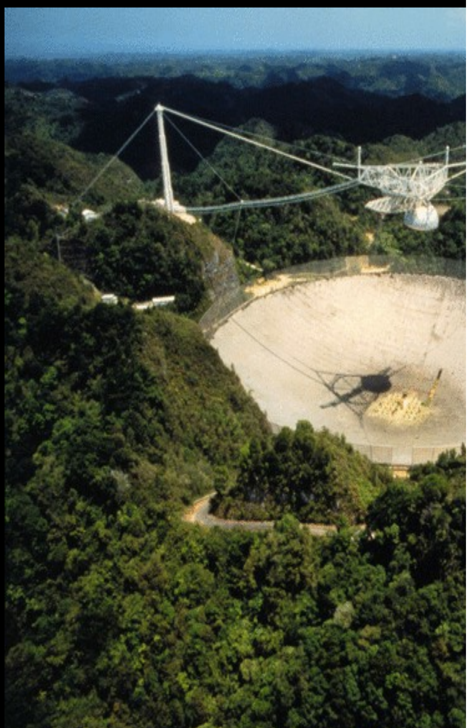
EPTA/LEAP **(Large European Array for Pulsars)**

NANOGrav **(North American nHz Observatory for Gravitational Waves)**

PPTA **(Parkes Pulsar Timing Array)**



A worldwide observational effort



INTERNATIONAL PULSAR TIMING ARRAY

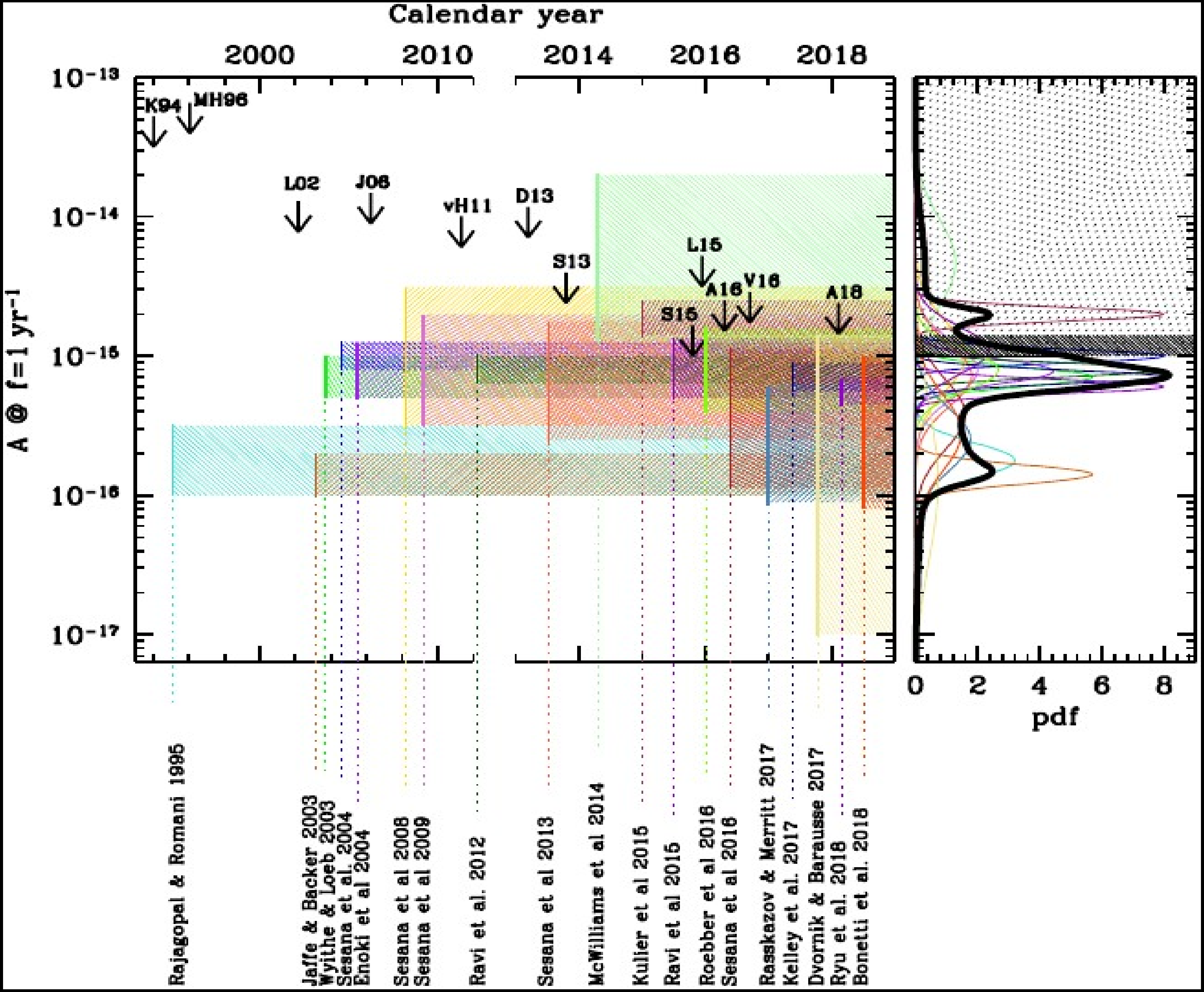
IPTA

nHz

aves)

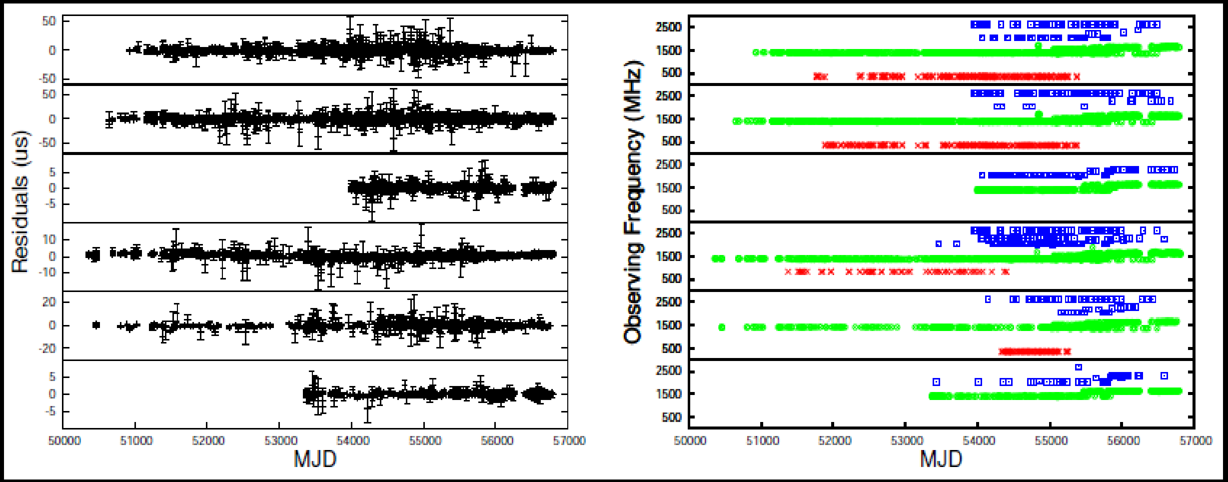
PPT

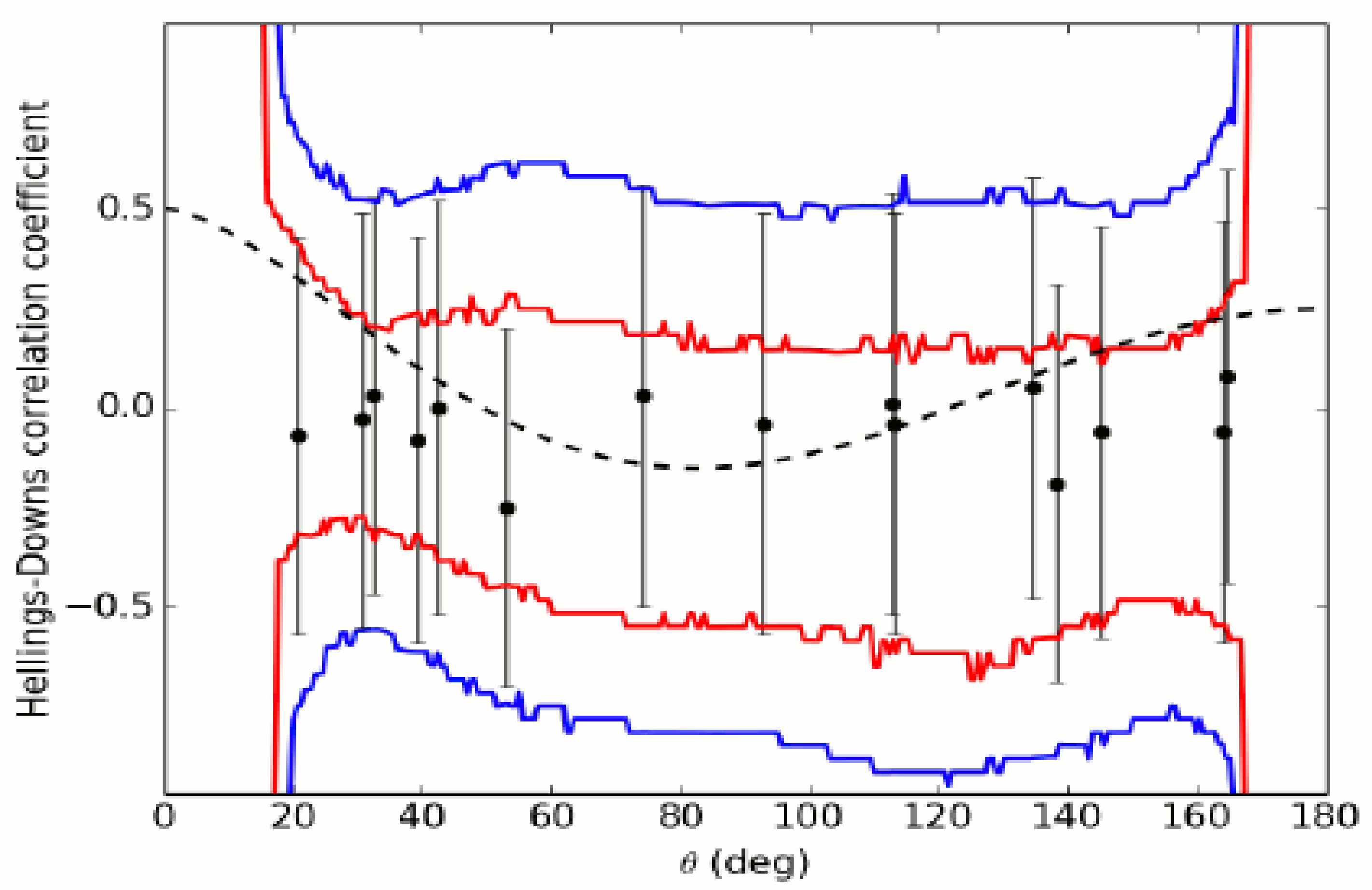
...in theory...



Calendar year
2000
2010
2014
2016
2018
A @ f=1 yr⁻¹
K94
MH96
L02
J06
vH11
D13
S13
L15
A16
V16
S15
A18
pdf
0
2
4
6
8
Rajagopal & Romani 1995
Jaffe & Backer 2003
Wyithe & Loeb 2003
Sesana et al. 2004
Enoki et al 2004
Sesana et al 2008
Sesana et al 2009
Ravi et al. 2012
Sesana et al 2013
McWilliams et al 2014
Kulier et al 2015
Ravi et al 2015
Roebber et al 2016
Sesana et al 2016
Rasskazov & Merritt 2017
Kelley et al. 2017
Dvornik & Barausse 2017
Ryu et al. 2018
Bonetti et al. 2018

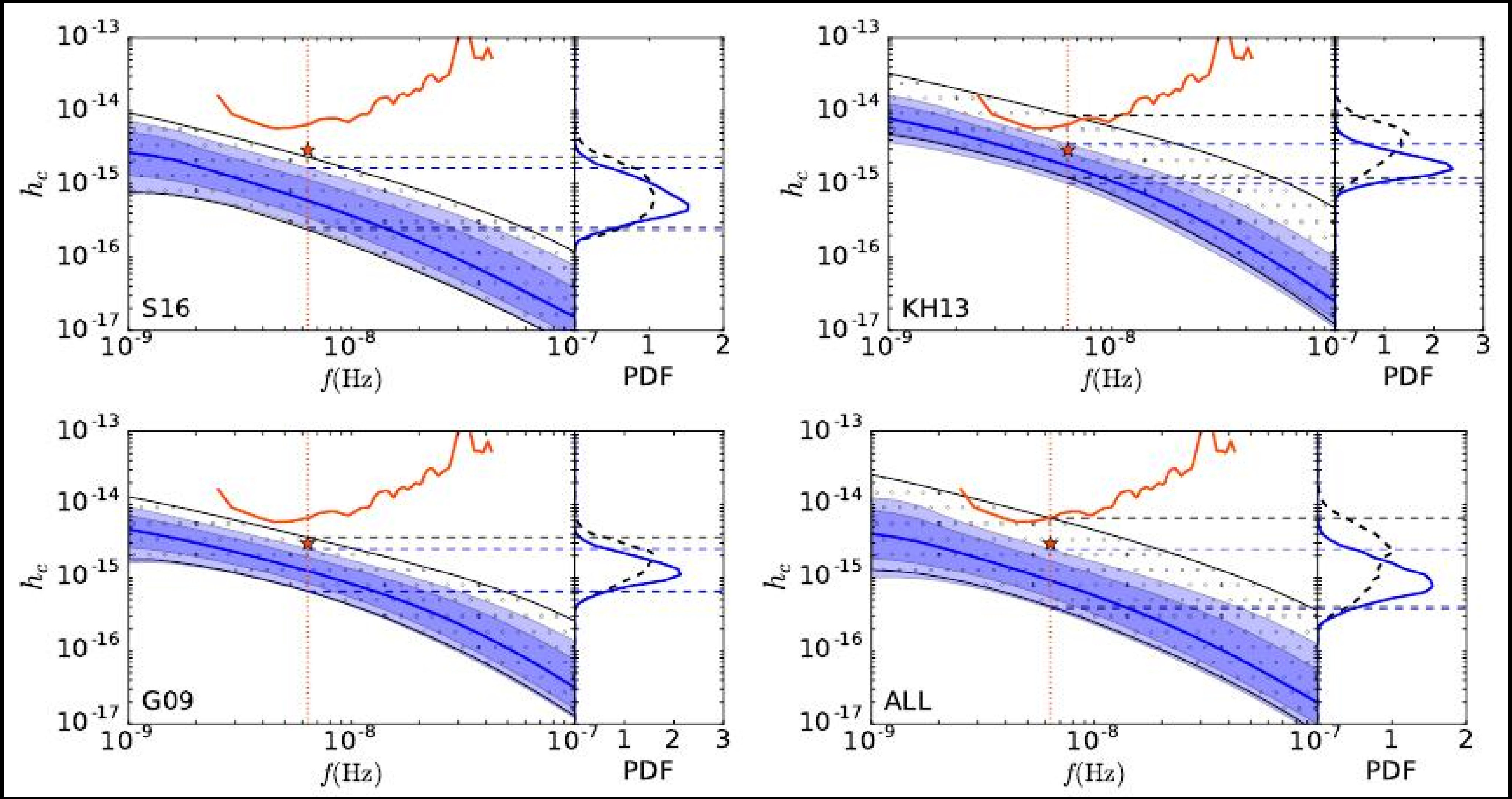
Pulsar correlations **(EPTA, Lentati et al. 2015)**





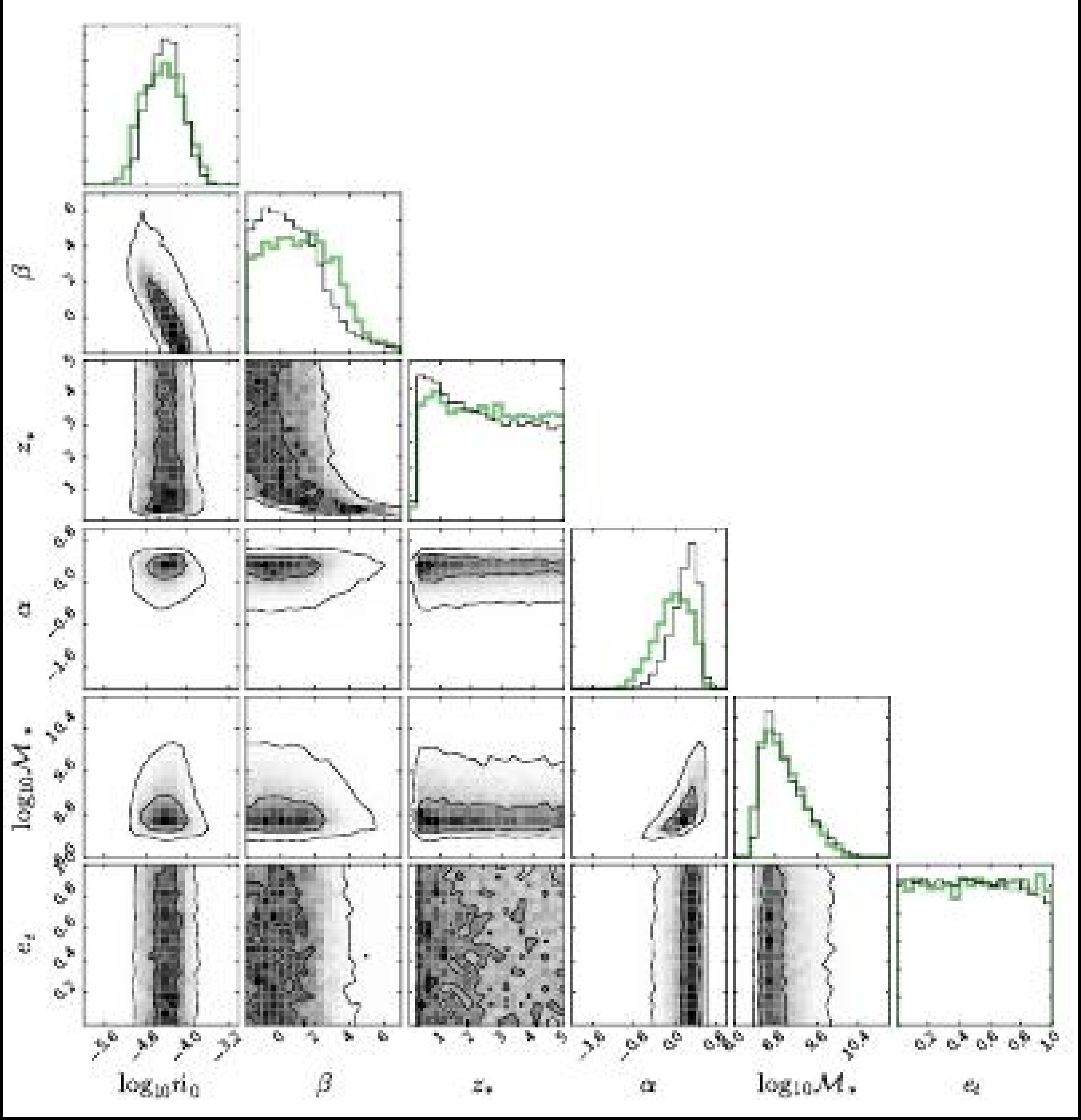
...not quite...

-Comprehensive set of semianalytic models anchored to observations of galaxy mass function and pair fractions **(AS 2013, 2016)**
-Include different BH mass-galaxy relations
-Include binary dynamics (coupling with the environment/eccentricity)



(Middleton et al., submitted)

...not quite...



SMBHB population described by an analytic model (Chen et al. 2016, 2017)

Can put constraints on the parameters

Prior and posterior distributions on the parameters look pretty similar

The limit is not very informative (yet)

The future

MeerKAT, South Africa (2017)

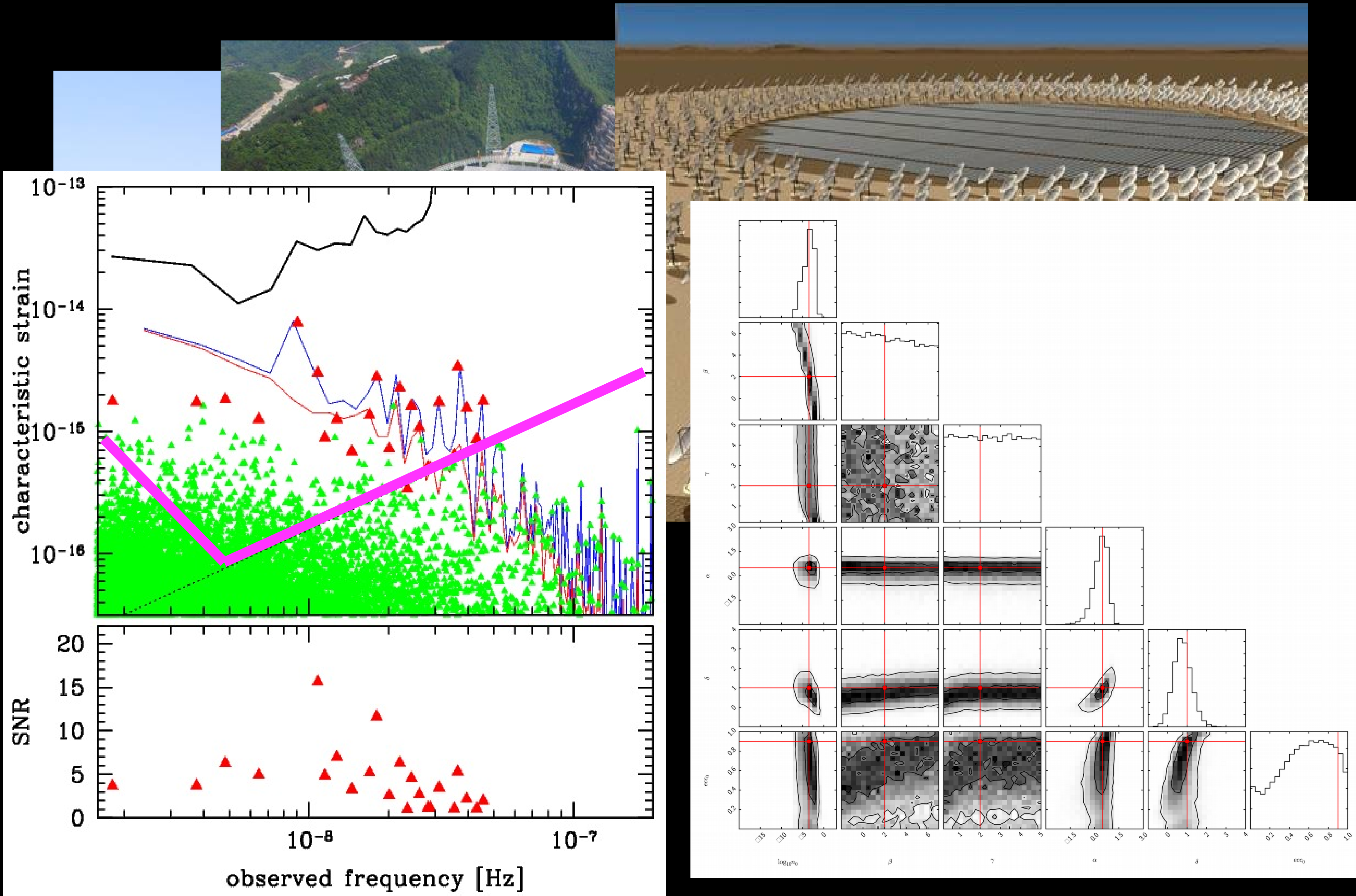
The future

FAST, China (2017)

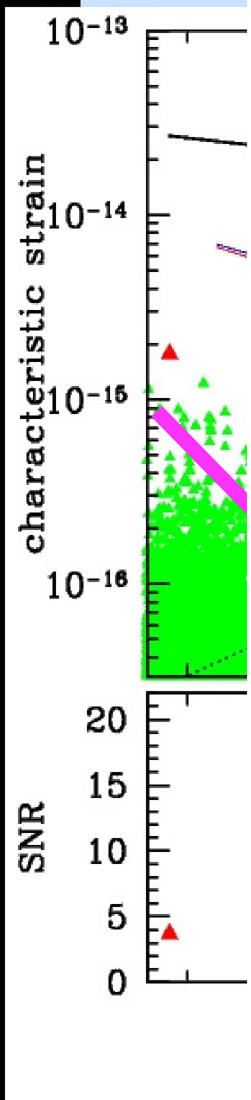
The future

Square Kilometre Array (SKA, 2021+)

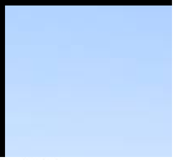
The future

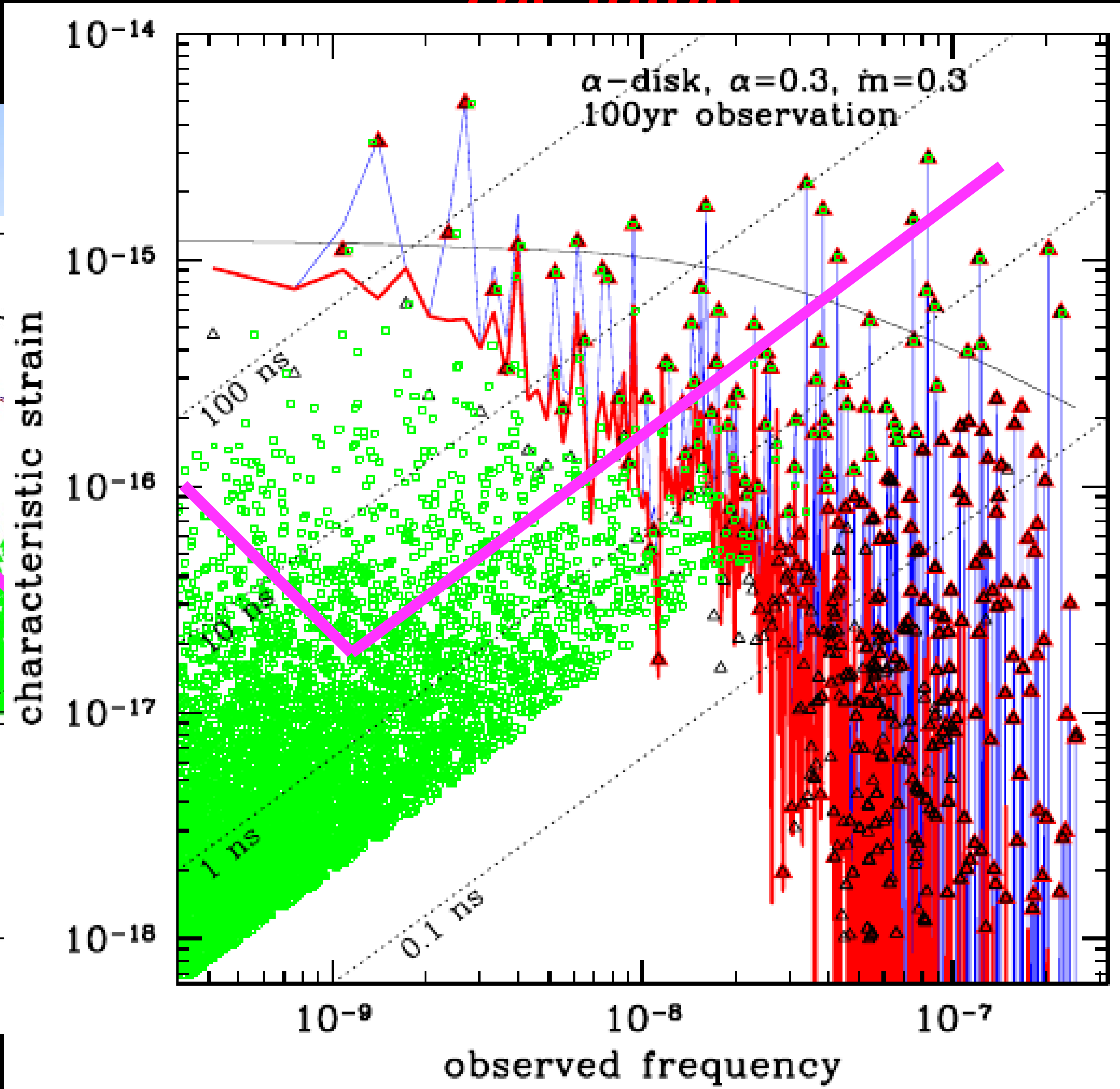

characteristic strain
SNR
observed frequency [Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-7}
20
15
10
5
0

The future

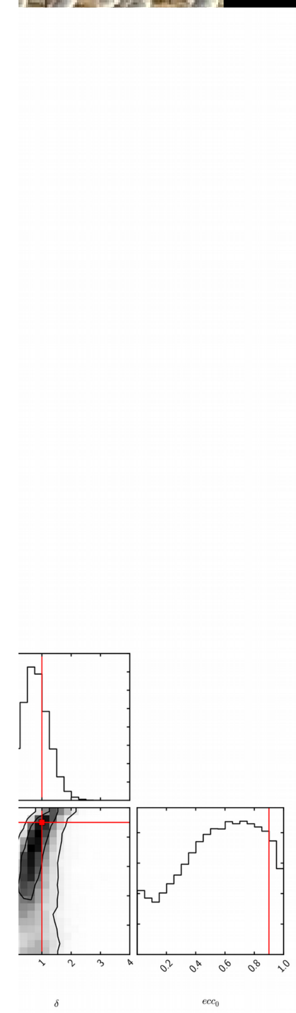


characteristic strain
SNR



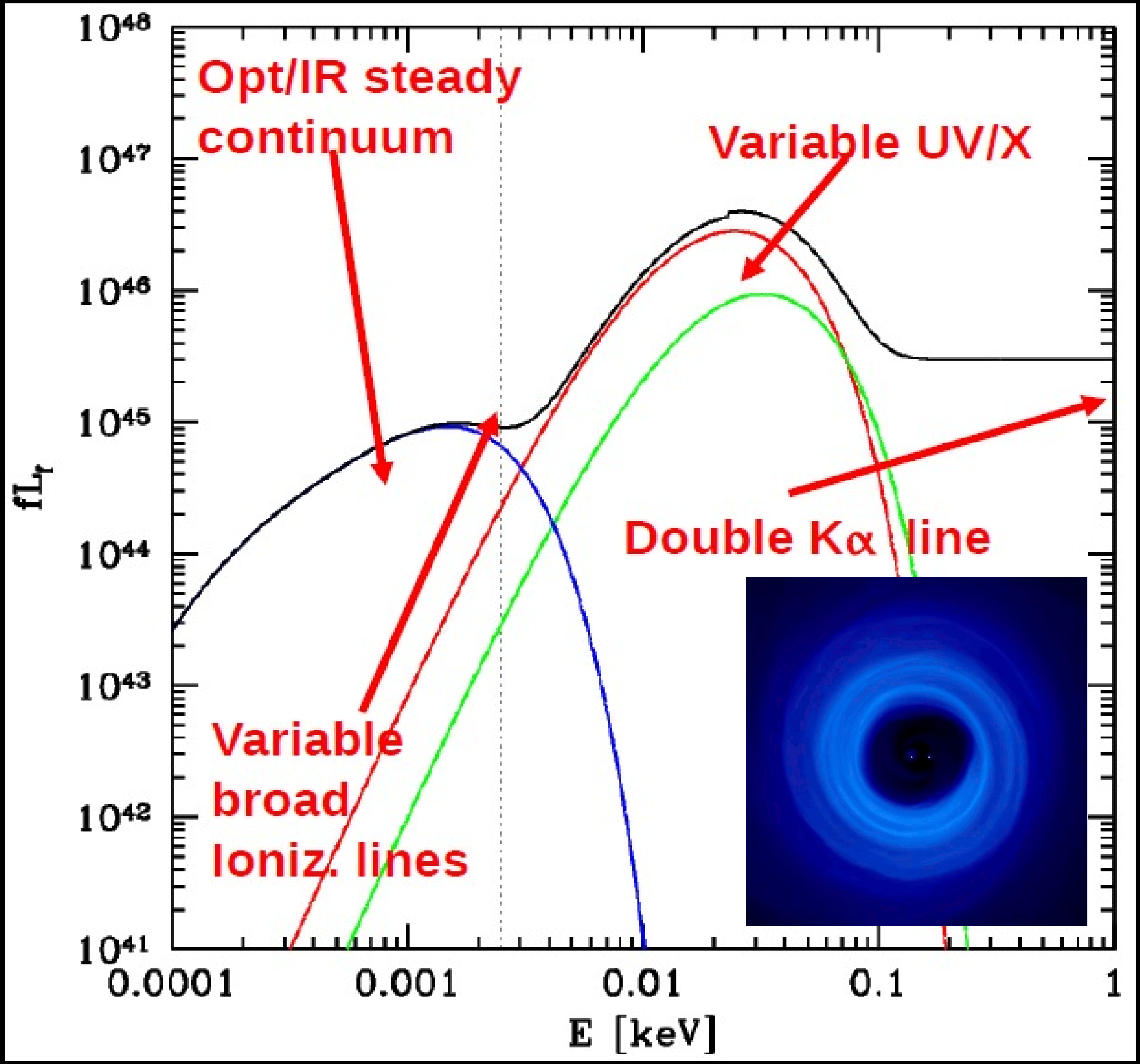


α−disk, α=0.3, ṁ=0.3
100yr observation
characteristic strain
observed frequency
100 ns
10 ns
1 ns
0.1 ns



Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013)

A variety of possibilities:

Optical/IR dominated by the outer disk: Steady/modulated?

UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

Variable broad emission line in response to the varying ionizing continuum?

Double fluorescence lines?

Doggybag

LISA will probe a number of GW sources at low frequency.

- -galactic binaries
- -extreme mass ratio inspirals
- -LIGO sources
- -SMBHB cosmic history

LISA sources will be invaluable tools for astrophysics, cosmology and fundamental physics

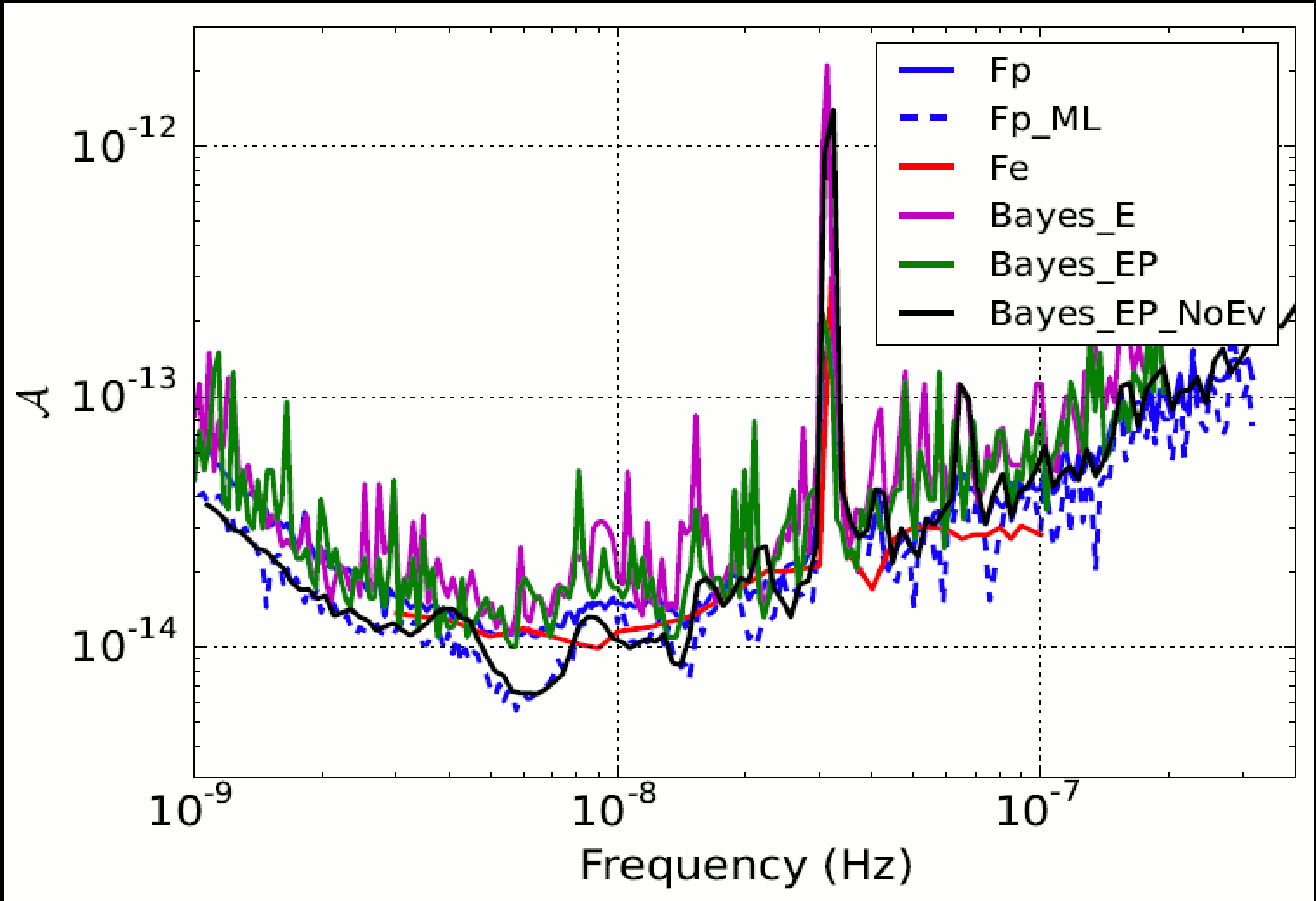
PTAs can provide unique information about the dynamics and merger history of MBHBs (e.g. merger rate density, environmental coupling, eccentricity, etc.)

Current PTA limits are getting extremely interesting, showing some tension with vanilla models for the cosmic SMBHB population, but nothing can be ruled out yet

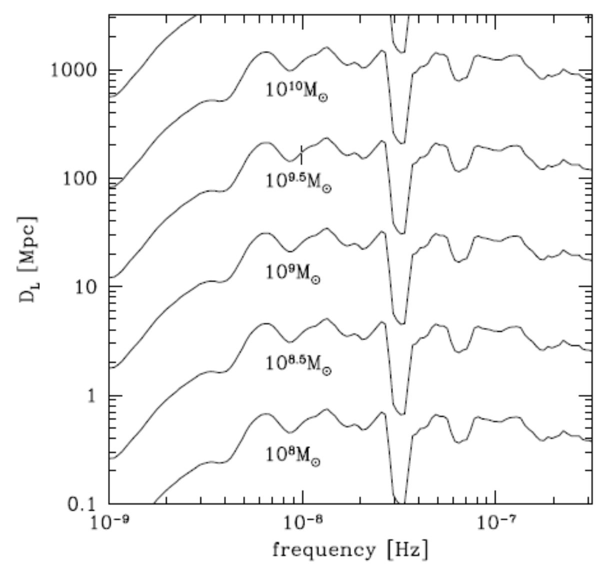
Limits on continuous GWs

(EPTA, Babak et al. 2015)

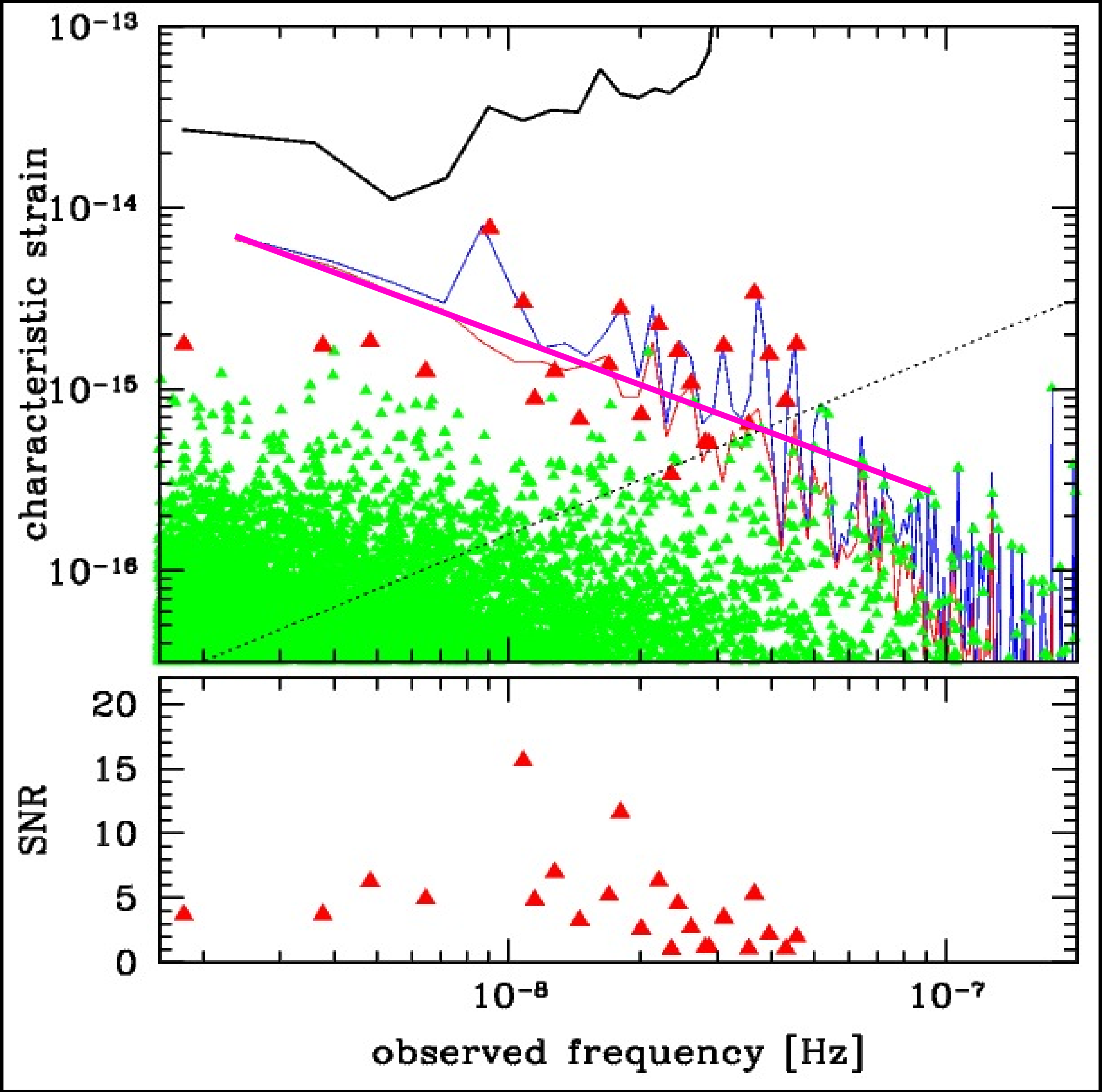
Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes
Bayes_E	Fixed ML	41	7	E	Full
Bayes_EP	Fixed ML	6	$7 + 2 \times 6$	E+P Ev	Full
Bayes_EP_NoEv	Fixed ML	41	7	E+P NoEv	Pulsar phase marginalization
Bayes_EP_NoEv_noise	Searched over	6	$7 + 5 \times 6$	E+P NoEv	Pulsar phase marginalization



Data are not yet very constraining, we can rule out very massive systems to ~200Mpc, well beyond Coma



Resolvable sources (AS et al 2009)



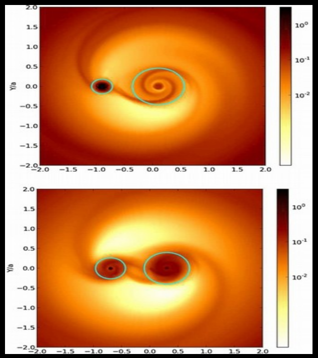
*It is not smooth

*It is not Gaussian

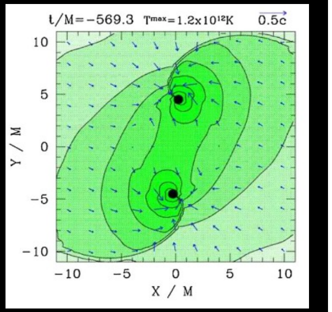
*Single sources might pop-up

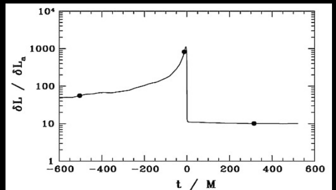
*The distribution of the brightest sources might well be anisotropic

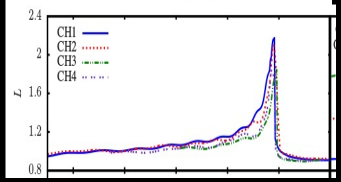
Associated electromagnetic signatures LISA



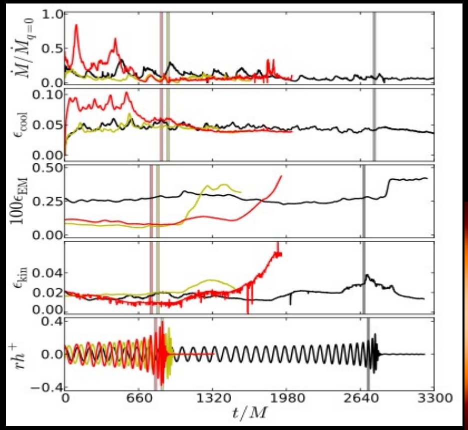
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

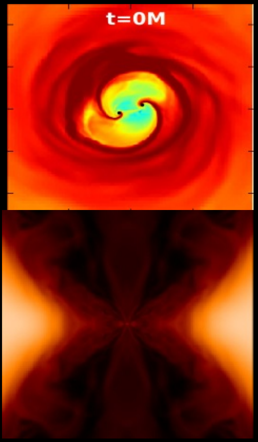






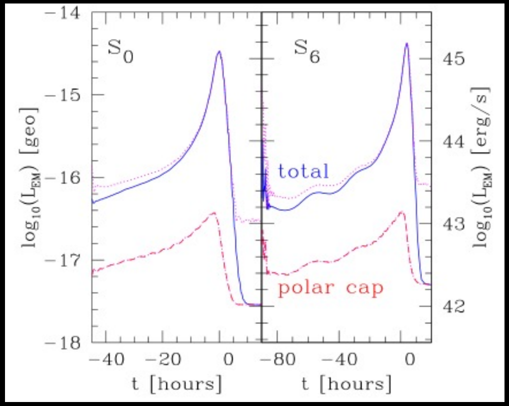
Simulations in hot gaseous clouds. Significan flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)

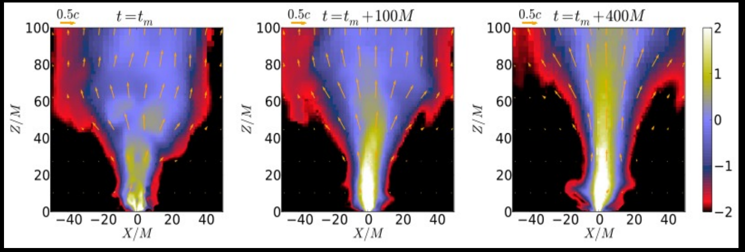




Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

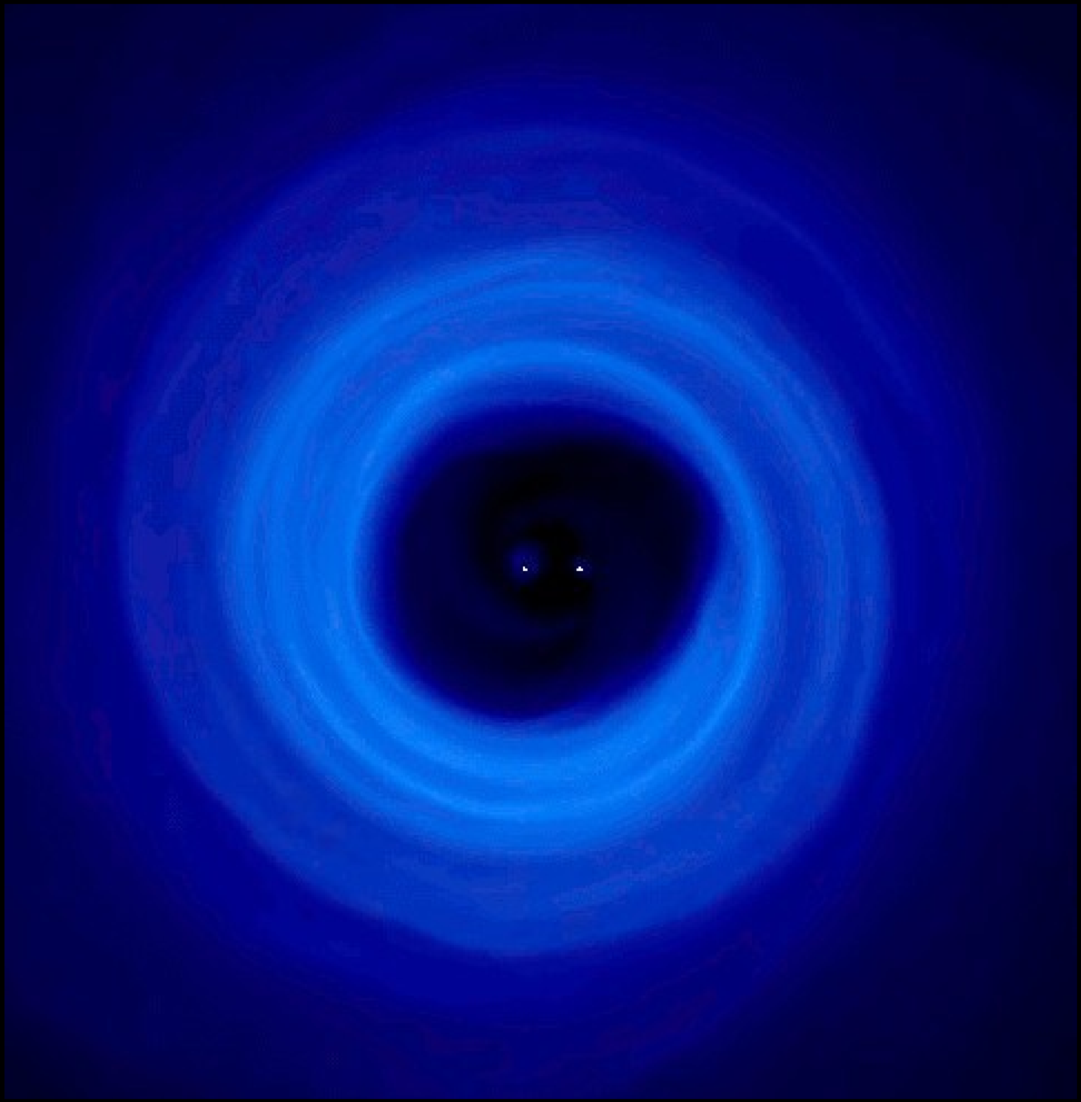
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)





Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012,
Tanaka et al. 2012, Burke-Spolaor 2013)

Associated electromagnetic signatures PTA

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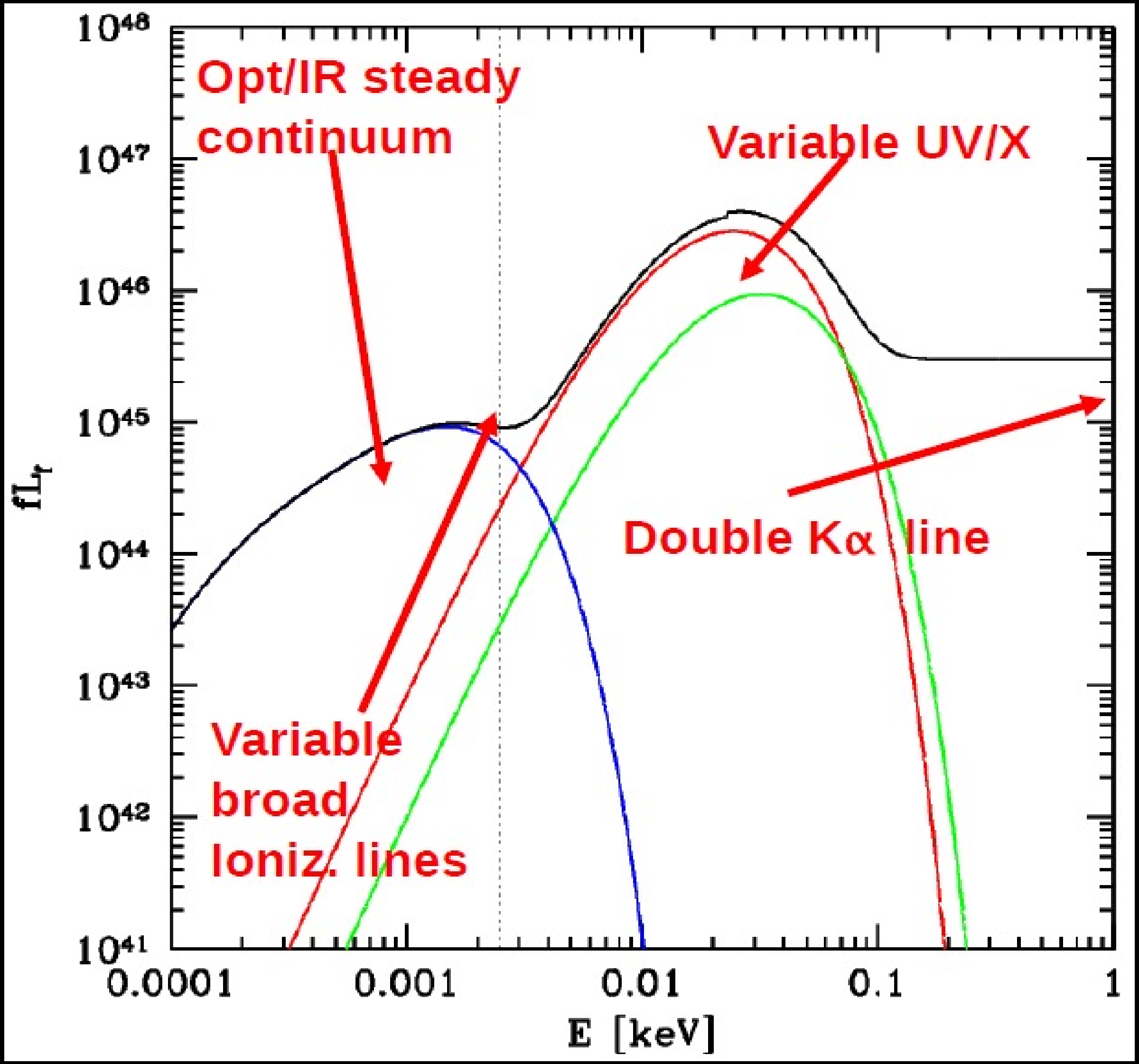

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A variety of possibilities:

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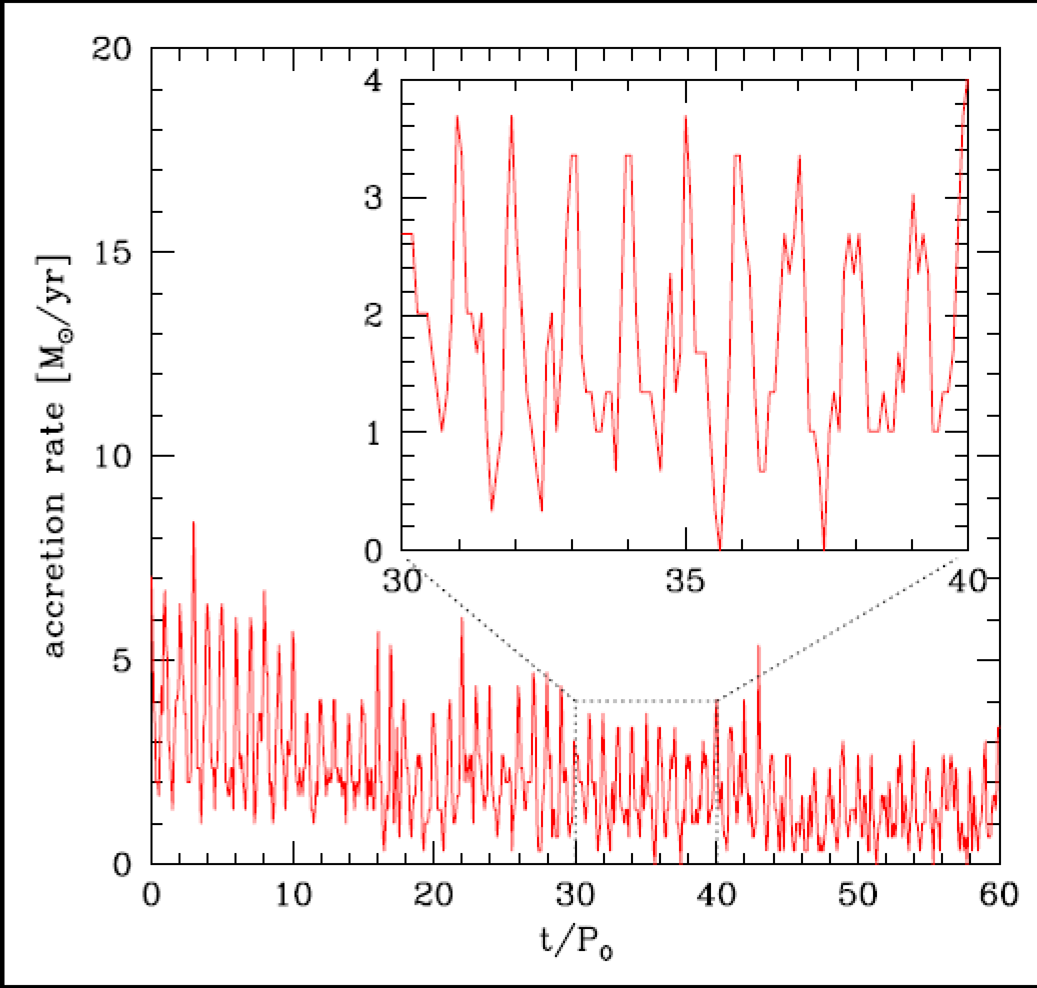
X rays variable from periodic shocks or intermittent corona?

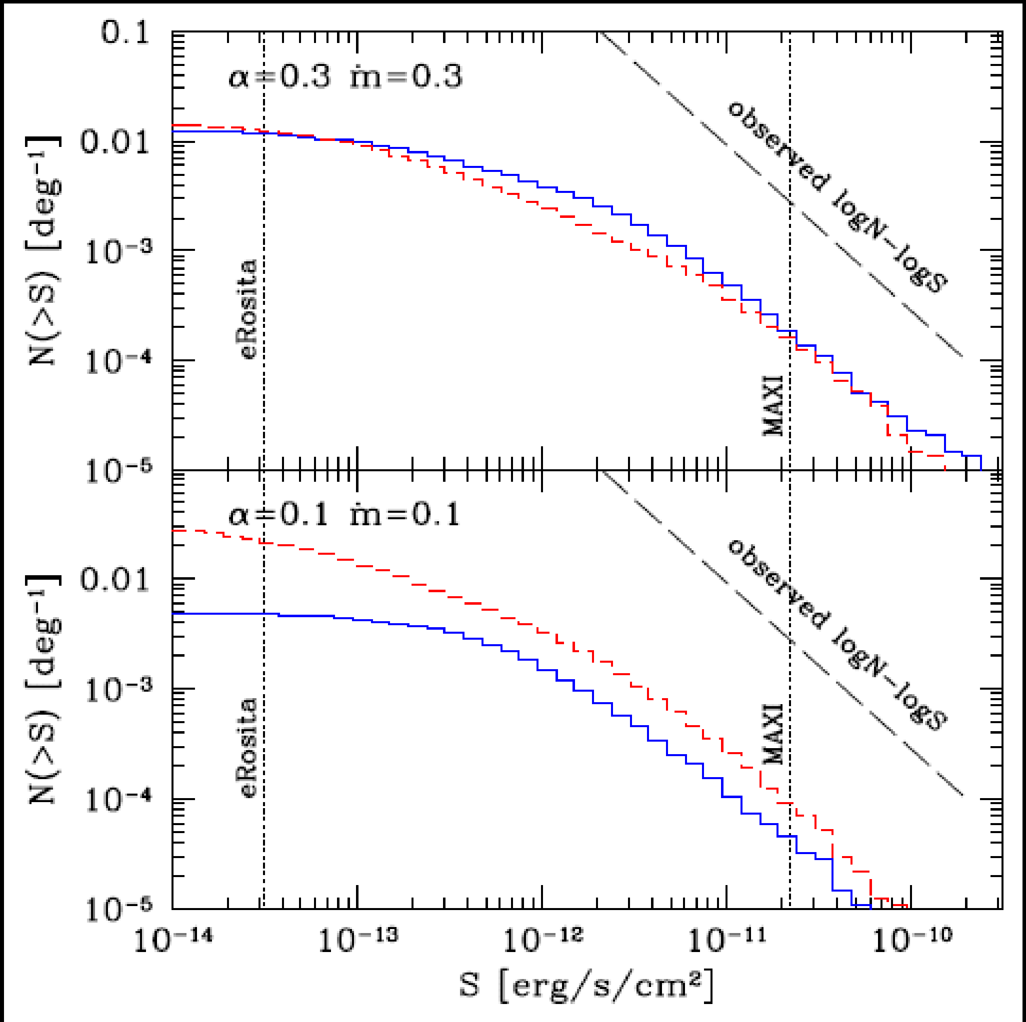
Variable broad emission line in response to the varying ionizing continuum?

Double fluorescence lines?

Example: variability

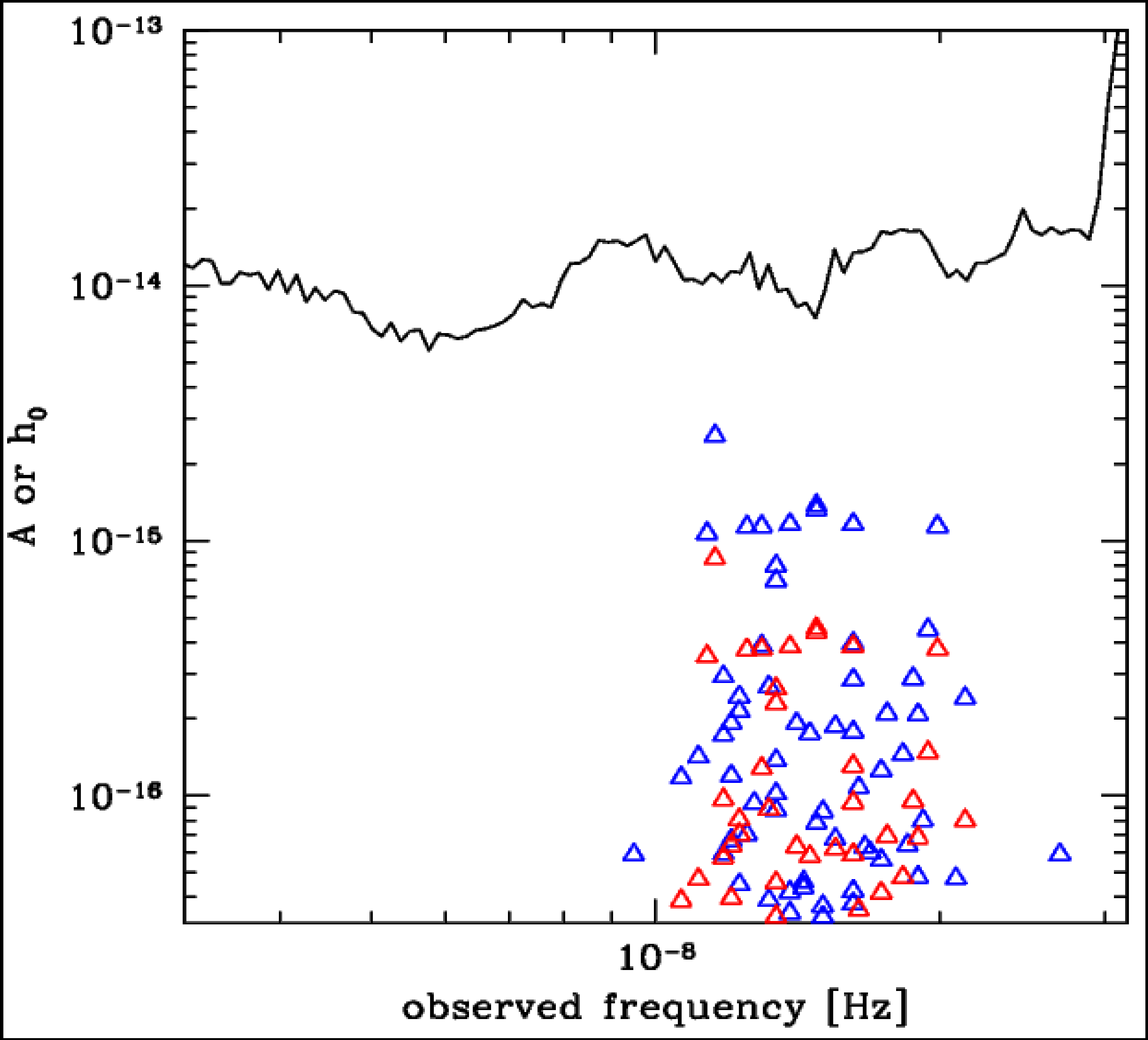


Applying this model to a tipical MBH binary population we get ~100 sources at the eRosita flux limit

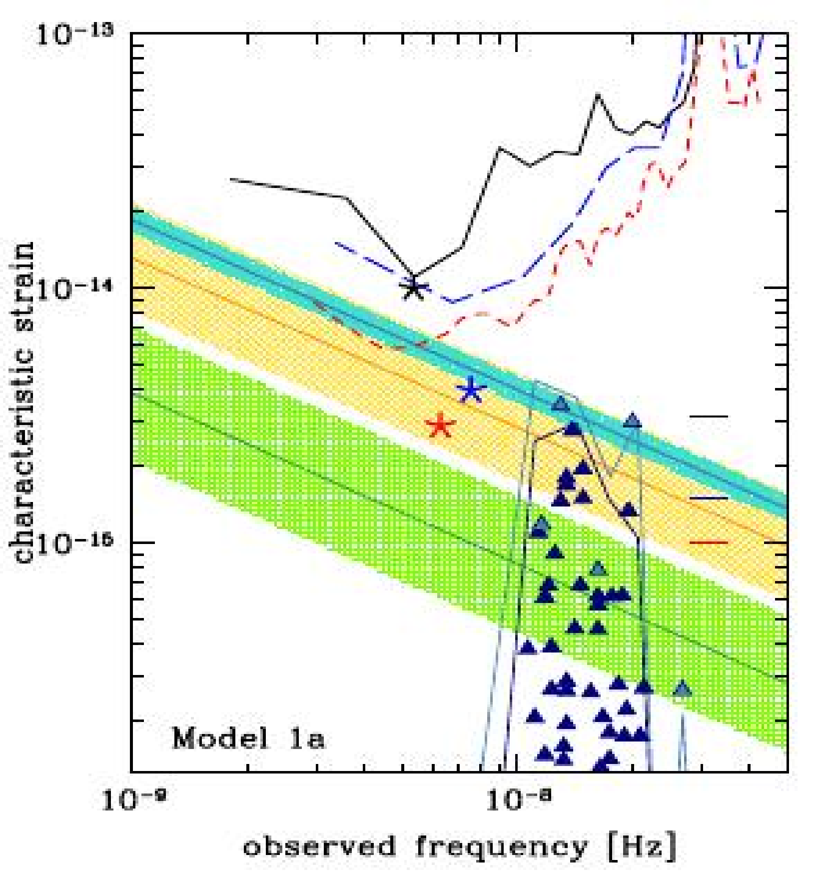


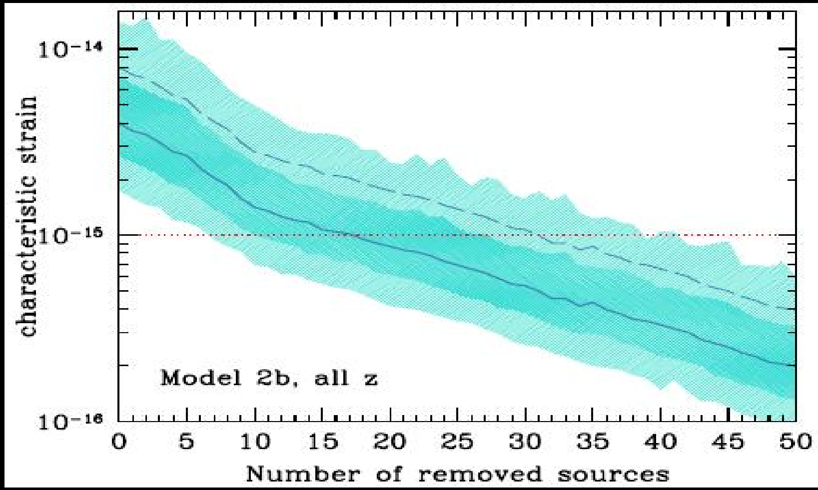
Streams feed the inner minidisk extremely intermittent mass inflow.

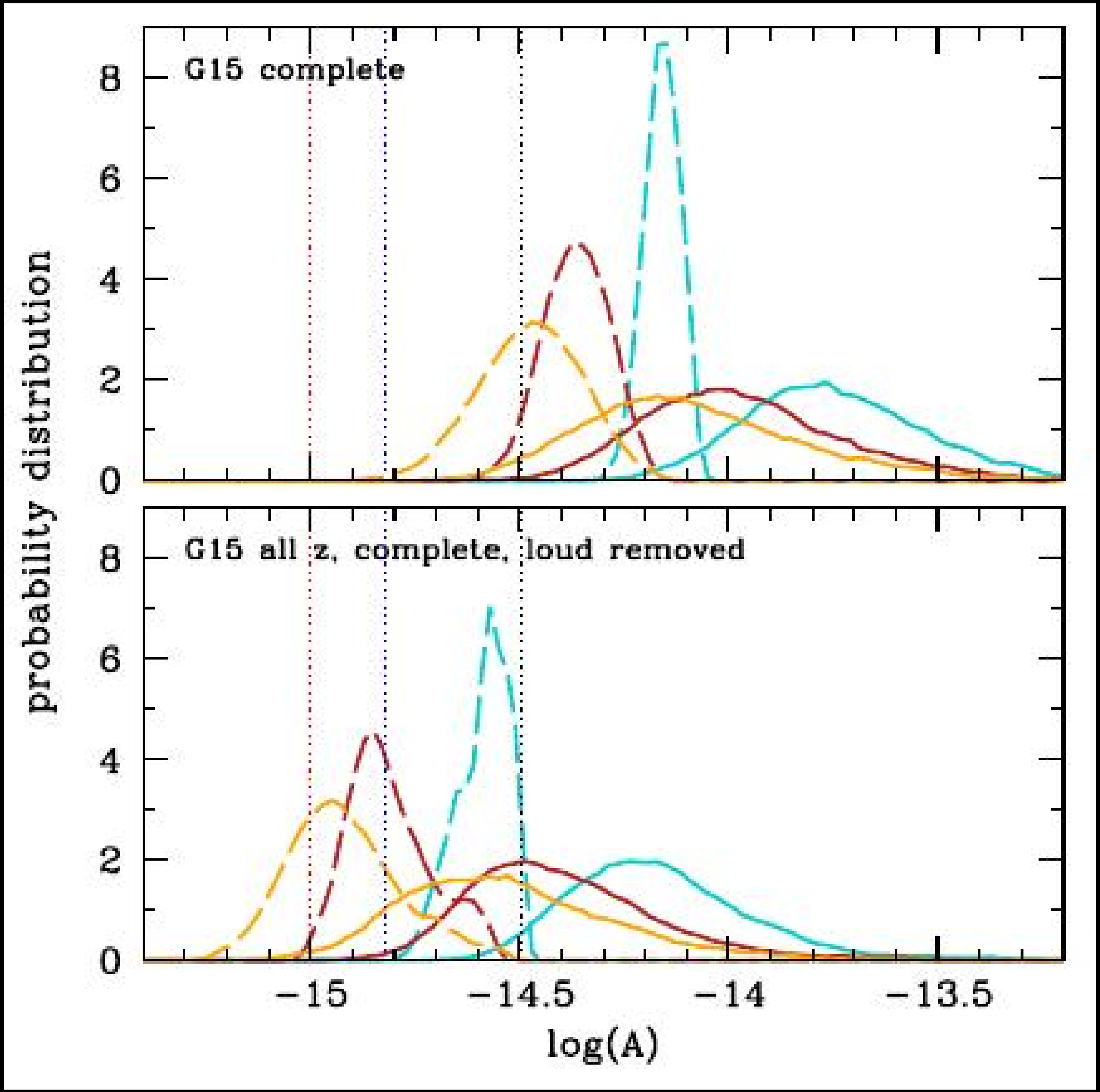
Strain amplitude of individual sources



Extrapolated GWB

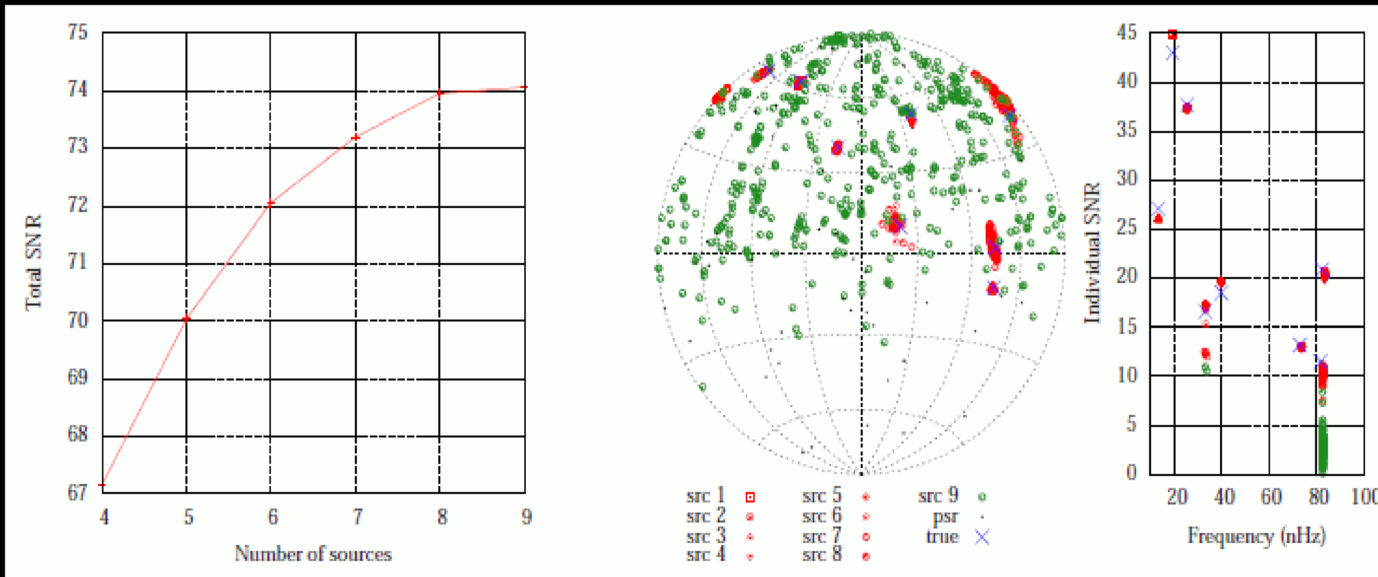






GWB 3-to-15 times larger than PTA limits
Most of the candidates cannot be SMBHBs (AS et al 2017)

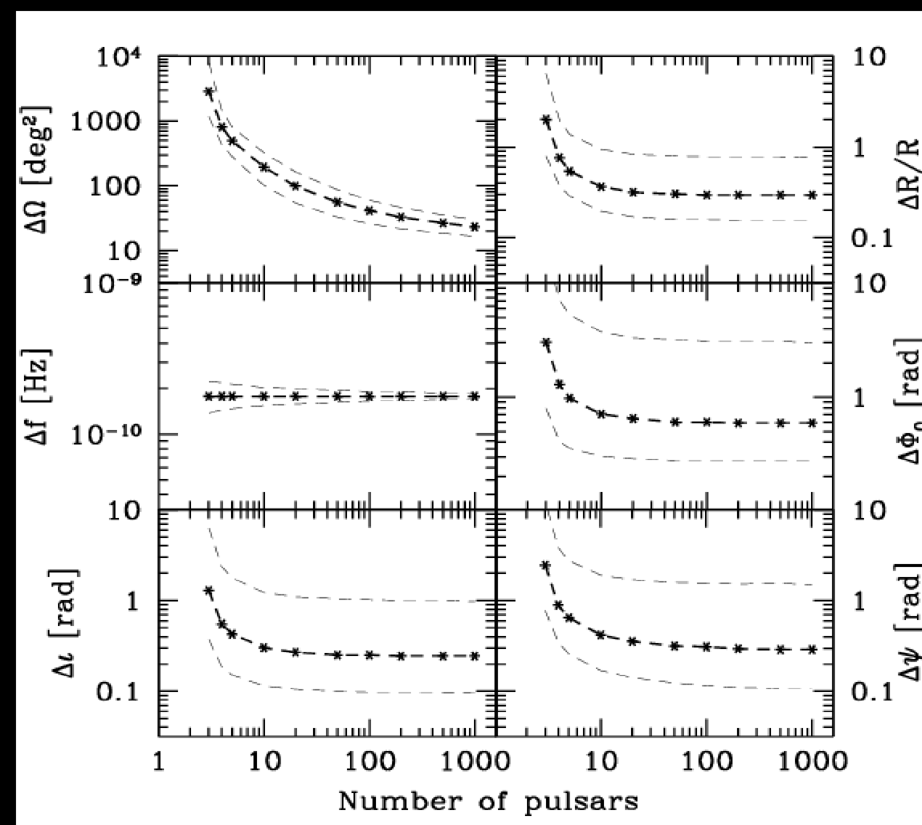
Identification and sky localization



We can recover multiple sources in PTA data
(Babak & AS 2012 Petiteau Babak AS Araujo 2013)

Sources can be localized in the sky
(AS & Vecchio 2010, Ellis et al. 2012).

For example, the largest SNR source shown in the previous slide can be located by SKA in the sky with a sky accuracy <10deg^2

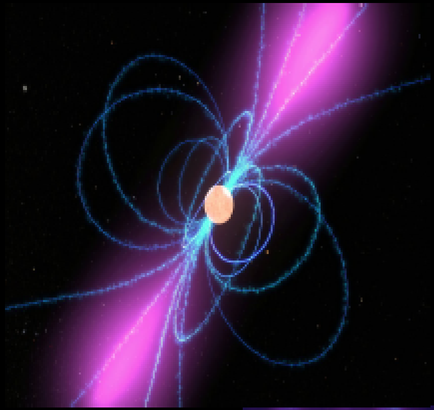


Gravitational wave sources

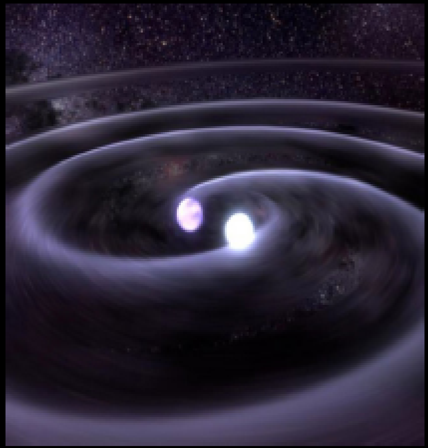
Massive compact systems with a time varying mass quadrupole momentum:

1-collapses and explosions (supernovae, GRBs)

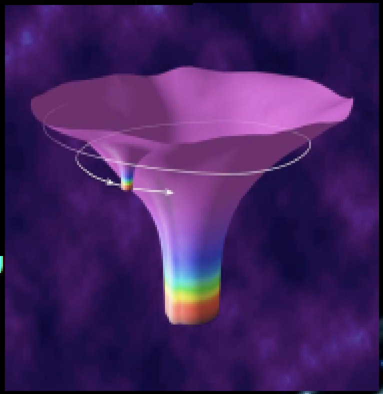
2-rotating asymmetric objects
(pulsars, MSPs)



3-binary systems:

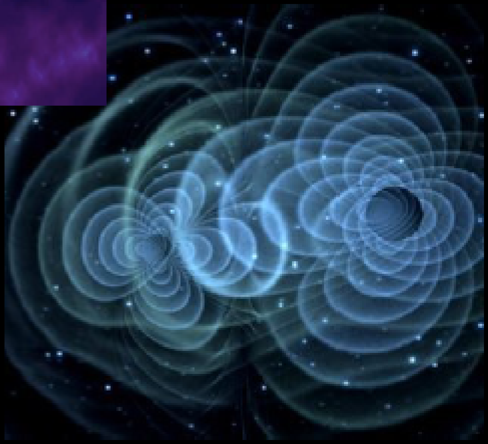


a-stellar compact remnants
(WD-WD, NS-NS, NS-BH, BH-BH)



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

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



MBHB population models

Semianalytic models for galaxy and MBH formation and evolution (Barausse).

The explored scenarios cover a wide range of merger histories:

- -Heavy seeds no time delays
- -Heavy seeds time delays
- -PopIII seeds time delays