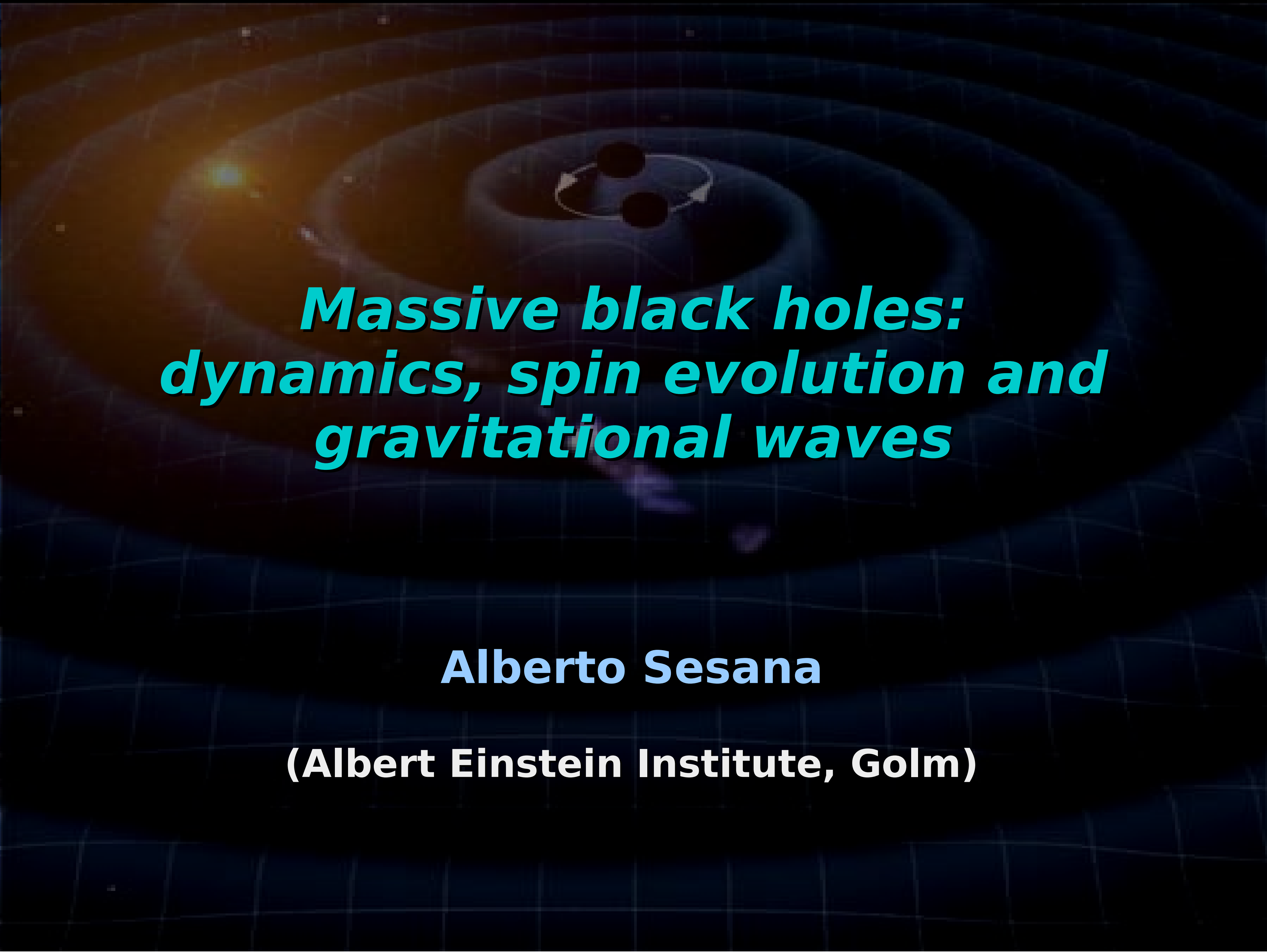


Massive black holes: dynamics, spin evolution and gravitational waves

Alberto Sesana

(Albert Einstein Institute, Golm)

OUTLINE

> Brief introduction to structure formation

> Semianalytic hierarchical model for galaxy and massive black hole (MBH) evolution

> Evolving the MBH spins

> Probing MBH binaries (MBHBs) with gravitational wave observations
  *eLISA
  *Pulsar Timing Arrays

Observational facts

1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive MBH has been found in the center.

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

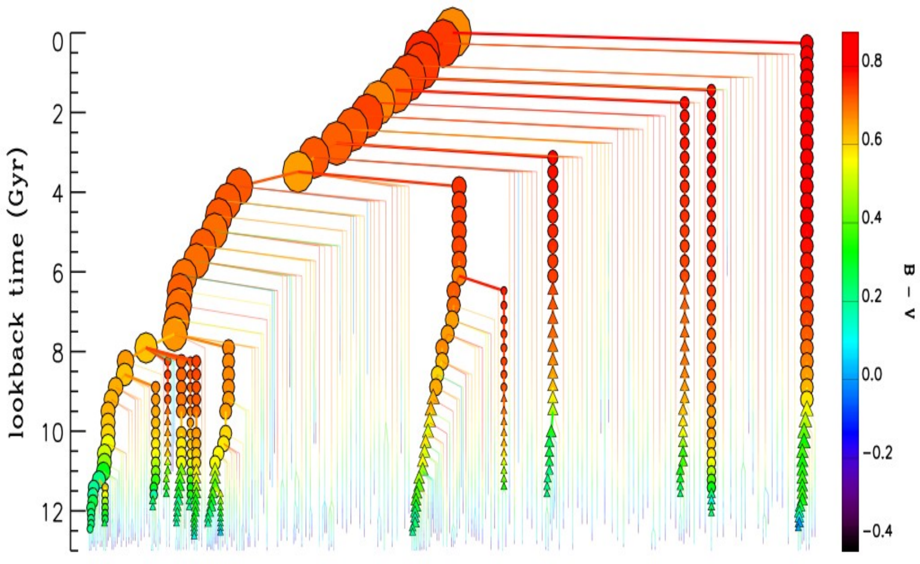
3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

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

Outstanding question in contemporary astrophysics:

to understand the MBH formation and evolution

Structure formation in a nutshell



From De Lucia et al 2006

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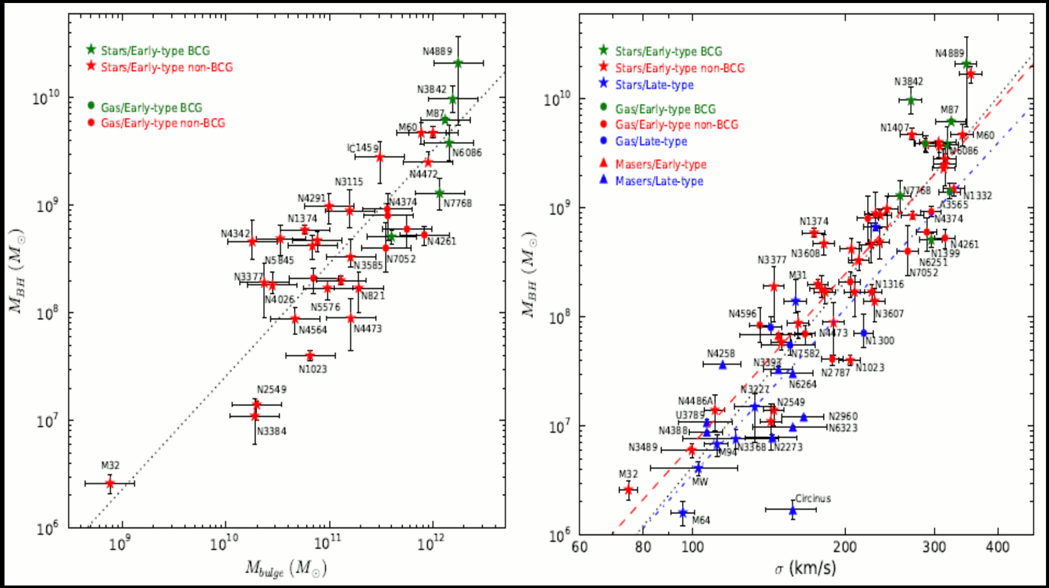

Ferrarese & Merritt 2000, Gebhardt et al. 2000

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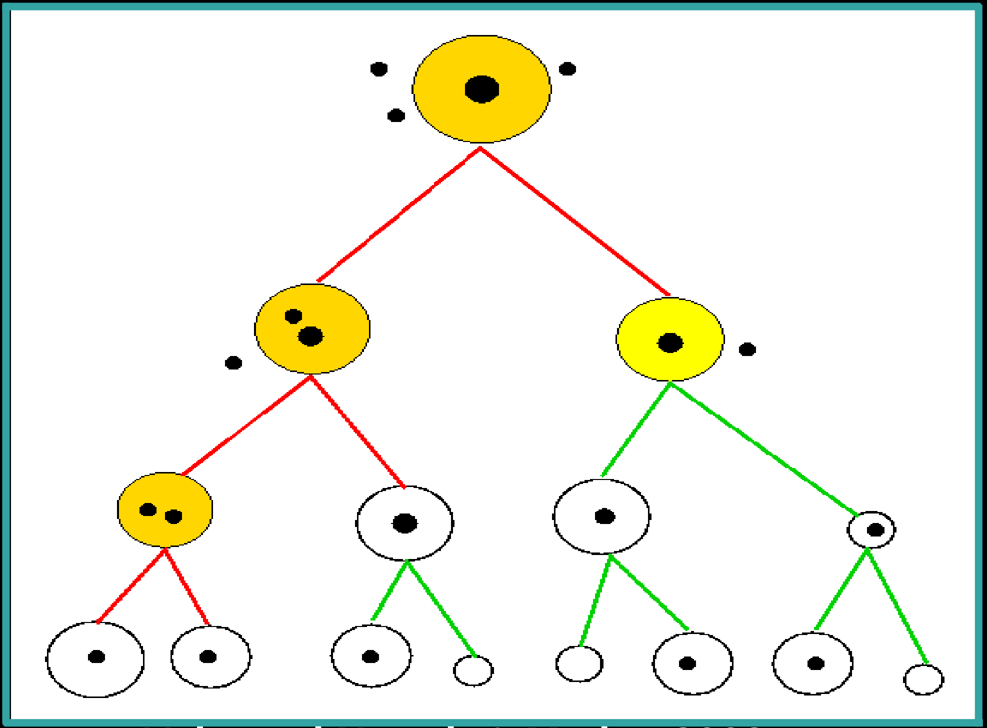
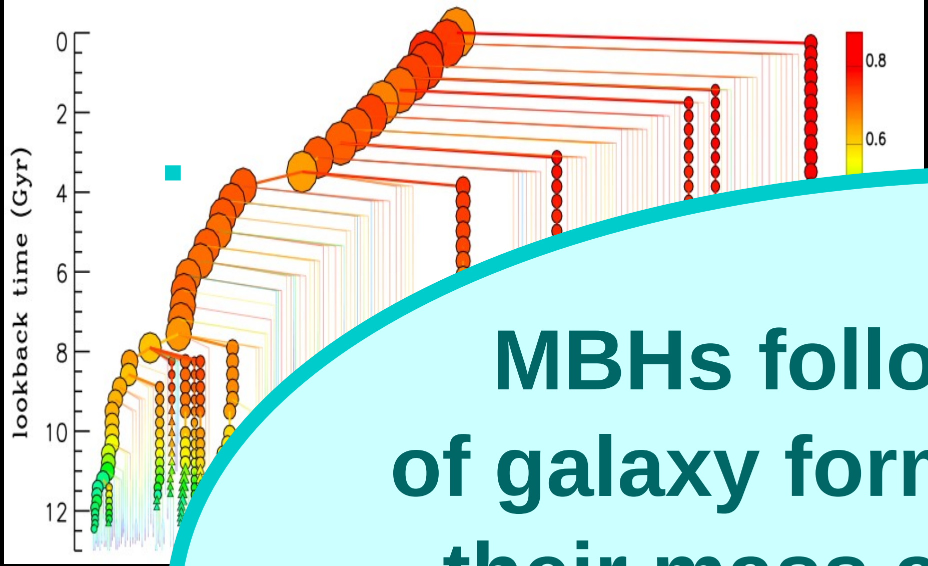


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



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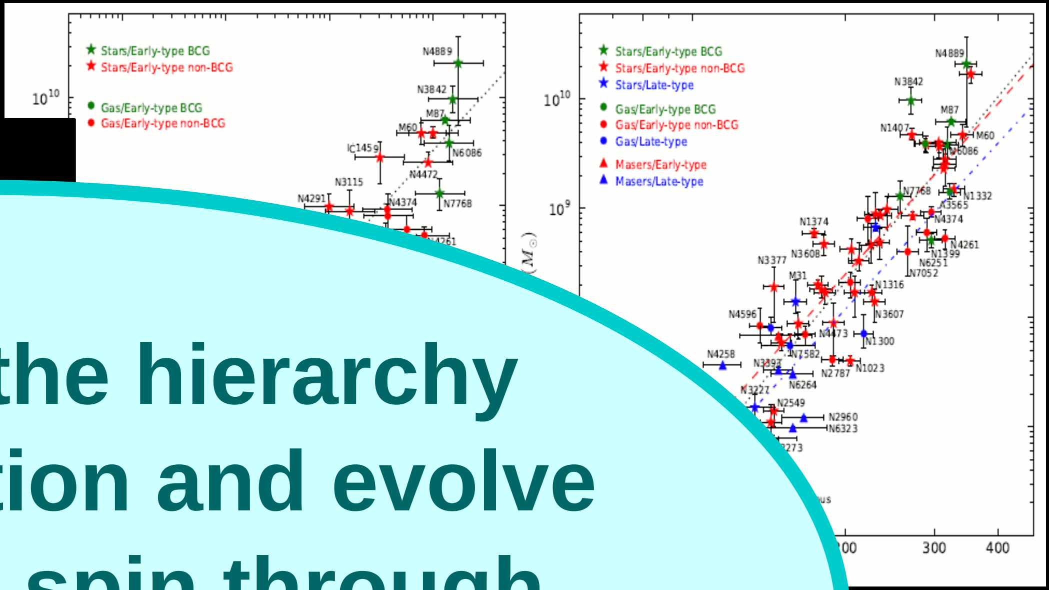
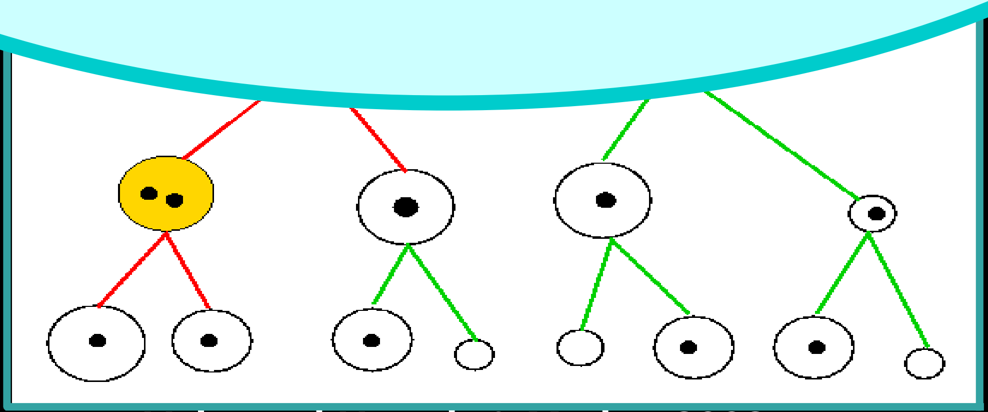


l. 2000

MBHs follow the hierarchy
of galaxy formation and evolve
their mass and spin through
a sequence of gas accretion episodes
and mergers with other MBHs



Volonteri Haardt & Madau 2003

Too fast for chaotic, to slow for coherent: the missing link between accretion, massive black hole spins and galaxy kinematics

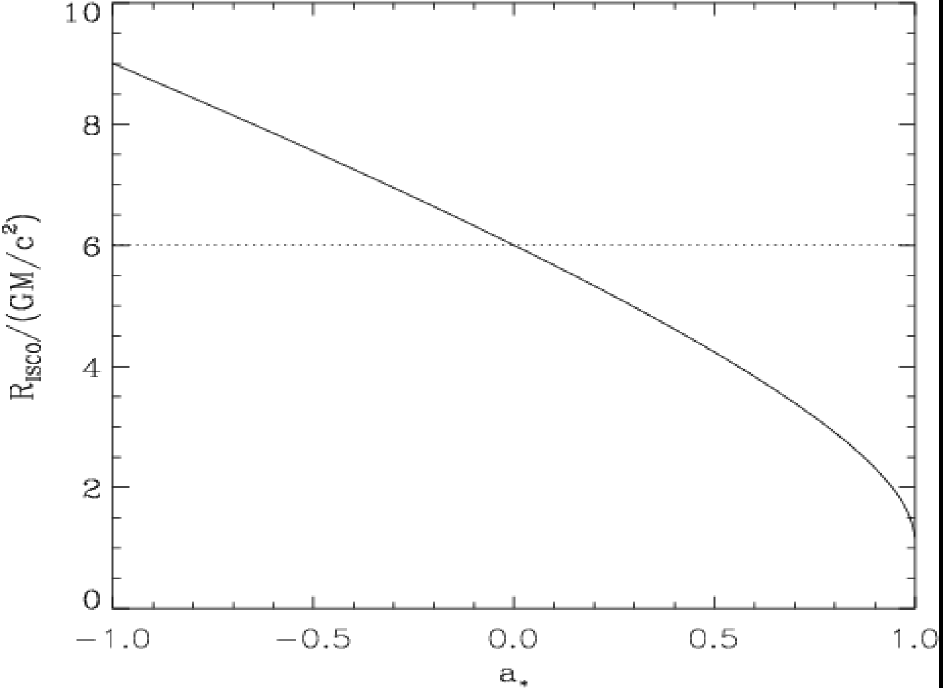
(AS et al. 2014, in collaboration with
Enrico Barausse, Massimo Dotti and Elena Rossi)

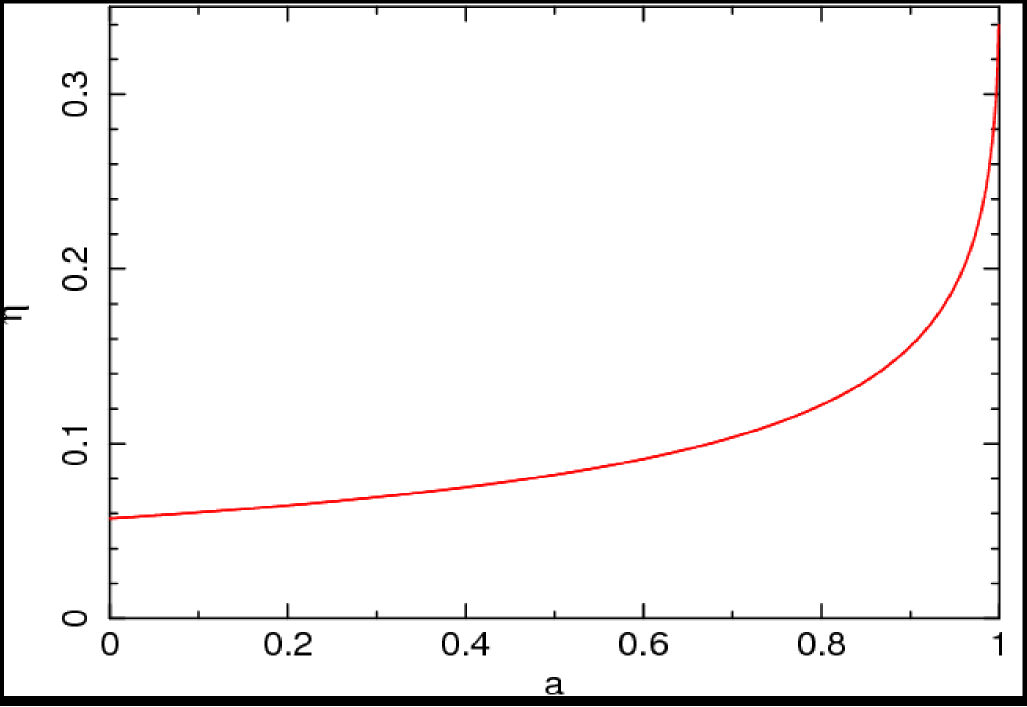
Why do we care about spins?

Astrophysical BHs are described by *two parameters: mass (M) and spin (a)*

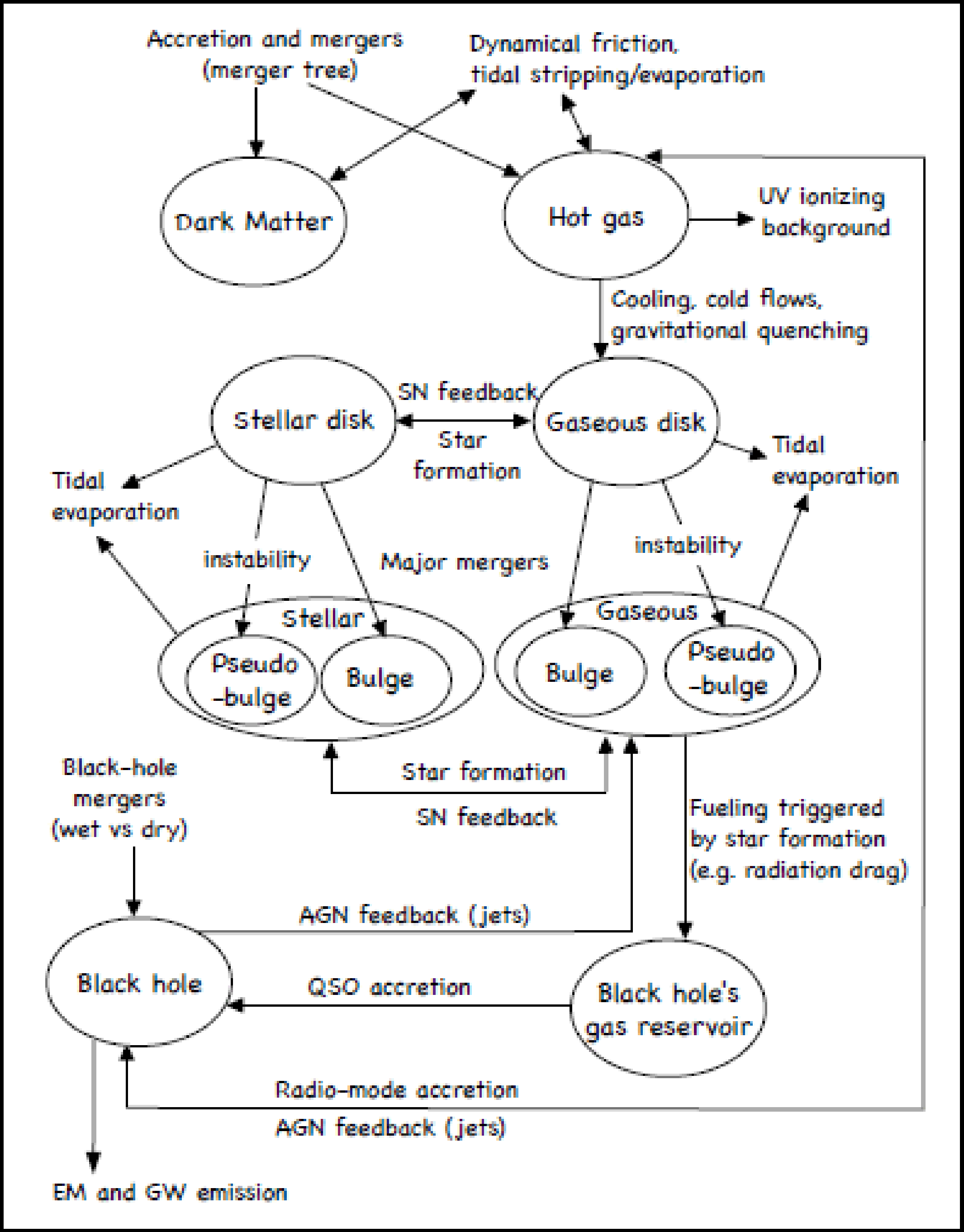
MBH spin is poorly known, but are very important for a number of reasons:

-regulate the mass-radiation conversion during accretion
-are probably responsible for launching relativistic jets (feedback)
-strong impact on gravitational wave emission and recolis
-may provide stringent tests of GR and the BH solution





Galaxy formation and evolution model



We adapt the model of
Barausse (2012)

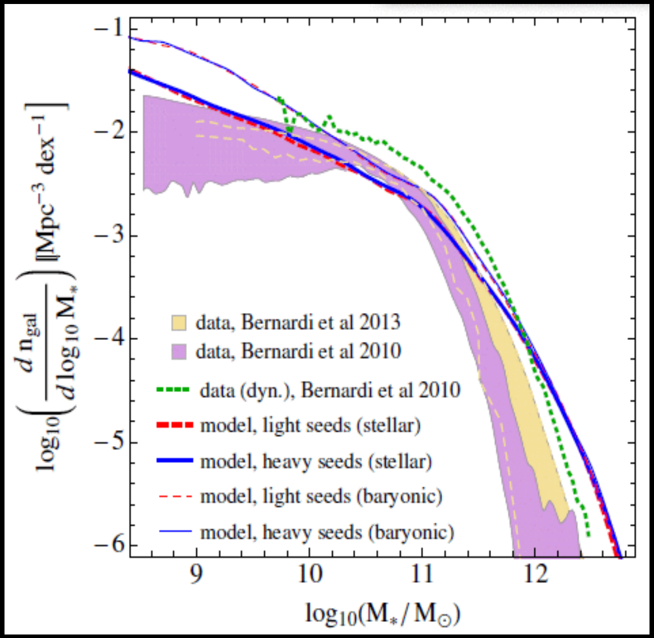
Semianalytic galaxy formation model including:

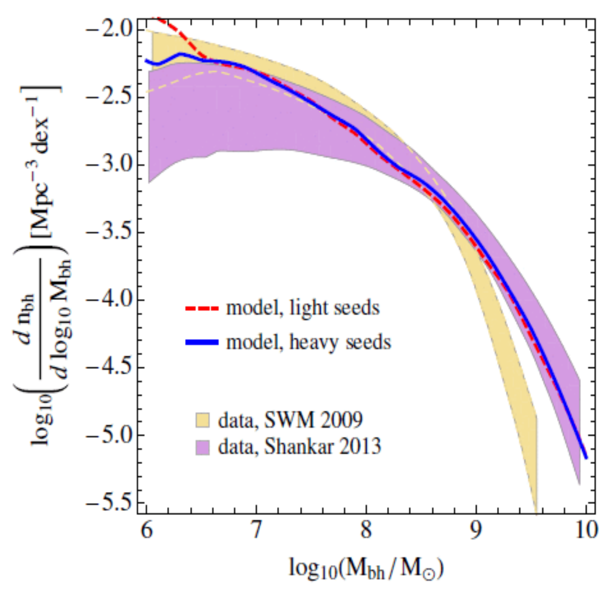
- **-hot-cold gas phase**
- **-star formation**
- **-disk instabilities**
- **-galaxy and MBH mergers+recoils**
- **-MBH feeding+feedback**

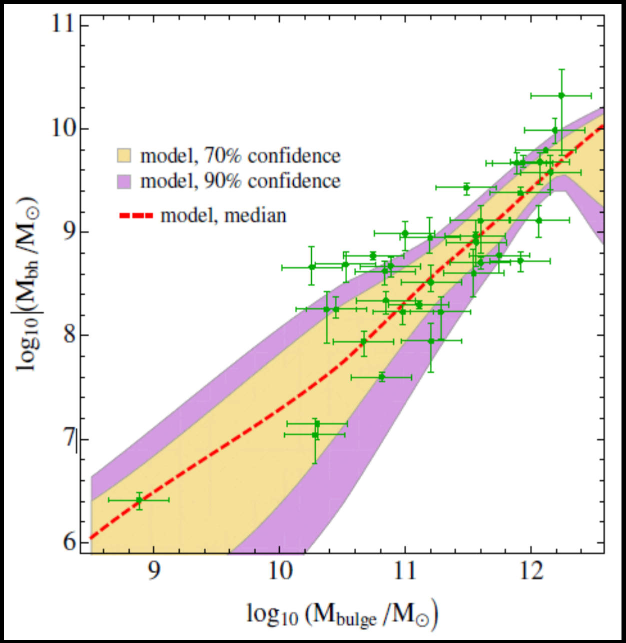
Can keep track of the galaxy morphology:

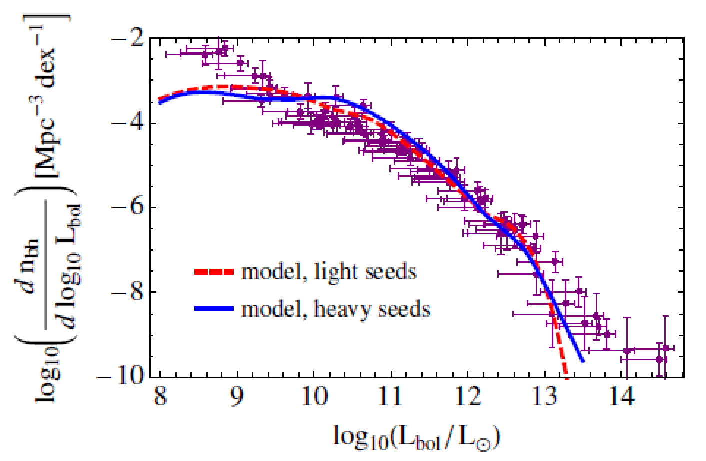
Spirals/ellipticals/irregulars

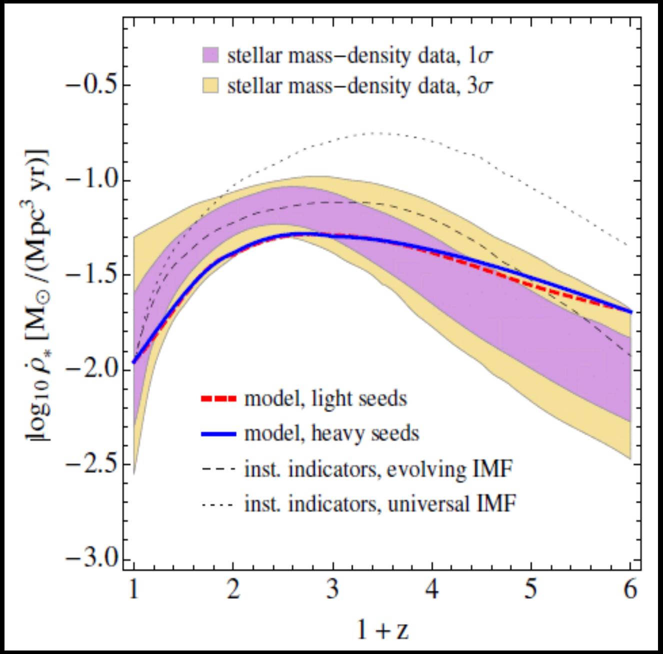
Model calibration

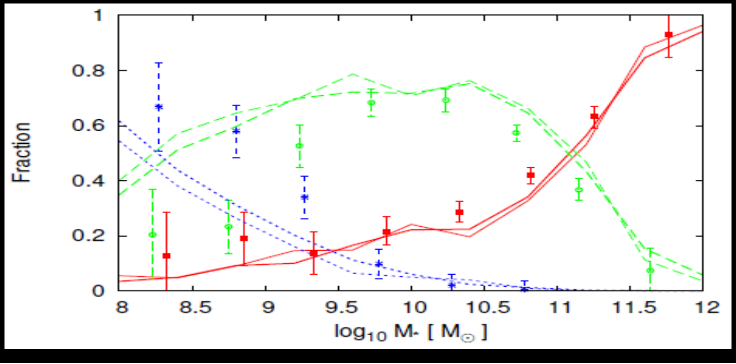


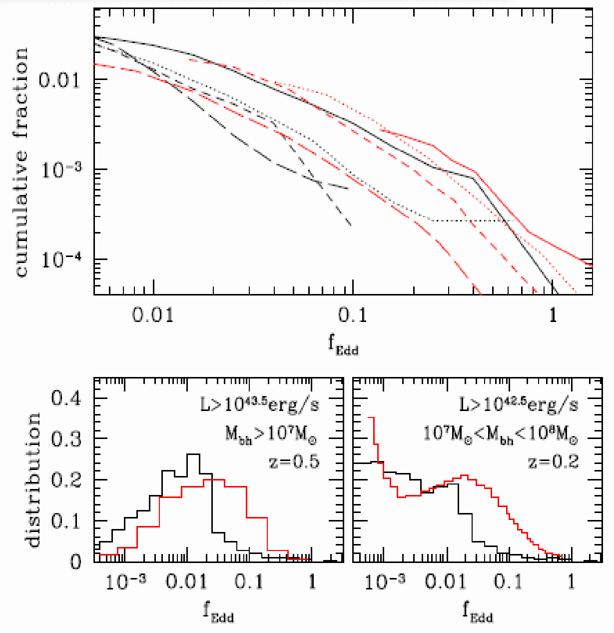












Bardeen Petterson effect

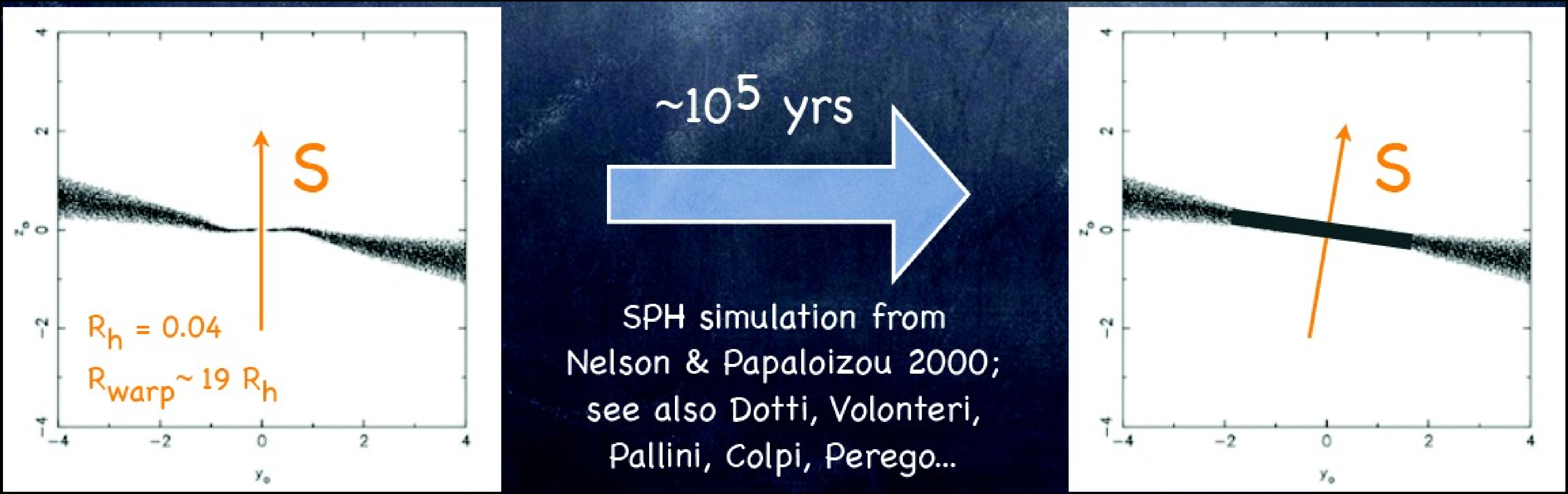
BH frame dragging exert a torque onto the disk

Each disk annulus precess around the BH

Annuli at different distance precess at different speed

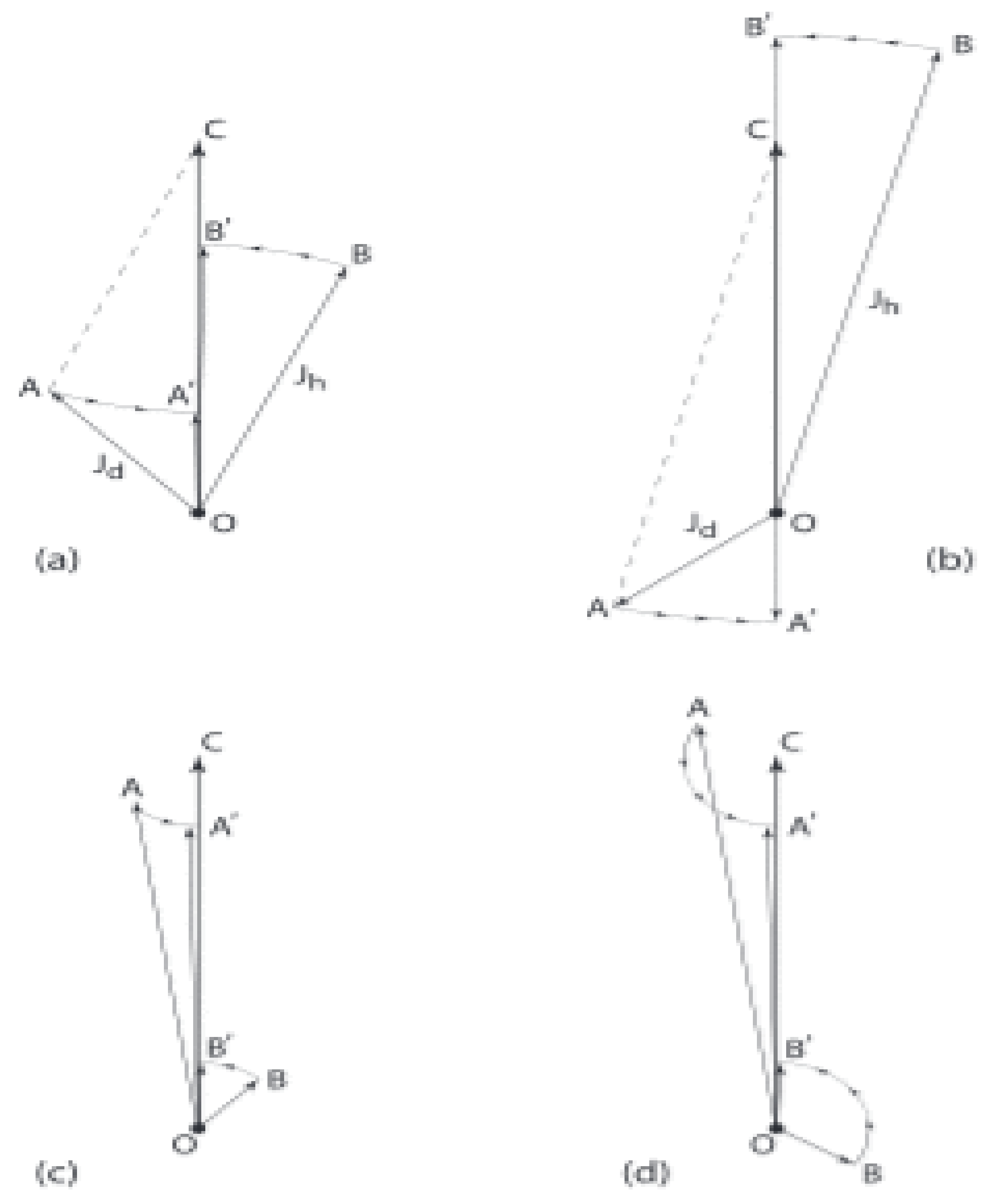
Friction between annuly make them align

The *BH spin and disk angular momentum align*



SPH simulation from Nelson & Papaloizou 2000; see also Dotti, Volonteri, Pallini, Colpi, Perego...

Alignment or anti-alignment?



If $J_{disk} \ll S_{bh}$ then the disk and the BH can actually anti-aling (King et al. 2005)

Condition for anti-alignment

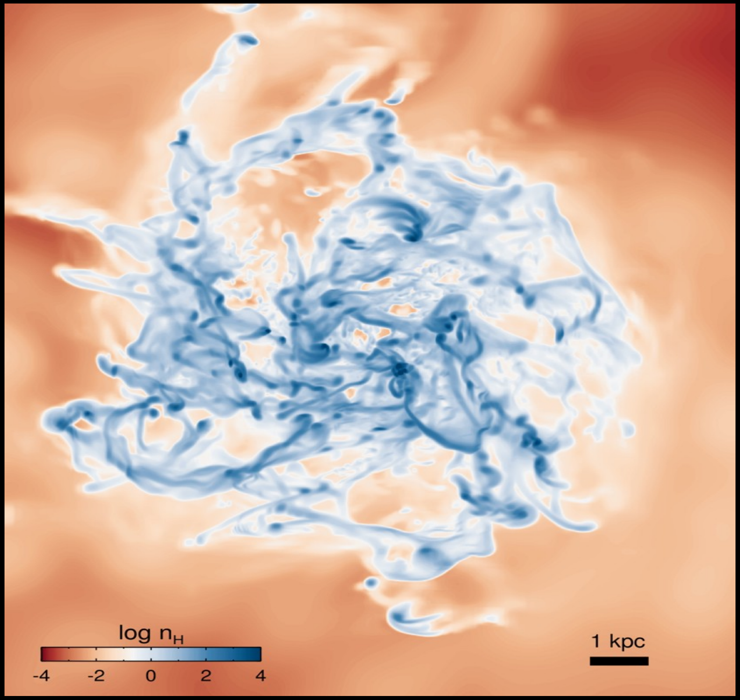
$$\cos\theta < -\frac{J_d}{2J_h}.$$

Two proposed MBH feeding scenarios

Clumpy environment:
-small clouds coming from all directions
-$J_{disk}<<S_{bh}$

50% of the clumps align,
50% of the clumps antialign

Chaotic accretion--->spindown

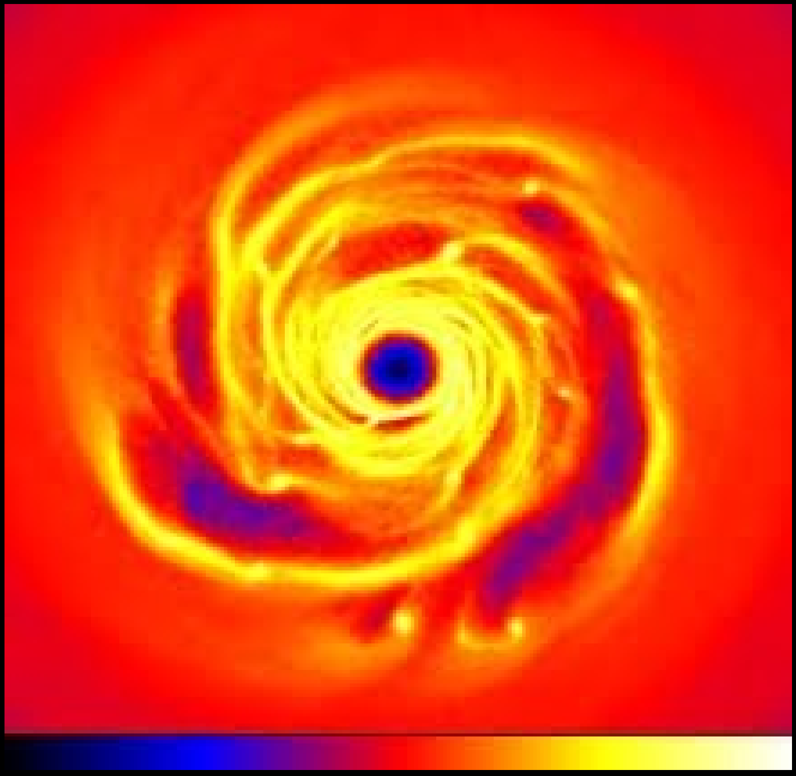


VS

Massive coherent structure
-single circumnuclear disk
-$J_{disk}>>S_{bh}$

Single prolonget accretion event

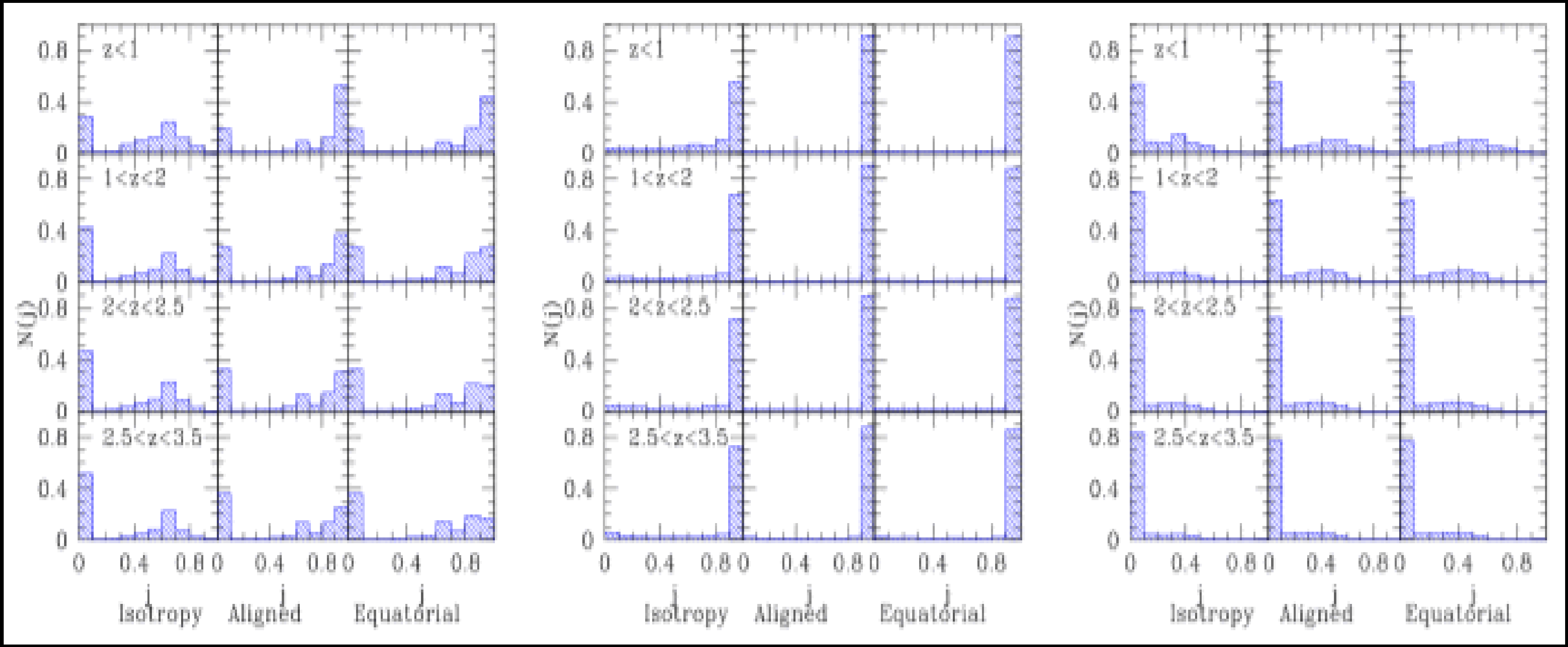
Coheren accretion--->spinup



The two simple models were implemented by Berti and Volonteri (2008).
Two distinct outcomes:

-Coherent scenario: most of the SMBH are maximally spinning at all redshift
-Chaotic scenario: most of ths SMBH have spin <0.1

Results are independent on galaxy morphology



Berti & Volonteri 2008

The spin evolution depend on the relative fraction of clouds that align/anti-align

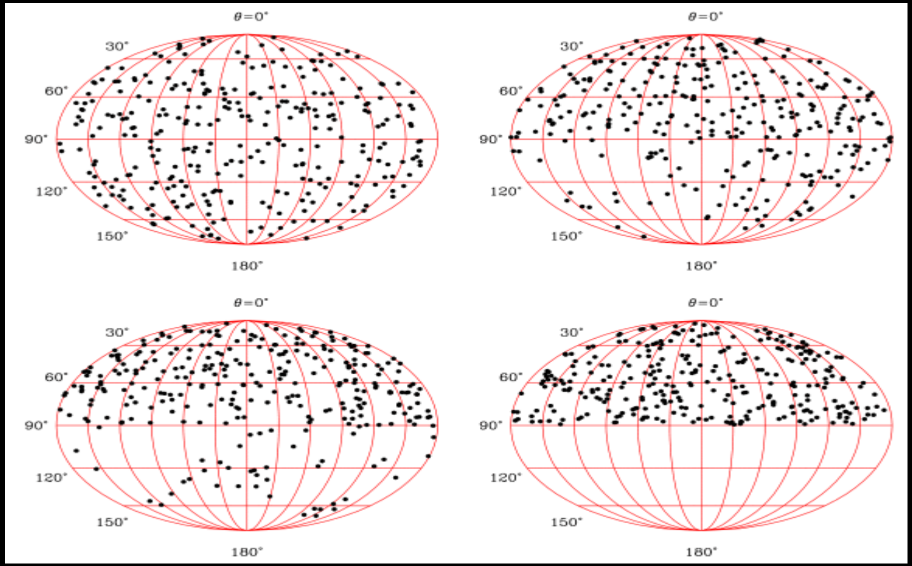
$$\begin{array}{ll} w = 1 & \text{if} \quad J_{\rm disk} > 2J_{\rm bh} \\ w = F + \frac{J_{\rm disk}}{2J_{\rm bh}}(1-F) & \text{if} \quad J_{\rm disk} < 2J_{\rm bh} \, . \end{array}$$

This fraction depends on the relative importance of the coherent vs turbolent motion of the clouds in the galaxy:

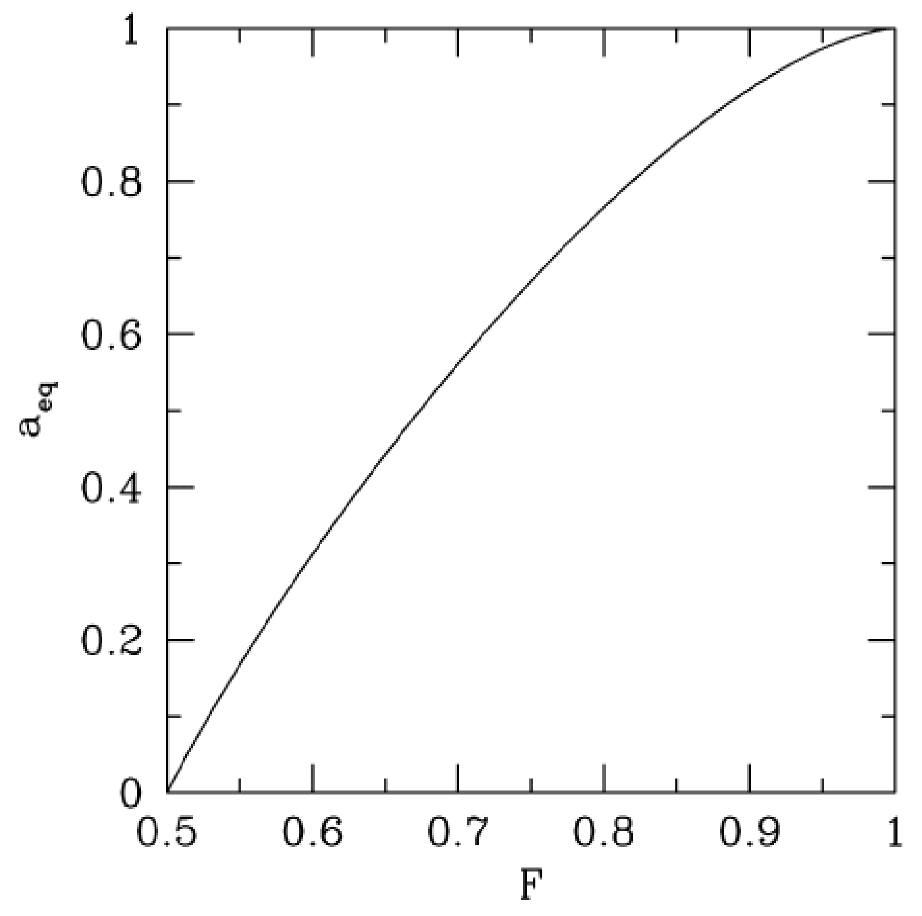
v=rotational velocity
σ=velocity dispersion

$$\begin{array}{ll} v/\sigma > 1 & \rightarrow \; F = 1\,; \\ v/\sigma = 0 & \rightarrow \; F = 0.5\,; \\ 0 < v/\sigma < 1 & \rightarrow \; F = (1 + v/\sigma)/2\,. \end{array}$$

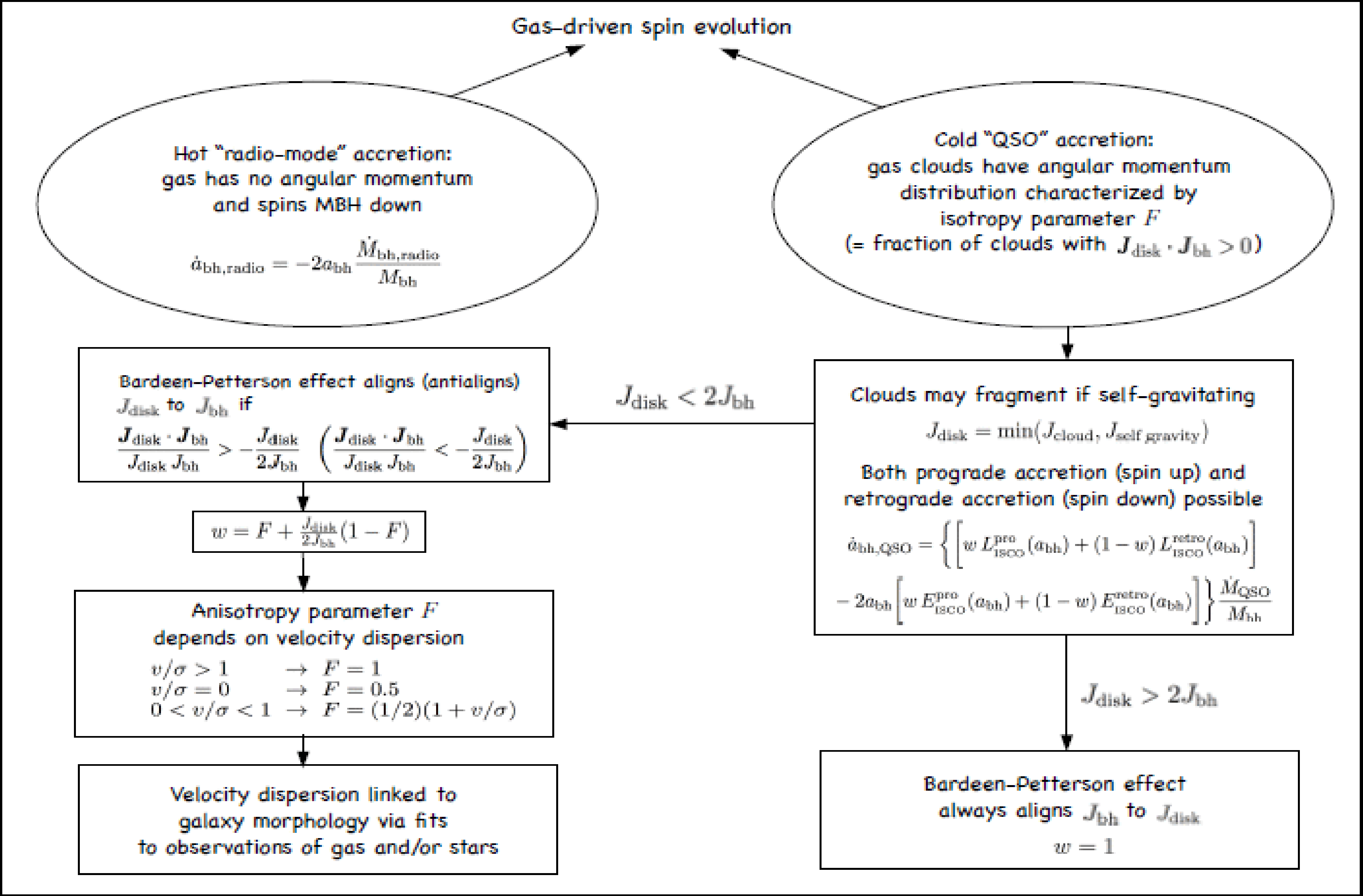
The ratio *v/σ* determines the equilibrium spin of the MBH



Dotti et al. 2013



Spin evolution model



Gas–driven spin evolution

Hot "radio-mode" accretion:
gas has no angular momentum
and spins MBH down

$$\dot{a}_{\rm bh,radio} = -2a_{\rm bh}\frac{\dot{M}_{\rm bh,radio}}{M_{\rm bh}}$$

Cold "QSO" accretion:
gas clouds have angular momentum
distribution characterized by
isotropy parameter F
(= fraction of clouds with $\boldsymbol{J}_{\rm disk}\cdot\boldsymbol{J}_{\rm bh} > 0$)

Clouds may fragment if self-gravitating

$$J_{\rm disk} = \min(J_{\rm cloud}, J_{\rm self\ gravity})$$

Both prograde accretion (spin up) and
retrograde accretion (spin down) possible

$$\dot{a}_{\rm bh,QSO} = \Big\{\Big[w\,L^{\rm pro}_{\rm ISCO}(a_{\rm bh}) + (1-w)\,L^{\rm retro}_{\rm ISCO}(a_{\rm bh})\Big] - 2a_{\rm bh}\Big[w\,E^{\rm pro}_{\rm ISCO}(a_{\rm bh}) + (1-w)\,E^{\rm retro}_{\rm ISCO}(a_{\rm bh})\Big]\Big\}\frac{\dot{M}_{\rm QSO}}{M_{\rm bh}}$$

$J_{\rm disk} < 2J_{\rm bh}$

Bardeen–Petterson effect aligns (antialigns)
$J_{\rm disk}$ to $J_{\rm bh}$ if

$$\frac{\boldsymbol{J}_{\rm disk}\cdot\boldsymbol{J}_{\rm bh}}{J_{\rm disk}\,J_{\rm bh}} > -\frac{J_{\rm disk}}{2J_{\rm bh}} \quad \left(\frac{\boldsymbol{J}_{\rm disk}\cdot\boldsymbol{J}_{\rm bh}}{J_{\rm disk}\,J_{\rm bh}} < -\frac{J_{\rm disk}}{2J_{\rm bh}}\right)$$

$$w = F + \frac{J_{\rm disk}}{2J_{\rm bh}}(1-F)$$

Anisotropy parameter F
depends on velocity dispersion

$v/\sigma > 1 \rightarrow F = 1$
$v/\sigma = 0 \rightarrow F = 0.5$
$0 < v/\sigma < 1 \rightarrow F = (1/2)(1 + v/\sigma)$

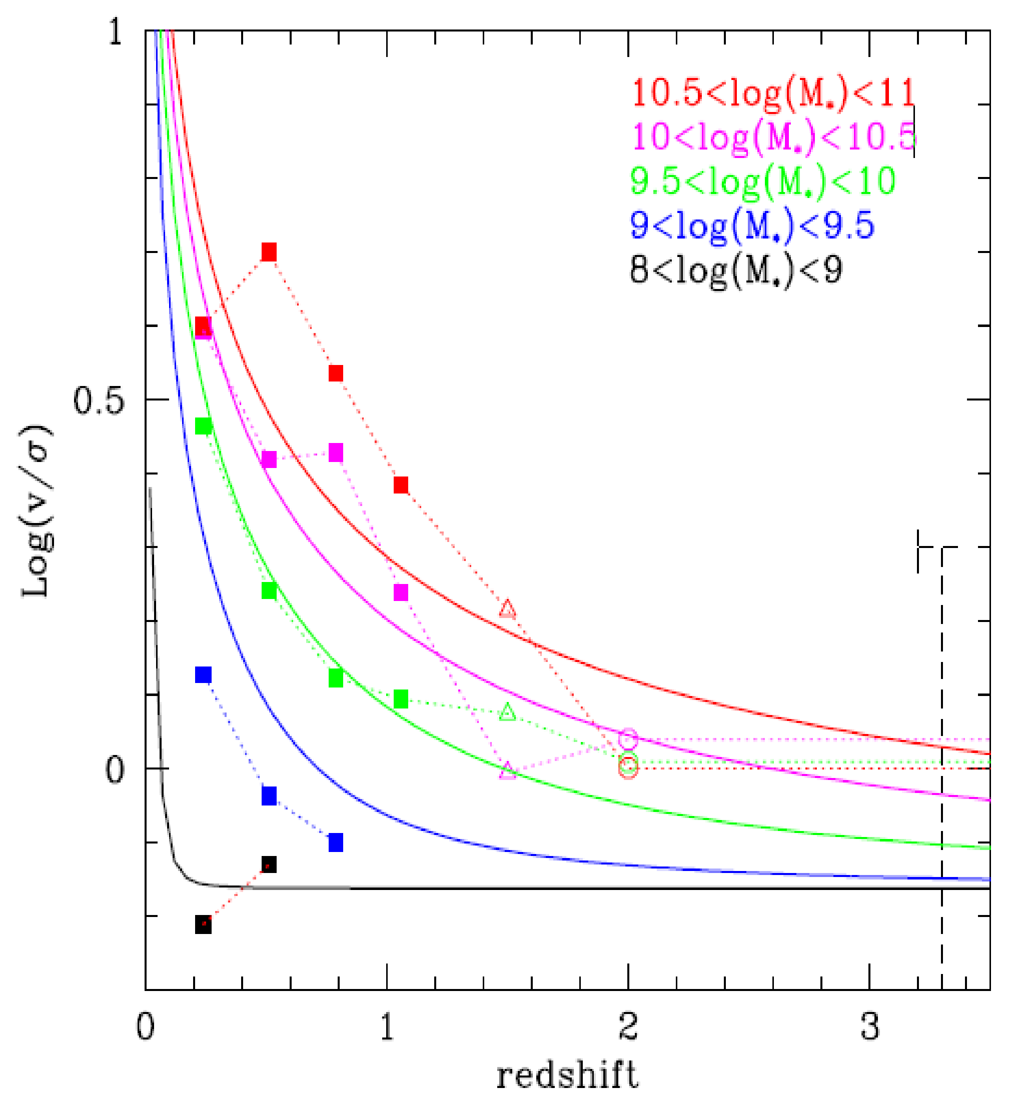
Velocity dispersion linked to
galaxy morphology via fits
to observations of gas and/or stars

$J_{\rm disk} > 2J_{\rm bh}$

Bardeen–Petterson effect
always aligns $J_{\rm bh}$ to $J_{\rm disk}$
$w = 1$

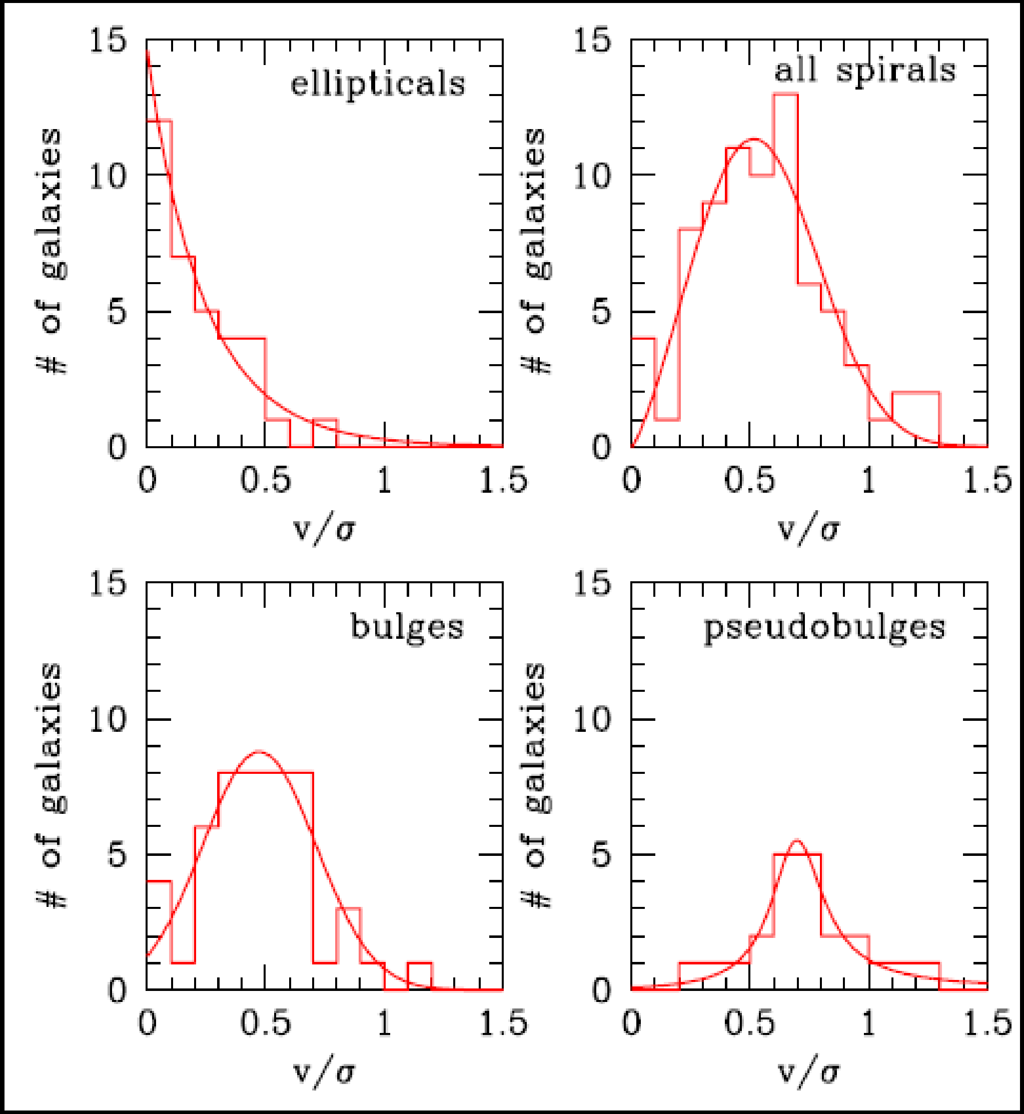
Observational determination of v/σ

Large scale dynamics of spiral disks



Kassin et al. 2012, Epinat et al. 2009, Law et al. 2009

Stellar dynamcis in ellipticals and spiral bulges and pseudobulges



Cappellari et al. 2013, Fabricius et al. 2012

Different accretion flow-galaxy dynamics connections:

-*Disk* model: v/σ anchored to the large scale gas dynamics in spirals and to the stellar dynamics in ellipticals

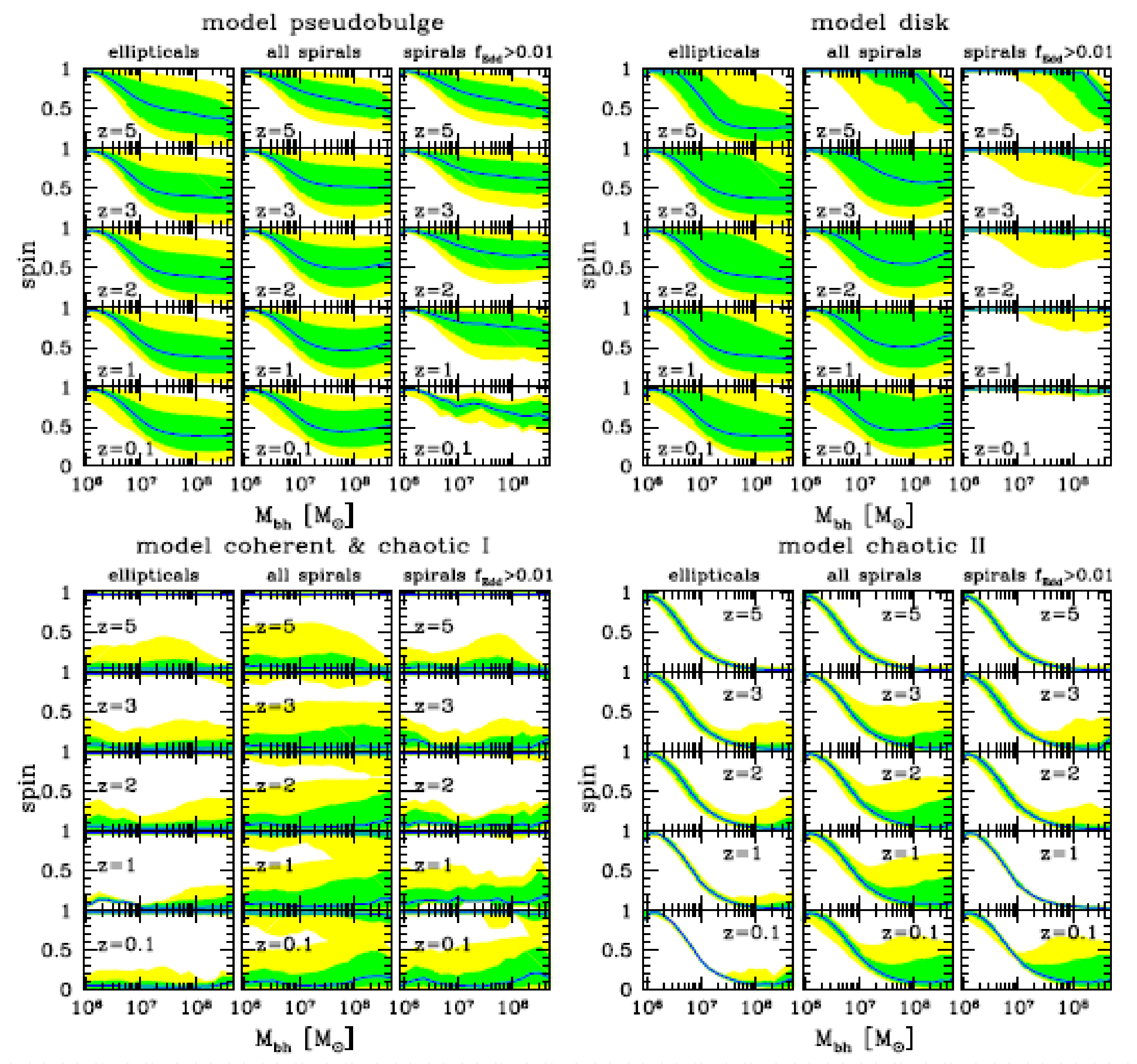
-*Bulge* model: v/σ anchored to the stellar dynamics in the bulge both in ellipticals and in spirals (no distinction bulge vs pseudobulge)

-*Pseudobulge* model: v/σ same as Bulge but with distinction bulge vs pseudobulge

-*Coherent* model: always prograde accretion (no connection with galactic kinematics)

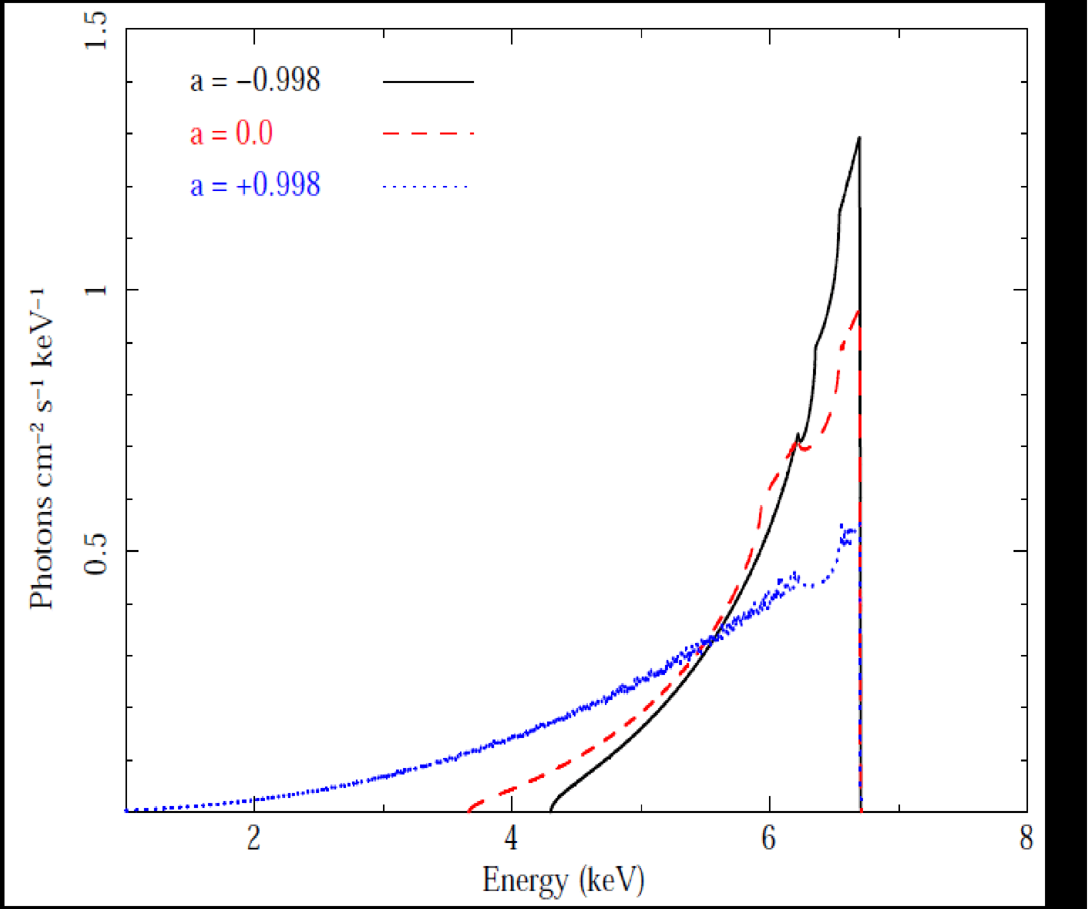
-*Chaotic* model: random accretion of small clumps (no connection with galactic kinematics)

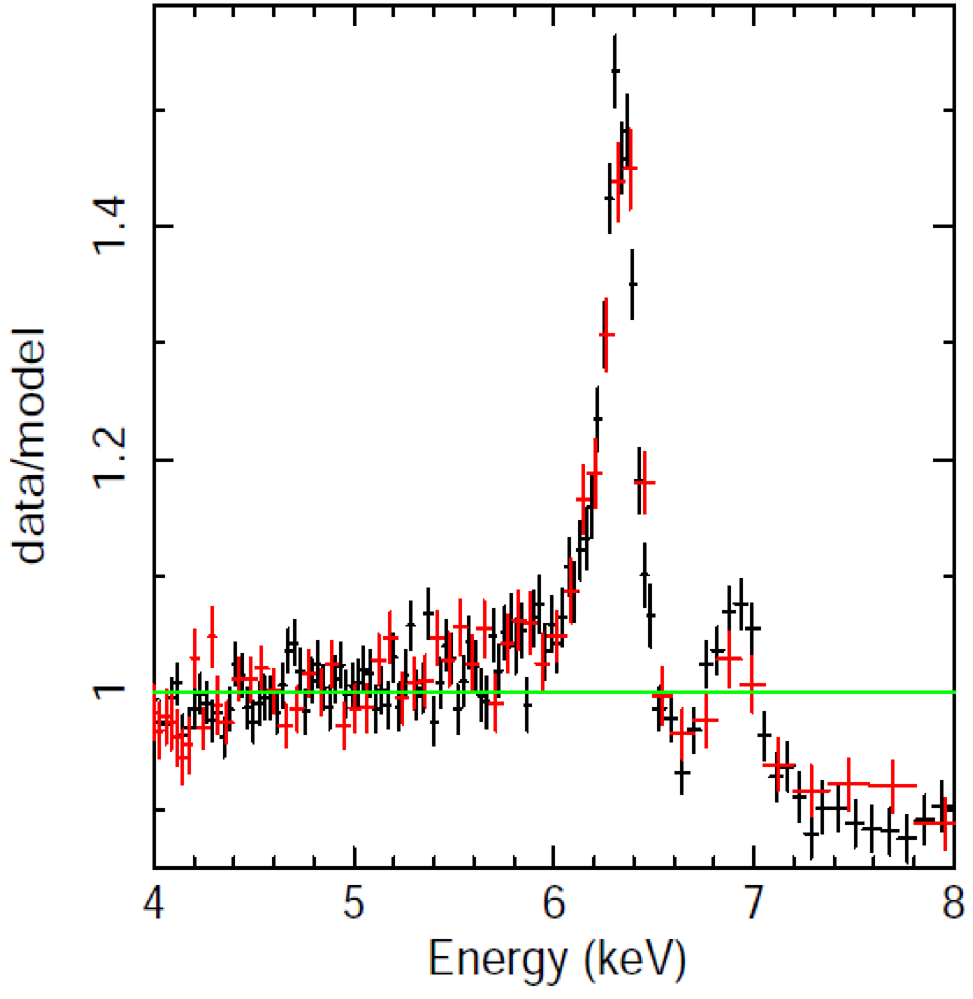
Spin evolution with redshift



Measuring MBH spins

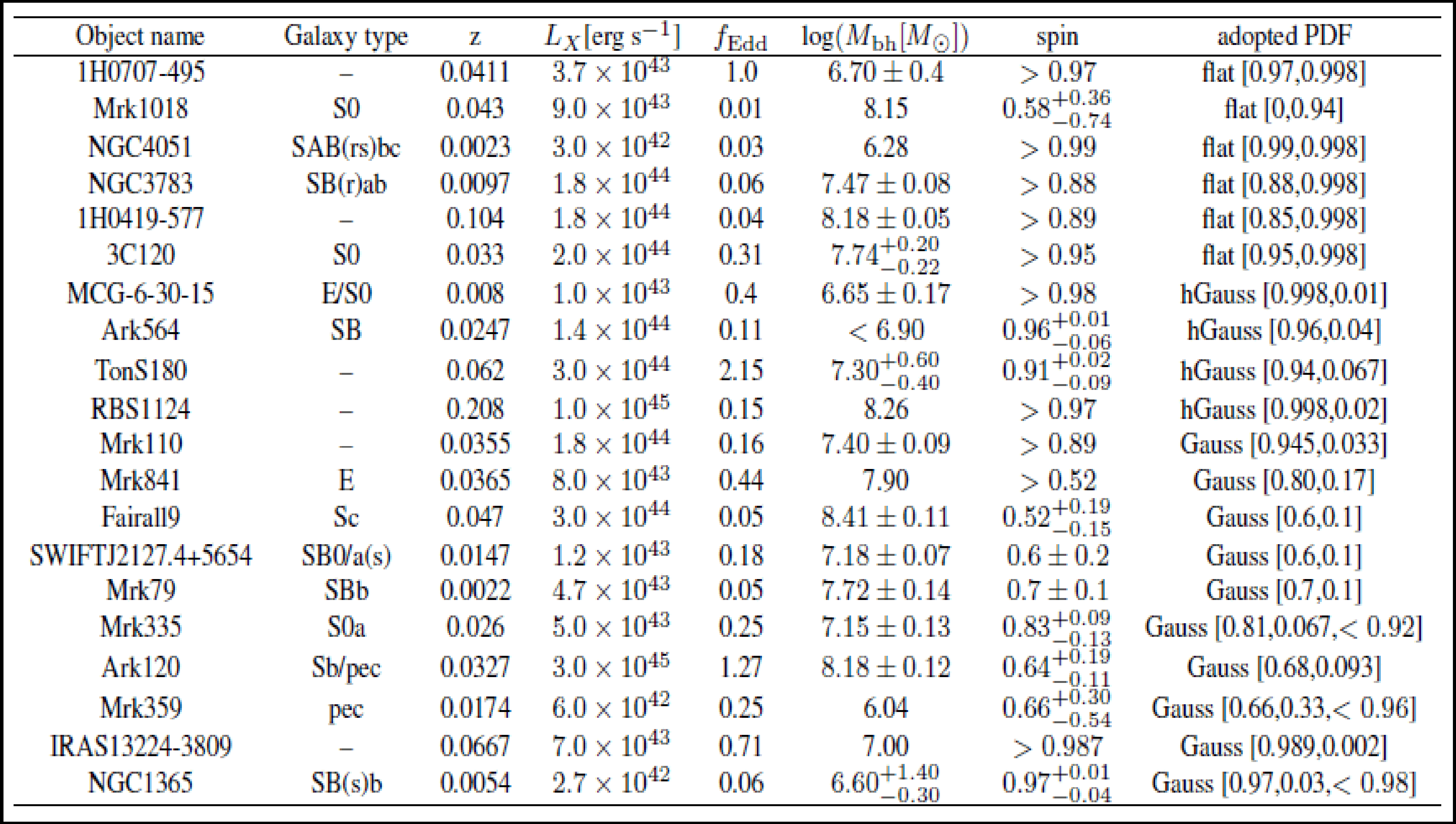
Brennemann 2013





-Measurement from reflection iron lines
-the flux come mostly from few Schw radii: it is *very sensitive to the spin*
-the higher the spin, the smaller is the ISCO and the broader is the line
 (gravitational redshift)
-Measurements involve complex multi-parameter fitting procedures

Measured spin sample



Object name	Galaxy type	z	L_X[erg s^{-1}]	$f_{\rm Edd}$	log($M_{\rm bh}$[$M_\odot$])	spin	adopted PDF
1H0707-495	–	0.0411	3.7×10^{43}	1.0	6.70 ± 0.4	> 0.97	flat [0.97,0.998]
Mrk1018	S0	0.043	9.0×10^{43}	0.01	8.15	$0.58^{+0.36}_{-0.74}$	flat [0,0.94]
NGC4051	SAB(rs)bc	0.0023	3.0×10^{42}	0.03	6.28	> 0.99	flat [0.99,0.998]
NGC3783	SB(r)ab	0.0097	1.8×10^{44}	0.06	7.47 ± 0.08	> 0.88	flat [0.88,0.998]
1H0419-577	–	0.104	1.8×10^{44}	0.04	8.18 ± 0.05	> 0.89	flat [0.85,0.998]
3C120	S0	0.033	2.0×10^{44}	0.31	$7.74^{+0.20}_{-0.22}$	> 0.95	flat [0.95,0.998]
MCG-6-30-15	E/S0	0.008	1.0×10^{43}	0.4	6.65 ± 0.17	> 0.98	hGauss [0.998,0.01]
Ark564	SB	0.0247	1.4×10^{44}	0.11	< 6.90	$0.96^{+0.01}_{-0.06}$	hGauss [0.96,0.04]
TonS180	–	0.062	3.0×10^{44}	2.15	$7.30^{+0.60}_{-0.40}$	$0.91^{+0.02}_{-0.09}$	hGauss [0.94,0.067]
RBS1124	–	0.208	1.0×10^{45}	0.15	8.26	> 0.97	hGauss [0.998,0.02]
Mrk110	–	0.0355	1.8×10^{44}	0.16	7.40 ± 0.09	> 0.89	Gauss [0.945,0.033]
Mrk841	E	0.0365	8.0×10^{43}	0.44	7.90	> 0.52	Gauss [0.80,0.17]
Fairall9	Sc	0.047	3.0×10^{44}	0.05	8.41 ± 0.11	$0.52^{+0.19}_{-0.15}$	Gauss [0.6,0.1]
SWIFTJ2127.4+5654	SB0/a(s)	0.0147	1.2×10^{43}	0.18	7.18 ± 0.07	0.6 ± 0.2	Gauss [0.6,0.1]
Mrk79	SBb	0.0022	4.7×10^{43}	0.05	7.72 ± 0.14	0.7 ± 0.1	Gauss [0.7,0.1]
Mrk335	S0a	0.026	5.0×10^{43}	0.25	7.15 ± 0.13	$0.83^{+0.09}_{-0.13}$	Gauss [0.81,0.067,< 0.92]
Ark120	Sb/pec	0.0327	3.0×10^{45}	1.27	8.18 ± 0.12	$0.64^{+0.19}_{-0.11}$	Gauss [0.68,0.093]
Mrk359	pec	0.0174	6.0×10^{42}	0.25	6.04	$0.66^{+0.30}_{-0.54}$	Gauss [0.66,0.33,< 0.96]
IRAS13224-3809	–	0.0667	7.0×10^{43}	0.71	7.00	> 0.987	Gauss [0.989,0.002]
NGC1365	SB(s)b	0.0054	2.7×10^{42}	0.06	$6.60^{+1.40}_{-0.30}$	$0.97^{+0.01}_{-0.04}$	Gauss [0.97,0.03,< 0.98]

-Measurement from reflection iron lines

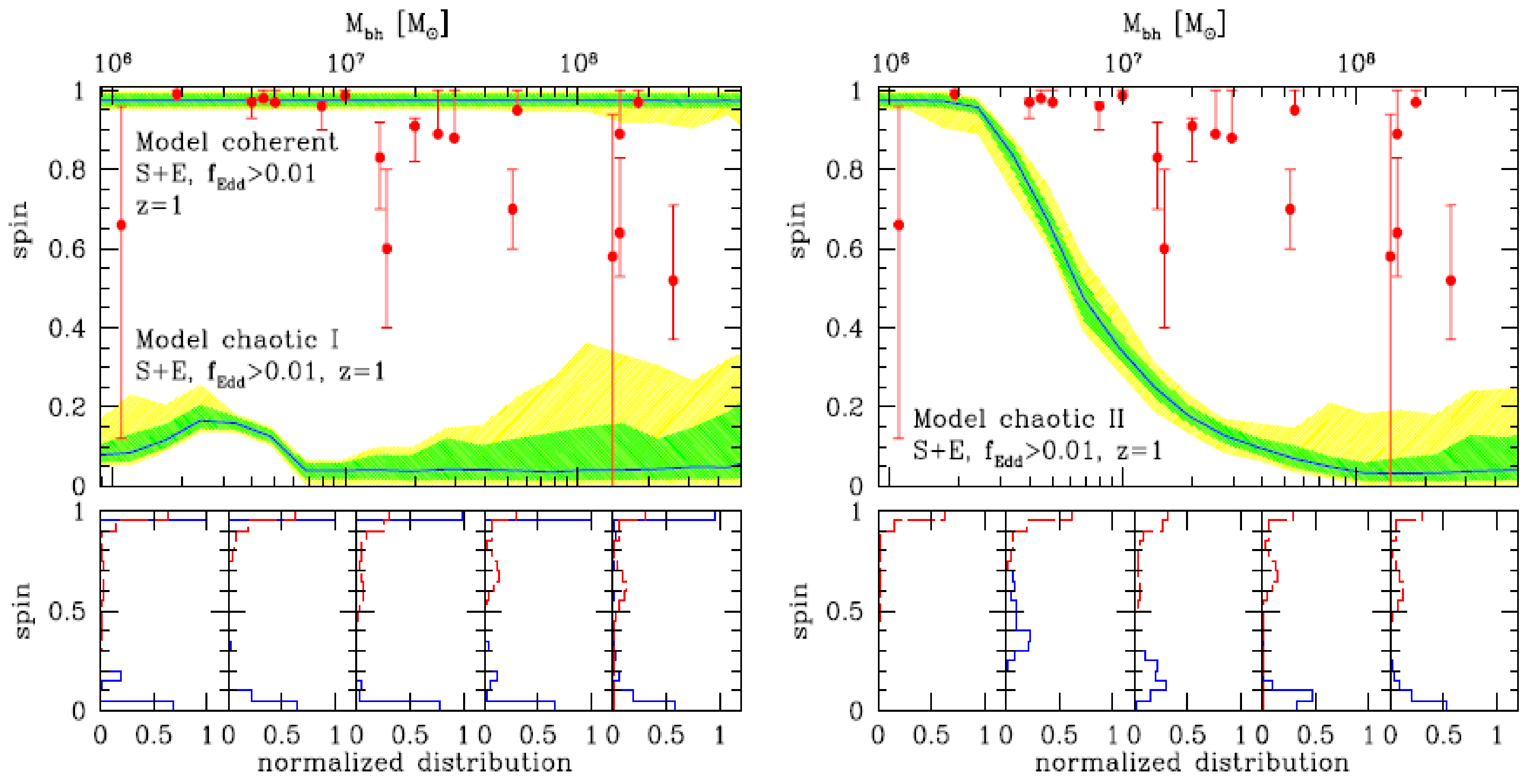
-poor statistics: 20 objects at $z<0.1$

-select luminous ($f_{\rm Edd}>0.01$) X-ray sources

-most of the systems are Syefert galaxies (spirals and lenticular)

Comparison with observations: coherent and chaotic models

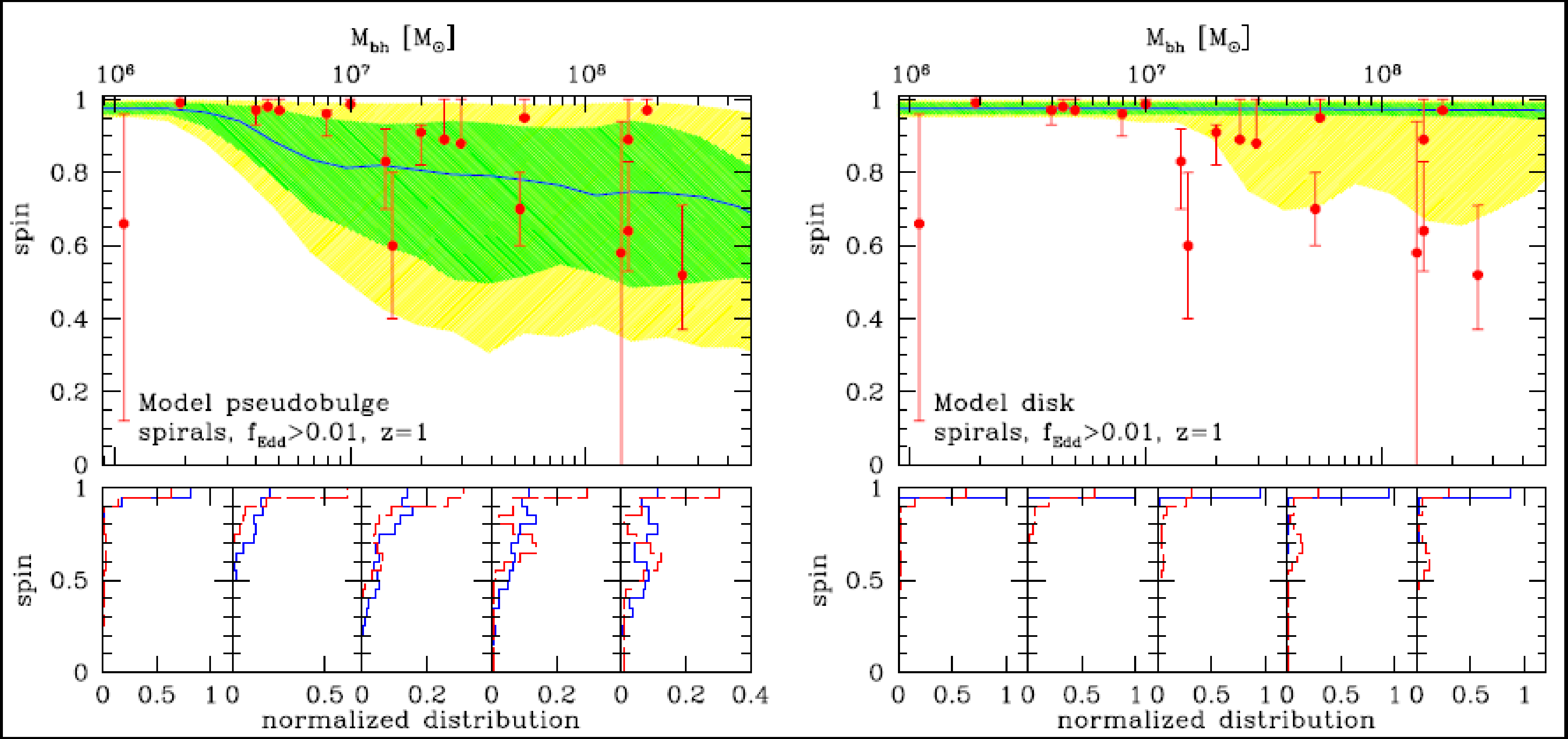
We select a subsample compatible with the observed systems: accreting SMBHs in spiral galaxies



Models fail badly when contrasted to observations

Comparison with observations: disk and pseudobulge models

We select a subsample compatible with the observed systems: accreting SMBHs in spiral galaxies

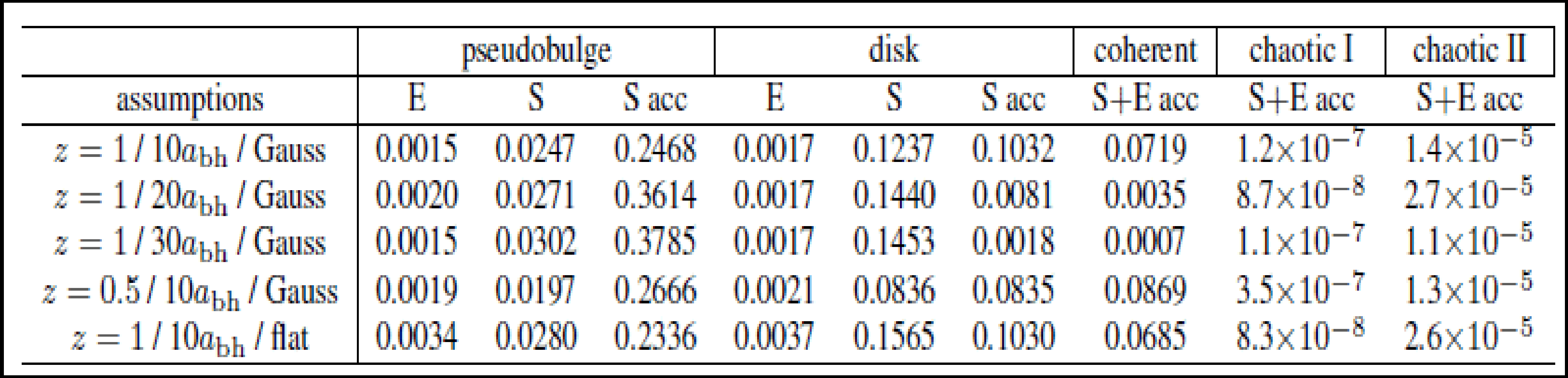


The *pseudobulge* model reproduces the observations fairly well (bulge model gives similar reuslts)

The *disk* models is only marginally consistent with observations (there are many outliers)

Comparison with observations: statistical analysis

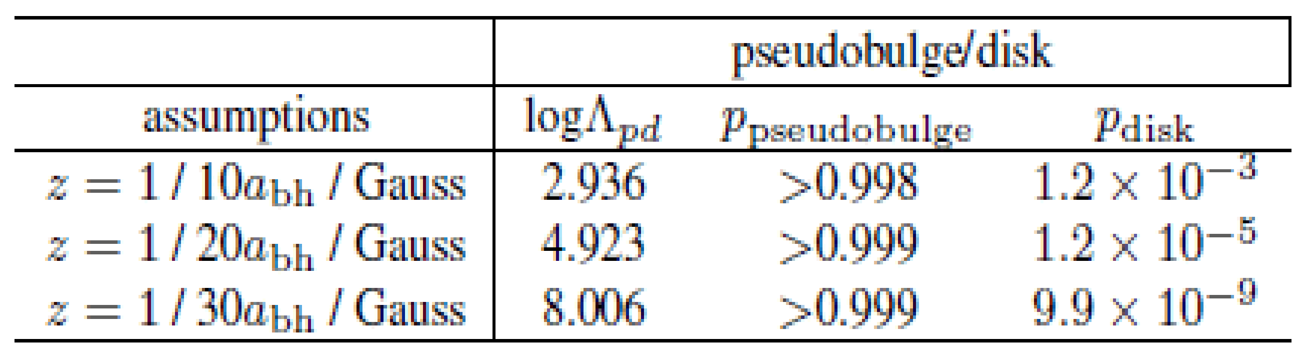
We compare the observed sample to the theoretical distribution by performing a 2D (mass-spin) KS test



	pseudobulge			disk			coherent	chaotic I	chaotic II
assumptions	E	S	S acc	E	S	S acc	S+E acc	S+E acc	S+E acc
$z = 1\,/\,10a_{\rm bh}$ / Gauss	0.0015	0.0247	0.2468	0.0017	0.1237	0.1032	0.0719	1.2×10^{-7}	1.4×10^{-5}
$z = 1\,/\,20a_{\rm bh}$ / Gauss	0.0020	0.0271	0.3614	0.0017	0.1440	0.0081	0.0035	8.7×10^{-8}	2.7×10^{-5}
$z = 1\,/\,30a_{\rm bh}$ / Gauss	0.0015	0.0302	0.3785	0.0017	0.1453	0.0018	0.0007	1.1×10^{-7}	1.1×10^{-5}
$z = 0.5\,/\,10a_{\rm bh}$ / Gauss	0.0019	0.0197	0.2666	0.0021	0.0836	0.0835	0.0869	3.5×10^{-7}	1.3×10^{-5}
$z = 1\,/\,10a_{\rm bh}$ / flat	0.0034	0.0280	0.2336	0.0037	0.1565	0.1030	0.0685	8.3×10^{-8}	2.6×10^{-5}

We compute the likelihood of the data given the models and the odds ratio between different pair of models

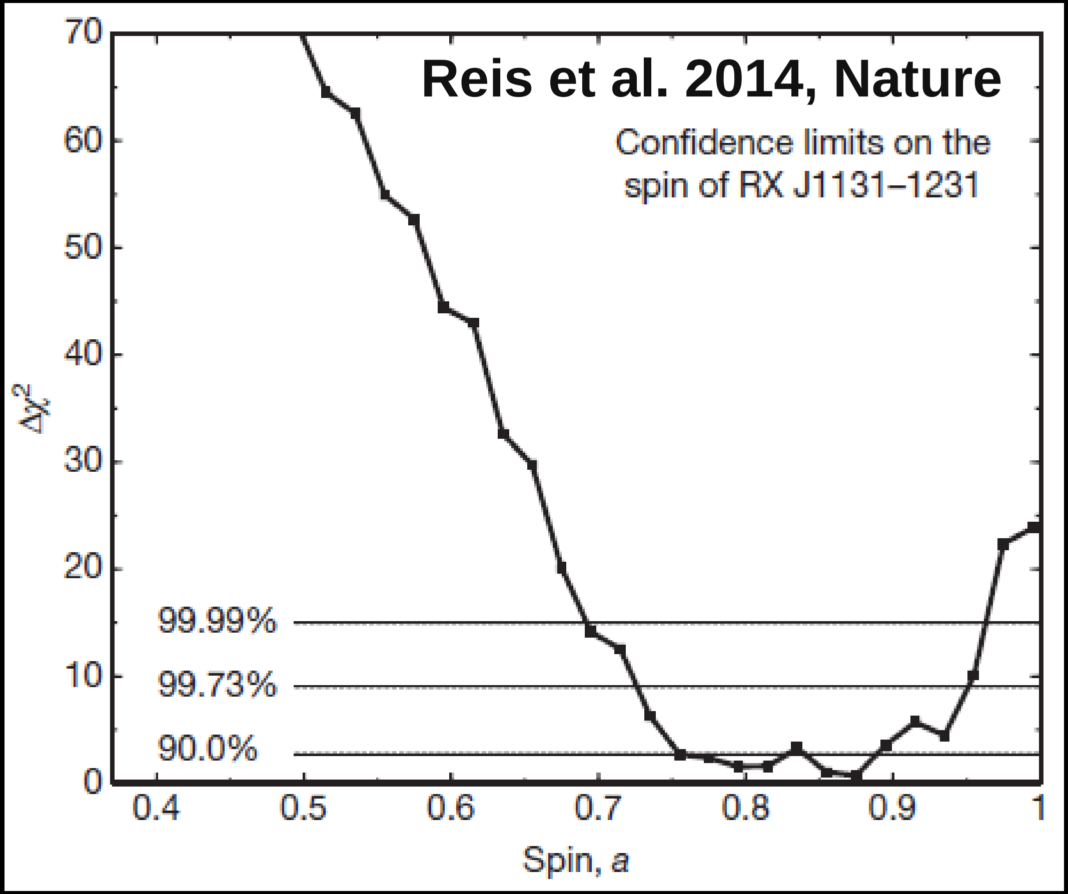
(in a 2 model comparison test this tell which models is more likely to generate the data and with what confidence)



	pseudobulge/disk		
assumptions	$\log\Lambda_{pd}$	$p_{\rm pseudobulge}$	$p_{\rm disk}$
$z = 1\,/\,10a_{\rm bh}$ / Gauss	2.936	>0.998	1.2×10^{-3}
$z = 1\,/\,20a_{\rm bh}$ / Gauss	4.923	>0.999	1.2×10^{-5}
$z = 1\,/\,30a_{\rm bh}$ / Gauss	8.006	>0.999	9.9×10^{-9}

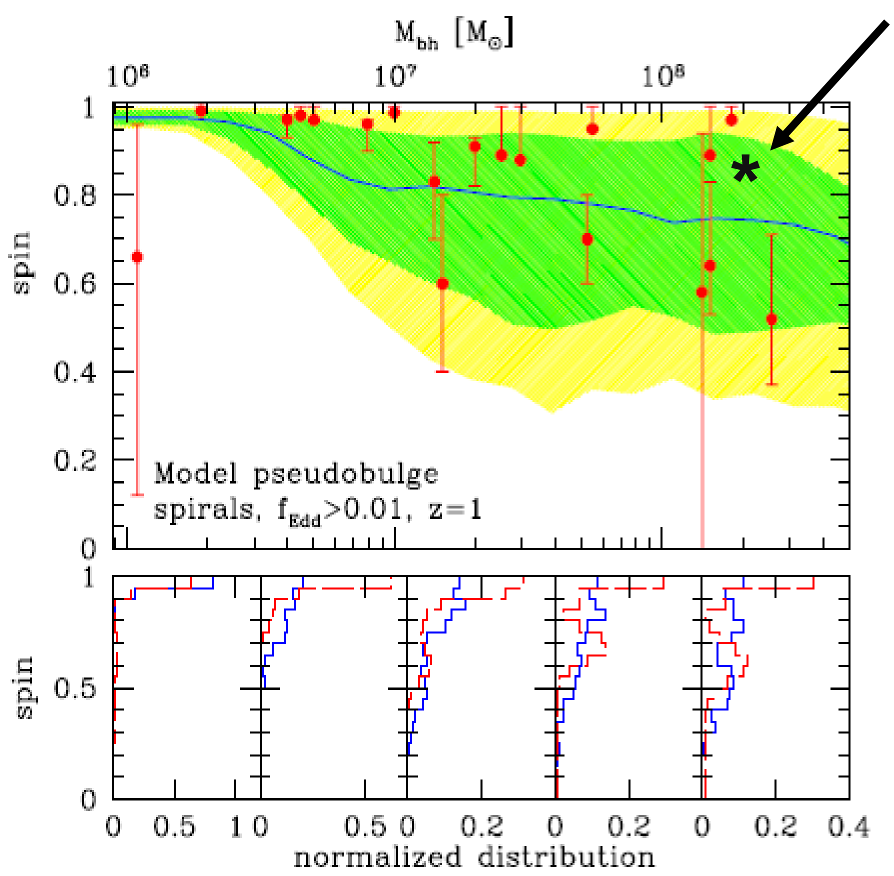
Going beyond the local Universe

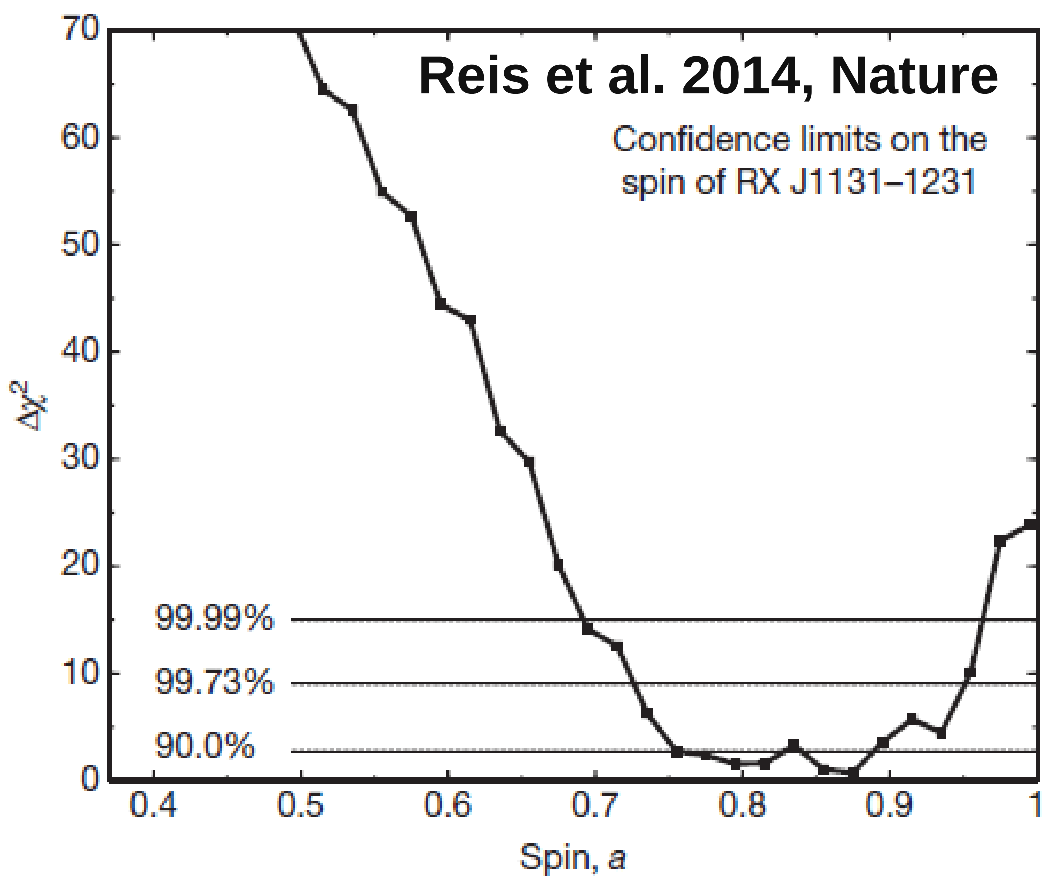
Lensed quasar at z=0.66
a=0.87+0.06-0.15
M_{bh}=2*10^8 solar masses
Host is a spiral galaxy


Reis et al. 2014, Nature

Going beyond the local Universe

Lensed quasar at *z*=0.66
***a*=0.87+0.06-0.15**
M_{bh}=2*10^8 solar masses
Host is a spiral galaxy




Reis et al. 2014, Nature

Confidence limits on the spin of RX J1131–1231

Fully consistent with the range predicted by our *pseudobulge/bulge* model

Gravitational wave astrophysics:
the low frequency regime

EPTA

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

Gravitational Wave Astronomy in Space
eLISA/NGO

Gravitational waves: a short intro

Consider a small metric perturbation

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

The linearization of the EEs results in a wave equation

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

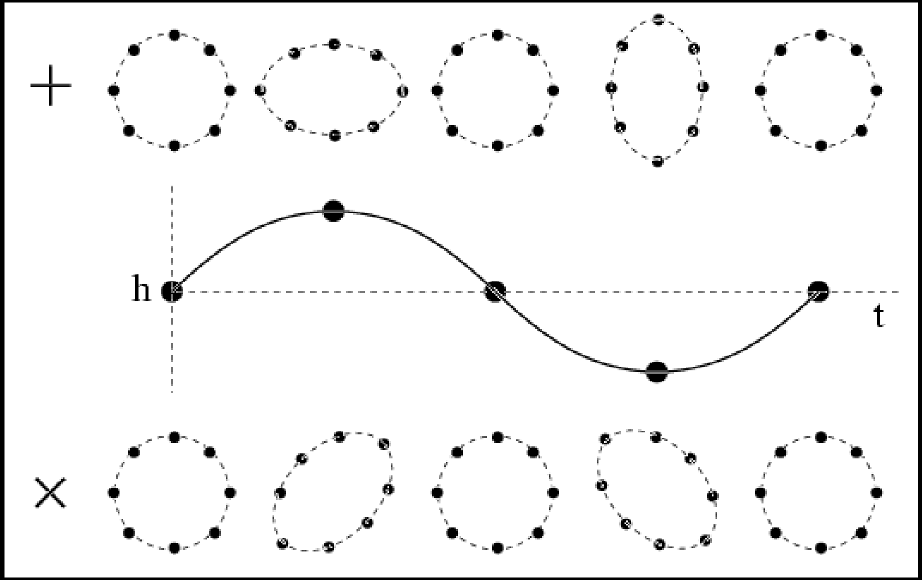
$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 + h_{+}^{TT} & h_{\times}^{TT} \\ 0 & 0 & h_{\times}^{TT} & 1 - h_{+}^{TT} \end{pmatrix}$$

The solution is a wave travelling
At the speed of light:
GRAVITATIONAL WAVES

$$\bar{h}^{ij}(t, r) = \frac{2G}{c^4}\left[\frac{d^2}{dt^2} q^{ij}\left(t - \frac{r}{c}\right)\right]$$

They are proportional to the Second derivative of the mass quadrupol moment and they carry an energy given by

$$L_{gw} = \frac{G}{5c^5}\left\langle \sum_{ij} \frac{d^3}{dt^3} Q_{ij}\left(t - \frac{x}{c}\right) \frac{d^3}{dt^3} Q^{ij}\left(t - \frac{x}{c}\right)\right\rangle$$



GWs are transversal and have two independent polarizations

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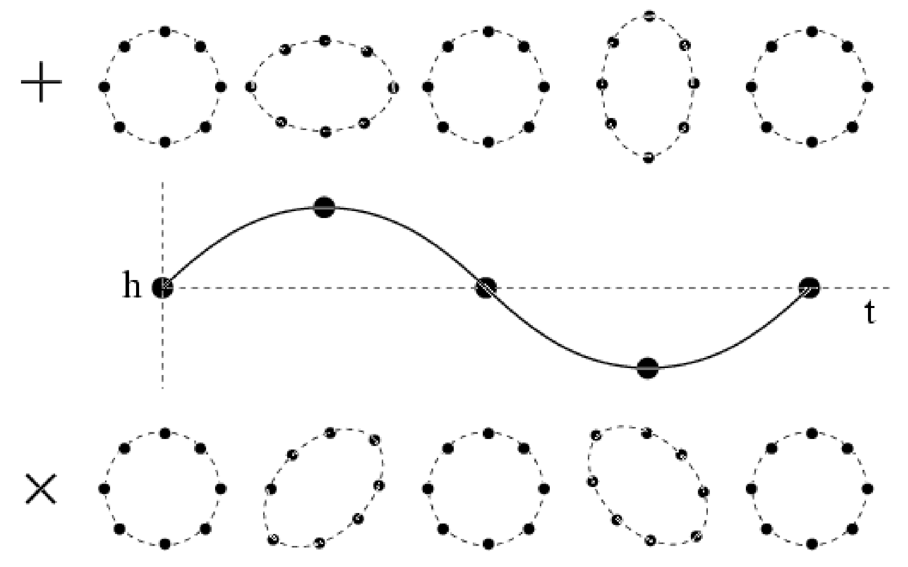

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$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ & & & h^{TT}_{\times} \end{pmatrix}$$

The solu

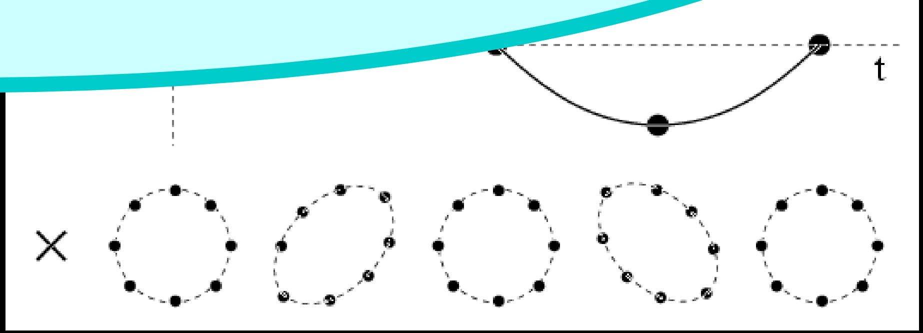
At t

We need very massive systems with varying quadrupole moment: we need astrophysical binaries! possibly BH binaries!

They are proportio

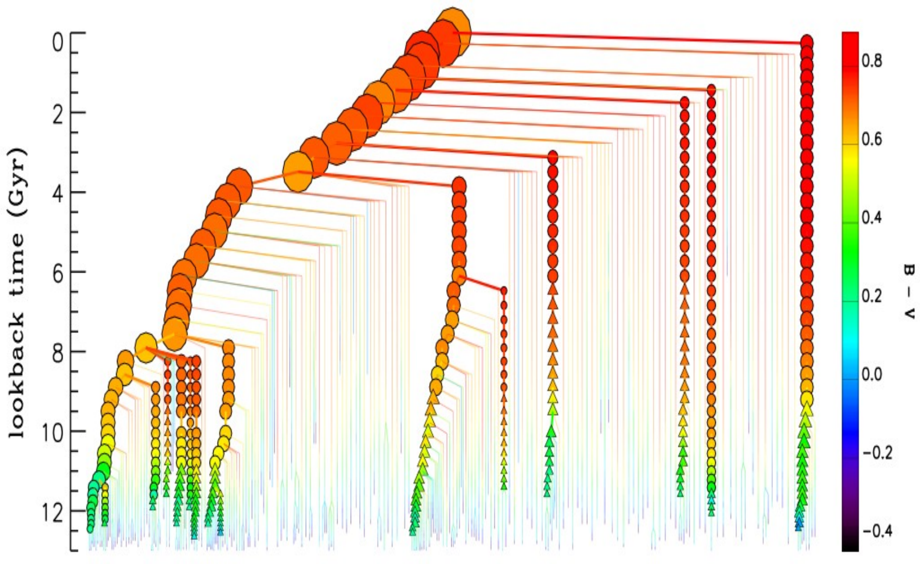
Second derivative of the mass quadrupol moment and they carry an energy given by

$$L_{gw} = \frac{G}{5c^5} \left\langle \sum_{ij} \frac{d^3}{dt^3} Q_{ij}\left(t - \frac{x}{c}\right) \frac{d^3}{dt^3} Q^{ij}\left(t - \frac{x}{c}\right) \right\rangle$$



GWs are transversal and have two independent polarizations

Structure formation in a nutshell



From De Lucia et al 2006

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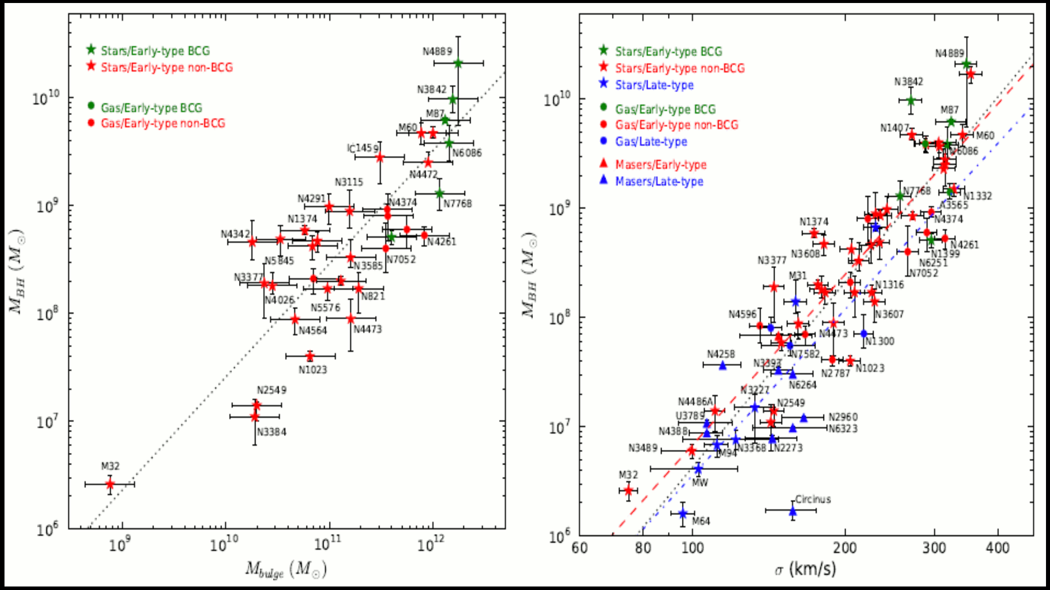
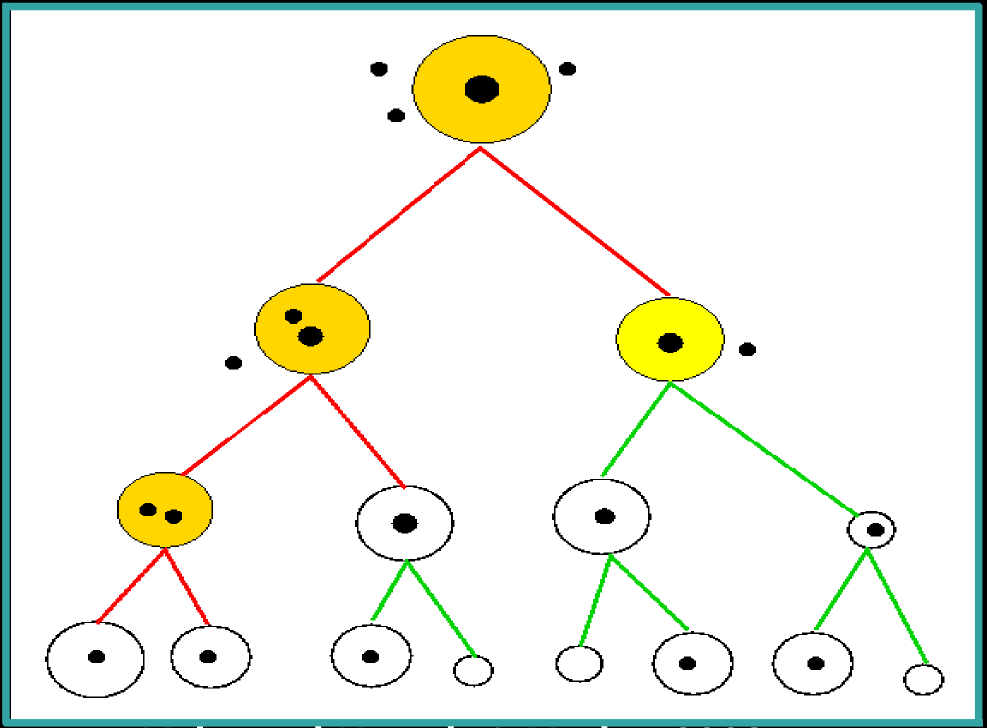


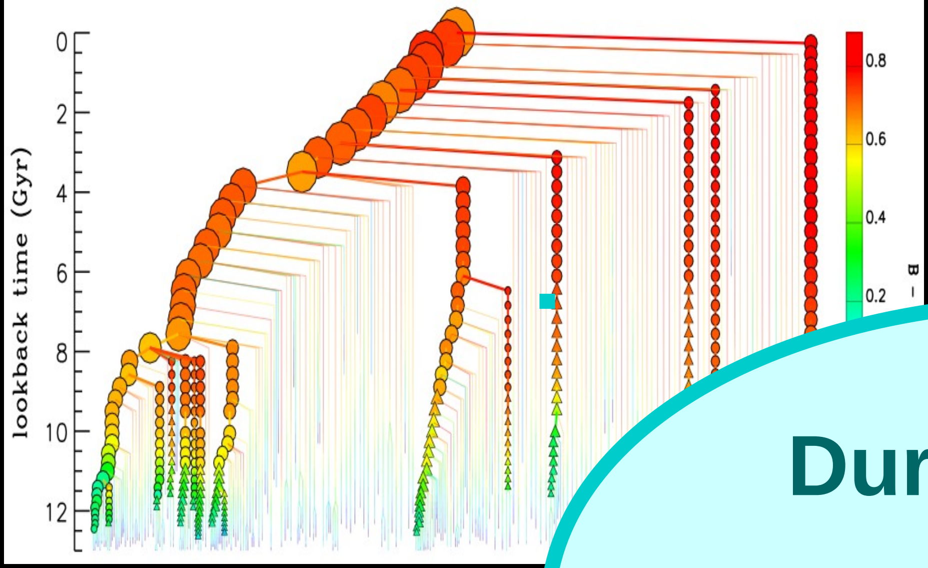
Ferrarese & Merritt 2000, Gebhardt et al. 2000

=



Volonteri Haardt & Madau 2003

Structure formation in a nutshell



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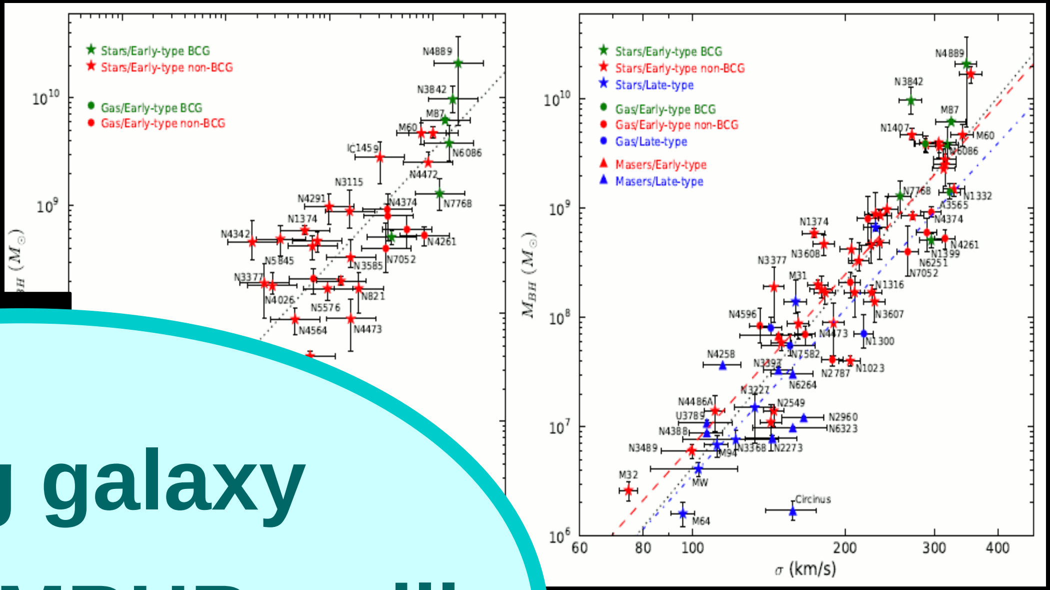
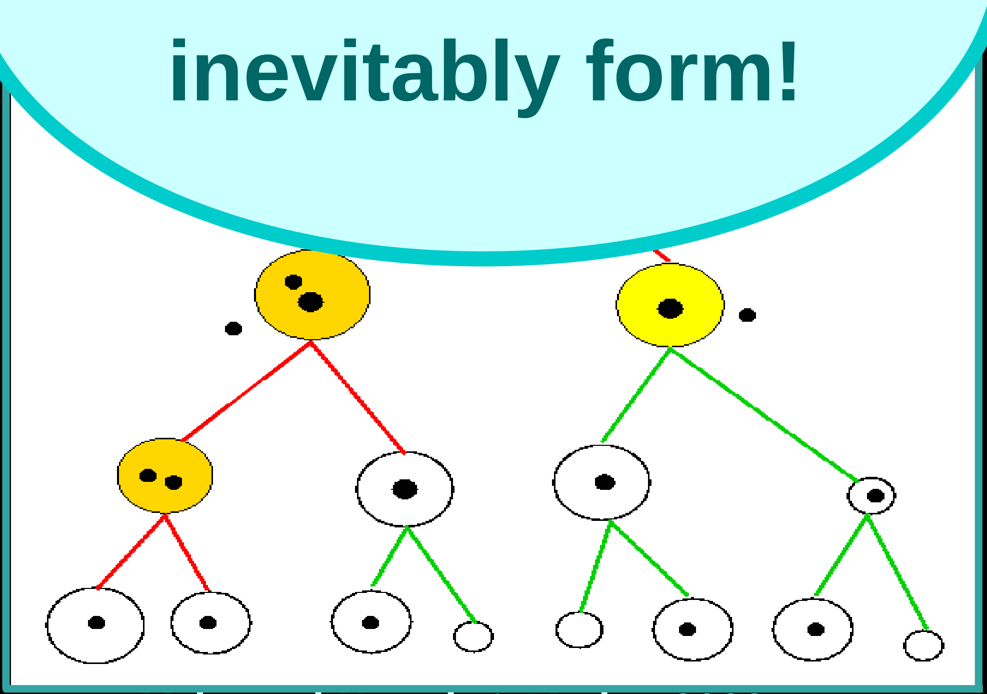


From De Lucia et al 2006

, Gebhardt et al. 2000

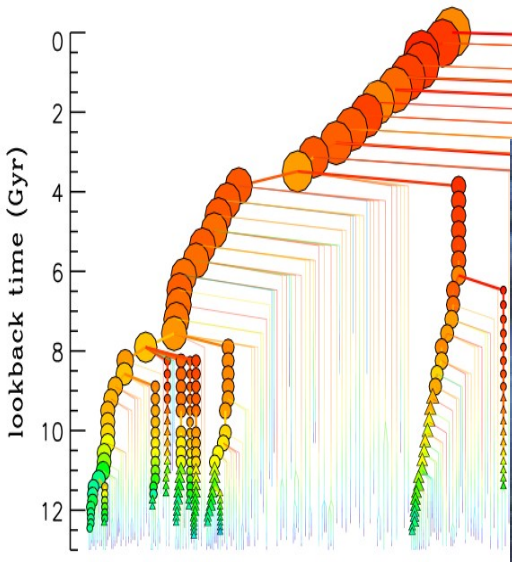
During galaxy mergers, MBHBs will inevitably form!

=

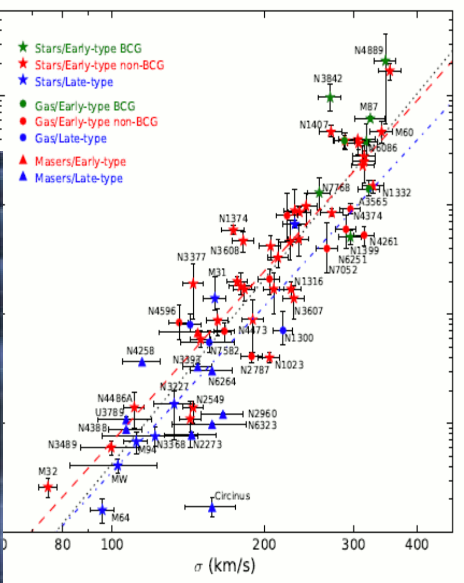


Volonteri Haardt & Madau 2003

Structure formation in a nutshell



From De Lucia et al 200



Gebhardt et al. 2000

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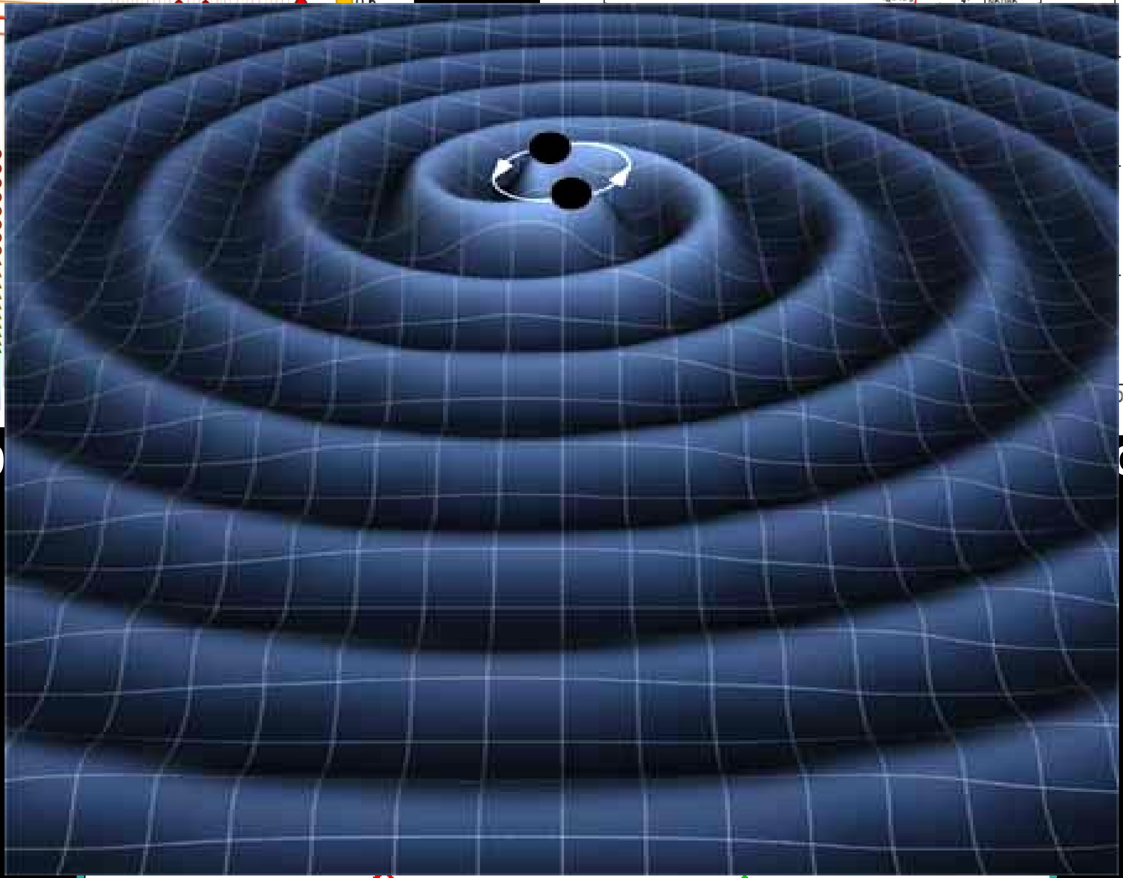
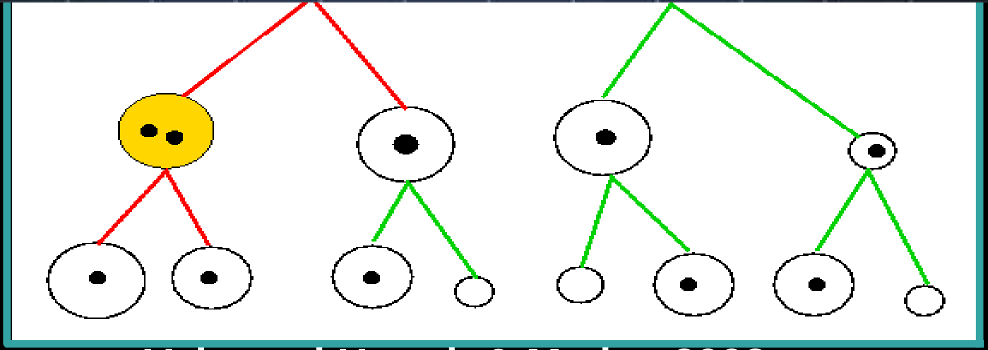




Volonteri Haardt & Madau 2003

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

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

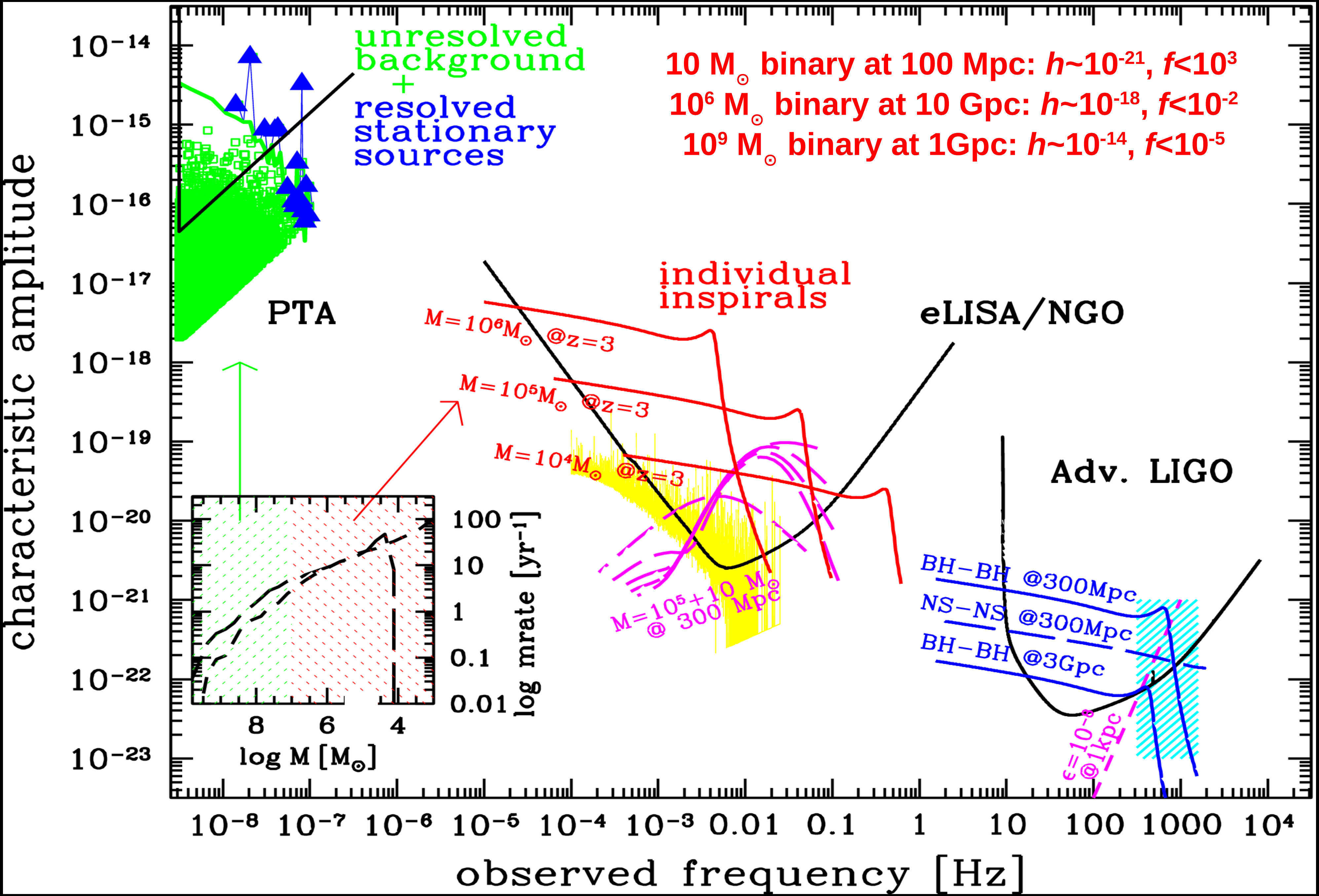
$$f \sim \frac{c}{2\pi R_s} \sim 10^4\mathrm{Hz}\frac{M_\odot}{M}$$

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

Coverage of the GW spectrum



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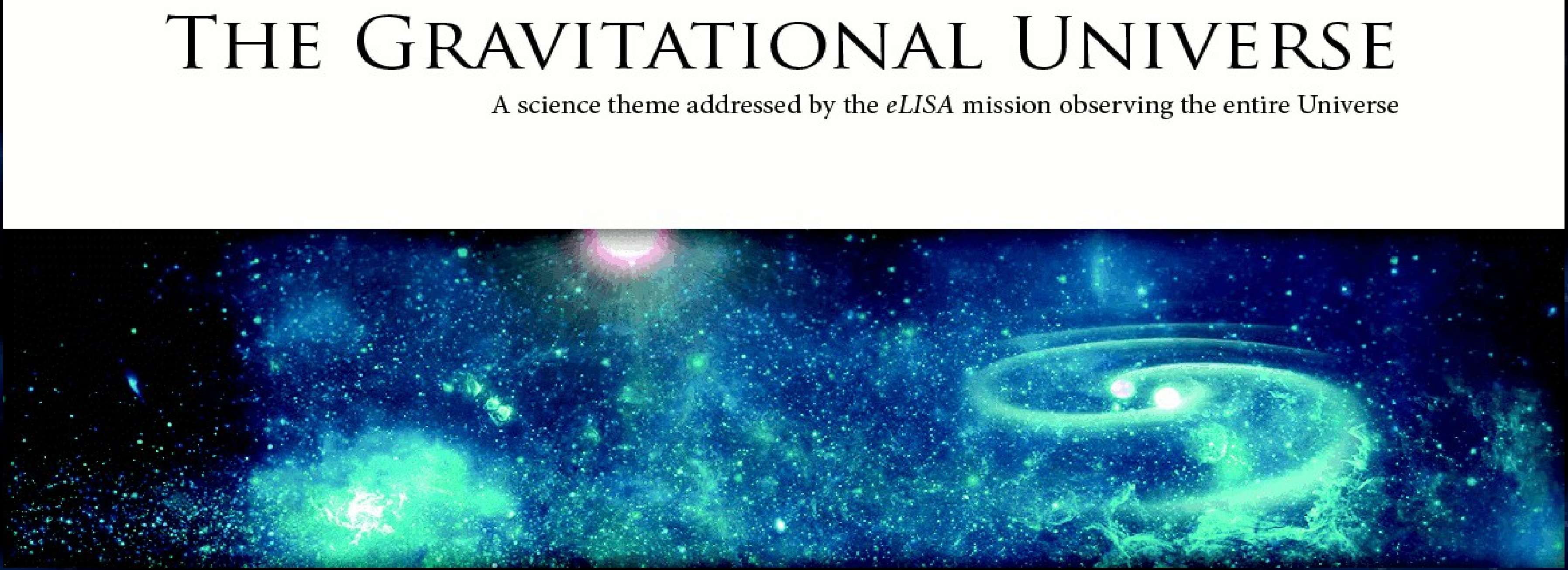
AS 2013

eLISA science



THE GRAVITATIONAL UNIVERSE

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

The eLISA Consortium, arXiv:1305.5720

eLISA science

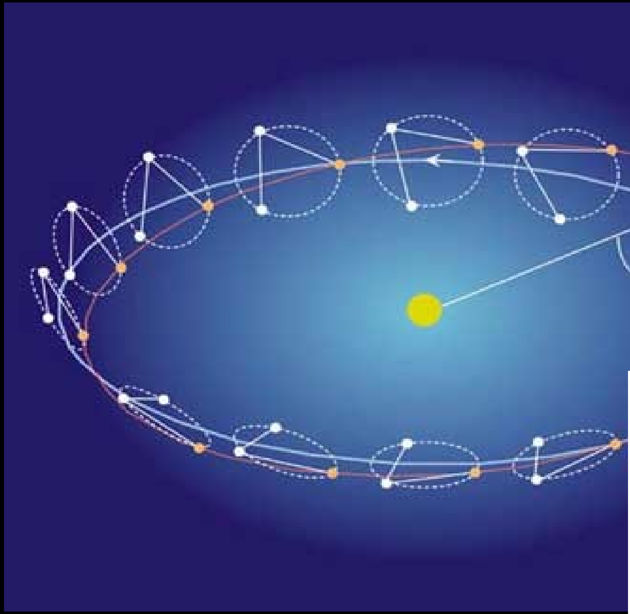
THE GRAVITATIONAL UNIVERSE

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

selected by ESA for L3 (2034)

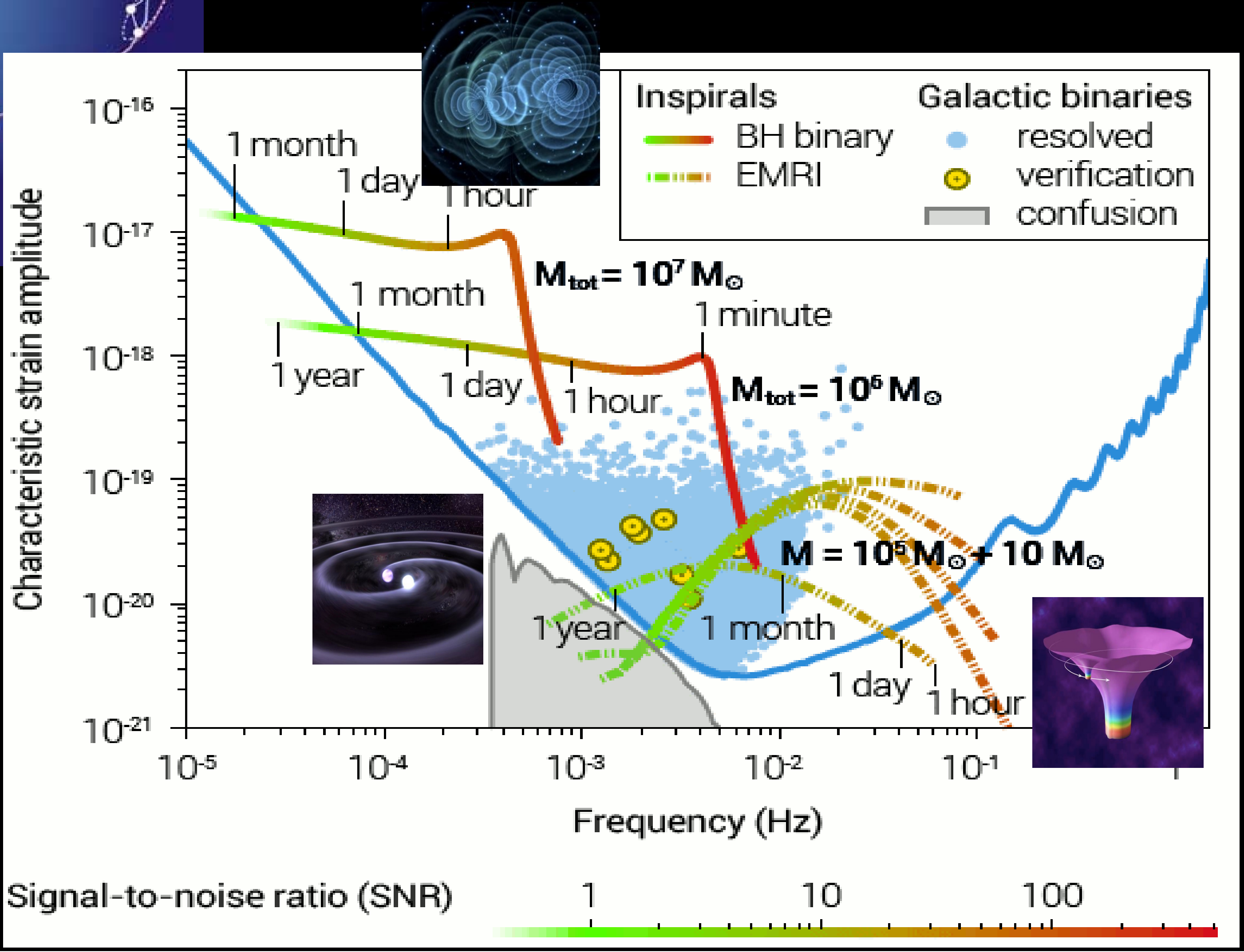
The eLISA Consortium, arXiv:1305.5720

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



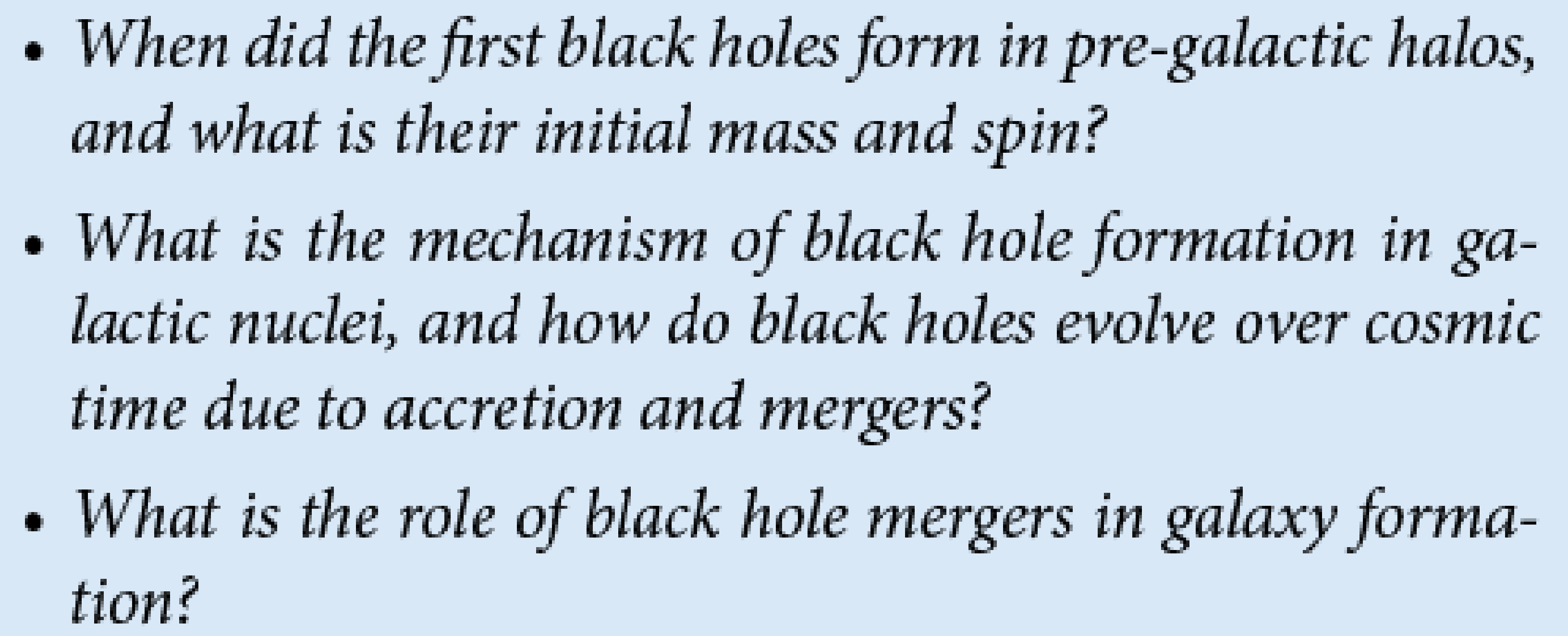
eLISA **is sensitive at mHz frequency, where the evolution of MBH binaries is fast.**

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

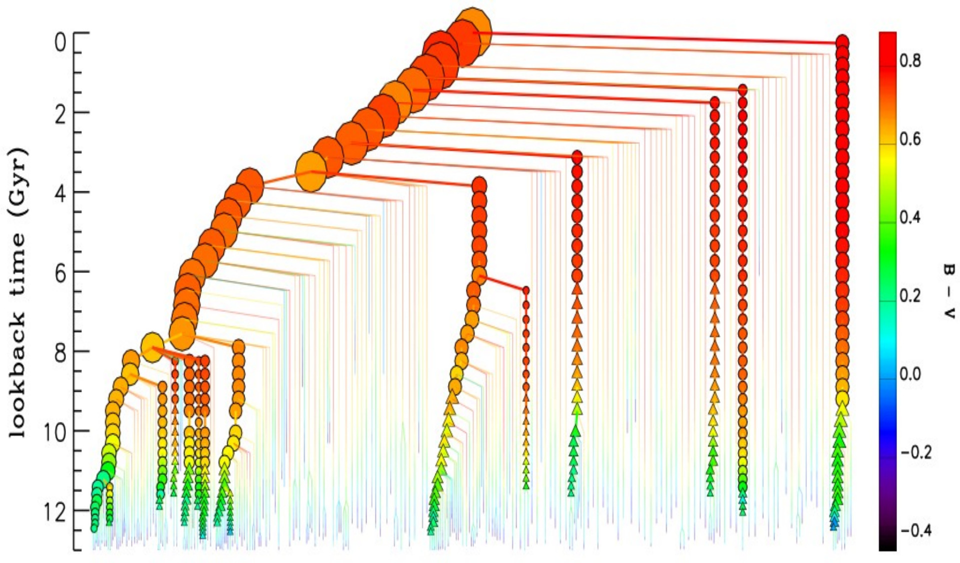


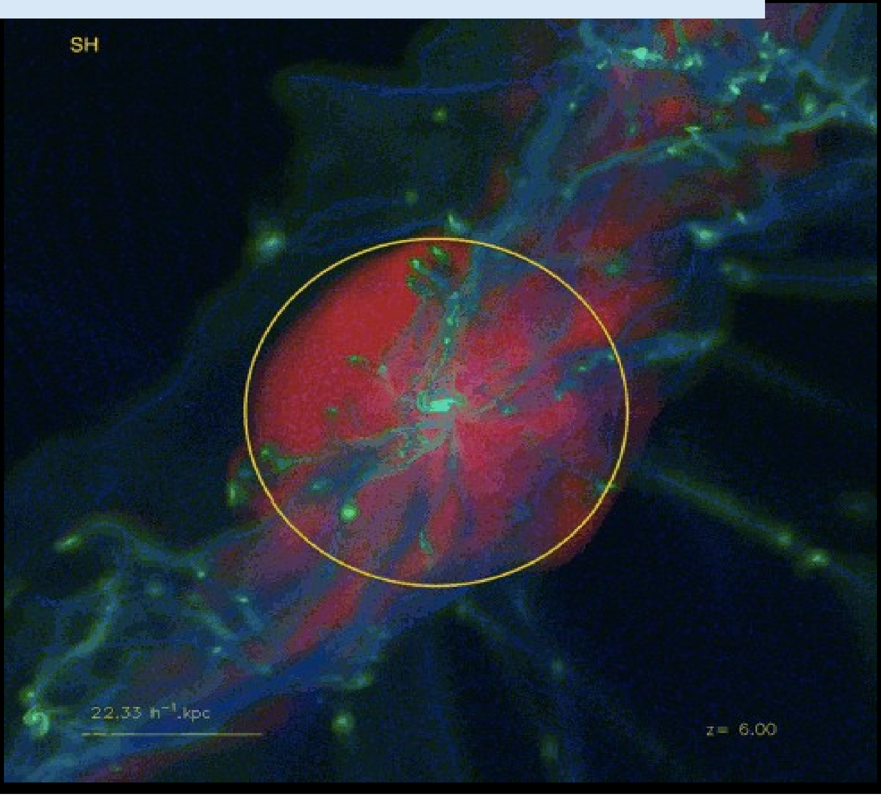
- **-same orbit as *LISA***
- **-1Gm armlength**
- **-four laser links**
- **-max 6 year lifetime**

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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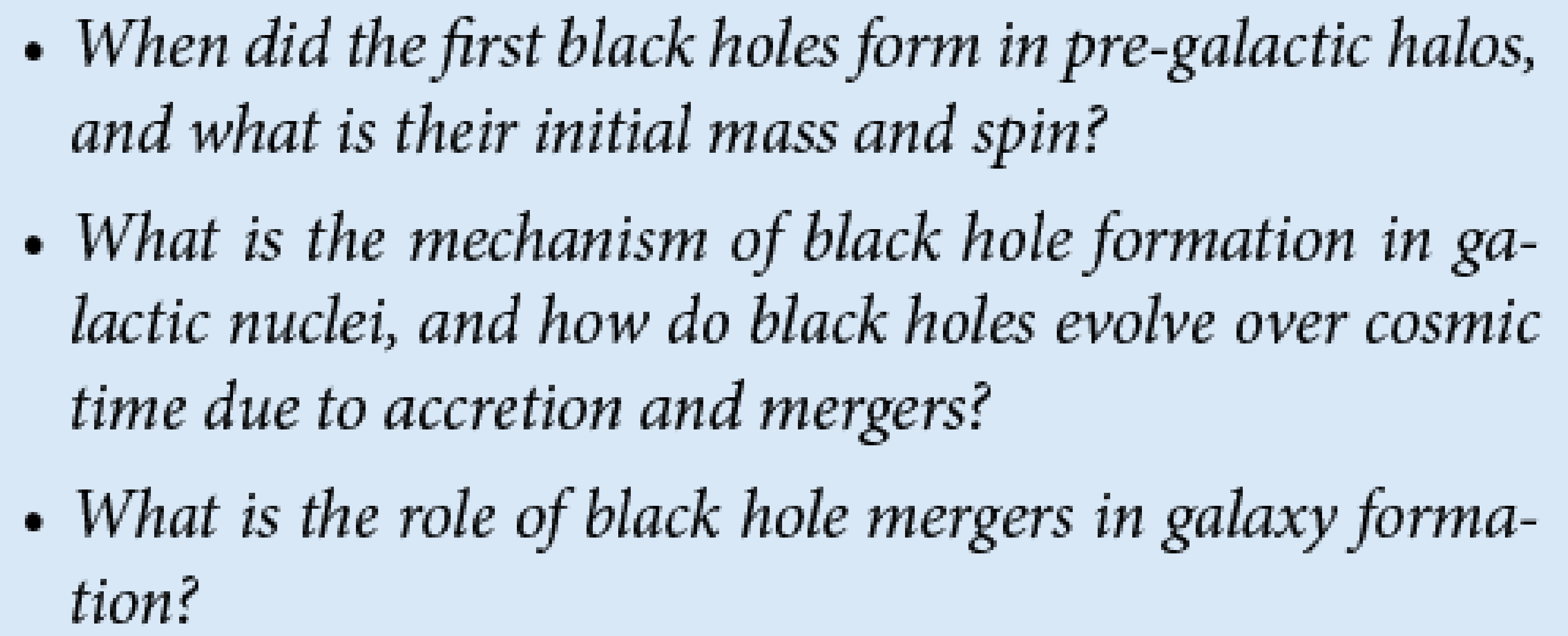

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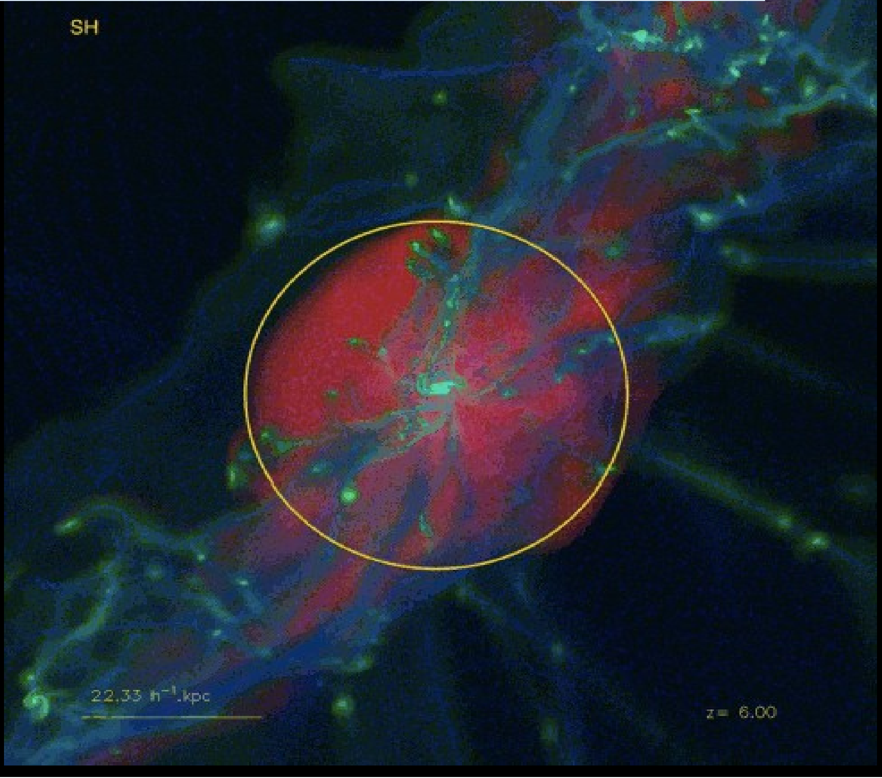

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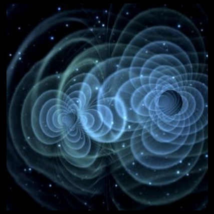

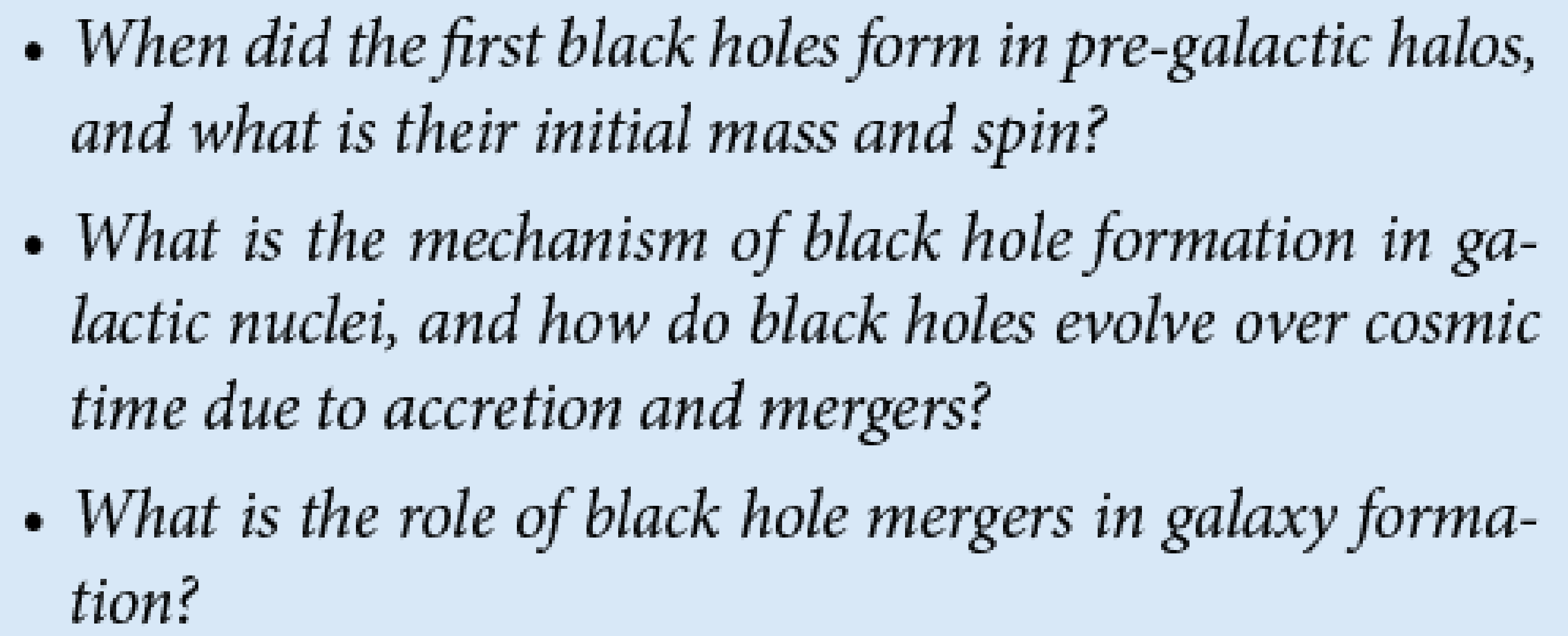

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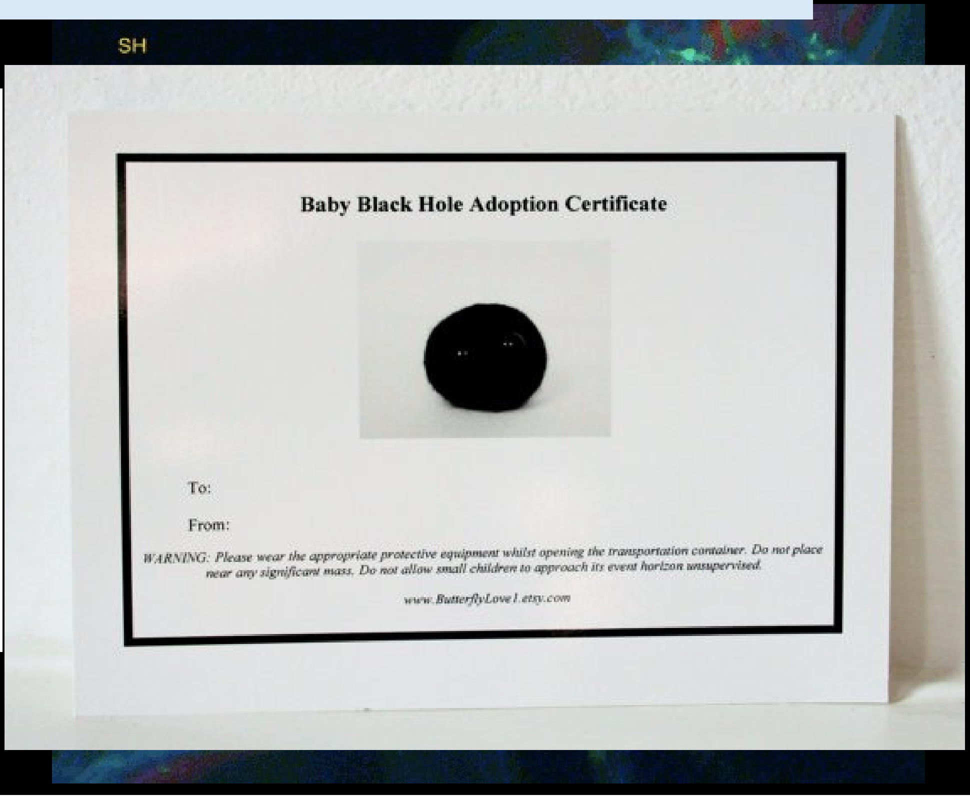


Baby Black Hole Adoption Certificate

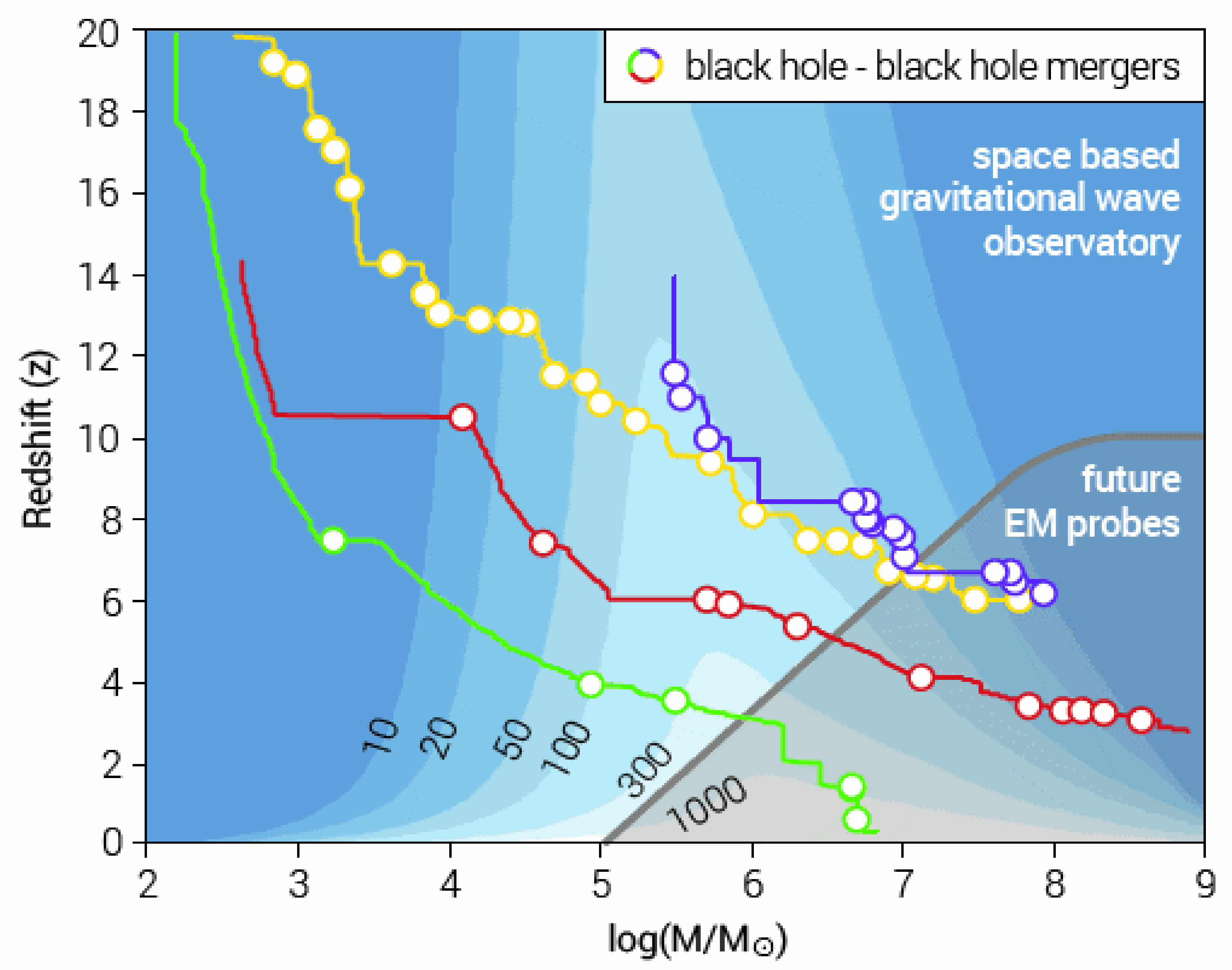
To:

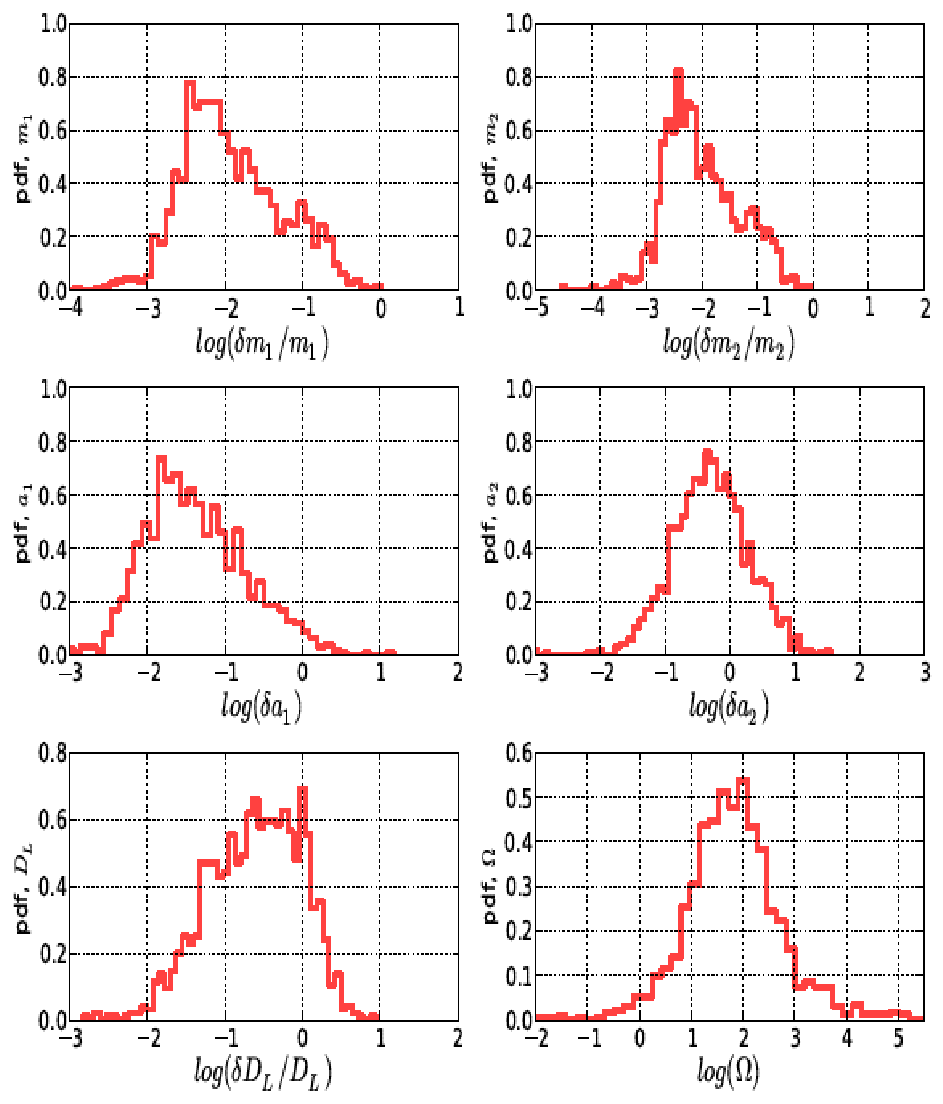
From:

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

eLISA coverage of the Universe





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

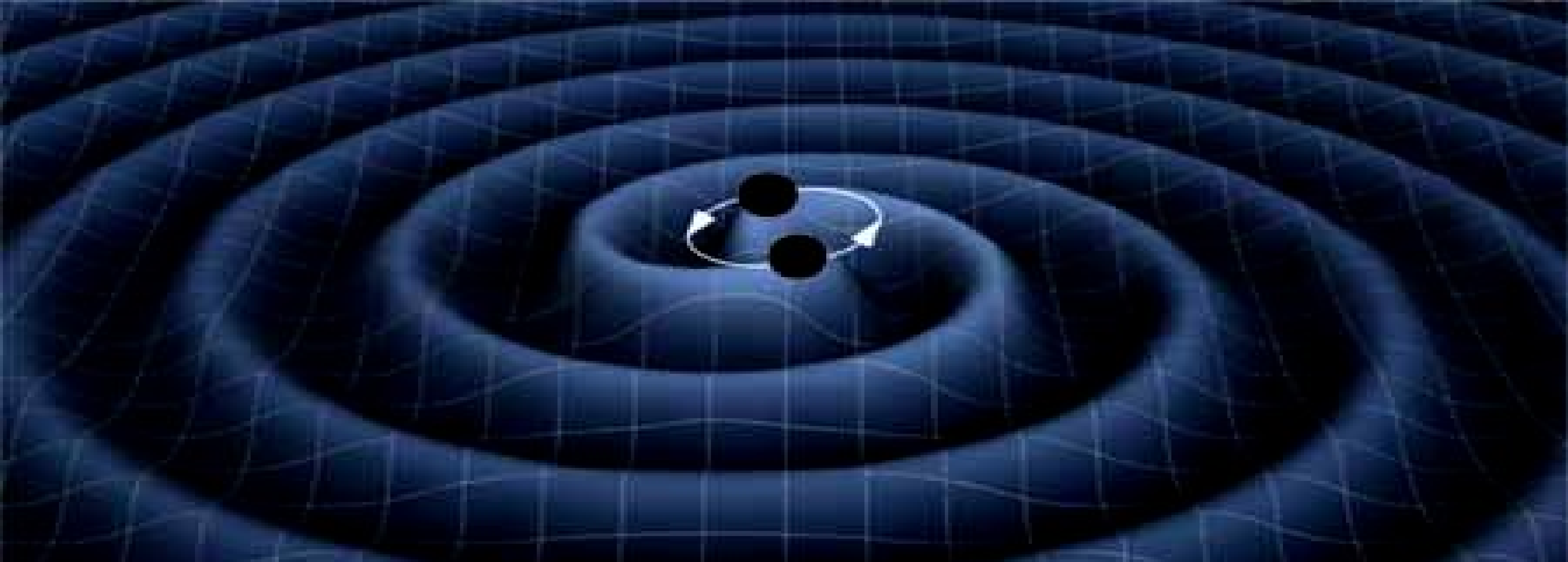
Results of the eLISA science case:

>Individual sources:

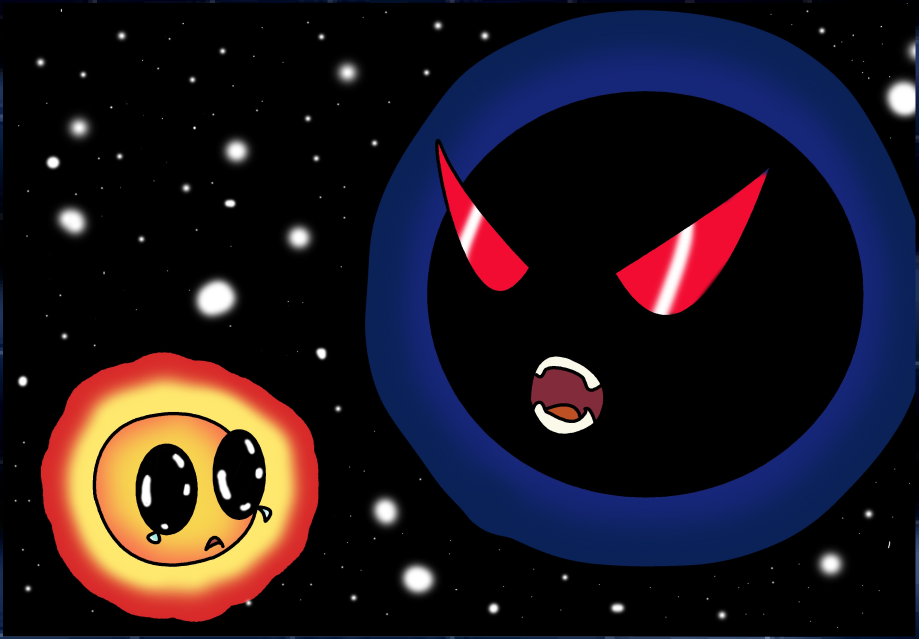
- -Individual (redshifted) masses to <1% relative accuracy
- -spin of the primary hole to <0.1 (in many cases to <0.01)
- -sky location to 10-1000 deg
- -luminosity distance to <10% in most cases
- -no emphasis on multimessenger astronomy

>Population studies:

- -few detection will enable sensible astrophysical statements about MBH seeds and cosmic growth
- -test made mainly on a discrete set of models



Black hole beasts: PTA



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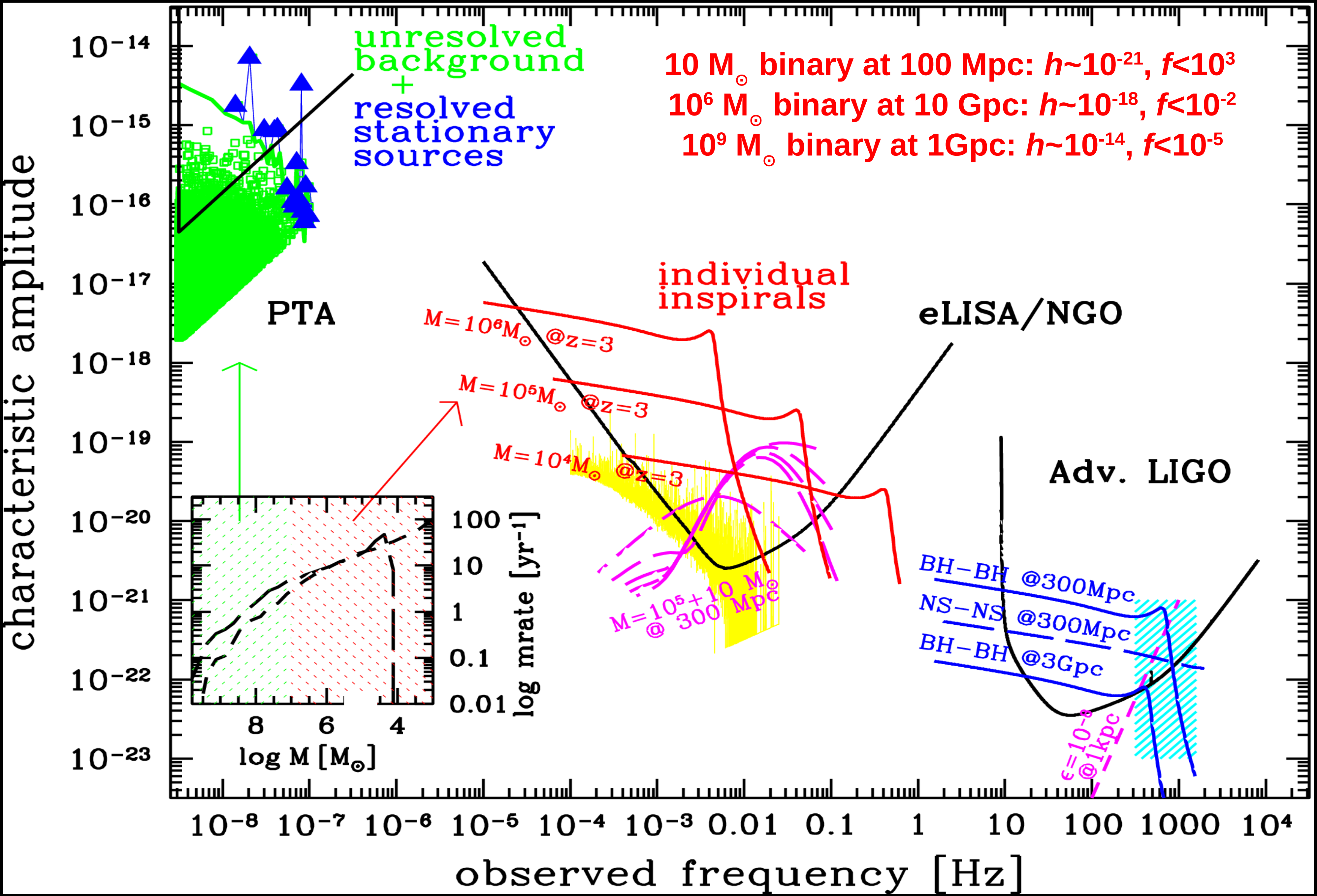

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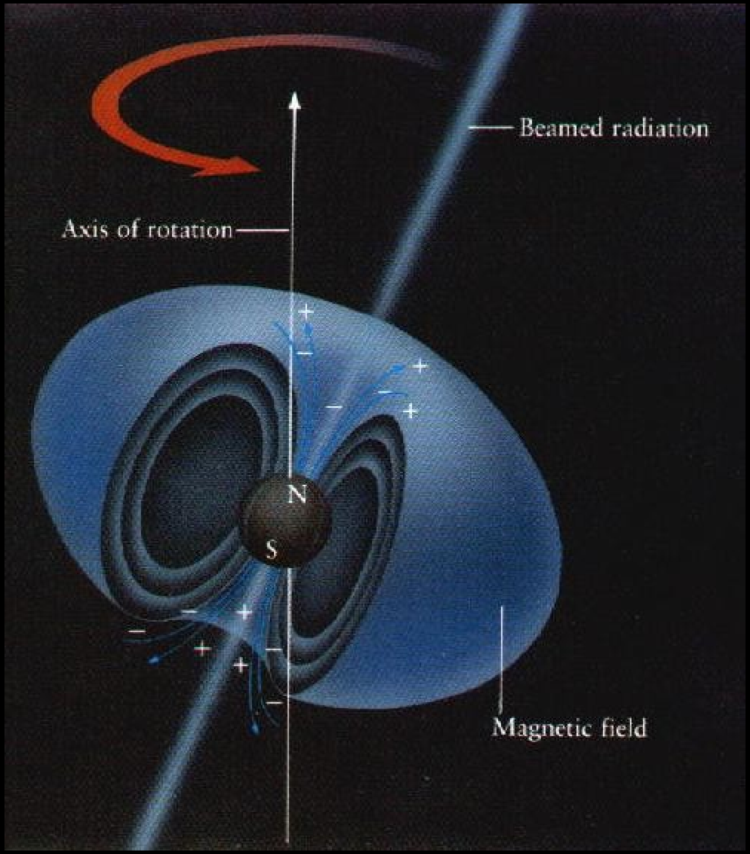
AS 2013

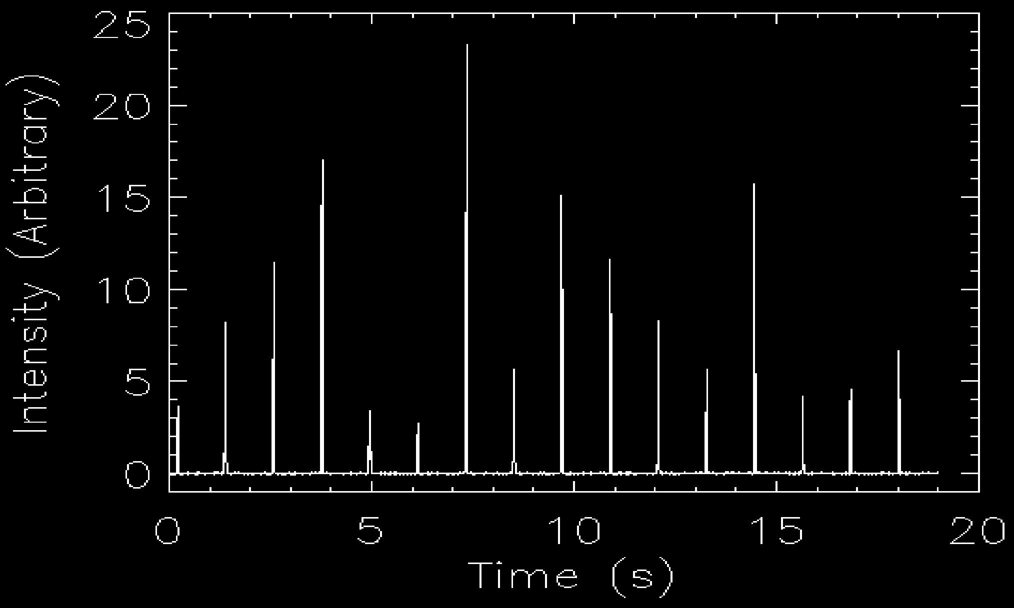
What is pulsar timing?

Pulsars are neutron stars that emit regular burst of radio radiation

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

1- Obseve 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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- -coordinate transformations
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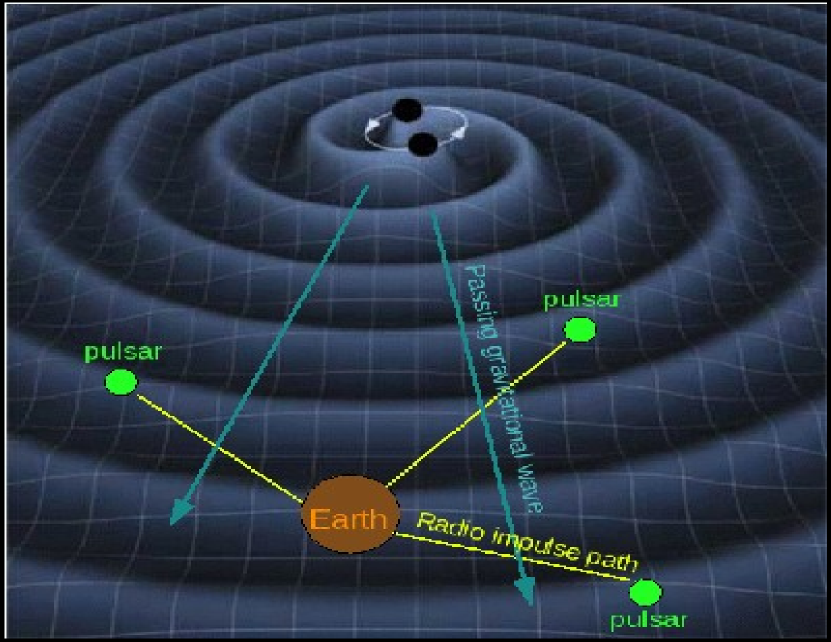
3-Calculate the timing residual *R*

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

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

The timing residual R



The GW passage cause a modulation of the MSP frequency

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

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

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

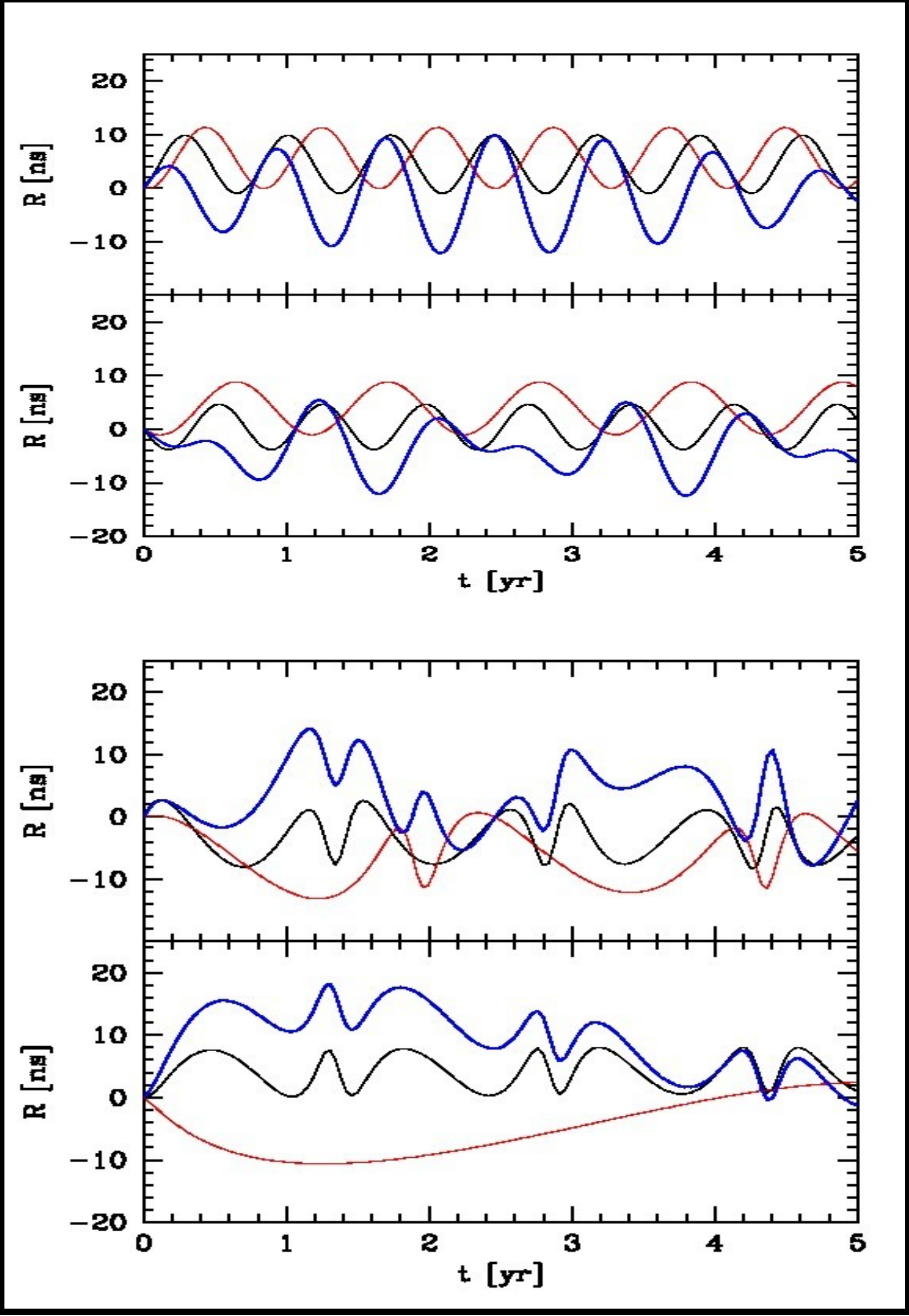
(Sazhin 1979, Helling & Downs 1983, Jenet et al. 2005, Sesana Vecchio & Volonteri 2009)

R~h/(2πf)

$$\begin{aligned} &= \frac{\mathcal{M}^{5/3}}{D}\,[\pi f(t)]^{-1/3} \\ &\simeq 25.7\left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3}\left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\ &\quad\times\left(\frac{f}{5\times10^{-8}\,\mathrm{Hz}}\right)^{-1/3}\,\mathrm{ns} \end{aligned}$$

Examples of signals

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



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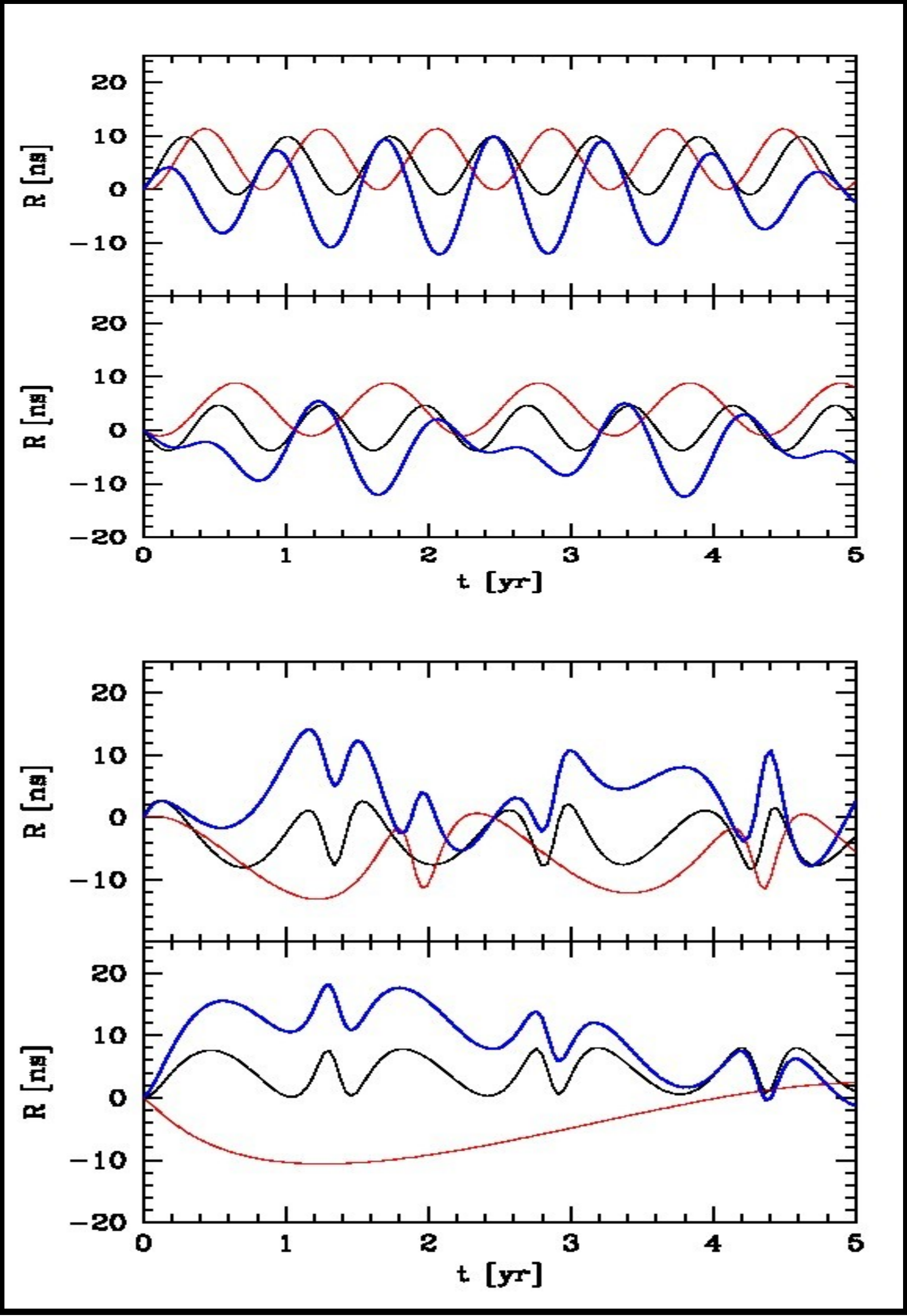
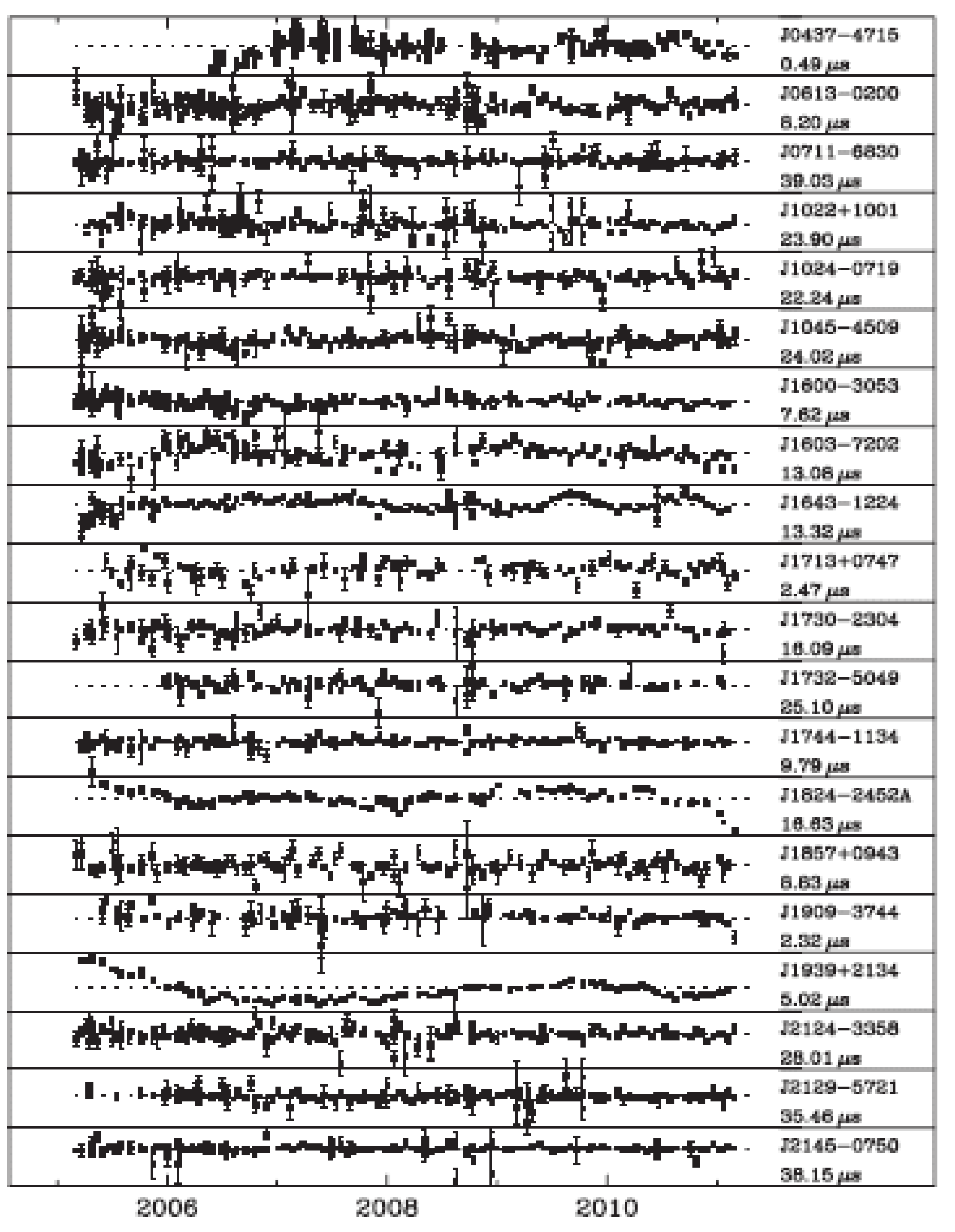
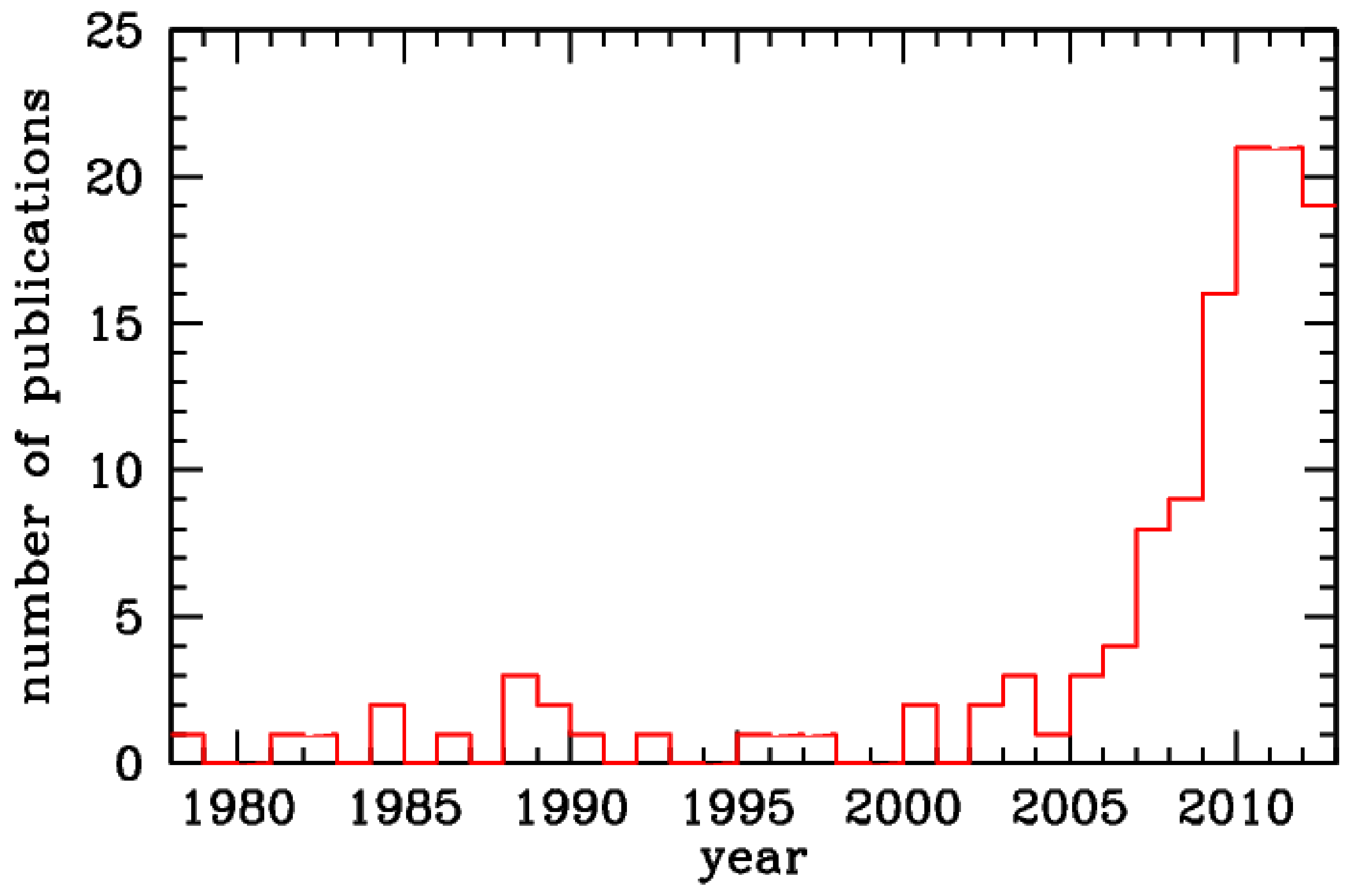


The cruel reality



Manchester et al. 2013

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



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

Theory of GW background from SMBHs

Consider a class of sources with differential number density $d^2n/dzdM$ emitting an energy spectrum $dE/d\ln f$

$$h_c^2(f) = \frac{4G}{\pi c^2 f^2} \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^2 n}{dz d\mathcal{M}} \frac{1}{1+z} \frac{dE_{\rm gw}}{d\ln f_r}$$

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

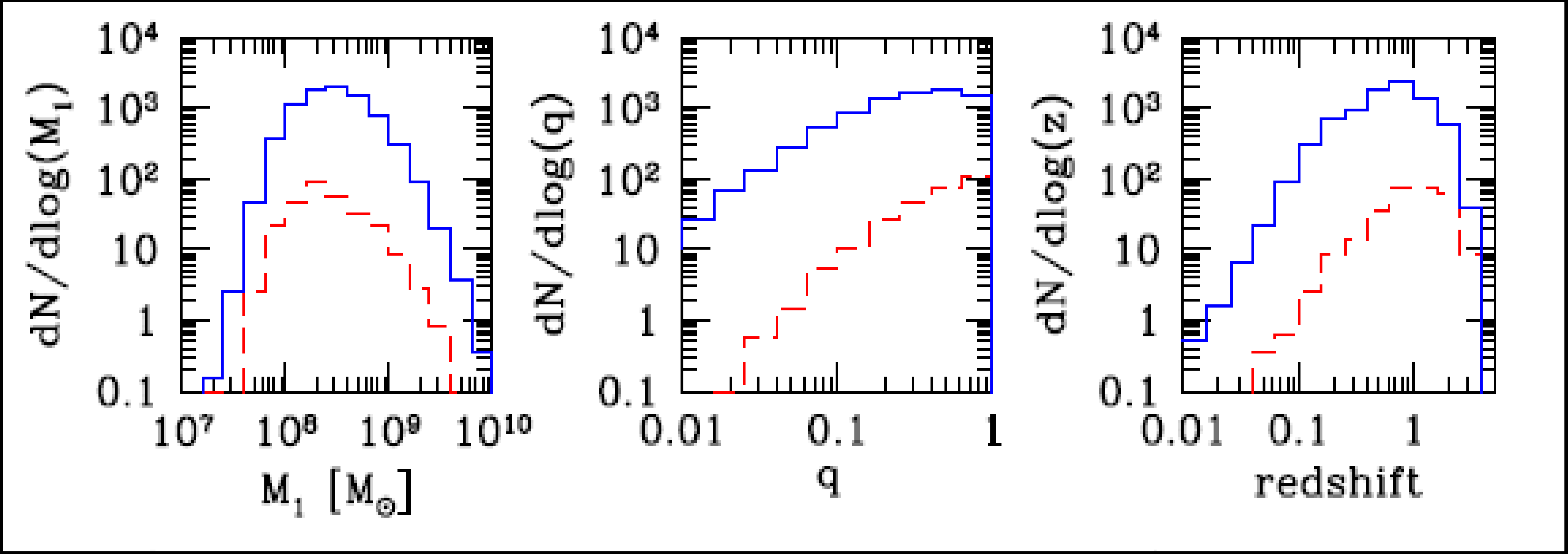
For MBHBs $dN/d\ln f \propto f^{-8/3}$

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

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

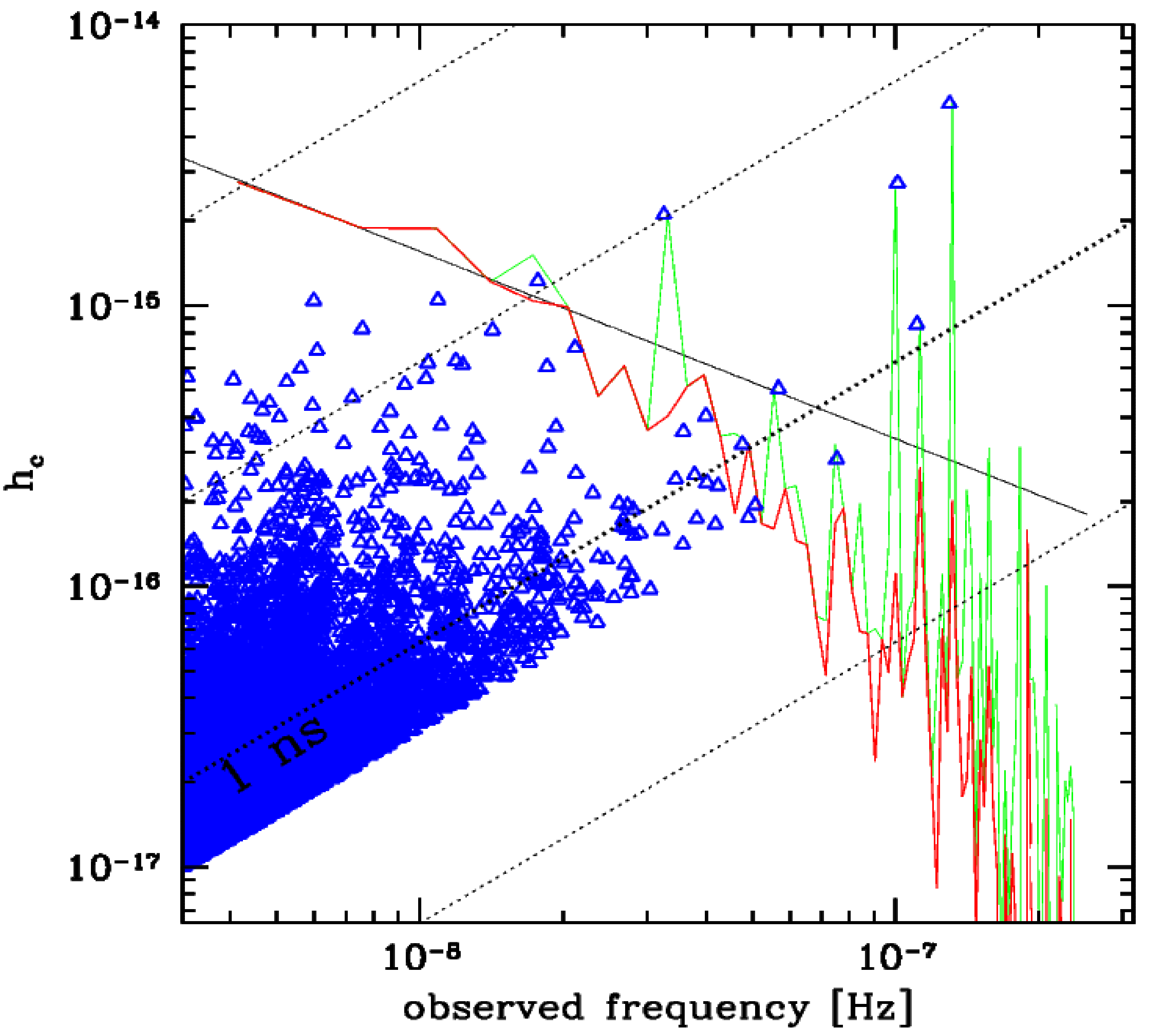
(Phinney 2001, Jaffe & Backer 2003, Wyithe & Loeb 2003, Sesana et al. 2004, Enoki et al. 2004)

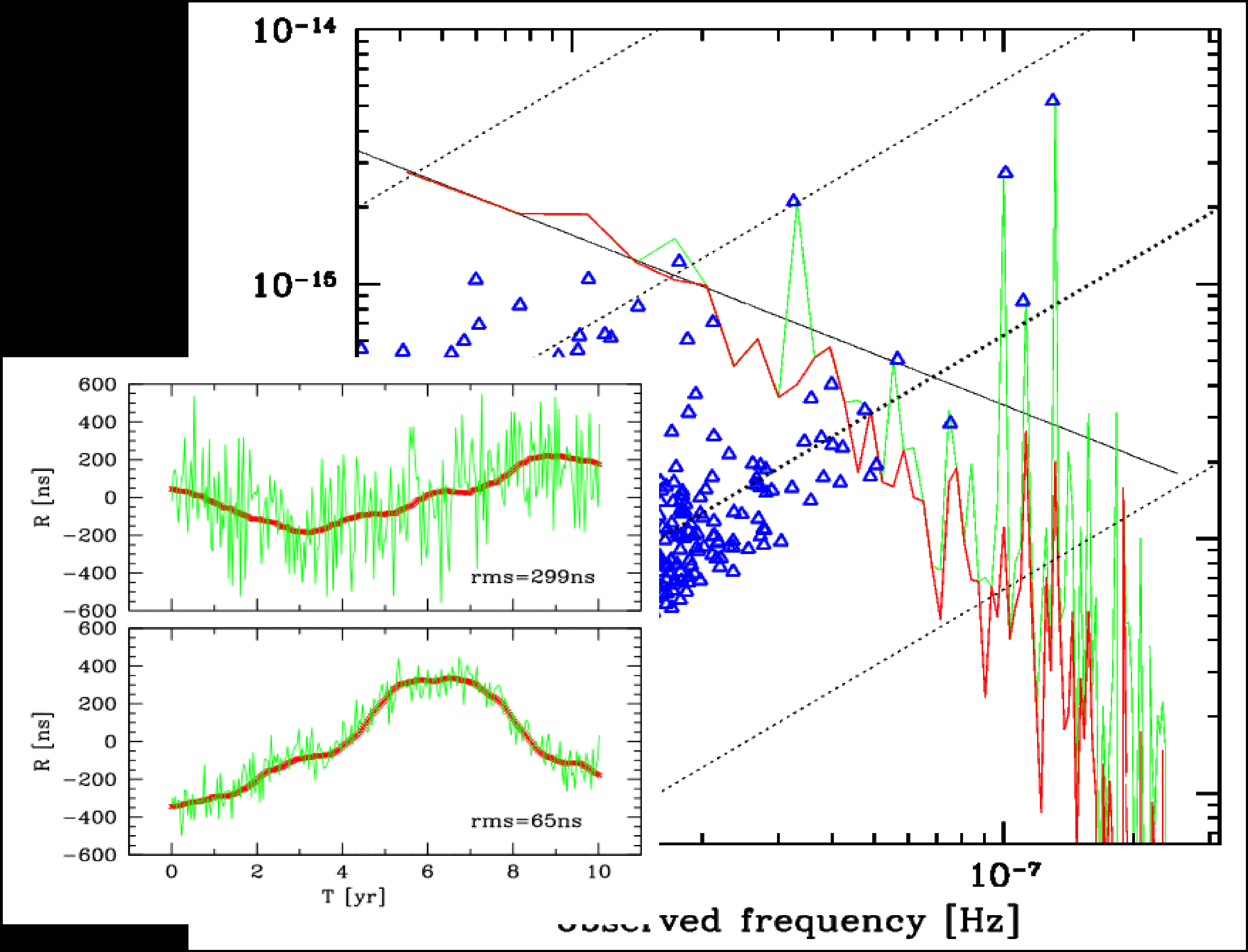
Detail of the contributing population

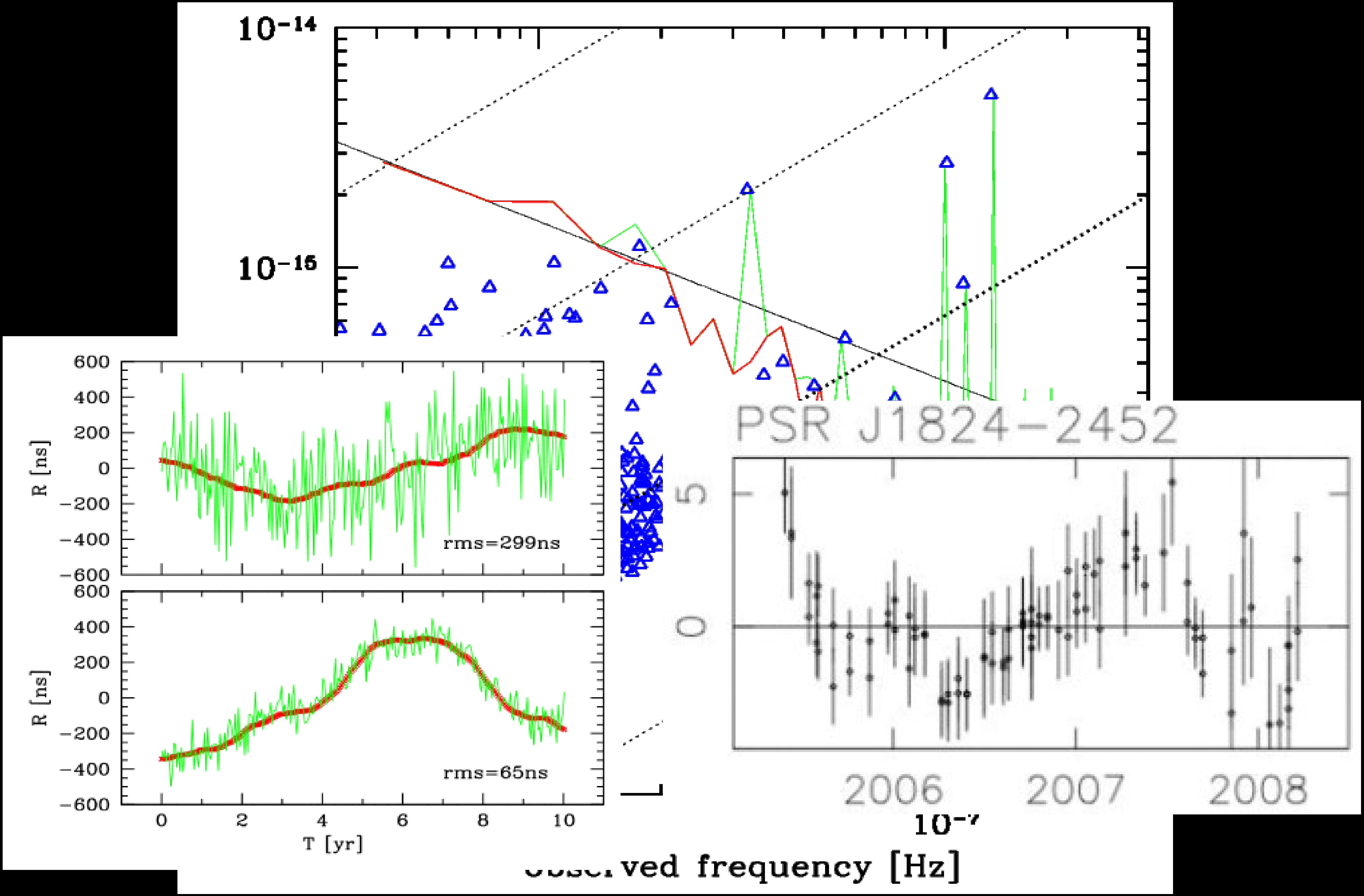


-sensitive to massive (>$10^8 M_\odot$), cosmologically nearby (*z*<2) binaries: complementary to the LISA range (AS et al. 2008, 2009).

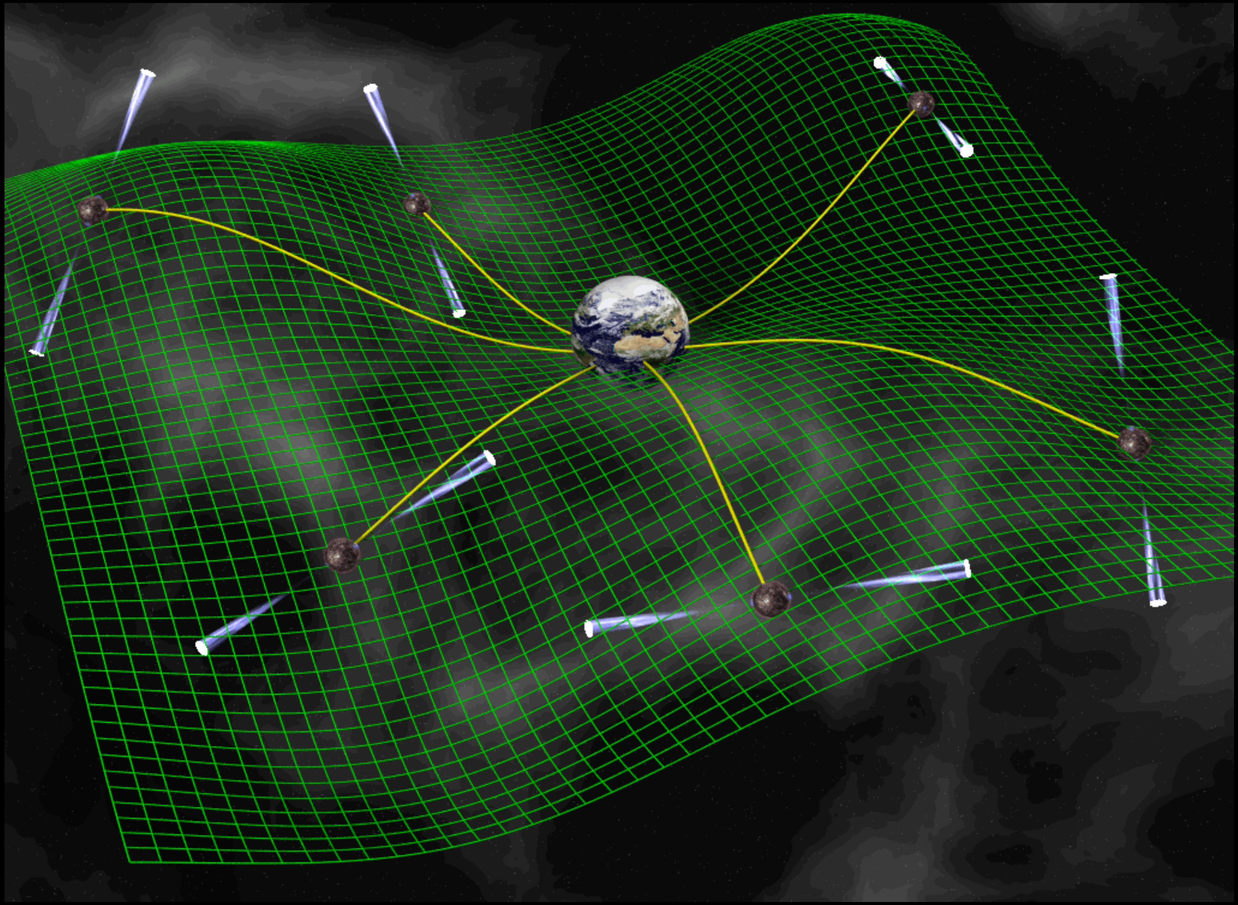
-if a source can be individually resolved, its sky position can be pinned down to ~1-50deg^2 accuracy (AS & Vecchio 2010). Promising prospects for multimessenger astronomy (massive+nearby---> bright counterparts)


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


10^{-14}
10^{-15}
10^{-7}
ved frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]

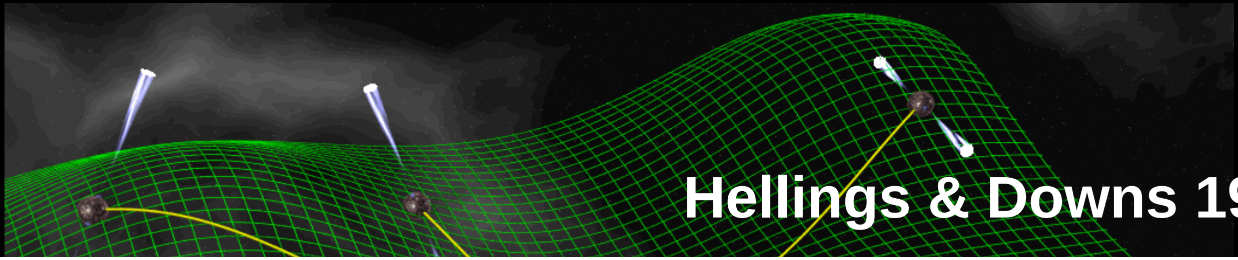


There are, however, many other sources of red noise in pulsar timing: intrinsic spin noise, DM effects, etc.

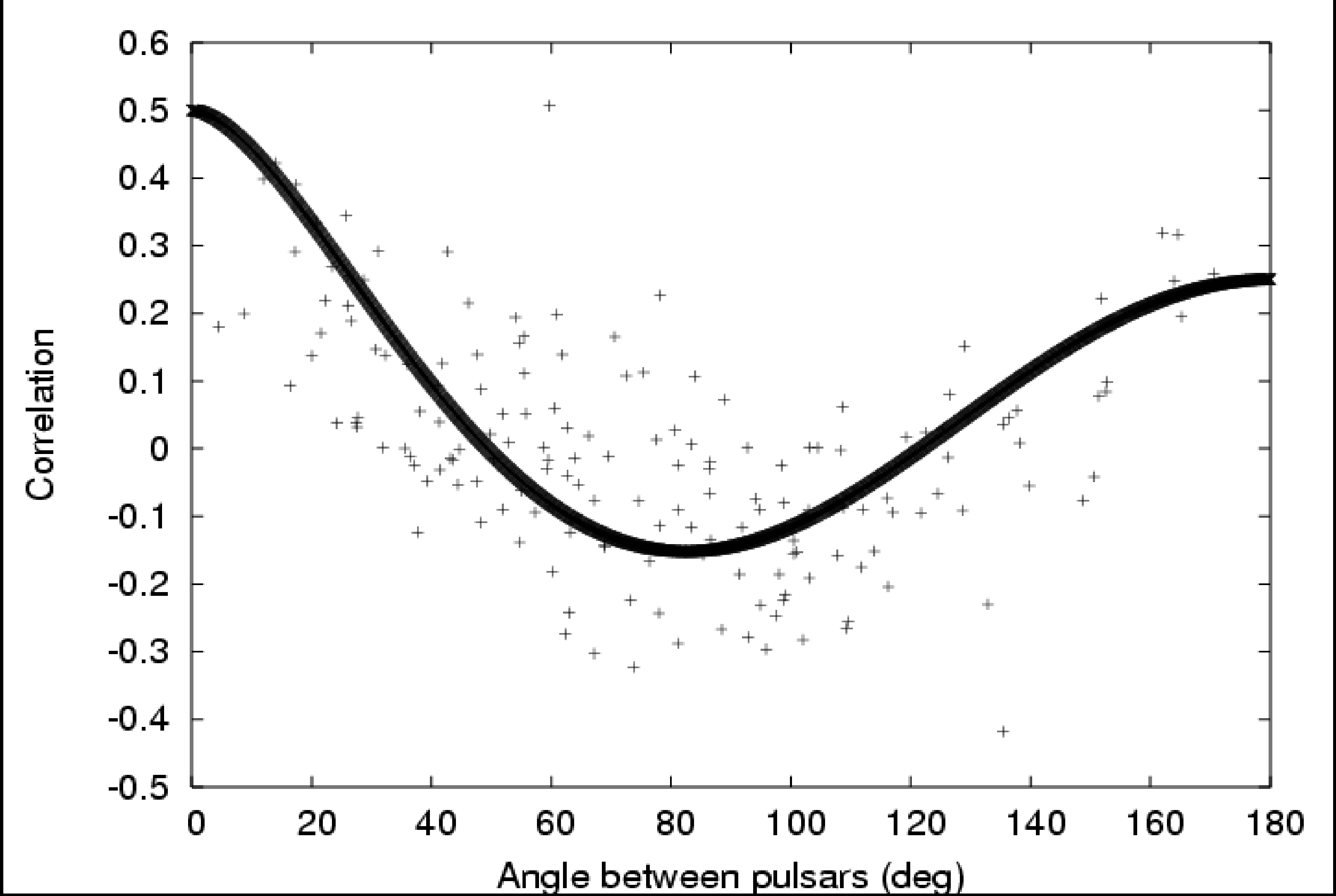


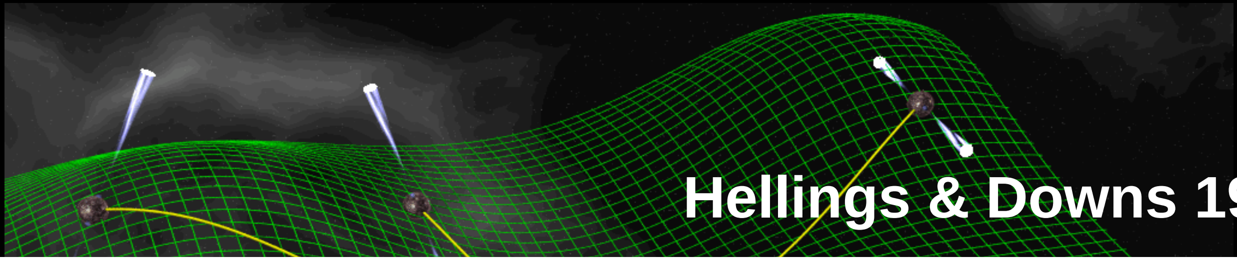
This very red signal has a peculiar correlation pattern among different pairs of pulsars, given by the quadrupolar nature of gravitational waves

Other sources of red noise are uncorrelated!

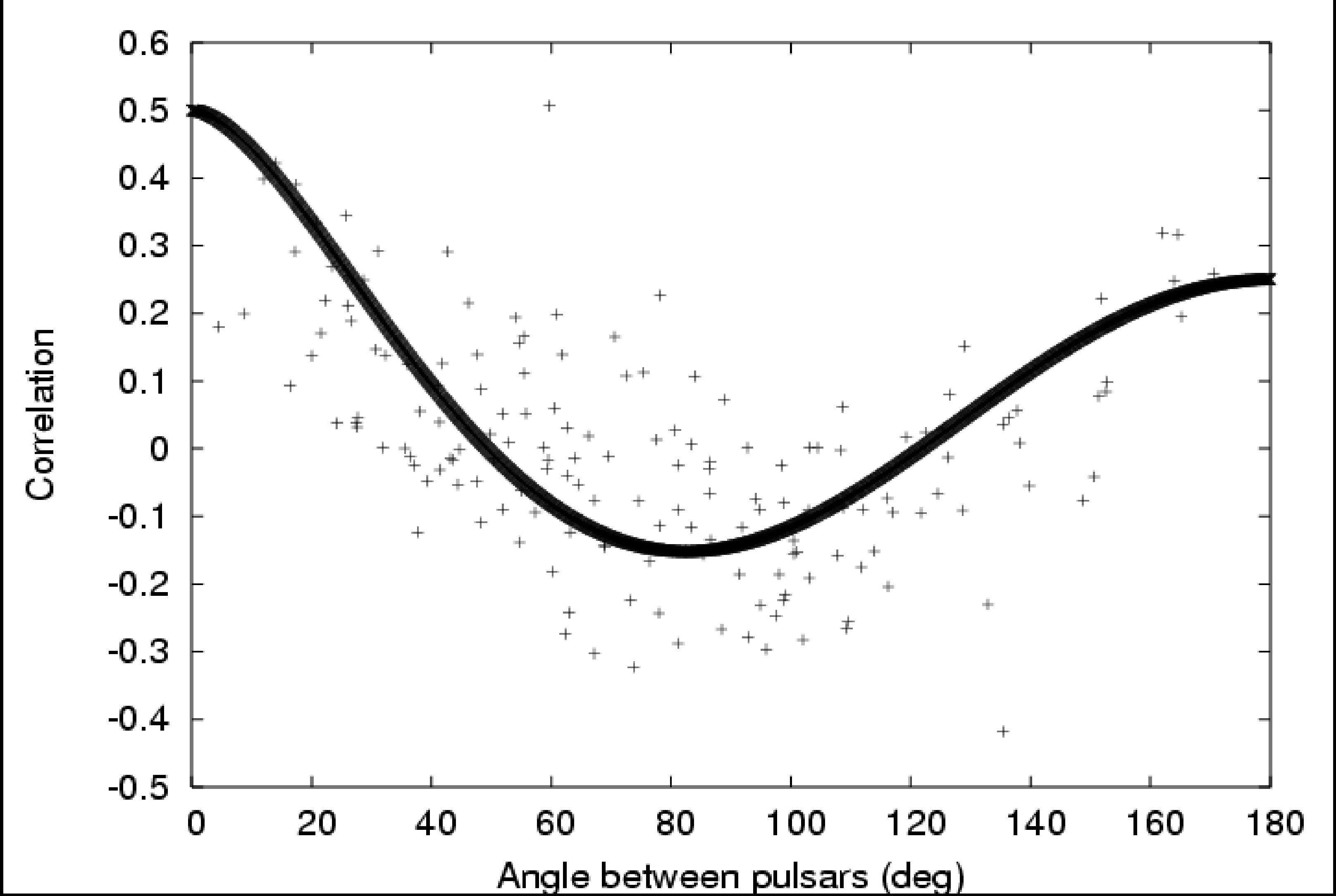


Hellings & Downs 1983





Hellings & Downs 1983

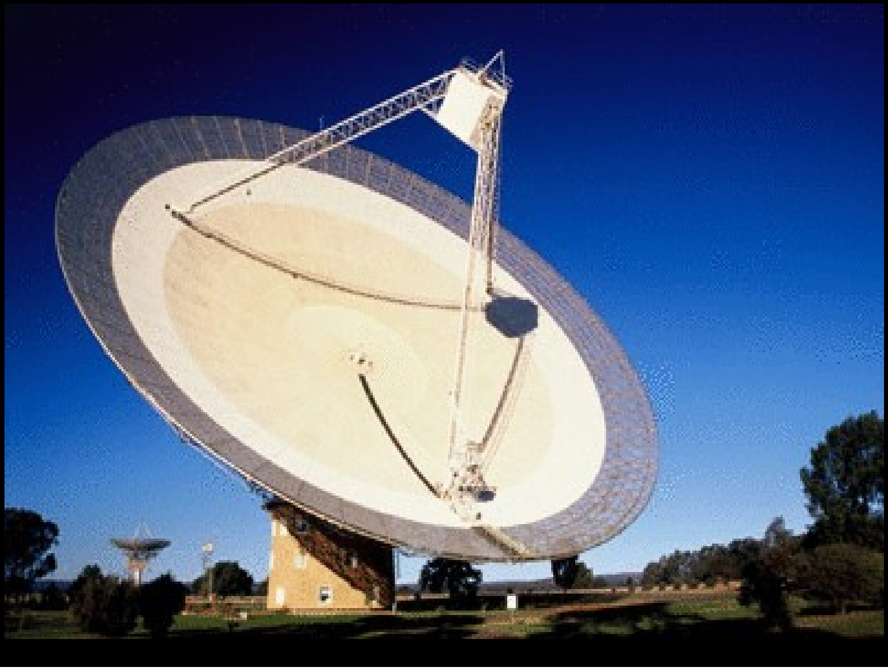


IT IS ESSENTIAL TO CORRELATE THE SIGNAL OF AS MANY PULSARS AS POSSIBLE

The pulsar timing arrays network

EPTA/LEAP (large European array for pulsars)

NanoGrav (north American nHz observatory for gravitational waves)



PPTA (Parkes pulsar timing array)

The pulsar timing arrays network

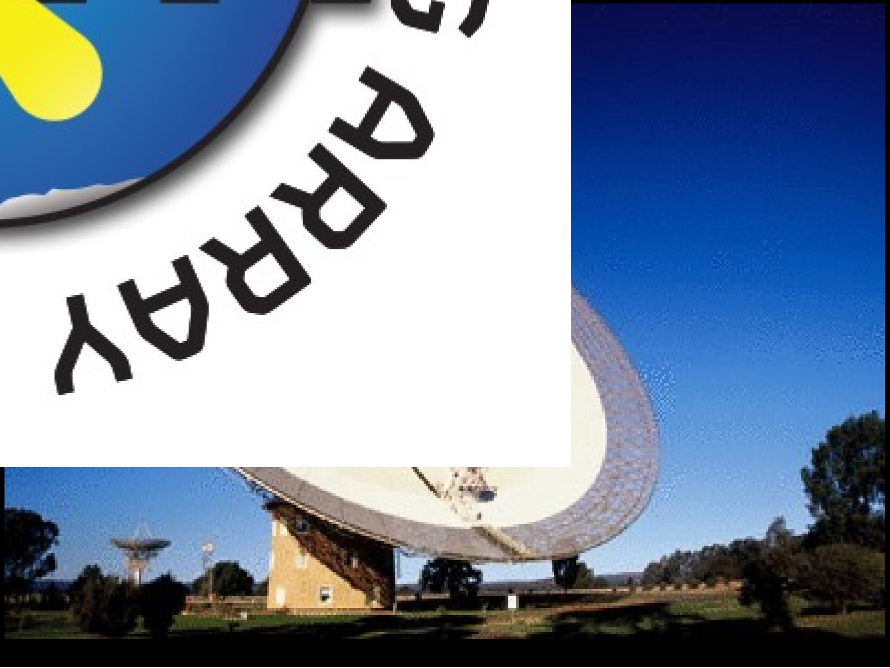
EPTA/LEAP (large European

INTERNATIONAL PULSAR TIMING ARRAY

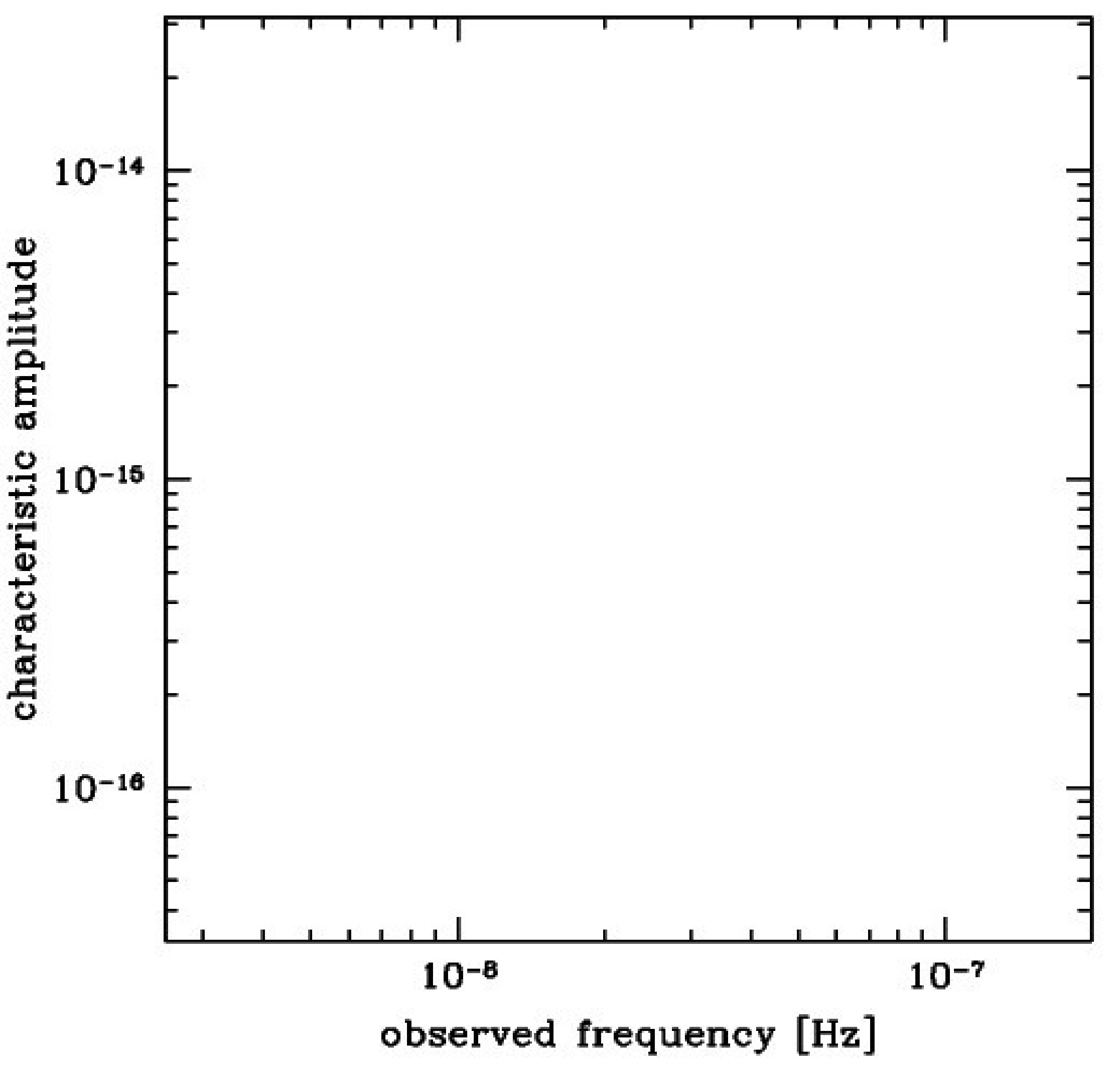
IPTA

rican nHz
onal waves)

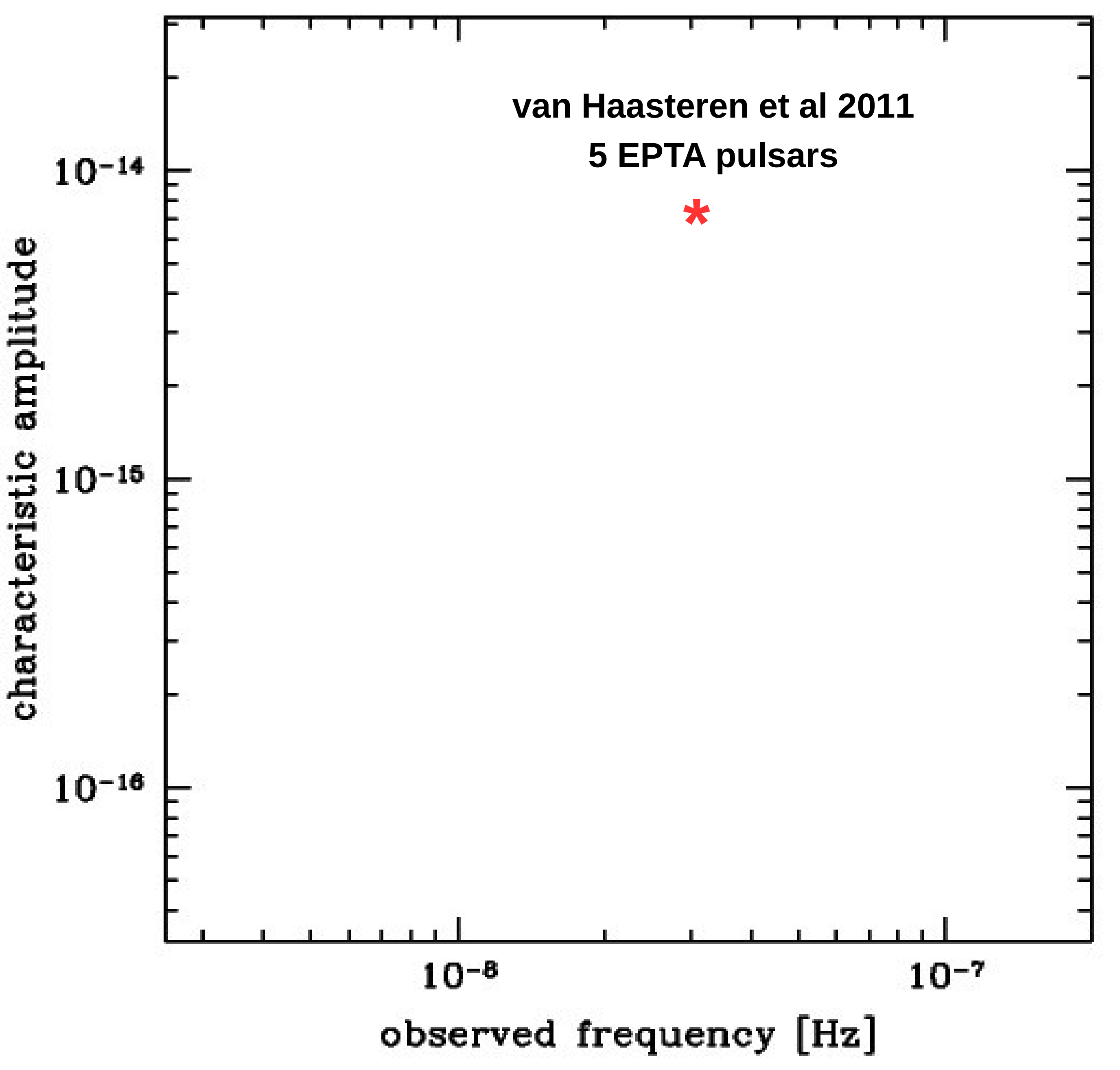
PPTA (Parke



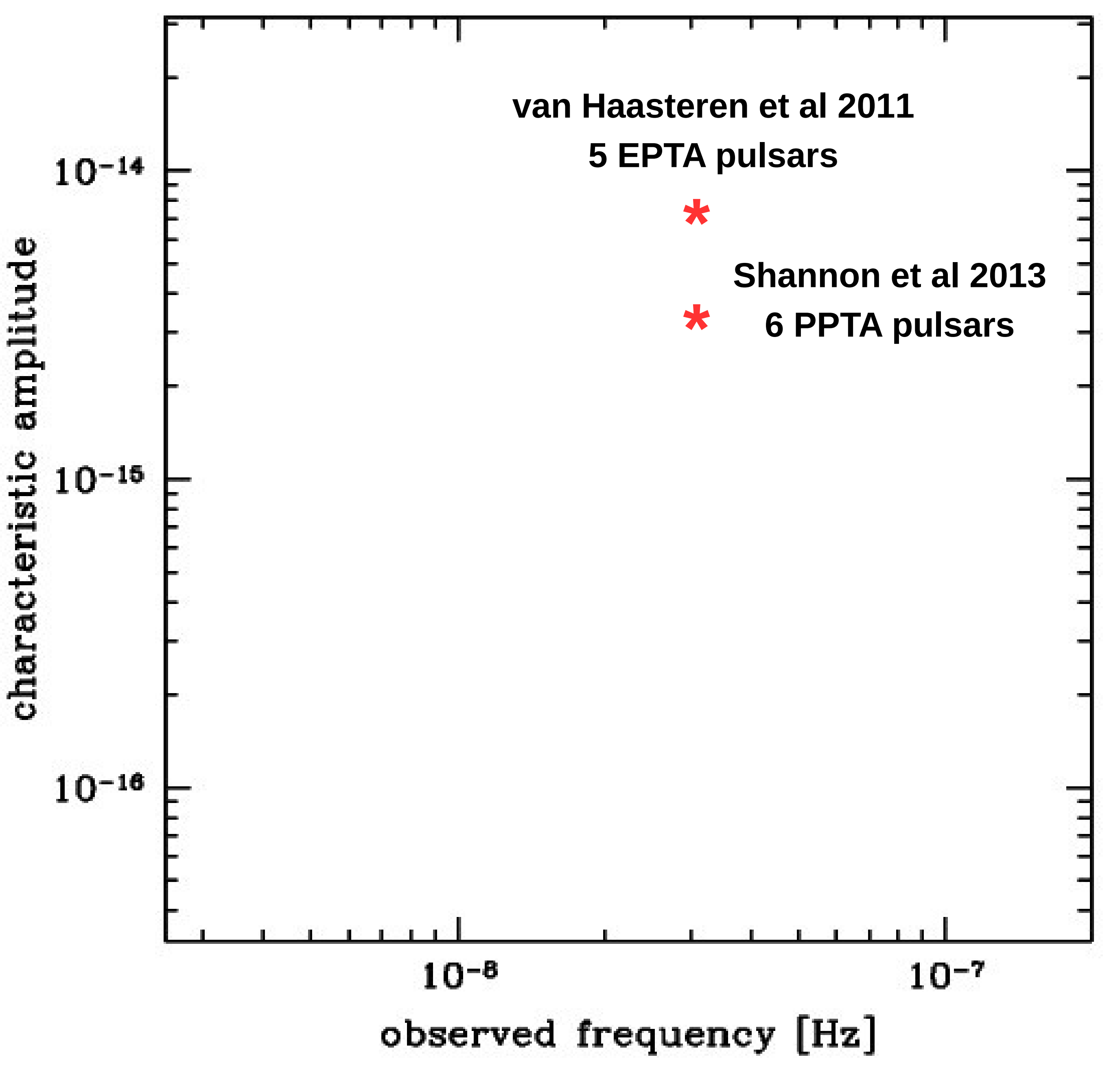
Where we stand: theory vs observations



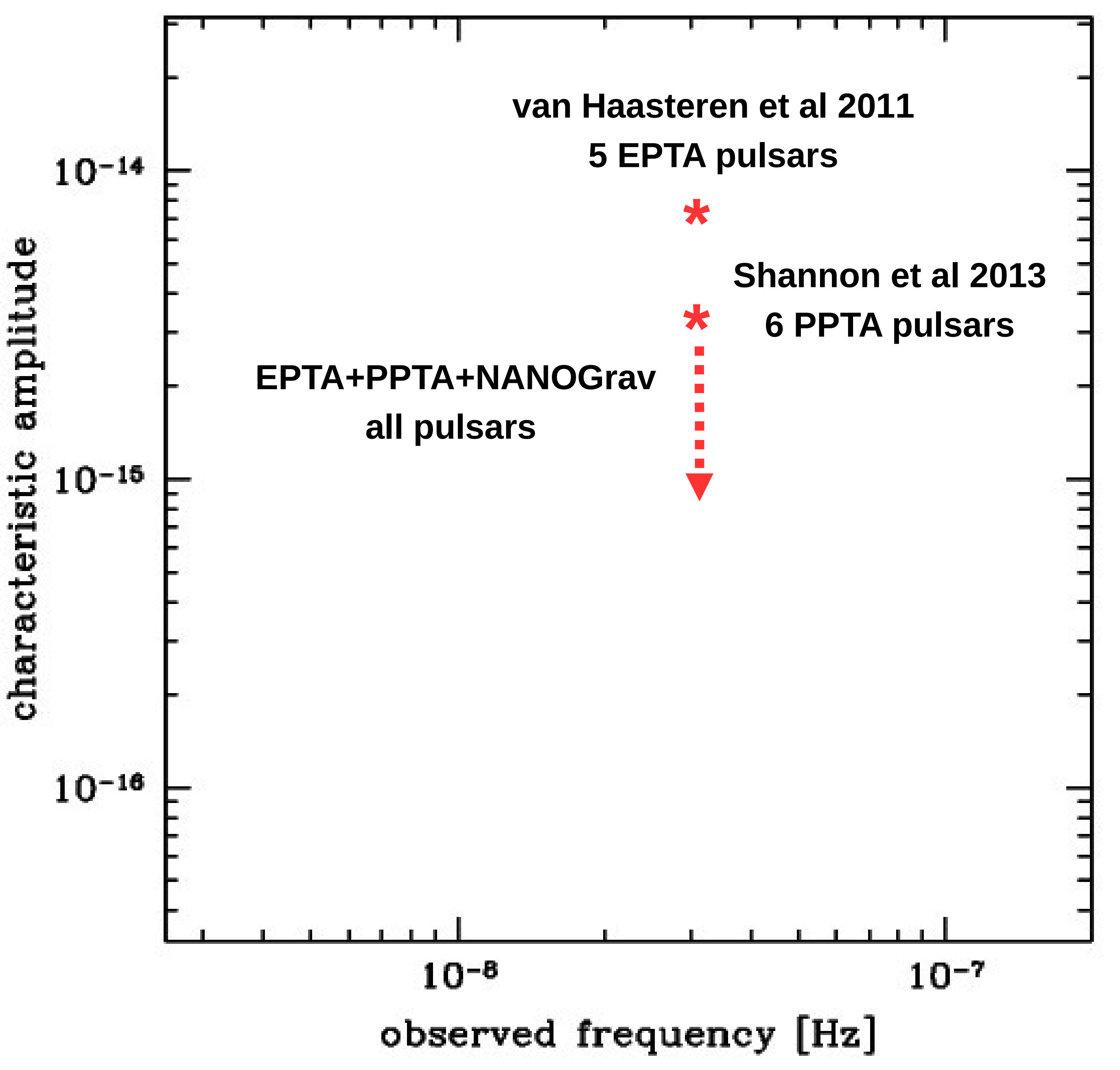
Where we stand: theory vs observations



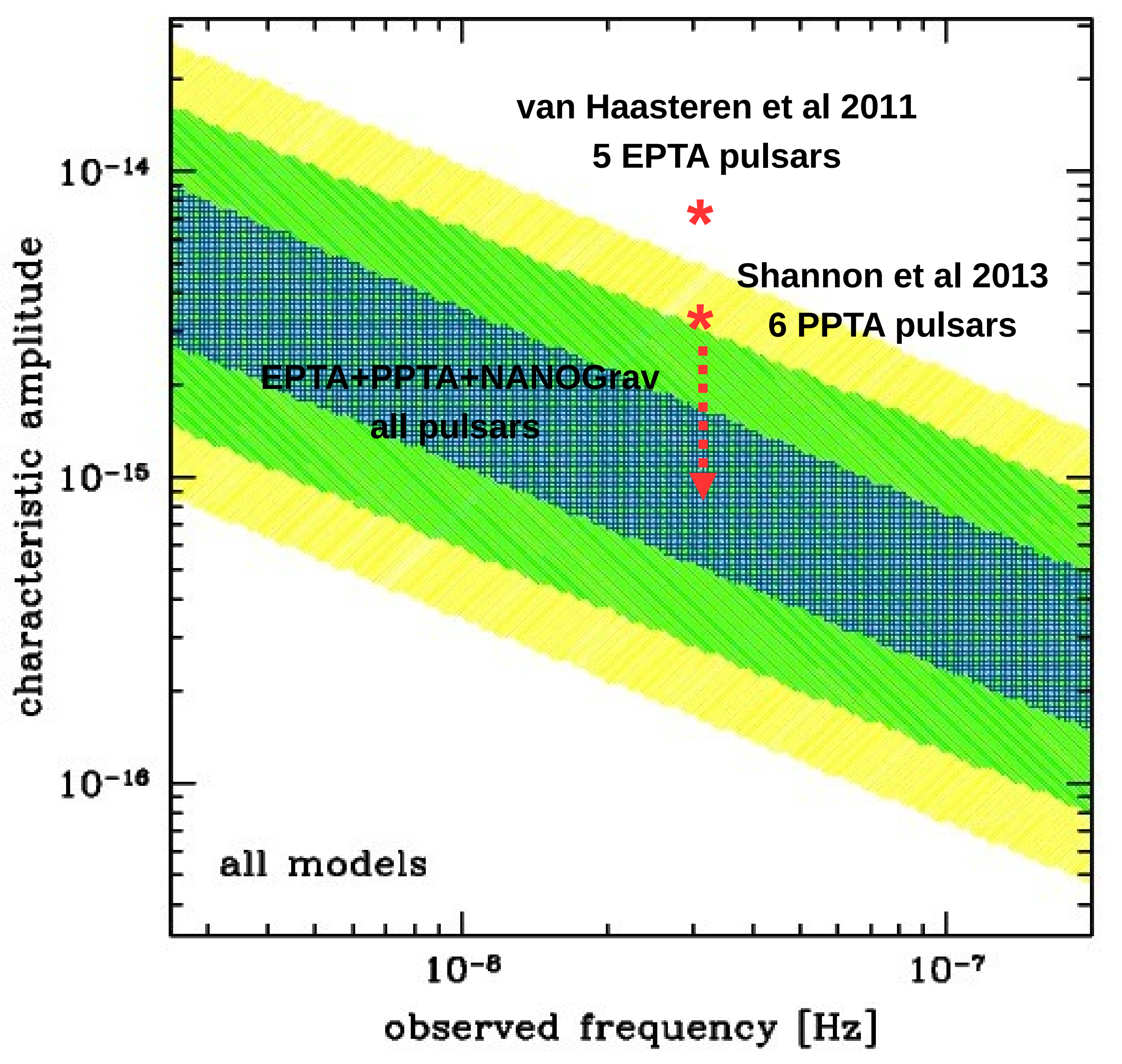
Where we stand: theory vs observations



Where we stand: theory vs observations

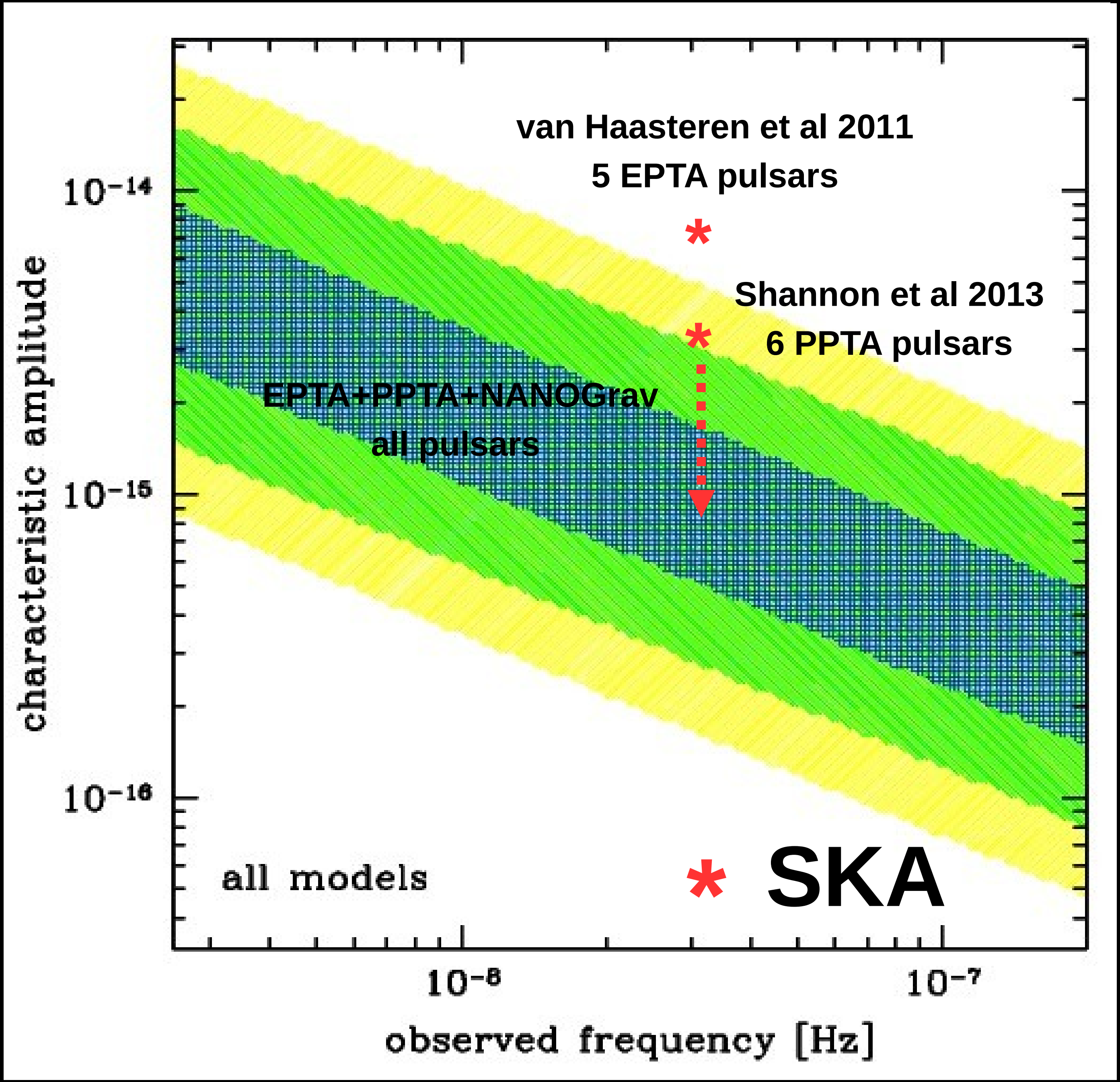


Where we stand: theory vs observations



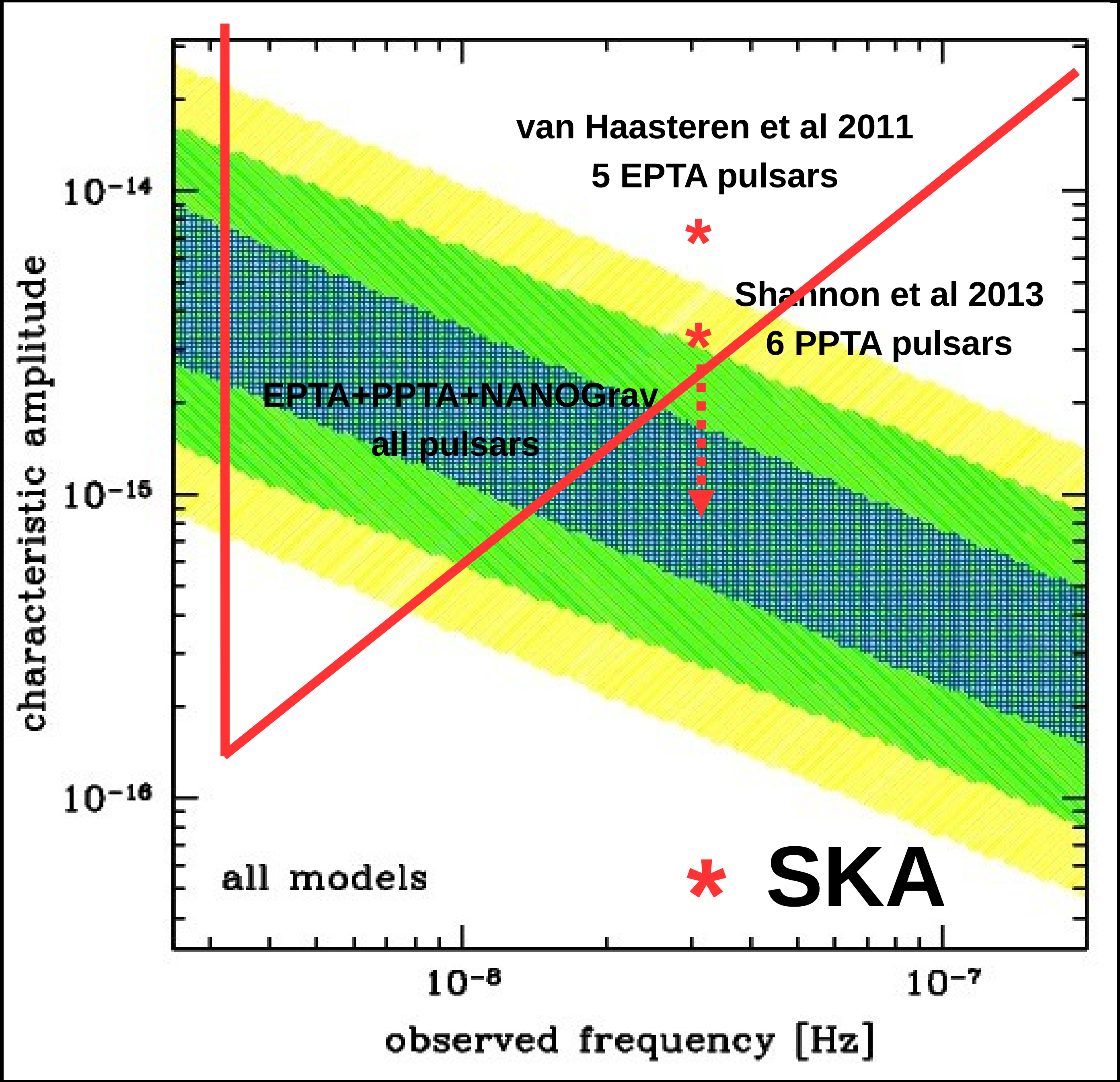
AS et al. 2008; AS et al. 2009; AS 2013

Where we stand: theory vs observations

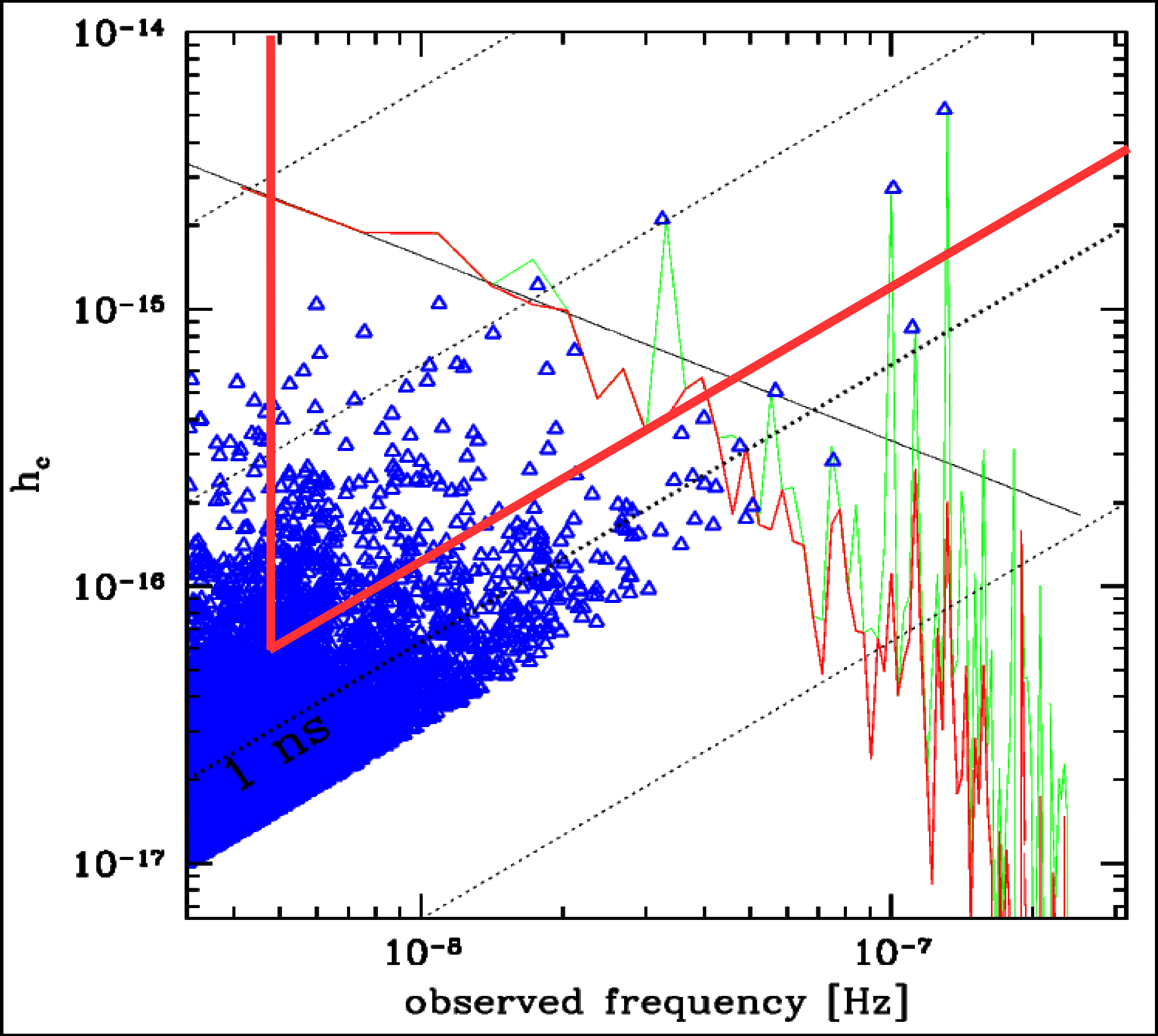


AS et al. 2008; AS et al. 2009; AS 2013

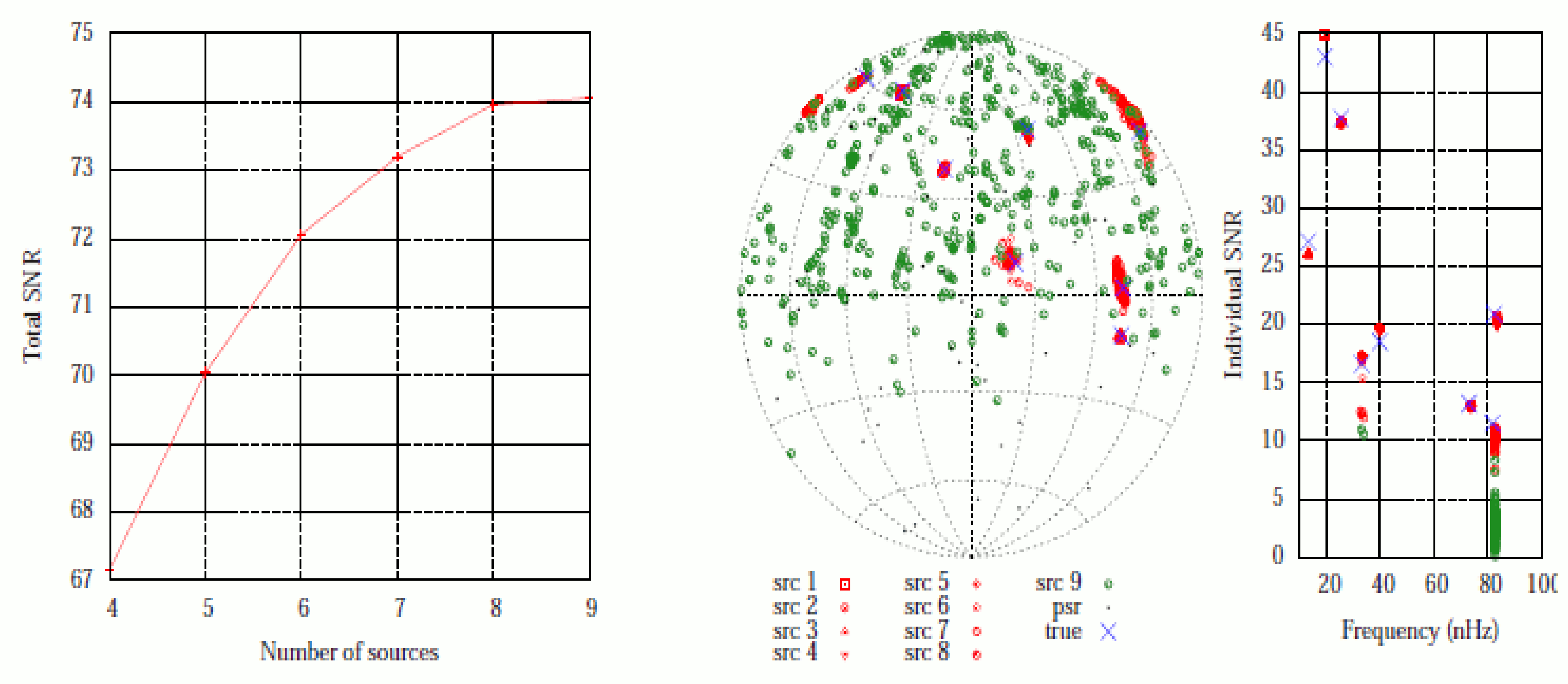
Where we stand: theory vs observations



AS et al. 2008; AS et al. 2009; AS 2013


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

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



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

-We can determine the source parameters with high accuracy:

> SNR within few%

> sky location within few deg offset

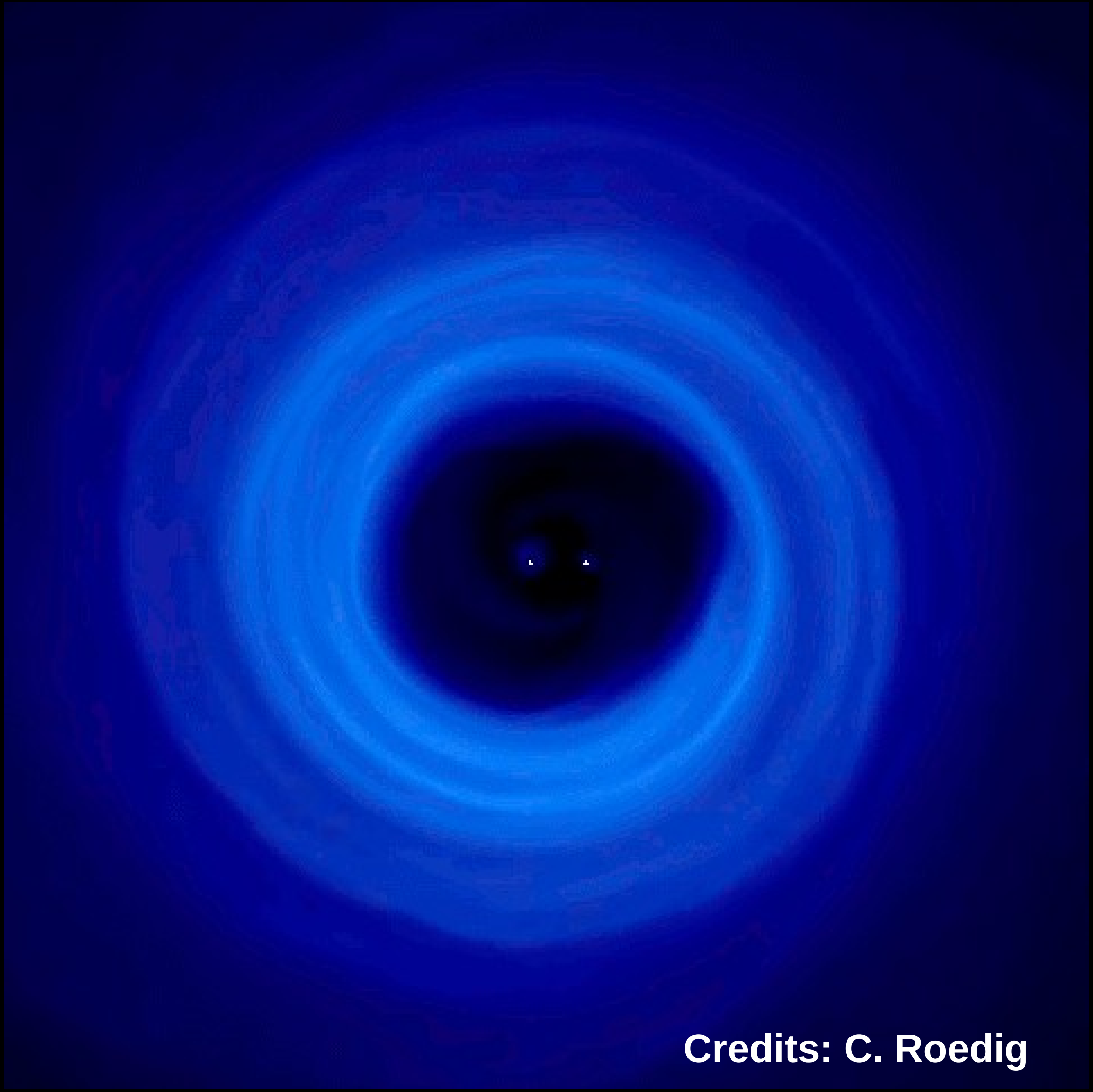
> frequency at sub-bin level

-Extremely promising, needs test on more realistic situations

ELECTROMAGNETIC COUNTERPARTS

Tanaka et al. 2012, AS et al. 2012

MBHB+circumbinary disk



Credits: C. Roedig

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

-UV generated by the Inner disks. Periodic variability.

-X ray corona. Periodic variability

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

-Double fluorescence 6.4keV Kα iron lines

ELECTROMAGNETIC COUNTERPARTS

Tanaka et al. 2012, AS et al. 2012

MBHB+circumbinary disk

Credits: C. Roedig

- *-Opt/IR dominated by the outer disk. Steady?*
- *-UV generated by the Inner disks. Periodic variability.*
- *-X ray corona. Periodic variability*
- *-Variable broad emission lines (in response to the UV/X ionizing continuum)*

More at the HE Seminar tomorrow

Summary:

Spins:

BHs can align or antialign with their accretion disks

So far, two limiting models (coherent and chaotic accretion) have been employed in the literature (with few exception)

We employ a semianalytic model for MBH and galaxy evolution, together with phenomenological prescriptions that *anchor the properties of the accretion flow to the kinematics of the host galaxy*

While the coherent and chaotic models fail, *our models fully accounts for the measured MBH spins*.

Gravitational waves:

Naturally emitted by MBHBs along the cosmic history

eLISA will see them across the Universe

PTA may lead to a *direct detection in the next 5+ years*