Astrophysics and detection of gravitational wave sources

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OUTLINE

LECTURE 6/7 (Tuesday afternoon): space based/PTA

-Massive black hole binaries (MBHBs): formation and dynamics
-LISA science with MBHBs
-Pulsar Timing Arrays (PTA): principles

LECTURE 8 (Wednesday morning): PTA

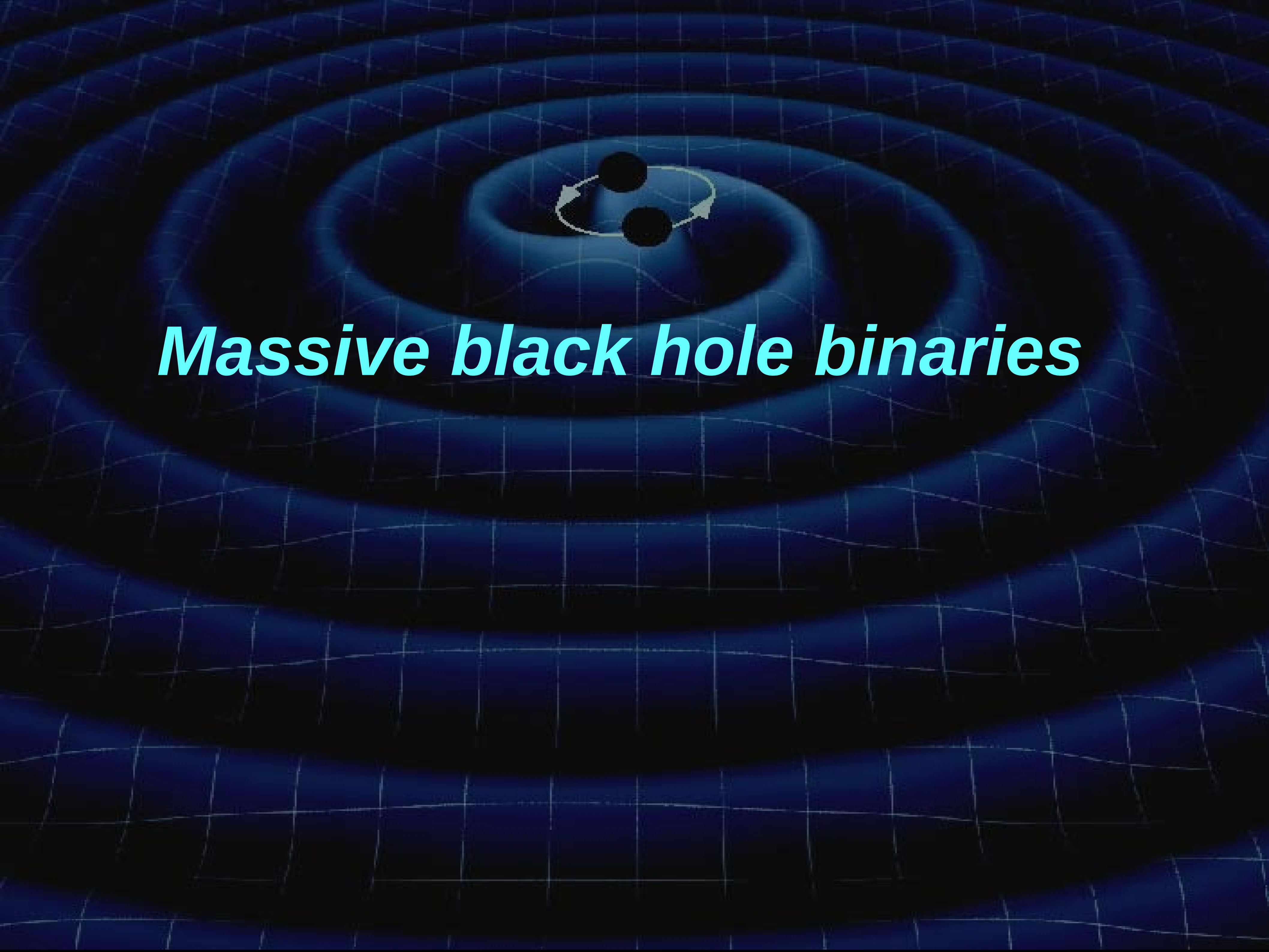
-MBHB detecion PTAs: status and prospects

***Physics of compact objects in GR and beyond**
(Prof. Gualtieri)

***Data analysis and GR tests**
(Prof. Del Pozzo)

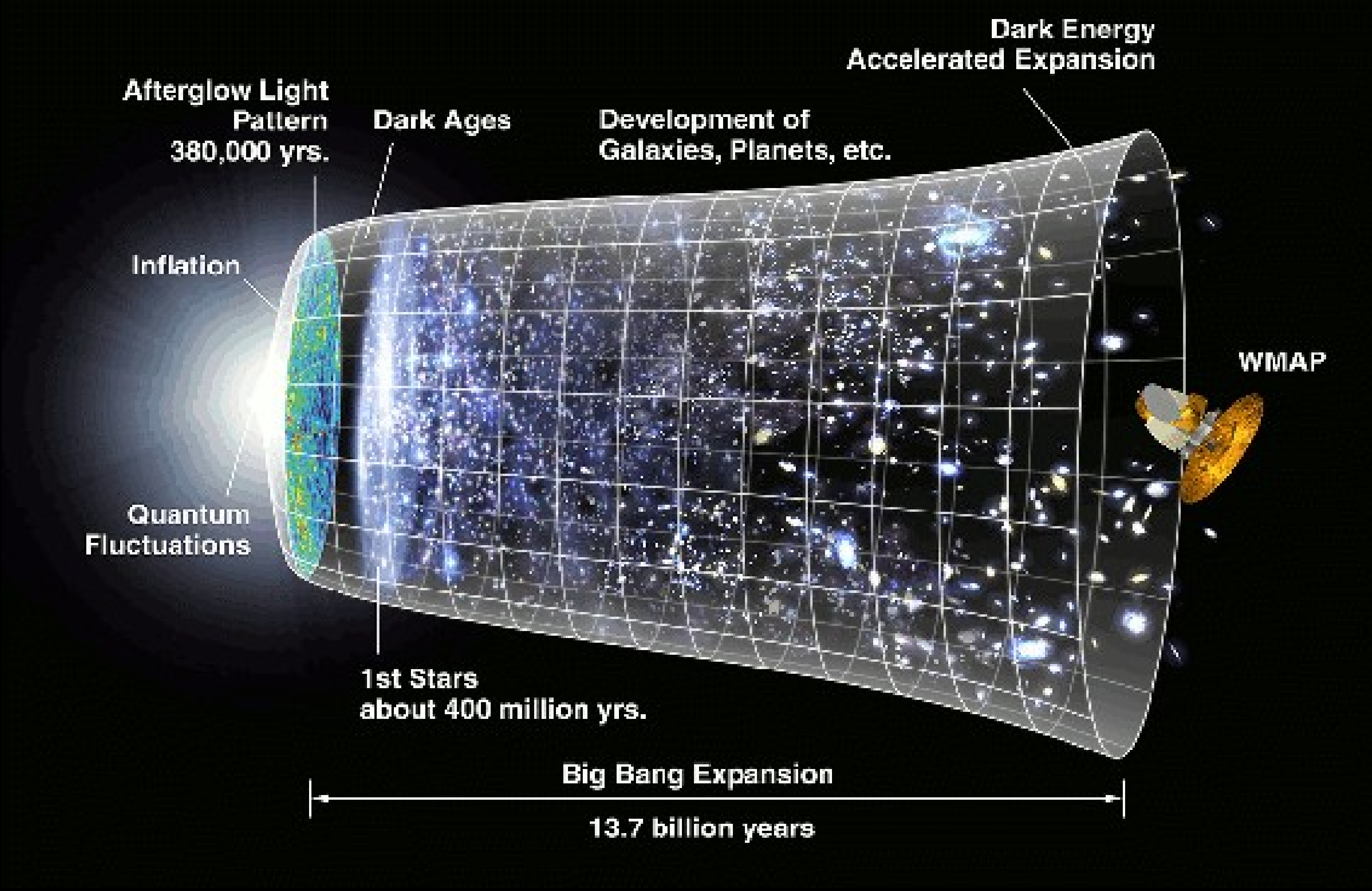
***Multimessenger astronomy with GW and EM signals**
(Prof. Branchesi)

Massive black hole binaries



Cosmology in two slides

According to our best cosmological models, we live in a ***ΛCDM Universe***. The energy content of the Universe is ***27%*** in the form of ***ordinary matter*** (~3% baryons, ~24% dark matter) and ***73%*** in the form of a ***cosmological constant*** (or Dark energy, or whatever), which would be responsible of the accelerated expansion.



The age of the Universe is ~14Gyr, during this time its size has expanded from a singularity to ~10^{28}cm.

Usually cosmologists describe the epochs of the Universe in terms of ***redshift***:

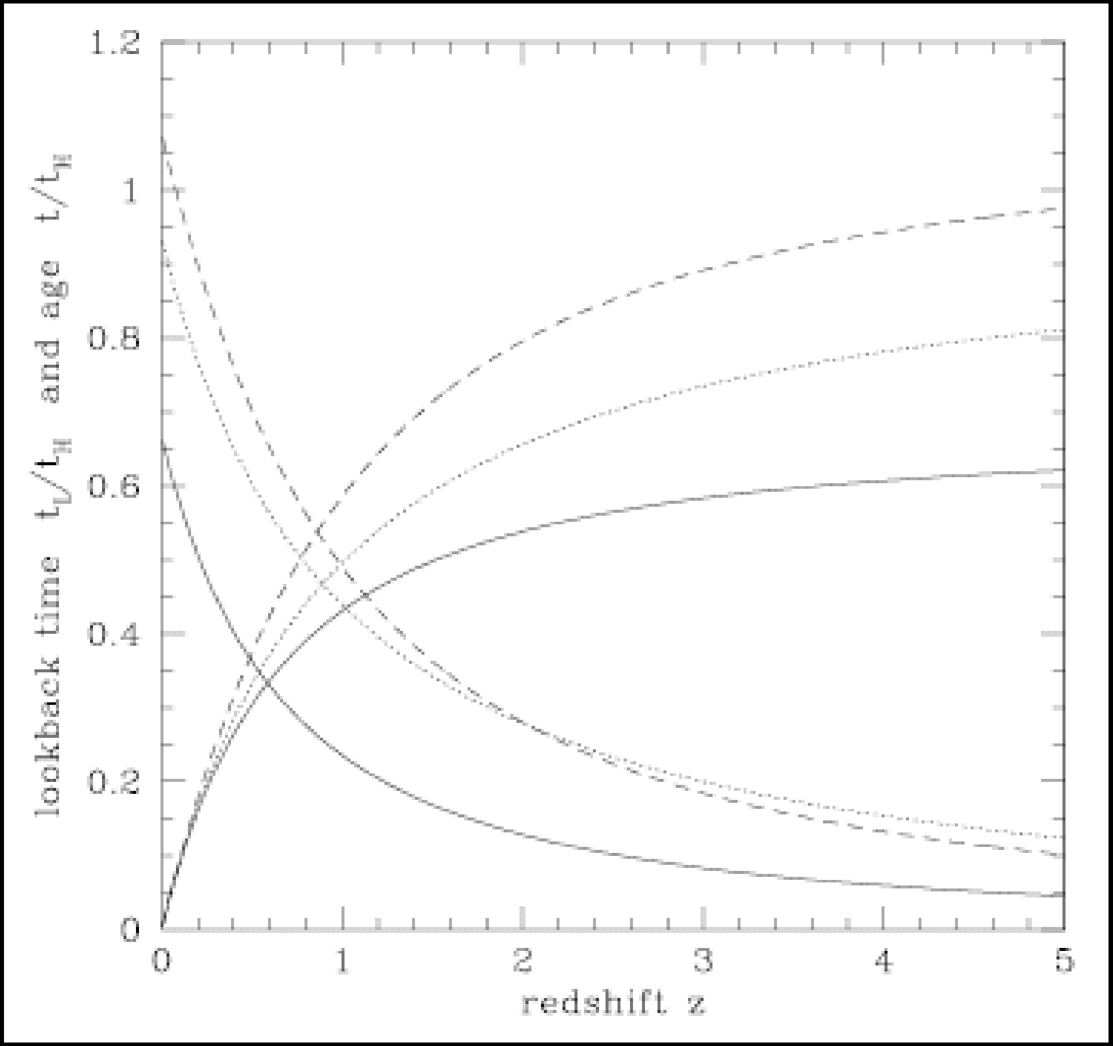
$$z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1$$

which describe how much the photons emitted at a given time are redshifted, because of the expansion, when they arrive on the Earth.
The redshift of a photon is related to the size of the Universe at the moment of its emission through:

$$1 + z = \frac{a(t_o)}{a(t_e)}$$

A given redshift correspond to a specific time in the past:

z=0 today
z=1 ~8Gyr ago
z=6 ~13Gyr ago (age of the Universe <1Gyr!)



Observational facts

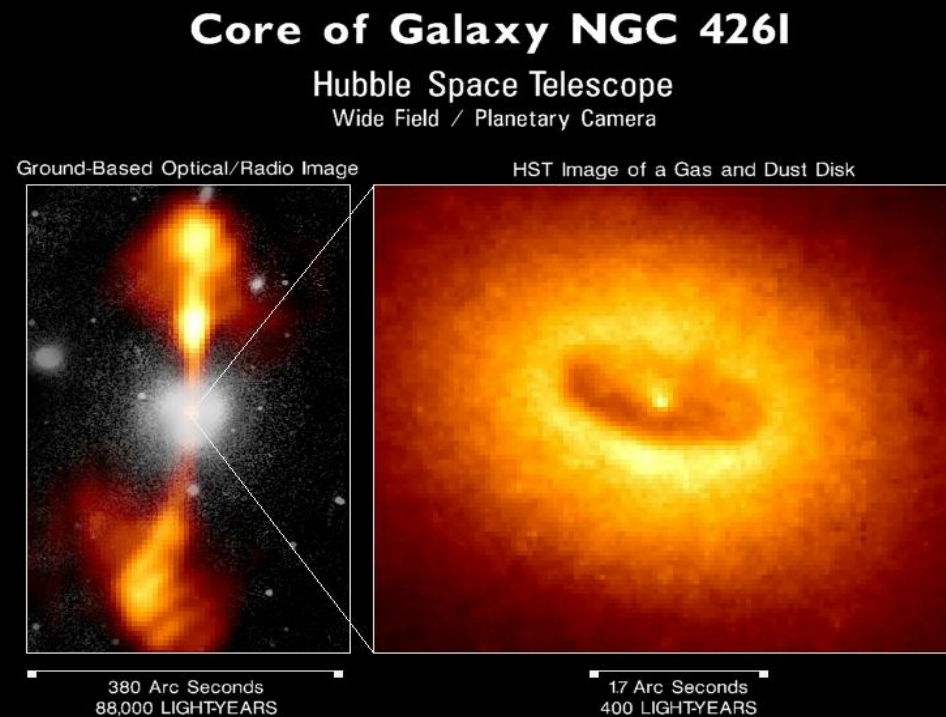
1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive black hole (MBH) has been found in the center.

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.

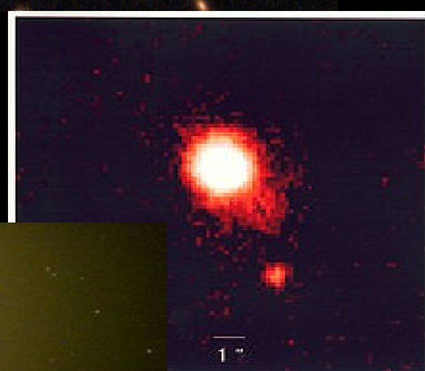
3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

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

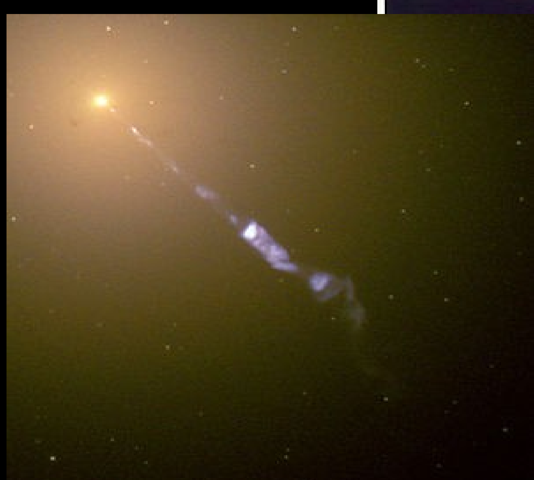
Our aim is to understand the MBH formation and evolution and to assess the consequences for GW astronomy

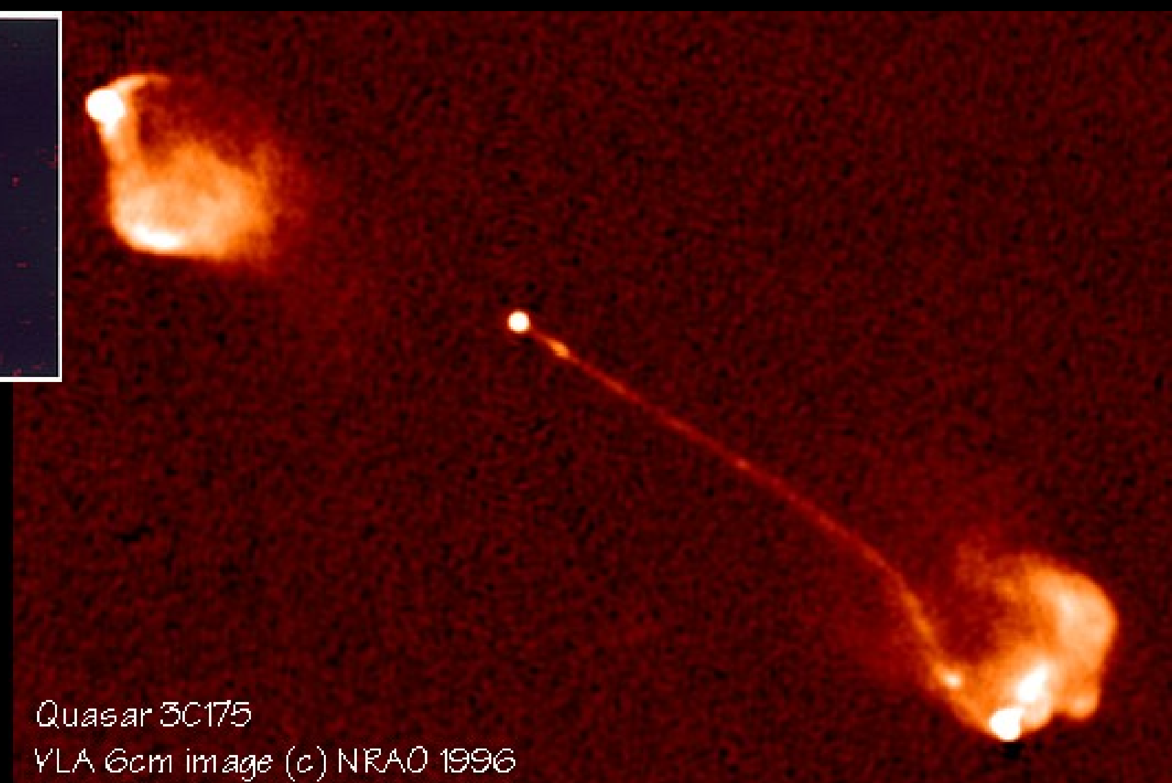


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

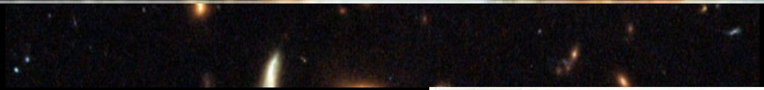


1"





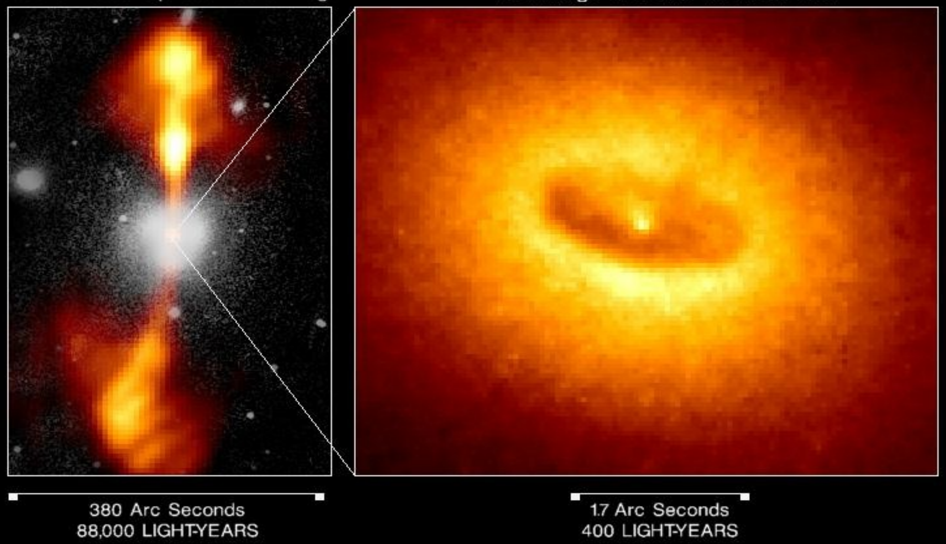
Quasar 3C175
VLA 6cm image (c) NRAO 1996

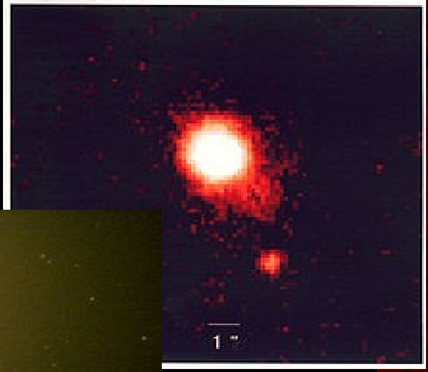


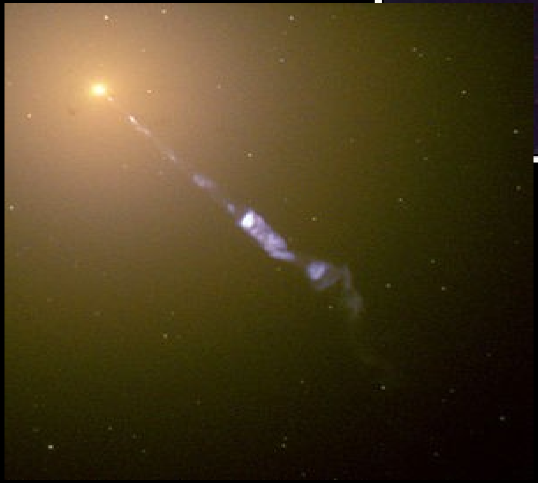
Core of Galaxy NGC 4261

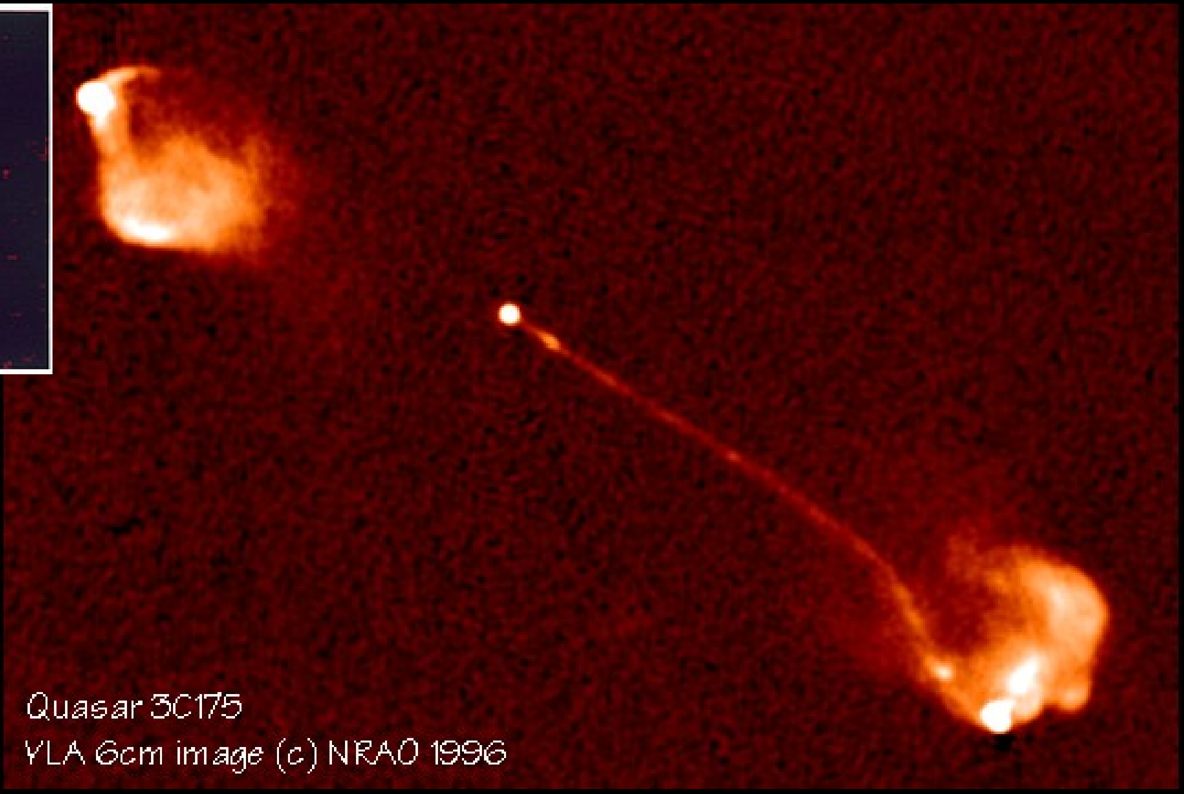
Hubble Space Telescope

Wide Field / Planetary Camera









Cosmological structure formation

(Binney & Tremaine, 1987, chapter 9)

The Universe after the Big Bang was not completely uniform

The matter content was (and is) dominated by dark matter. The *ratio dark matter/baryonic matter is ~10:1*

Gravitational instabilities due to non uniform matter distribution cause the matter to condense until small regions become gravitationally bound

These regions then decouple themselves from the global expansion of the universe and collapse, forming what we call the *first galactic minihalos*.

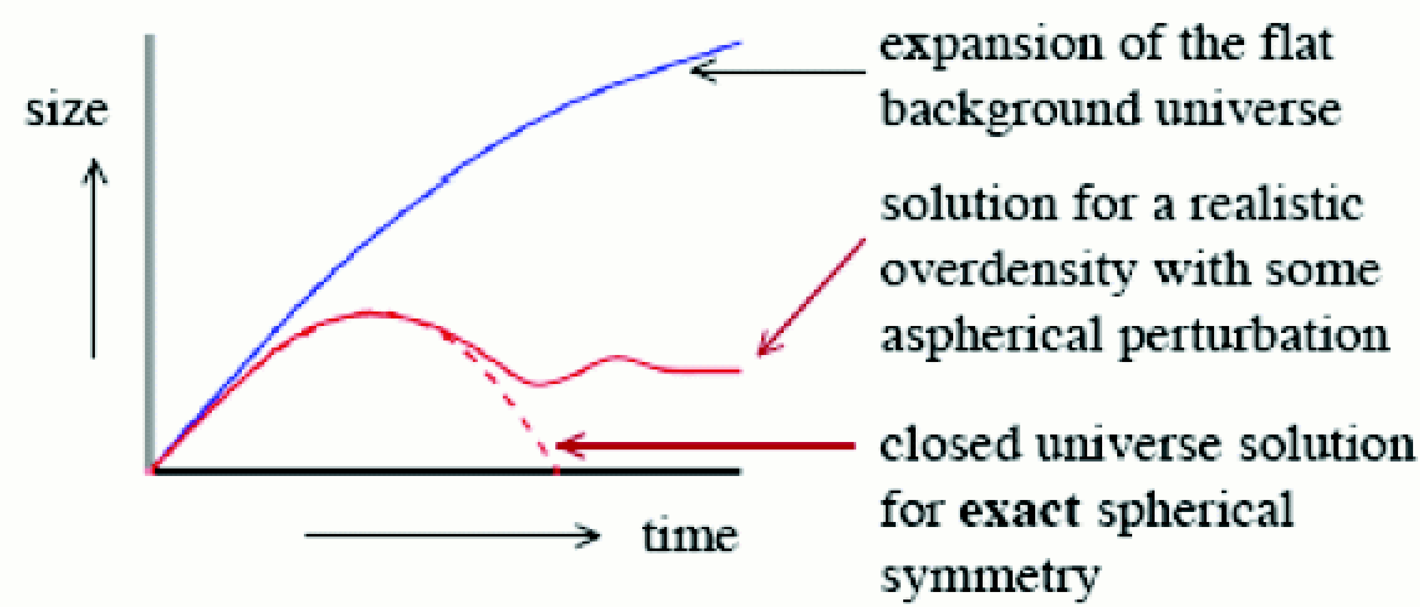
The baryonic matter feels the gravitational potential of these halos and falls at their center, forming the first protogalaxies

This *halos continuously form during the cosmic history and merge with each other* in what we call the *hierarchical scenario for galaxy formation*.

Halo formation: spherical collapse

Consider a flat, matter dominated Universe, and consider a region which is slightly denser than the mean density.

The self-gravitational force of the sphere depends only on the matter inside the sphere itself (Birkhoff's theorem), and the overdensity behaves like a small closed Universe.



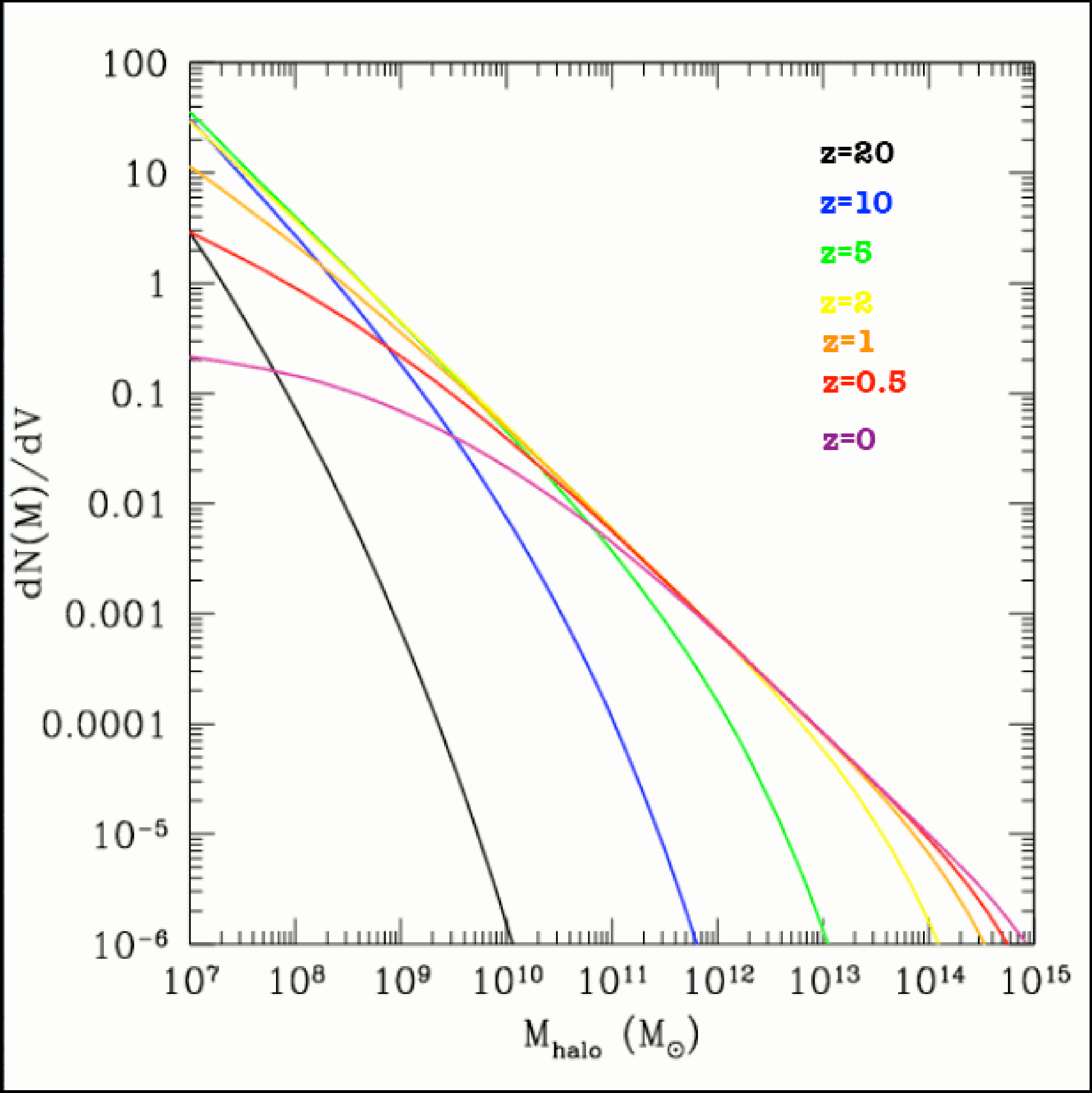
Schematic evolution:

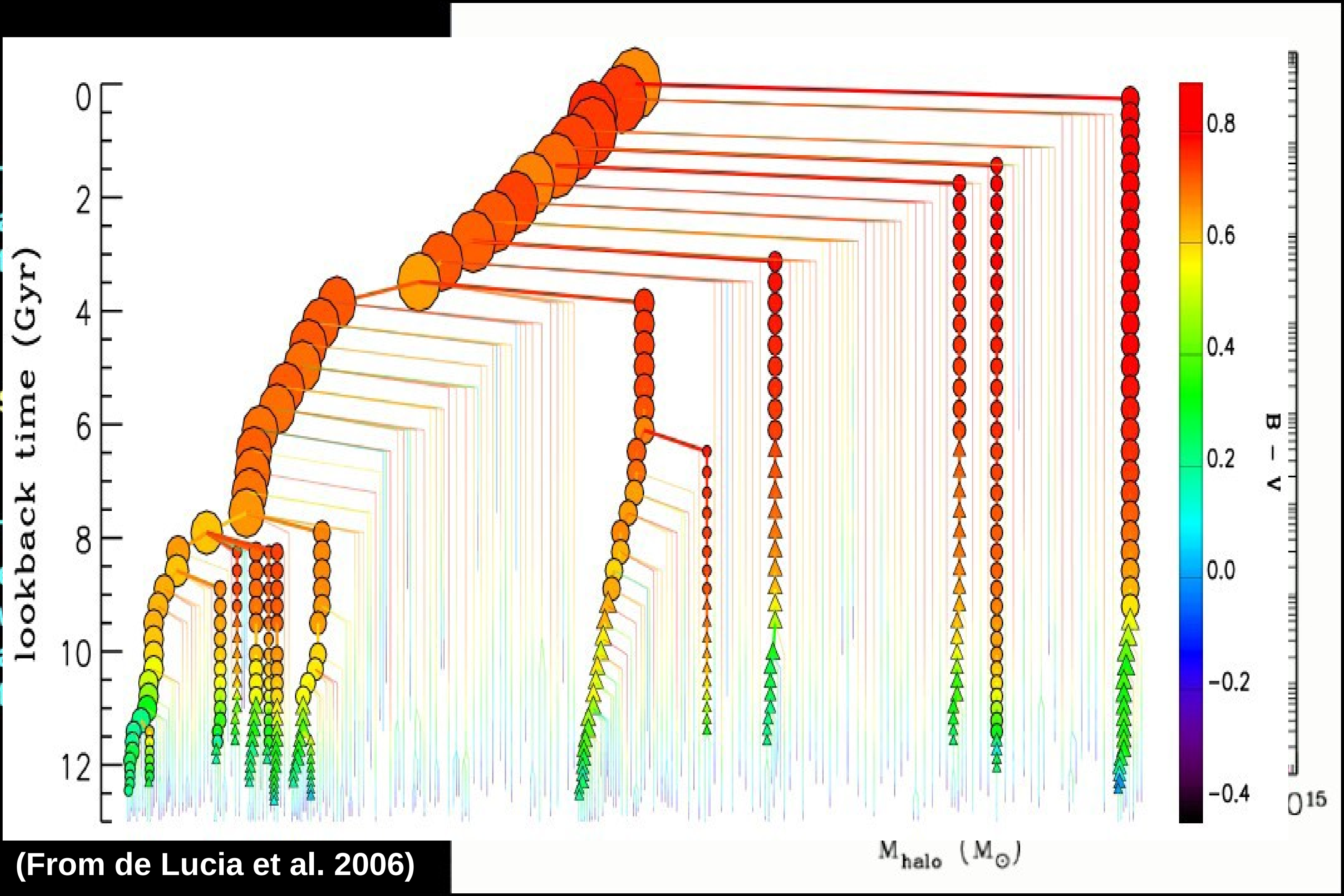
- Density contrast grows as universe expands
- Perturbation “turns around” at $R = R_{turn}$, $t = t_{turn}$
- If exactly spherical, collapses to a point at $t = 2\ t_{turn}$
- Realistically, bounces and **virializes** at radius $R = R_{virial}$

The typical halo mass is an increasing function of time: bottom-up or

HIERARCHICAL structure formation!

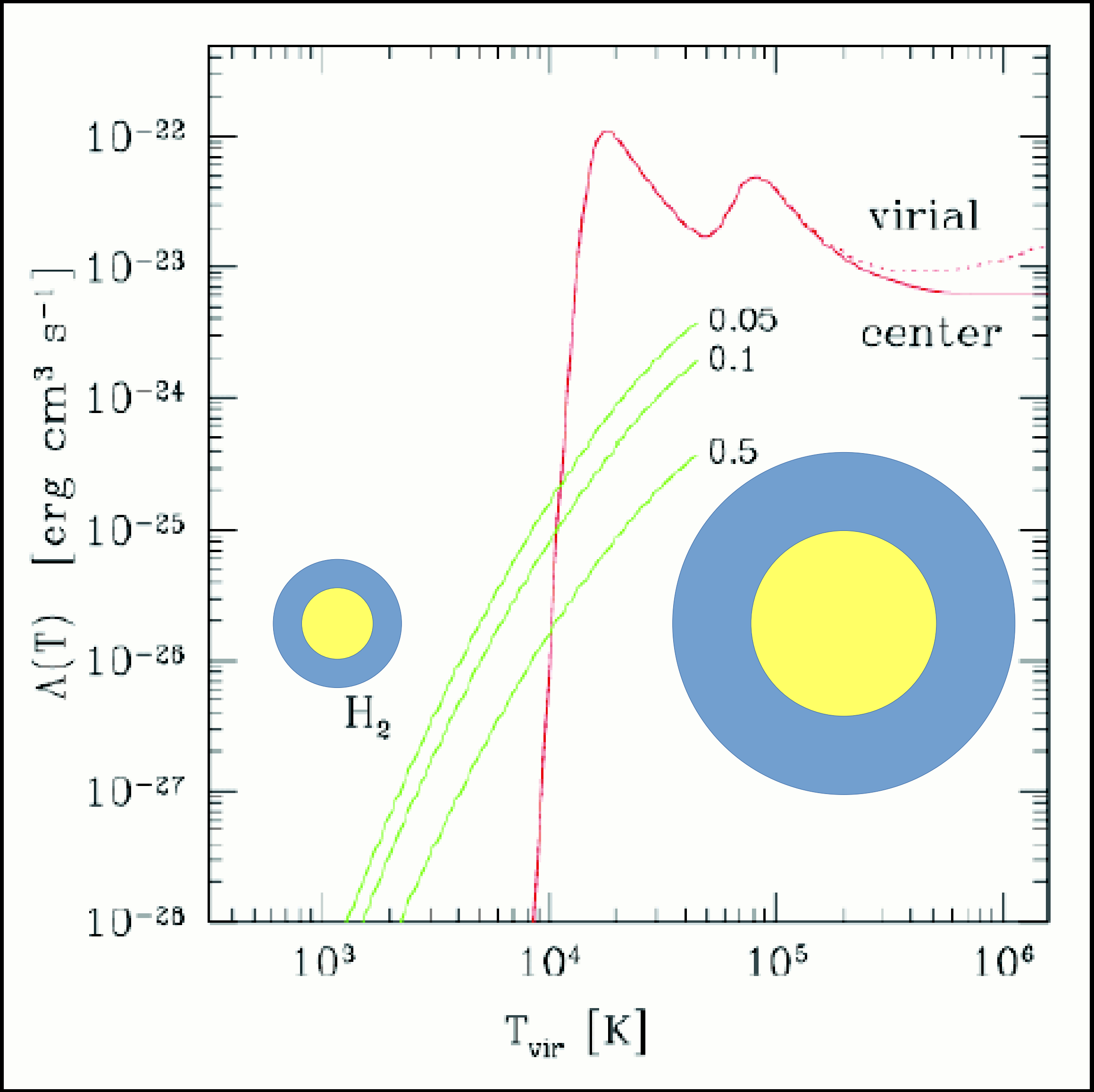
The halo mass function evolves in time (redshift) with larger halos forming at lower redshifts (later times).





(From de Lucia et al. 2006)

What happens to the baryons? In the early Universe most of the baryonic matter is in form of hot *atomic (H) or molecular (H_2) Hydrogen*.



Baryons need to cool down (i.e. loose energy) in order to condense in dense structures and form stars.

The only way to cool down is through transition between different atomic or molecular levels.

We need to excite high energy levels to radiate this energy away.

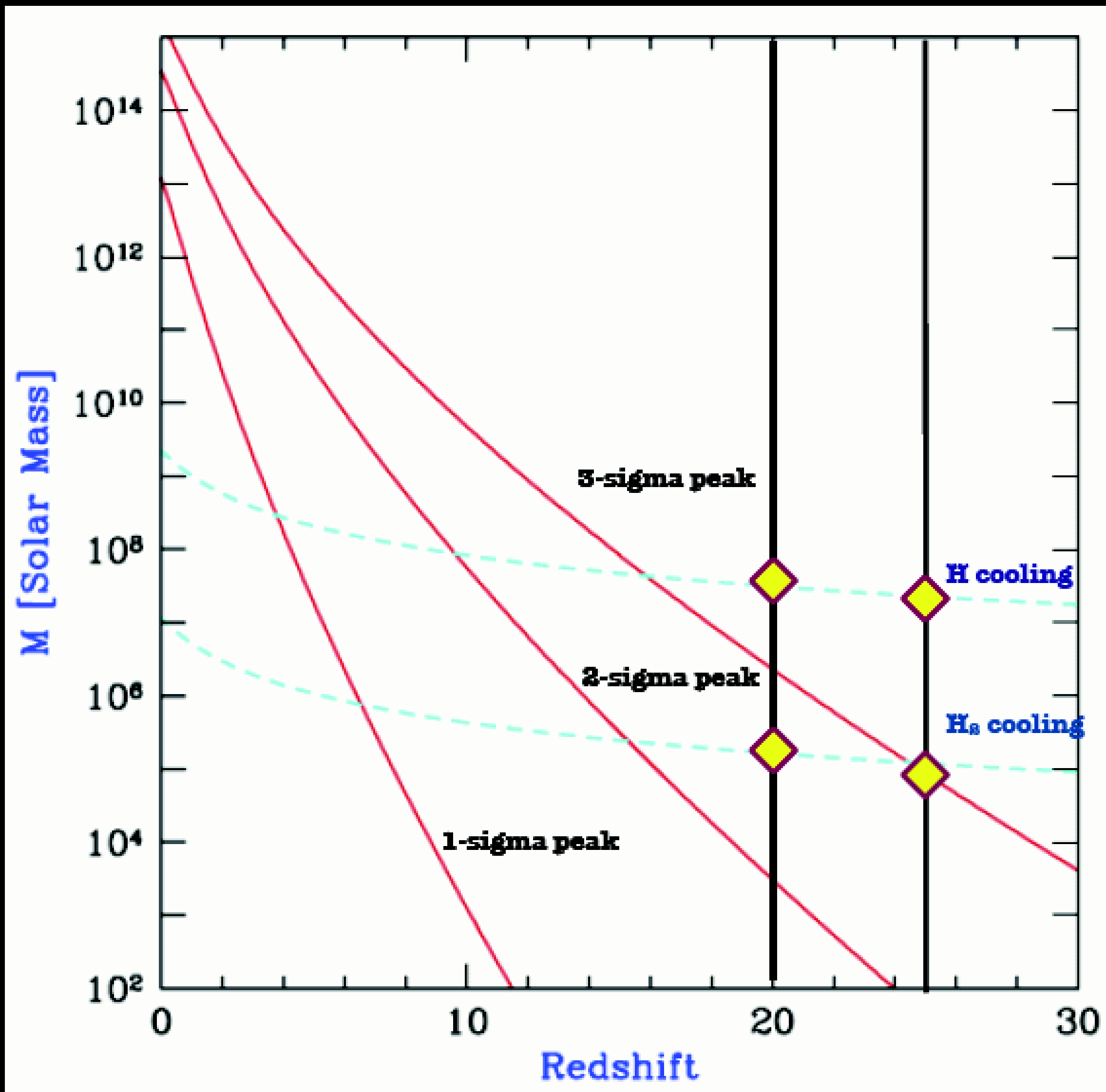
The only way is collisional excitation: *we need high temperatures!!!*

Atomic Hydrogen can cool only at temperatures>10^4K, while H_2 can cool already at 10^3K.

NOTE: Temperature increases with halo mass!

$$T_{\rm vir} = 1.98 \times 10^4 \left(\frac{\mu}{0.6}\right)\left(\frac{M}{10^8\ h^{-1}\ M_\odot}\right)^{2/3}\left[\frac{\Omega}{\Omega(z)}\ \frac{\Delta_c}{18\pi^2}\right]^{1/3}\left(\frac{1+z}{10}\right)\ \mathrm{K}$$

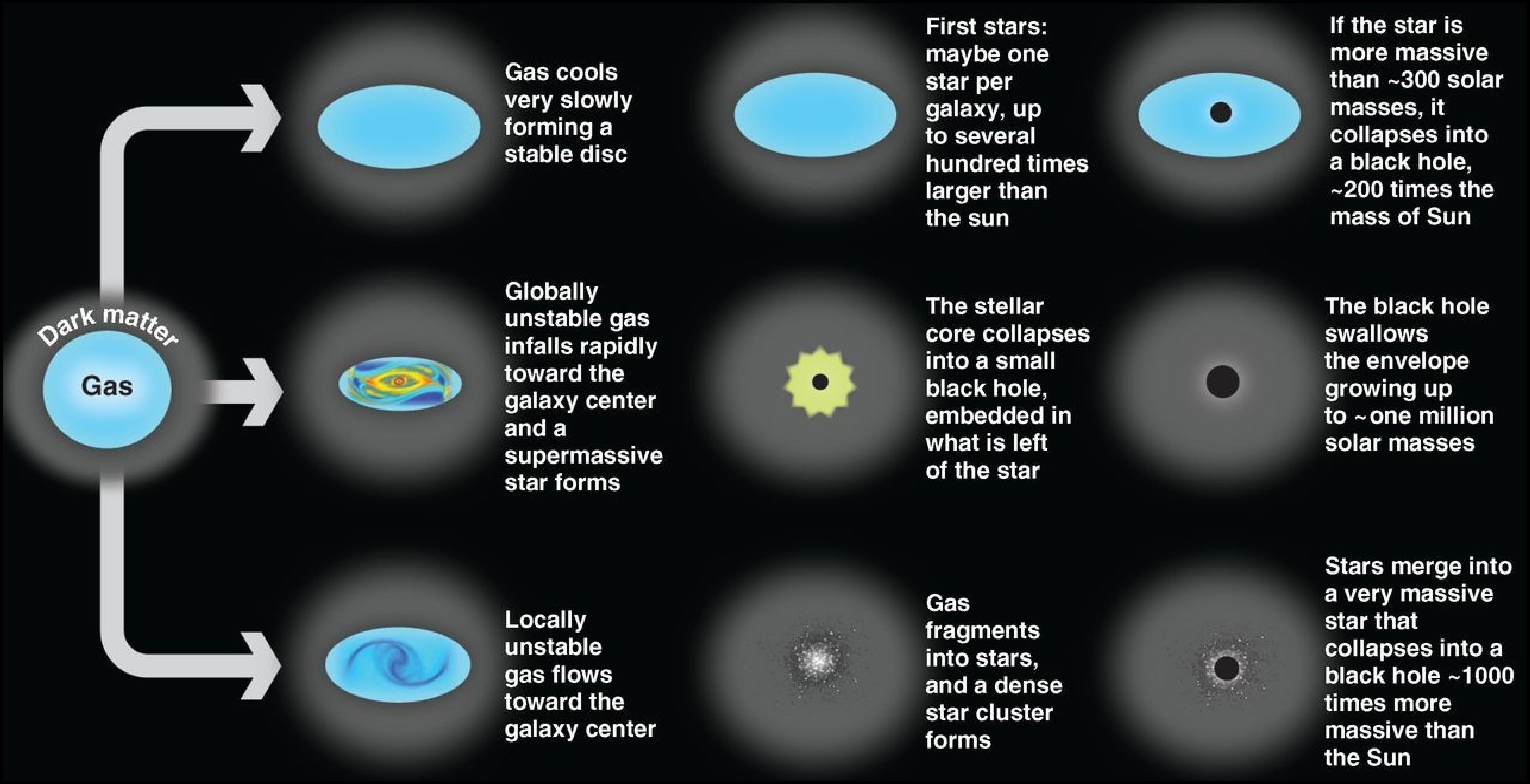
The *halo virial temperature is a function of the halo mass*. At high z, we need M>10^6 solar masses to cool H_2, and M>10^8 solar masses to cool H.



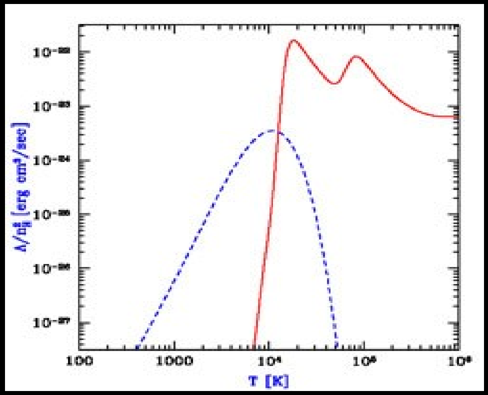
Such massive halos correspond to high sigma peaks of the density fluctuation field (nevermind). This means that are quite RARE!

BOTTOM LINE: BARION CONDENSATION IS POSSIBLE IN FAIRLY MASSIVE RARE HALOS AT REDSHIFT ~20.

Seed BH formation

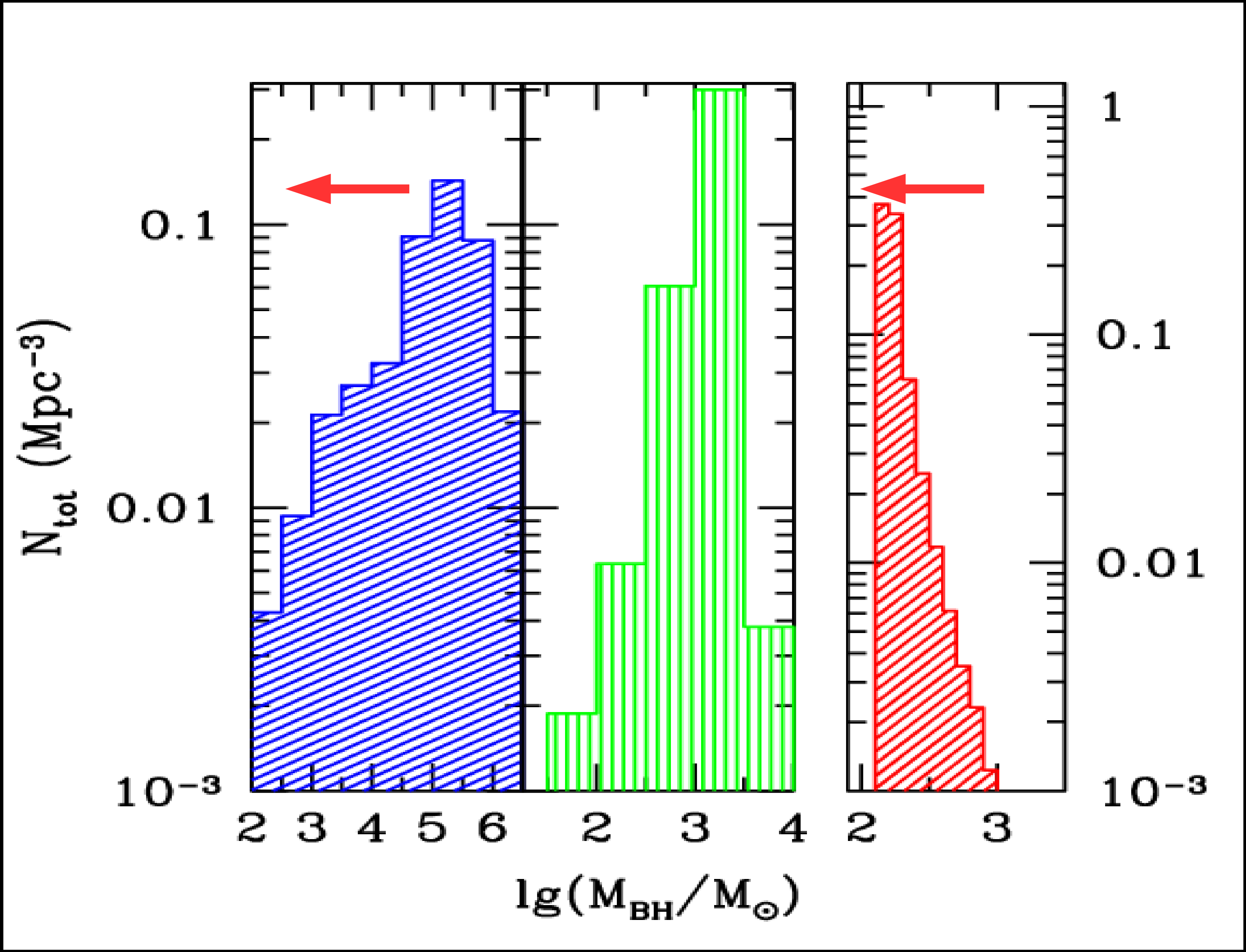


Critically depends on: -content of H2
-vicinity of an ionizing source
-fragmentation
-metallicity

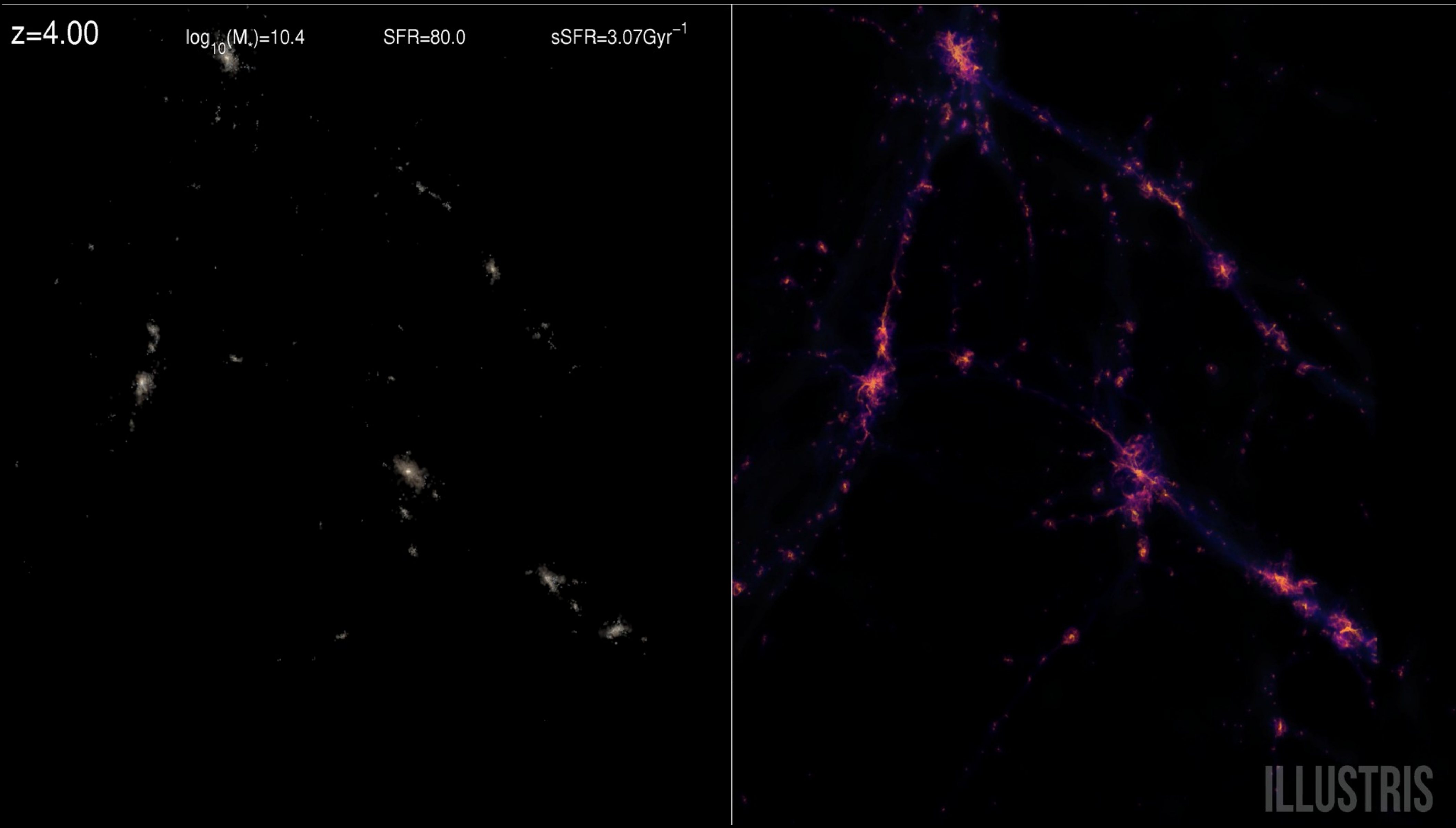


Seed BH mass function

Volonteri 2010



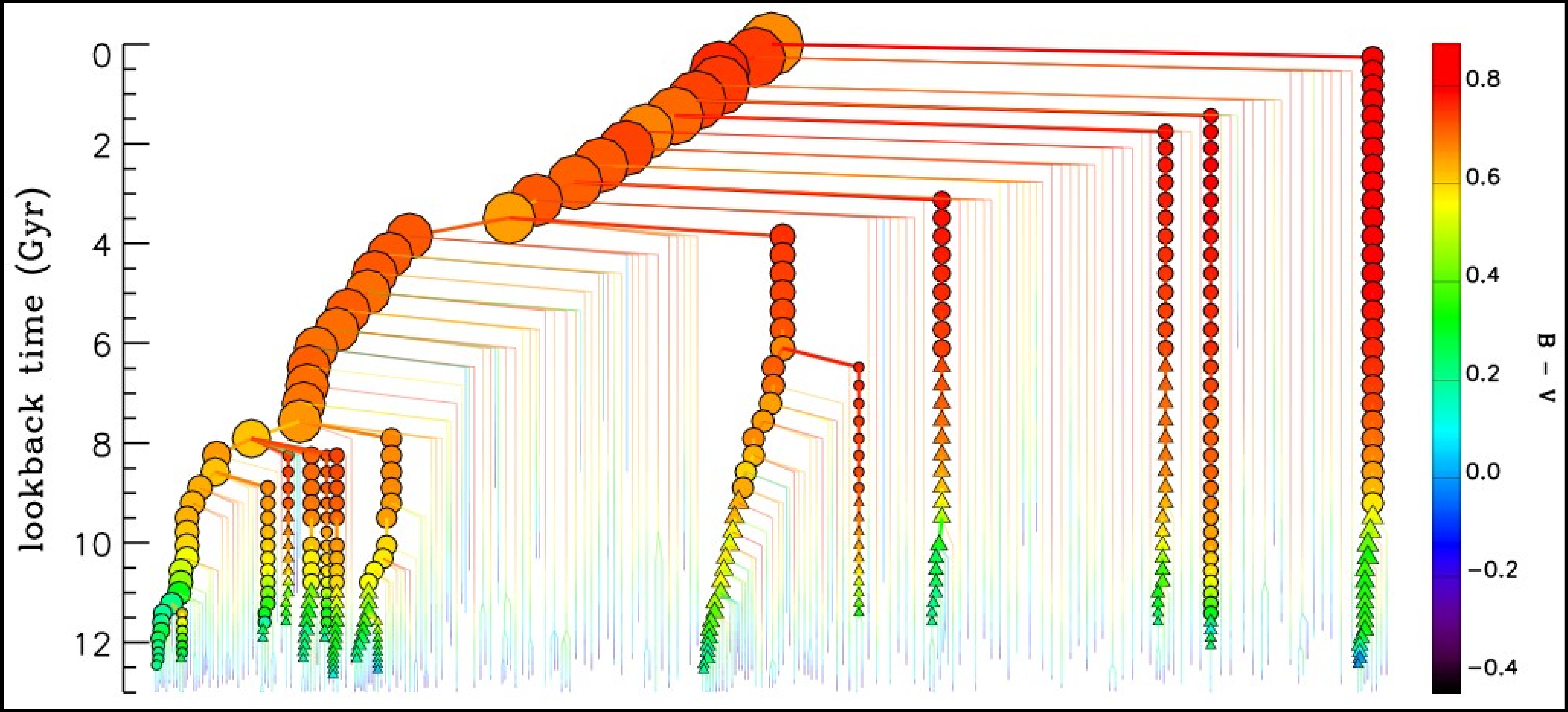
NOTE: The mass function can shift to lower values when wind mass loss and fragmentation are taken into account



z=4.00
$\log_{10}(M_*)$=10.4
SFR=80.0
sSFR=3.07Gyr^{-1}
ILLUSTRIS

HIERARCHICAL GALAXY EVOLUTION…

According to the Hierarchical scenario, protogalaxies formed in the first halos at high redshift merge feel each other gravitational attraction and merge together to form the galaxies we see today in the local Universe

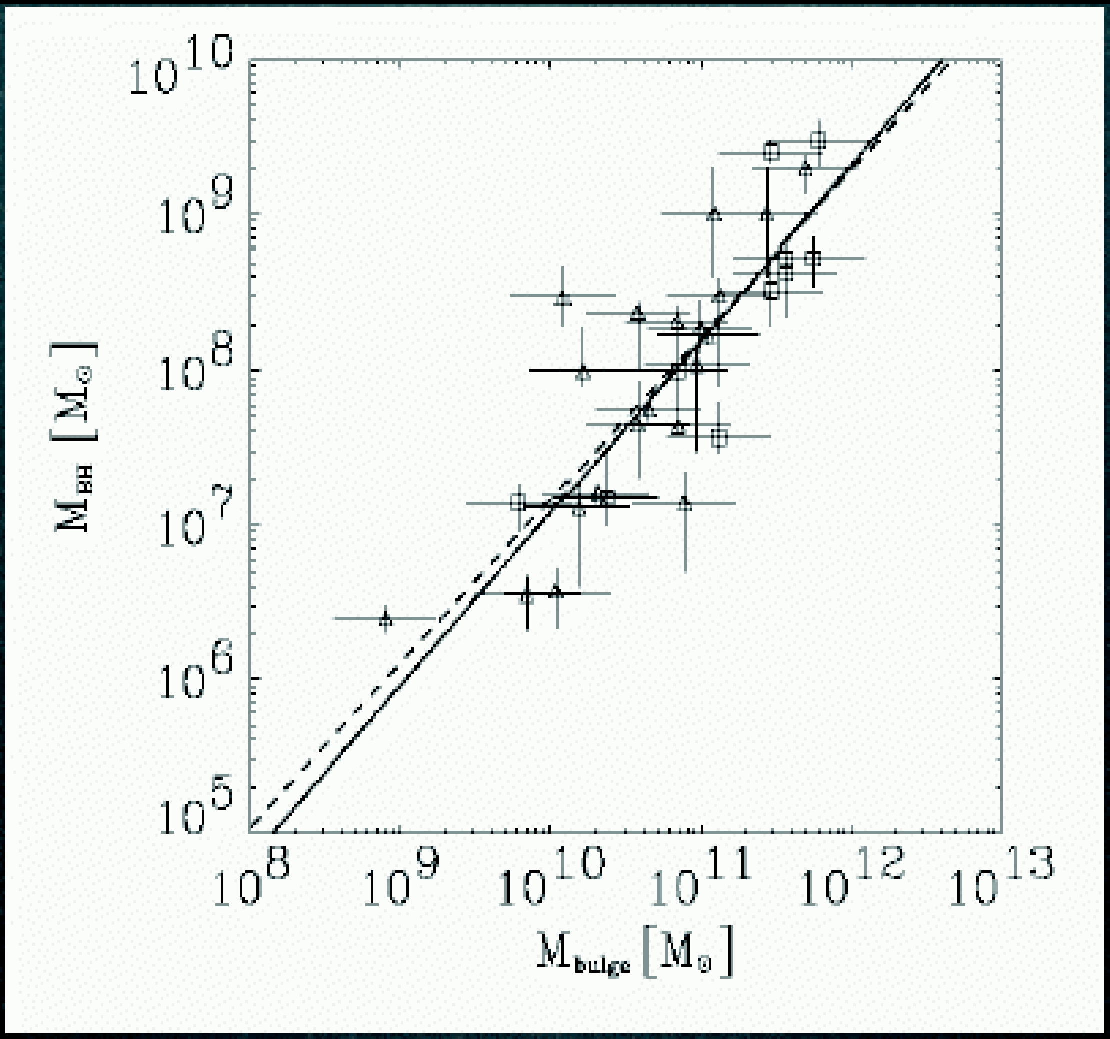


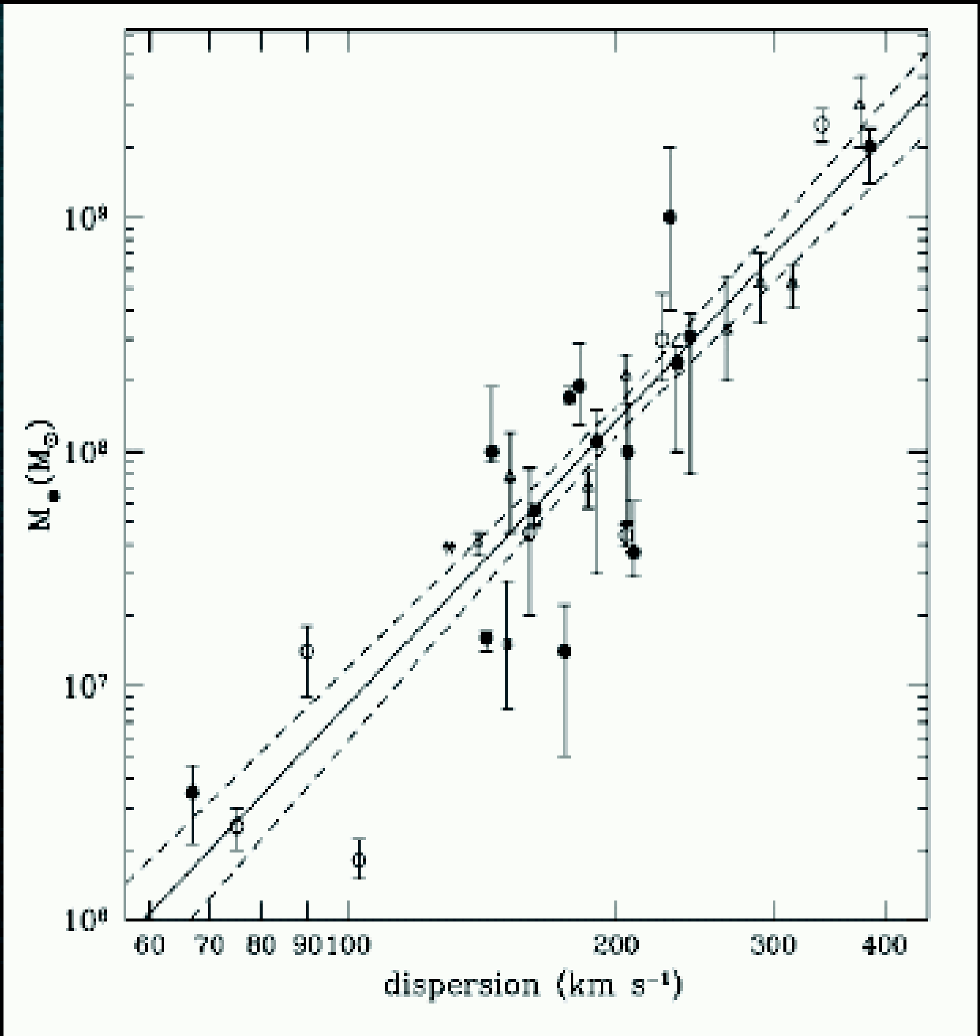
From De Lucia et al. 2006

...+ M_{BH}- BULGE RELATIONS...

Massive black holes (MBHs) are ubiquitous in the galaxy centres.

In the last decade, tight relation have been discovered, correlating the MBH mass with the host galaxy bulge mass (Magorrian et al. 1998) **and with the host bulge velocity dispersion** (Gebhardt et al. 2000, Ferrarese & Merrit 2000)**. This relation are a clear hint of a *coevolution of MBHs and host galaxies.***





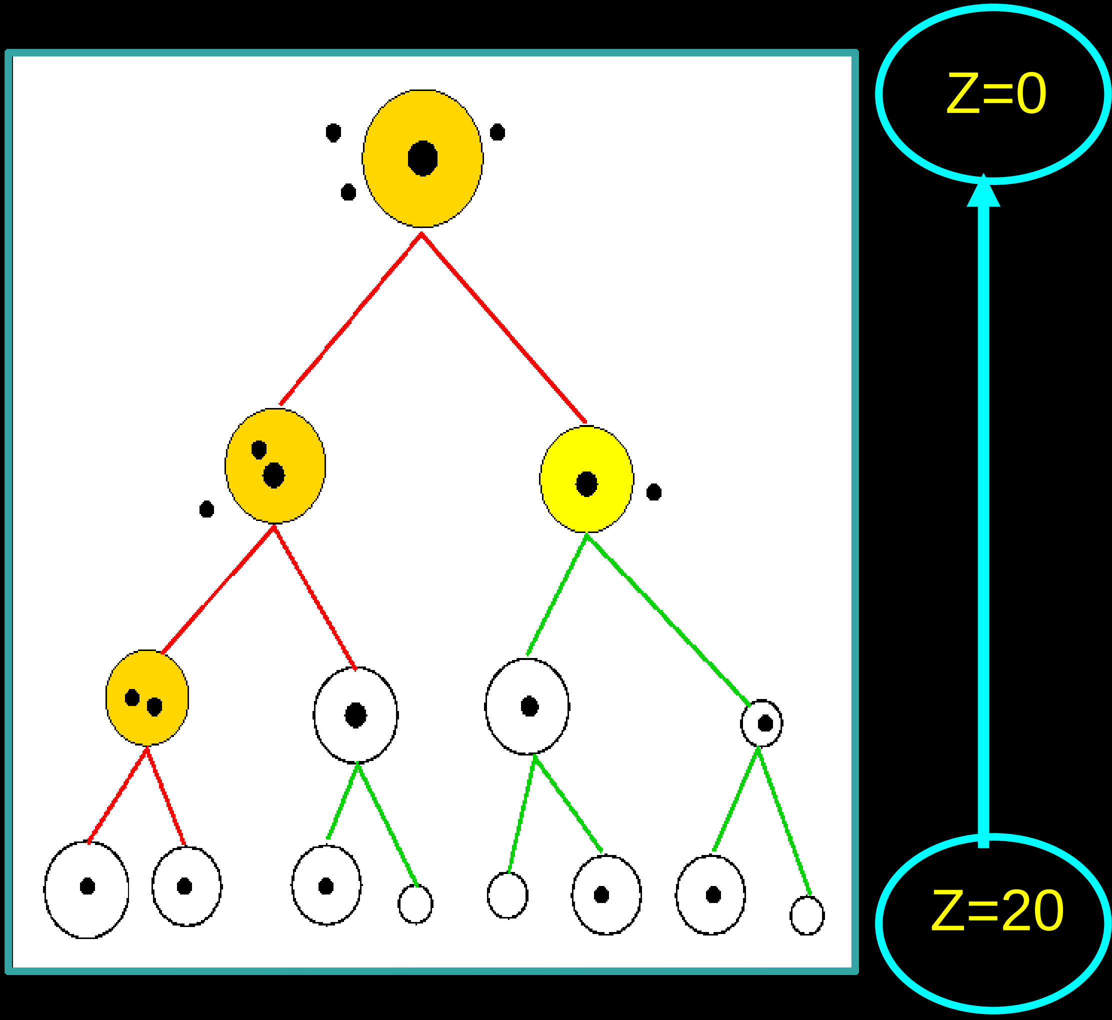
…= HIERARCHICAL MBH EVOLUTION

GENERAL FRAMEWORK: (Volonteri, Haardt & Madau 2003)

> The halo hierarchy can be traced backwards by means of EPS Monte-Carlo merger tree.

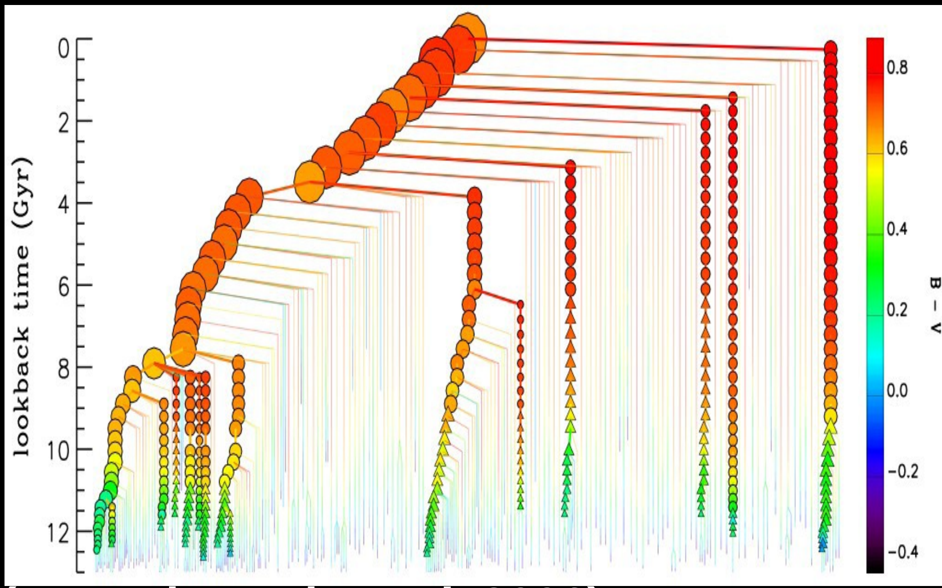
The semi-analytic code follows the accretion and the dynamical history of BHs in every single branch of the tree

The adopted threshold for density peaks hosting a seed ensures an occupation fraction of order unity today for halos more massive than $10^{11}M_{\odot}$

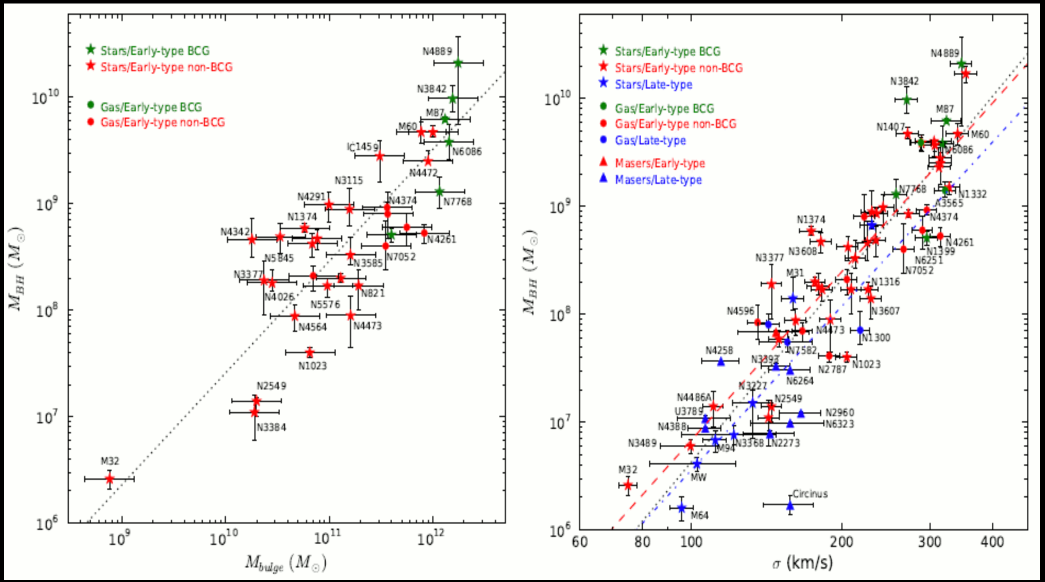


Binary merger trees starting at z=20
In a ΛCDM cosmology

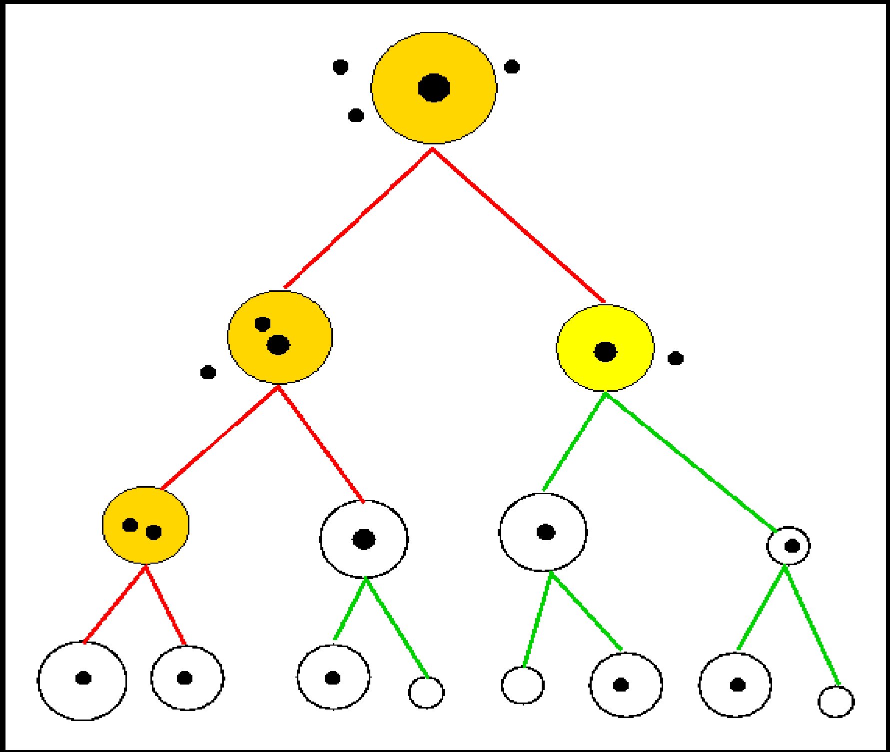
In a nutshell



(From de Lucia et al. 2006)

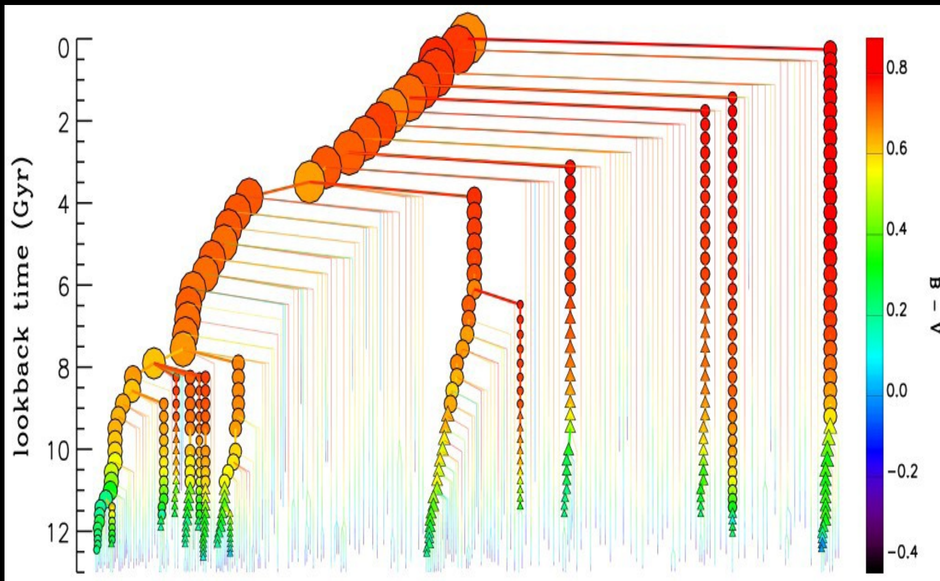


(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

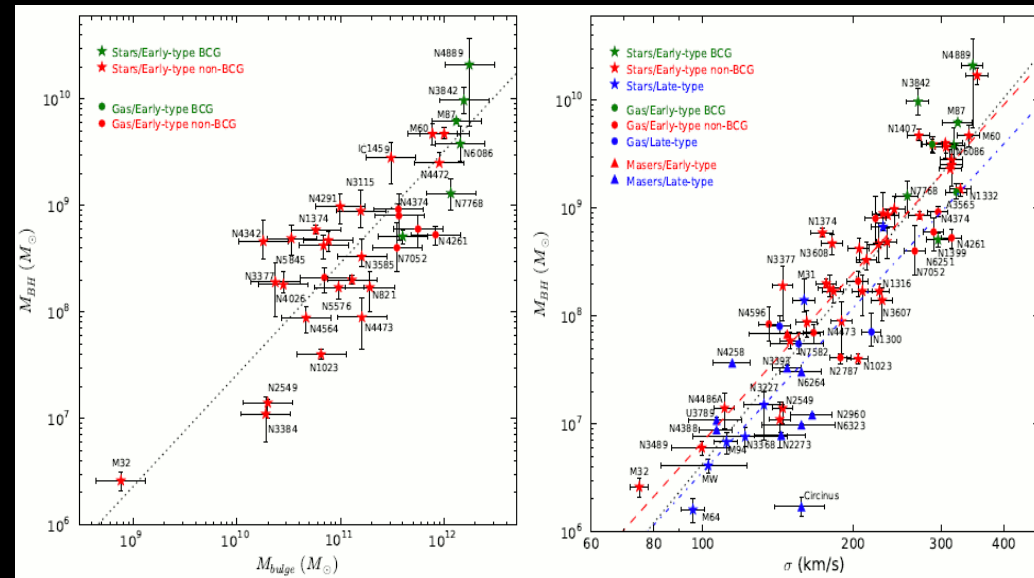


(Menou et al 2001, Volonteri et al. 2003)

In a nutshell



(From de Lucia et al. 2006)



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

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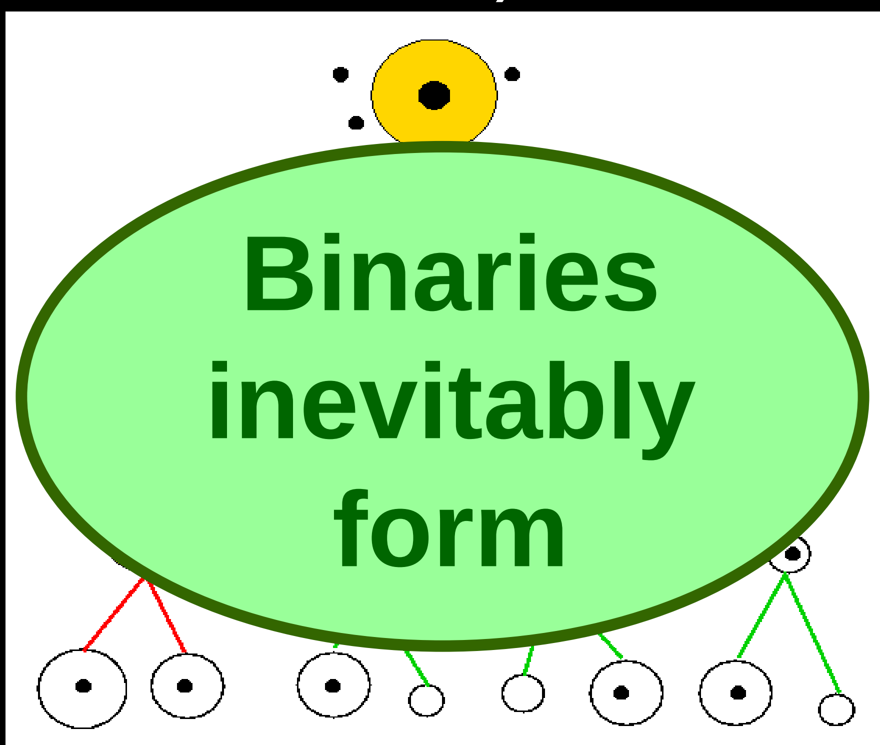


(Menou et al 2001, Volonteri et al. 2003)

*Where and when do the first MBH seeds form?

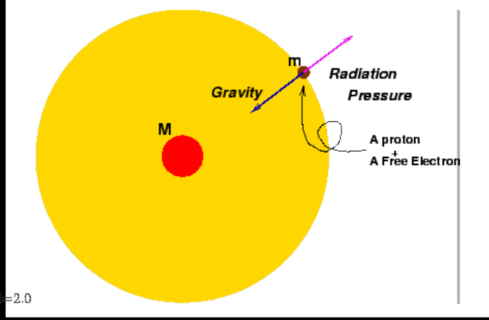
*How do they grow along the cosmic history?

*What is their role in galaxy evolution?

*What is their merger rate?

*How do they pair together and dynamically evolve?

Accretion



Gravitational instabilities drive cold gas toward the galactic nucleus, Gas forms a disk around the MBH, starting the accretion process.

Now consider a flux of proton &electrons with density ρ being accreted onto a BH of mass *M*. The accreting material emits radiation with a luminosity *L*. Equating the gravitational force (acting on the accreting material) to the force due to the radiation pressure (exerted by the outward radiation emitted by the accretion disk itself)

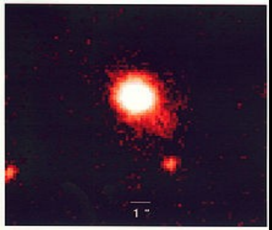
$$F_{\rm grav} = \frac{GM(m_e + m_p)}{r^2} \approx \frac{GMm_p}{r^2}$$

$$F_{\rm rad} = p_{\rm rad}\,\sigma_T = \frac{L/c}{4\pi r^2}\sigma_T$$

one found an equilibrium condition (in the spherical limit), which is commonly known as *Eddington accretion limit*, described by the *Eddington luminosity*:

$$L = \epsilon \dot{M} c^2$$

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}}$$



L_{EDD}=1.38x10^{38} erg/s for a solar mass BH and scales as the BH mass. A 10^9 solar mass MBH shines with a luminosity of about 10^{47} erg/s (10^{14} Suns or 1000 MWs)!!!!!

This imply an accretion in mass given by:

$$\frac{dM}{dt} = 2.5 \times 10^{-8} \left(\frac{M}{\mathrm{M}_\odot}\right) \mathrm{M}_\odot \mathrm{yr}^{-1}$$

MBHs CAN EFFICIENTLY INCREASE THEIR MASS!!!!!!

The natural timescale related to accretion is the Eddington timescale:

$$t_{\rm Edd} = \frac{Mc^2}{L_{\rm Edd}} = \frac{\sigma_T c}{4\pi G m_p} = 0.45{\rm Gyr}$$

$$\dot{M} = (1-\epsilon)\dot{M}_{\rm acc} = \frac{(1-\epsilon)}{\epsilon} f_{\rm Edd} \frac{M}{t_{\rm Edd}}$$

This defines the basic equation of mass growth via accretion

$$M(t) = M_0 e^{\frac{(1-\epsilon)}{\epsilon} f_{\rm Edd} \frac{(t-t_0)}{t_{\rm Edd}}}$$

Although often set to 0.1, ϵ is in fact an important parameter that depends on the spin. What is it?

$$\Delta E = -\frac{GmM}{2r_{\rm rim}} \Longrightarrow L = -\frac{dE}{dt} = \frac{G\dot{M}M}{2r_{\rm rim}},$$

$$L = \frac{1}{4\beta}\dot{M}c^2 = \epsilon \dot{M} c^2,$$

β=3 for a Sch. BH, β=1 for a max spinning BH and prograde accretion. The GR calculation gives

$$a = 0 \rightarrow \epsilon \approx 0.06 \rightarrow M = M_0 \; e^{\frac{t}{3\times 10^7 {\rm yr}}},$$

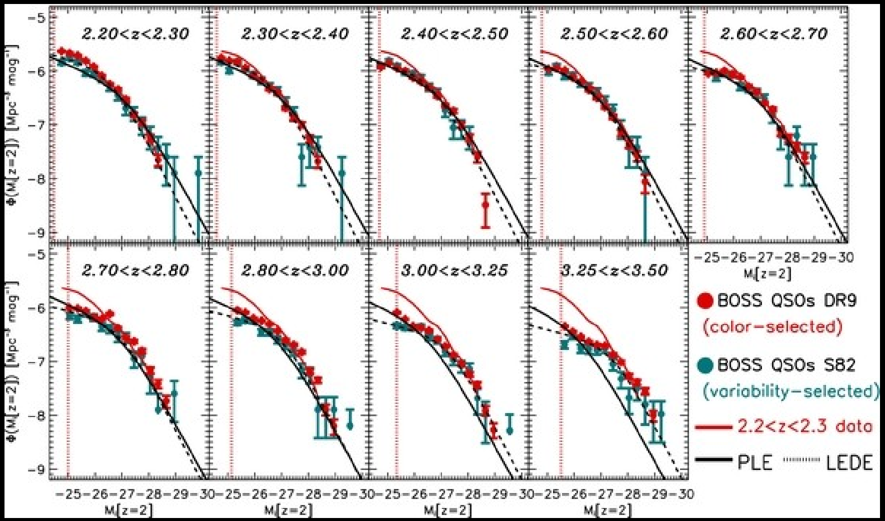
$$a = 0.998 \rightarrow \epsilon \approx 0.42 \rightarrow M = M_0 \; e^{\frac{t}{3\times 10^8 {\rm yr}}}$$

No problem accreting MBHs to 10^9 solar masses by z=0, but what about z>7 QSOs?

Evidence that MBHs grow mostly via radiative efficient accretion comes from the Soltan argument (1982).

By measuring the luminosity function of quasars, one can compute the energy density due to the light emitted by accreting MBHs

$$e = \frac{4\pi}{c}\int_0^\infty (1+z)dz \int_0^\infty n(S,z)S\ dS,$$



An energy density corresponds to an accreted mass density via

$$\rho_{\rm acc} = \frac{1-\epsilon}{\epsilon}\frac{e}{c^2}$$

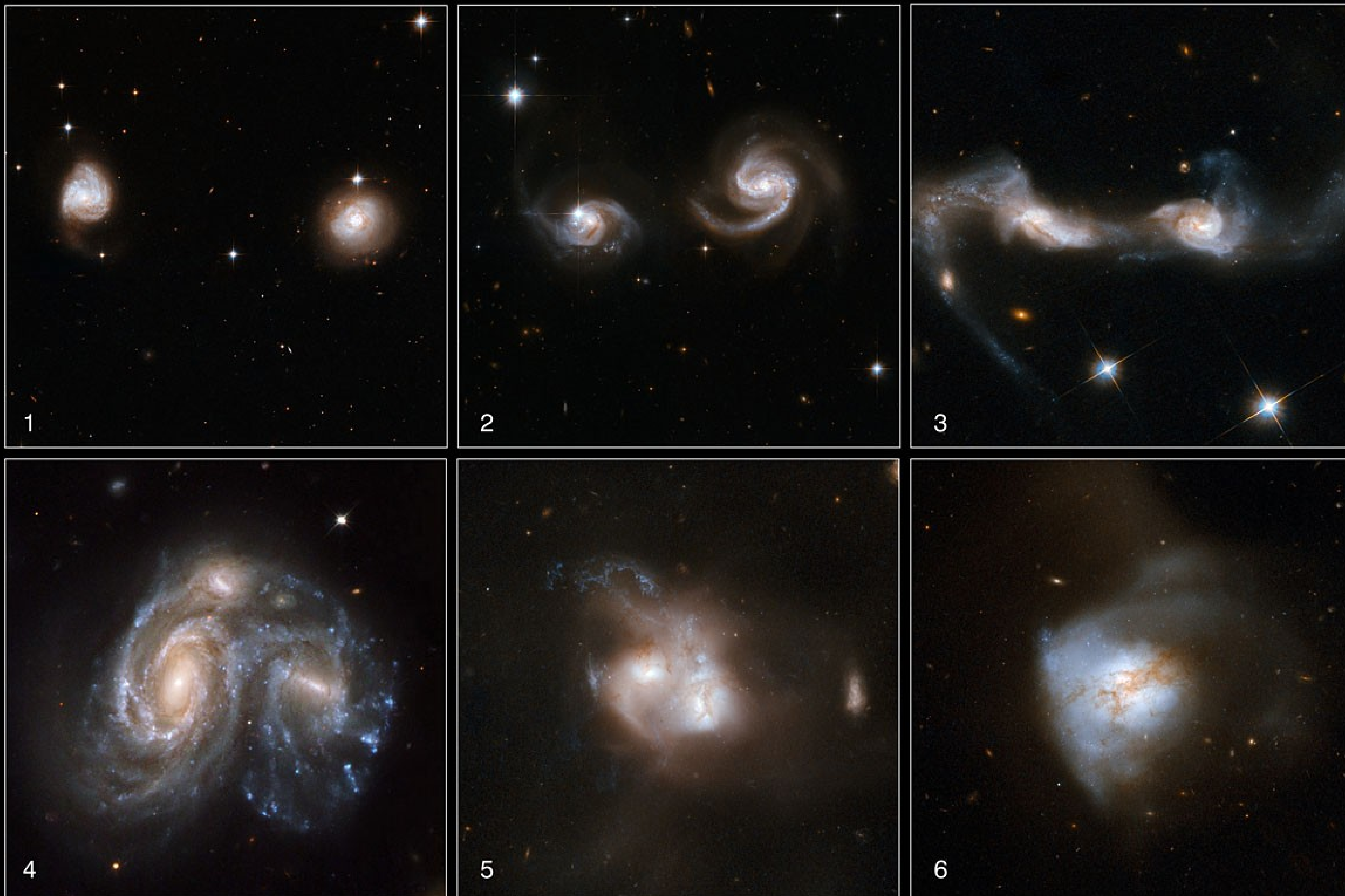
The luminosity function of quasars can be measured empirically so that the estimate of the accreted mass density can be compared to the current mass density in MBHs (which can be also measured):

$$\rho_{\rm acc} \approx 2.2\times 10^5 \left(\frac{0.1}{\epsilon}\right)\frac{M_\odot}{Mpc^3}$$

$$\rho_{\rm BH} \approx 3-5\times 10^5 \frac{M_\odot}{Mpc^3}.$$

About half quasars are obscured! Which brings the two estimates to match quite well.

Mergers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2
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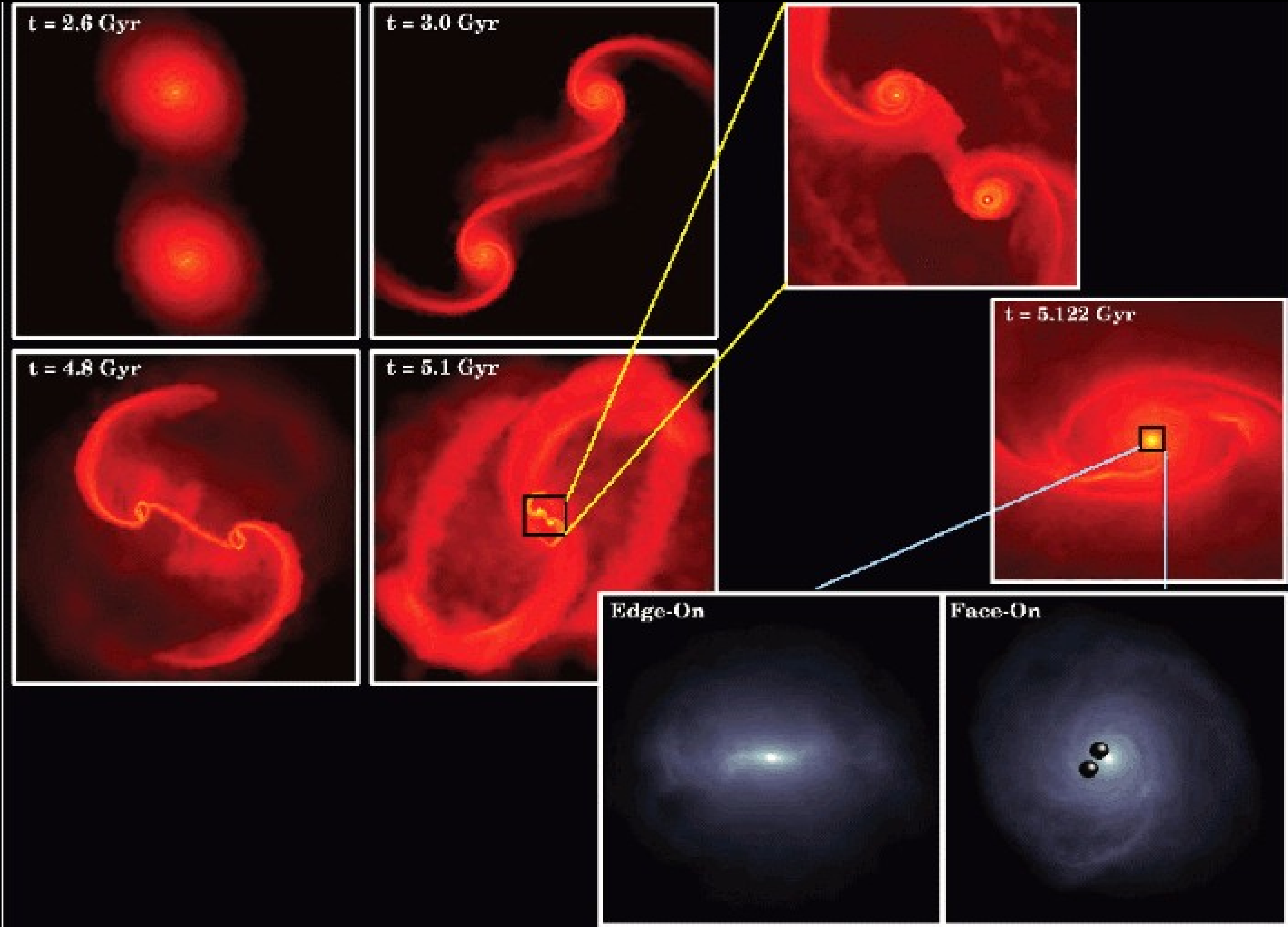
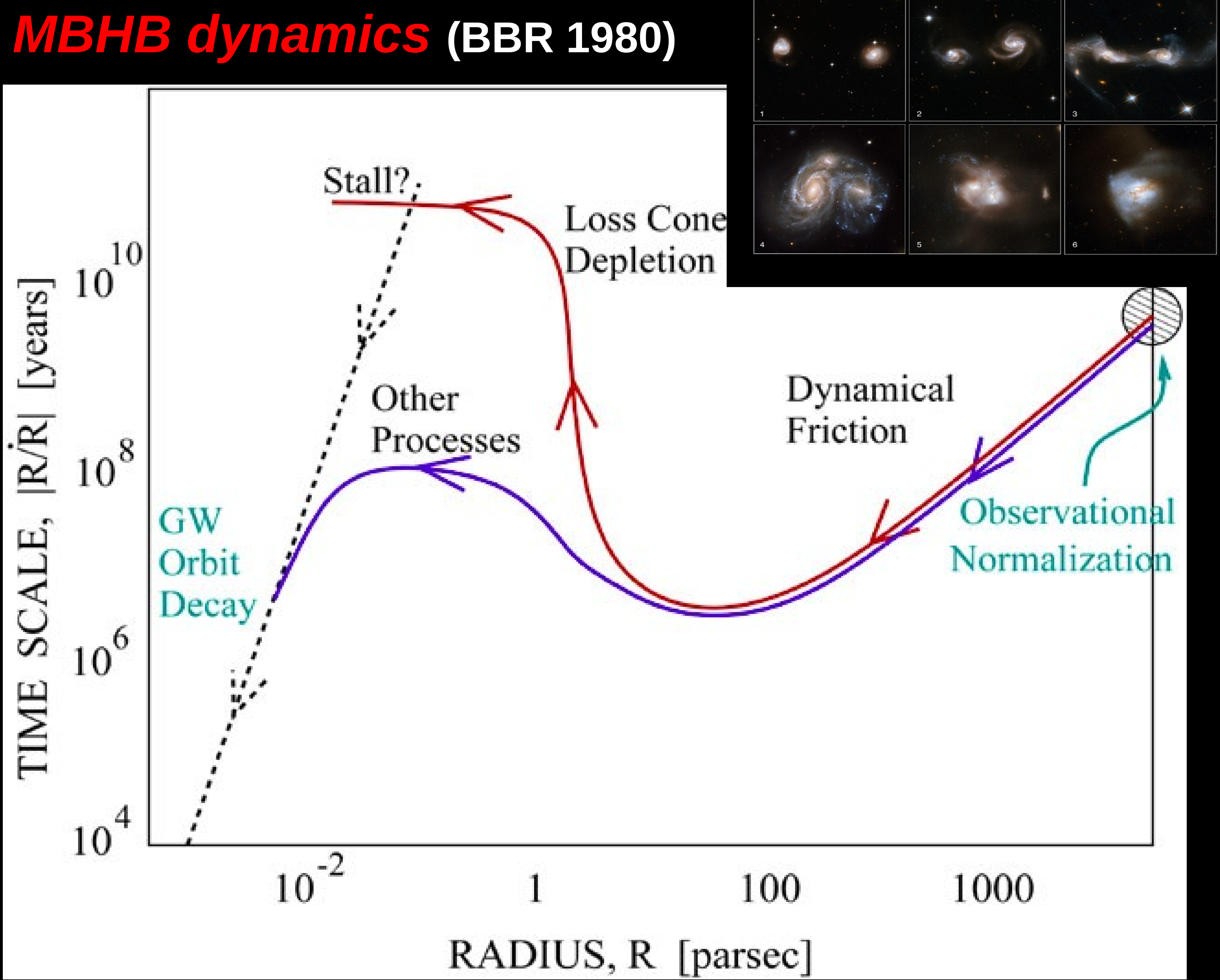
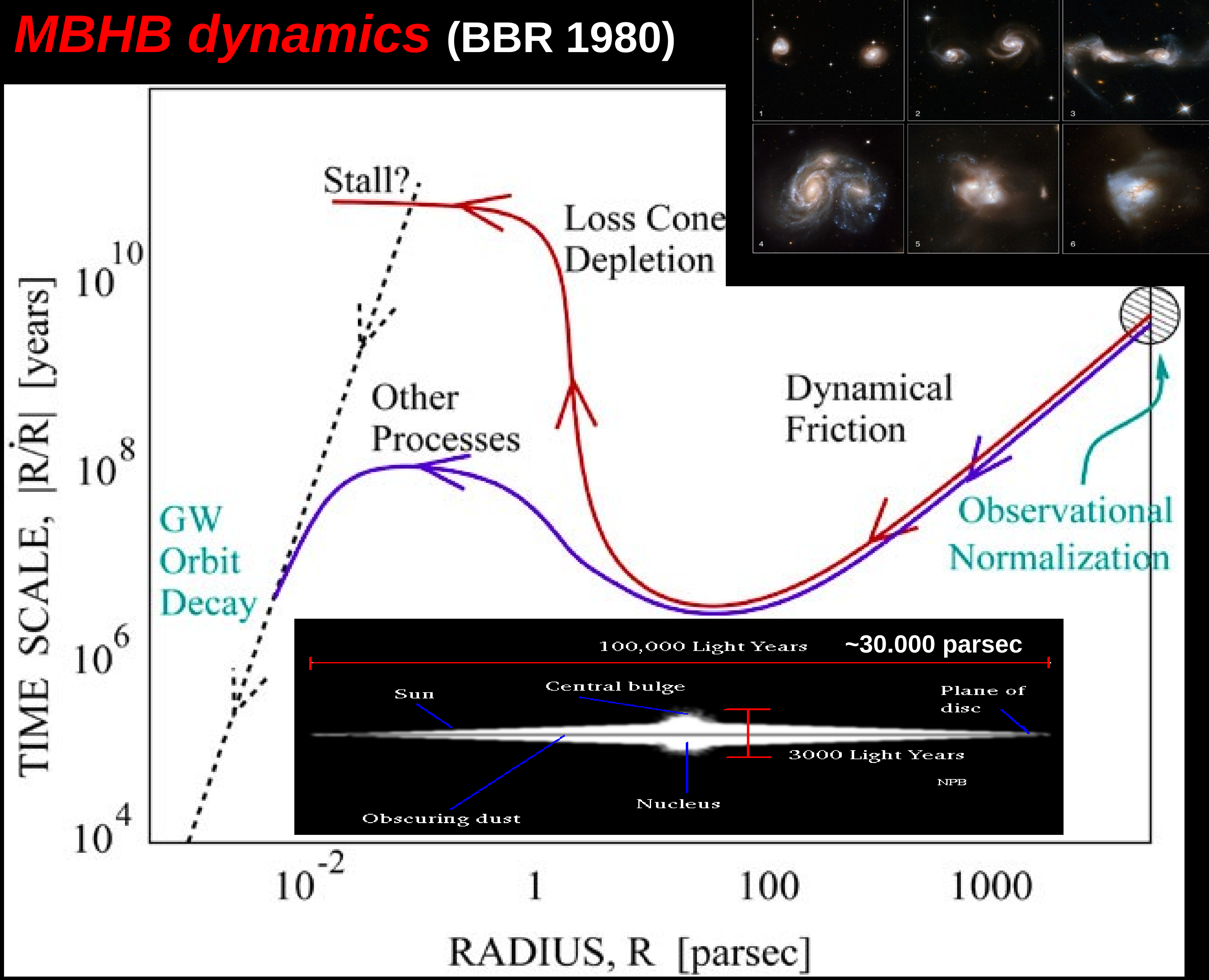

t = 2.6 Gyr
t = 3.0 Gyr
t = 4.8 Gyr
t = 5.1 Gyr
t = 5.122 Gyr
Edge-On
Face-On

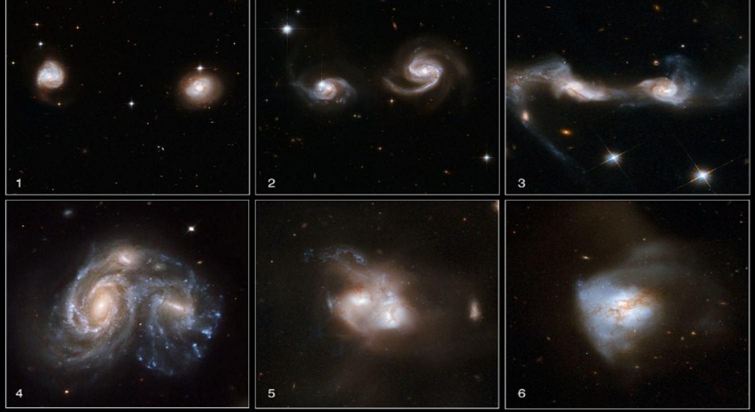
MBHB dynamics (BBR 1980)

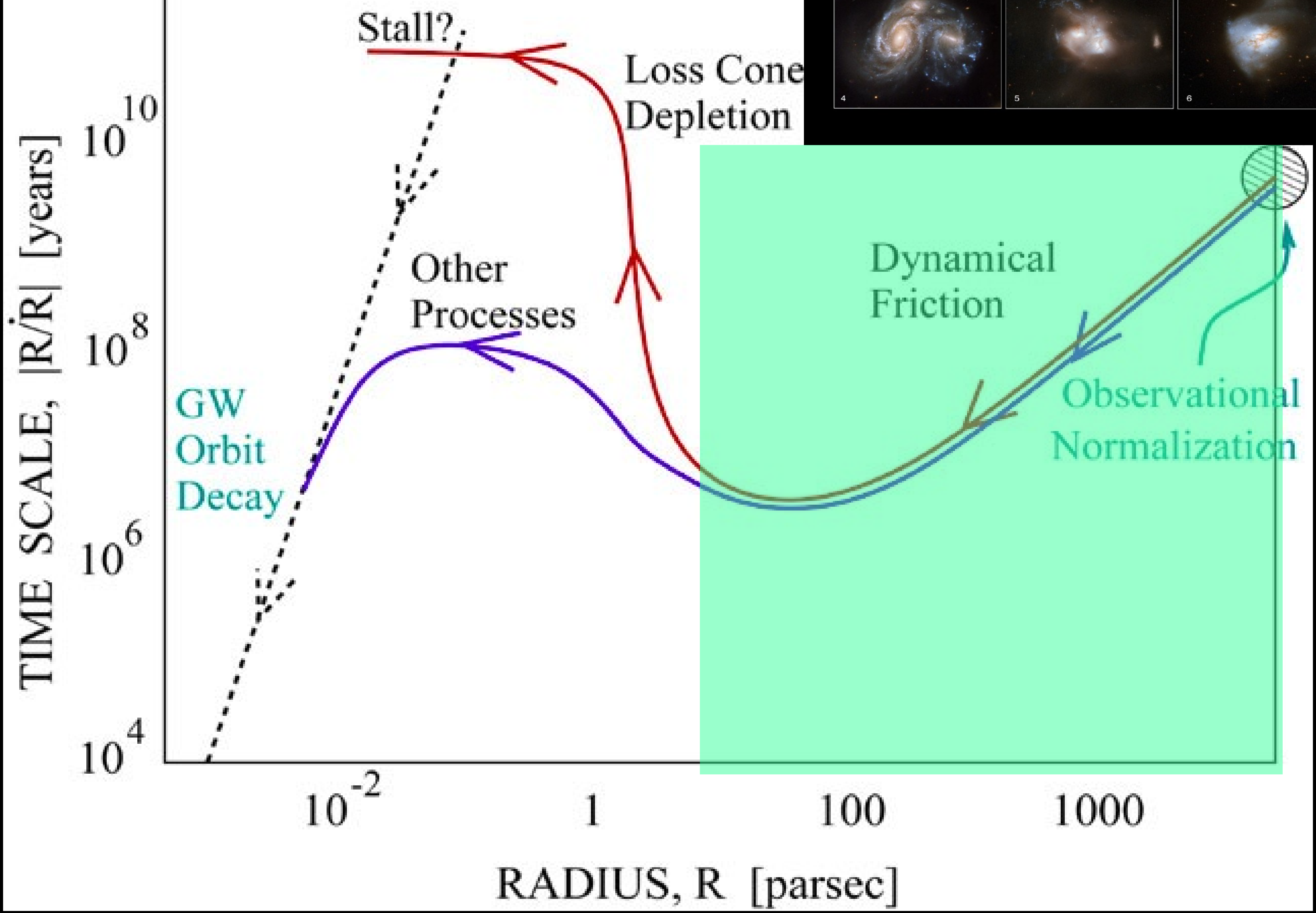


MBHB dynamics (BBR 1980)



MBHB dynamics (BBR 1980)

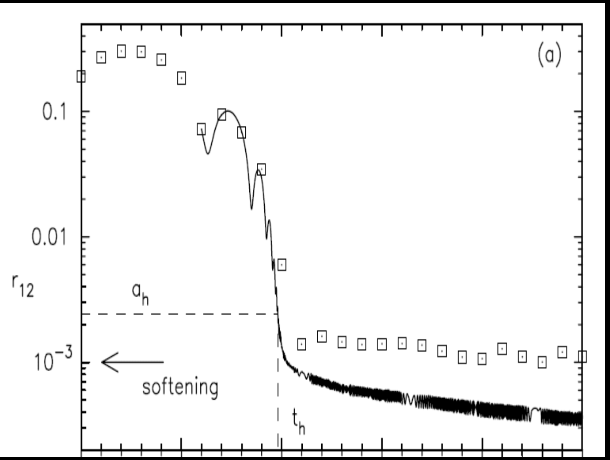




I-Dynamical friction: 10kpc-1pc

Consider a BH with mass M_{BH} moving with velocity V in a surrounding distribution of field star with a density ρ_* and a Maxwellian velocity distribution with dispersion σ. The drag exerted by the stars on the BH is given by:

$$\mathbf{F}_{\rm DF} = -4\pi \ln\Lambda G^2 M_{\rm BH}^2 \rho_* \left[{\rm erf}\left(\frac{V}{\sqrt{2}\sigma}\right) - \left(\sqrt{\frac{2}{\pi}}\frac{V}{\sigma}\right)\exp\left(-\frac{V^2}{2\sigma^2}\right)\right]\frac{\mathbf{V}}{V^3}$$



Milosavljevic & Merritt 2001

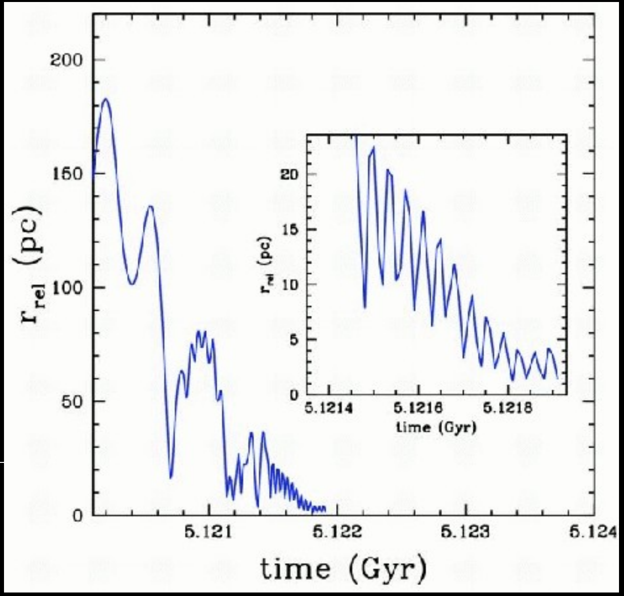
- in the limit V->0 this force is proportional to V
- in the limito of V>>σ this force is proportional to $1/V^2$
- the drag is maximum for $V=\sigma$

In a gaseous medium the formula is similar:

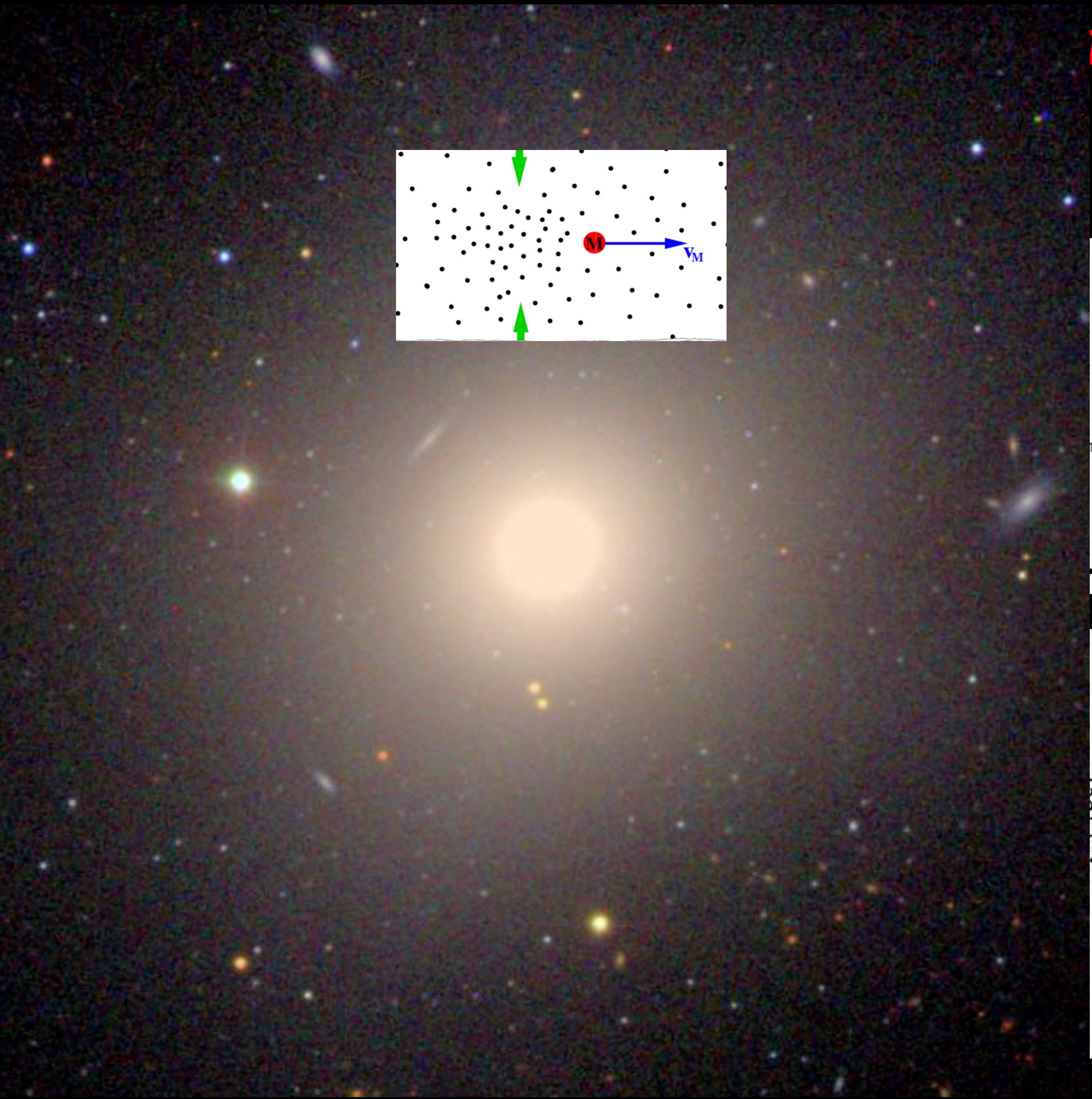
$$\mathbf{F}_{\rm DF}^{\rm gas} = -4\pi \ln\left[\frac{b_{\rm max}}{b_{\rm min}}\frac{(\mathcal{M}^2-1)^{1/2}}{\mathcal{M}}\right] G^2 M_{\rm BH}^2 \rho_{\rm gas}\frac{\mathbf{V}}{V^3}, \quad {\rm for} \quad \mathcal{M} > 1$$

$$\mathbf{F}_{\rm DF}^{\rm gas} = -(4/3)\pi G^2 M_{\rm BH}^2 \rho_{\rm gas} \mathcal{M}^3 \mathbf{V}/V^3 \propto M_{\rm BH}^2 \rho_{\rm gas} \mathbf{V}/c_{\rm s}^3 \ {\rm for}\ \mathcal{M} \ll 1$$

but now $\mathcal{M} = V/c_{\rm s}$ is the gas speed of sound.
Again the drag is maximum when $V=c_s$, and is comparable to the stellar case.

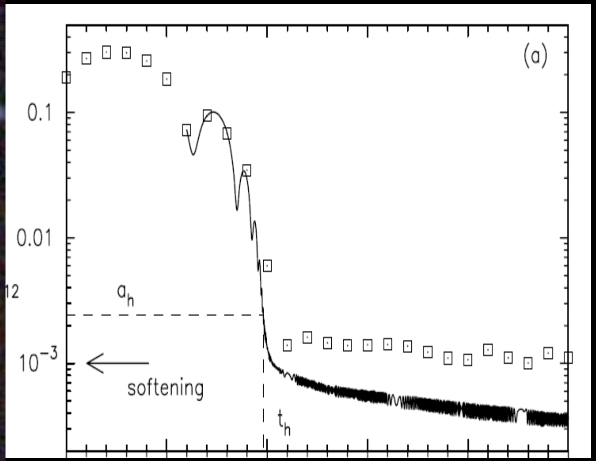


Colpi & Dotti 2009

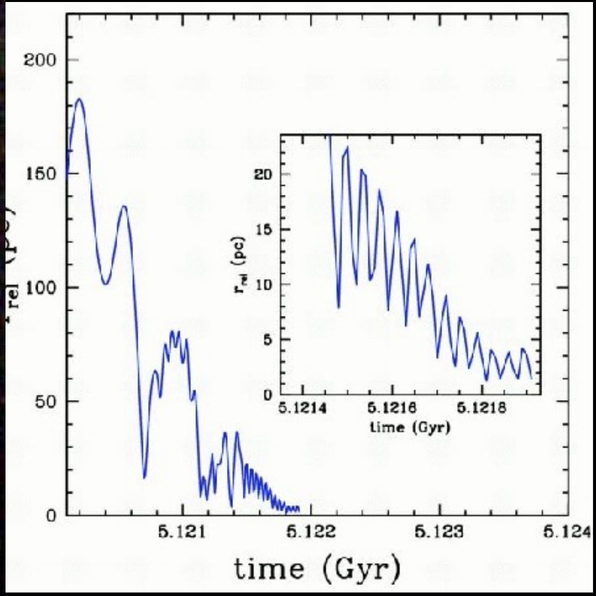


1pc

a surrounding
lian velocity
stars on the BH is



Milosavljevic & Merritt 2001



Colpi & Dotti 2009

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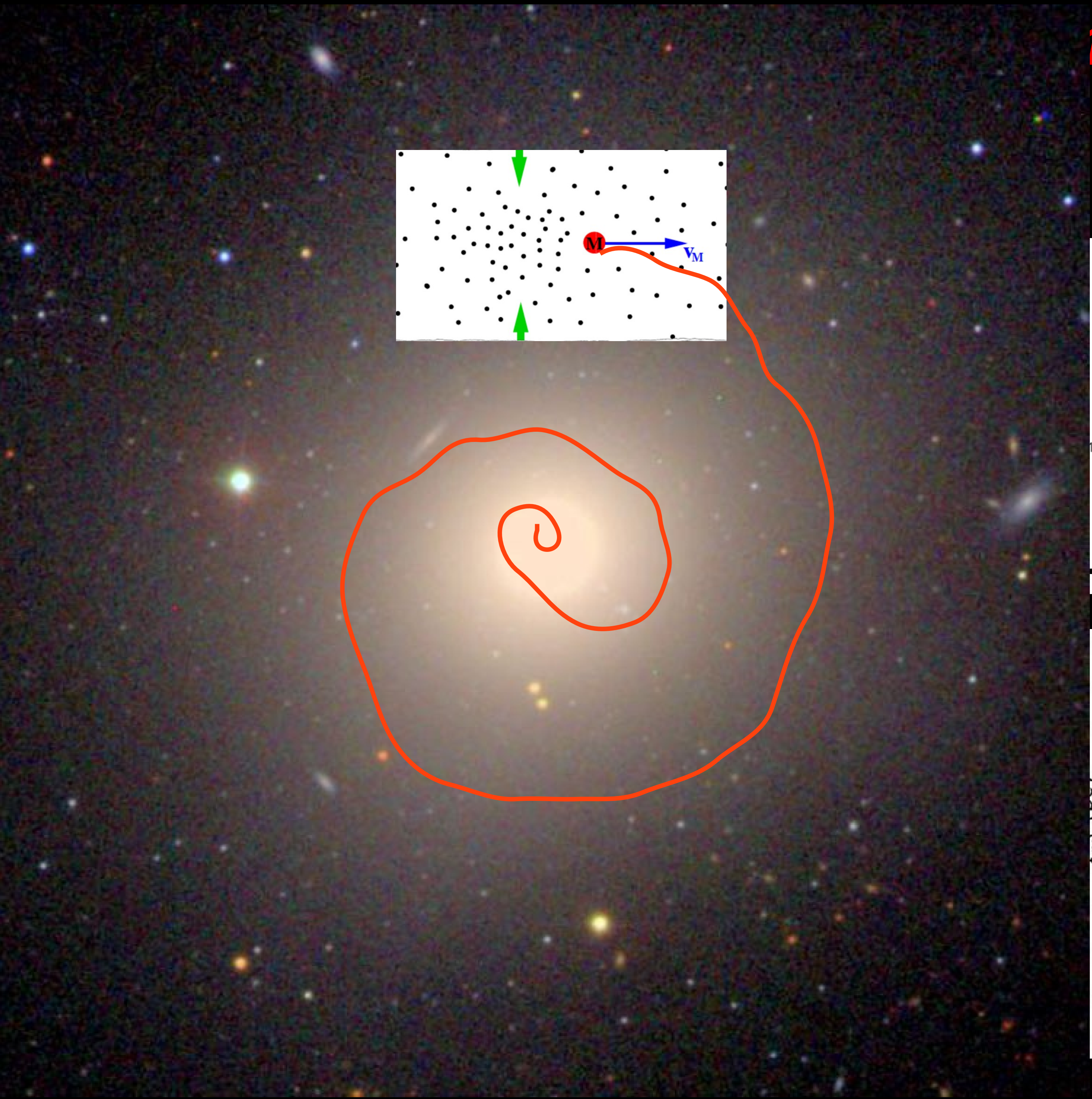
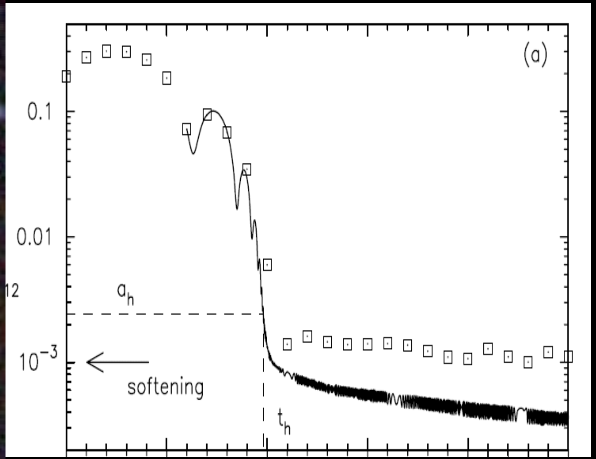
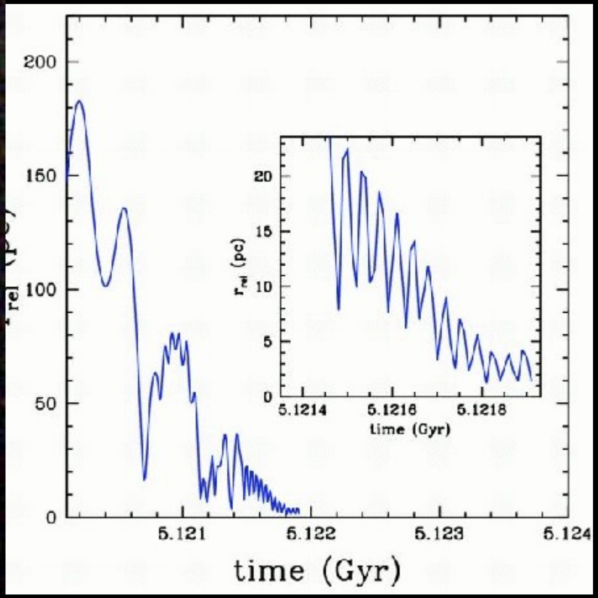
stars on the BH is



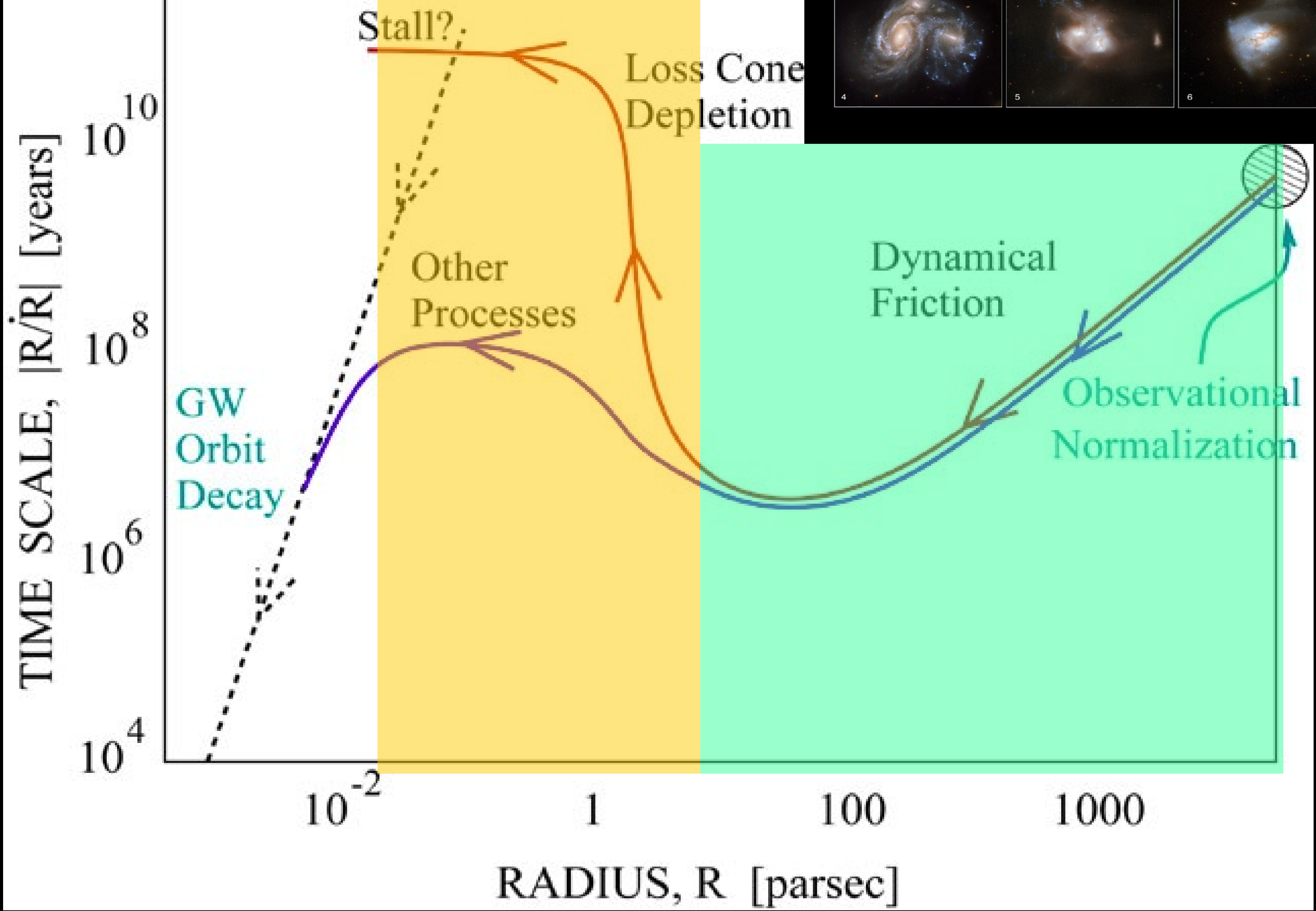


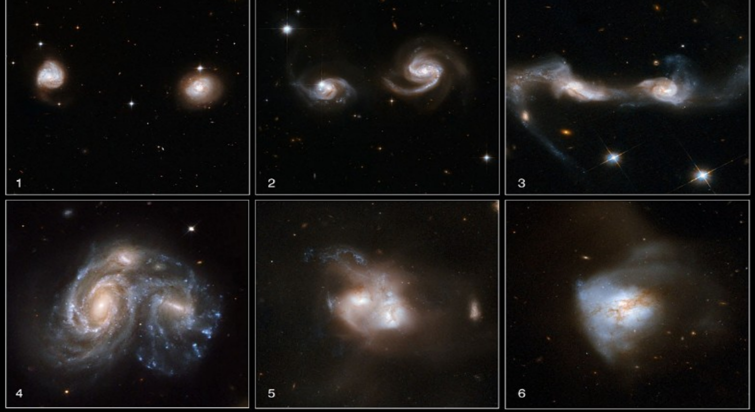
Milosavljevic & Merritt 2001



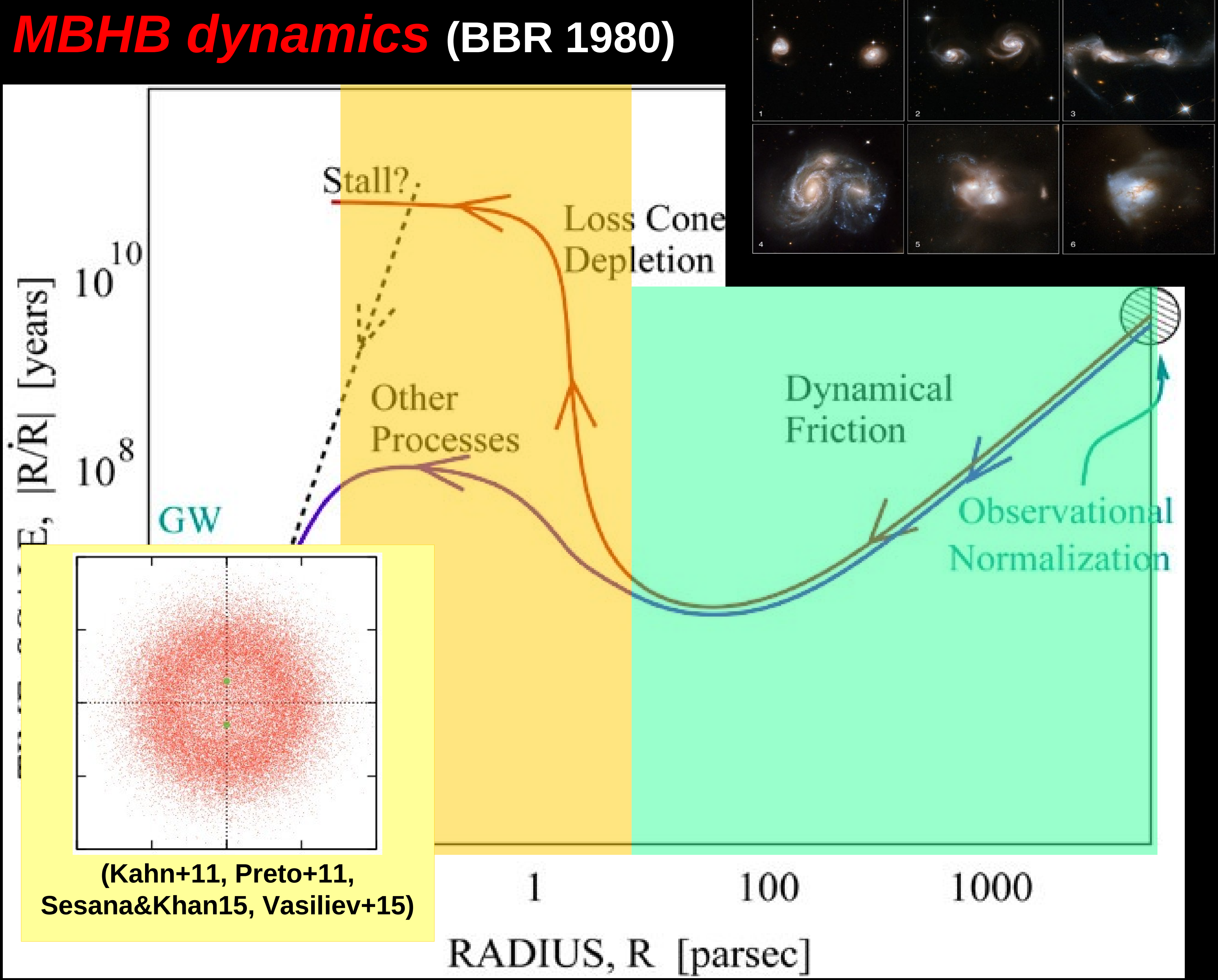
Colpi & Dotti 2009

MBHB dynamics (BBR 1980)

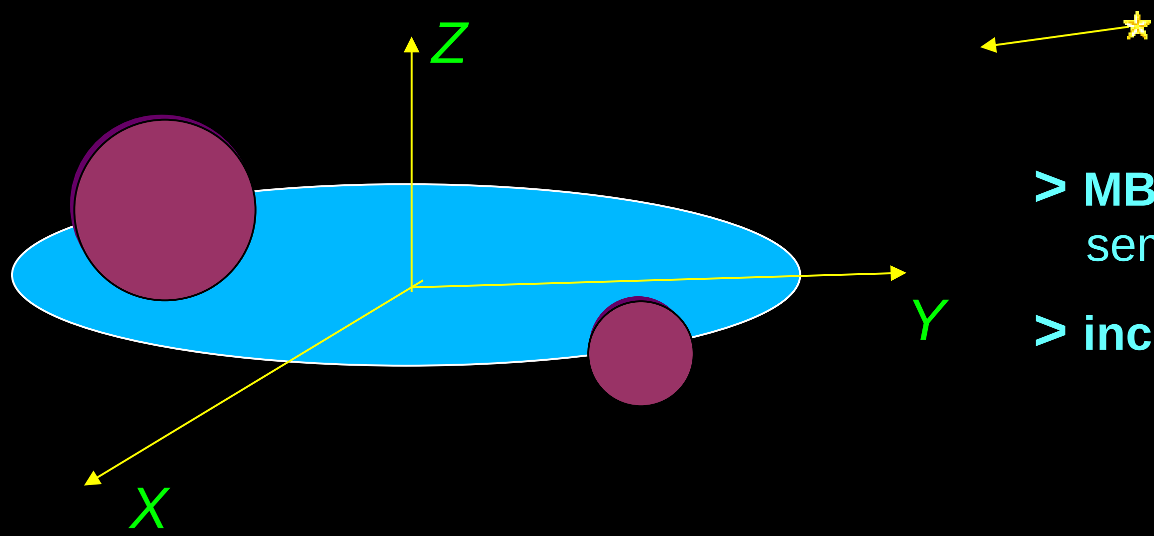




MBHB dynamics (BBR 1980)



2a-stellar scattering



> **MBHB** ***M_1>M_2*** on a keplerian orbit with semimajor axis ***a*** and eccentricity ***e***

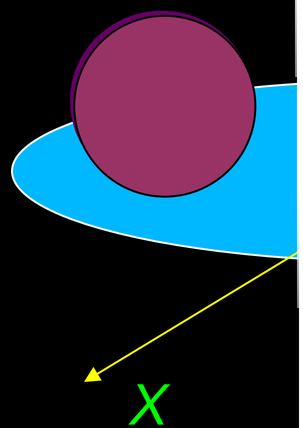
> **incoming star** with ***m_* <<M_2*** and velocity **v**

A star on a intersecting orbit receive a kick taking away from the binary an amount of energy of the order $(3/2)Gm_*\mu_{\rm BH}/a$

This energy, and the relative angular momentum carried away, can be used to define dimensionless rate that describe the evolution of the binary.

$$\frac{dN}{dt} = n\Sigma\sigma = \frac{2\pi G(M_1 + M_2 + m_3)na}{\sigma}$$

2a-stellar scattering



orbit with
tricity ***e***

and velocity **v**

A star on a i
an amount o
nary

This energy
used to defi
binary.
be
e

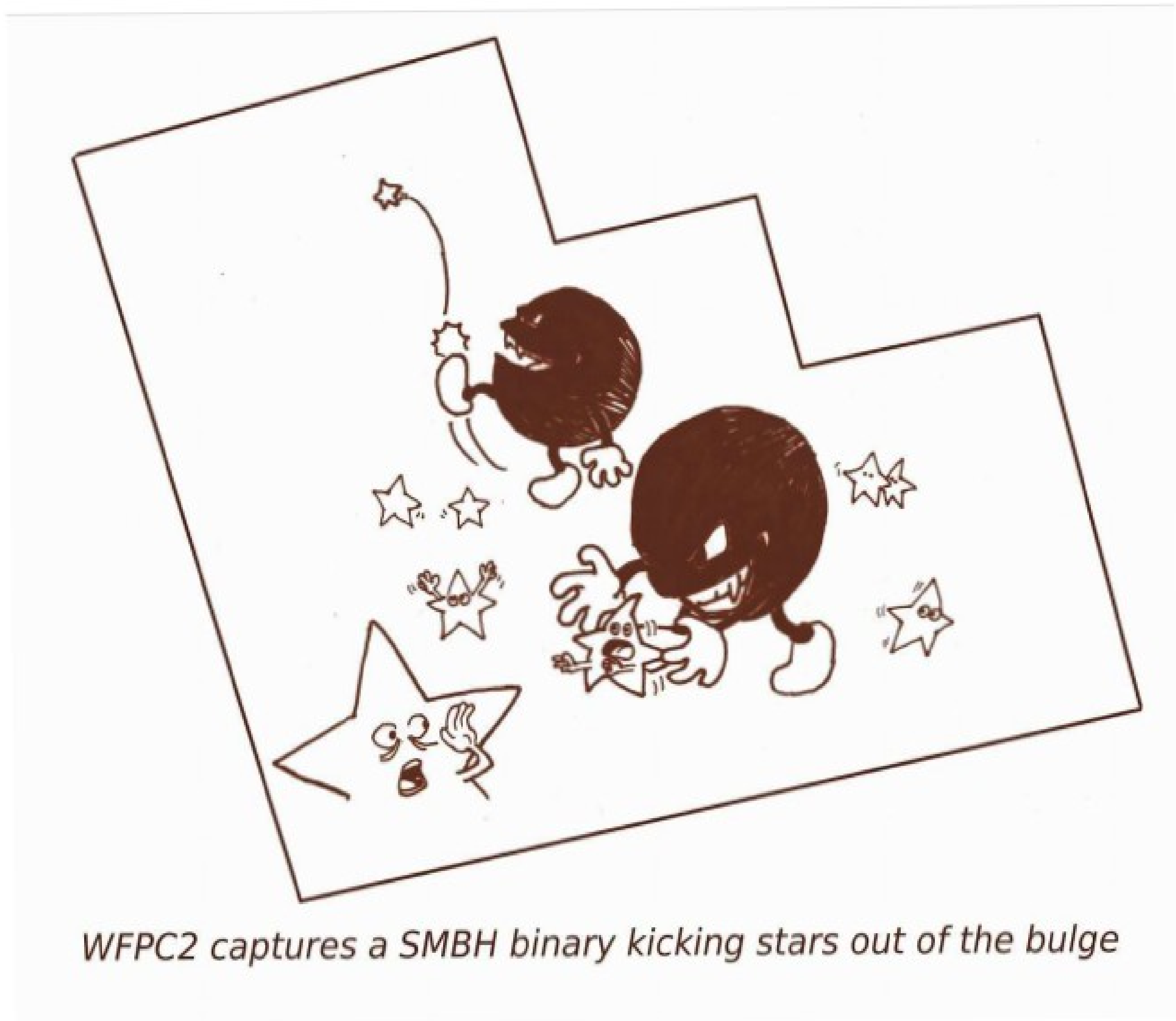


FIG. 7.— Cartoon showing a pair of supermassive black holes kicking stars away as they dance towards coalescence at the centre of a galaxy. Credit: Paolo Bonfini.

$$\frac{da}{dt} = \frac{da}{dt}\Big|_{3b} + \frac{da}{dt}\Big|_{\rm gw} = -Aa^2 - \frac{B}{a^3},$$

$$A = \frac{GH\rho_{\rm inf}}{\sigma_{\rm inf}}, \quad B = \frac{64G^3 M_1 M_2 M F(e)}{5c^5},$$

$$a_{*/\rm gw} = \left[\frac{64G^2\sigma_{\rm inf} M_1 M_2 M F(e)}{5c^5 H \rho_{\rm inf}}\right]^{1/5}$$

Triaxiality of the merger remnant keeps the 'loss cone full' and the hardening rate ~constant

The evolution of the binary can be simply obtained by combining stellar and GW hardening (e.g. AS & Khan 2015)

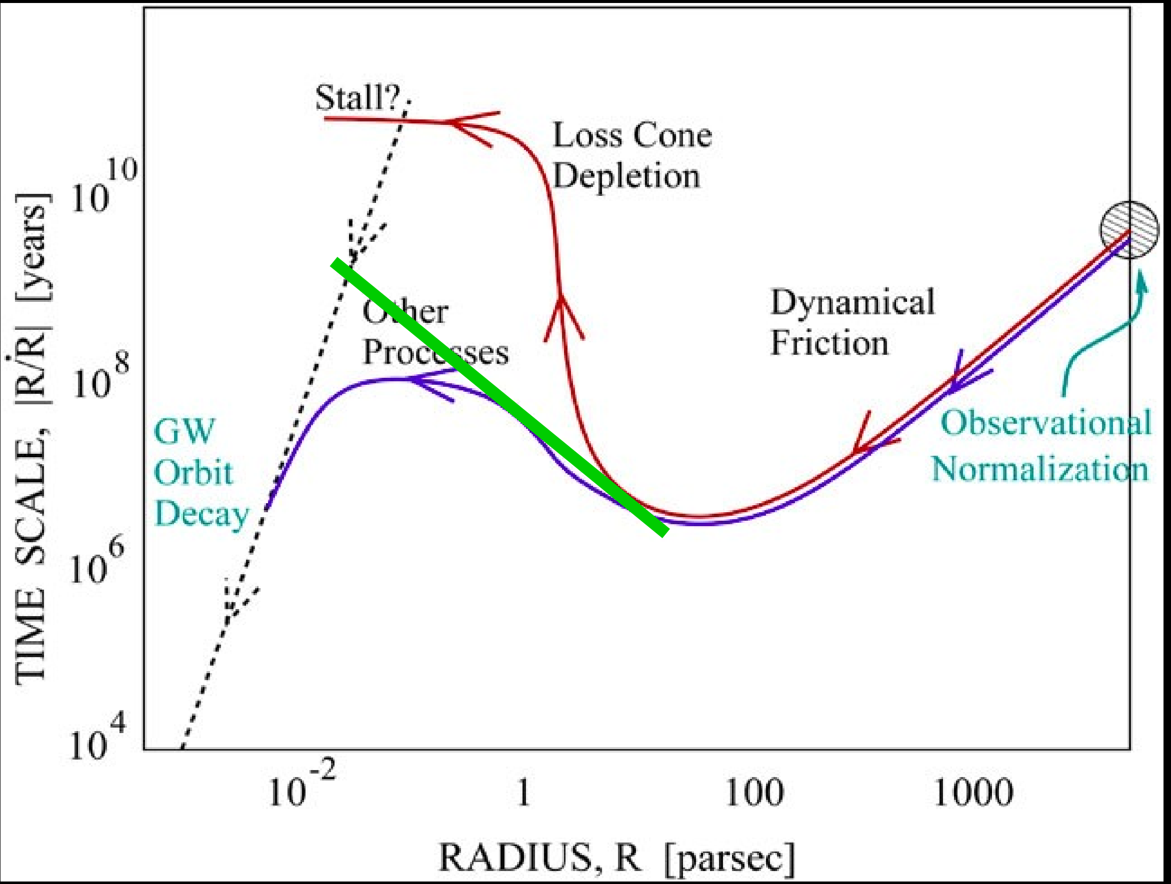
The binary spends most of its time at the transition separation

$$t(a_{*/\rm gw}) = \frac{\sigma_{\rm inf}}{GH\rho_{\rm inf} a_{*/\rm gw}}.$$

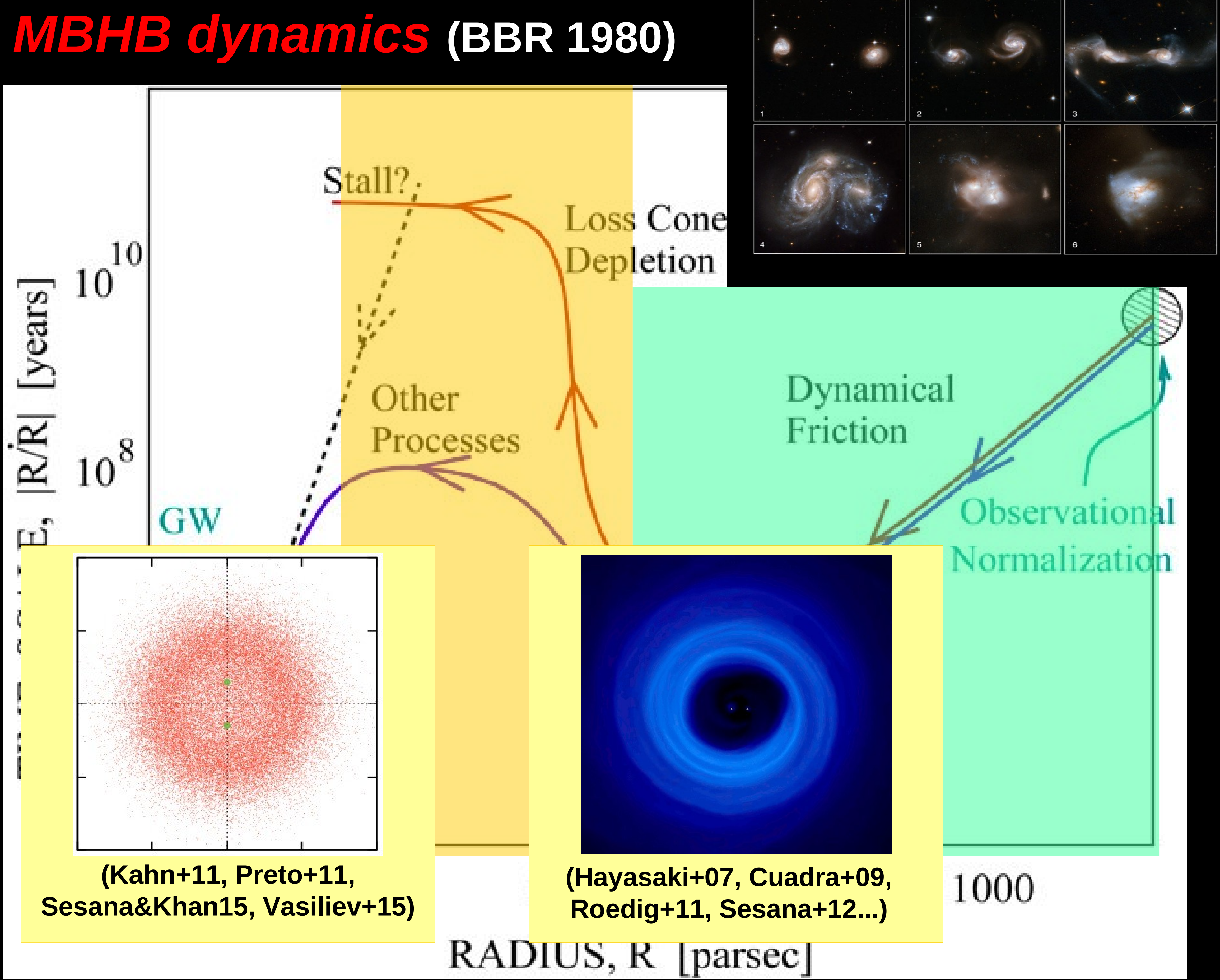
Assuming an isothermal sphere and a simple M-sigma relation

$$a_{*/\rm gw} \approx 0.01\,{\rm pc}\left(\frac{M}{10^8 {\rm M}_\odot}\right)^{3/4}$$

$$t(a_{*/\rm gw}) \approx 10^8 {\rm yr}.$$



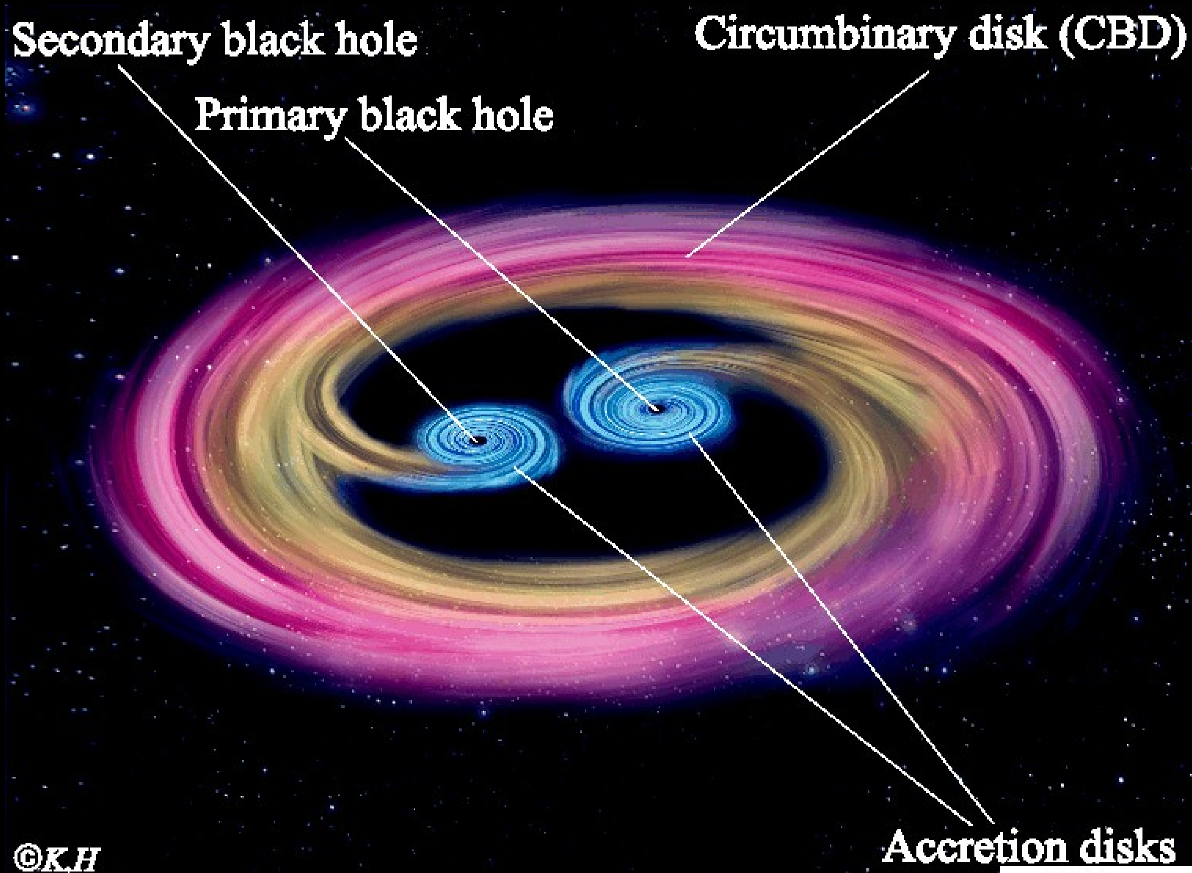
MBHB dynamics (BBR 1980)



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

(Hayasaki+07, Cuadra+09, Roedig+11, Sesana+12...)

2b-Circumbinary disk-driven binaries



Gas inflows with a constant accretion rate. Its change in angular momentum is

$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

The binary acts as a dam holding the gas at r_{gap} .

Therefore is injecting in the disk an angular momentum equal and opposite to the above

Therefore the angular momentum of the binary also evolve as

$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

Using $L = \mu\sqrt{GMa}$ and assuming that the mass ratio does not change one get the equation

$$\frac{da}{a} = -2\sqrt{2}\frac{dM}{\mu}$$

The binary makes ~3 e-folds by accreting a mass equal to mu. Assuming Eddington limited accretion this happens in ~4 x 10^7 yrs. (Dotti+15)

Supermassive black hole triplets

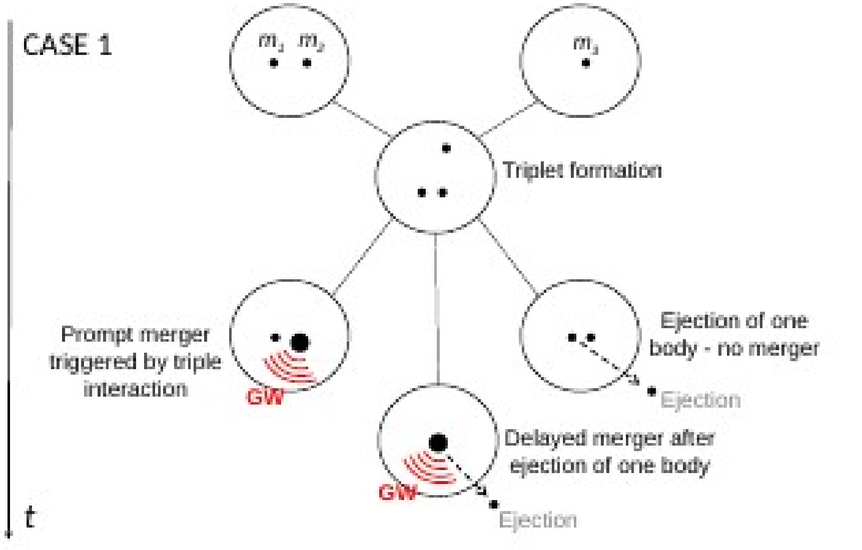


Figure 1. Cartoon representation of how triple MBH interactions are treated in the semianalytic model described in Section 2.

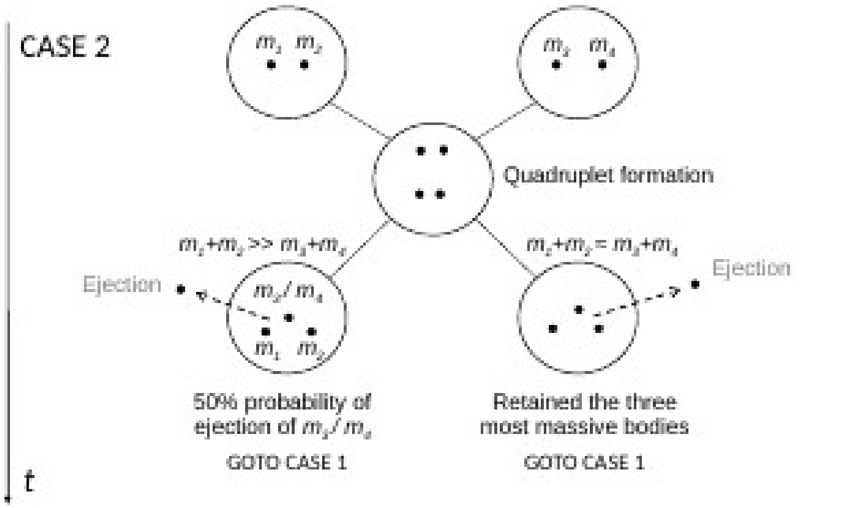
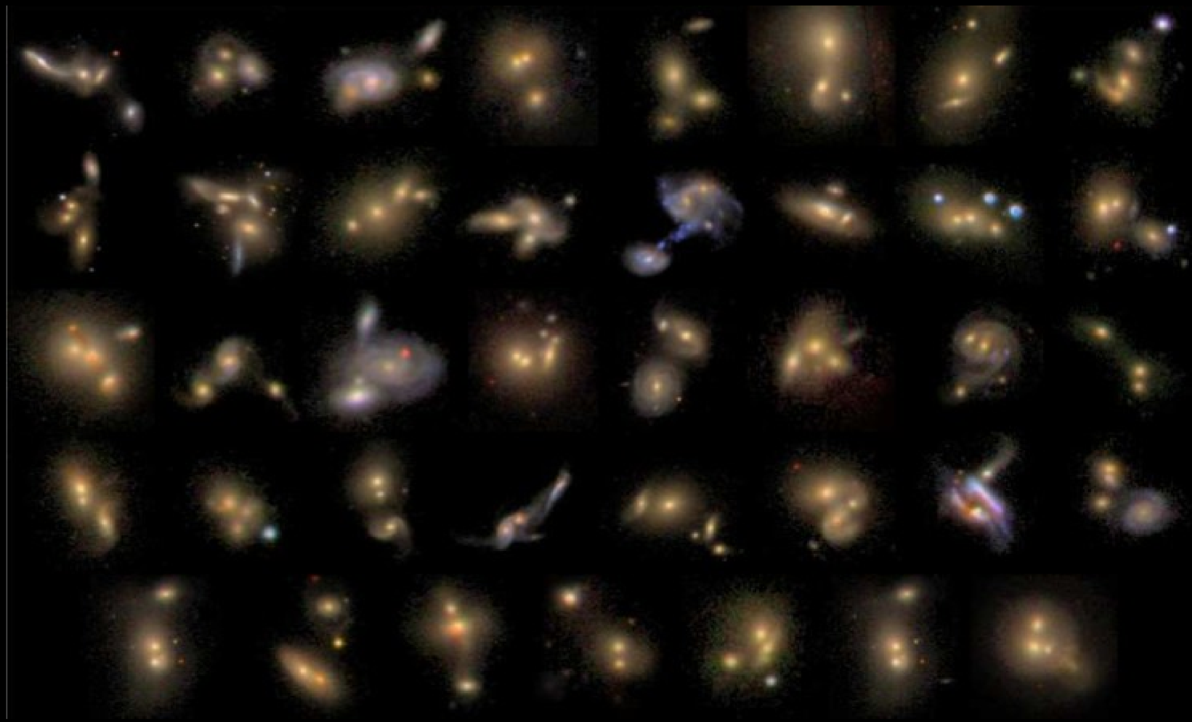


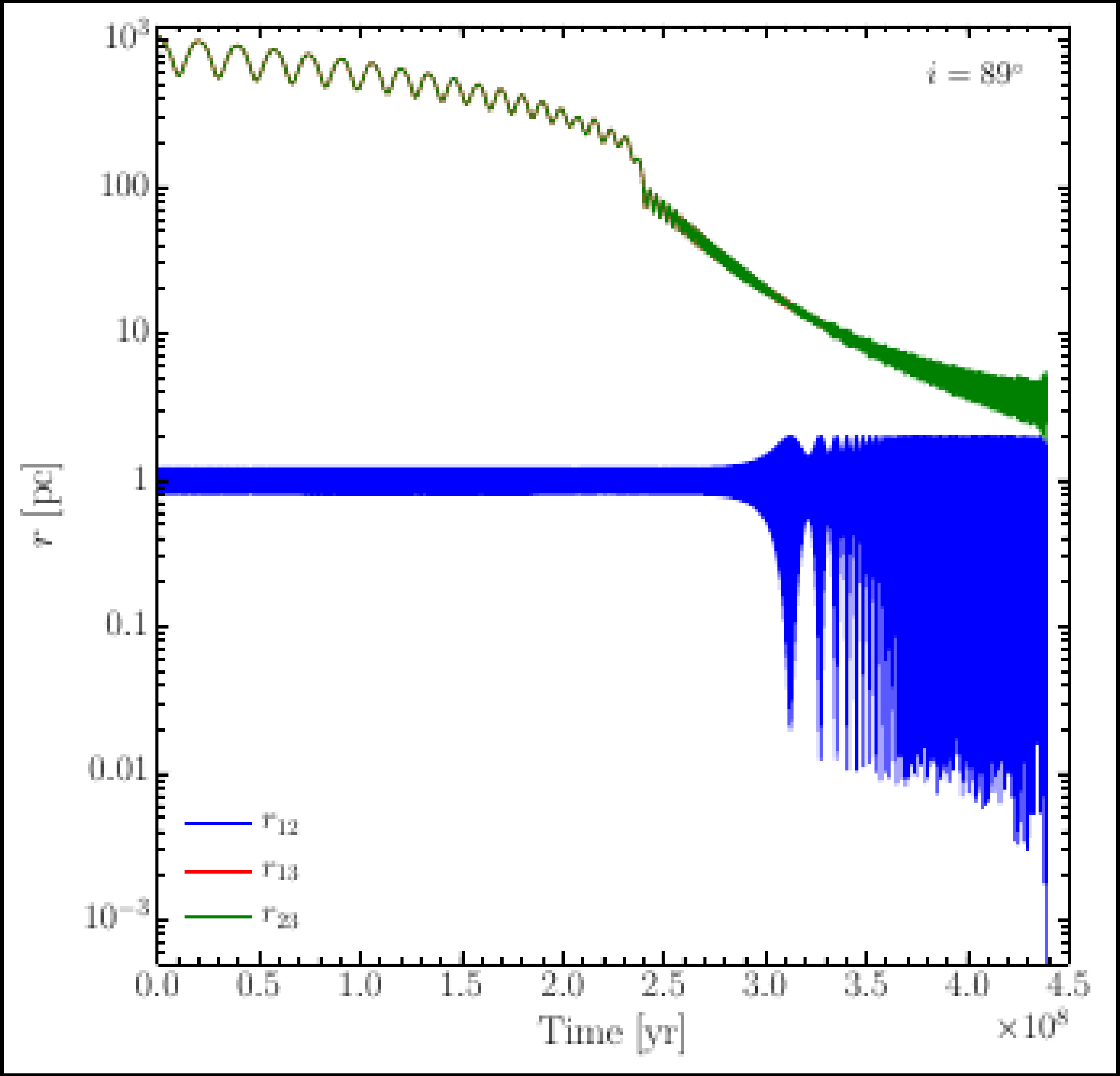
Figure 2. Same as figure 1, but for quadruple interactions.



merger timescales comparable with galaxy subsequent merger timescale

There is a concrete possibility of injecting a third MBH in the system when the binary is still 'slowly hardening'
(Hoffmann & Loeb 2007; Amaro-Seoane, AS, et al. 2010; Bonetti+16; Bonetti+17a,b; Ryu+17)

Integration of the 3-body dynamics



We designed a code for evolving MBHB triplets including

-PN dynamics up to 2.5 order, including all terms consistently derived from the 3-body Hamiltonian

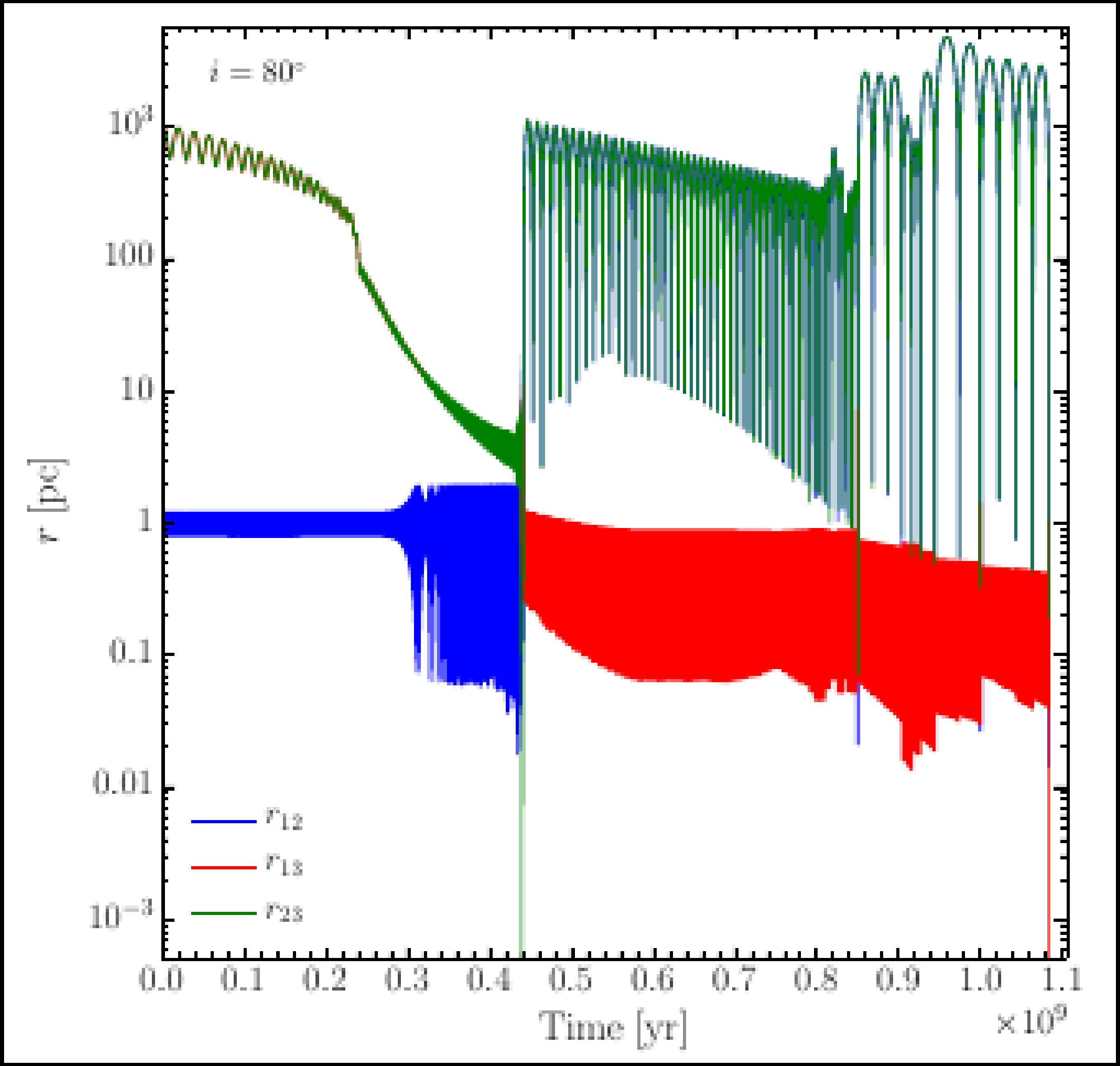
-Dynamical friction (Chandrasekhar 1943)

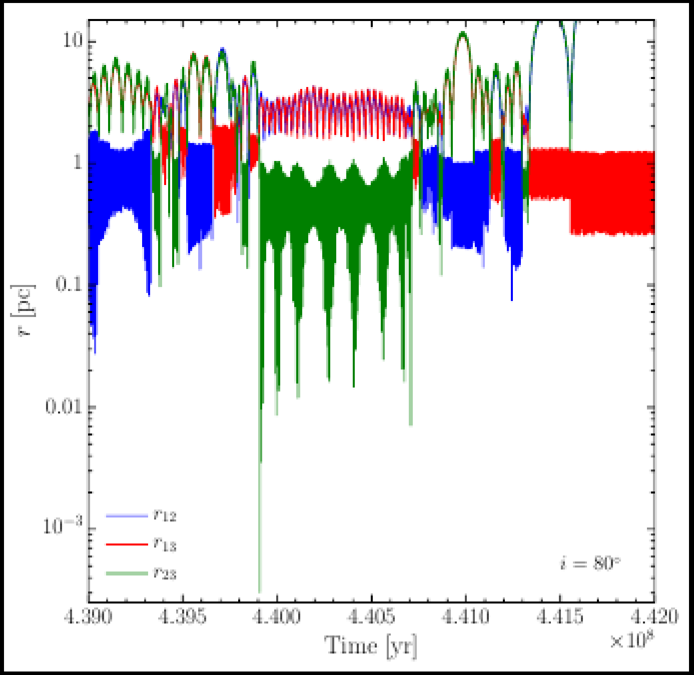
-Stellar hardening (Sesana 2006)

-Spherical external potential

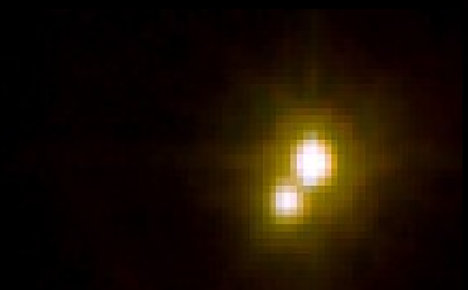
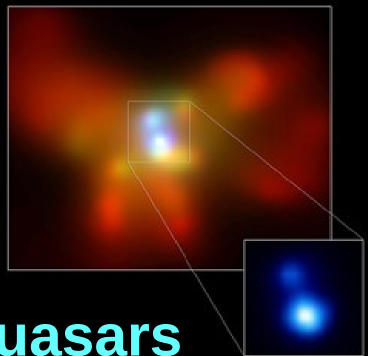
The code has been extensively tested reproducing results from the literature.

It can handle complex chaotic dynamics

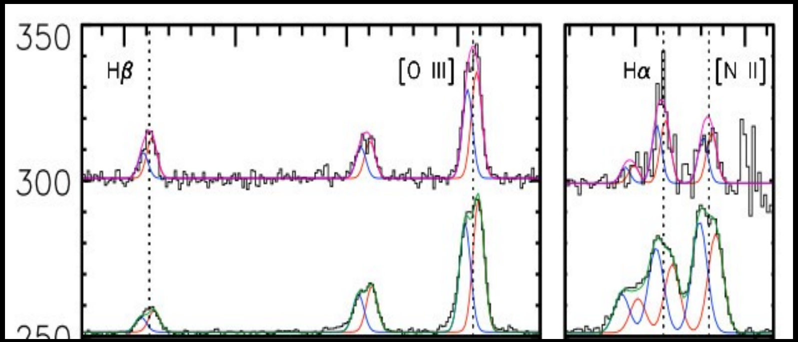




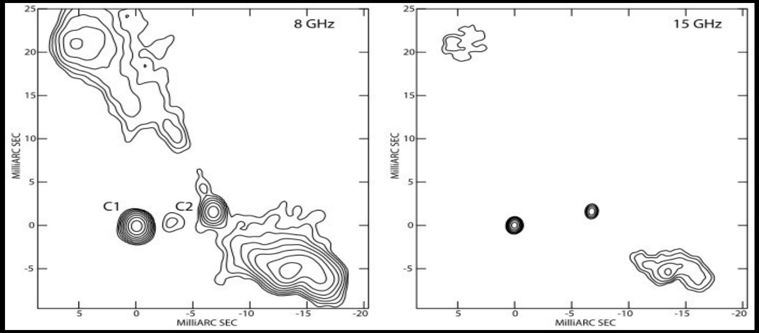
But do we see them?

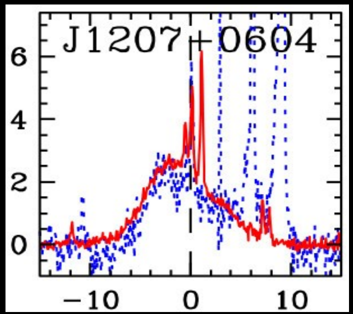
10 kpc: double quasars
(Komossa 2003)

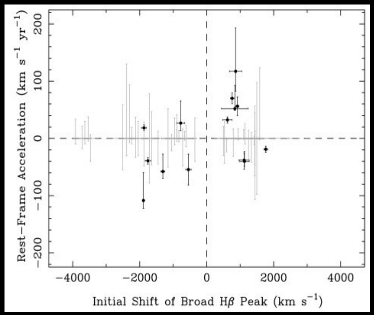


1 kpc: double peaked NL
(Comerford 2013)

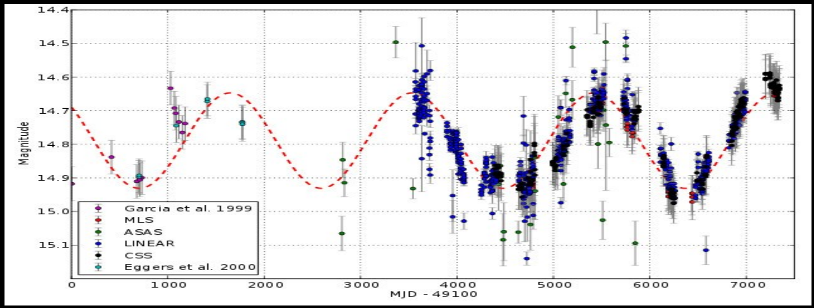


10 pc: double radio cores
(Rodriguez 2006)

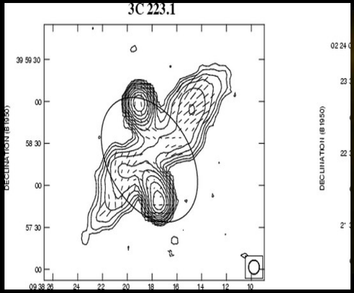




1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)

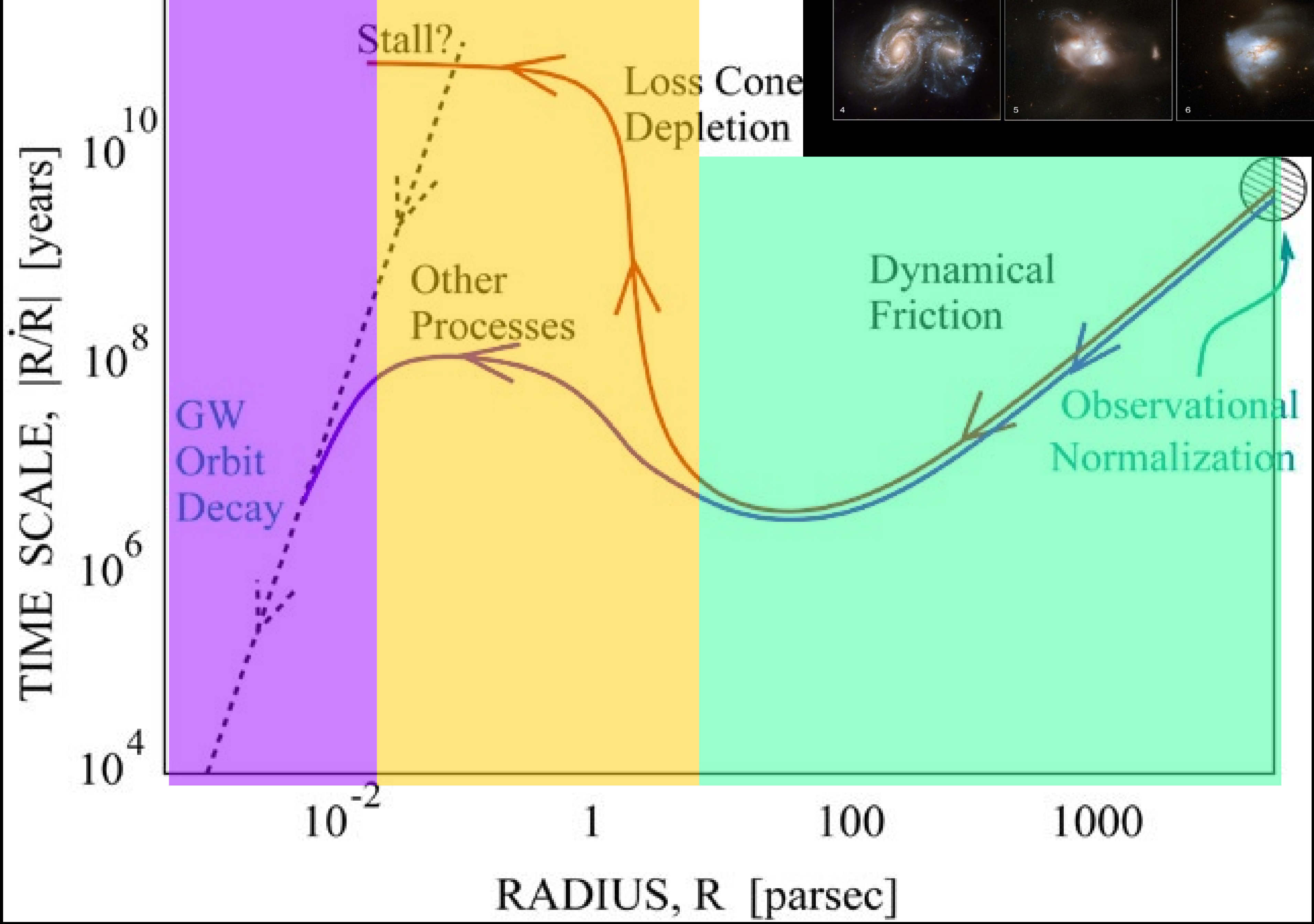


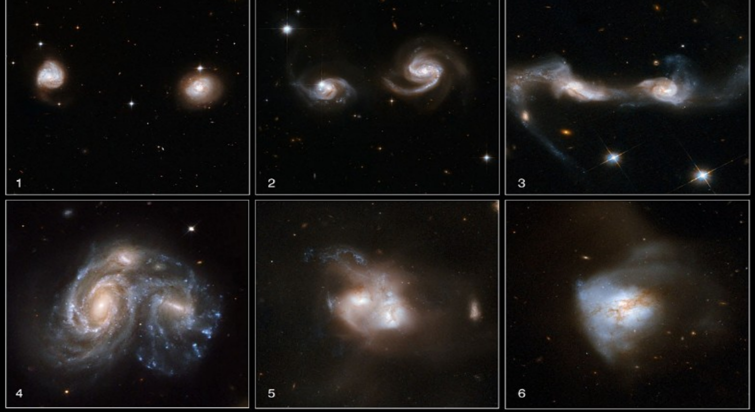
0.01 pc: periodicity (Graham 2015)



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

MBHB dynamics (BBR 1980)





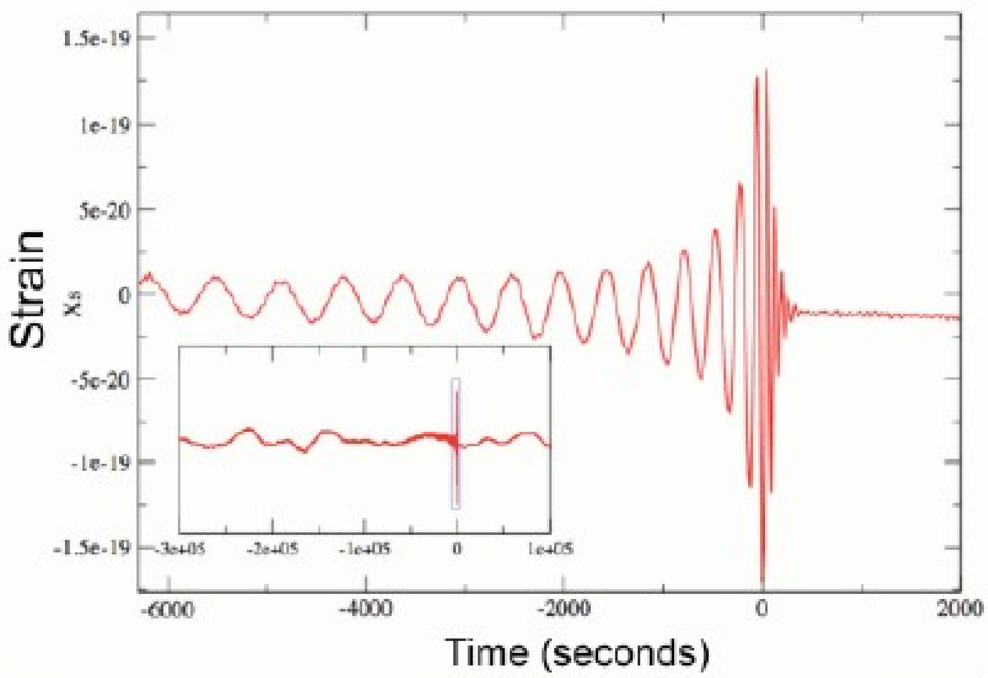
Gravitational waves

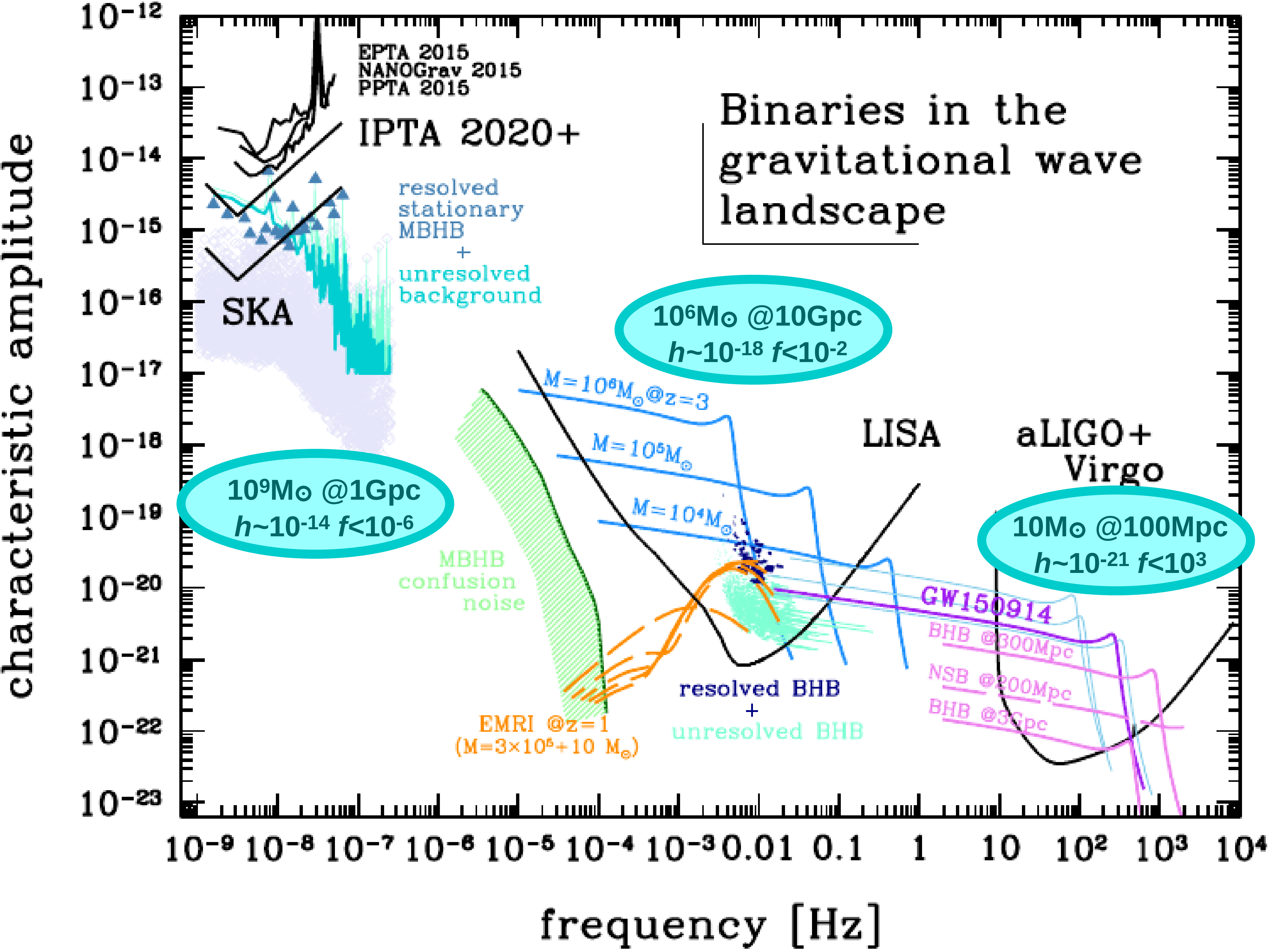
If the binary overcome the final parsec problem then it coalesces on a timescale given by:

$$t_{\rm GW} = \frac{5c^5}{256G^3}\frac{a^4}{M_1M_2MF(e)} \approx 0.25\mathrm{Gyr}\left(\frac{MM_1M_2}{10^{18.3}\ \mathrm{M_\odot}^3}\right)^{-1} F(e)^{-1}\left(\frac{a}{0.001\mathrm{pc}}\right)^4$$

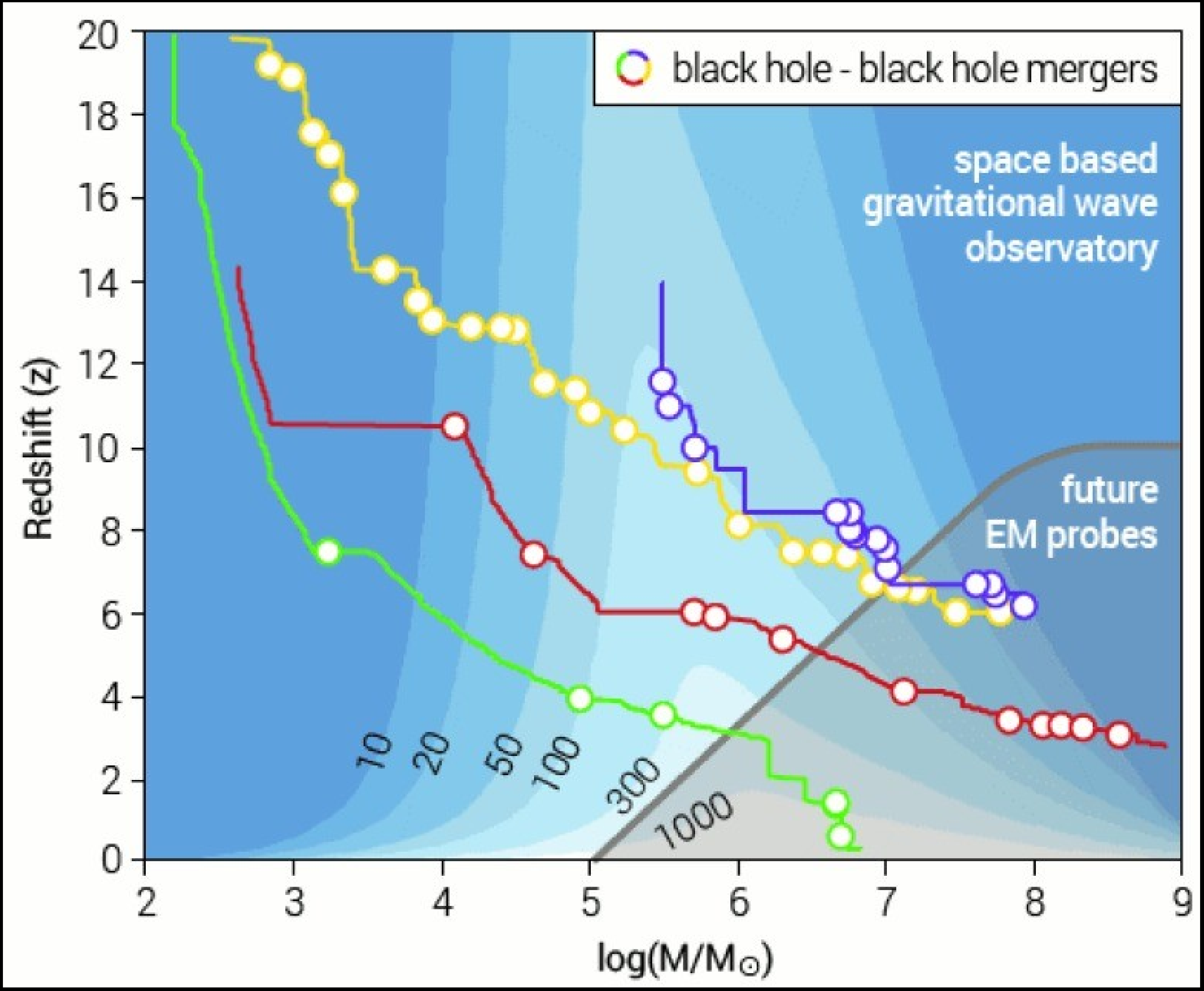
producing the *loudest gravitational wave signals in the Universe!*

Simulated LISA data stream at merger event,
two $10^5 M_\odot$ BH at z=5 including simulated noise (S/N~500)





characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB + unresolved background
Binaries in the gravitational wave landscape
10⁶M⊙ @10Gpc h~10⁻¹⁸ 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



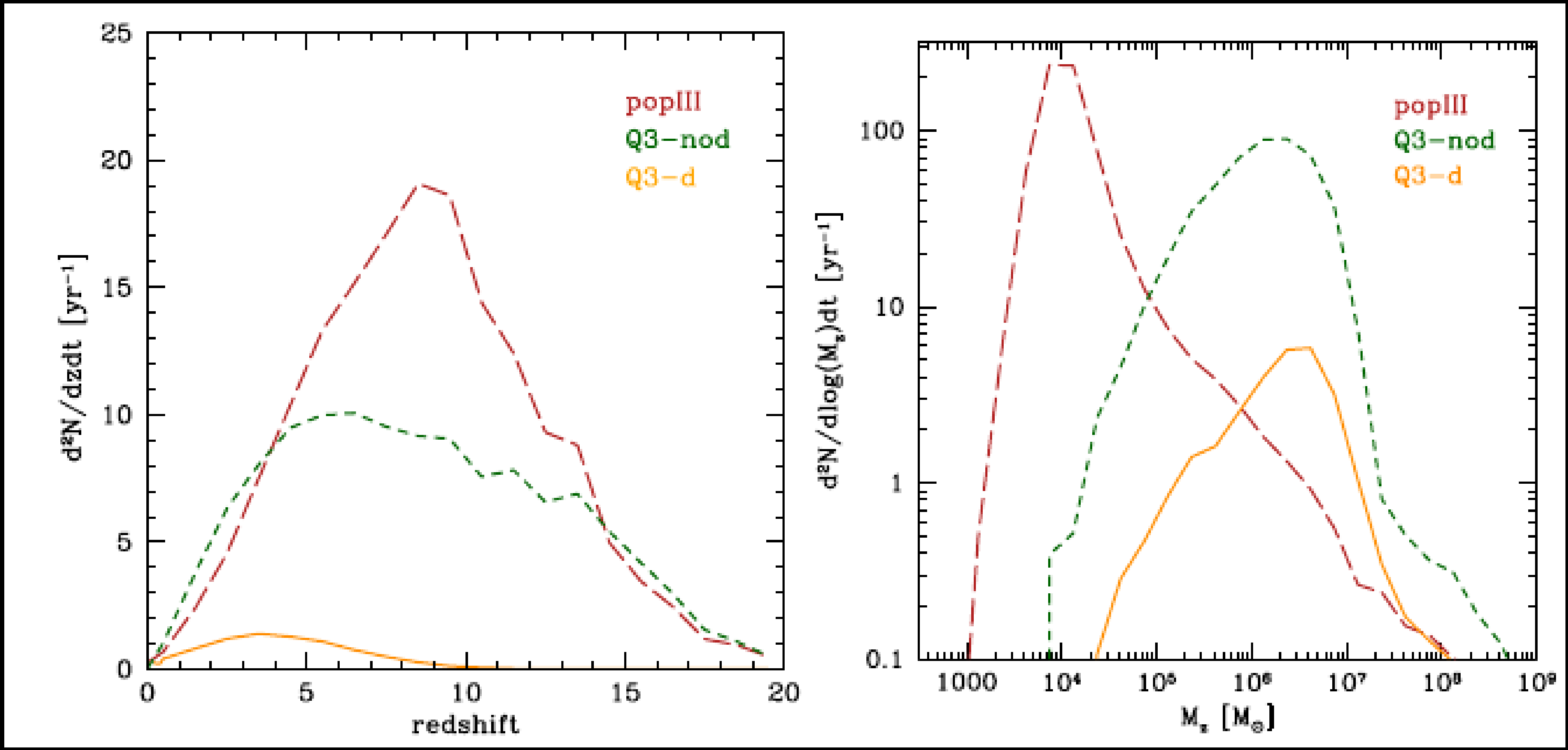
black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
Redshift (z)
log(M/M⊙)
10
20
50
100
300
1000

MBHB population models

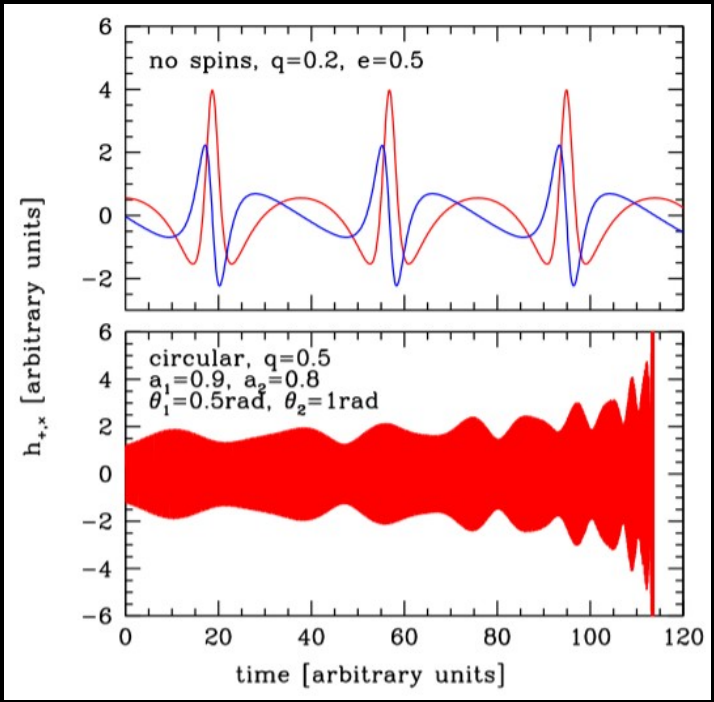
Semianalytic models for galaxy and MBH formation and evolution (Barausse).

The explored scenarios cover a wide range of merger histories:

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



What LISA will measure



Assuming 4 years of operation:

~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

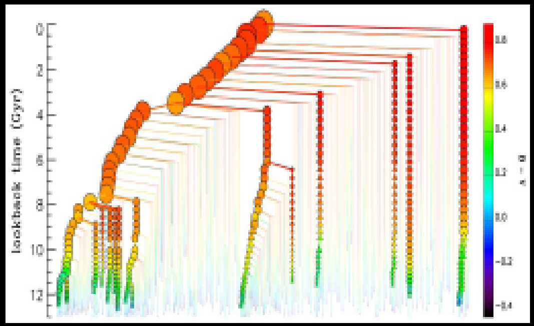
~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

MBH astrophysics with GW observations

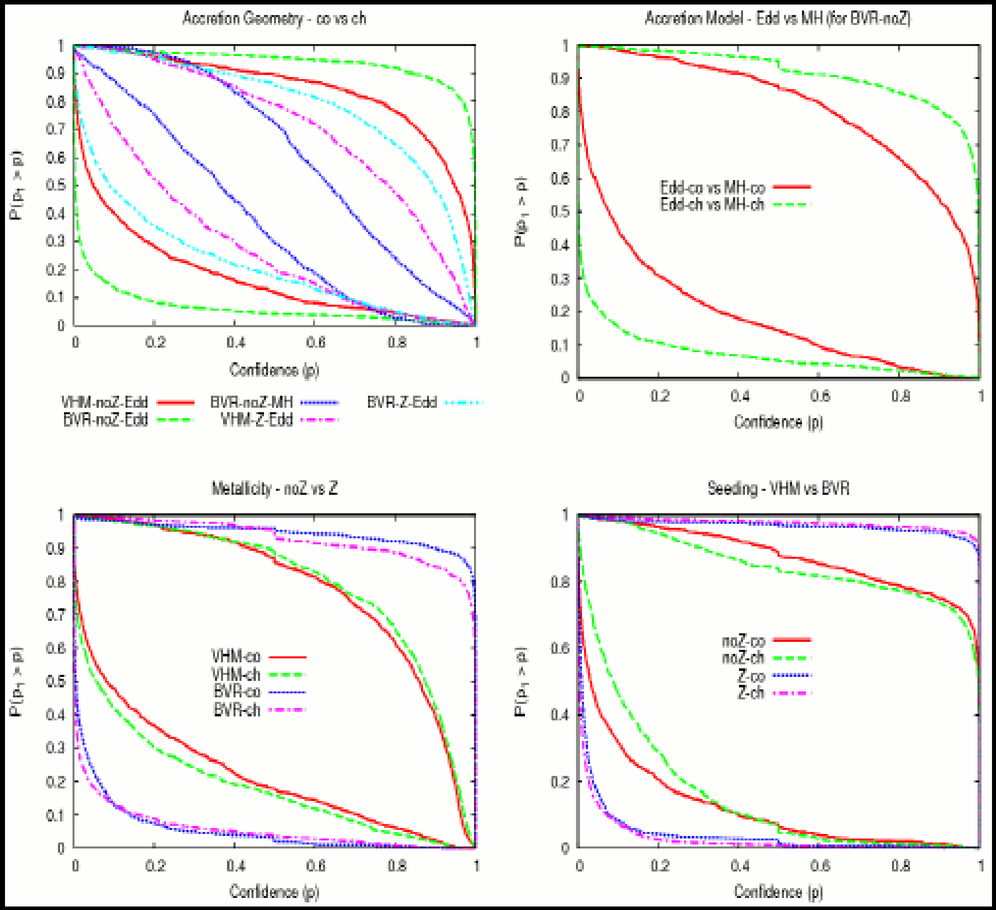
Astrophysical unknowns in MBH formation scenarios

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?

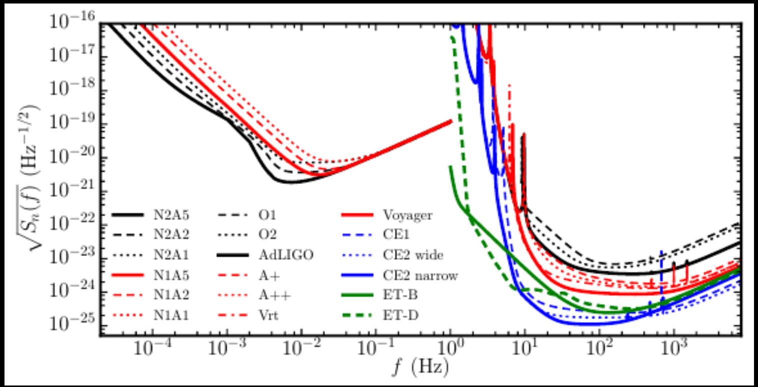
Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models



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

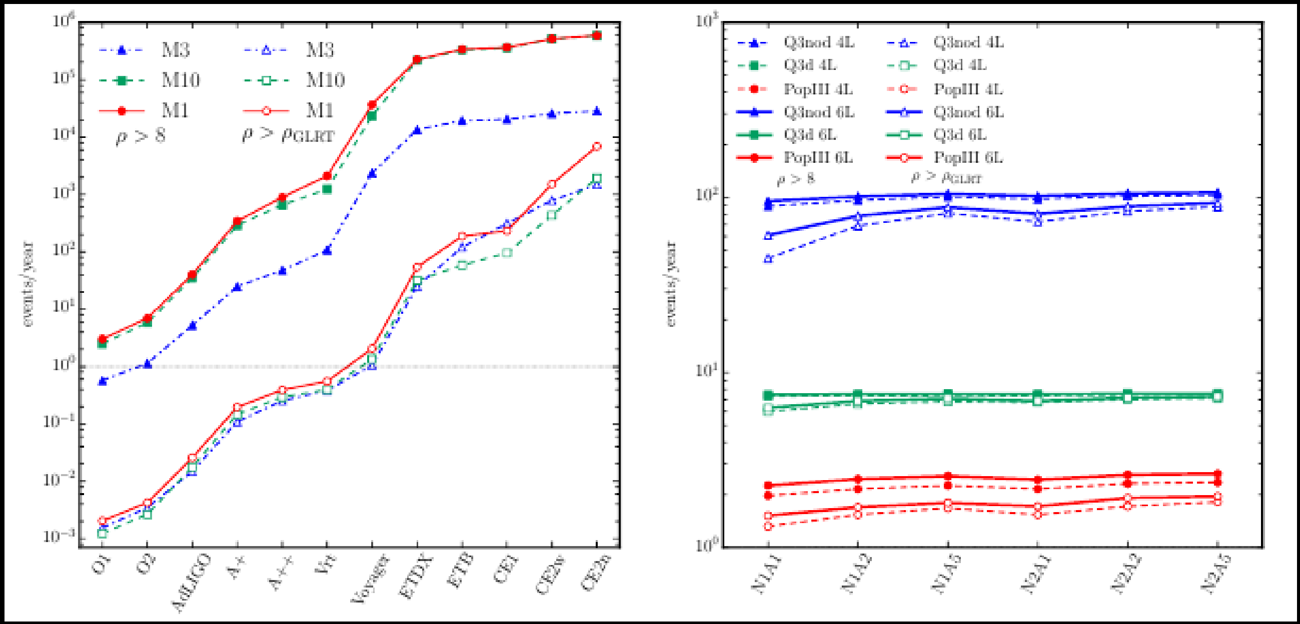
Resolving ringdown modes: BH spectroscopy

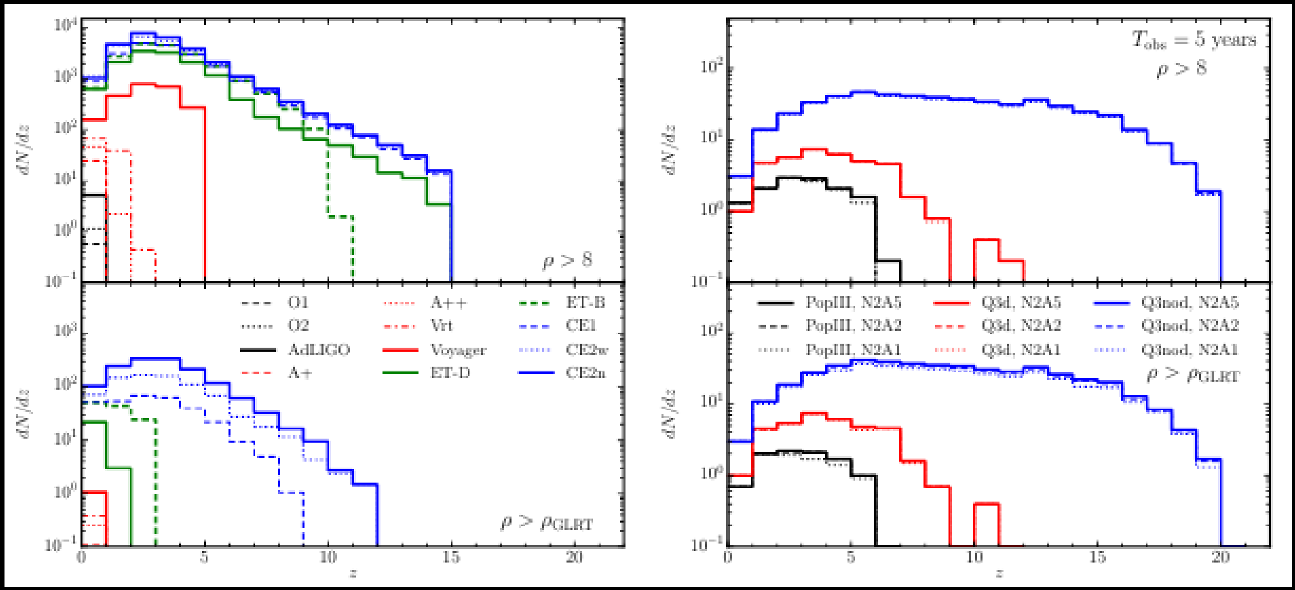
(Berti et al. 2016)



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

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





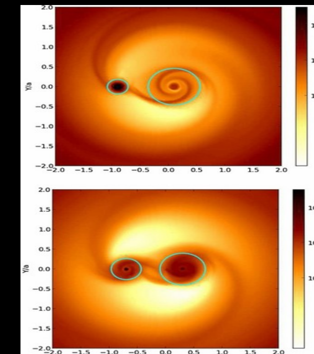
LIGO will not enable BH spectroscopy on individual BHB mergers

Voyager/ET type detectors are needed

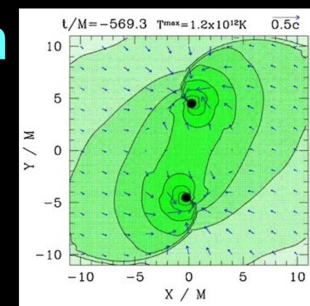
eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

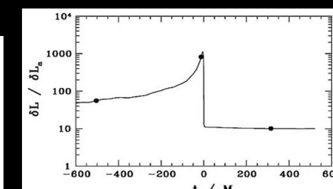
Associated electromagnetic signatures?

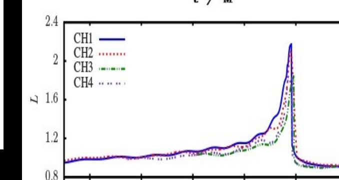
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)

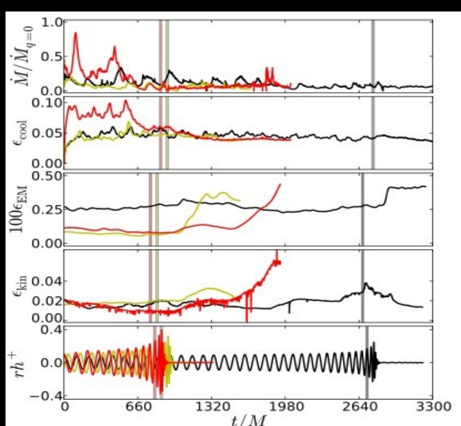


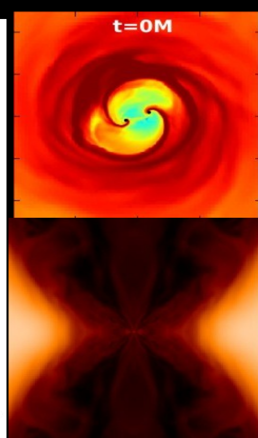
Simulations in hot gaseous clouds. Significan flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)





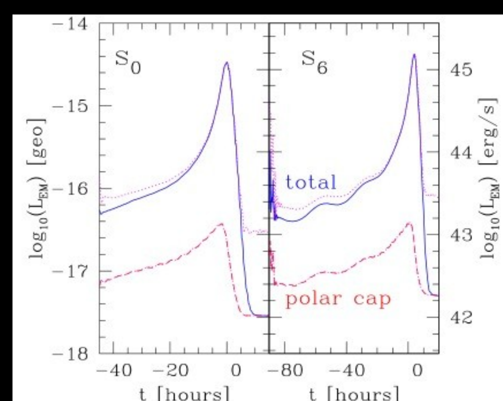


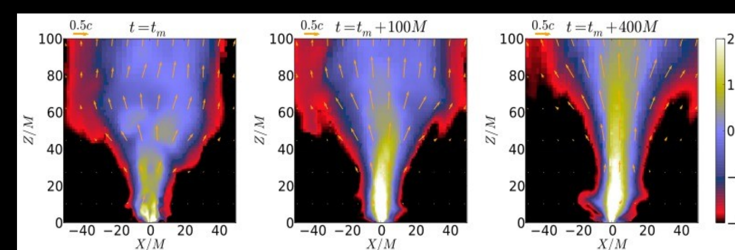




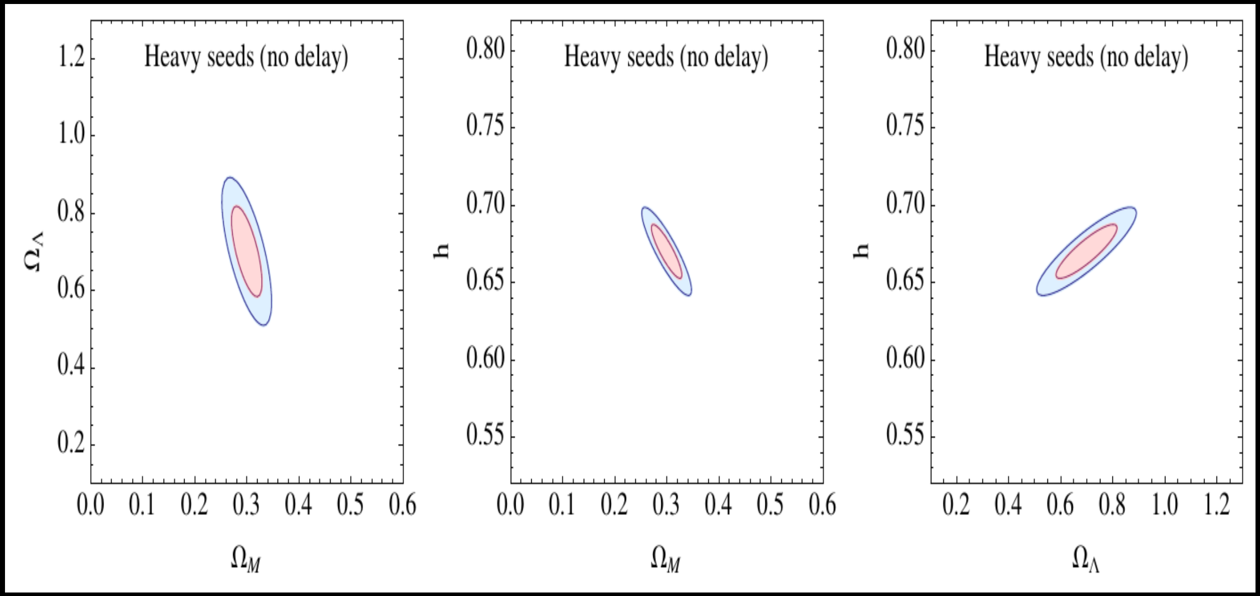
Simulations in disk-like geometry. Variability, but much weaker and unclear signatures
(Bode et al. 2012, Gold et al. 2014)

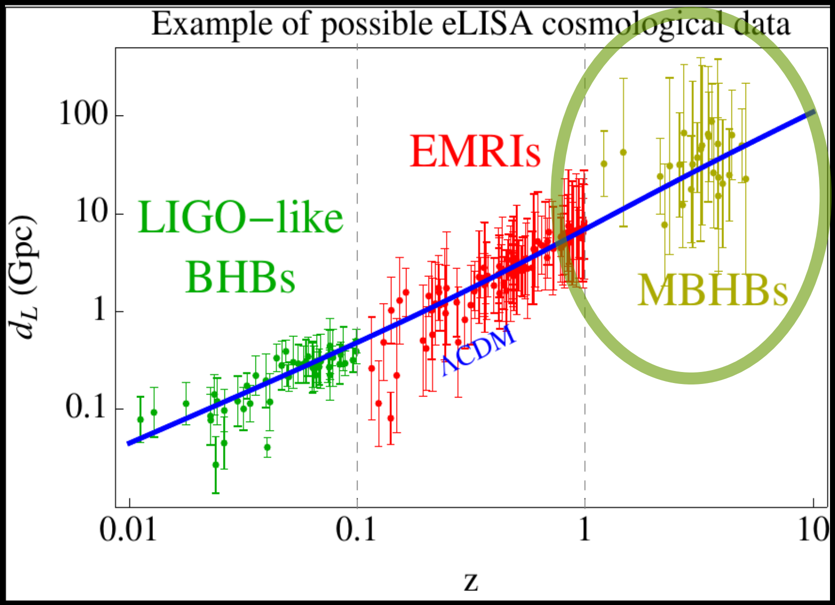
Full GR force free electrodynamics
(Palenzuela et al. 2010, 2012)

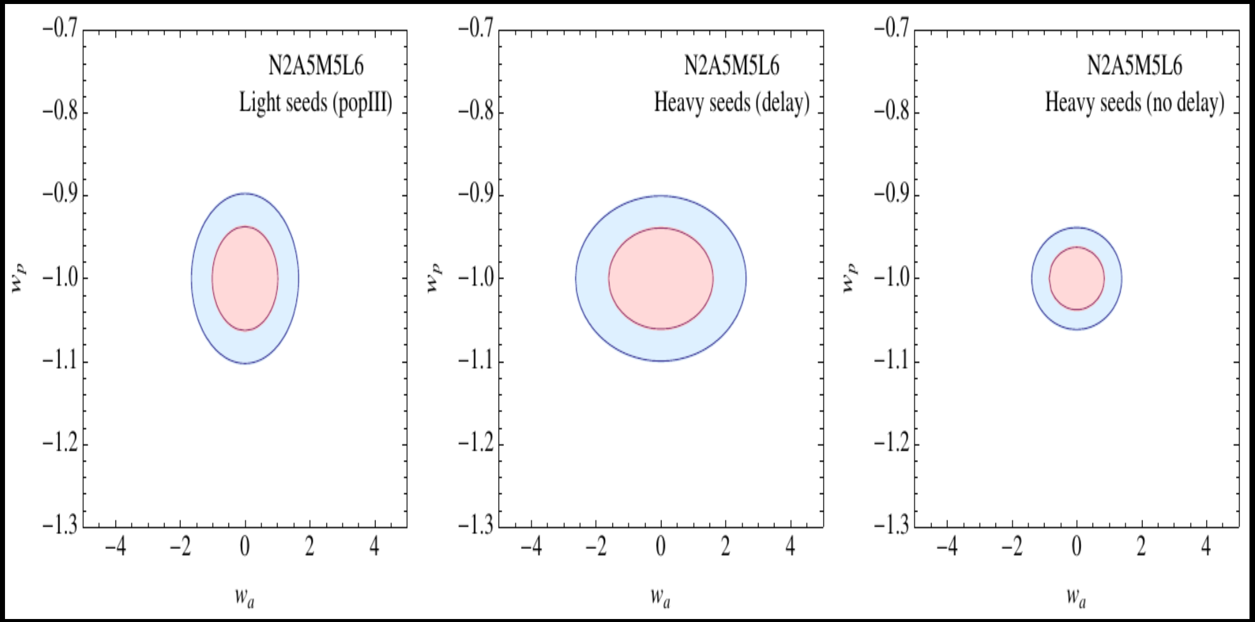




Cosmology with MBHBs



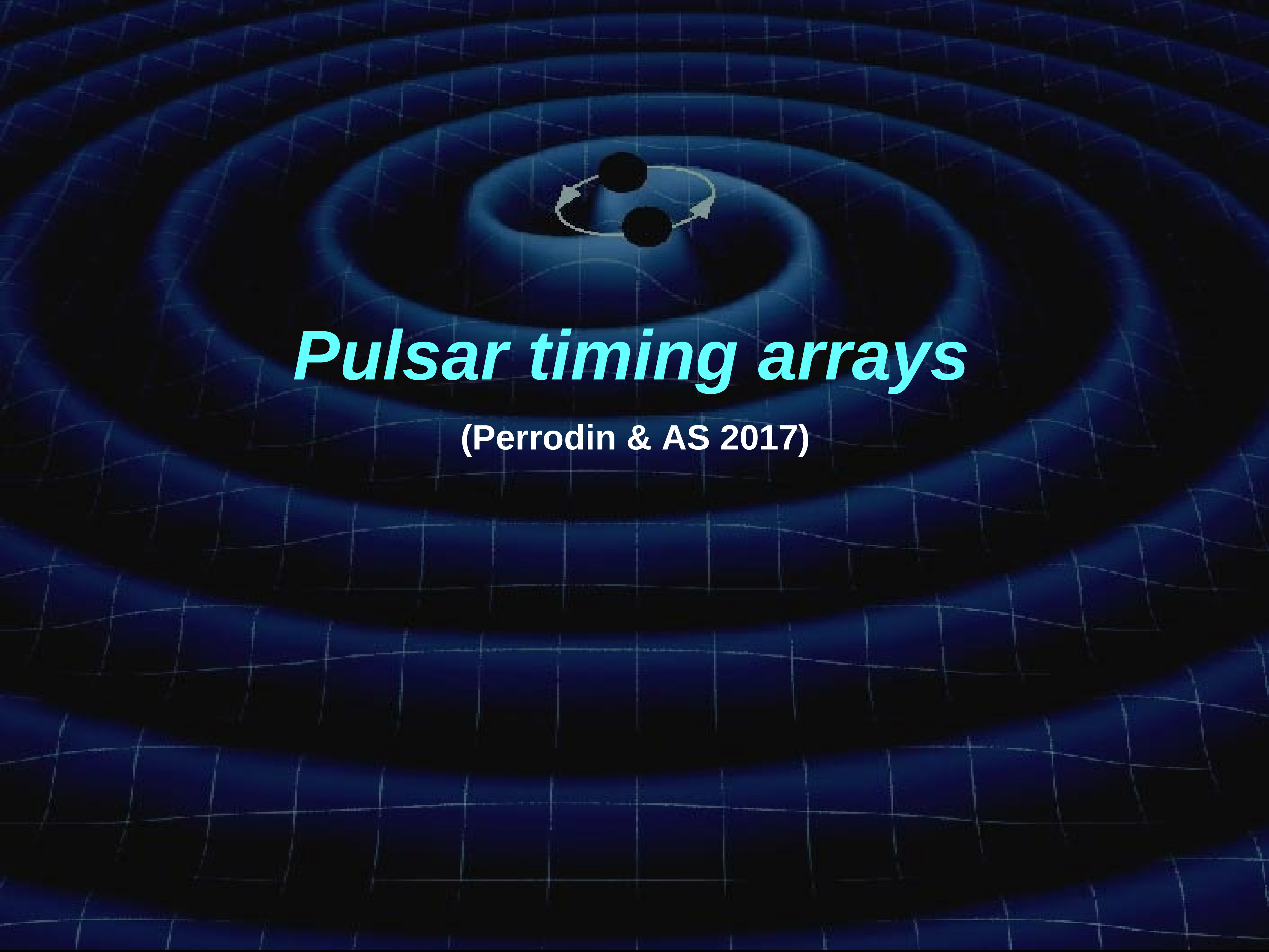




> Independent measurement of H_0 at 1-2% level

> Independent measurement of w_0 at 5-10% level (assuming H_0 known)

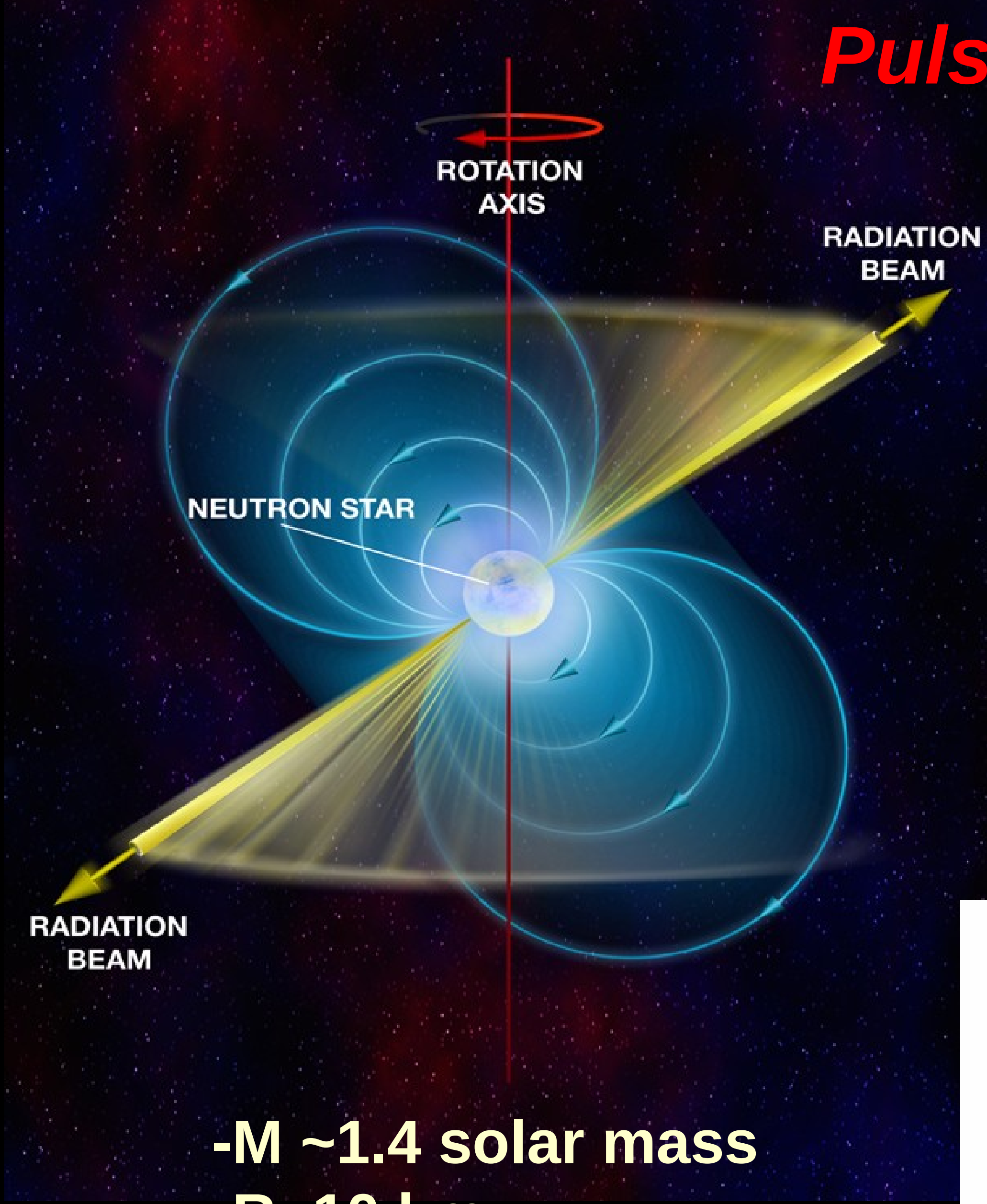
(Tamanini+ 2017)

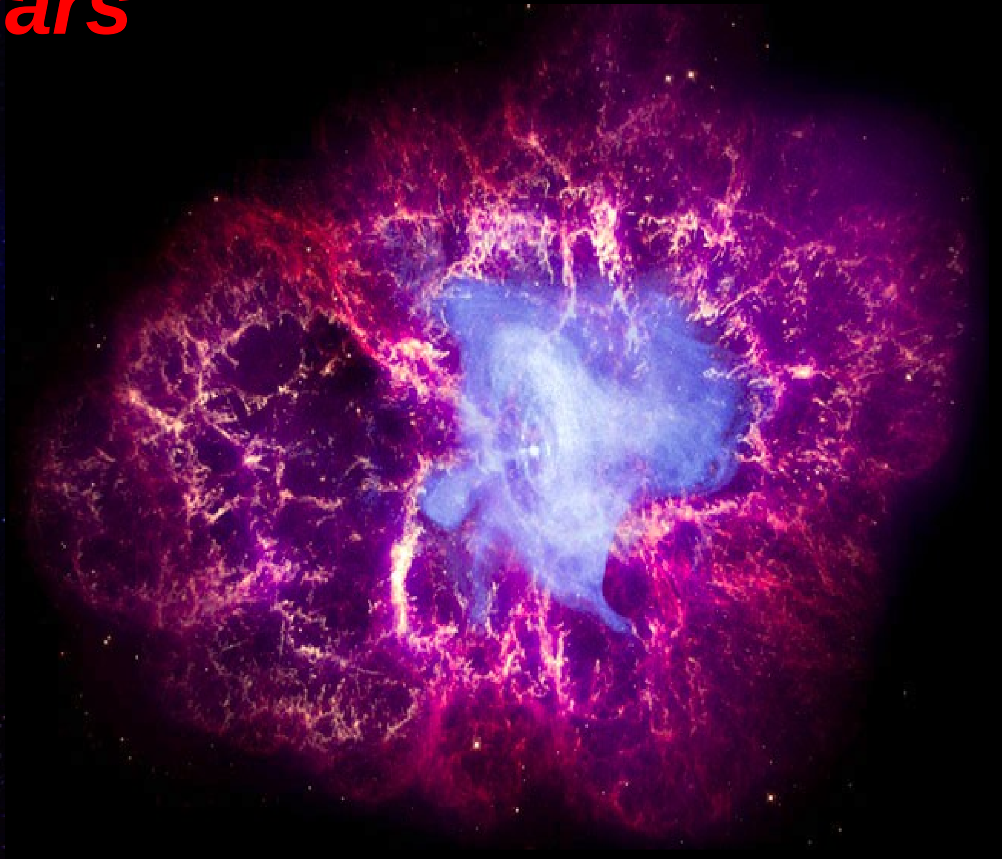


Pulsar timing arrays

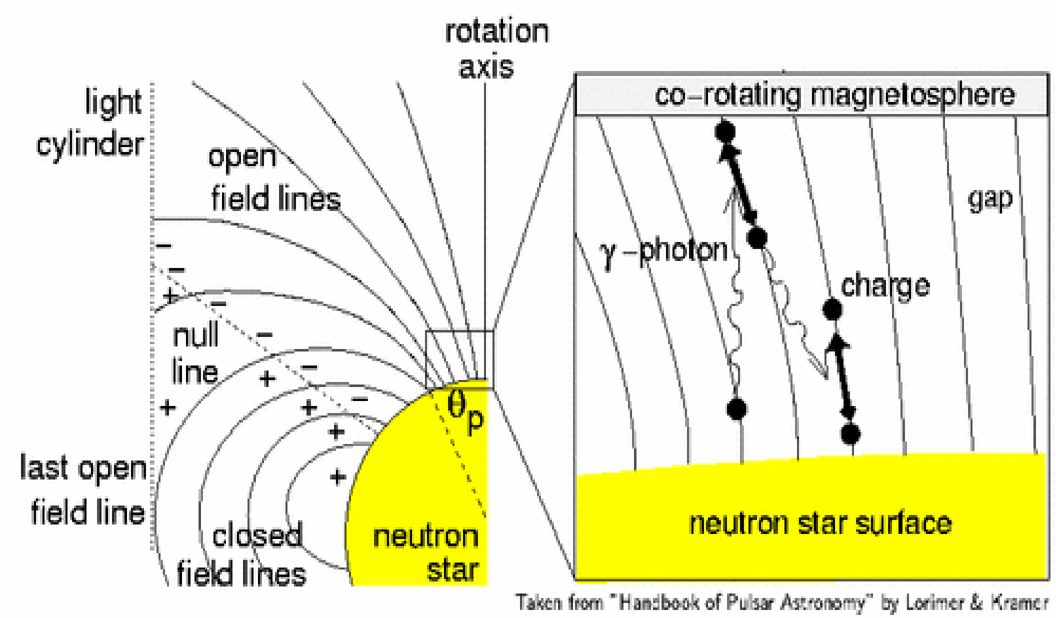
(Perrodin & AS 2017)

Pulsars

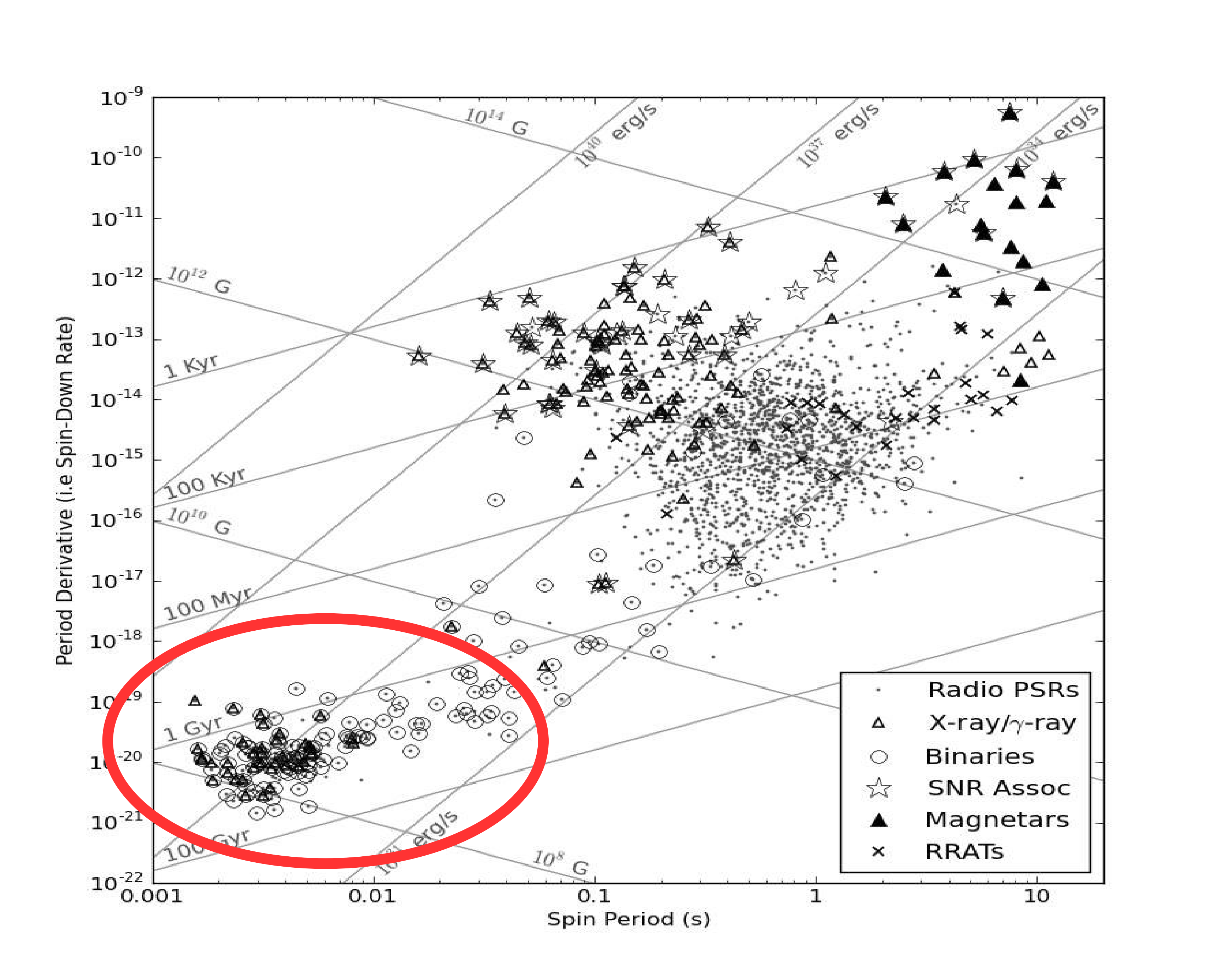




- $M \sim 1.4$ solar mass
- $R \sim 10$ km
- $P \sim 0.0014$-10 s
- $B \sim 10^8$ -10^{15} G



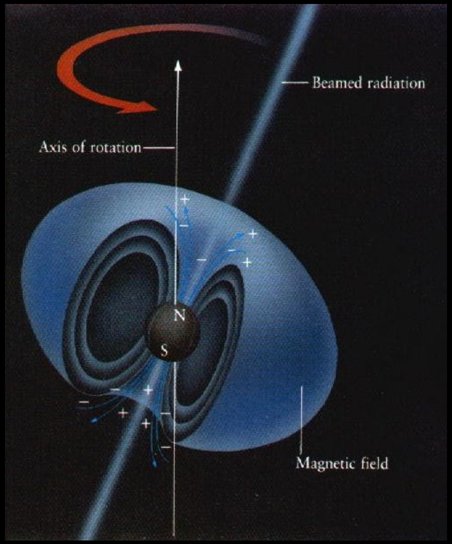
Millisecond pulsars



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



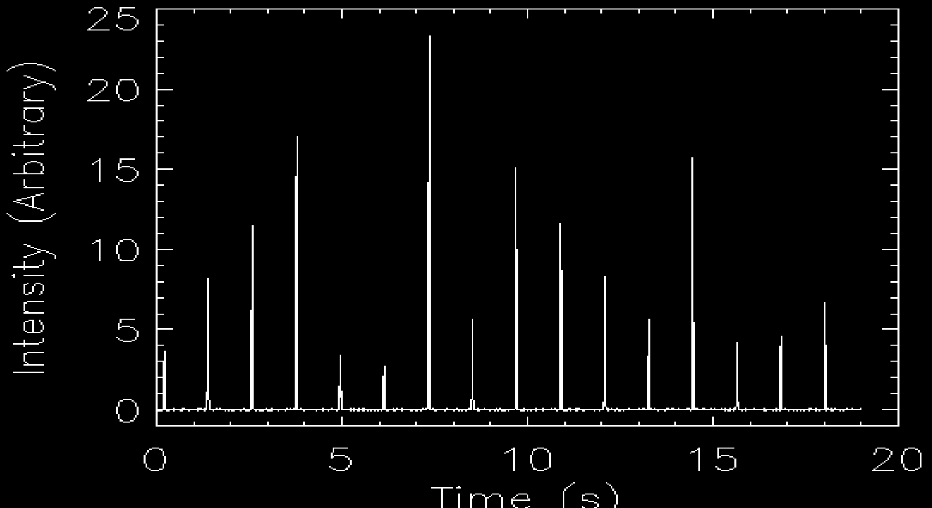
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

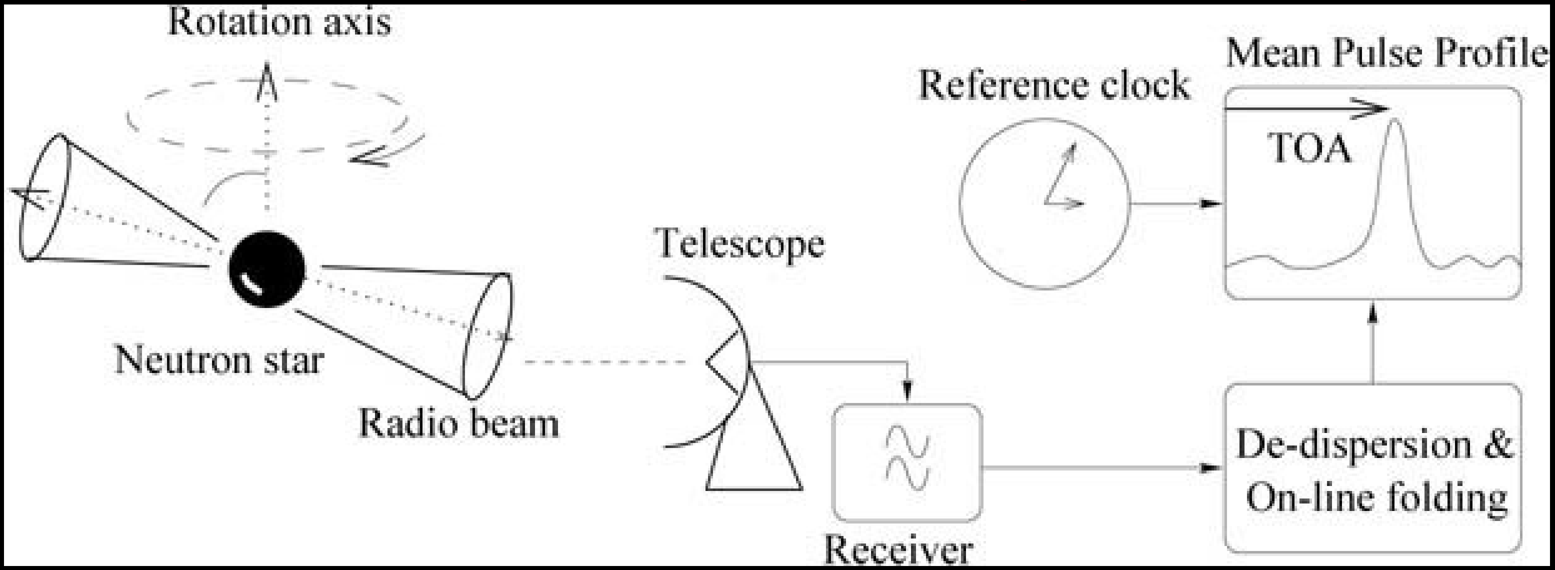
3-Compute the timing residual R

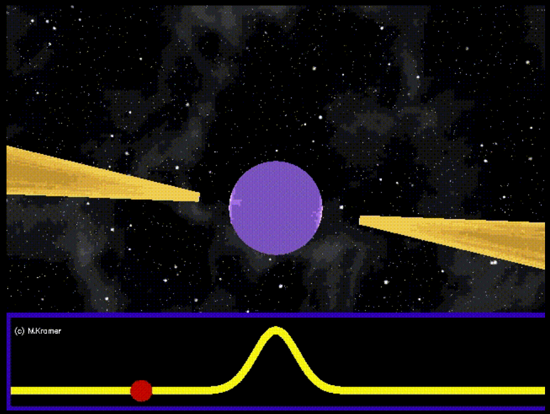
$$R = \mathrm{ToA} - \mathrm{ToA}_m$$

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*



Pulsar timing model





(Kramer & Lorimer 2005)

The N-th rotation of the pulsar is given in terms of the frequency as

$$N = N_0 + \nu\tau + \frac{1}{2}\dot{\nu}\tau^2 + \frac{1}{6}\ddot{\nu}\tau^3 + \ldots$$

Which can be inverted to get the time of arrival of the N-th pulse

$$t_{\mathrm{arr}} = \nu^{-1}N - \Delta_{\mathrm{R}}(u) - \Delta_{\mathrm{E}}(u) + \Delta_{\mathrm{S}}(u) - \frac{1}{2}\dot{\nu}\nu^{-3}N^2 - \frac{1}{6}\ddot{\nu}\nu^{-4}N^3 + \ldots$$

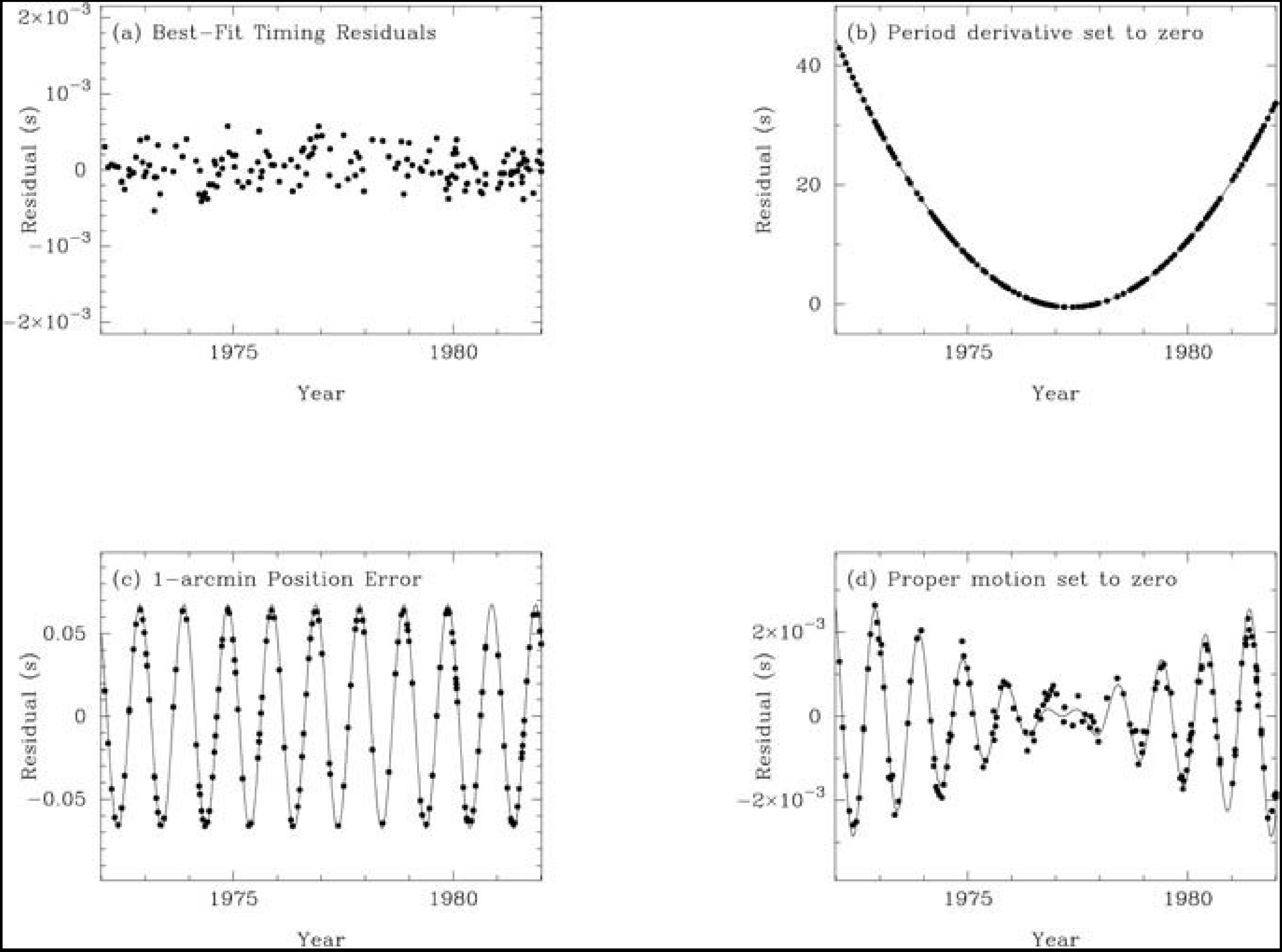
(Will 2006)

$t_{SSB} = t_{arr} + t_{clock} + t_{Earth} + DM/f^2$

(Hobbs+ 2006)

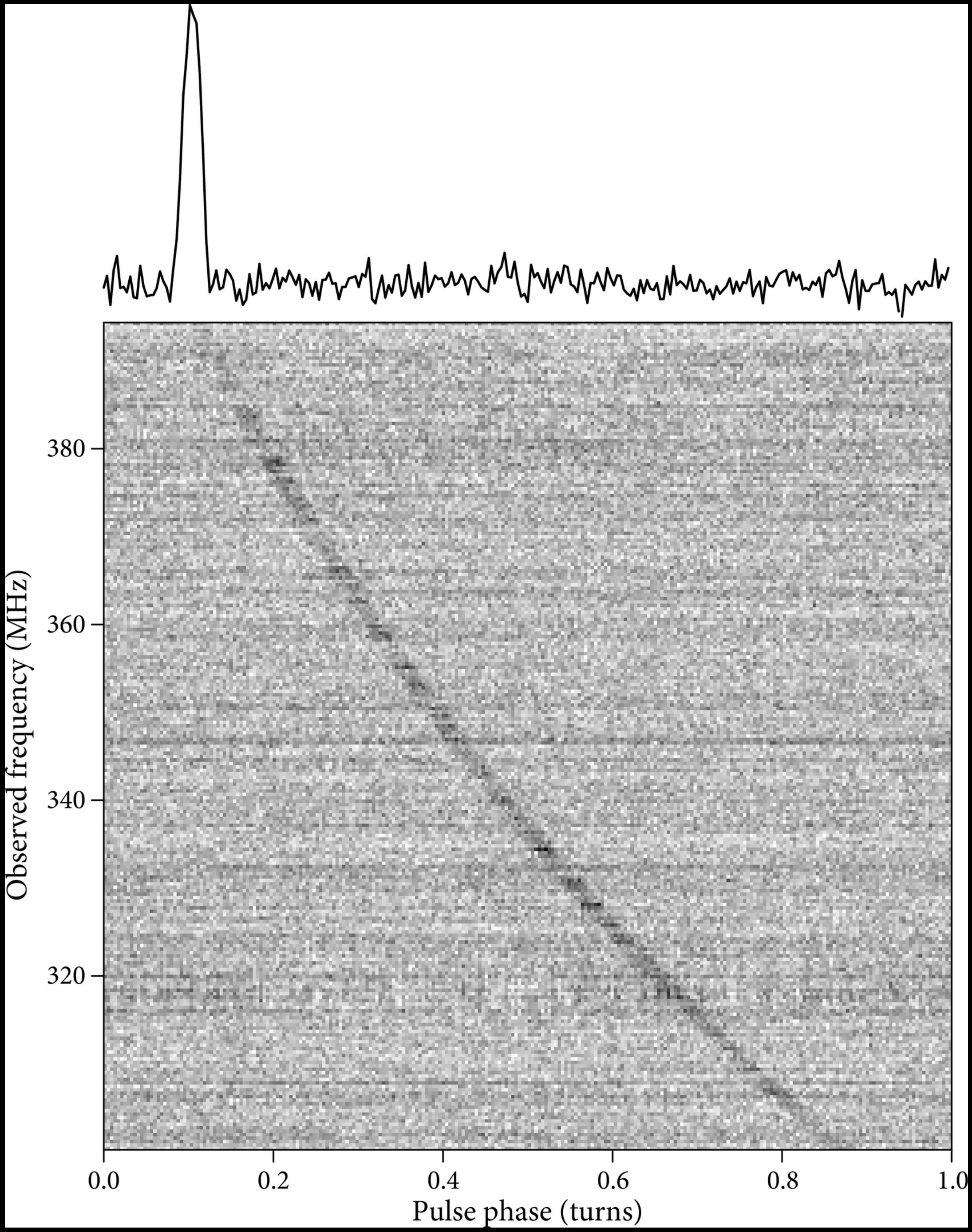
The timing model includes:

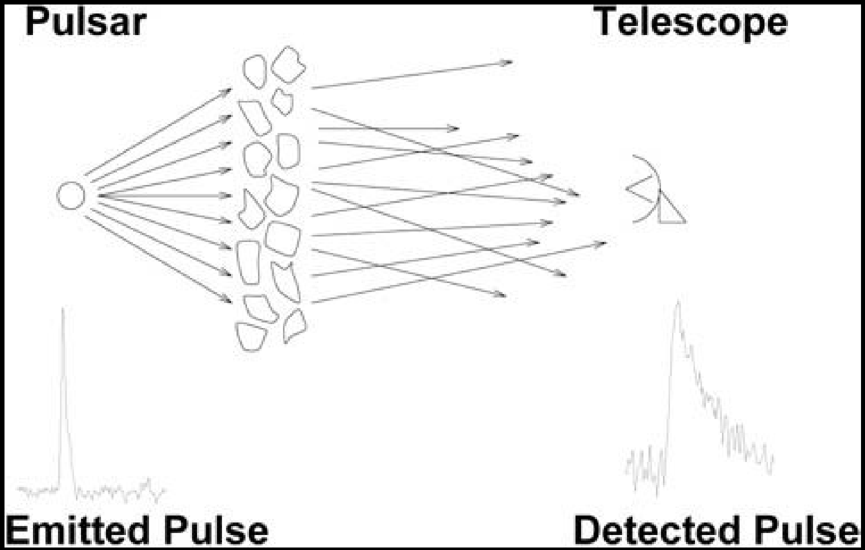
- Roemer, Einstein and Shapiro delays.
- pulsar frequency and freq derivatives
- pulsar position and proper motion
- dispersion measure
- clock corrections and Earth position wrt SSB

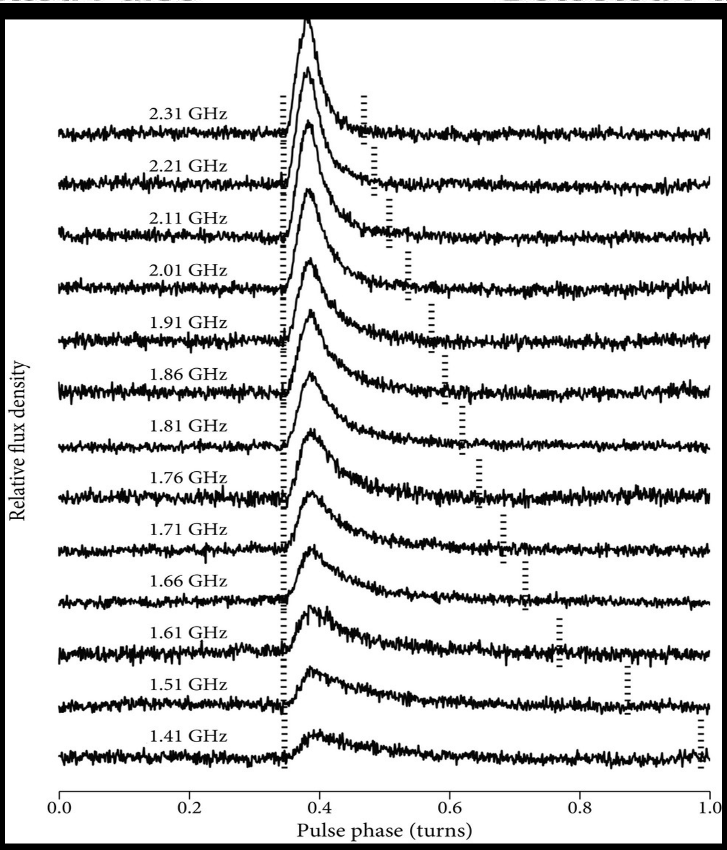


(Kramer & Lorimer 2005)

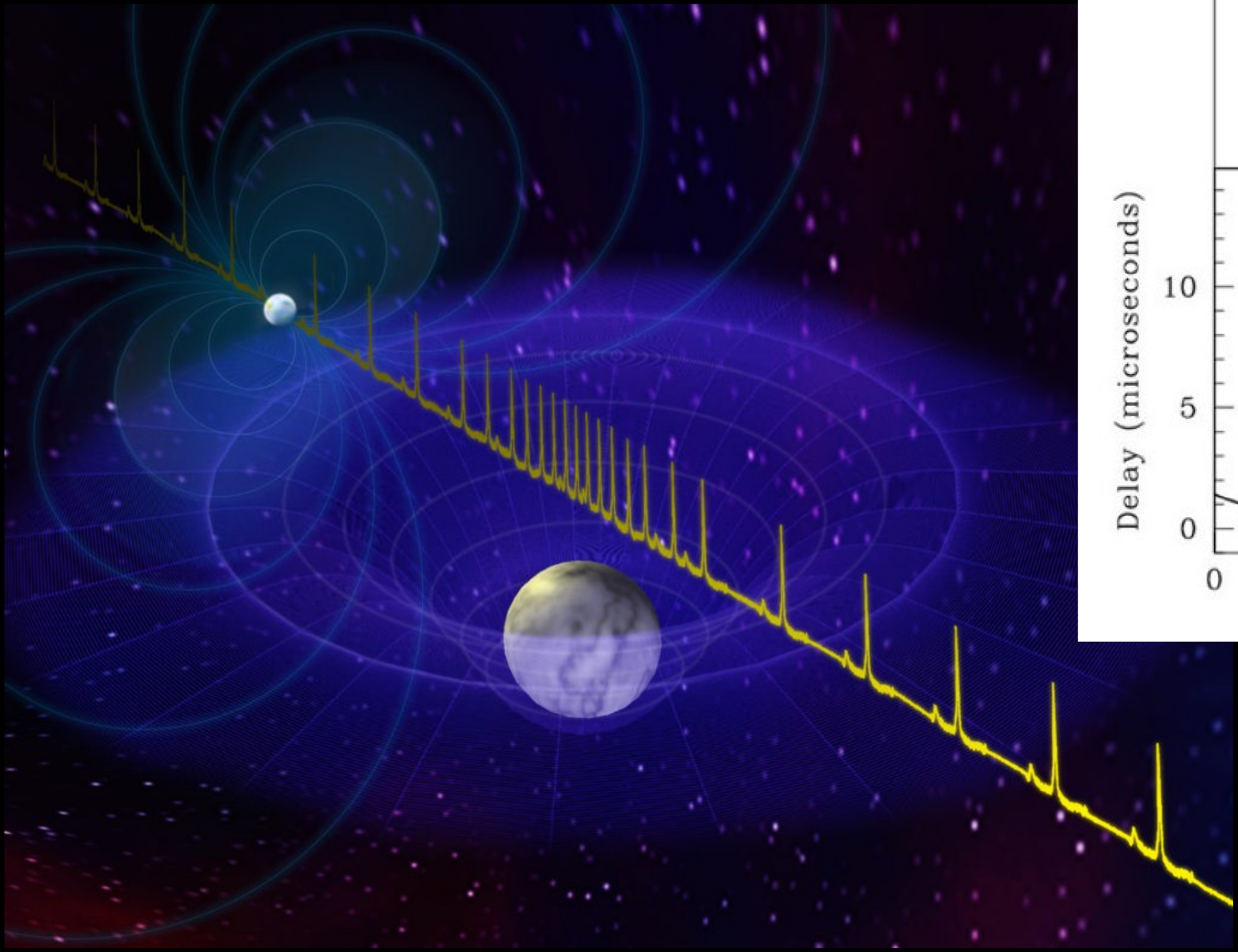
Dispersion measure due to scattering of radio photons by the interstellar medium

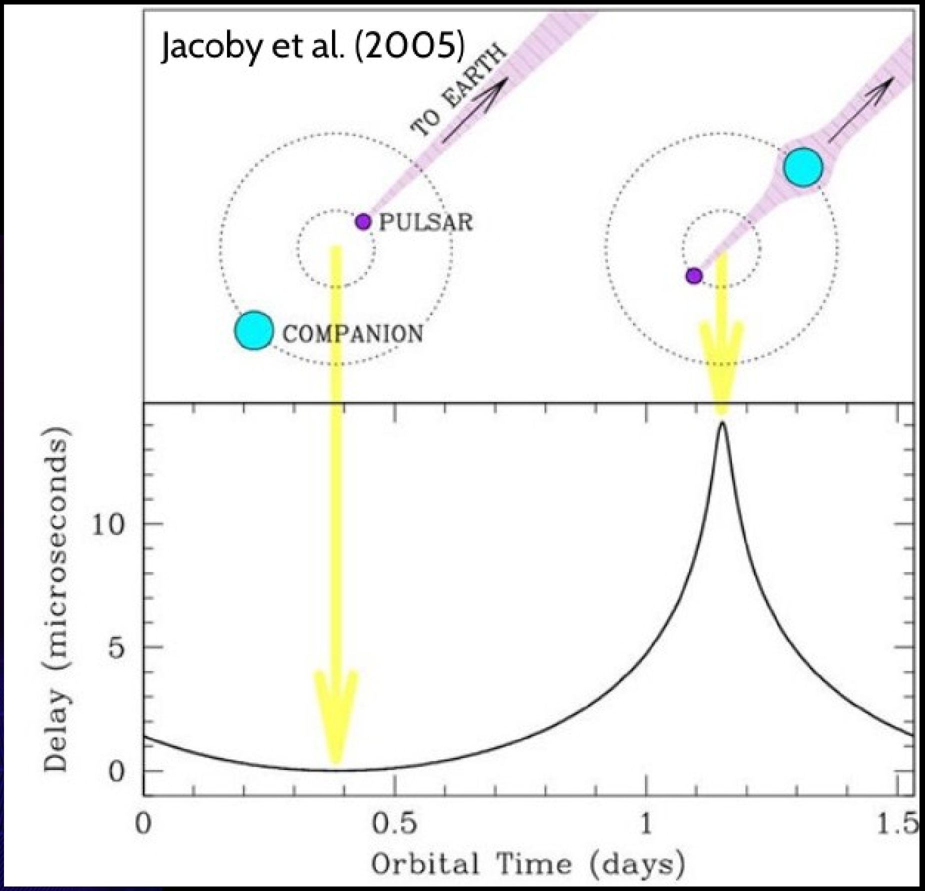




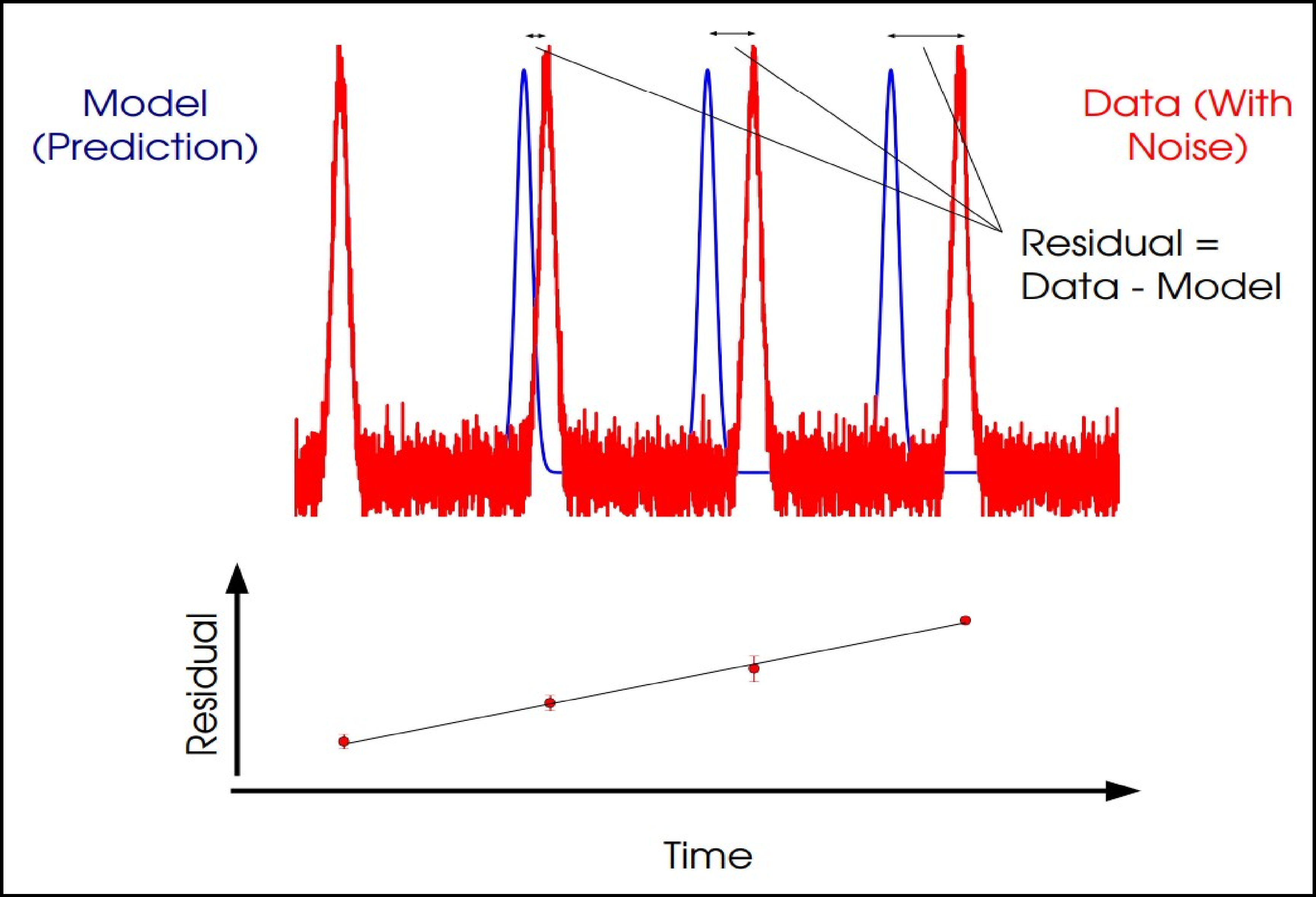


Shapiro delay due to photon passage in the gravitational potential well of the companion





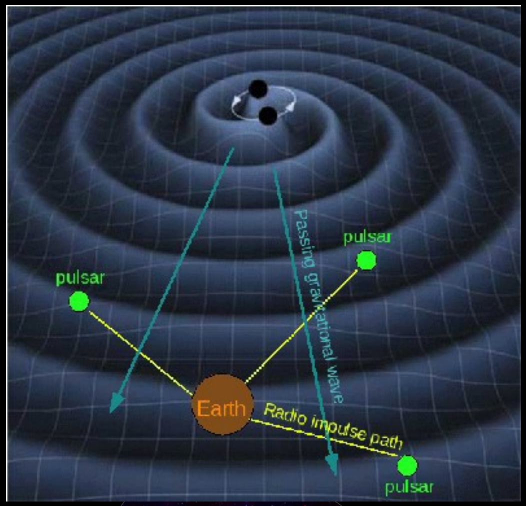
$$\Delta_S = -2r\ln[1 - e\cos E - s(\sin\omega(\cos E - e) + \sqrt{1-e^2}\cos\omega\sin E)]$$



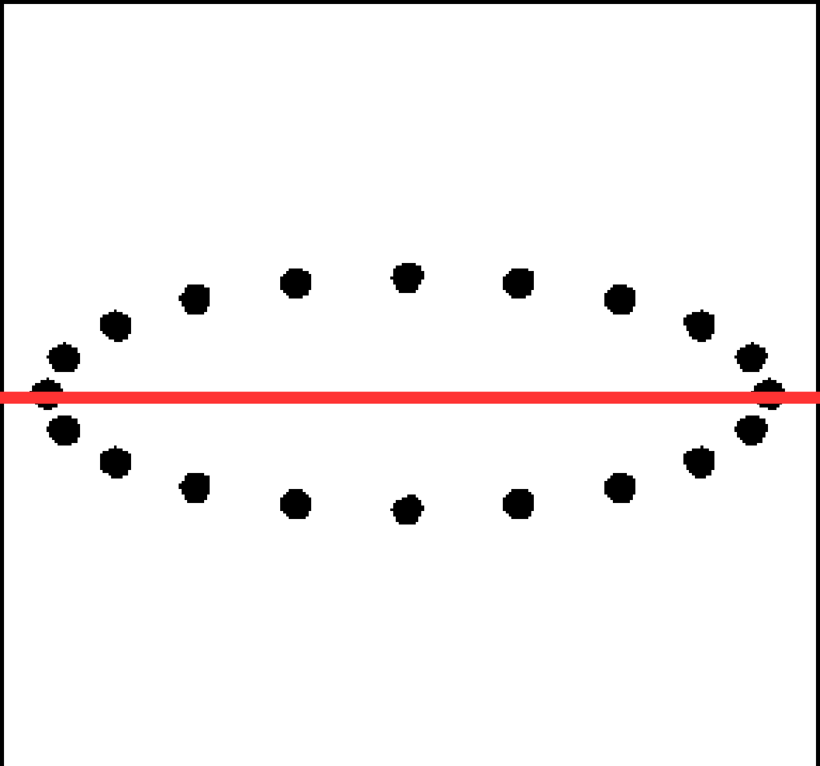
In the end you are left with your residual

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

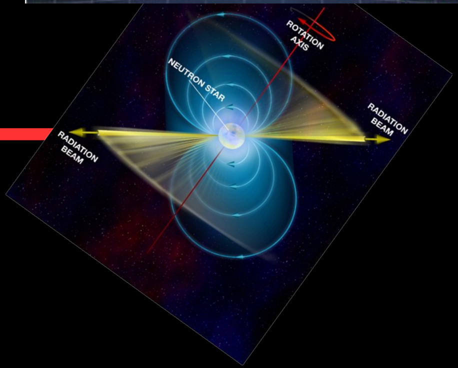
If everything is properly taken into account, *R* has the properties of a white noise and is described by its rms

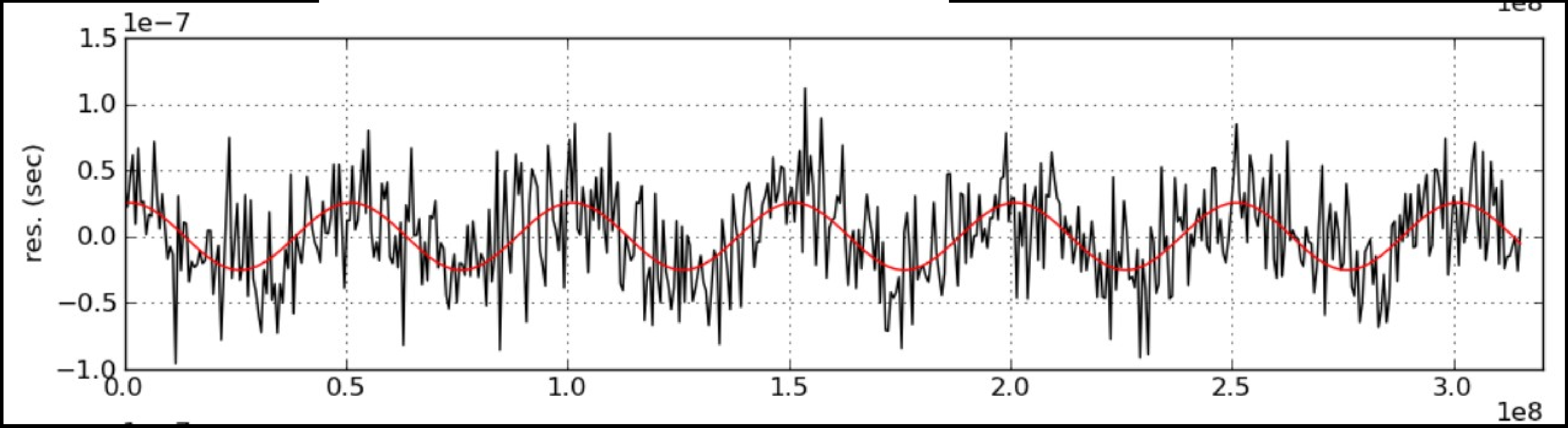


Earth



Pulsar

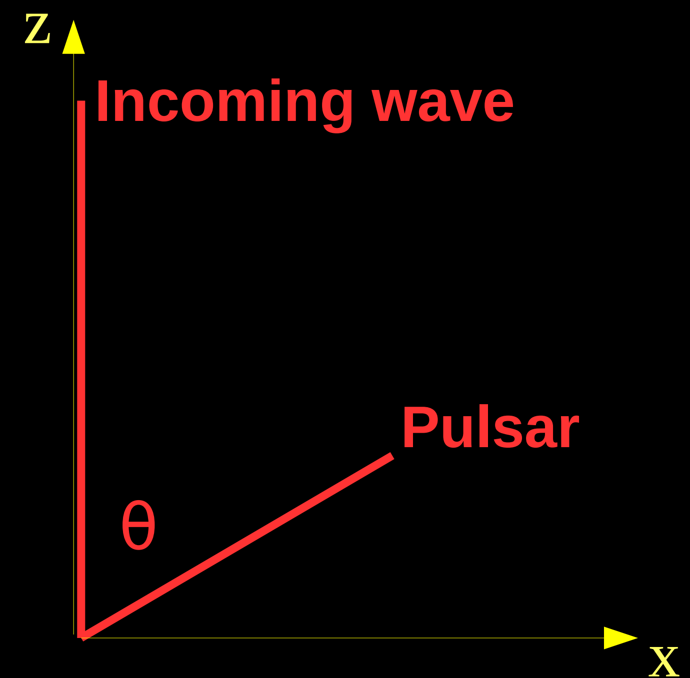




Equation of dopplershift for spacecraft ranging (Estabrook 1975)

$$z(t) = \frac{\nu(t) - \nu_0}{\nu_0} = \frac{\delta\nu(t)}{\nu_0}$$

$$z(t) = \frac{1}{2} p_i p_j \int_{t_p}^{t} dt' \frac{\partial}{\partial t'} h_{ij}[t', (t - t_p)\hat{p}]$$



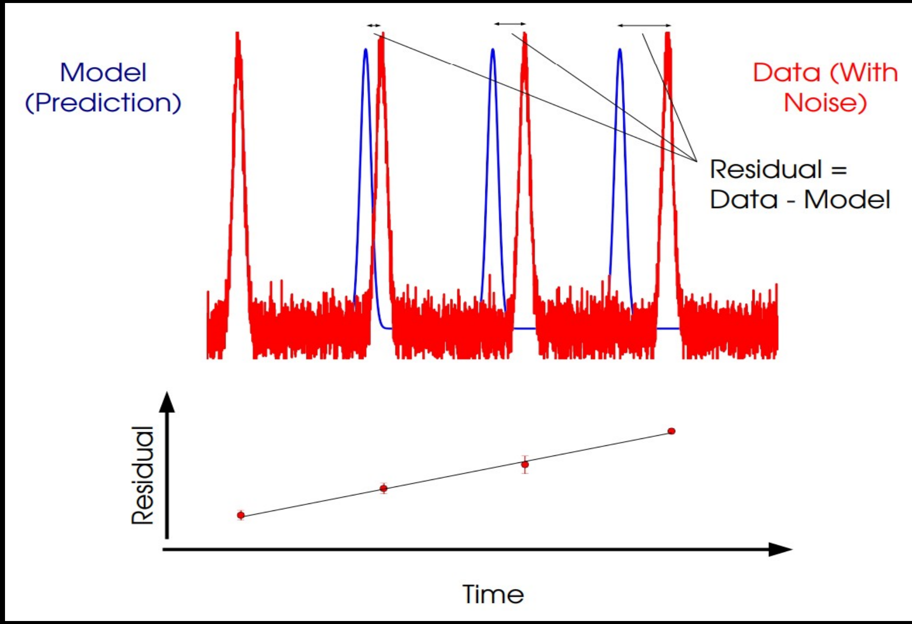
For the system on the right this becomes

$$z(t) = \frac{1}{2}(1 - \cos\theta)[h_{xx}(t_p) - h_{xx}(t)]$$

Where $t - t_p \equiv \tau = (L/c)(1 + \hat{\Omega} \cdot \hat{p})$

What PTA measures is the integral of this dephasing, which we call the ‘residual’

$$r(t) = \int_0^t dt' z(t', \hat{\Omega})$$

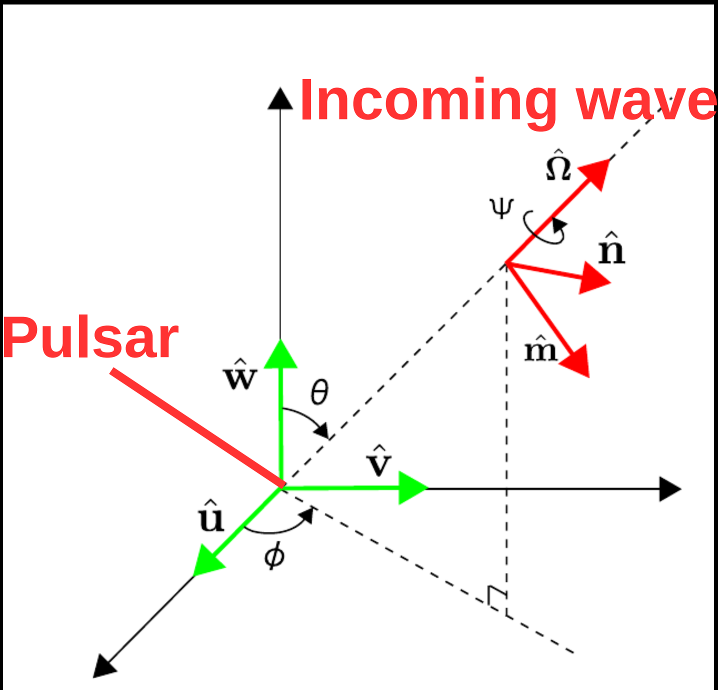


This can be generalized as we did for interferometers

$$\hat{\Omega} = -(\sin\theta\cos\phi)\,\hat{x} - (\sin\theta\sin\phi)\,\hat{y} - \cos\theta\,\hat{z}$$
$$\hat{p} = (\sin\theta_p\cos\phi_p)\,\hat{x} + (\sin\theta_p\sin\phi_p)\,\hat{y} + \cos\theta_p\,\hat{z}.$$

$$h_{ij}(t,\hat{\Omega}) = e^{+}_{ij}(\hat{\Omega})h_{+}(t,\hat{\Omega}) + e^{\times}_{ij}(\hat{\Omega})h_{\times}(t,\hat{\Omega})$$

$$e^{+}_{ij}(\hat{\Omega}) = \hat{m}_i\hat{m}_j - \hat{n}_i\hat{n}_j\,,$$
$$e^{\times}_{ij}(\hat{\Omega}) = \hat{m}_i\hat{n}_j + \hat{n}_i\hat{m}_j\,.$$



$$\hat{m} = (\sin\phi\cos\psi - \sin\psi\cos\phi\cos\theta)\hat{x} - (\cos\phi\cos\psi + \sin\psi\sin\phi\cos\theta)\hat{y} + (\sin\psi\sin\theta)\hat{z}\,,$$
$$\hat{n} = (-\sin\phi\sin\psi - \cos\psi\cos\phi\cos\theta)\hat{x} + (\cos\phi\sin\psi - \cos\psi\sin\phi\cos\theta)\hat{y} + (\cos\psi\sin\theta)\hat{z}.$$

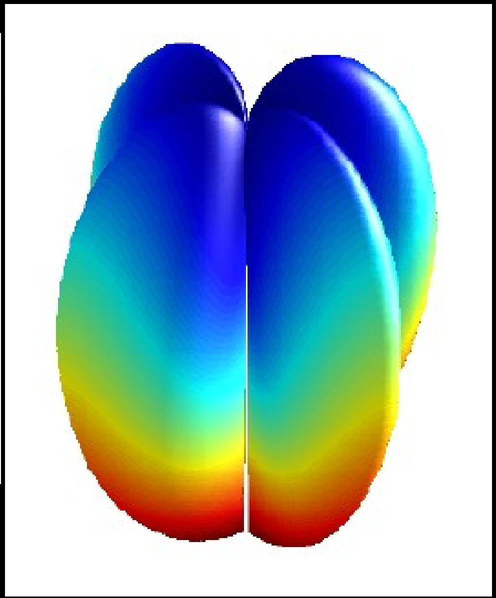
$$z(t,\hat{\Omega}) = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{p}^i\hat{\Omega}_i}\left\{e^{+}_{ij}(\hat{\Omega})\left[h_{+}(t_p,\hat{\Omega}) - h_{+}(t,\hat{\Omega})\right] - e^{\times}_{ij}(\hat{\Omega})\left[h_{\times}(t_p,\hat{\Omega}) - h_{\times}(t,\hat{\Omega})\right]\right\}$$

which can be written in compact form as

$$z(t,\hat{\Omega}) = \sum_A F^A(\hat{\Omega})[h_A(t_p,\hat{\Omega}) - h_A(t,\hat{\Omega})]$$

where

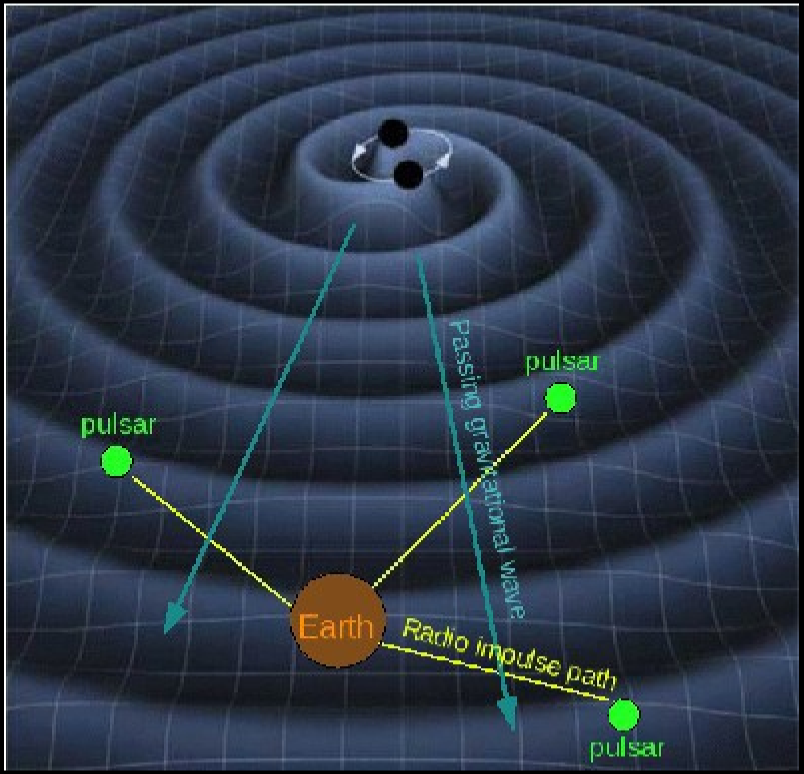
$$F^{+}(\hat{\Omega}) = \frac{1}{2}\frac{(\hat{m}\cdot\hat{p})^2 - (\hat{n}\cdot\hat{p})^2}{1+\hat{\Omega}\cdot\hat{p}}$$
$$F^{\times}(\hat{\Omega}) = \frac{(\hat{m}\cdot\hat{p})\,(\hat{n}\cdot\hat{p})}{1+\hat{\Omega}\cdot\hat{p}}\,.$$



Effect of gravitational waves

The GW passage causes a modulation of the observed pulse frequency

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

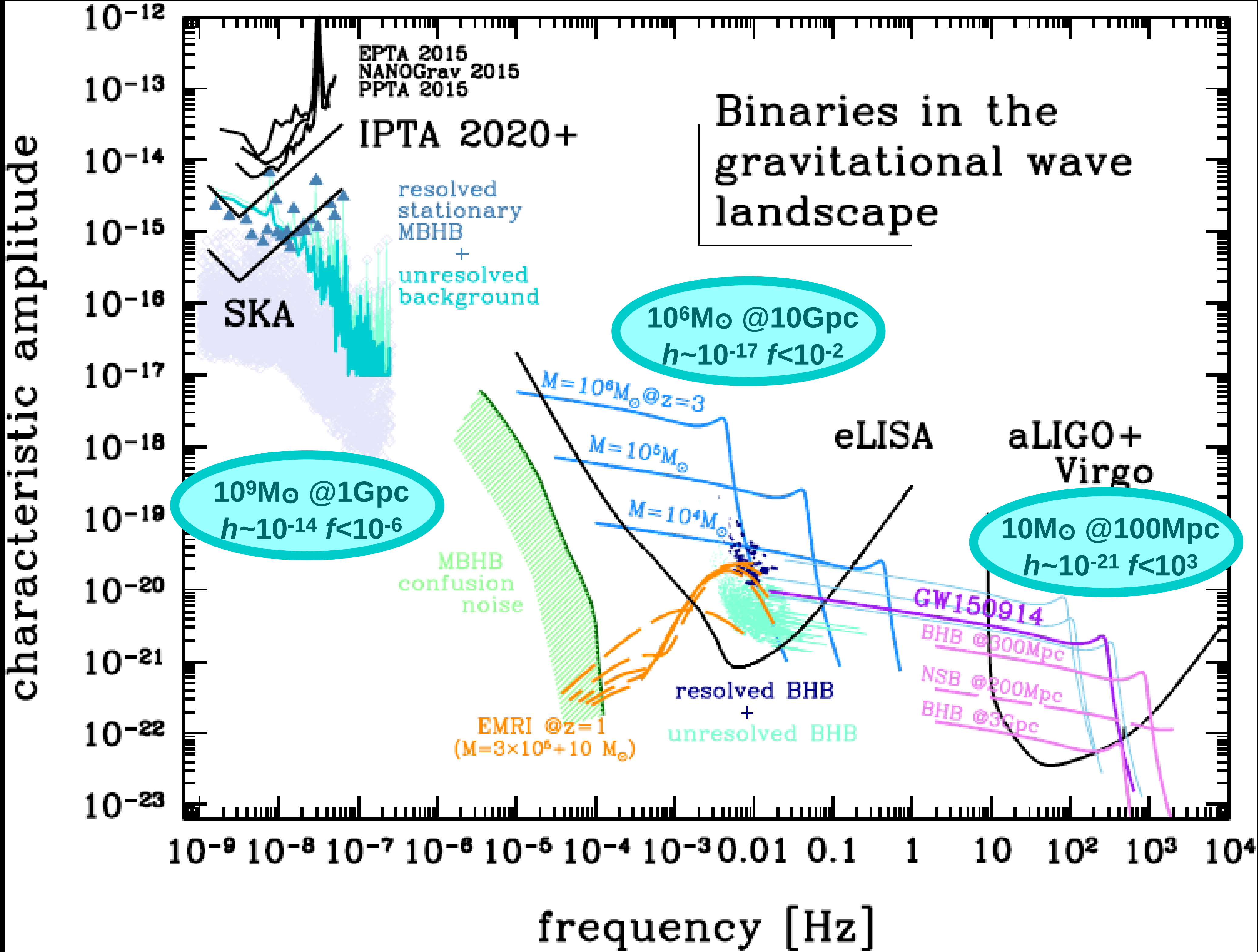


$$R(t) = \int_0^T \frac{\nu(t)-\nu_0}{\nu_0} dt$$

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

R~h/(2πf)

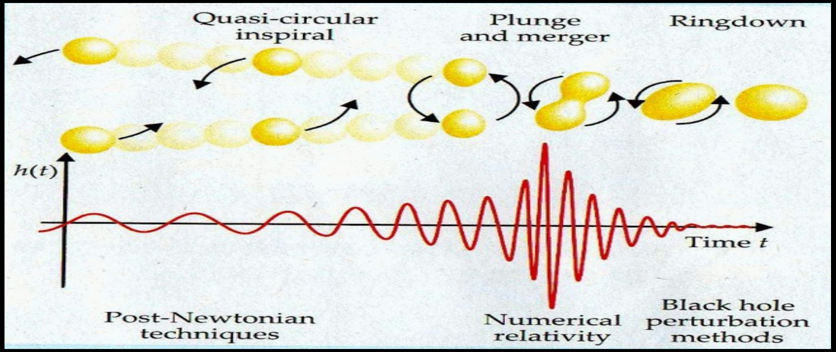
$$\begin{aligned} &= \frac{\mathcal{M}^{5/3}}{D} \left[\pi f(t)\right]^{-1/3} \\ &\simeq 25.7 \left(\frac{\mathcal{M}}{10^9\, M_\odot}\right)^{5/3} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\ &\quad \times \left(\frac{f}{5\times 10^{-8}\,\mathrm{Hz}}\right)^{-1/3} \mathrm{ns} \end{aligned}$$

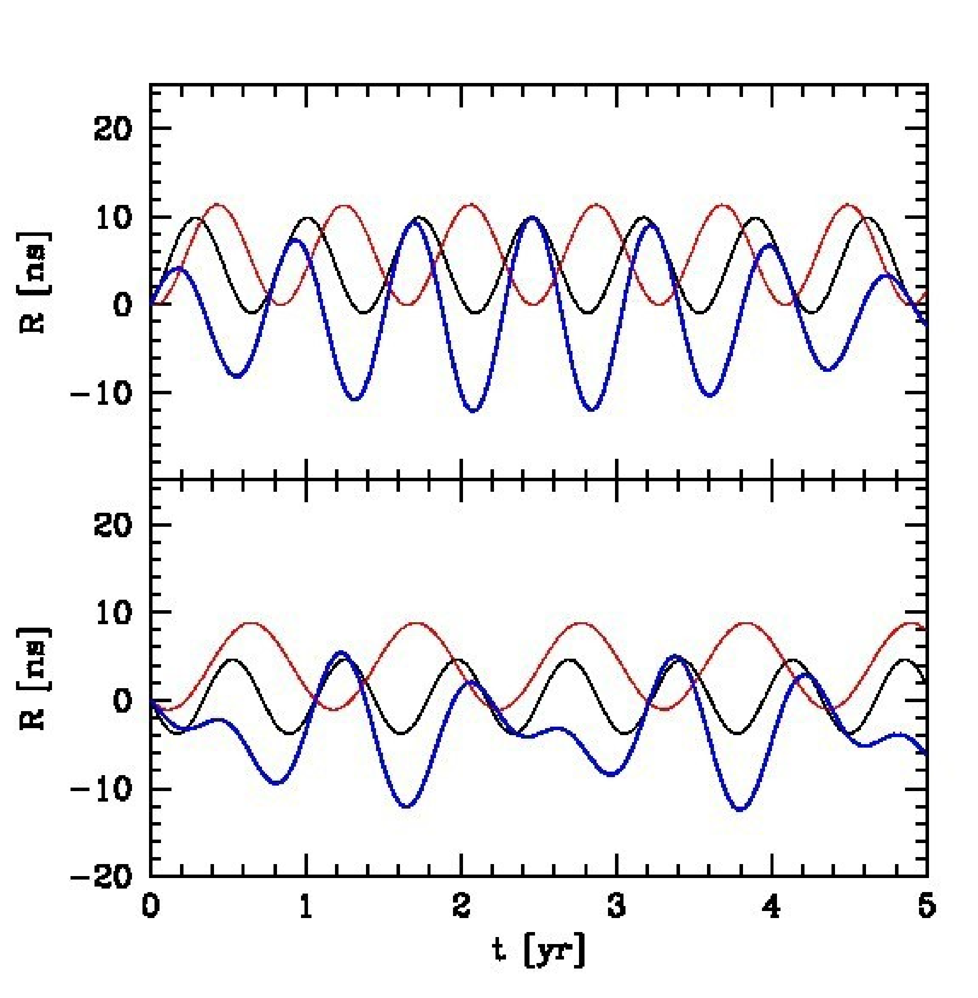


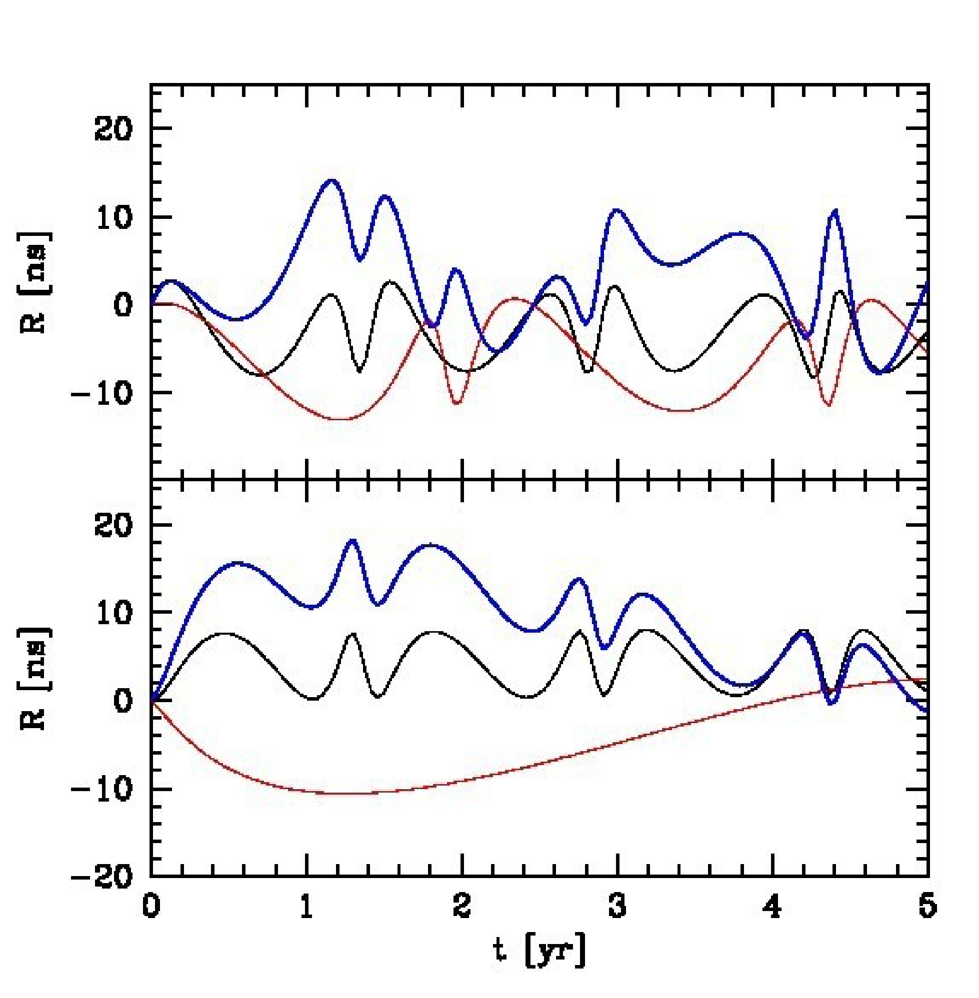
Binaries in the gravitational wave landscape
characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
10⁶M⊙ @10Gpc
h~10-17 f<10-2
10⁹M⊙ @1Gpc
h~10-14 f<10-6
10M⊙ @100Mpc
h~10-21 f<10³
M=10⁶M⊙@z=3
M=10⁵M⊙
M=10⁴M⊙
eLISA
aLIGO+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

Single MBHB timing residuals

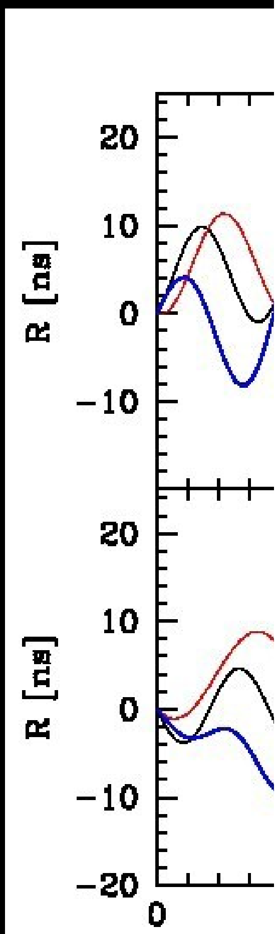
$$\frac{\nu(t)-\nu_0}{\nu_0} = \Delta h_{ab}(t) \equiv h_{ab}(t_{\rm p},\hat{\Omega}) - h_{ab}(t_{\rm ssb},\hat{\Omega})$$

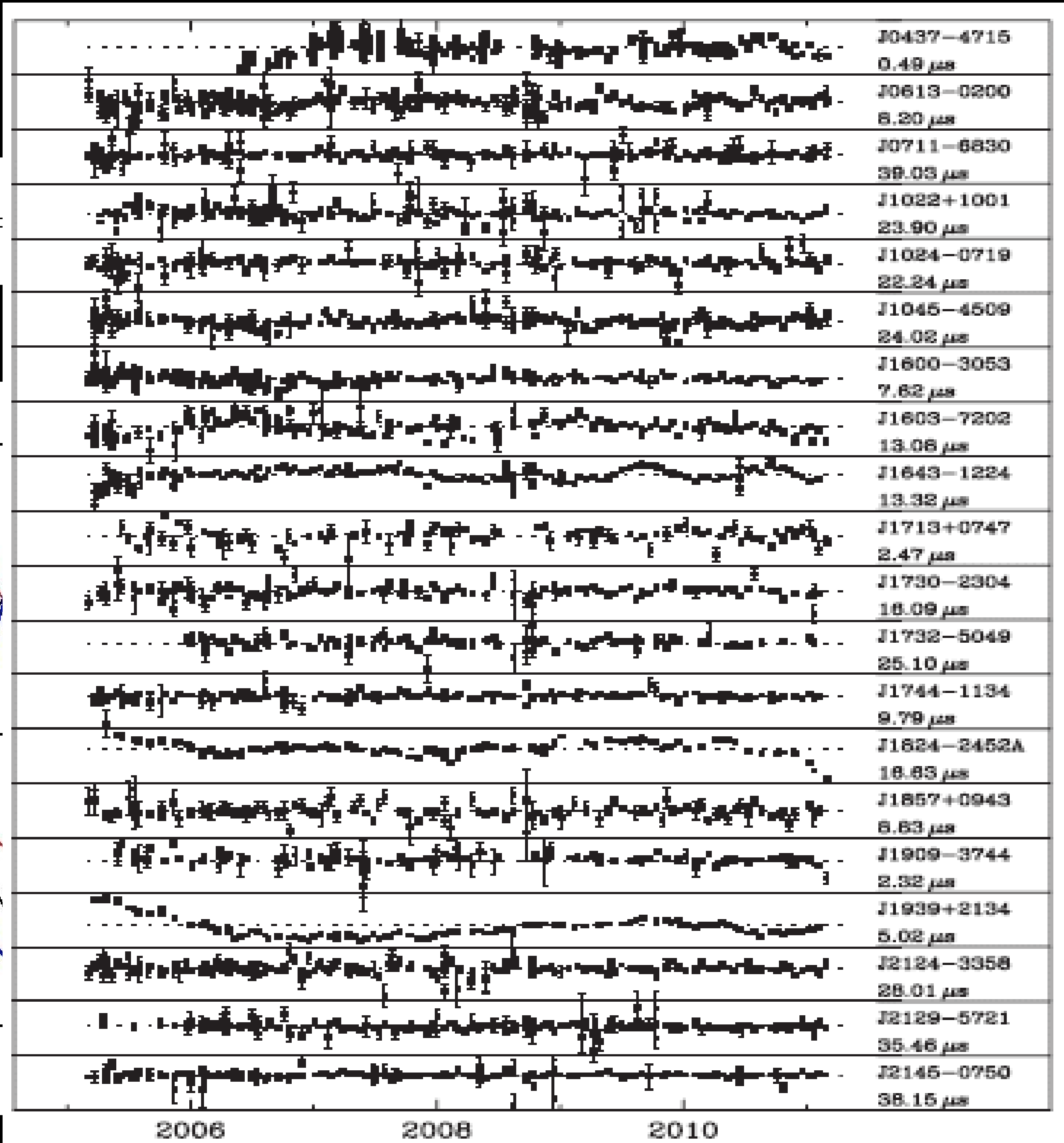


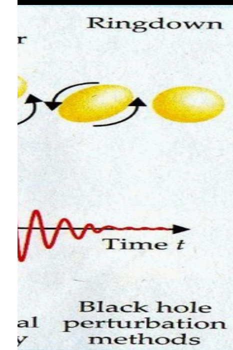


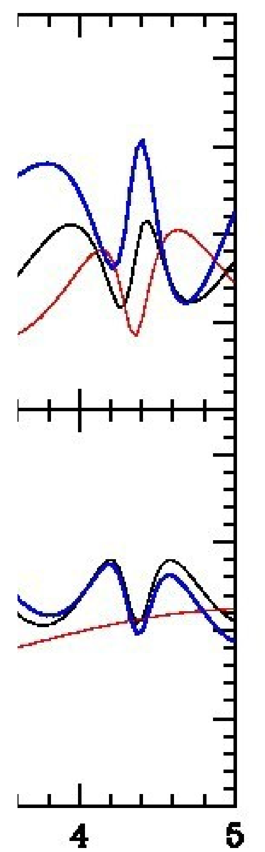


$$\frac{\nu(t)-\nu_0}{\nu_0} =$$

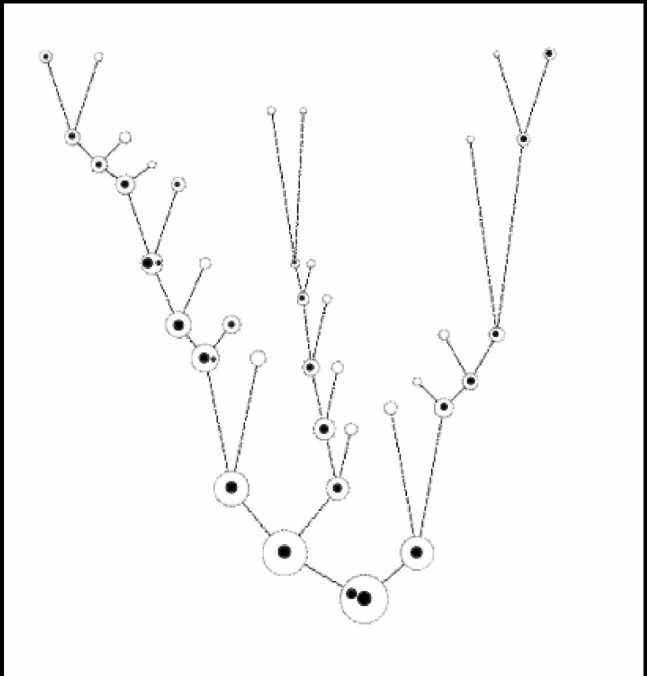








The expected GW signal in the PTA band



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

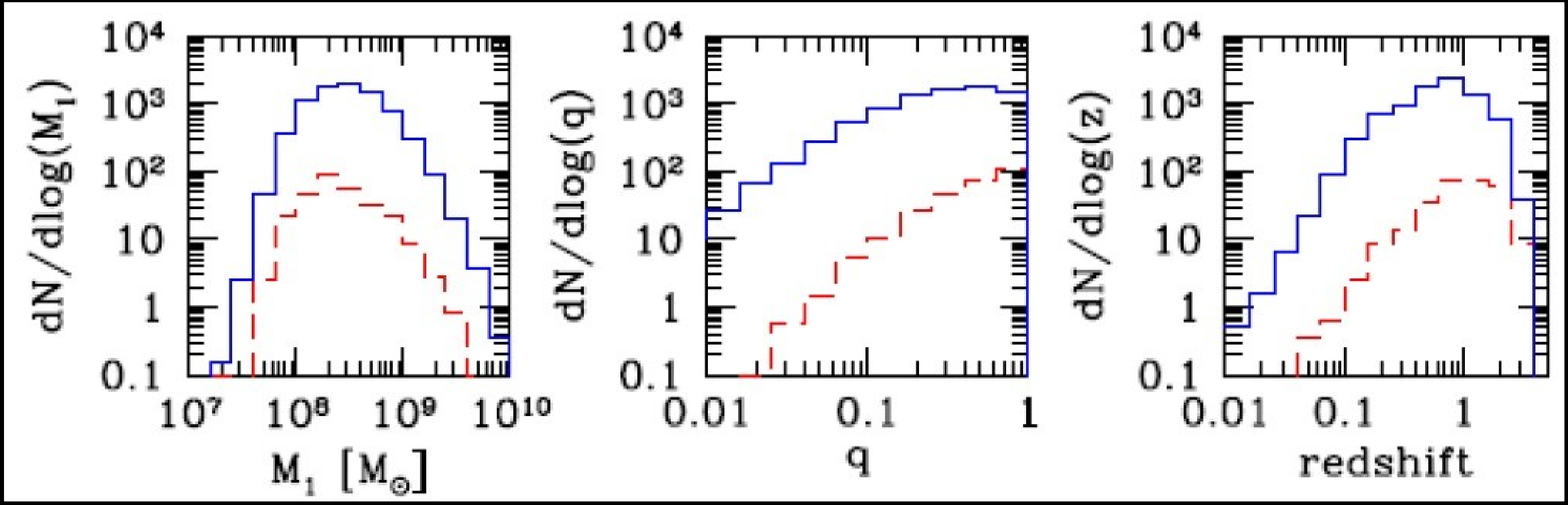
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3 N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

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

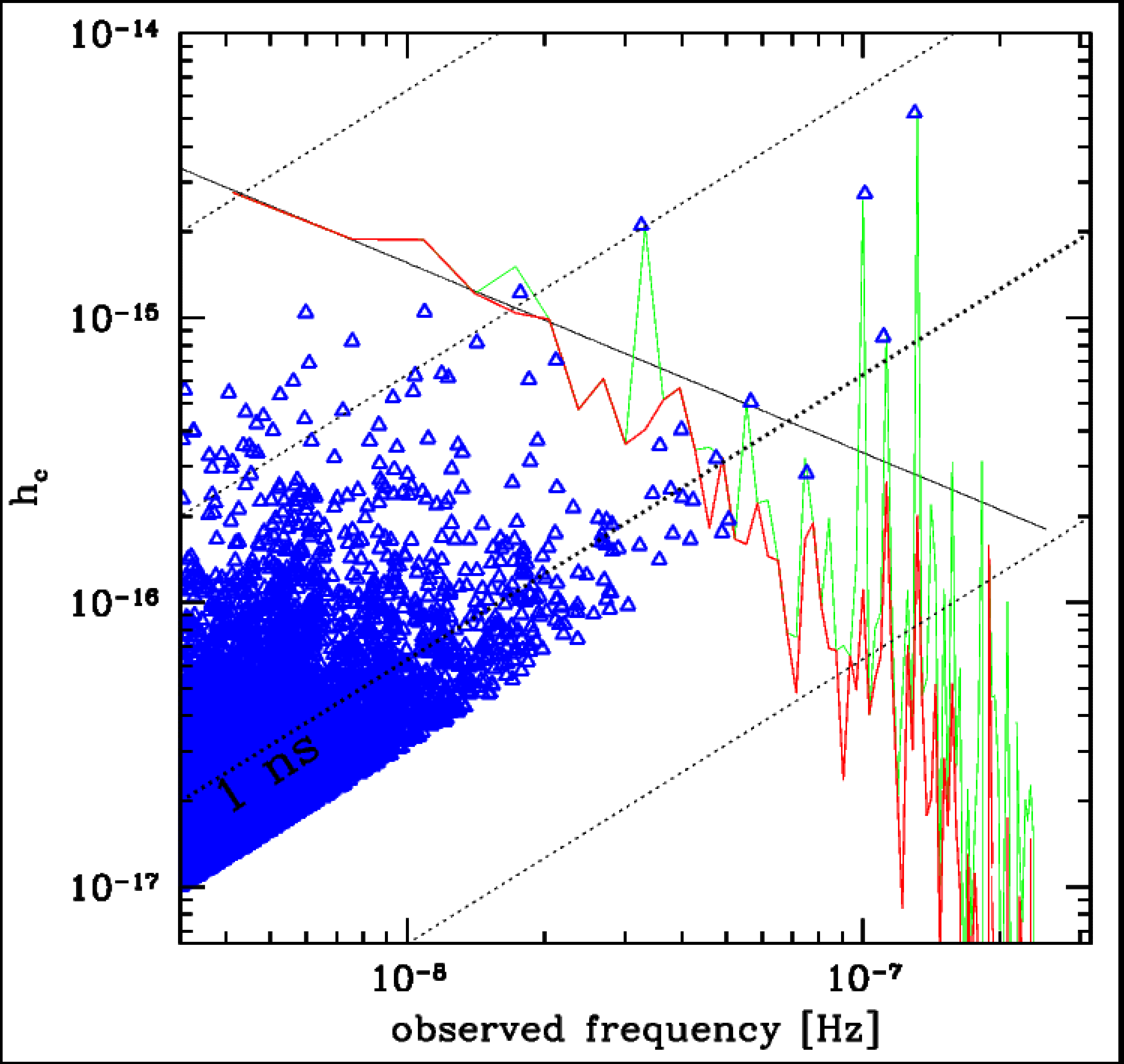
Theoretical spectrum: simple power law

(Phinney 2001)

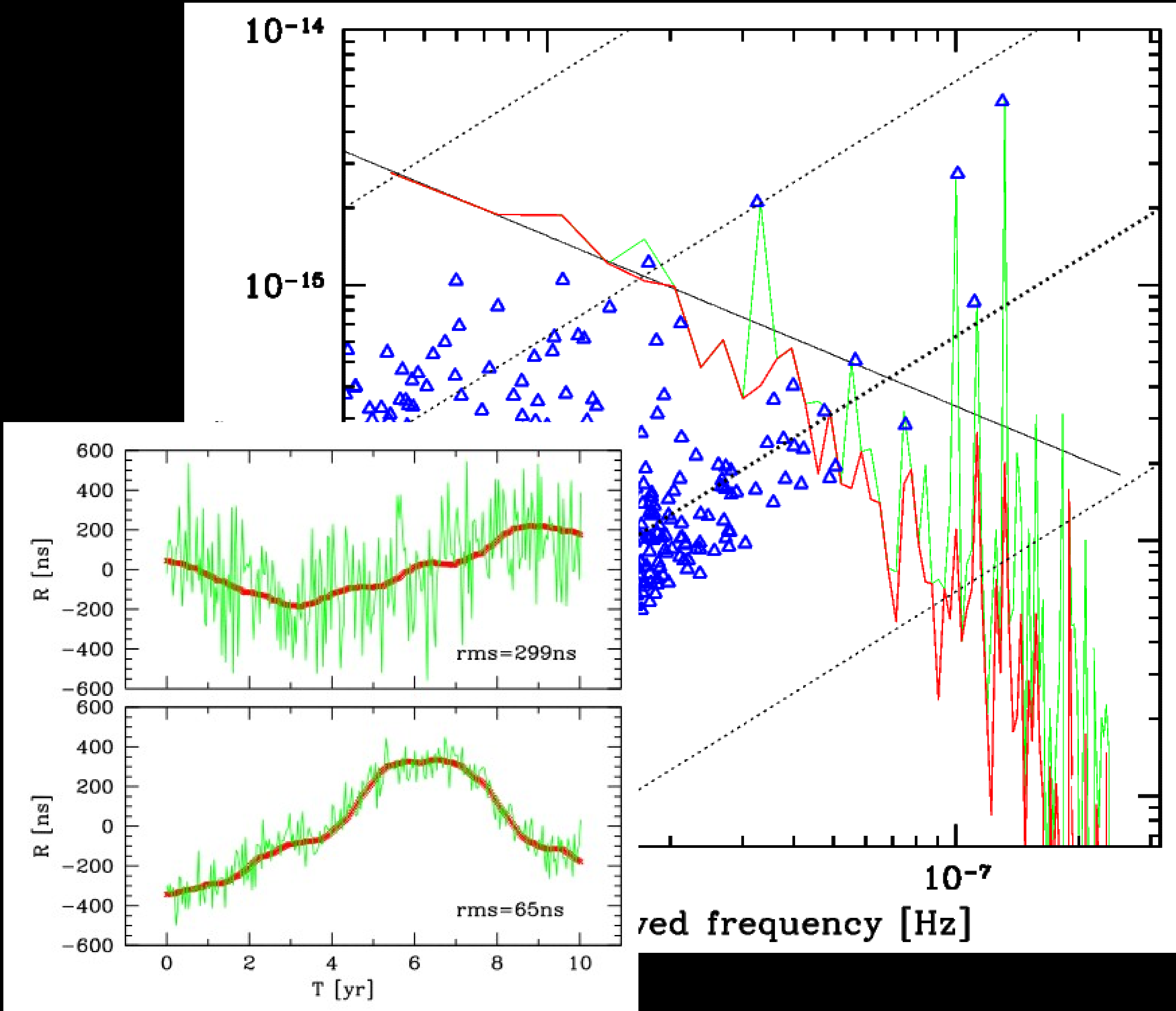
$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$



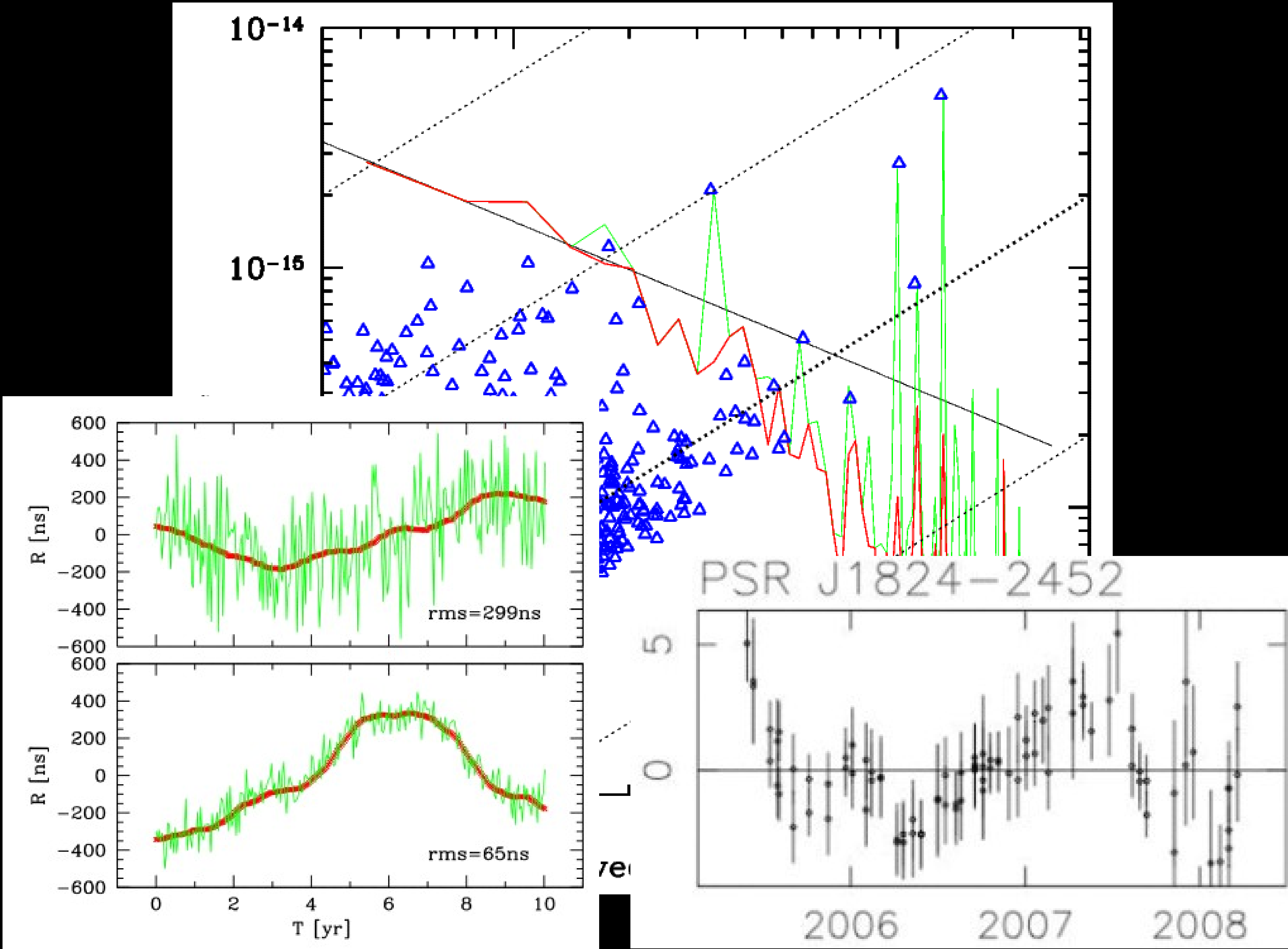
The signal is contributed by extremely massive ($>10^8 M_\odot$) relatively low redshift ($z<1$) MBH binaries (AS et al. 2008, 2012)



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

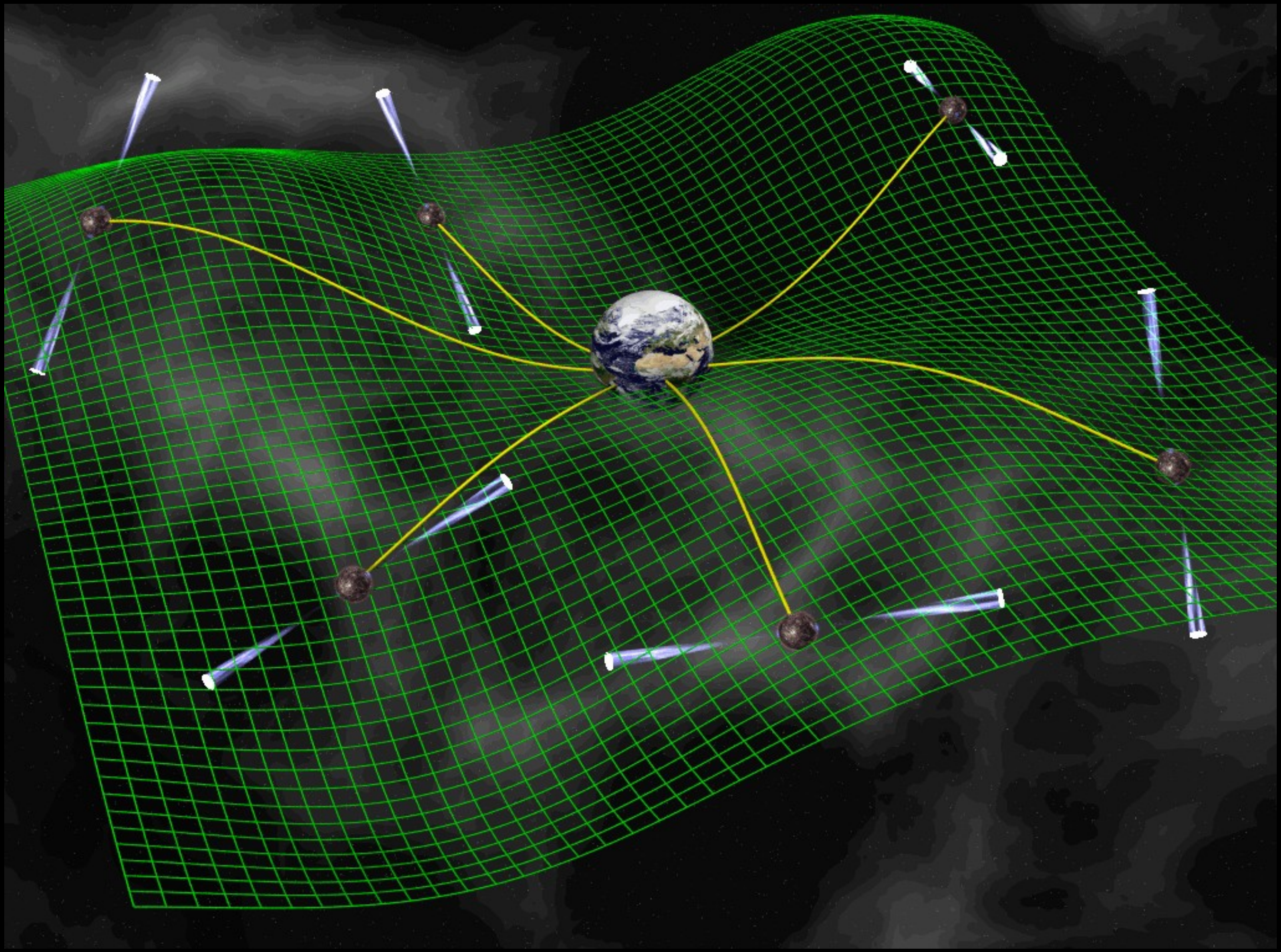


10−14
10−15
10−7
ved frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]



10^-14
10^-15
R [ns]
rms=299ns
rms=65ns
T [yr]
PSR J1824−2452
2006
2007
2008

We are looking for a correlated signal



For a superposition of waves we can write

$$z(t) = \sum_{A=+,\times} \int_{-\infty}^{\infty} df \int d^2\hat{\Omega}\, F^A(\hat{\Omega}) \tilde{h}_A(f,\hat{\Omega}) e^{-2\pi i f t} \left[1 - e^{-2\pi i f \tau}\right]$$

Unpolarized, isotropic, stationary signal

$$\langle \tilde{h}^*_A(f,\hat{\Omega}) \tilde{h}'_A(fi,\hat{\Omega}') \rangle = \delta(f-f') \frac{\delta^2(\hat{\Omega},\hat{\Omega}')}{4\pi} \delta_{AA'} \frac{1}{2} S_h(f)$$

$$\langle z_a(t) z_b(t) \rangle = \frac{1}{2} \int_{-\infty}^{\infty} df\, S_h(f) \int d^2\hat{\Omega} \frac{1}{4\pi} \sum_{A=+,\times} F_a^A(\hat{\Omega}) F_b^A(\hat{\Omega}).$$

The integral over dOmega gives

$$C(\zeta_{ab}) = \frac{1}{4} \left[1 + \frac{\cos\zeta_{ab}}{3} + 4(1-\cos\zeta_{ab}) \ln\left(\sin\frac{\zeta_{ab}}{2}\right)\right]$$

We can then get the correlation in the residual by integrating to find

$$r_{ab} = \langle r_a(t) r_b(t) \rangle$$

$$r_{ab} = C(\zeta_{ab}) \int_0^{\infty} df \frac{S_h(f)}{4\pi^2 f^2}$$

Using

$$h_c^2(f) = 2 f S(f)$$

$$\frac{2\pi^2}{3H_0^2} f^2 h_c^2(f) = \frac{1}{\rho_c} \frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}\ln f} \equiv \Omega_{\mathrm{gw}}(f)$$

$$P_h(f) = \frac{h_c^2(f)}{12\pi^2 f^3}$$

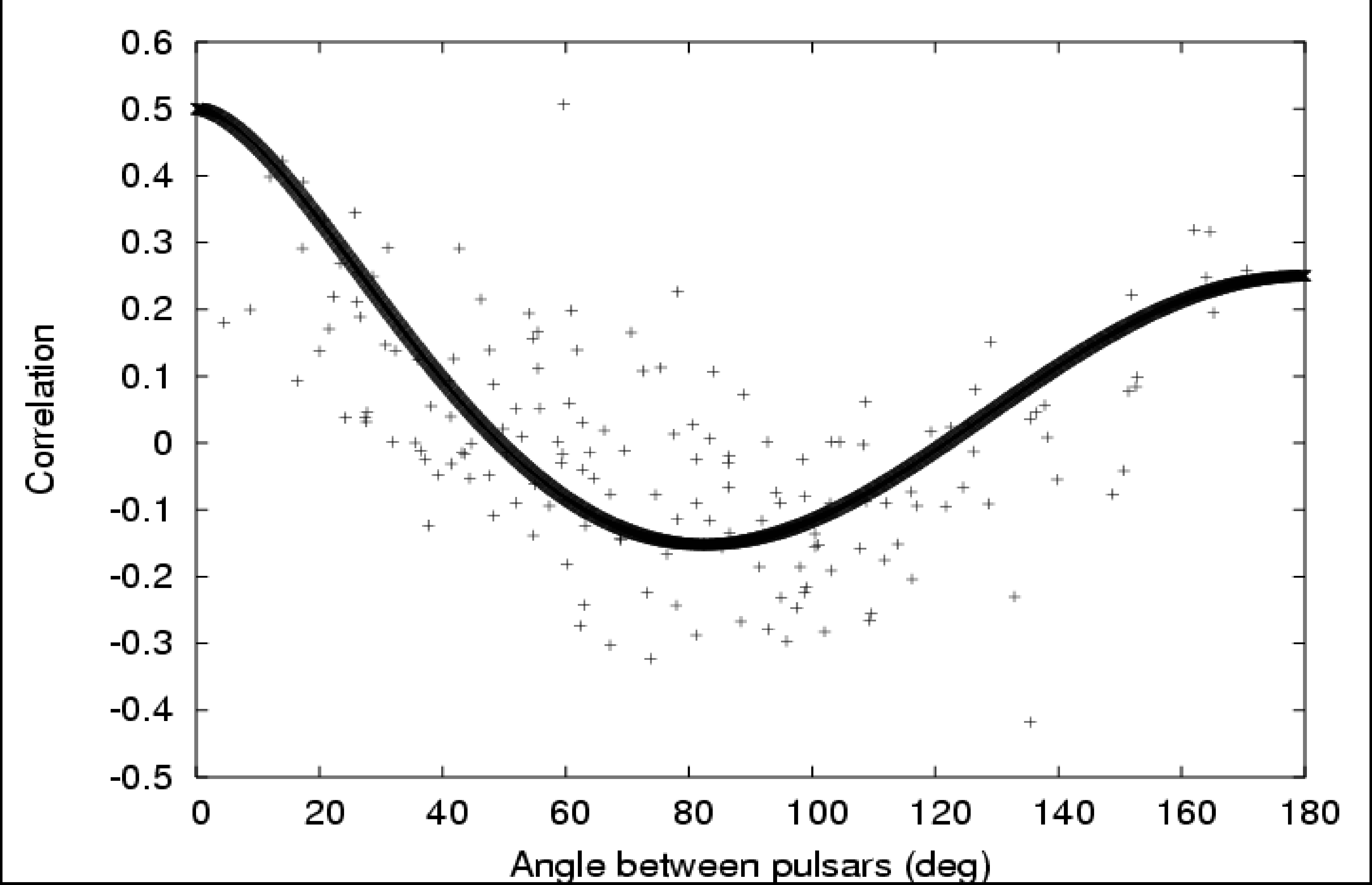
We finally get

$$r_{ab} = \Gamma(\zeta_{ab}) \int_0^{\infty} df\, P_h(f)$$

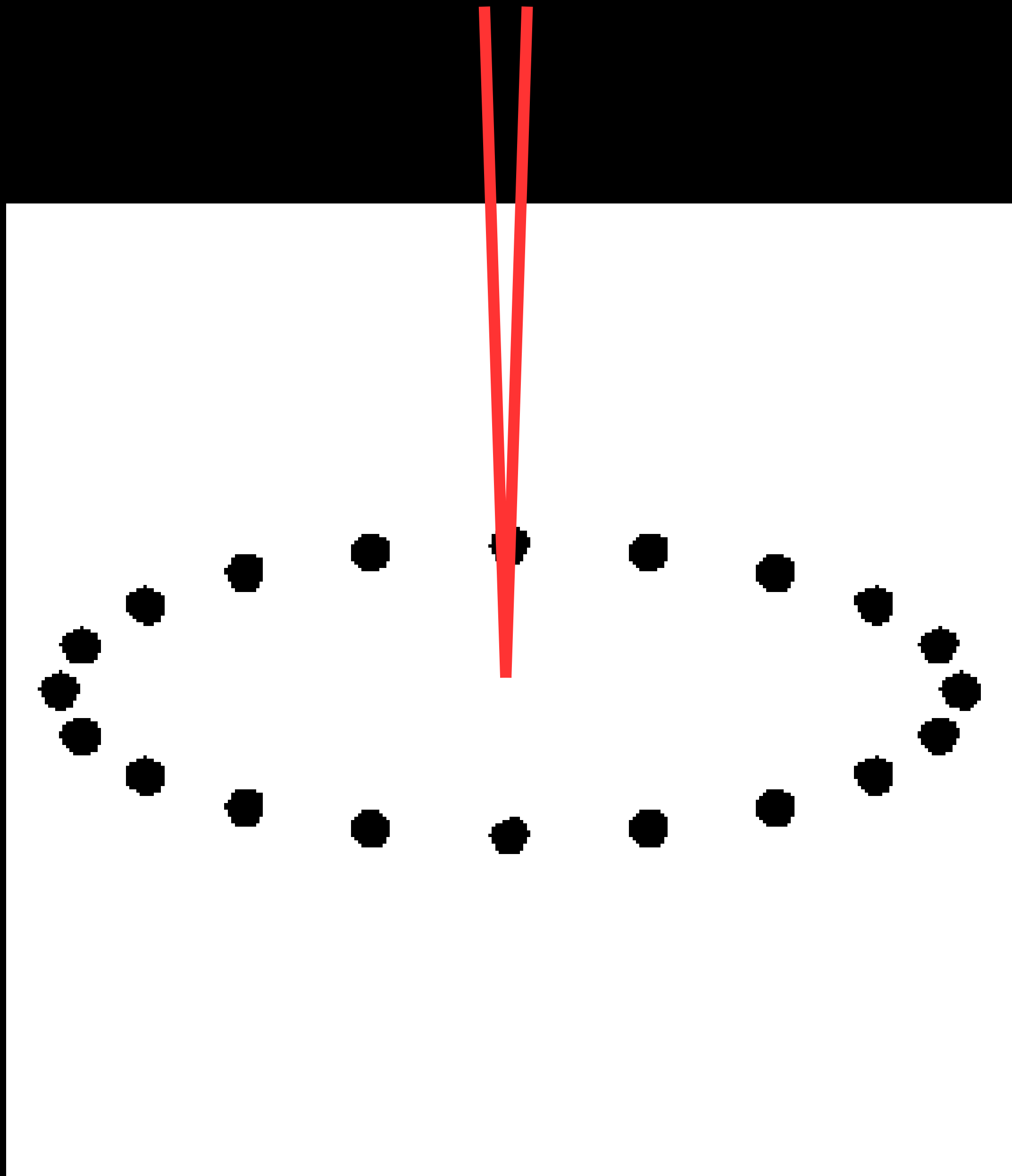
$$\Gamma(\zeta_{ab}) = \frac{3}{2} C(\zeta_{ab})(1+\delta_{ab})$$

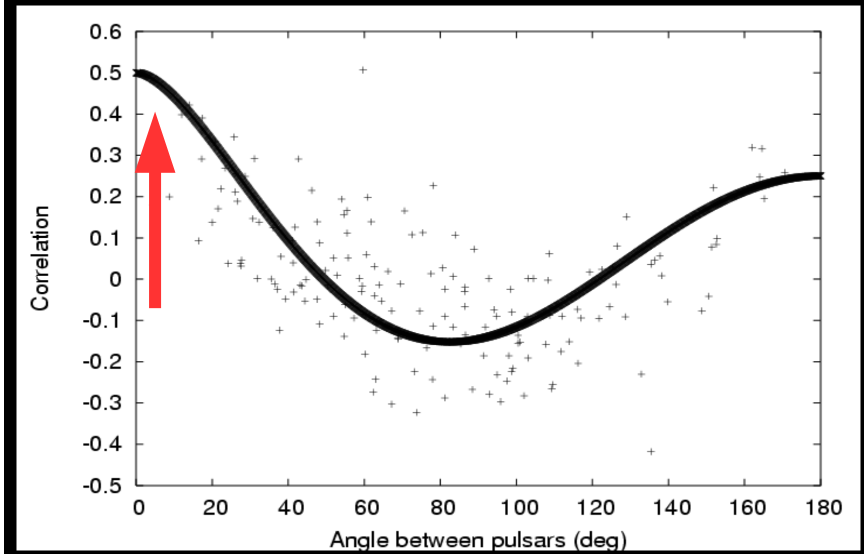
Is known as Helling & Downs curve

We are looking for a correlated signal

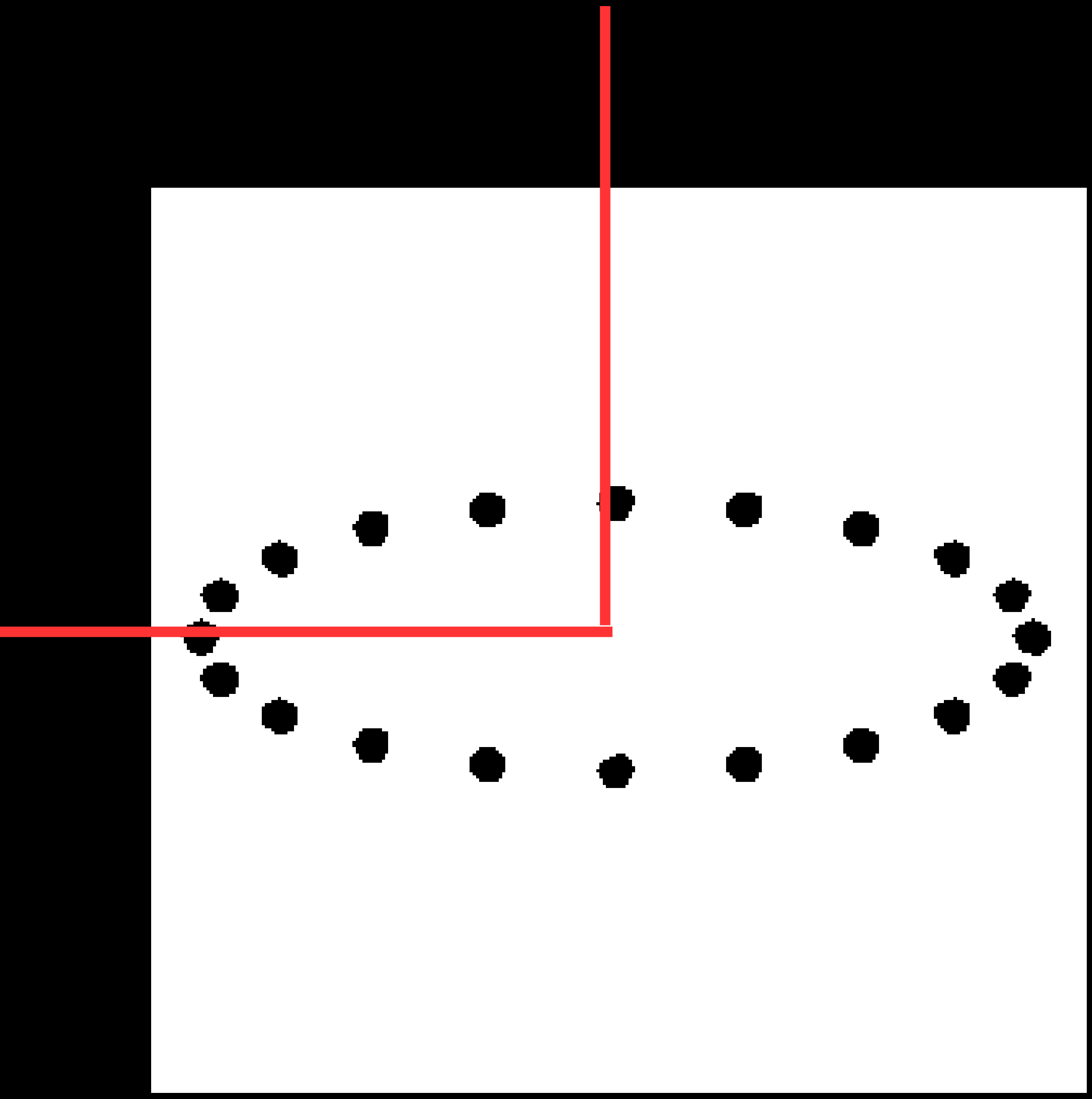


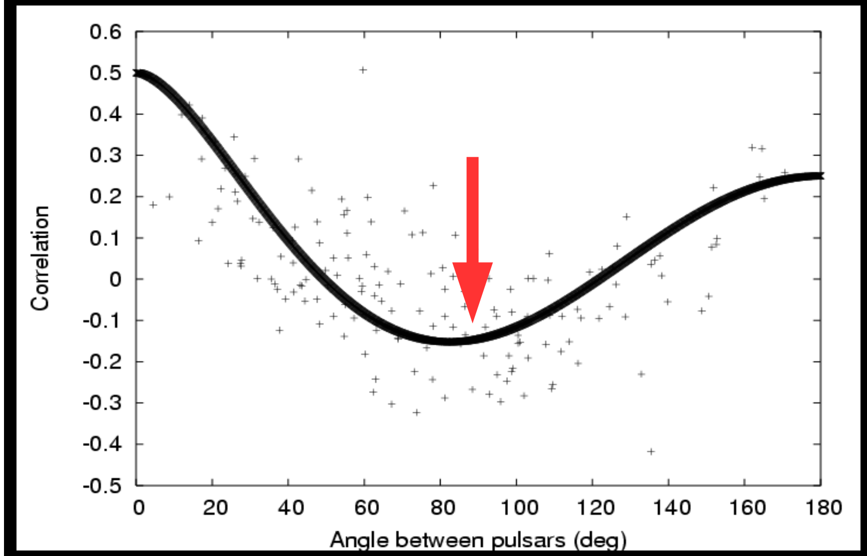
(Hellings & Downs 1983)



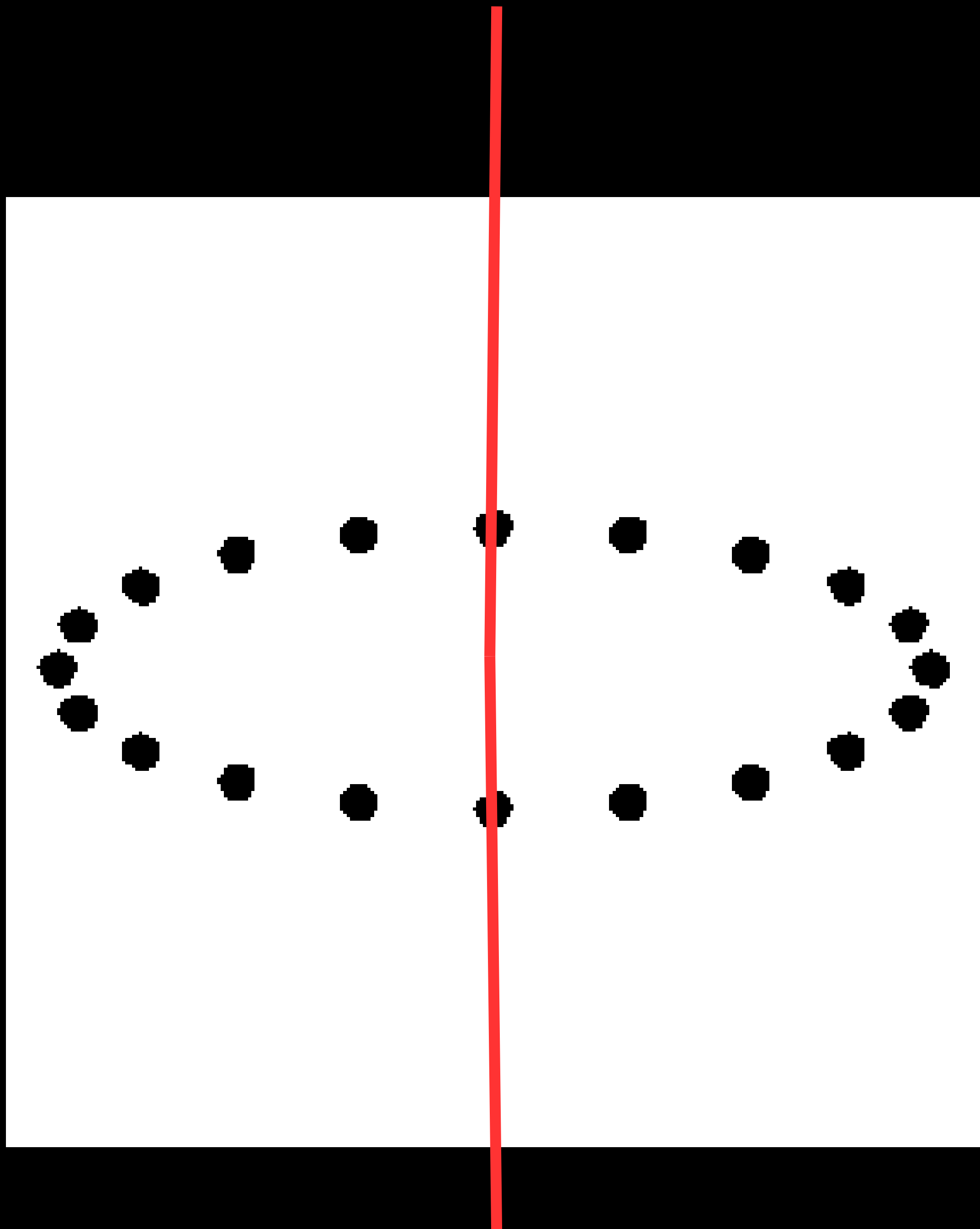


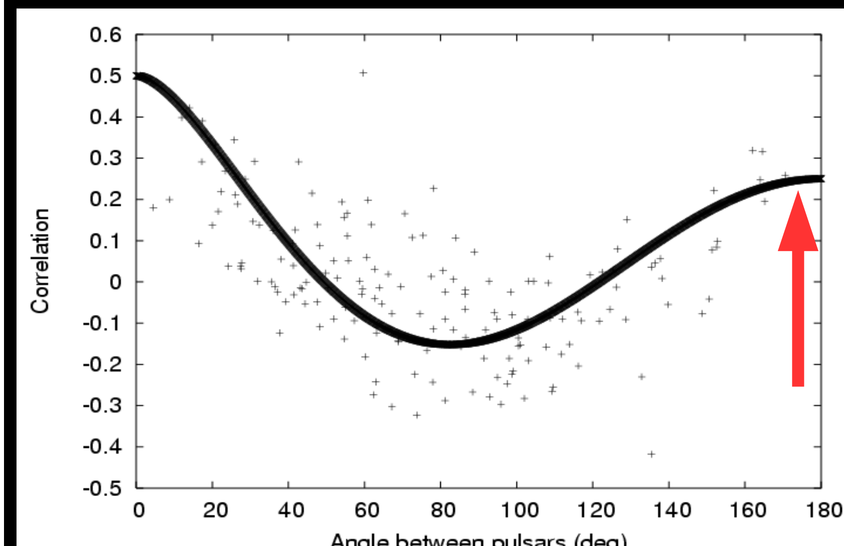
Correlation
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
20
40
60
80
100
120
140
160
180
Angle between pulsars (deg)





Correlation
Angle between pulsars (deg)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
20
40
60
80
100
120
140
160
180





0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Correlation
0
20
40
60
80
100
120
140
160
180
Angle between pulsars (deg)

Likelihood function

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

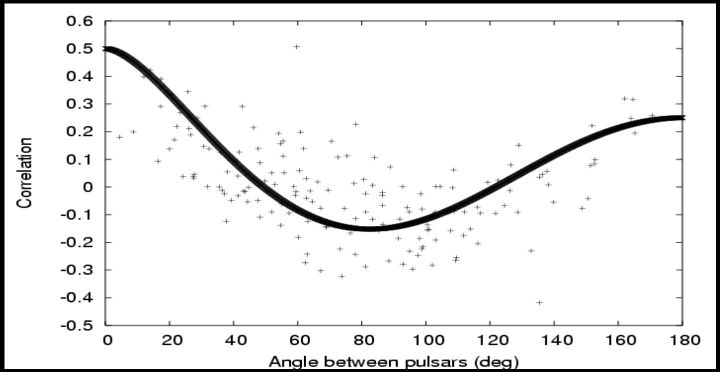
$$\mathcal{L}(\vec{\delta t}|\vec{\theta},\vec{\lambda}) = \frac{1}{\sqrt{(2\pi)^{n-m} det(G^T C G)}} \times$$
$$\exp\left(-\frac{1}{2}(\vec{\delta t}-\vec{r})^T G (G^T C G)^{-1} G^T (\vec{\delta t}-\vec{r})\right),$$

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

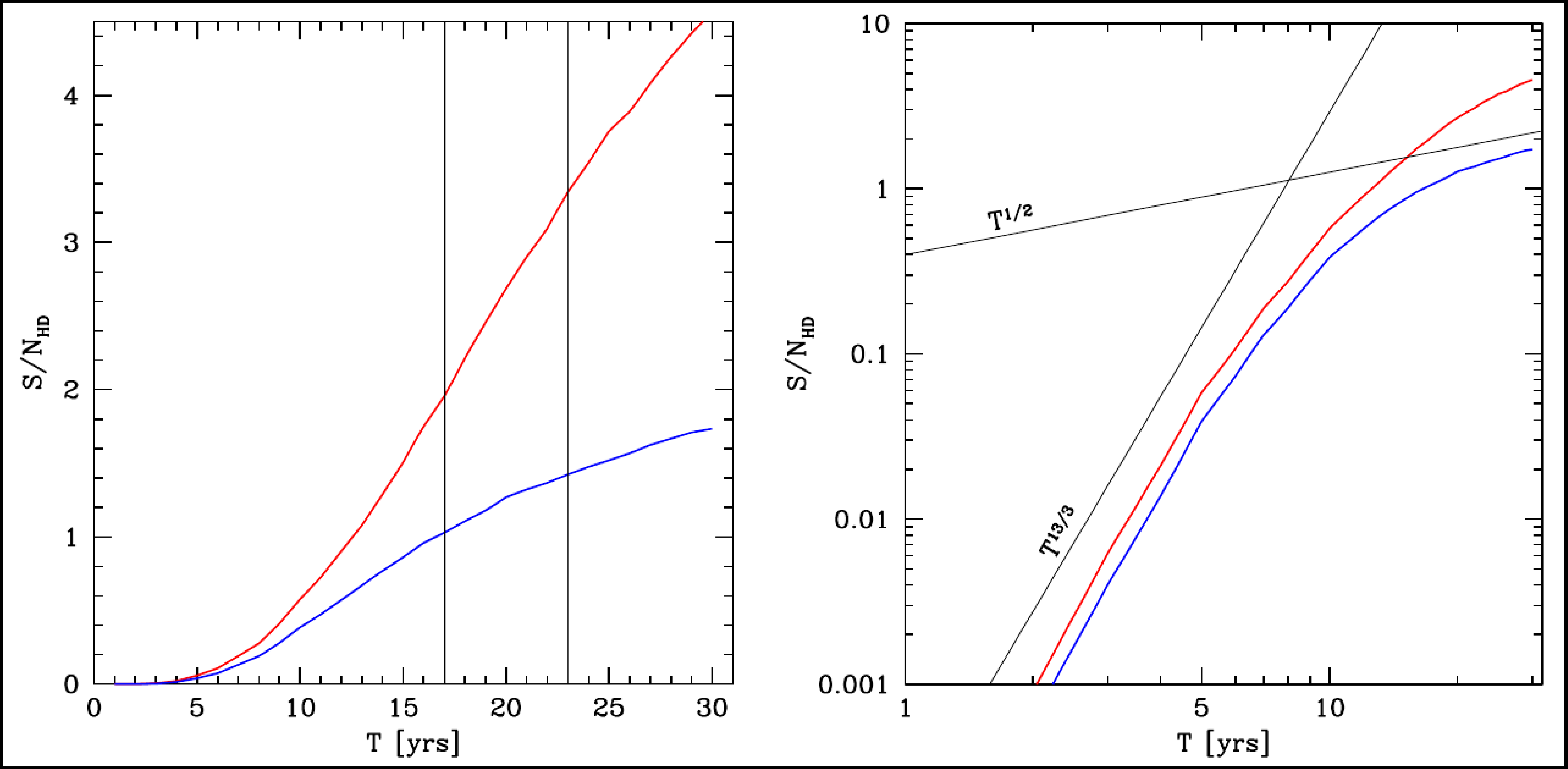
$$\Gamma_{ab} = \frac{3}{8\pi}(1+\delta_{ab})\int_{S^2} d\hat{\Omega}\; P(\hat{\Omega}) \sum_{A} F_a^A(\hat{\Omega}) F_b^A(\hat{\Omega})$$

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

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



Emergence of the GW signal in theory



$$\rho^2 = 2 \sum_{a=1,M} \sum_{b>a} T_{ab} \int \frac{\Gamma_{ab}^2 P_h^2}{P_{n,ab}^2} df,$$

$$\rho \approx 2 \times 10^{-13} N M \sigma^{-2} A^2 T^{10/3}$$

$$P_{n,ab}^2 = P_a P_b + P_h [P_a + P_b] + P_h^2 (1 + \Gamma_{ab})^2$$

$$\rho \approx T^{1/2} \Gamma M (f_{\max} - f_{\min})^{1/2} \approx \Gamma M \Sigma^{1/2}$$

A worldwide observational effort

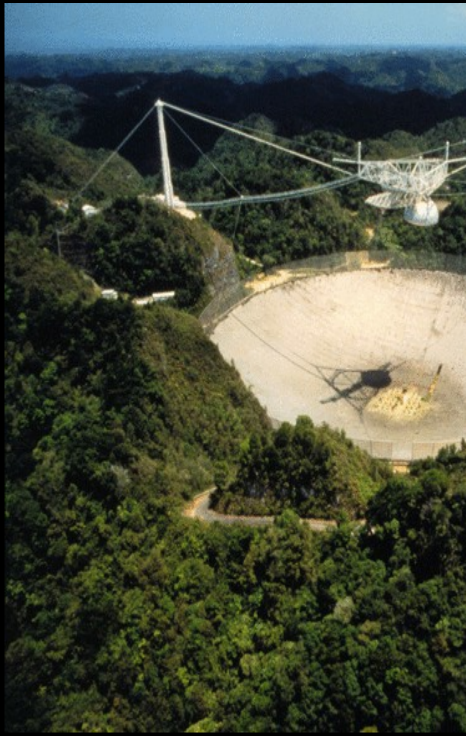
EPTA/LEAP (Large European Array for Pulsars)

NANOGrav (North American nHz Observatory for Gravitational Waves)

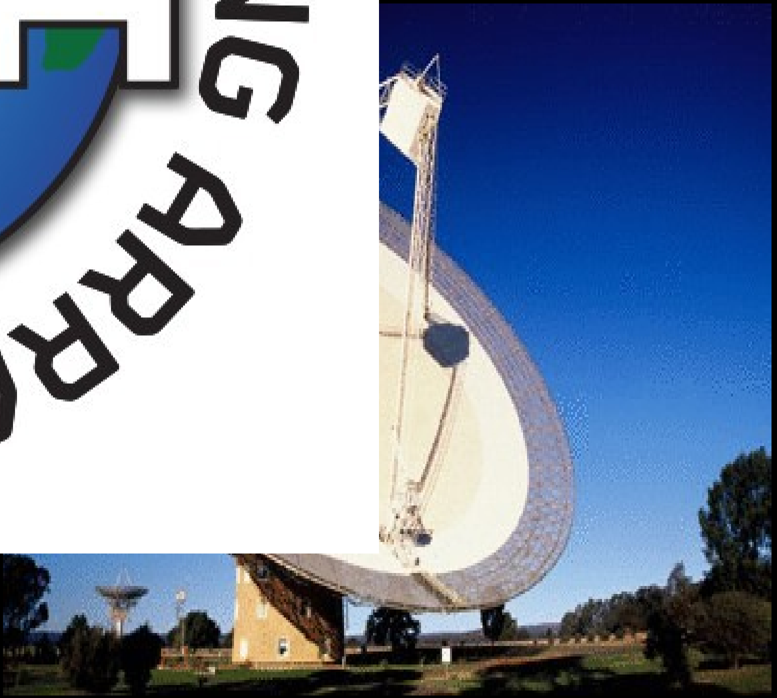
PPTA (Parkes Pulsar Timing Array)

A worldwide observational effort

E

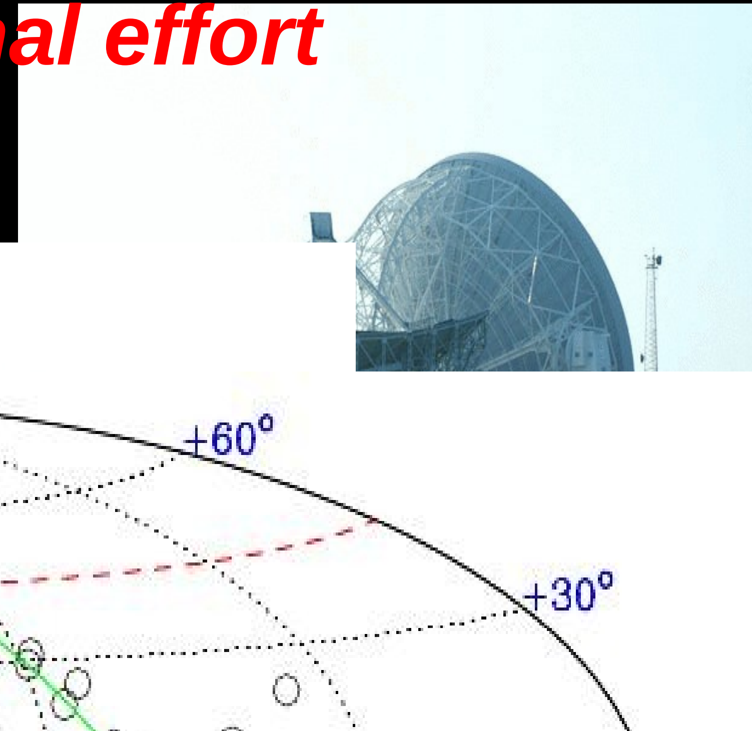


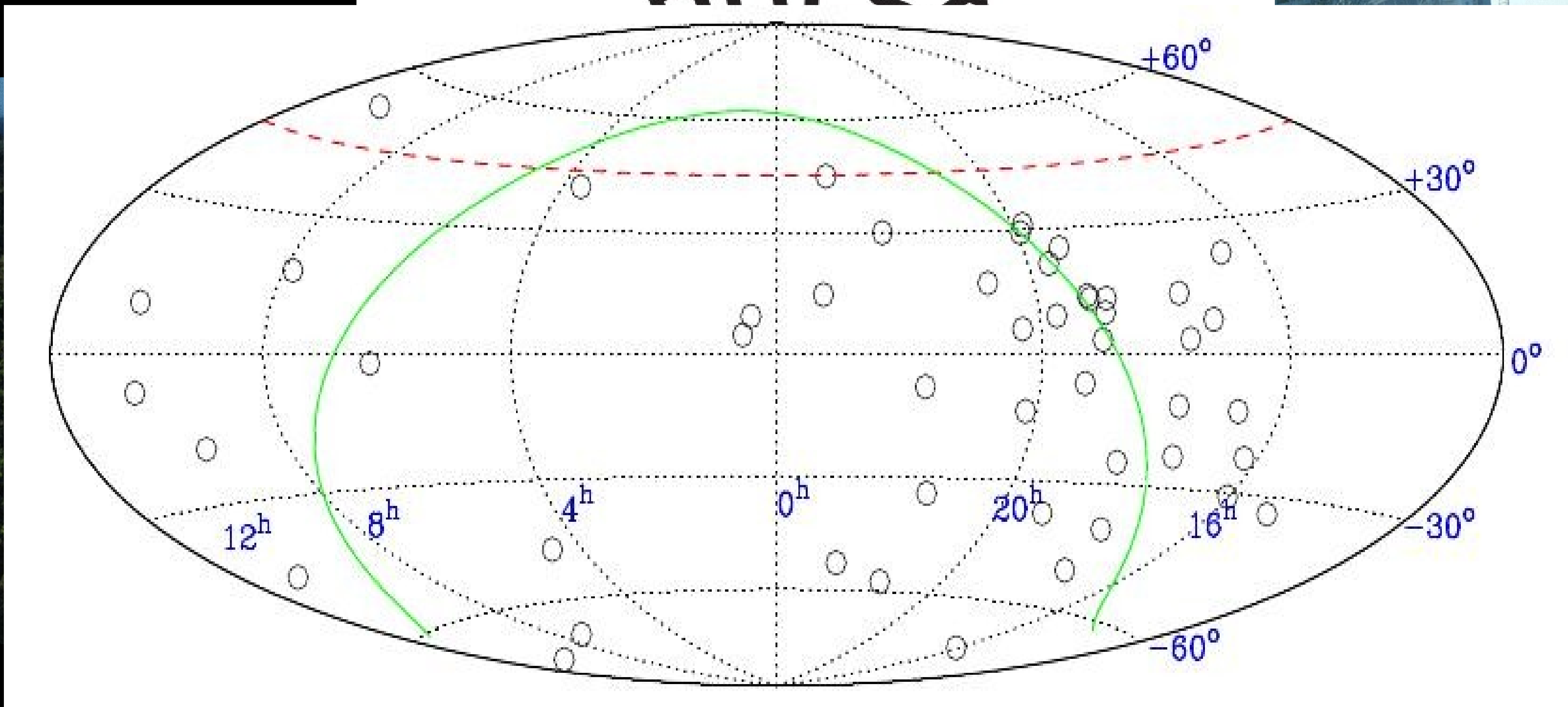
nHz
aves)



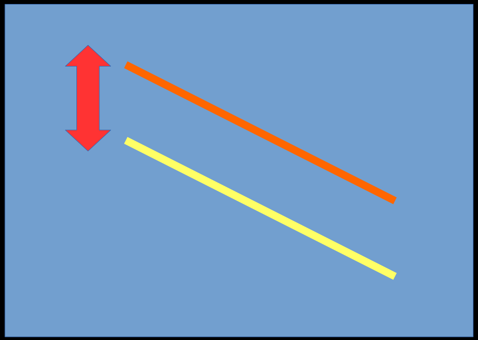
PPT

A worldwide observational effort





The overall GW signal



Population parameters

1-Galaxy merger rate <-----> MBHB merger rate

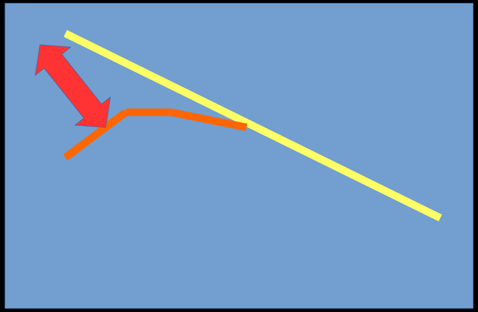
affects the number of sources at each frequency ---> N_0

2-MBH mass – merging galaxy relation

affects the mass of the sources ----> M_c

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \frac{d^4N}{dz\,dM_1\,dq\,dt_r} \frac{dt_r}{d\ln f_{\mathrm{K},r}} \times h^2(f_{\mathrm{K},r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{\mathrm{K},r})]}{(n/2)^2} \delta\left[f - \frac{n f_{\mathrm{K},r}}{1+z}\right].$$

$$h_c(f) \propto n_0^{1/2} f^{-\gamma} M_c^{5/6}$$



Local dynamics

1-Accretion (when? how?)

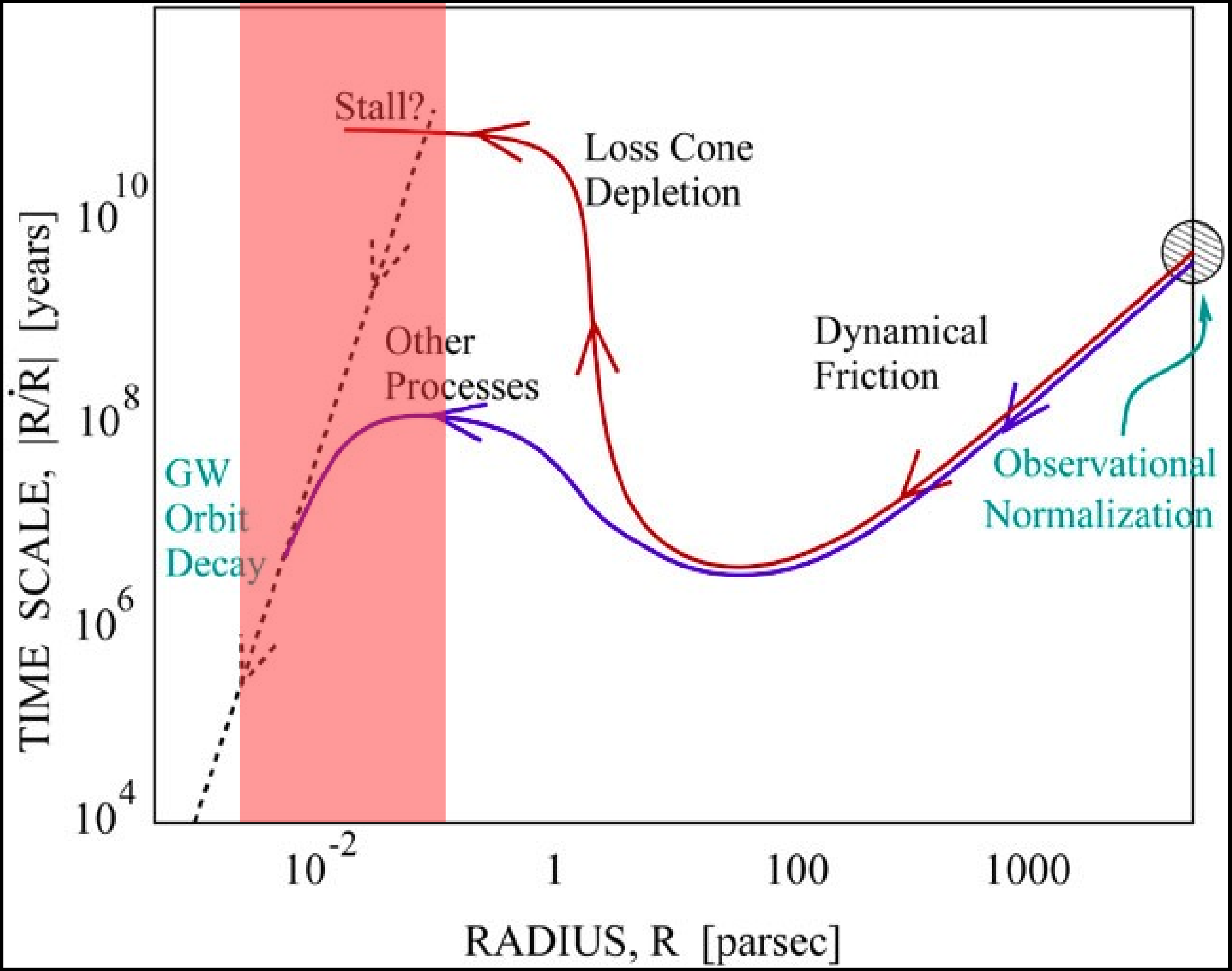
affects the mass of the sources ---> M_c

2-MBHB – environment coupling (gas & stars)

affects the chirping rate of the binaries ---> γ

affects the eccentricity ---> chirping rate ----> γ & single source detection

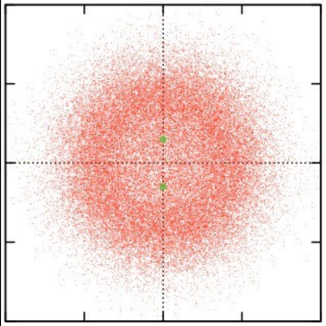
Uncertainty in the GW background shape



STELLAR DRIVEN BINARIES

assuming stars are supplied to the binary loss cone at a constant rate:

$$\frac{da}{dt} = \frac{a^2 G\rho}{\sigma} H$$



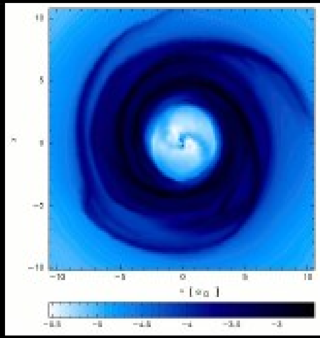
$$dt/d\ln f \;\propto\; f^{2/3} M_1^{2/3}$$

$$h_c \propto M_1^2 q f$$

GAS DRIVEN BINARIES

self-consistent solution for the binary-disk interaction with no leakage in the cavity:

$$\frac{da}{dt} = \frac{2\dot{M}}{\mu}(a a_0)^{1/2}$$



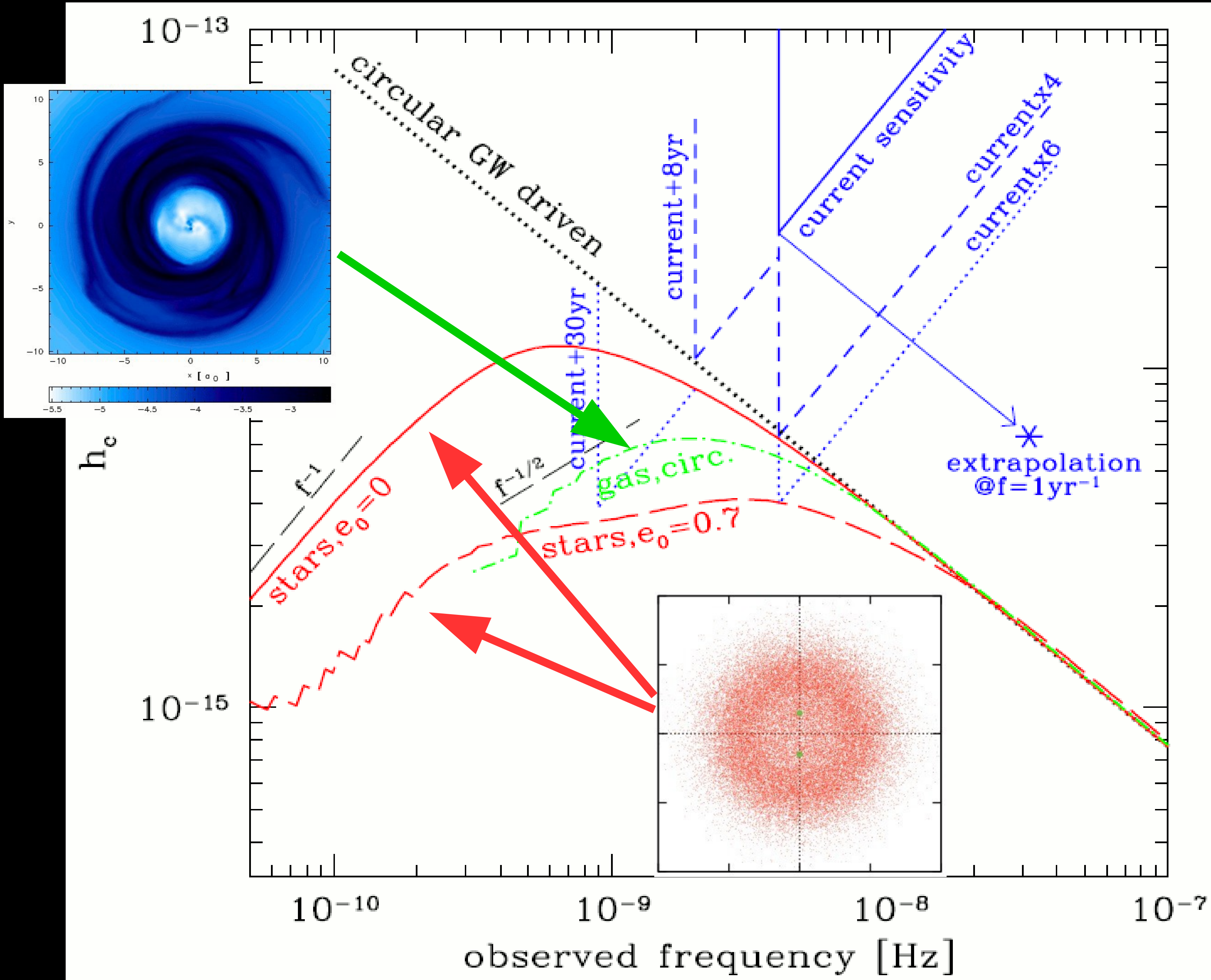
$$dt/d\ln f \;\propto\; f^{-1/3} M_1^{1/6}$$

$$h_c \propto M_1^{7/4} q^{3/2} f^{1/2}$$

Transition frequency

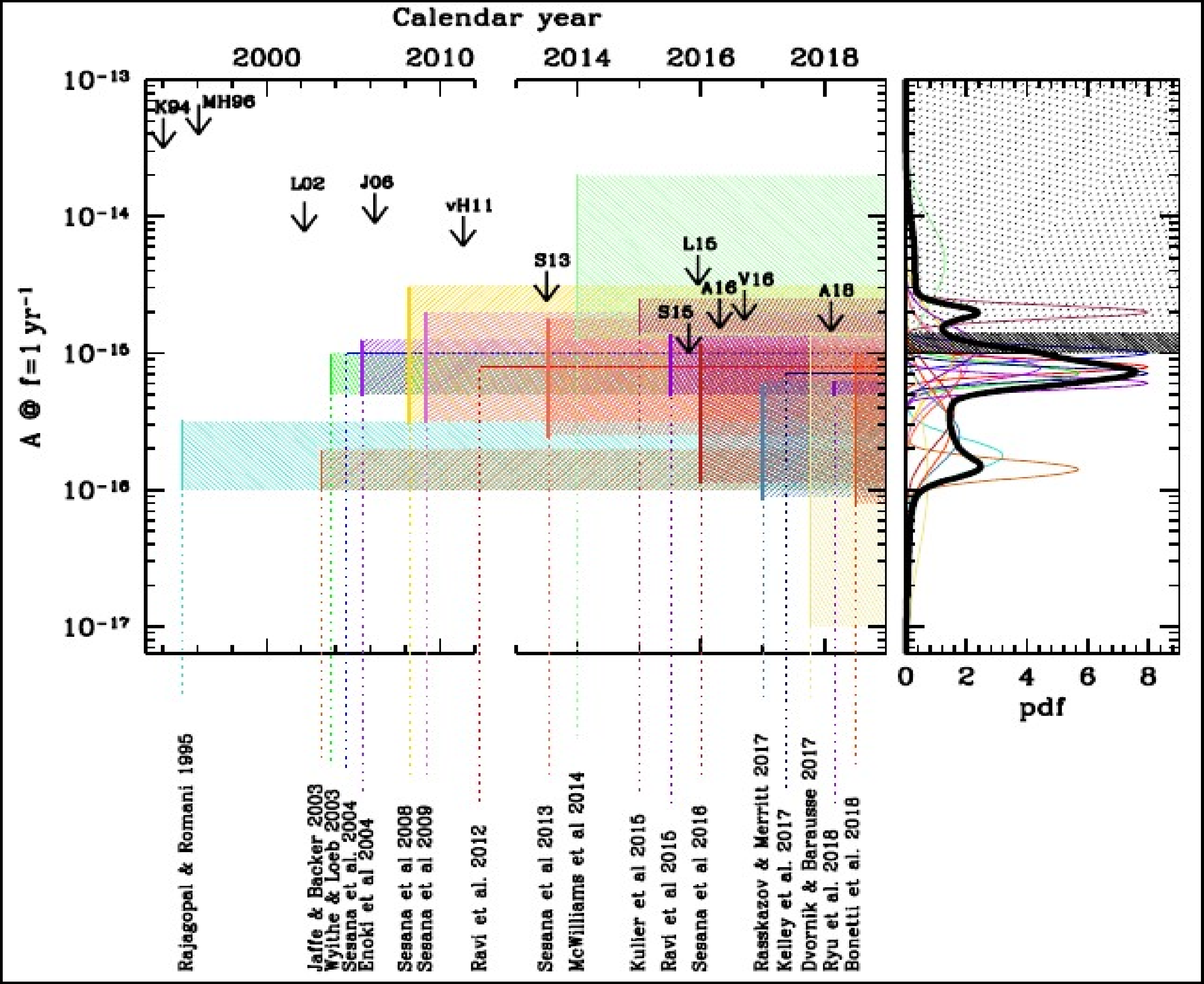
$$f_{\rm star/GW} \approx 5 \times 10^{-9} M_8^{-7/10} q^{-3/10}$$

$$f_{\rm gas/GW} \approx 5 \times 10^{-9} M_8^{-37/49} q^{-69/98}$$

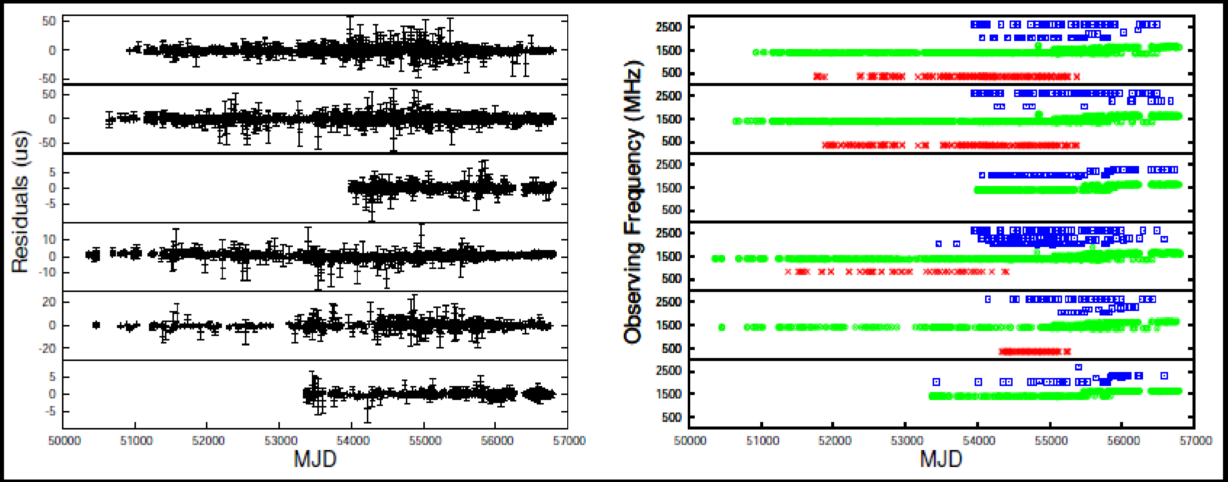


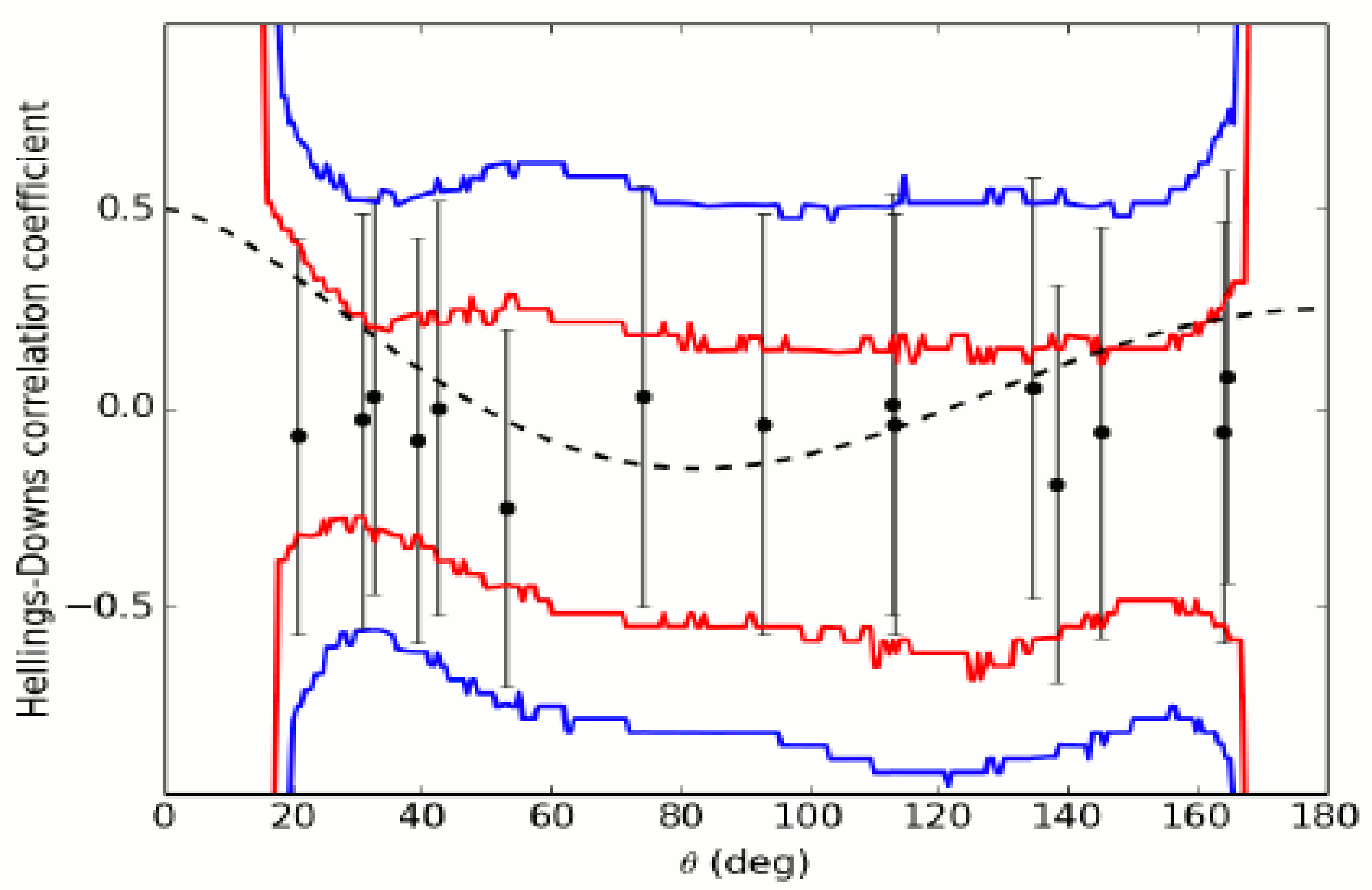
(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)

Theory and observations progression



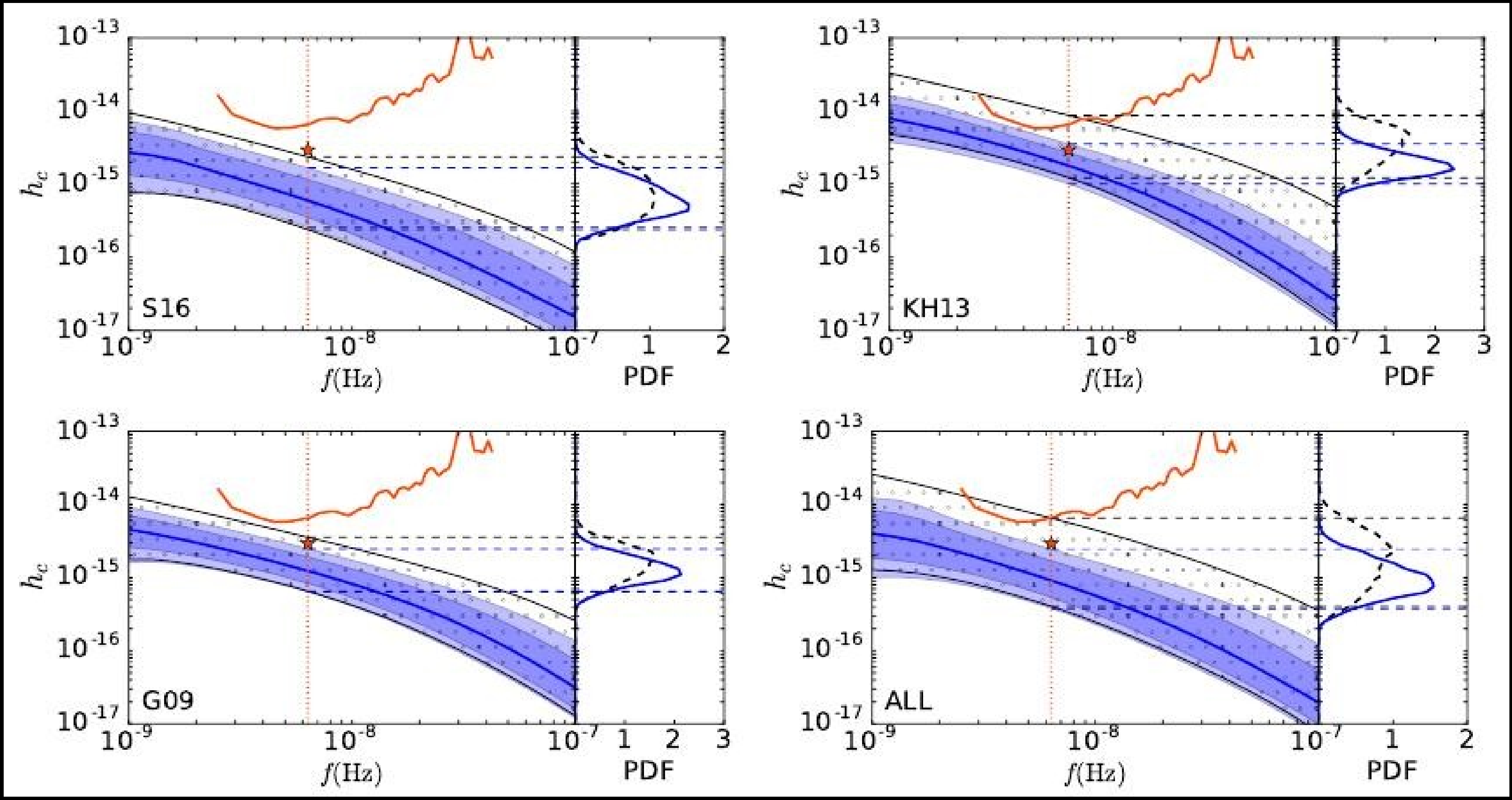
Example of non-detection (EPTA, Lentati et al. 2015)





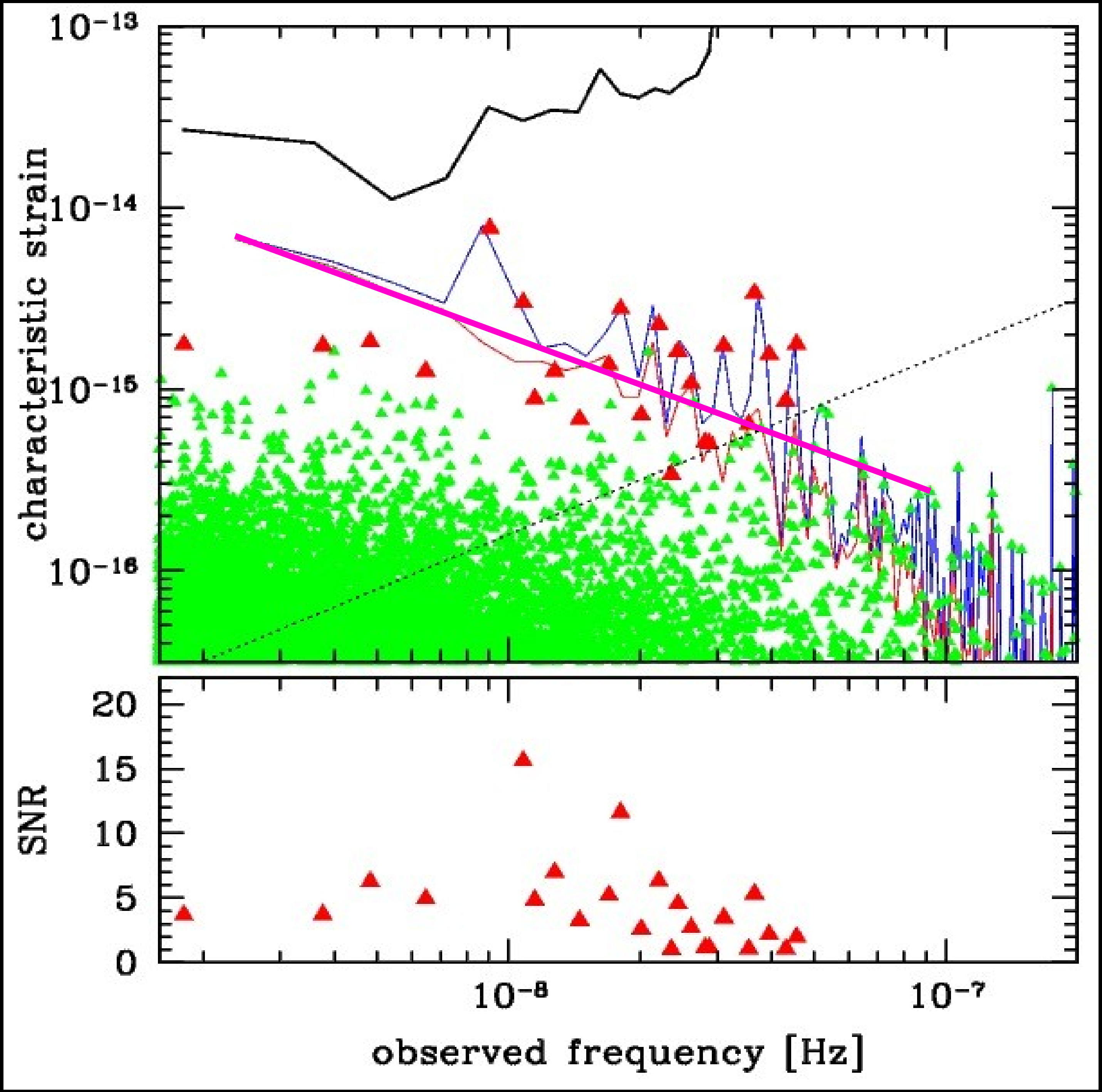
Current limits not quite constraining

-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., 2018)

The nature of the signal



*It is not smooth

*It is not Gaussian

*Single sources might pop-up

*The distribution of the brightest sources might well be anisotropic

Continuous GW analysis

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

The correlation matrix C is now defined by a deterministic signal that for circular GW driven binaries takes the form:

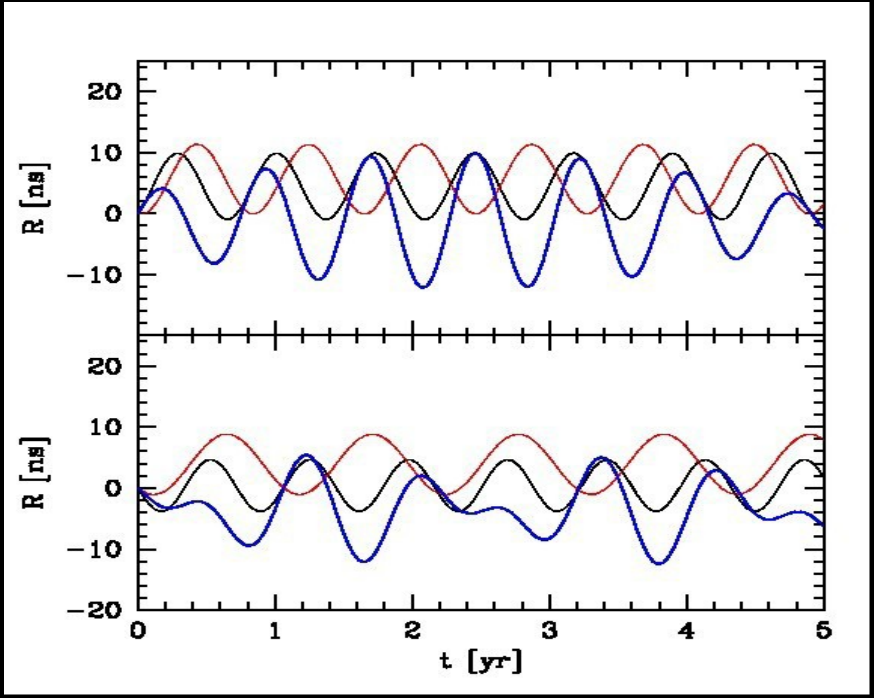
$$r_a(t) = r_a^p(t) - r_a^e(t),$$

where

$$r_a^e(t) = \frac{\mathcal{A}}{\omega}\left\{(1+\cos^2\iota)F_a^+\left[\sin(\omega t+\Phi_0)-\sin\Phi_0\right] + 2\cos\iota F_a^\times\left[\cos(\omega t+\Phi_0)-\cos\Phi_0\right]\right\},$$

$$r_a^p(t) = \frac{\mathcal{A}_a}{\omega_a}\left\{(1+\cos^2\iota)F_a^+\left[\sin(\omega_a t+\Phi_a+\Phi_0)-\sin(\Phi_a+\Phi_0)\right] + 2\cos\iota F_a^\times\left[\cos(\omega_a t+\Phi_a+\Phi_0)-\cos(\Phi_a+\Phi_0)\right]\right\},$$

$$\mathcal{A} = 2\frac{\mathcal{M}_c^{5/3}}{D_L}(\pi f)^{2/3}$$

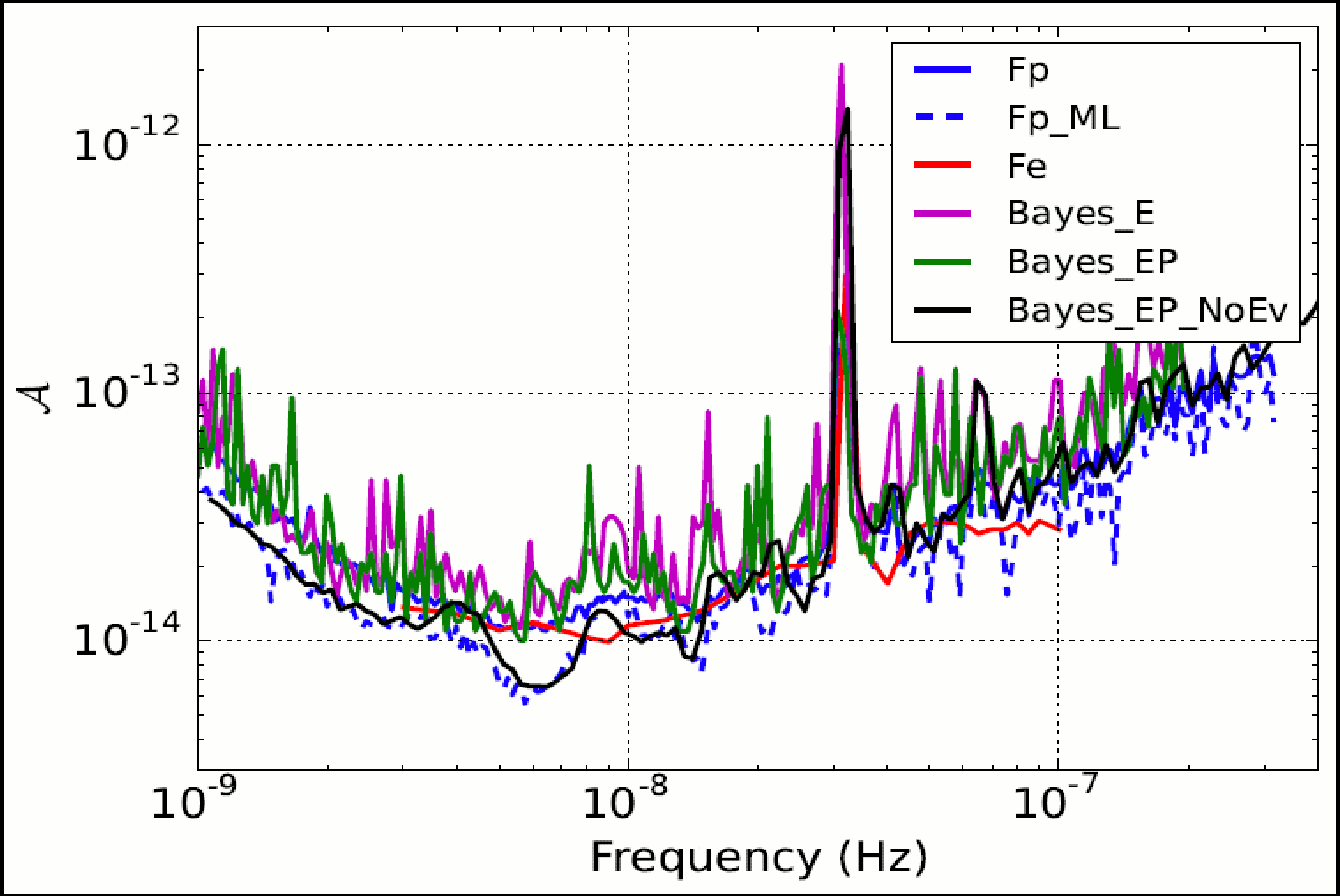


The signal depends on several parameters, and consists of two superimposed sinusoids

Limits on continuous GWs

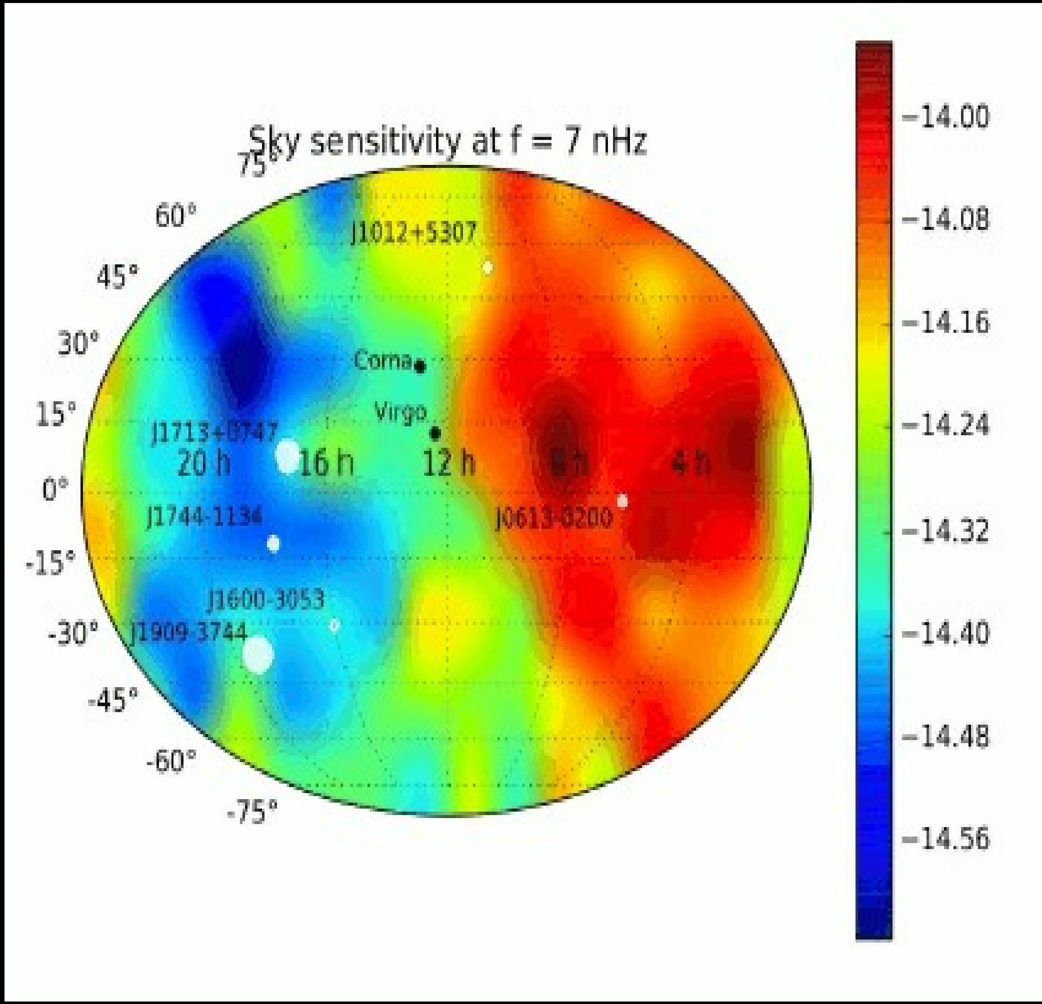
(EPTA, Babak et al. 2015)

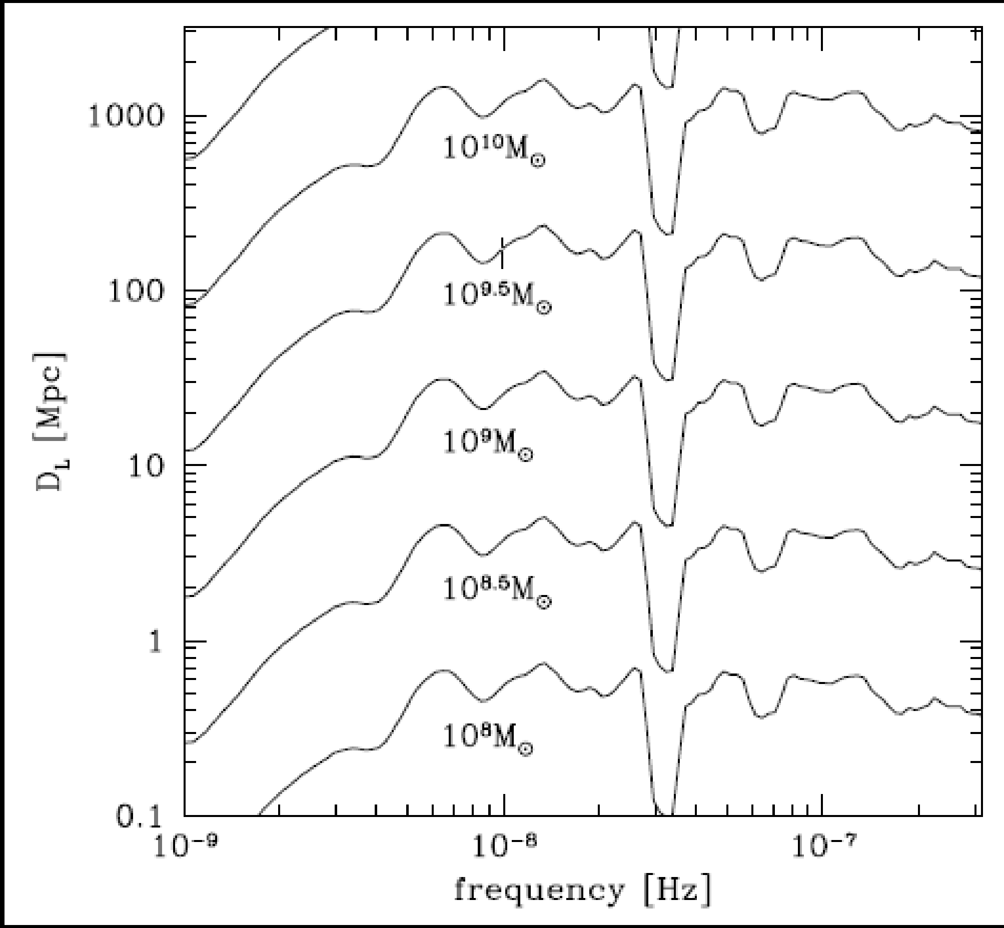
Search ID	Noise treatment	N pulsars	N parameters	Signal model	Likelihood
Fp_ML	Fixed ML	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fp	Sampling posterior	41	1	E+P NoEv	Maximized over 4 constant amplitudes plus pulsar phase
Fe	Fixed ML	41	3	E	Maximized over 4 constant amplitudes
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



Astrophysical implications

The array sensitivity is function of the sky location, we can build sensitivity skymaps

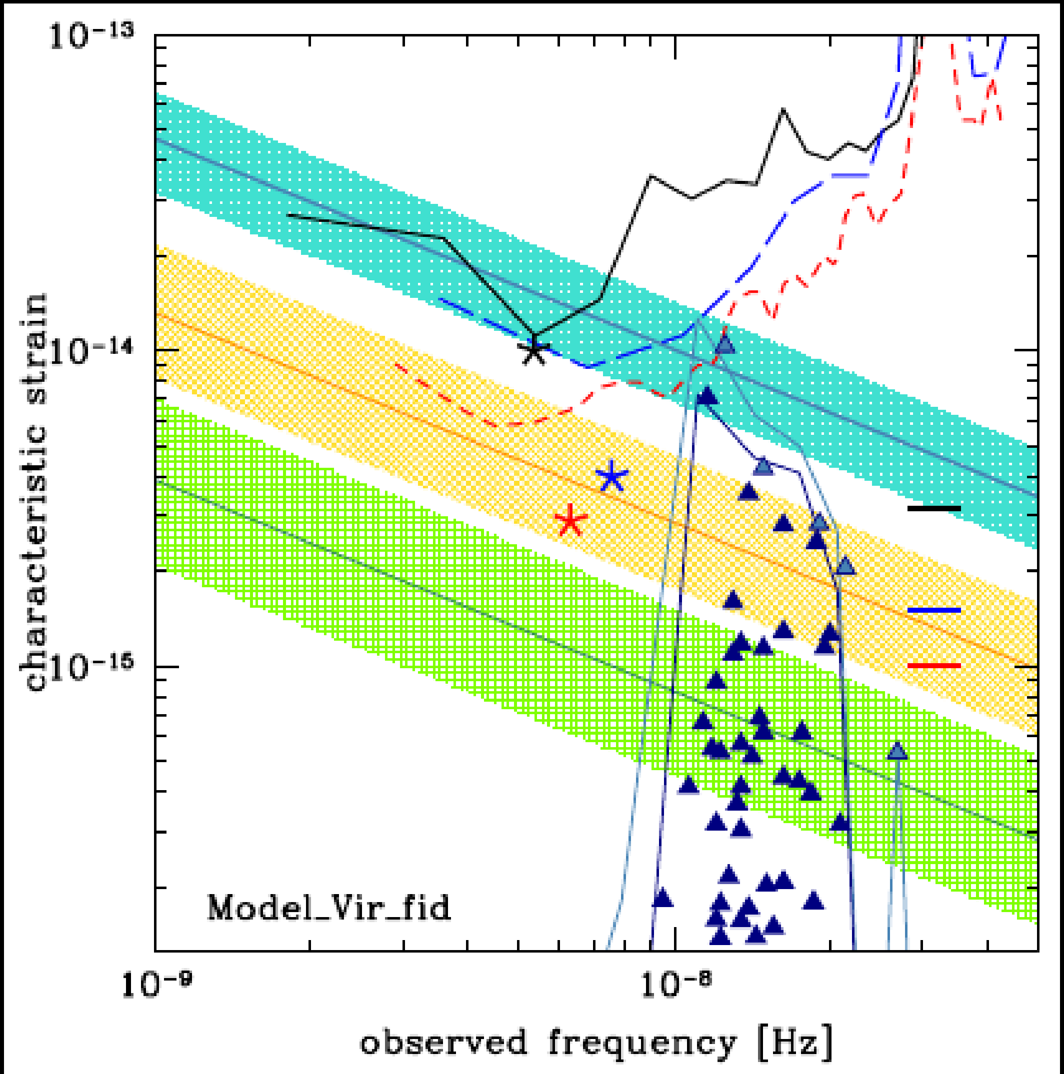


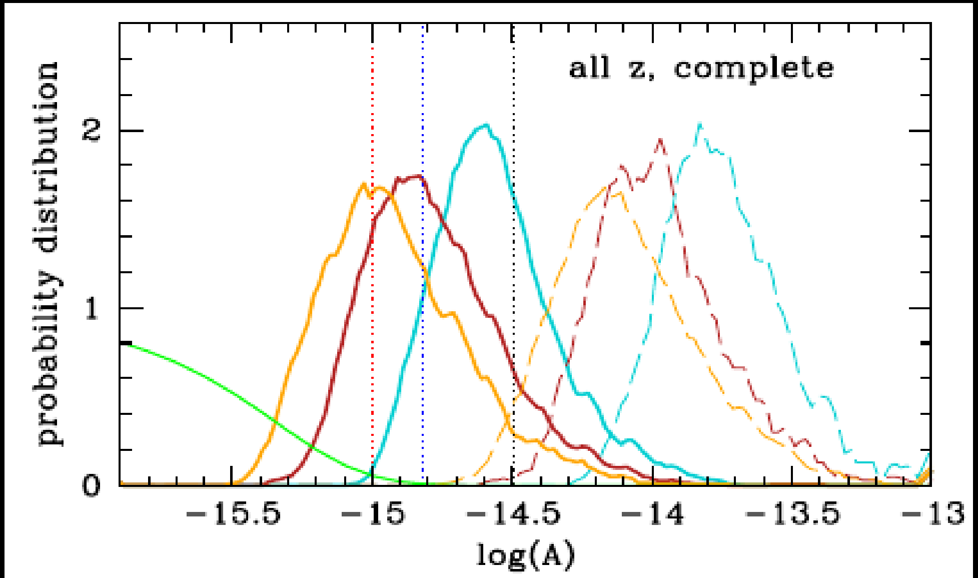


Data are not yet very constraining, we can rule out very massive systems to ~200Mpc, well beyond Coma

Constraining astrophysical candidates

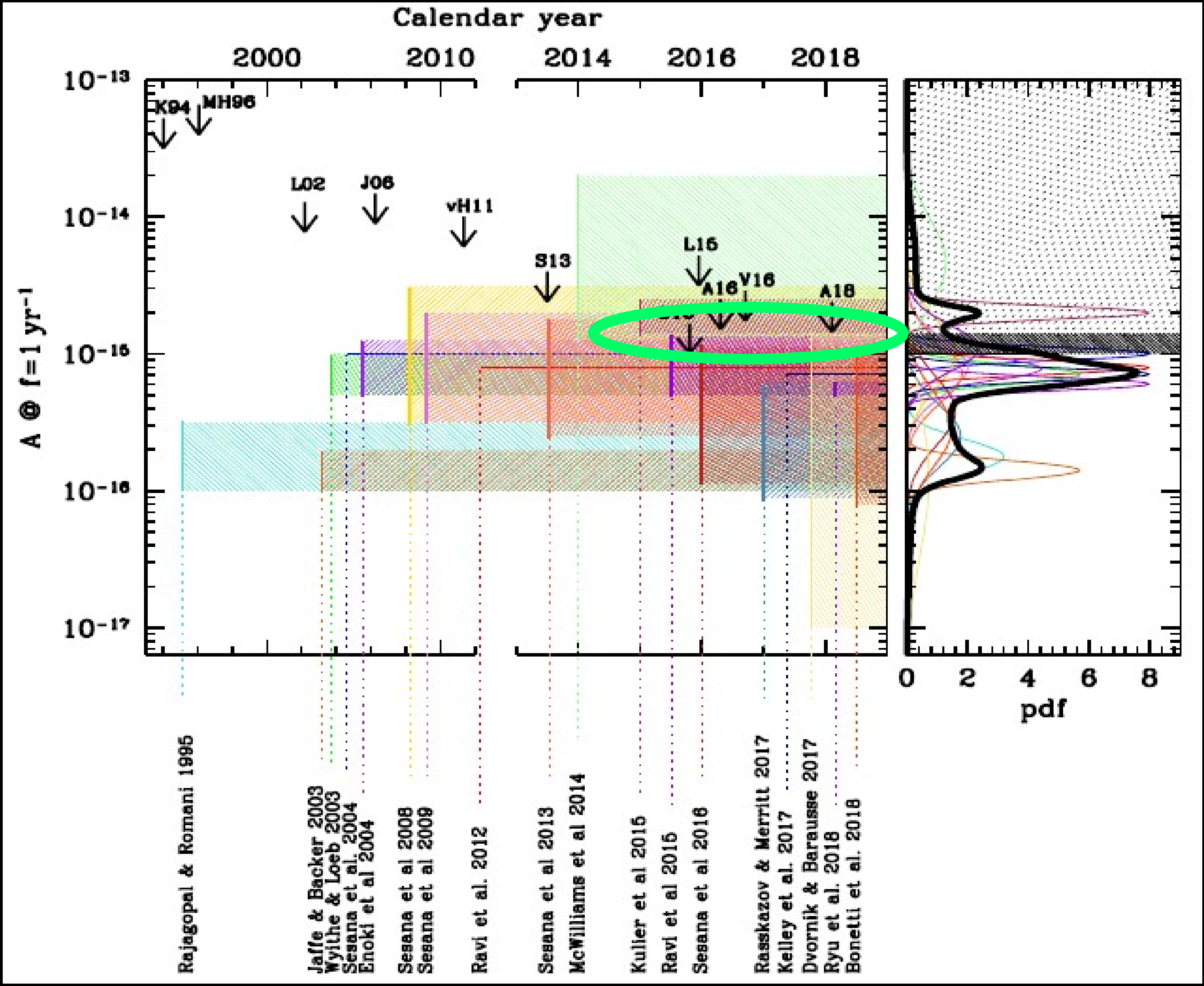
- -Graham et al. 2015: 111 candidates from CRTS
- -Charisi et al 2016: 33 candidates from PTF
- -All candidates are individually consistent with PTA limits
- -The implied total signal is in tension with PTA limits at 2 – 3 sigma level (Sesana et al. 2018)





model pair	odds ratio & probabilities		
	$\log\Lambda_{NB}$	p_N	p_B
N/True_hiq	2.61	0.9976	0.0024
N/True_fid	1.52	0.9709	0.0291
N/True_loq	1.10	0.9267	0.0733
N/Vir_hiq	11.1	> 0.9999	$< 10^{-11}$
N/Vir_fid	6.67	> 0.9999	$< 10^{-6}$
N/Vir_loq	5.22	> 0.9999	$< 10^{-5}$

...but...



Calendar year
2000
2010
2014
2016
2018
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
A @ f=1 yr^{-1}
K94
MH96
L02
J06
vH11
S13
L15
A16
V16
A18
0
2
4
6
8
pdf
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
Sesana et al 2016
Rasskazov & Merritt 2017
Kelley et al. 2017
Dvornik & Barausse 2017
Ryu et al. 2018
Bonetti et al. 2018

Limits published after 2015 are not solid:

1- Shannon et al 2015 → essentially a single pulsar limit.
This is a problem since you have to model the pulsar red noise and if your array is dominated by a single pulsar you can never know whether its red noise is intrinsic. → ‘over fitting’

2- Arzoumanian 2016, 2018 → Issues with solar system Ephemeridis.
The data show some evidence of correlated red signal, but it can be absorbed in uncertanties in the SSE

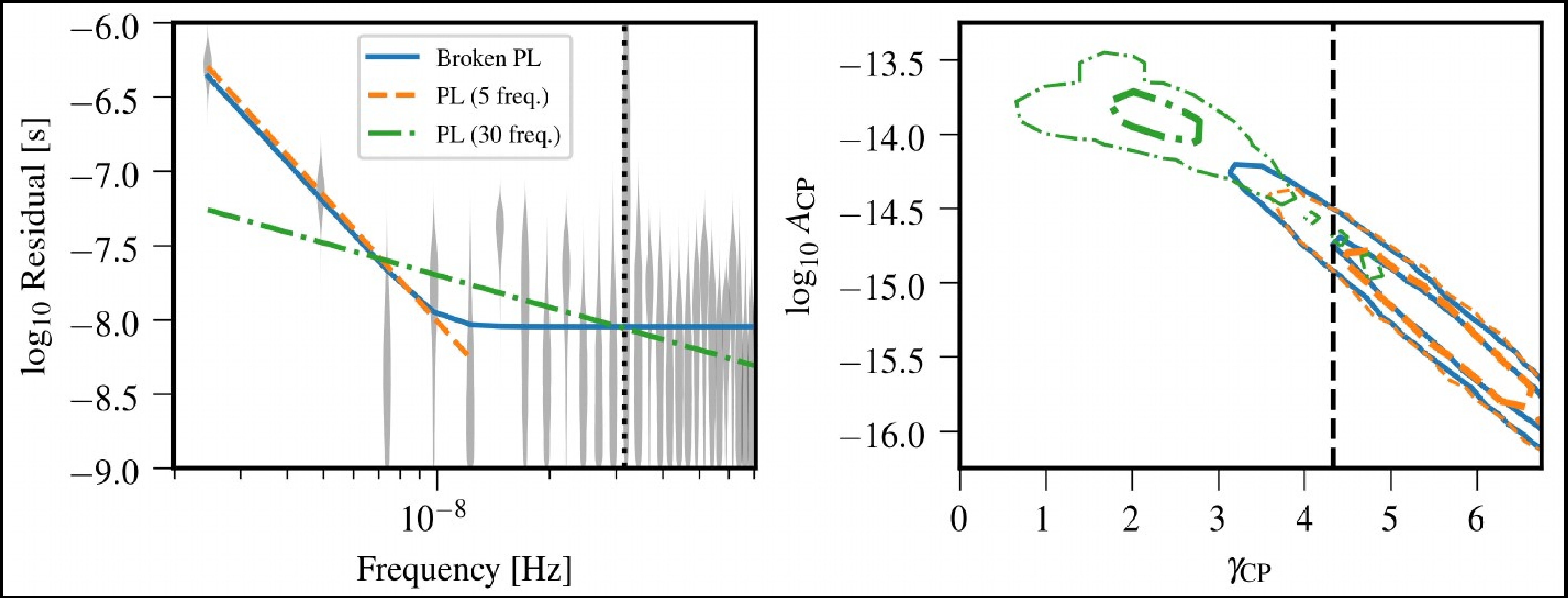
3- Since quite some time a common red signal has been present in several PTA data but it’s nature hasn’t be assessed (see point 2)

NOTE:

The choice of the prior in your analysis matters. When you think you don’t have a signal in the data, you use a log uniform prior in the amplitude to place an upper limit, which has the effect to likely push your UL down.

So it is possible that by assuming there is no signal in the data, the recent UL have been overestimated

NANOGrav 12.5 year analysis

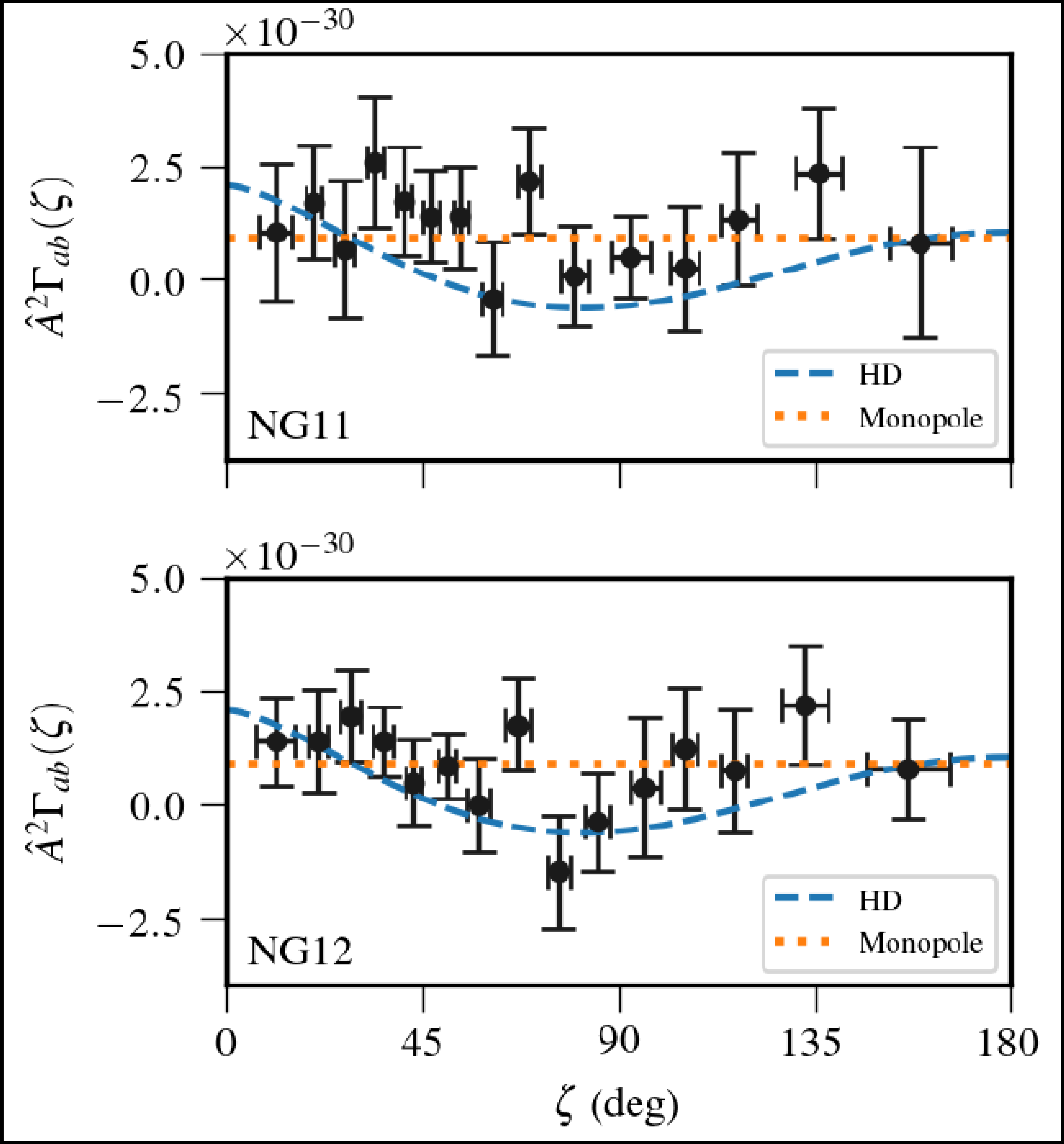


Full Bayesian analysis of 43 pulsars.
Schemes to account for SSE and other noises

Clear detection of a common red process.

If this was a GWB, then *A*~2x10^{-15}

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



Monopolar and Dipolar correlations seem disfavored.

However no evidence of HD correlation.

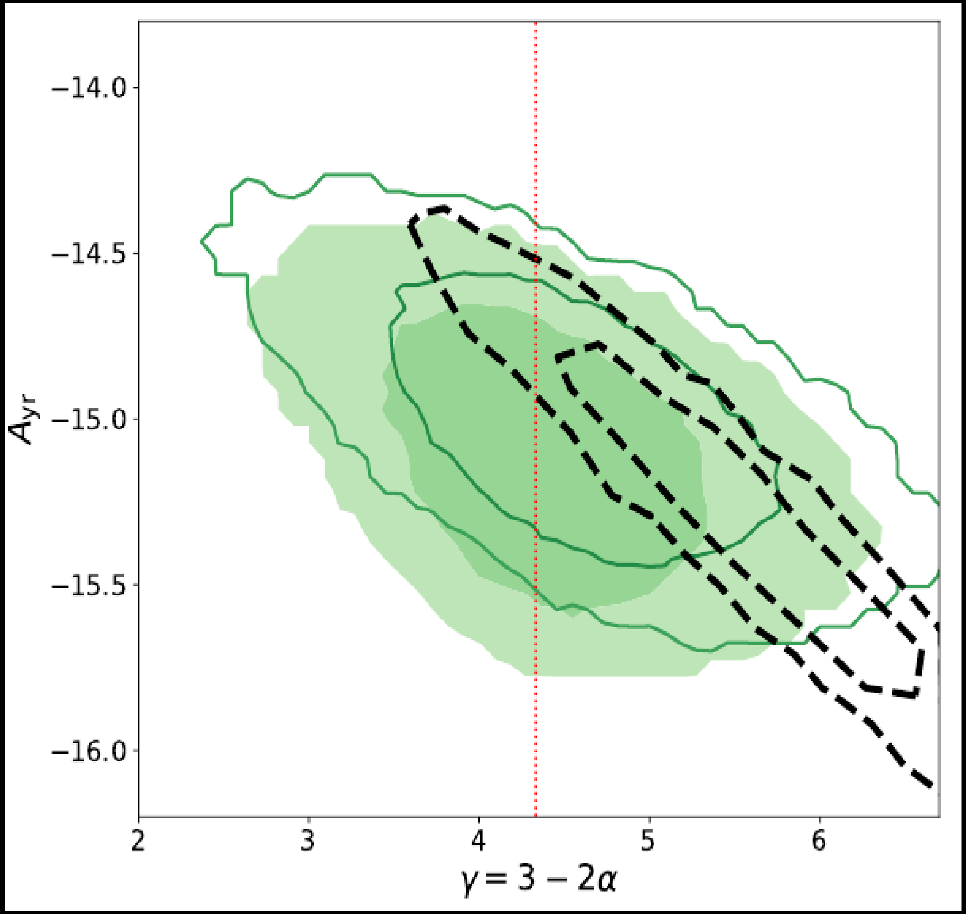
Interesting, seen in several PTA datasets, needs further investigation

MORE TO COME! Stay tuned!!

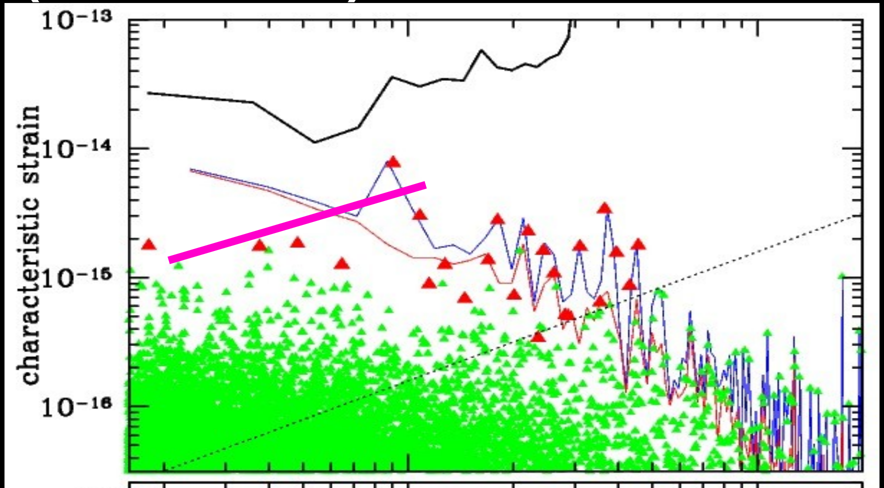
Signal interpretation arXiv:2011.01246

We now suppose for the sake of the argument that the signal is of GW origin.

A number of interpretations have been put forward in the literature including:
- first-order phase transitions
- cosmic strings
- domain walls
- large amplitude curvature perturbations
- primordial black holes
- inflation



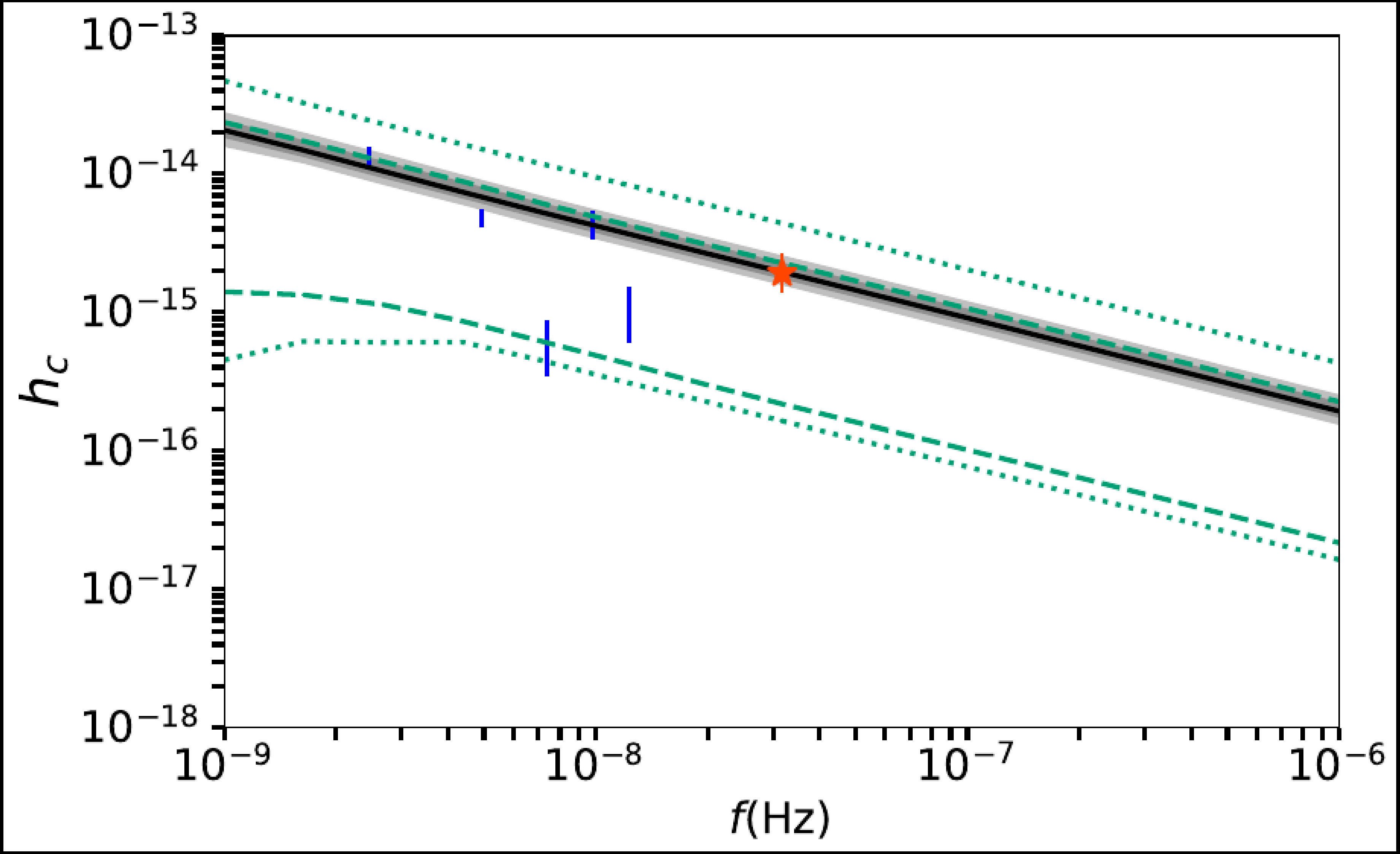
The signal is indeed fully consistent with an astrophysical population of MBHBs. This interpretation must therefore be preferred by virtue of Occam razor (Middleton+20)

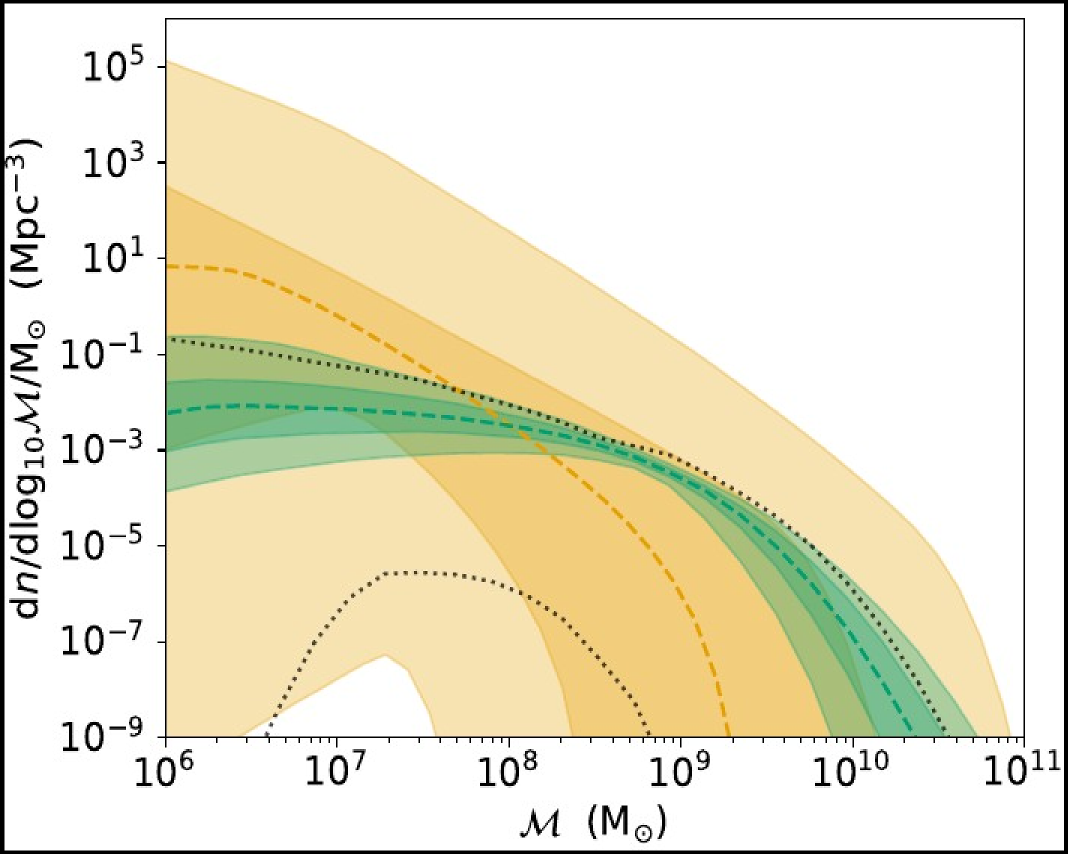


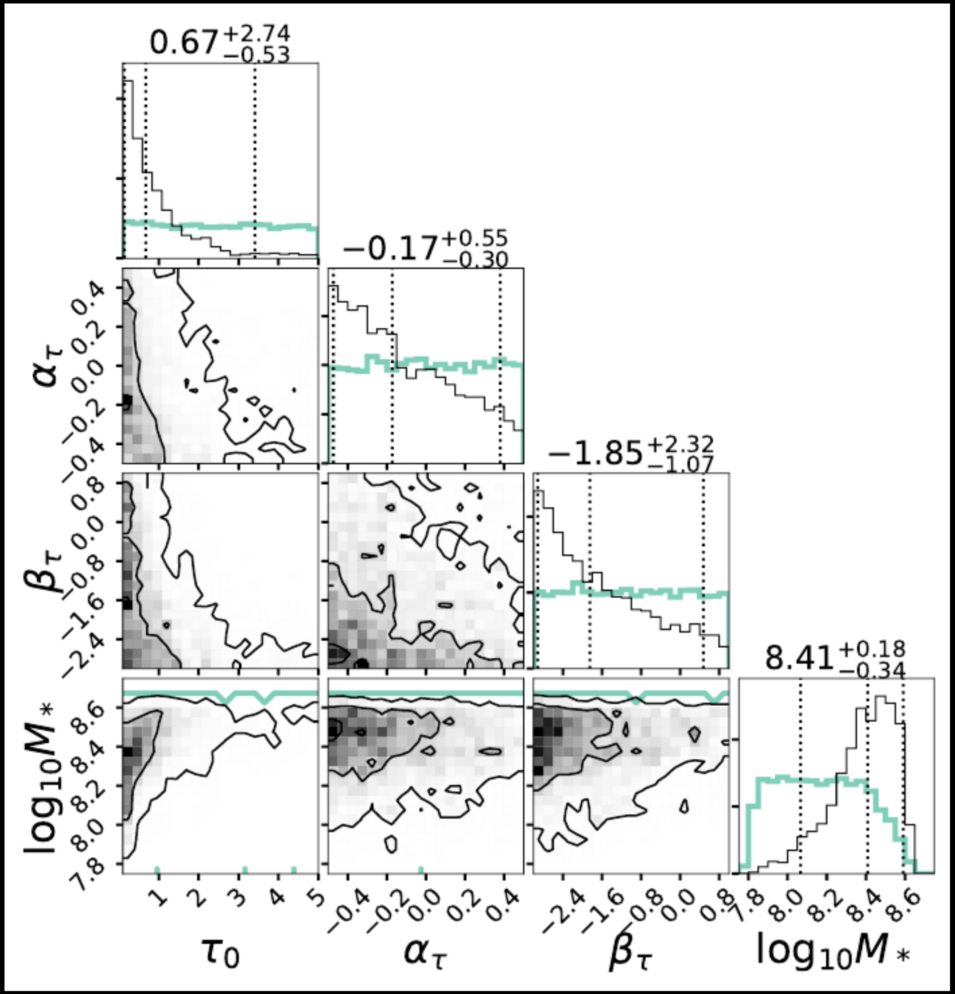
234k GWB realizations from Rosado et al 2020
Frequency binning of NANOGrav
Powerlaw fit to the 5 lowest frequency bins

Use the parametric model of Chen+19 to describe the spectrum as a function of astrophysical observables:

$$h_c^2(f) = \int dz \int d\mathcal{M} \frac{d^2 n}{dz d\mathcal{M}} h^2_{c,\mathrm{fit}}\left(f \frac{f_{p,0}}{f_{p,t}}\right) \times \left(\frac{f_{p,t}}{f_{p,0}}\right)^{-4/3} \left(\frac{\mathcal{M}}{\mathcal{M}_0}\right)^{5/3} \left(\frac{1+z}{1+z_0}\right)^{-1/3}$$







Can place unique astrophysical constraints on the merging MBHB population:

-MBHB do merge in nature!
-typical merger timescale is <3Gyr
-High MBH-bulge mass relations are favoured

The future

MeerKAT, South Africa (2017)

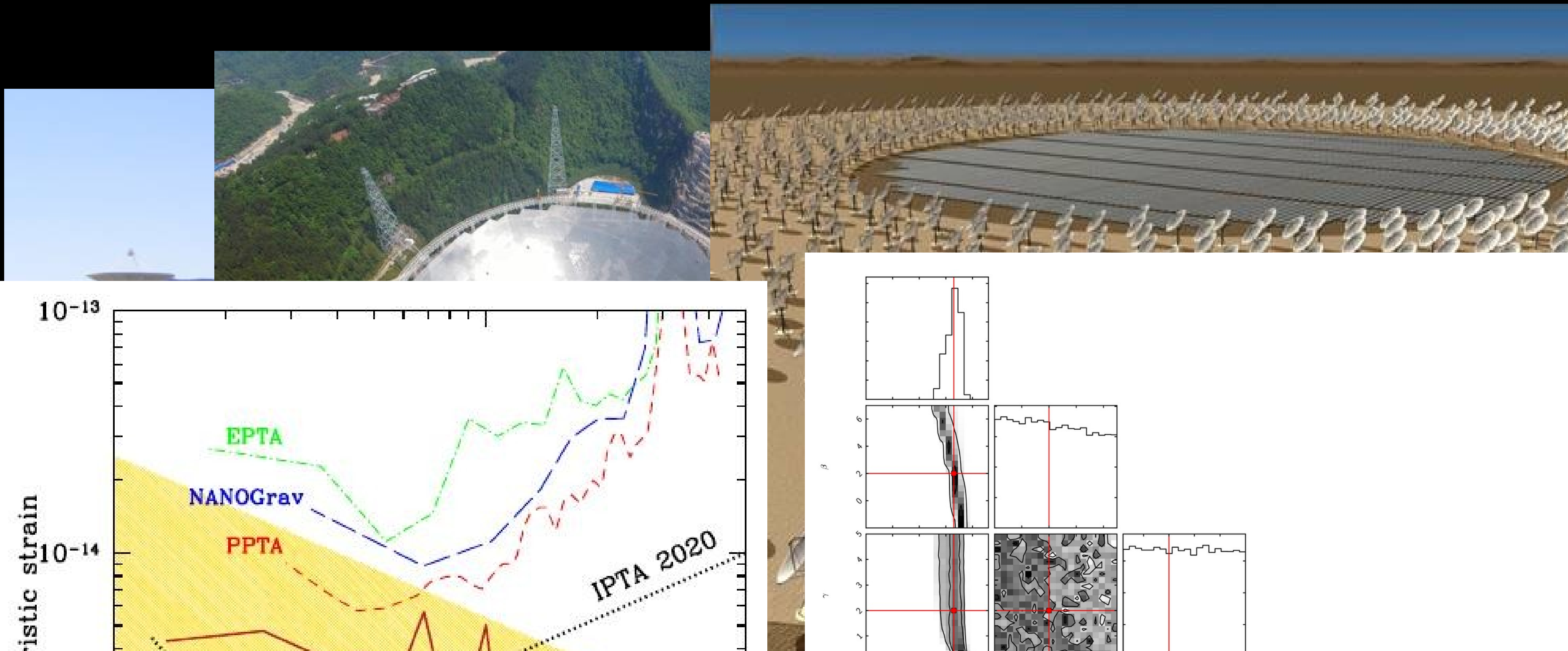
The future

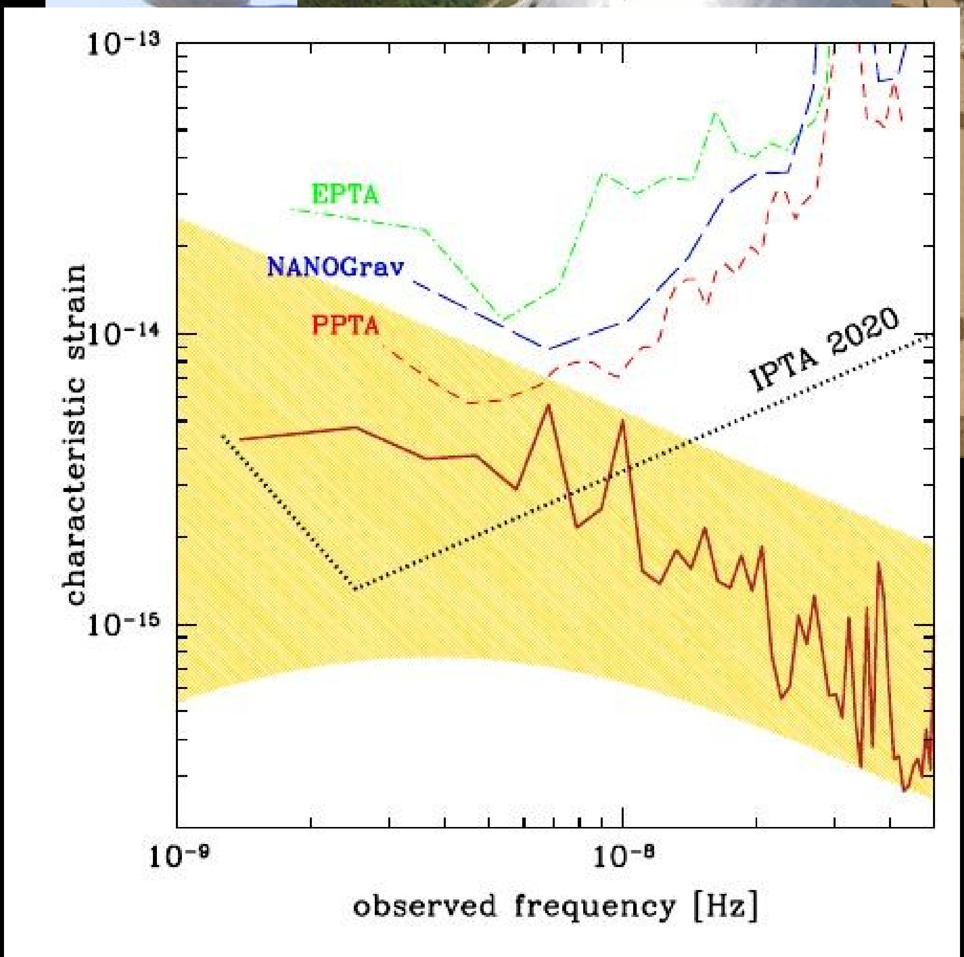
FAST, China (2017)

The future

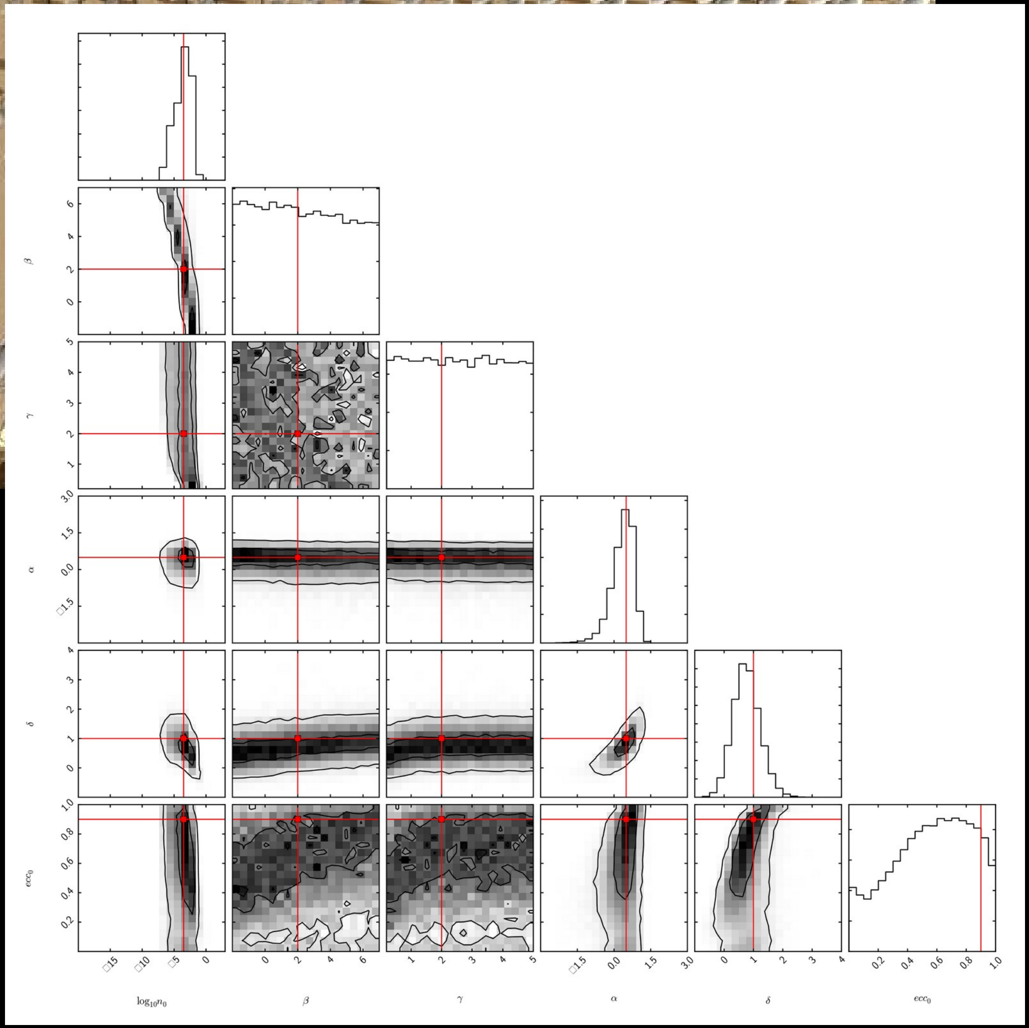
Square Kilometre Array (SKA, 2021+)

The future



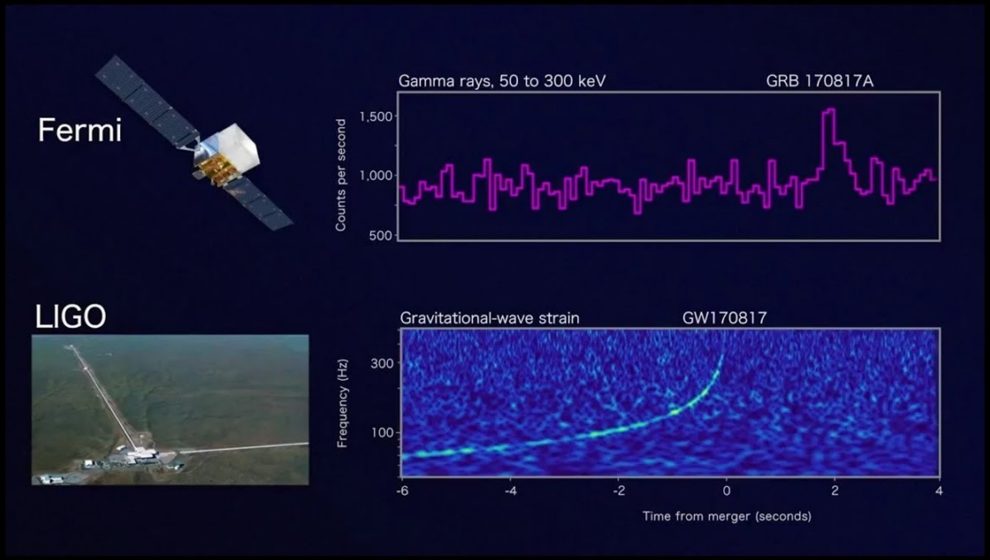


10^{-13}
10^{-14}
10^{-15}
EPTA
NANOGrav
PPTA
IPTA 2020
characteristic strain
10^{-9}
10^{-8}
observed frequency [Hz]

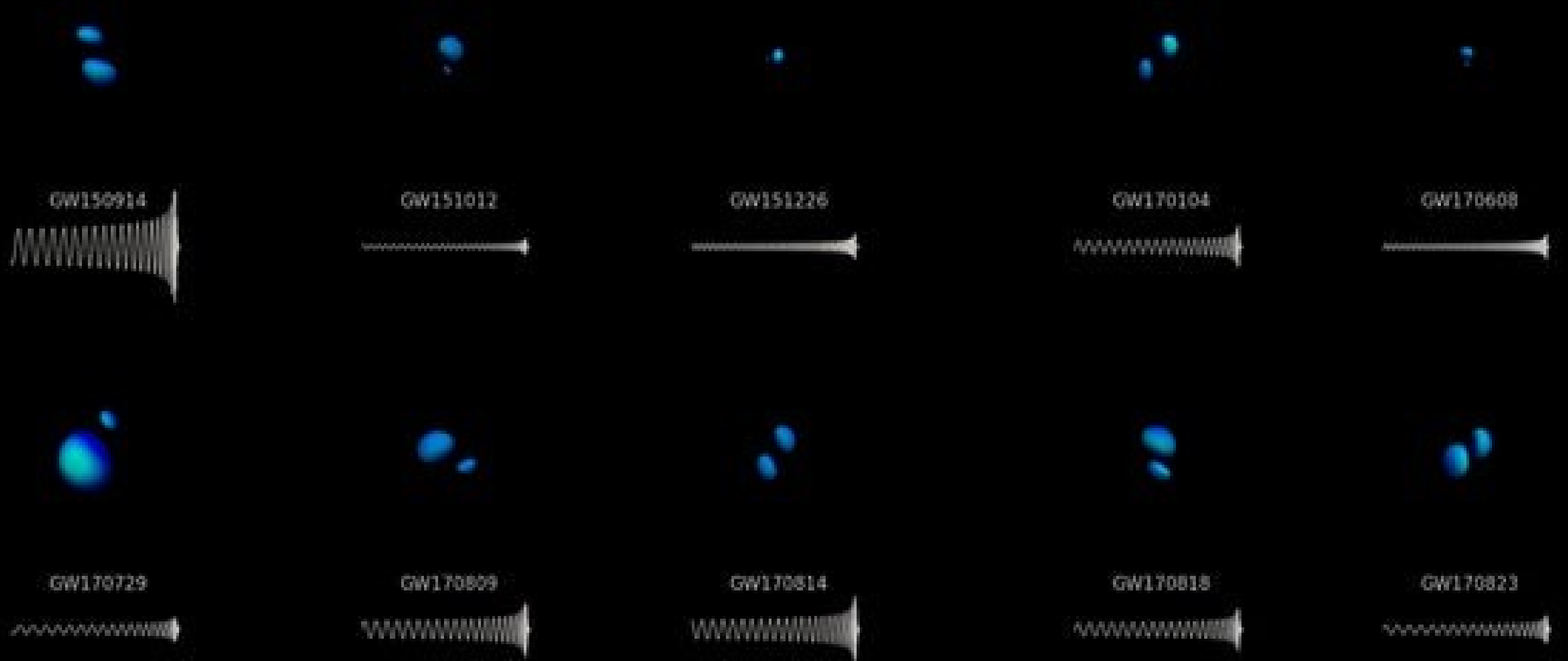


Habemus GWs!

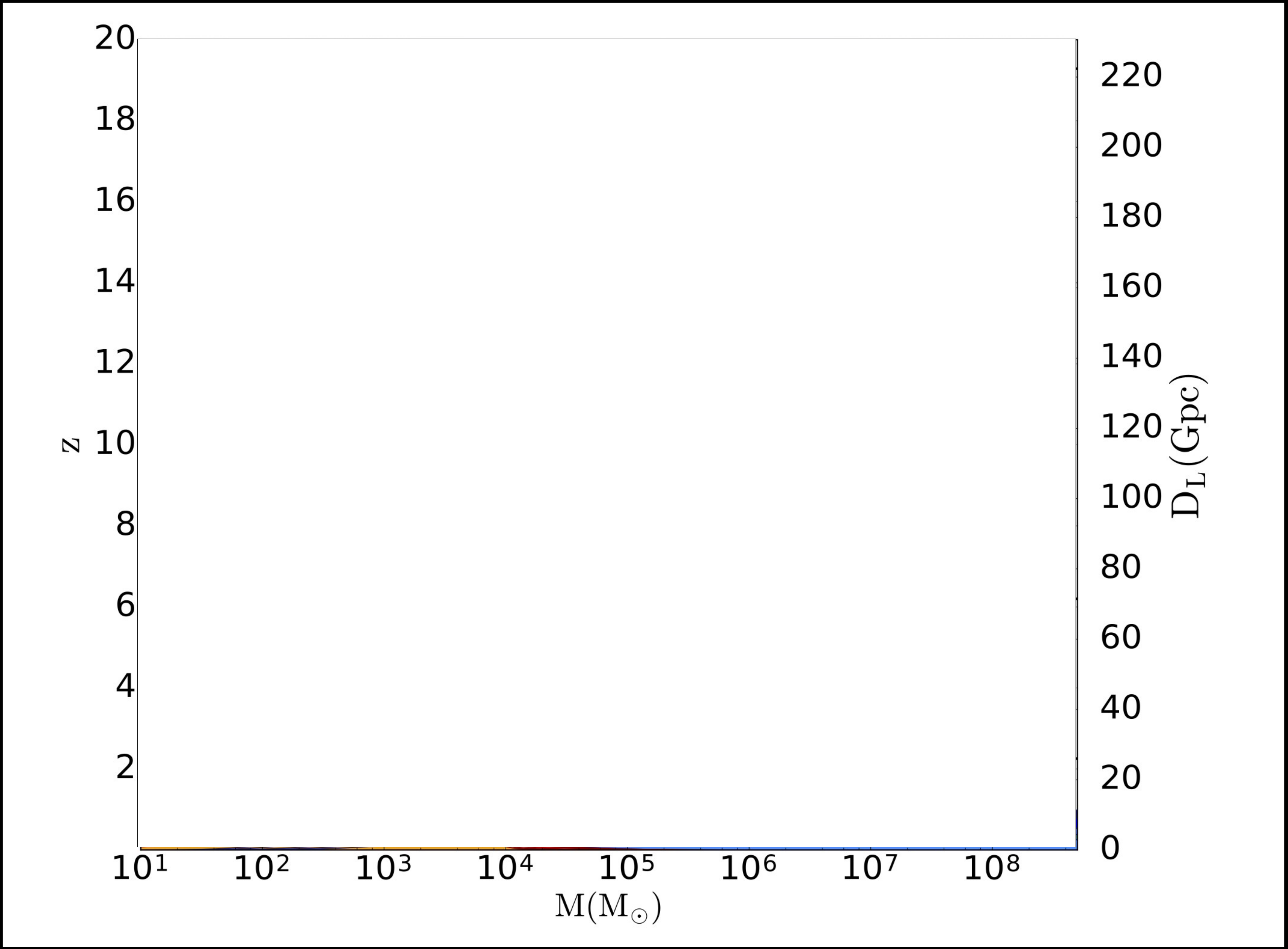
We see black hole binaries (BHB) and neutron star (NS) binaries coalescing for the first time (several Abbott+ 2016 2017)



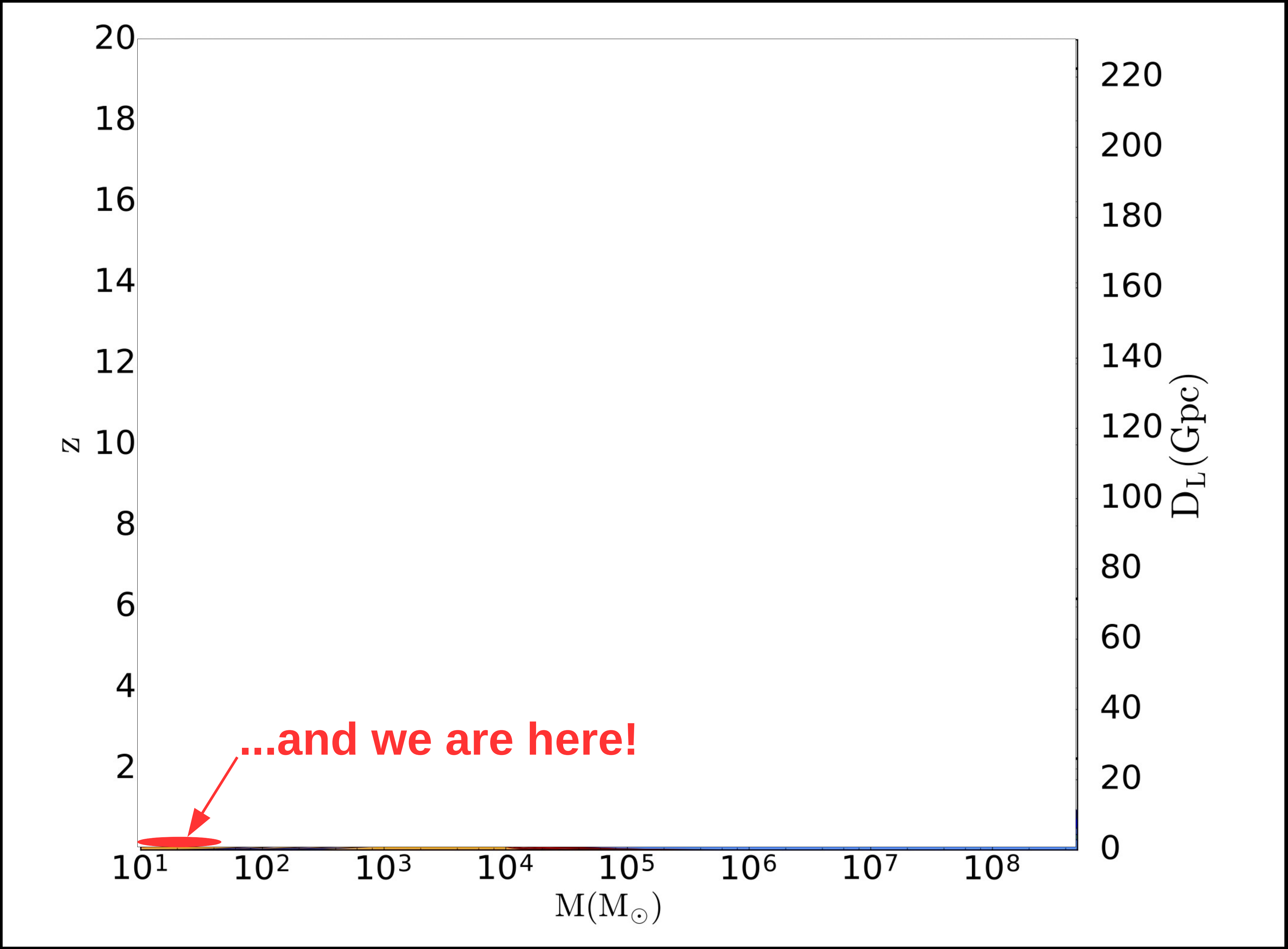
-GRB-NS merger connection
-Heavy element production
-NS EoS
-First tests of GR in the strong field regime
-Interesting astrophysical information (masses, spins)
→ Formation scenario?



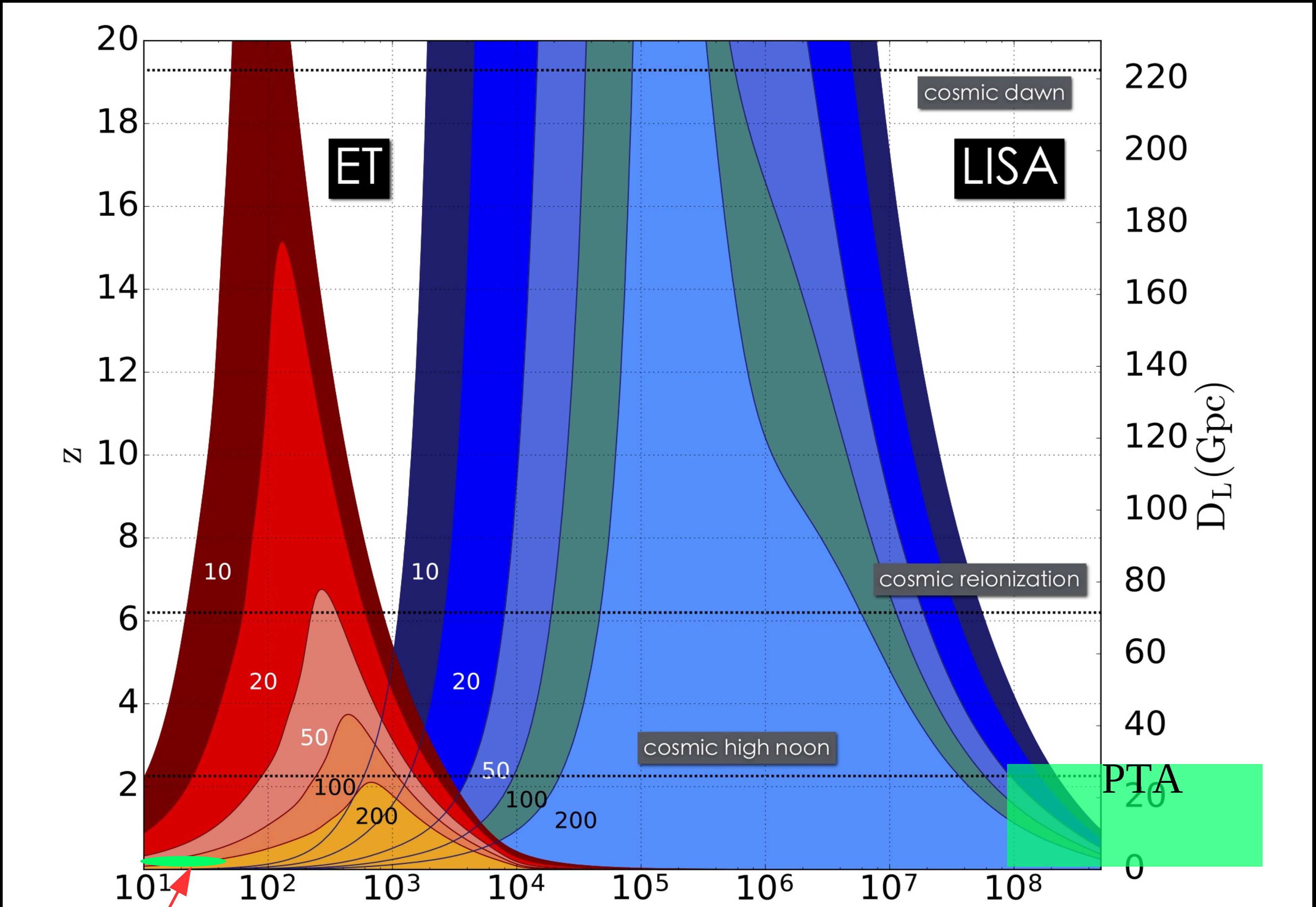
The parameter space of black holes



The parameter space of black holes



The parameter space of black holes



...and we are here!

The parameter space of black holes