Multimessenger opportunities with Massive Black Hole Binaries

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OUTLINE

Dynamics of MBH binary (MBHB) formation and dynamics

emission from MBHBs: gravitational waves (GWs) and electromagnetic (EM) radiation

Multimessenger astronomy with LISA and Athena (and LSST/Rubin)

Multimessenger astronomy with pulsar timing arrays (PTAs)

Observational facts

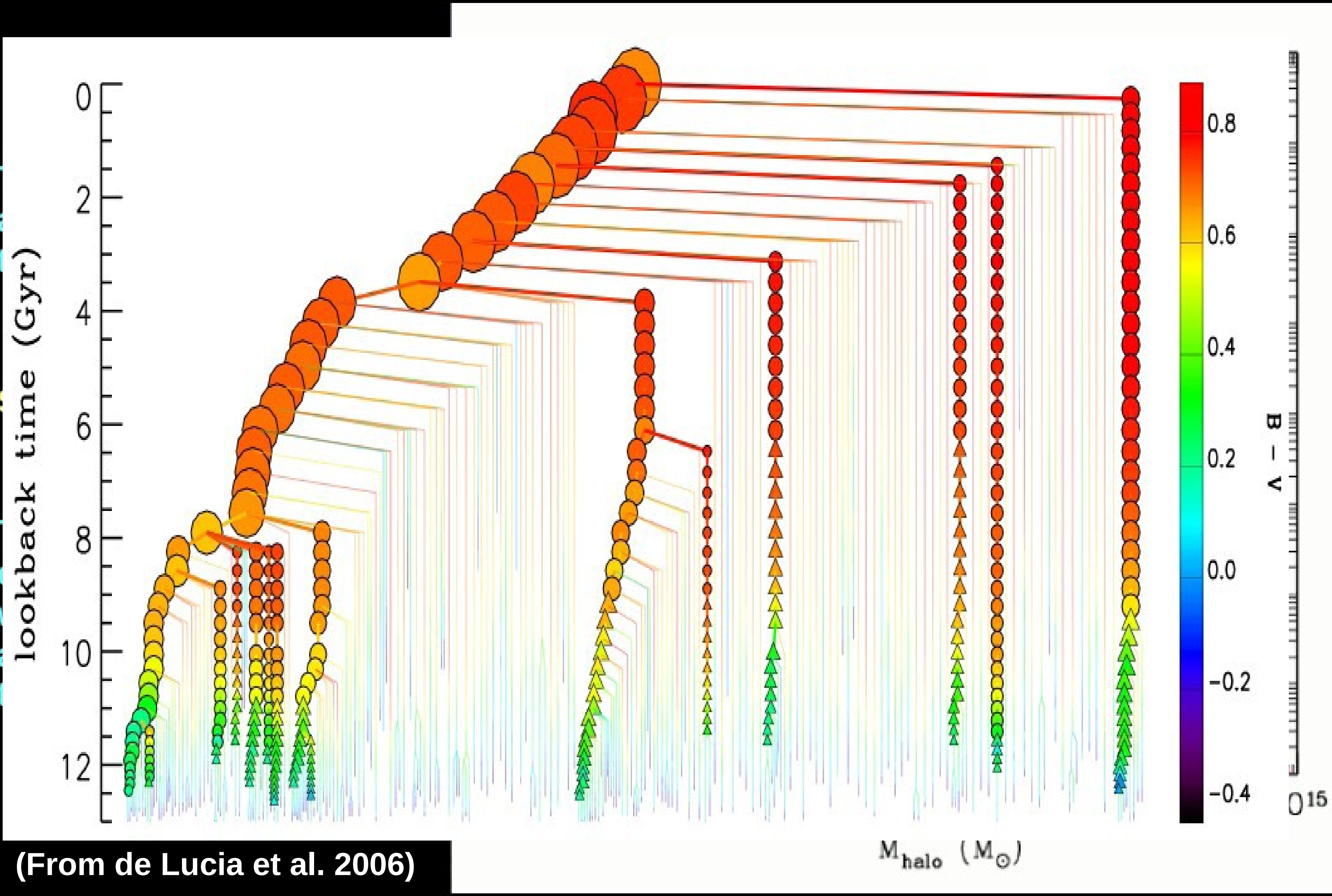
1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

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

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

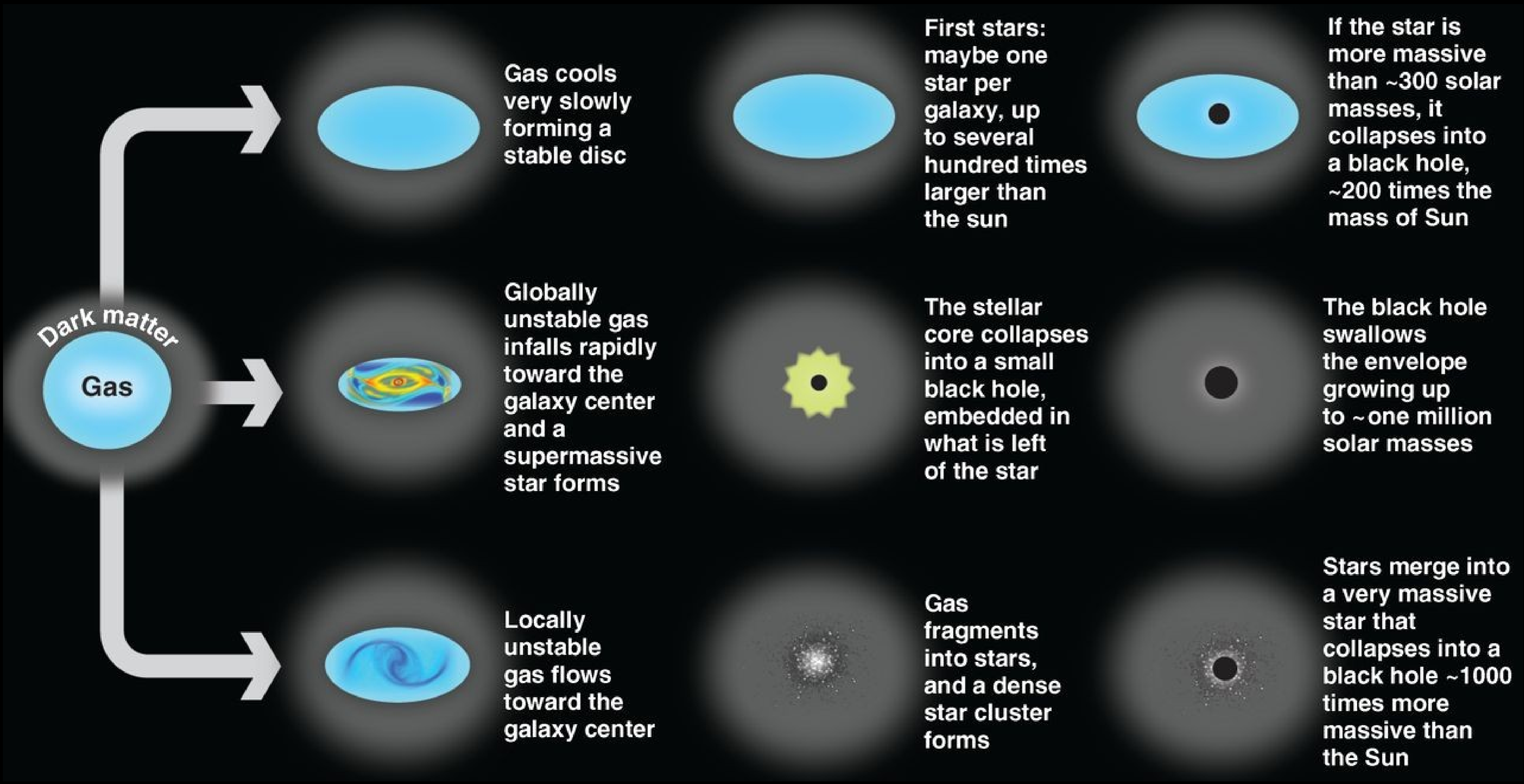
THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy

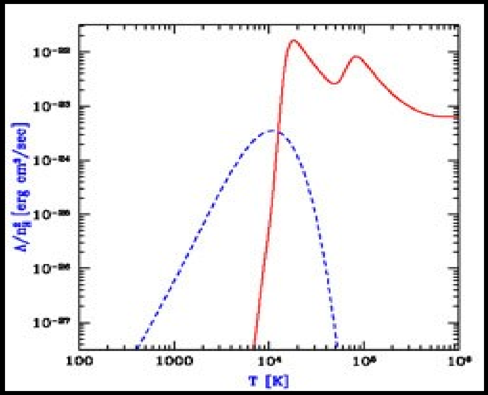


(From de Lucia et al. 2006)

Seed BH formation

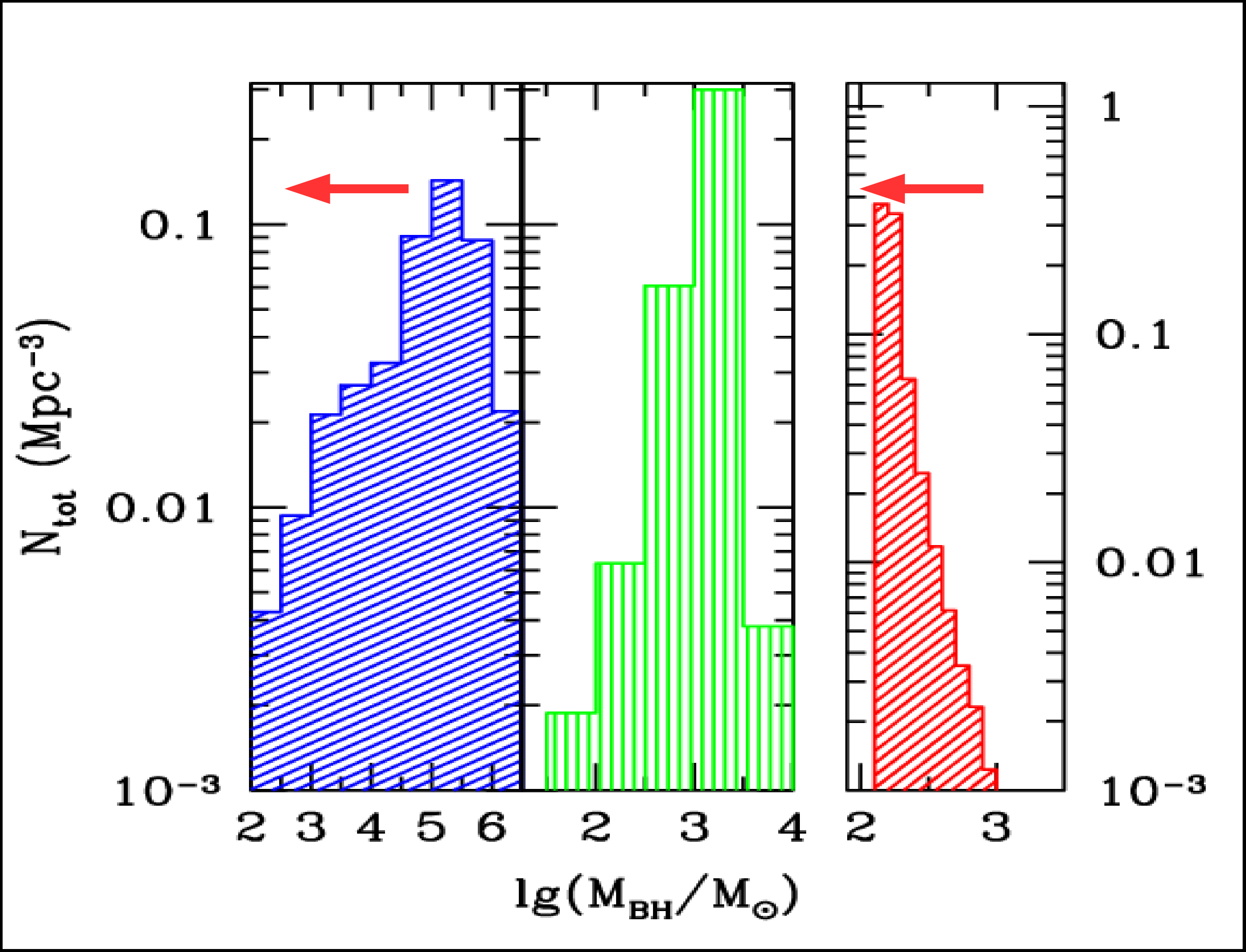


Critically depends on: -content of H2
-vicinity of an ionizing source
-fragmentation
-metallicity



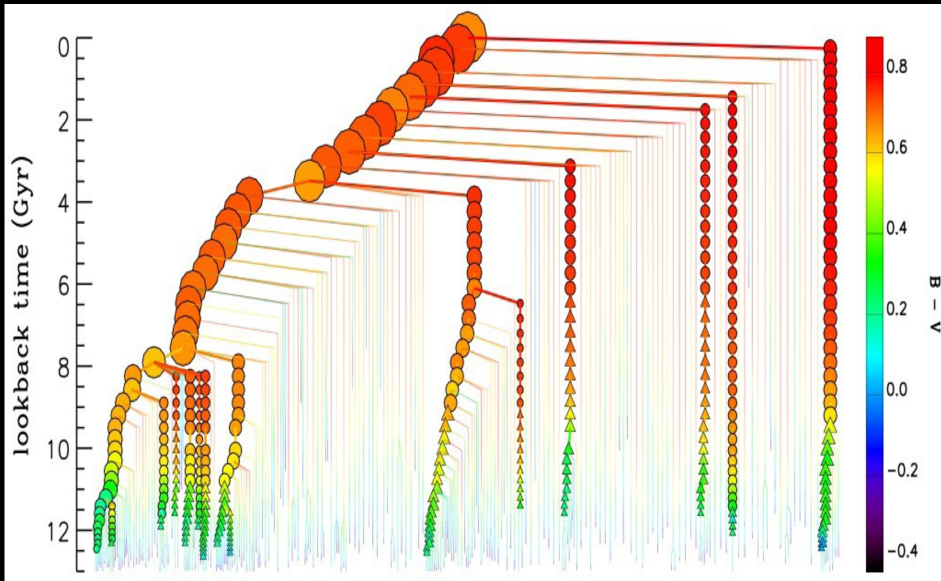
Seed BH mass function

Volonteri 2010



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

In a nutshell



(From de Lucia et al. 2006)

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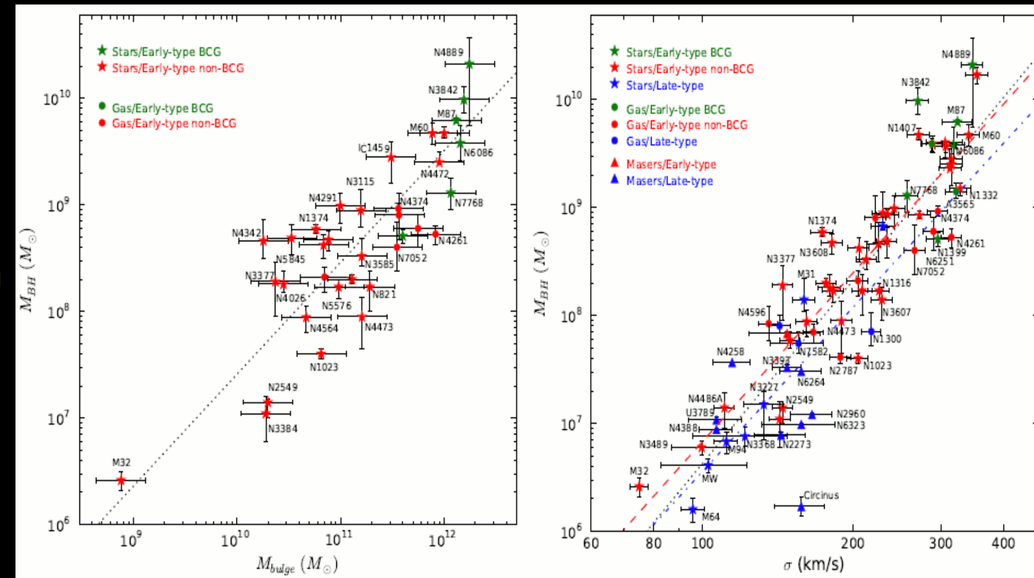

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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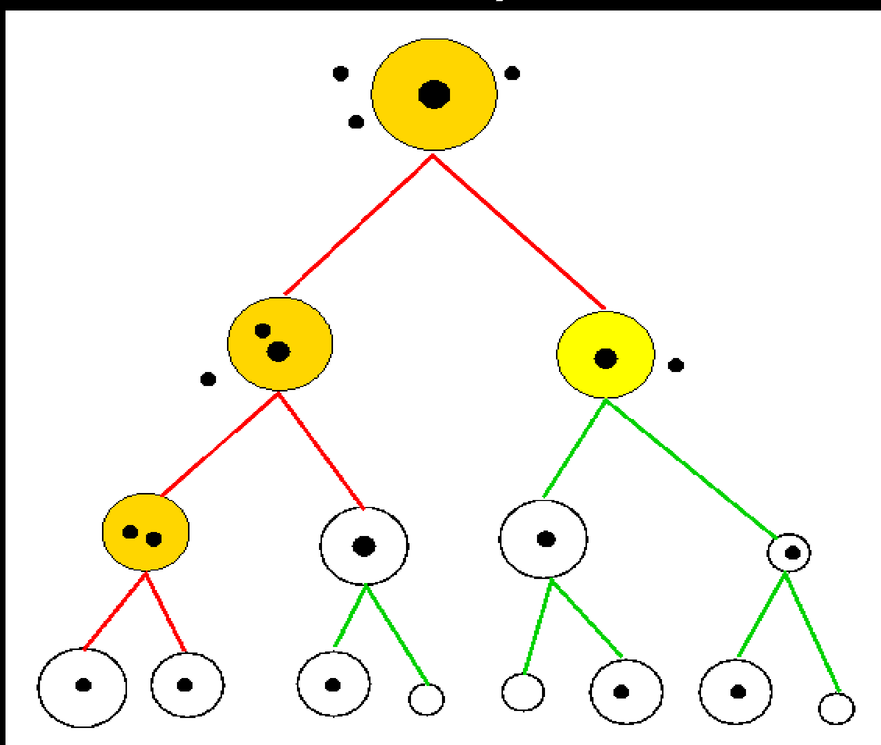
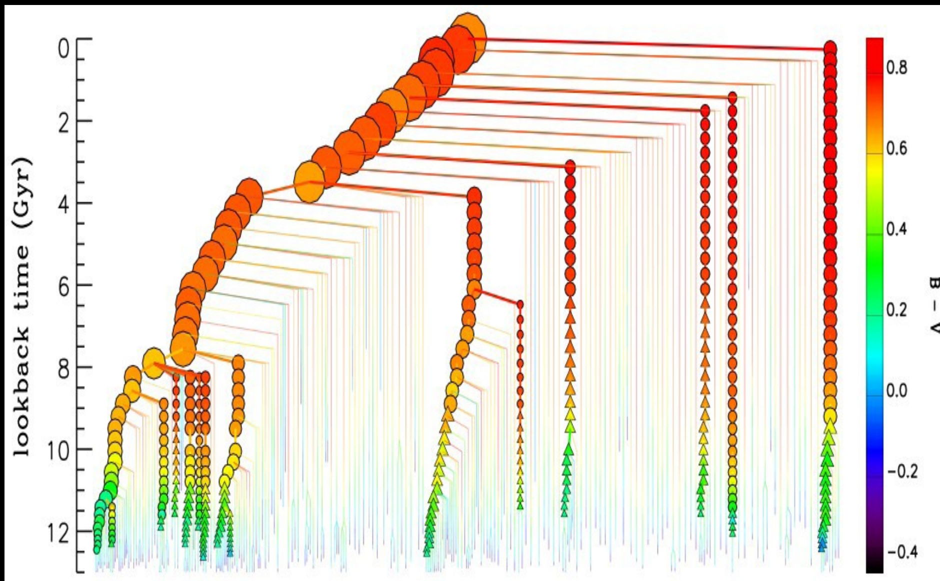


(Menou et al 2001, Volonteri et al. 2003)

In a nutshell



(From de Lucia et al. 2006)

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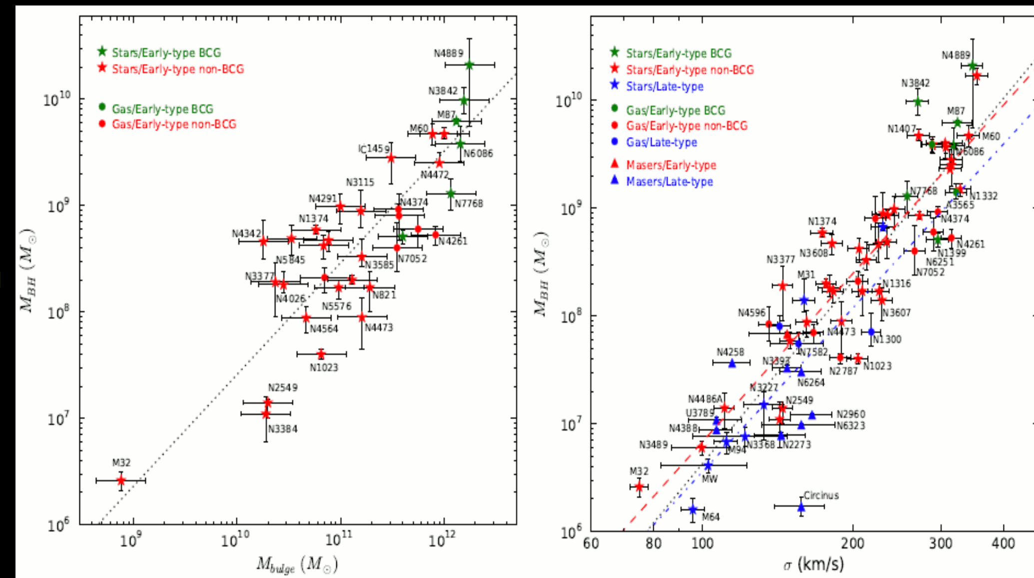

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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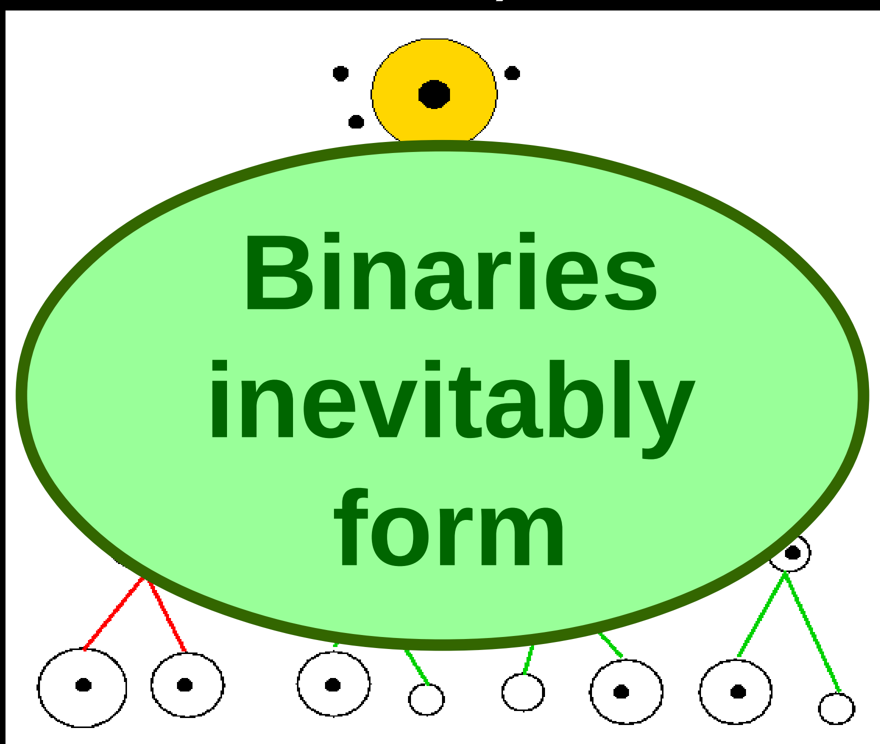
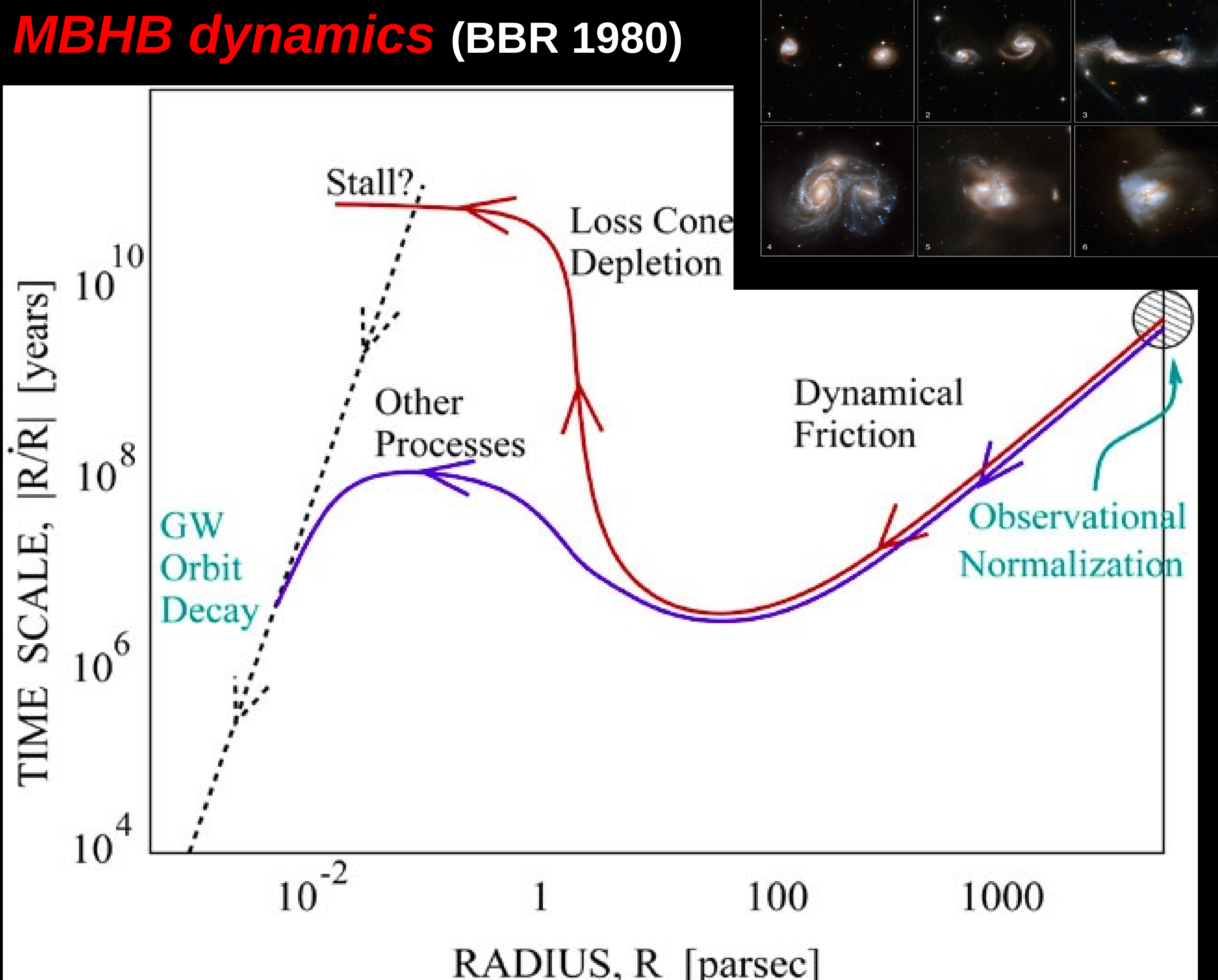


(Menou et al 2001, Volonteri et al. 2003)

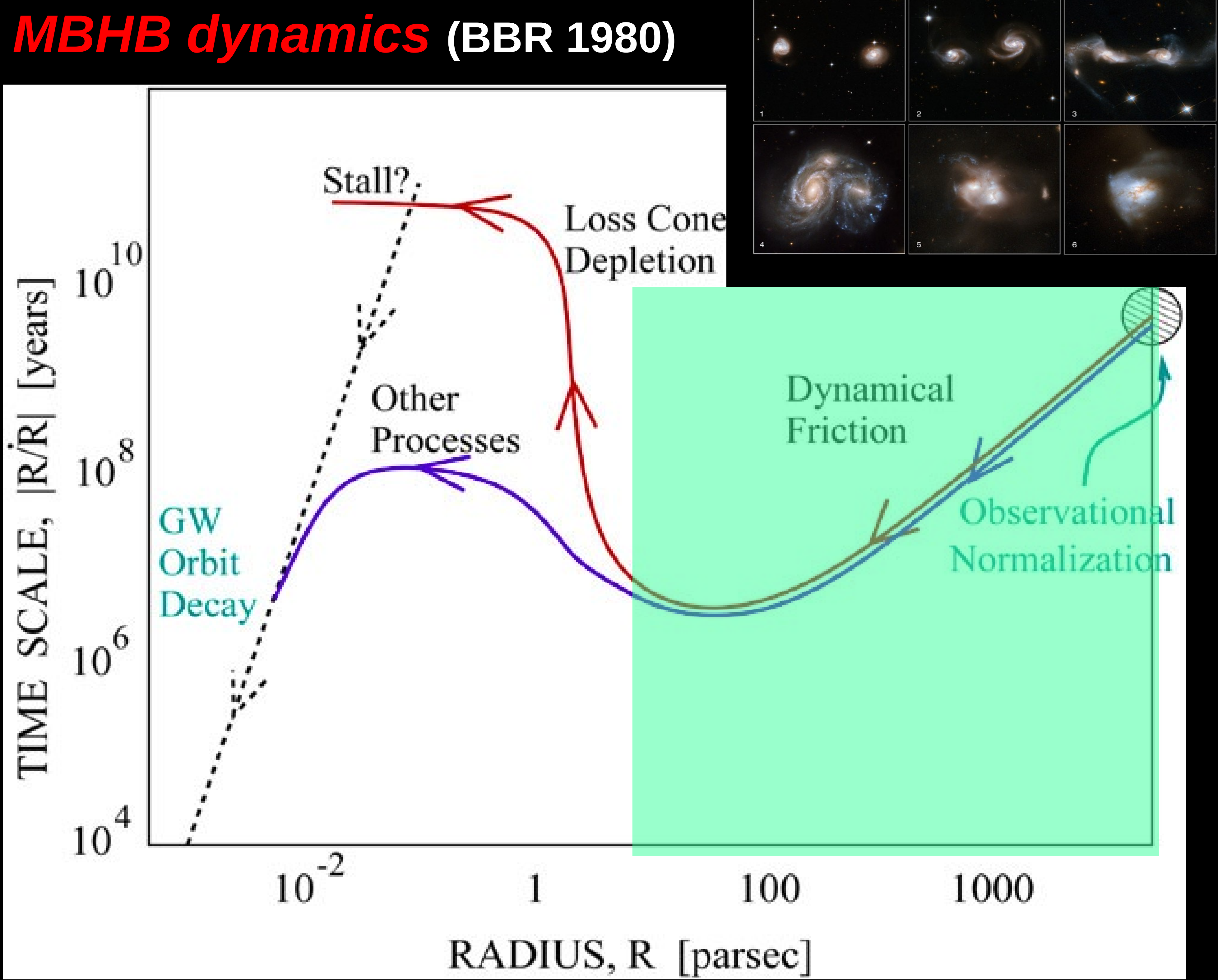
*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?

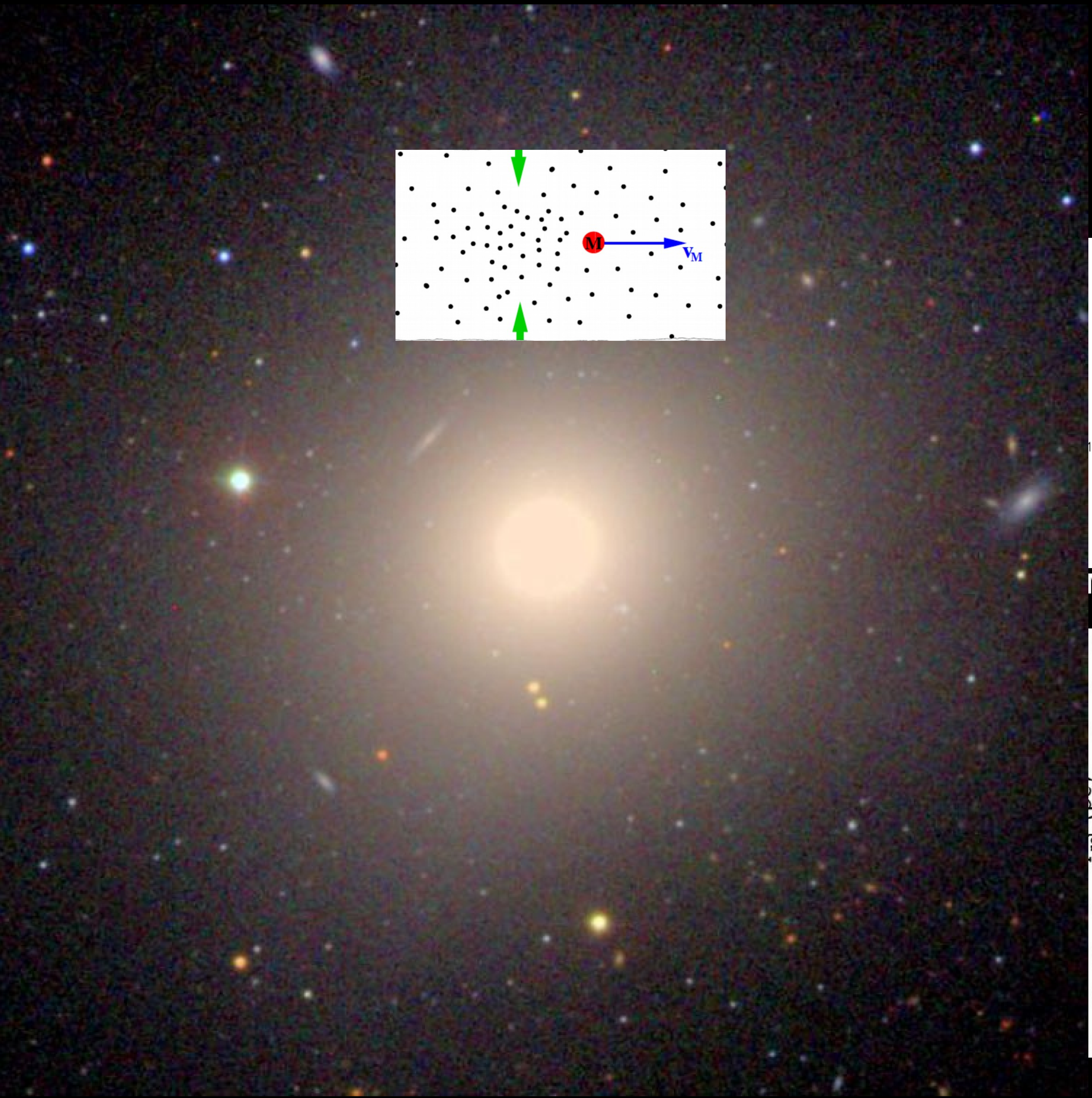
Mergers

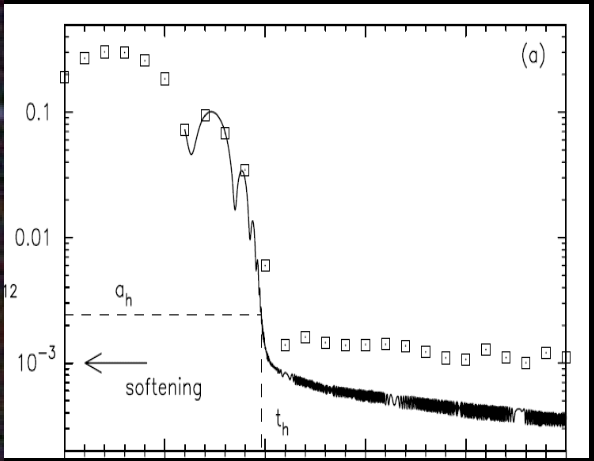
MBHB dynamics (BBR 1980)



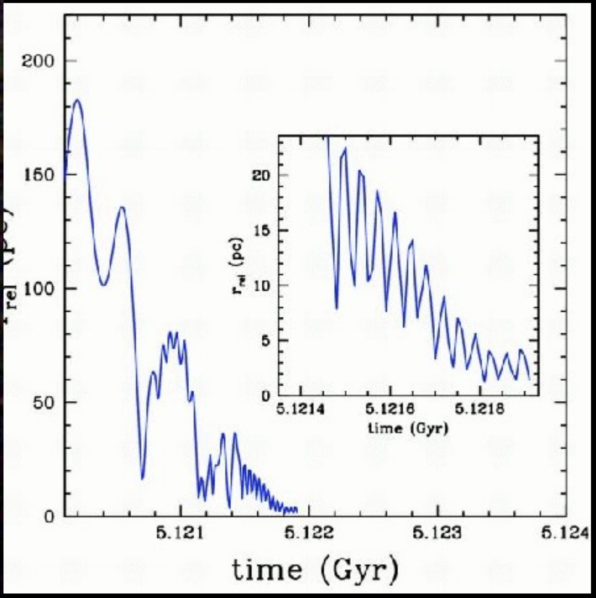
MBHB dynamics (BBR 1980)



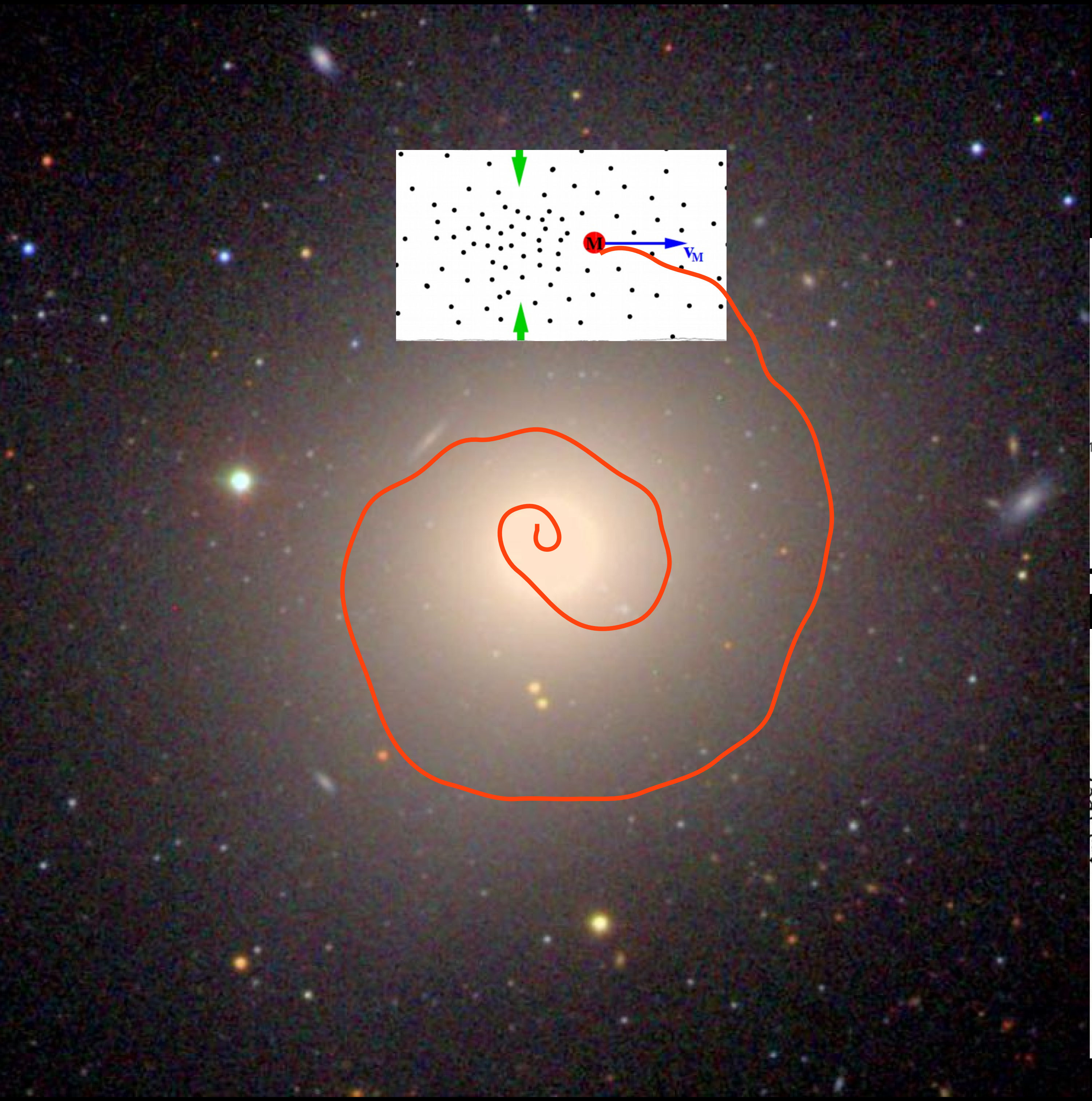


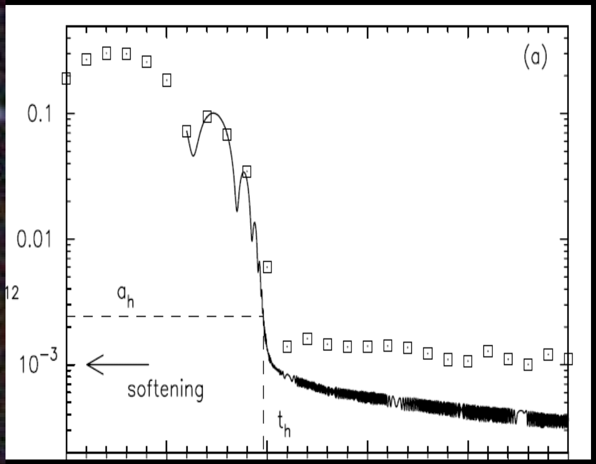


Milosavljevic & Merritt 2001



Colpi & Dotti 2009





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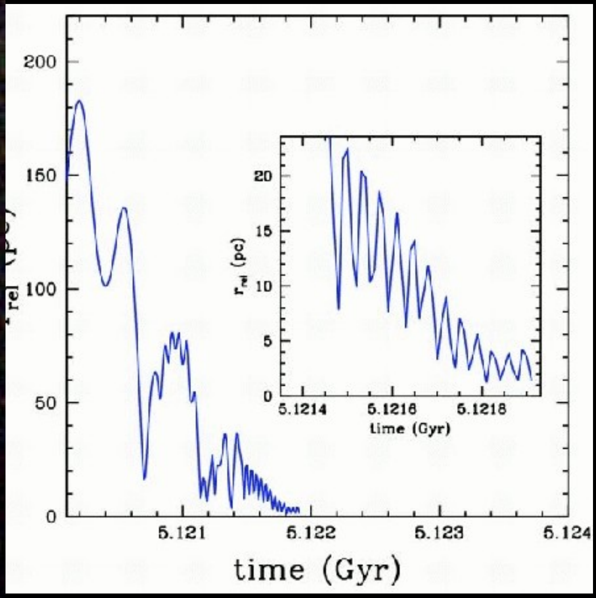

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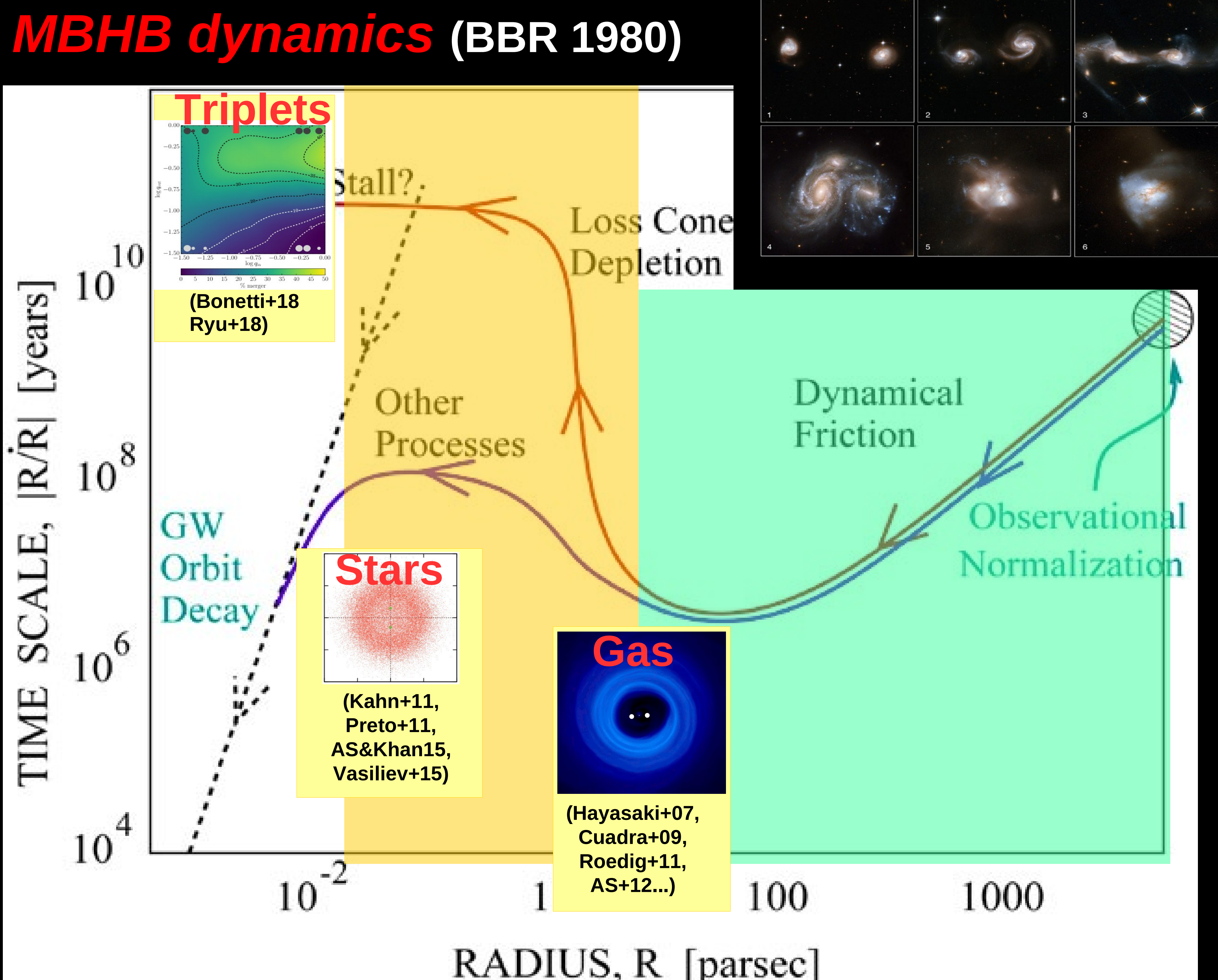
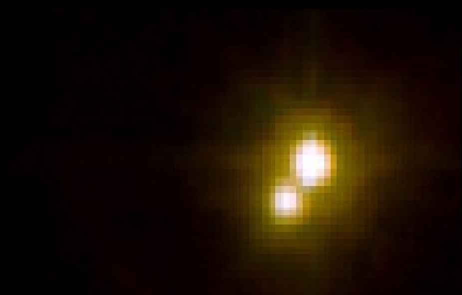
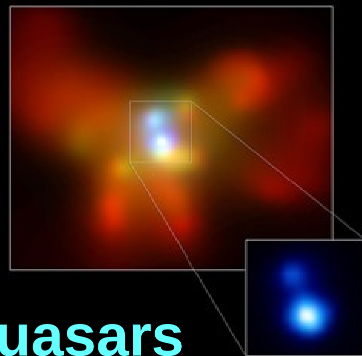
MBHB dynamics (BBR 1980)

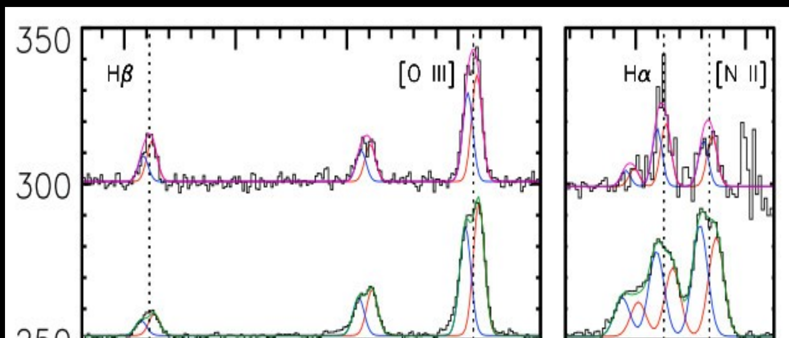


But do we see them?

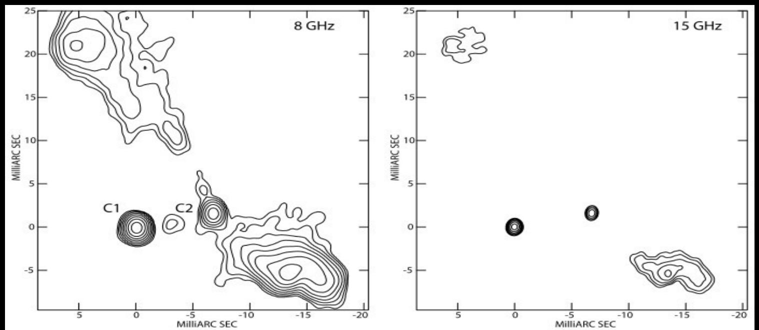




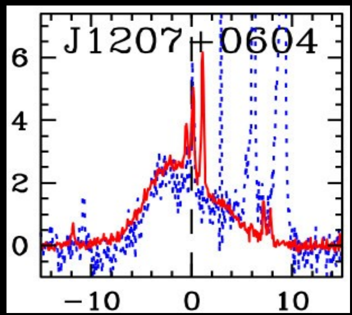
10 kpc: double quasars
(Komossa 2003)

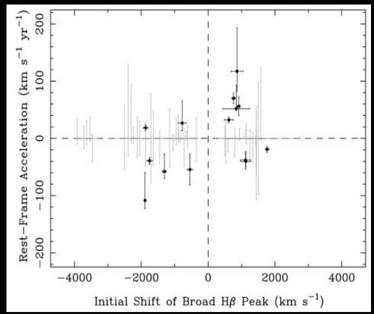


1 kpc: double peaked NL
(Comerford 2013)

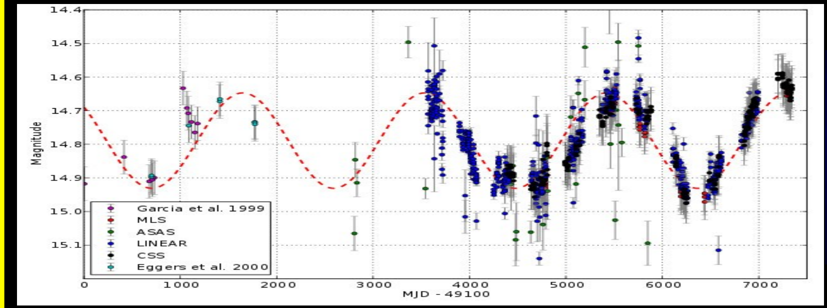


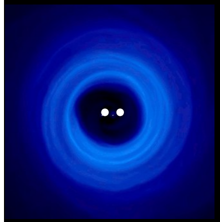
10 pc: double radio cores
(Rodriguez 2006)



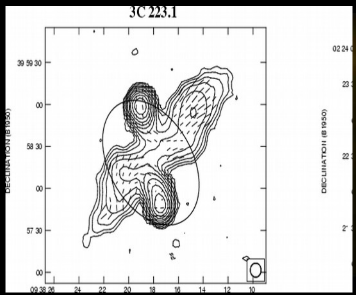


1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



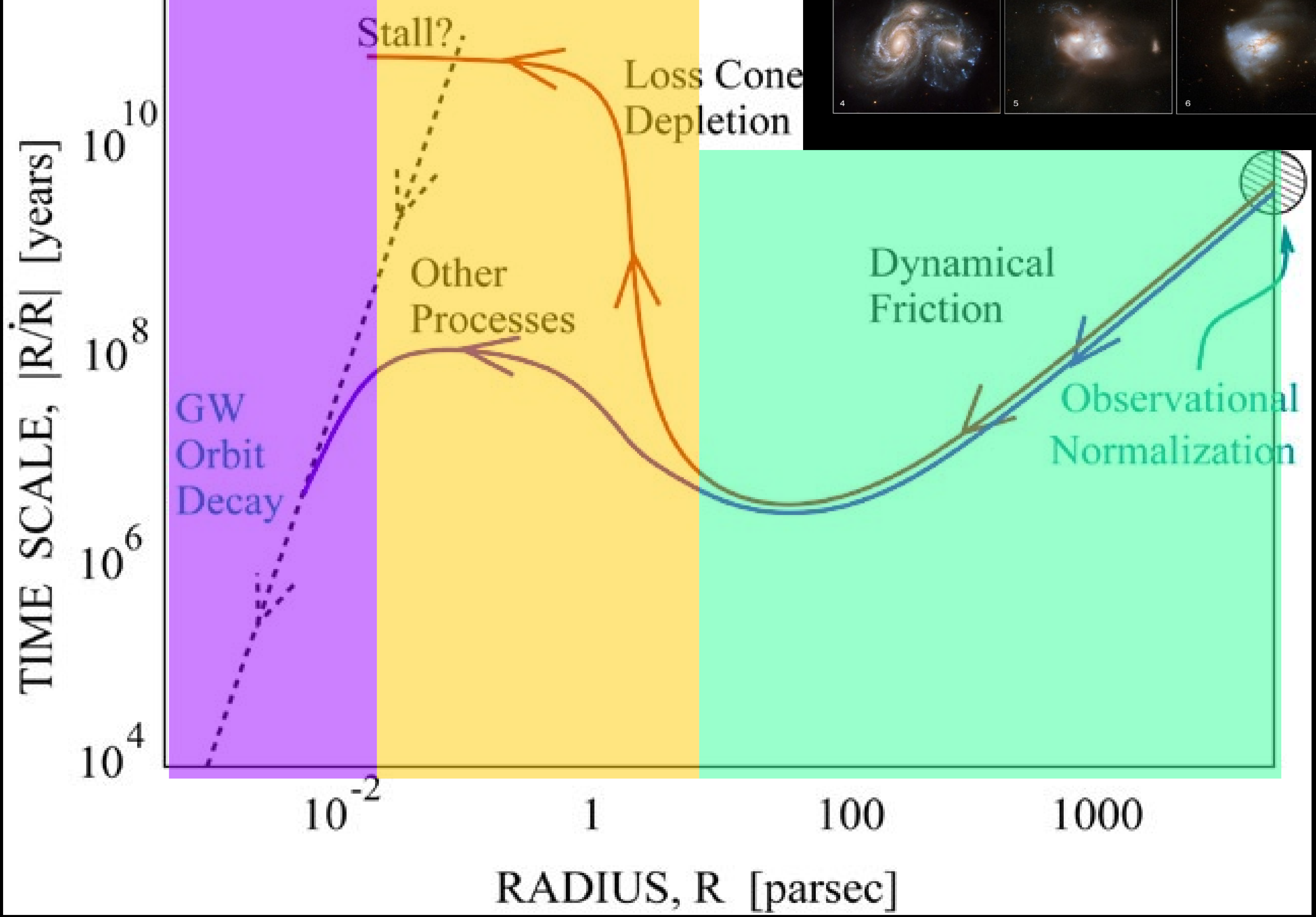


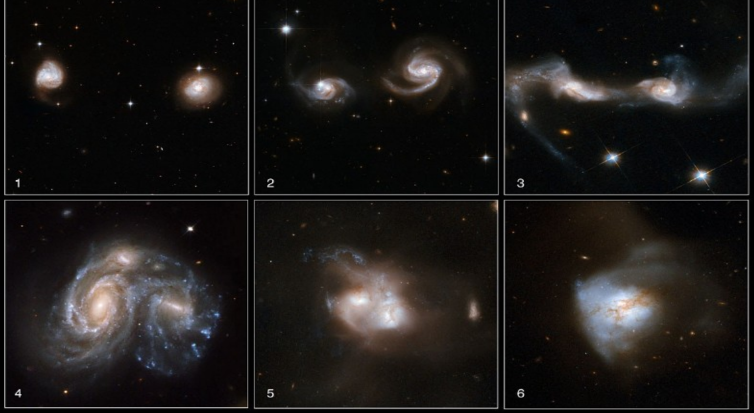
0.01 pc: periodicity (Graham 2015)



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

MBHB dynamics (BBR 1980)



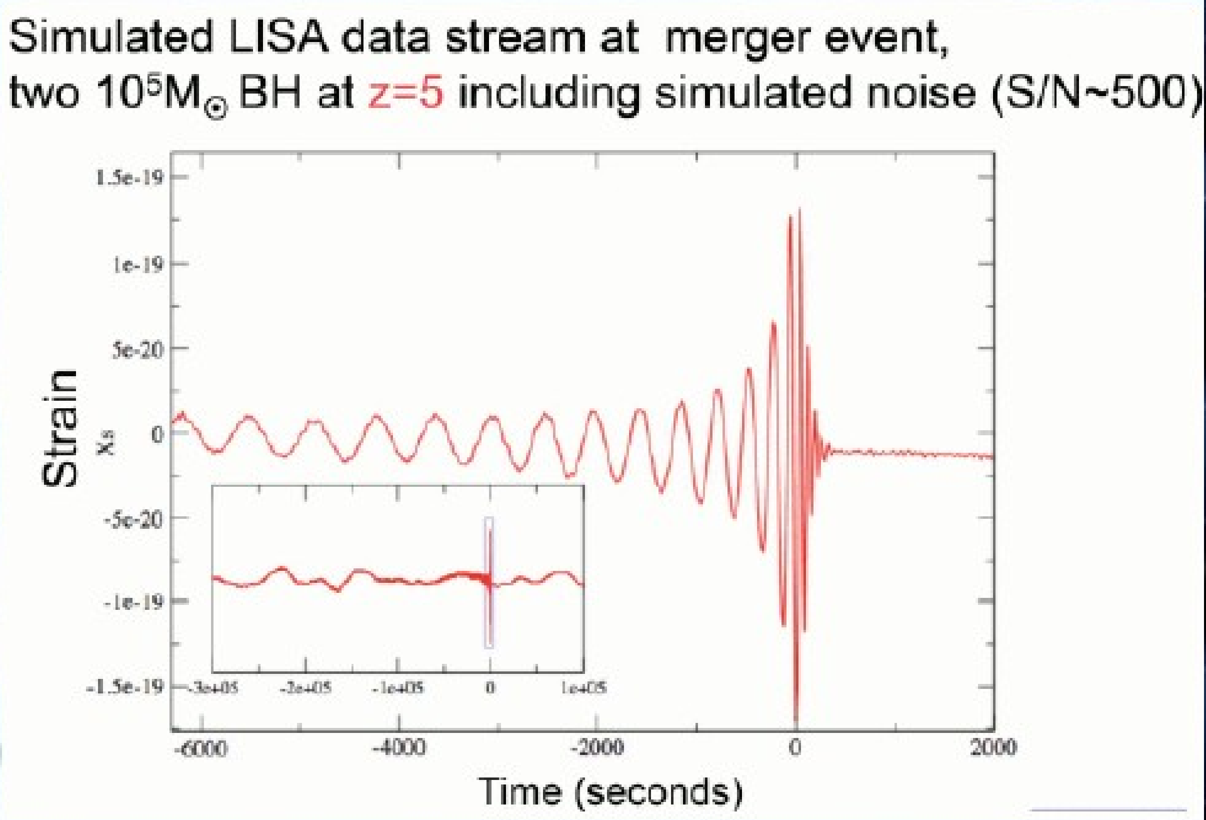


Gravitational waves

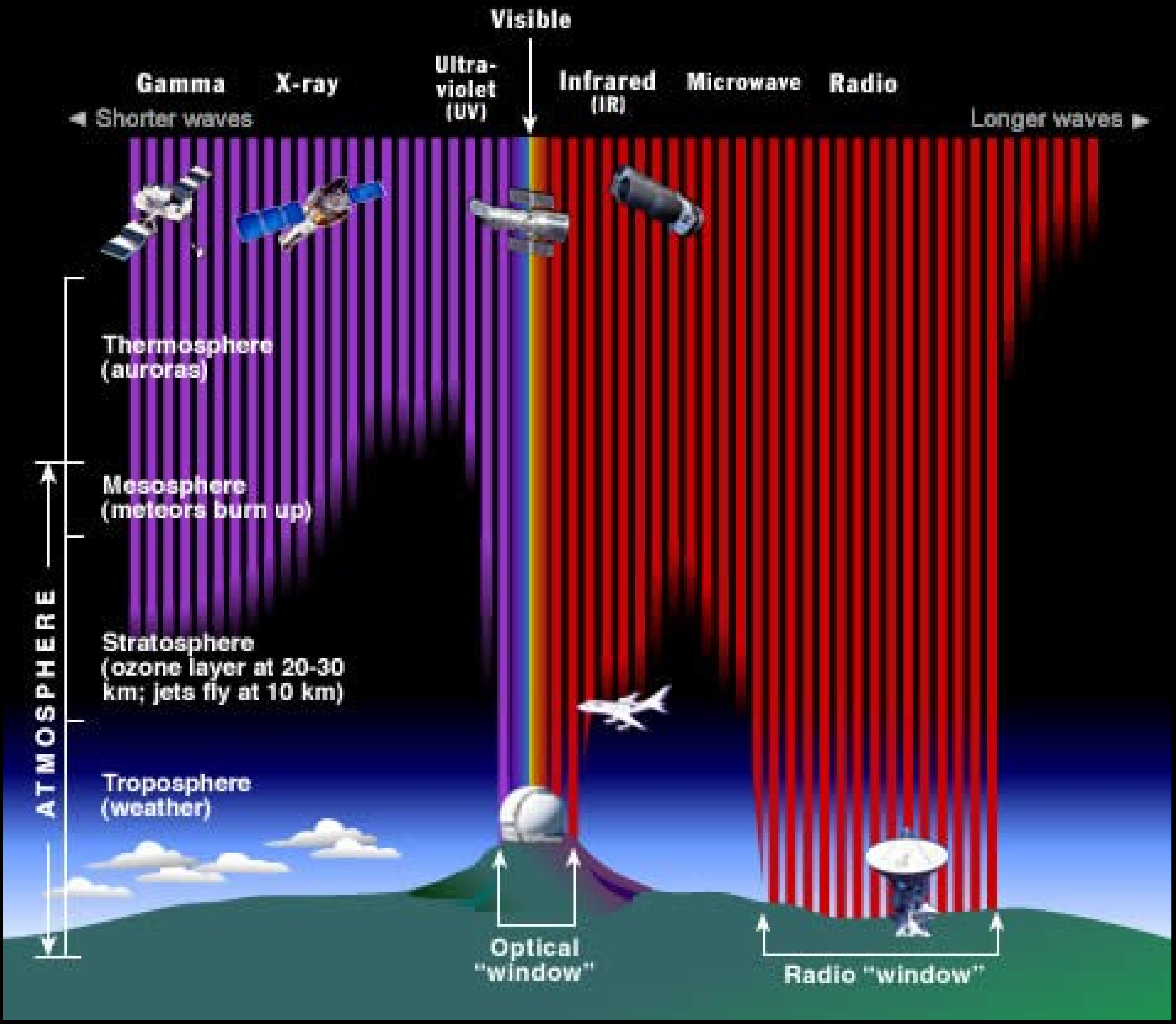
If the binary overcome the final parsec problem then it coalesces on a timescale given by:

$$t_{\rm GW} = \frac{5c^5}{256G^3}\frac{a^4}{M_1 M_2 M F(e)} \approx 0.25{\rm Gyr}\left(\frac{M M_1 M_2}{10^{18.3}\ {\rm M_\odot}^3}\right)^{-1} F(e)^{-1}\left(\frac{a}{0.001{\rm pc}}\right)^4$$

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



Electromagnetic radiation spectrum



Pan-cromatica vision of the Universe

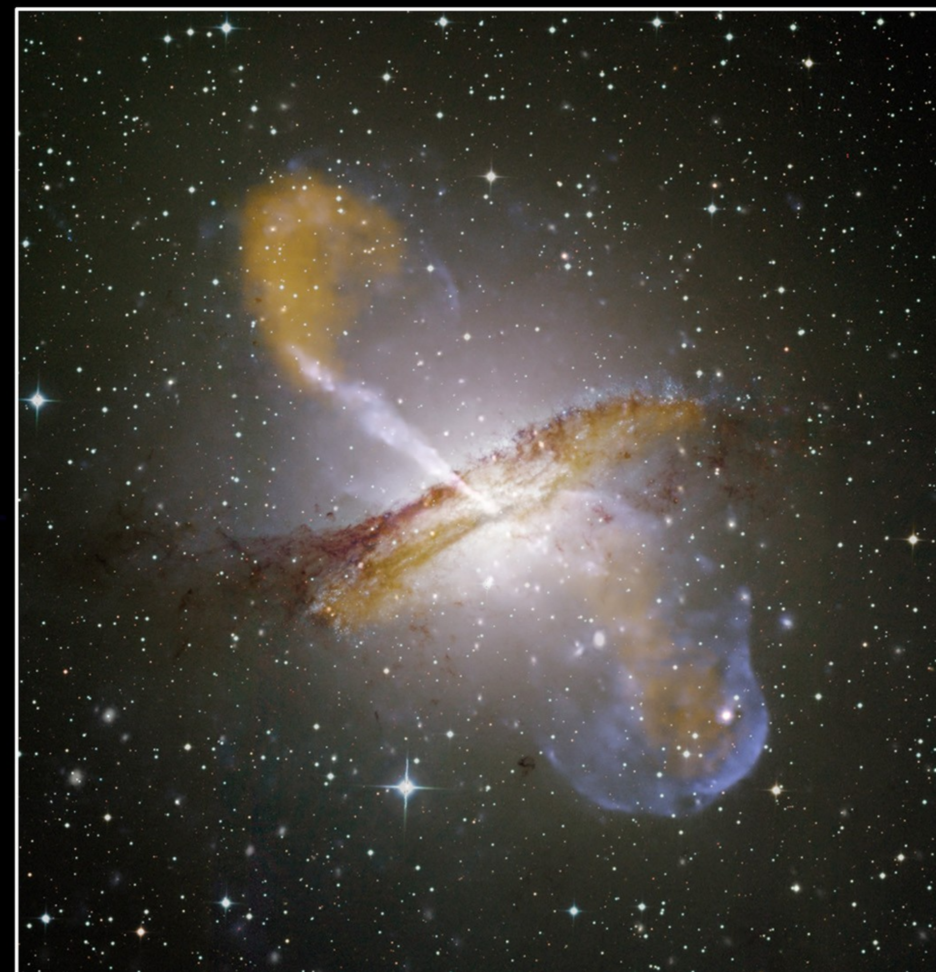
Different wavelengths are key to access different information

- **-Optical:** thermal phenomena, dust absorption, stars
- **-infrared:** reprocessing from dust, cold gas
- **-X ray:** violent phenomena, shocks, hot gas, accretion

X ray

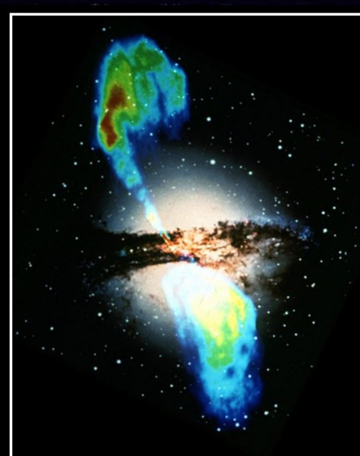
UV

Optical

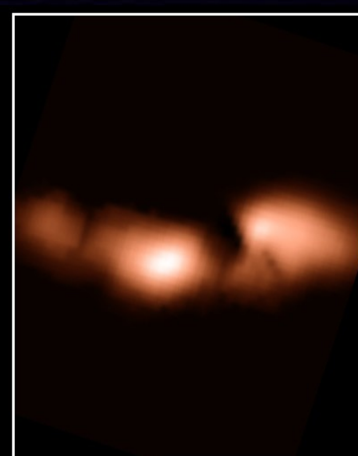


MIR

Radiocontinuum

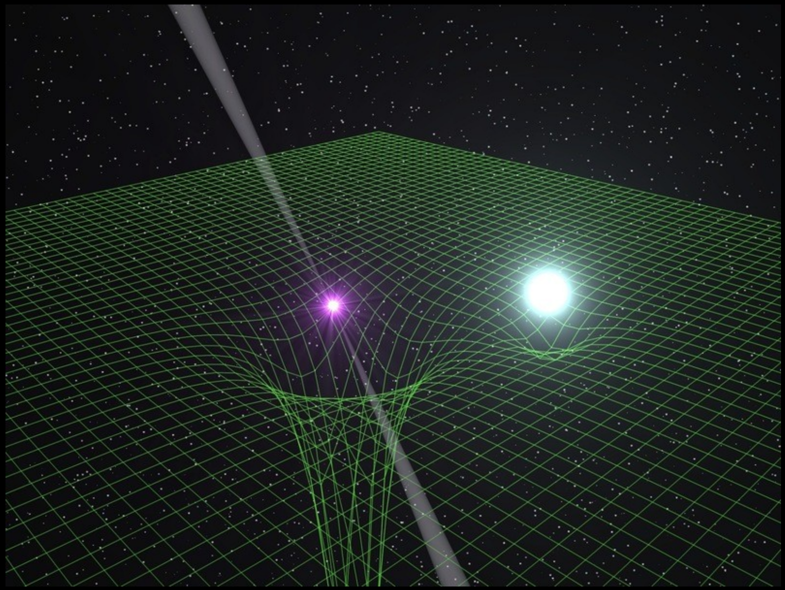


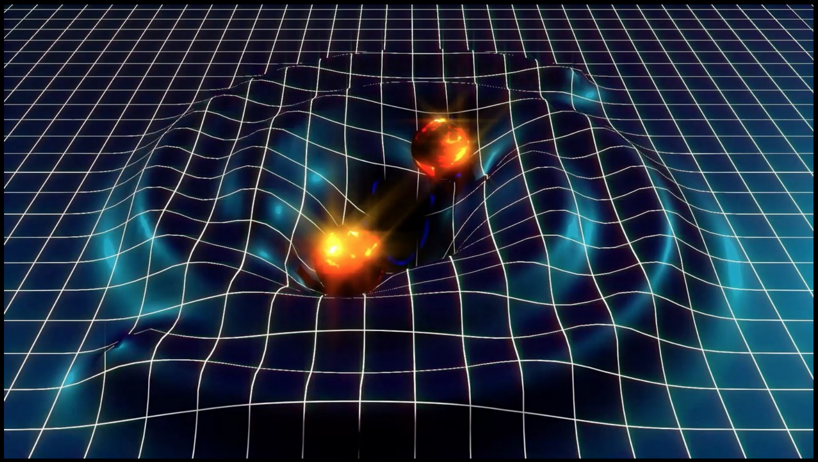
H I



X ray + Optical + Submillimetre + Radio Composition

What happens if two compact objects (e.g. black holes) orbit each other?





The space distortion changes in time, following the motion of the two objects

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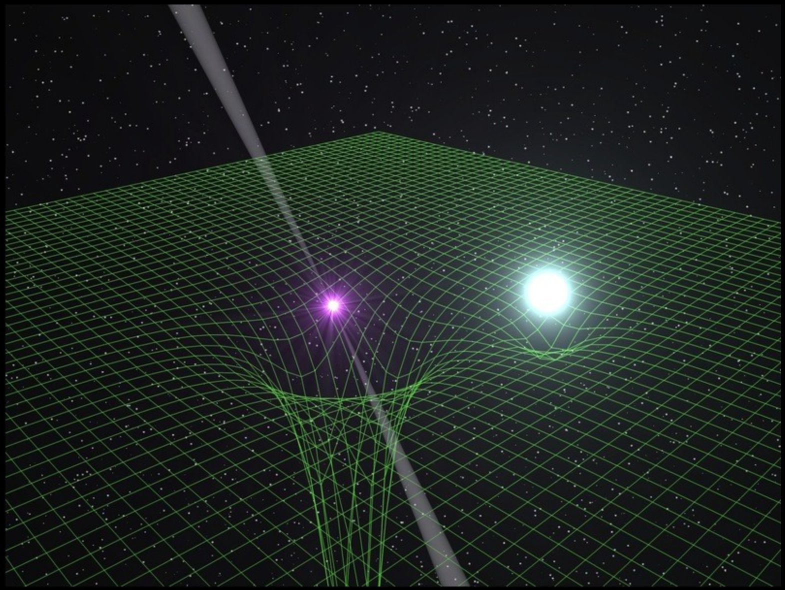

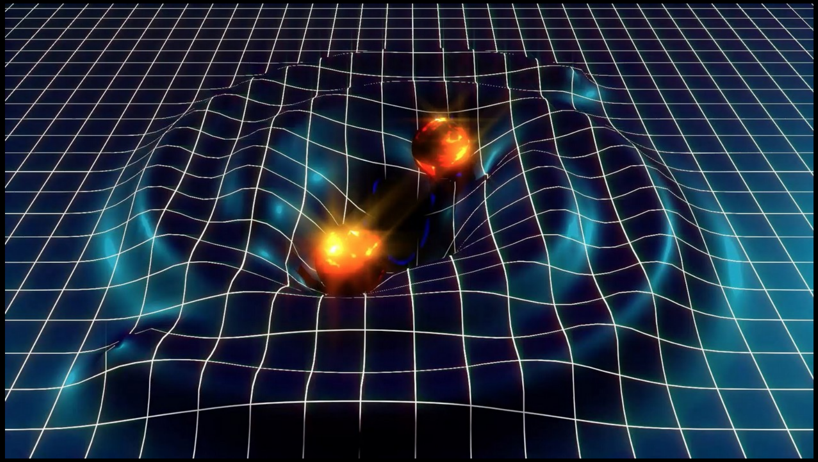

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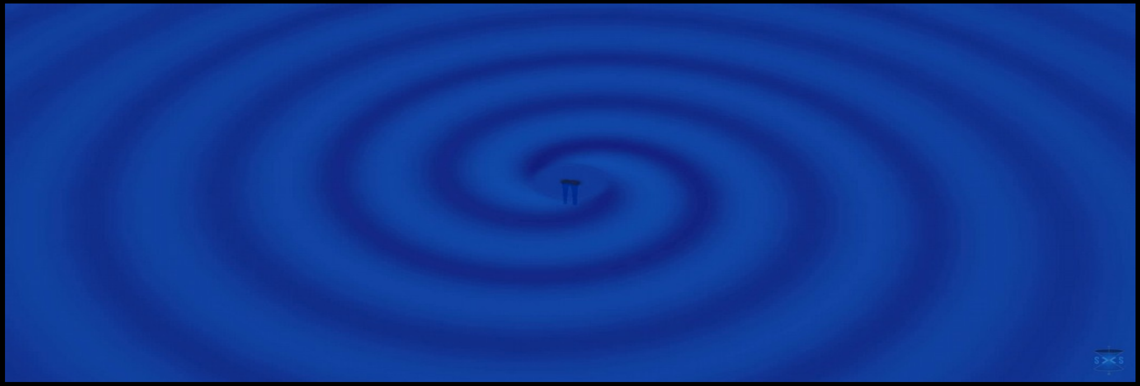
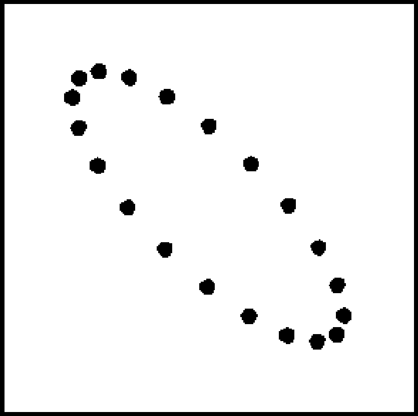
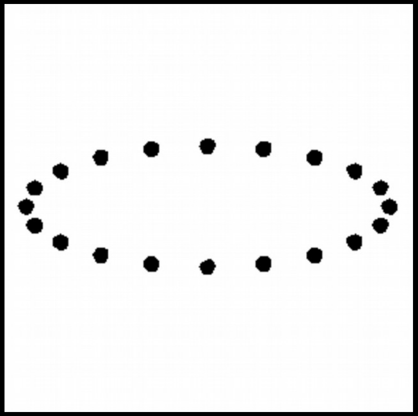
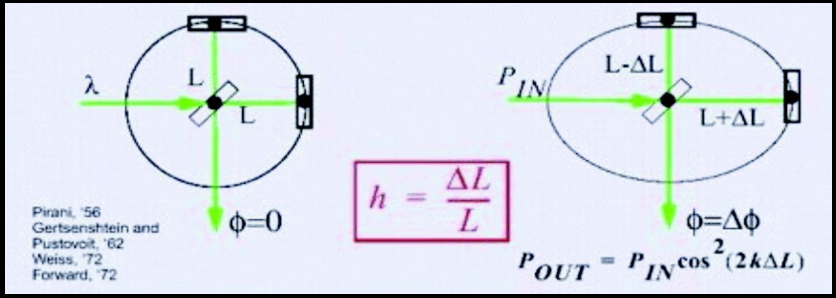






The distortion propagates outwards at the speed of light: **Gravitational waves!**

Transverse, two independent polarizations



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

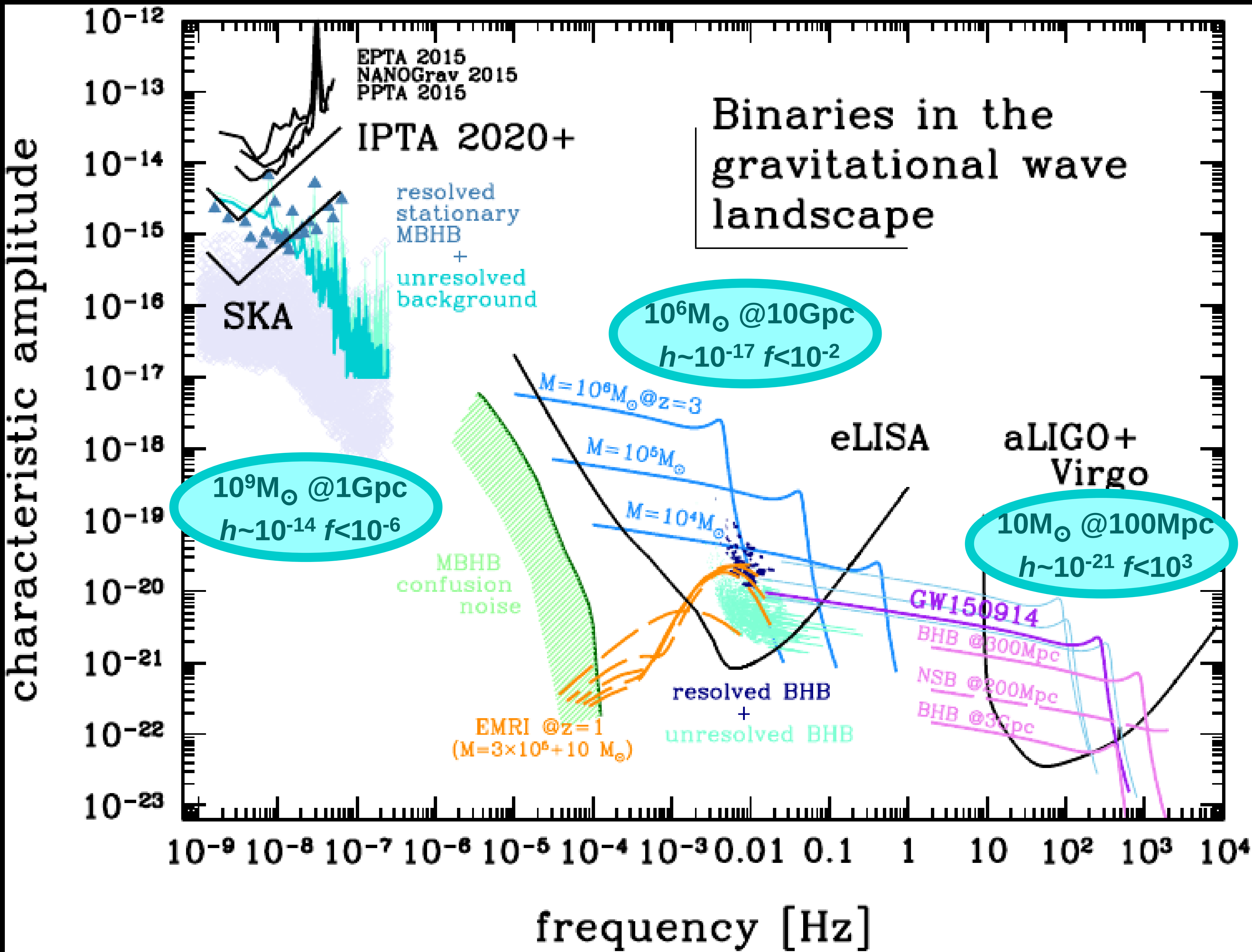
$$h \sim 10^{-20}\,\frac{M}{M_\odot}\,\frac{\mathrm{Mpc}}{D}$$

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

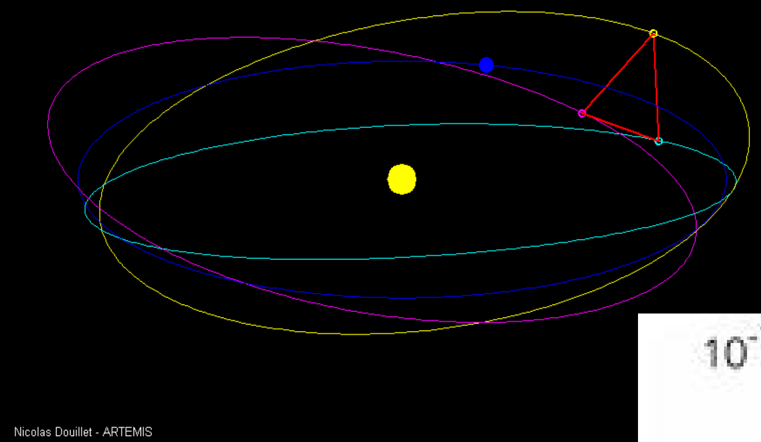
10 $M_\odot$ binary at 100 Mpc: $h \sim 10^{-21}$, $f < 10^{3}$

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

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


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

The Laser Interferometer Space Antenna

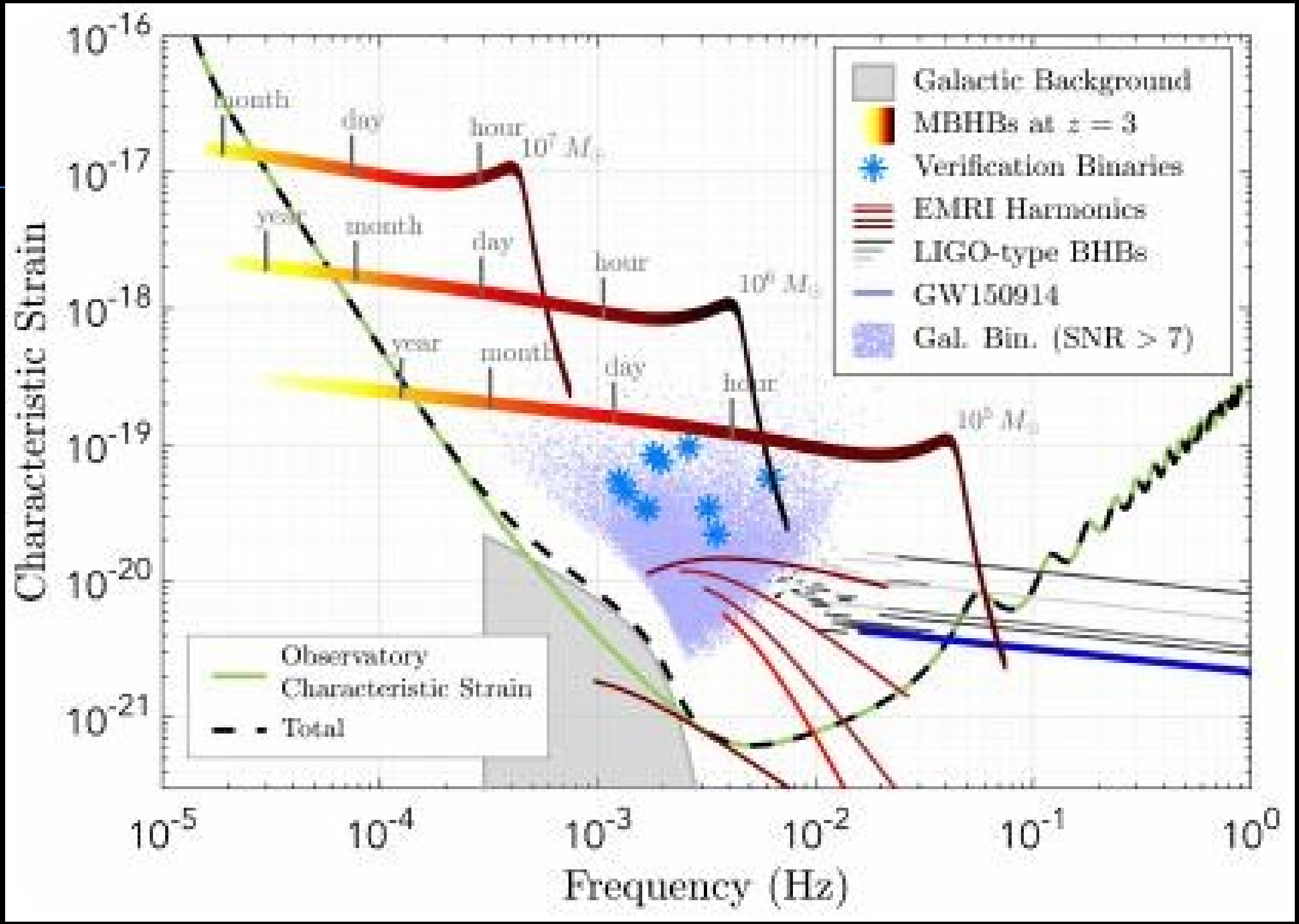


Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

3 satellites trailing the Earth connected through laser links

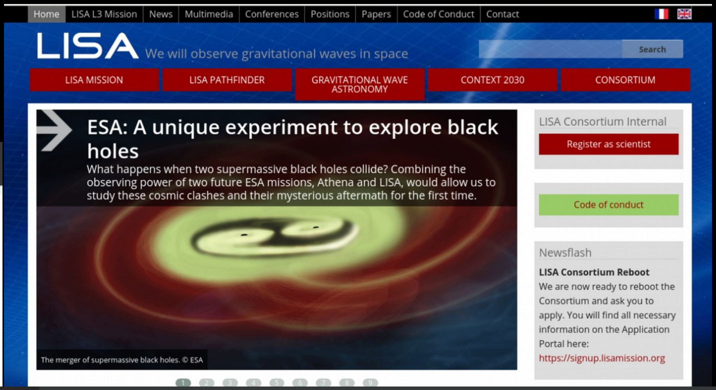
Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)

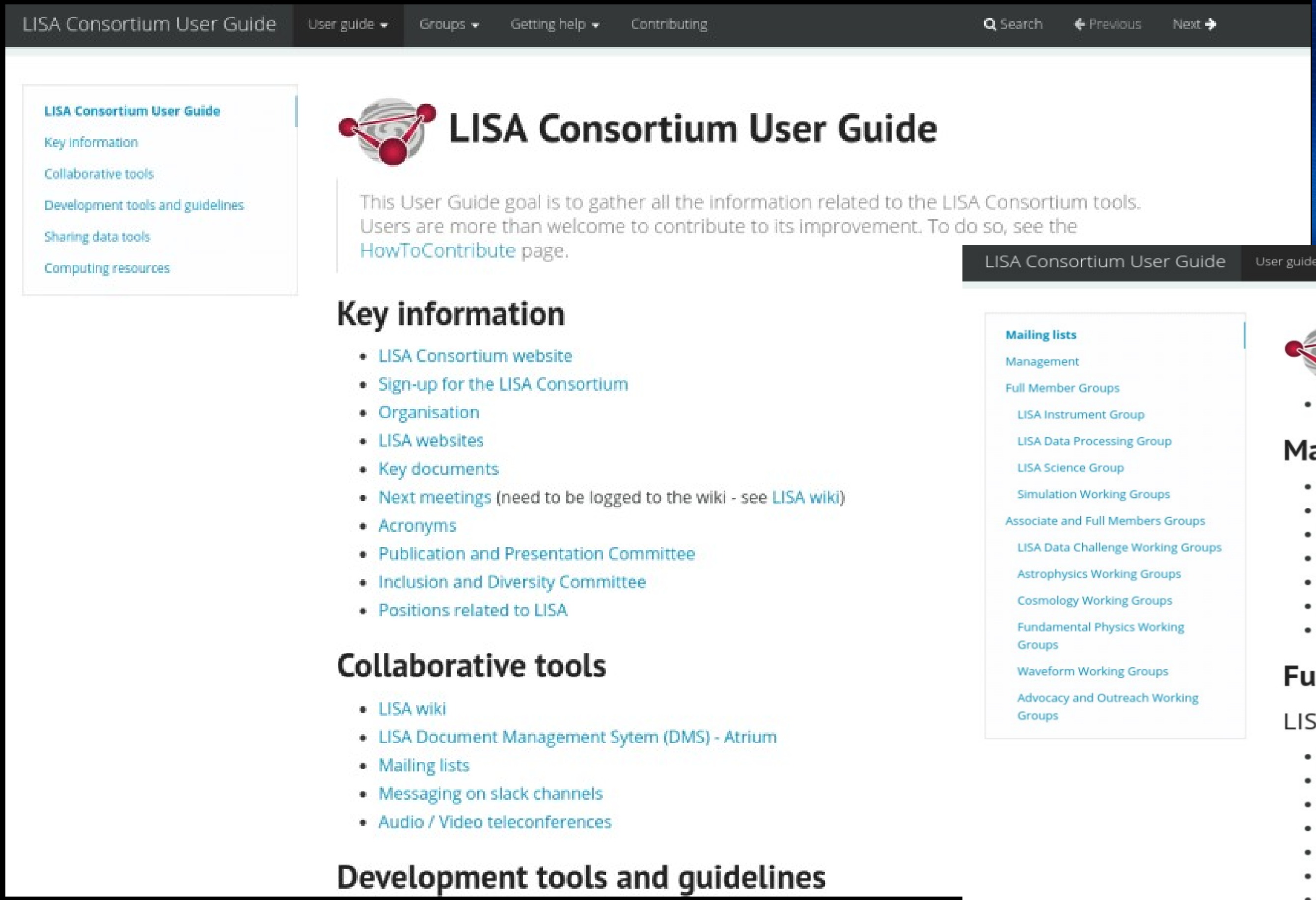


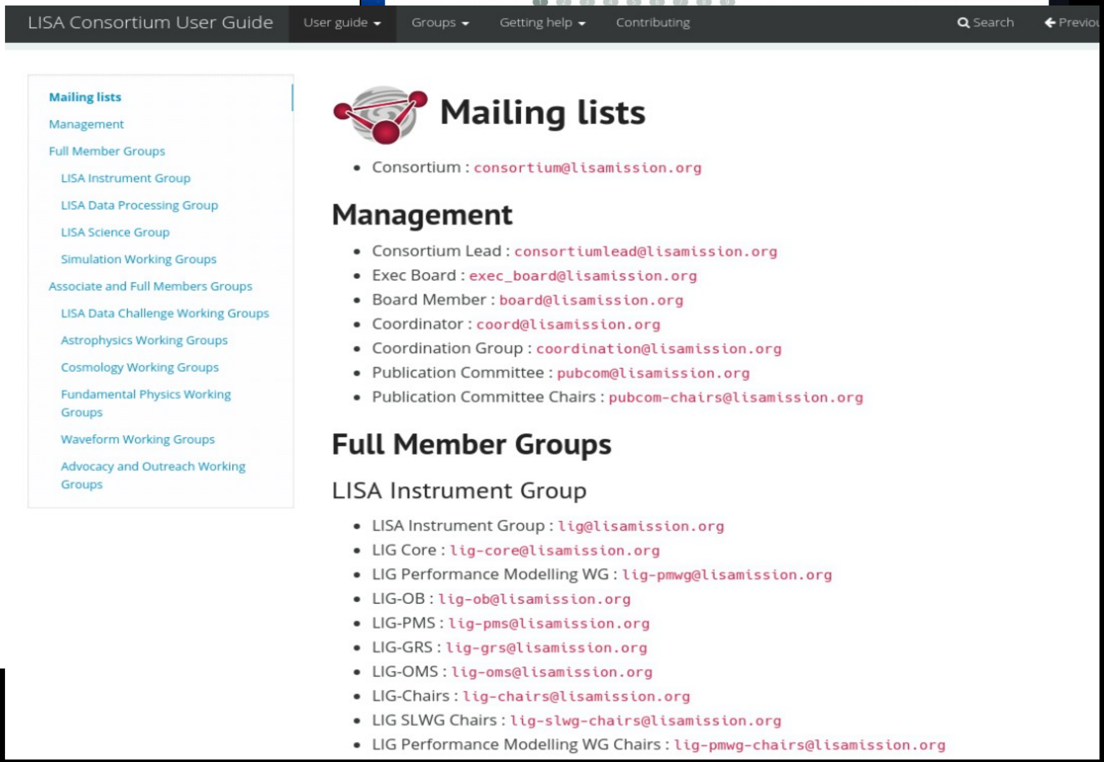
The LISA Consortium

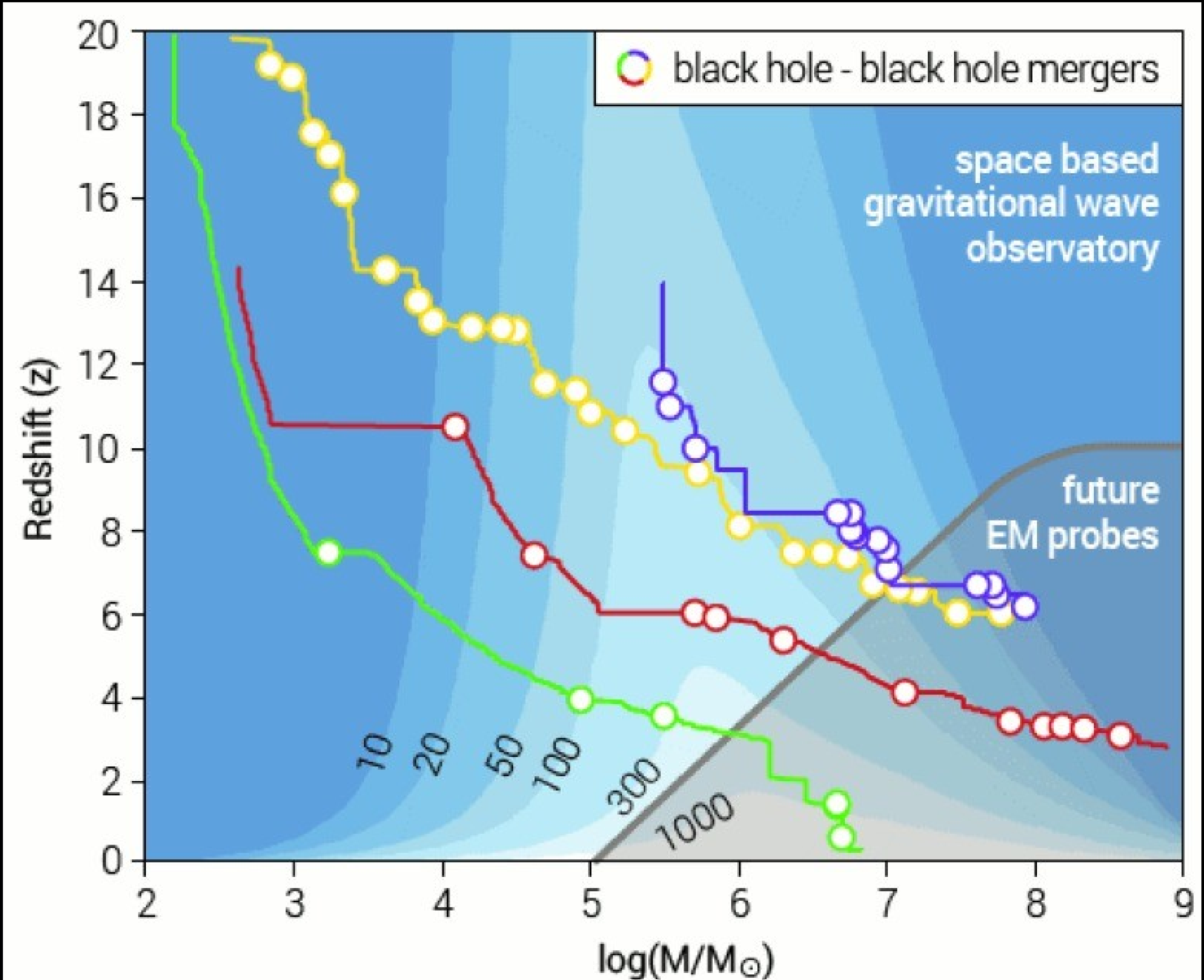
- Now a thriving community: 1300+ among full and associate members
- Several **working groups** connecting to the community: astrophysics, fundamental physics, cosmology, waveforms
- Several **working packages** defining deliverables
- 2 consortium meetings/yr, LISA symposium every 2 years, dedicated WG meetings every year

https://www.lisamission.org/









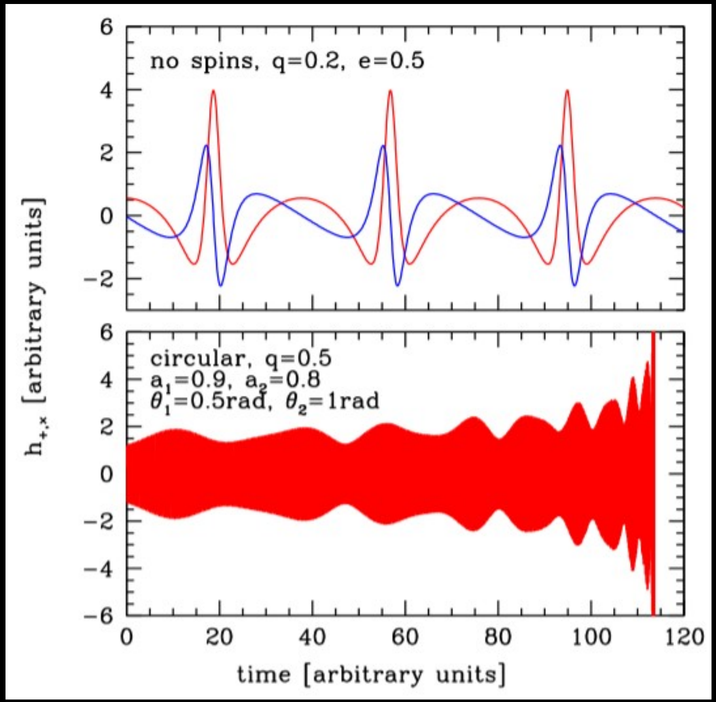
black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9

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%

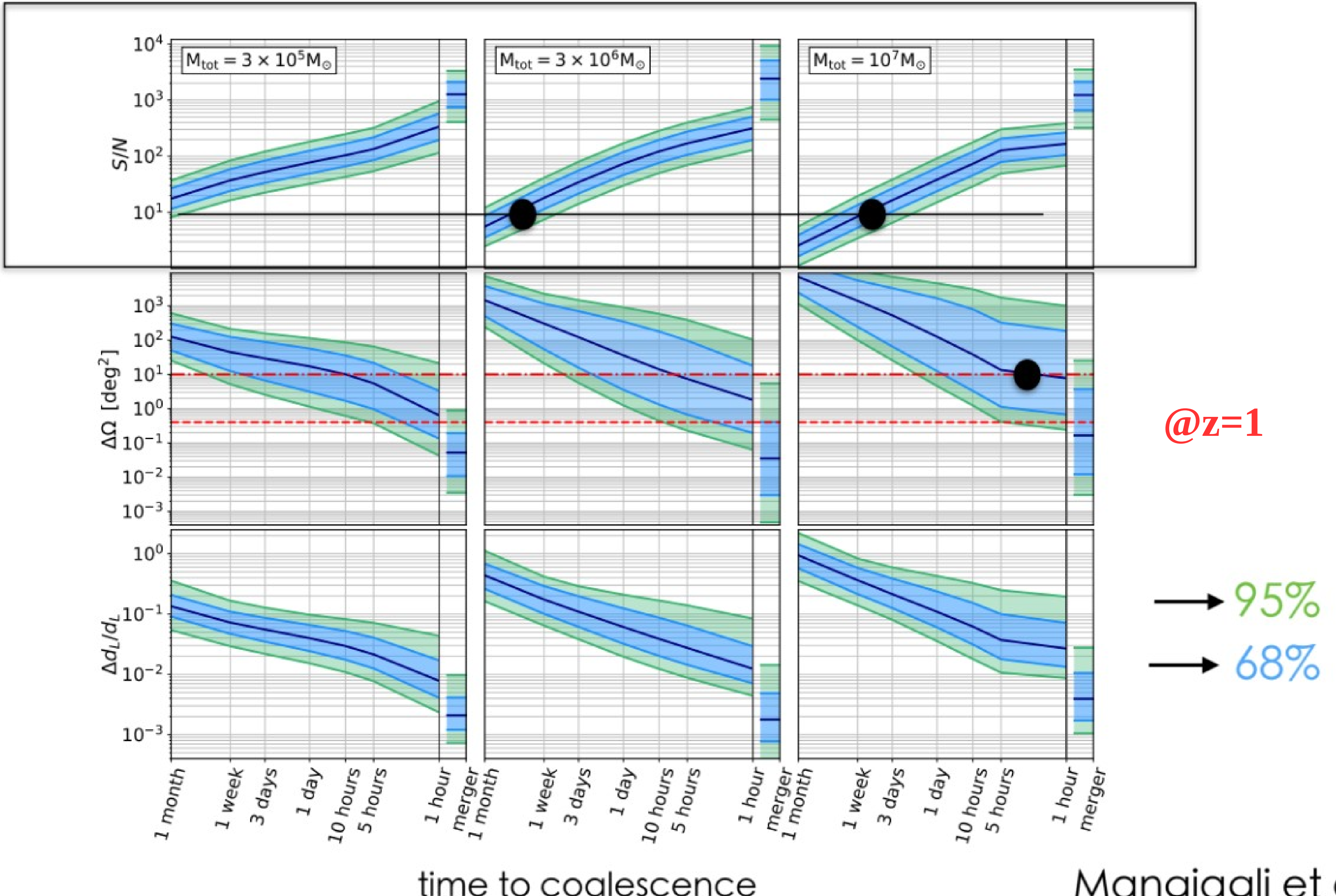
~50 systems with primary spin determined to 0.01

~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

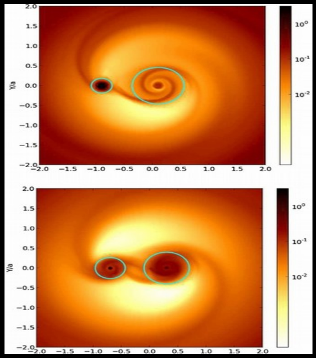
Examples of source localization



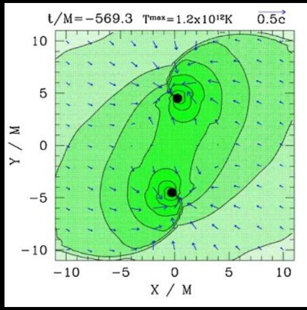
Mangiagli et

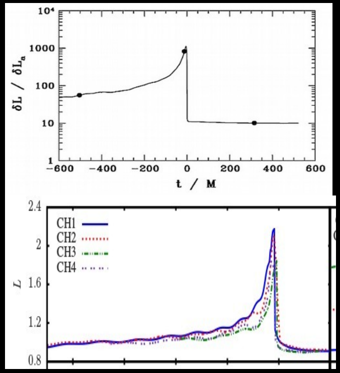
Associated electromagnetic signatures

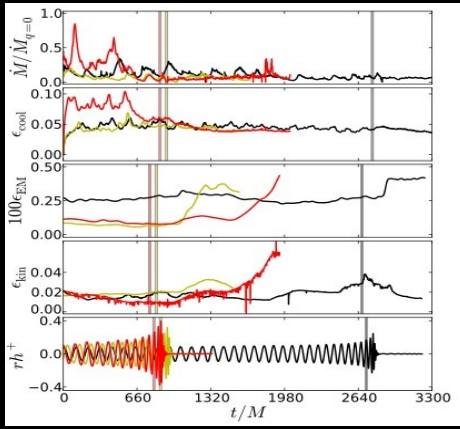
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005).
However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014, Tang et al. 2018...)

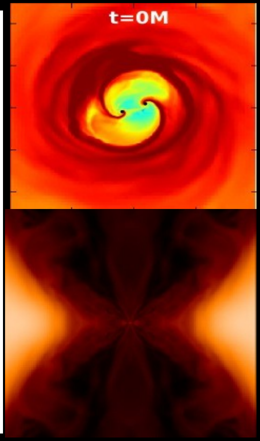


Simulations in hot gaseous clouds. Significant flare associated to merger (Bode et al. 2010, 2012, Farris et al 2012)



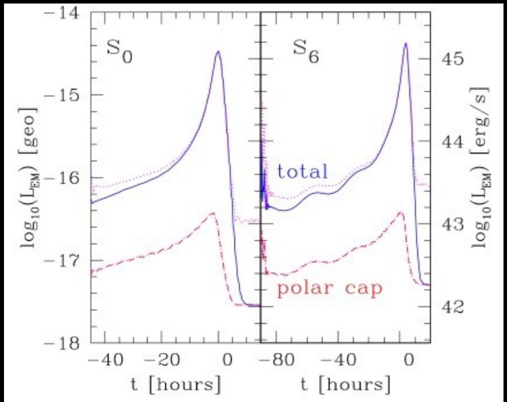


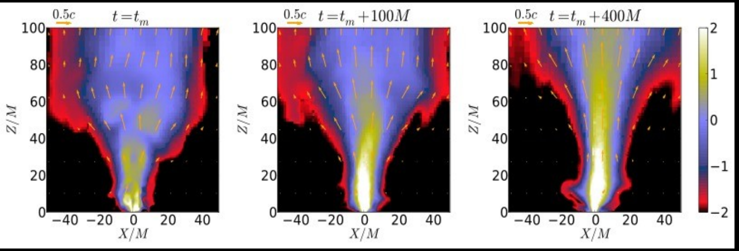


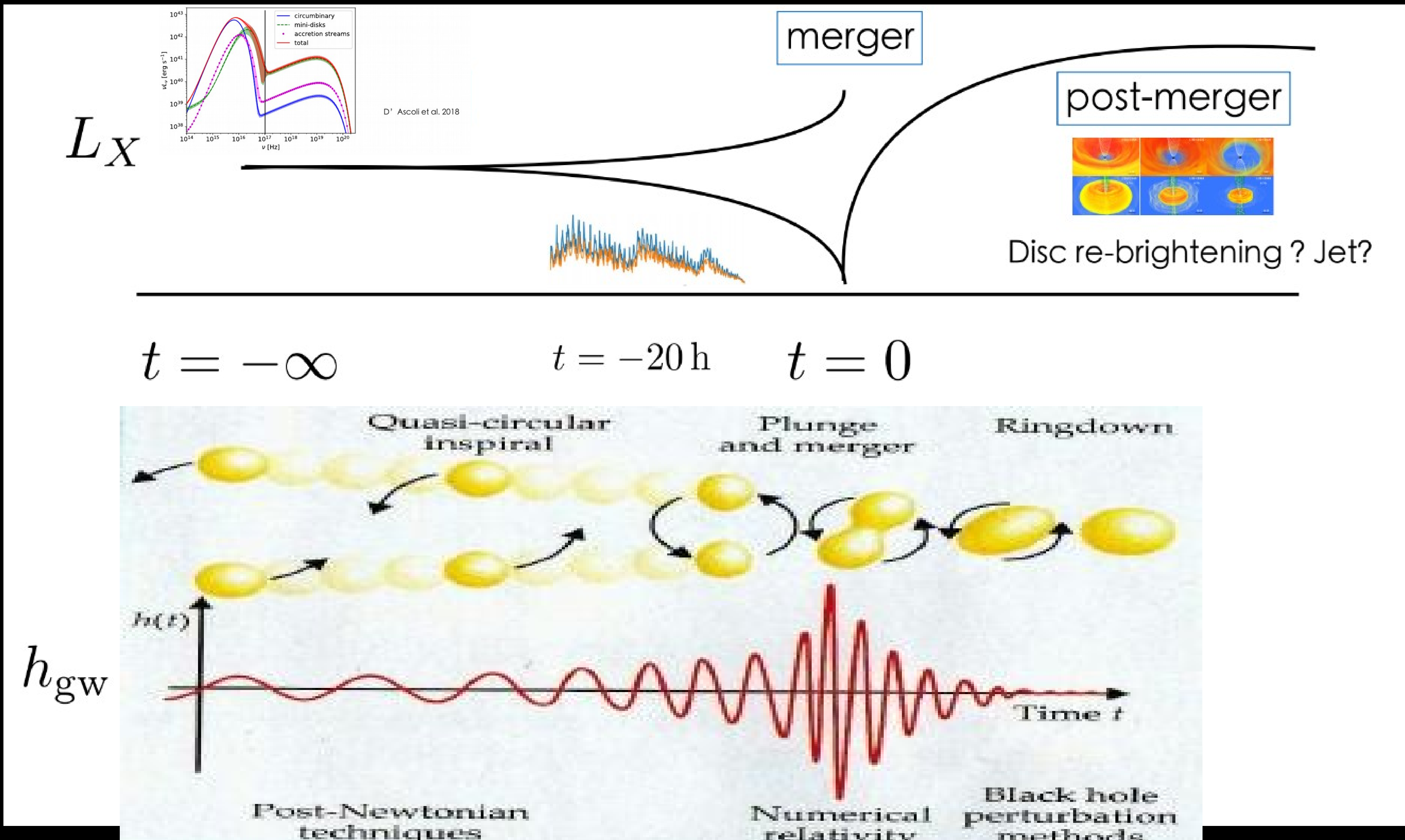


Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

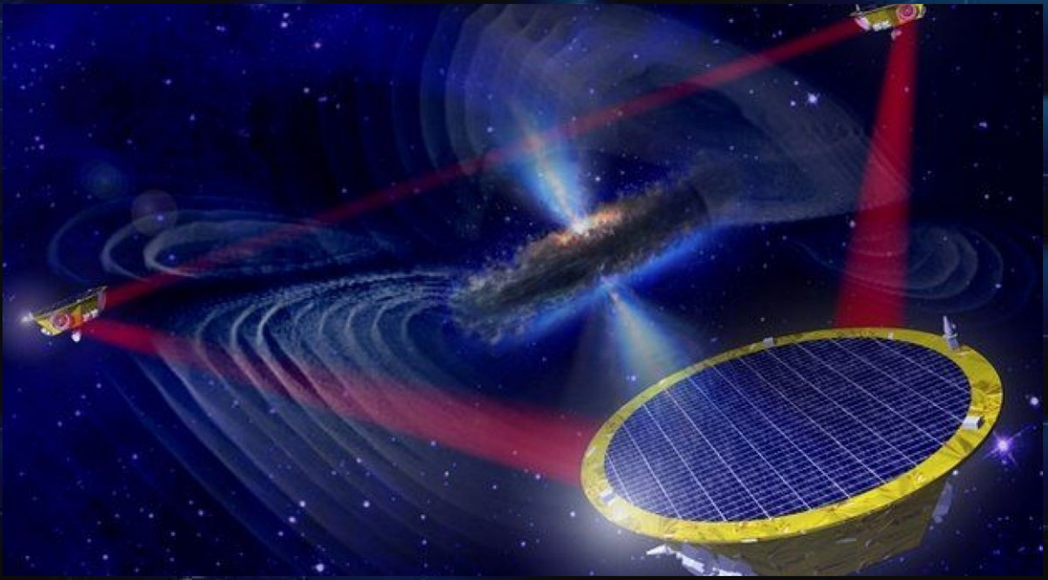
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)






circumbinary
mini-disks
accretion streams
total
ν [Hz]
D' Ascoli et al. 2018
L_X
merger
post-merger
Disc re-brightening ? Jet?
$t = -\infty$
$t = -20\,\mathrm{h}$
$t = 0$
$h_{\rm gw}$
Quasi-circular inspiral
Plunge and merger
Ringdown
$h(t)$
Time t
Post-Newtonian techniques
Numerical relativity
Black hole perturbation methods

Opportunities for LISA-Athena (LSST/Rubin) synergies

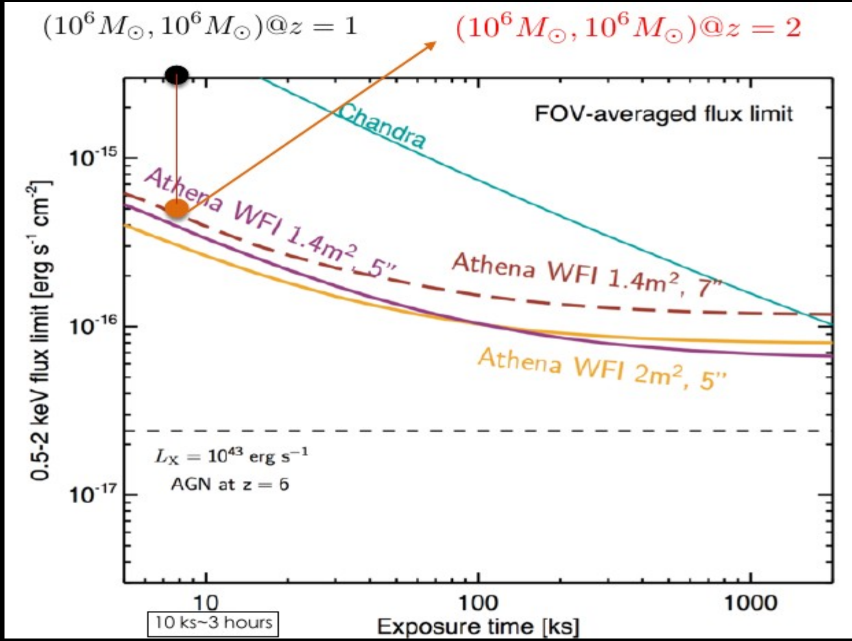


LSST

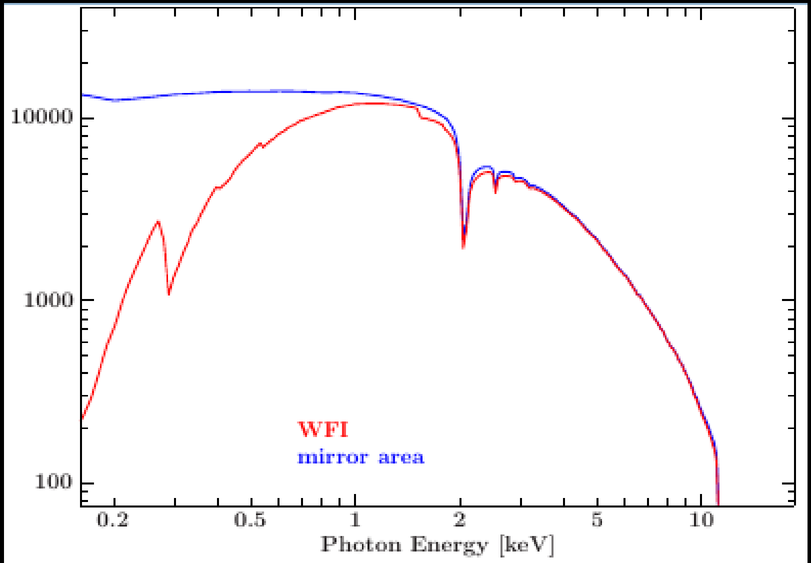
Large Synoptic Survey Telescope

Athena Wide Field Imager (WFI) (Rau+ 2015)

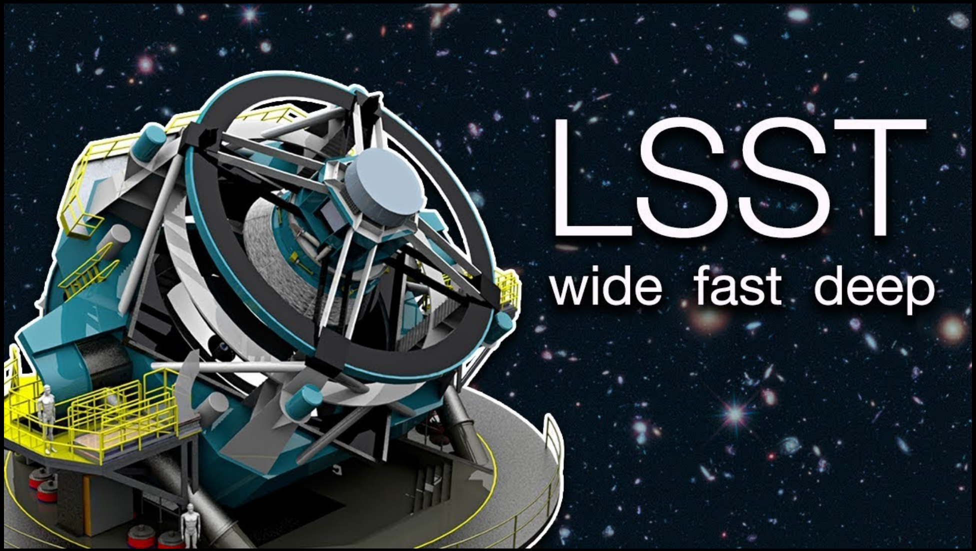
Parameter	Characteristic
Energy Range	0.1-15 keV
Field of View	ca. 40' x 40' (baseline)



- -X-ray telescope
- -L2 ESA mission (~2030)



LSST : Vera Rubin observatory

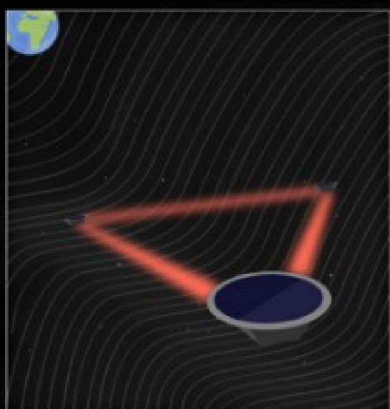


- -2022+
- -Optical telescope
- -9.6 square degree FoV
- -m~24 within 30s pointings in several different filters

→ HOW CAN LISA AND ATHENA WORK TOGETHER?

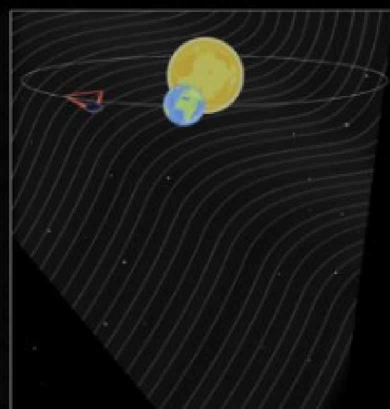
esa

About 1 month before



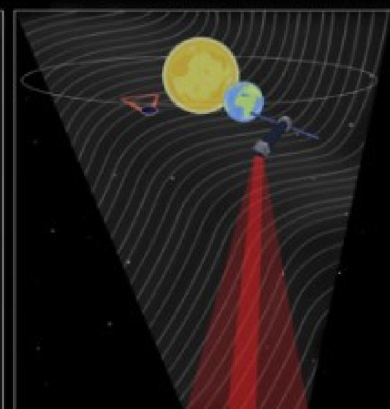
LISA detects gravitational waves from **supermassive black holes** spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown

2 weeks before



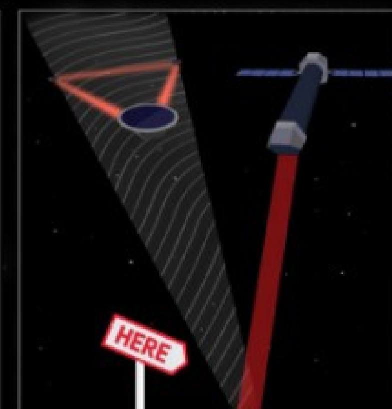
As the inspiral phase progresses, the gravitational wave signal gets stronger; meanwhile, LISA collects more data as it moves along its orbit, providing a **better localisation** of the source in the sky

1 week to several hours before



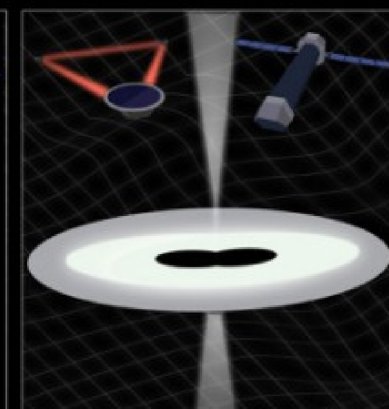
LISA indicates a **fairly large patch in the sky** (around 10 square degrees) where the source is located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (WFI)

A few hours before

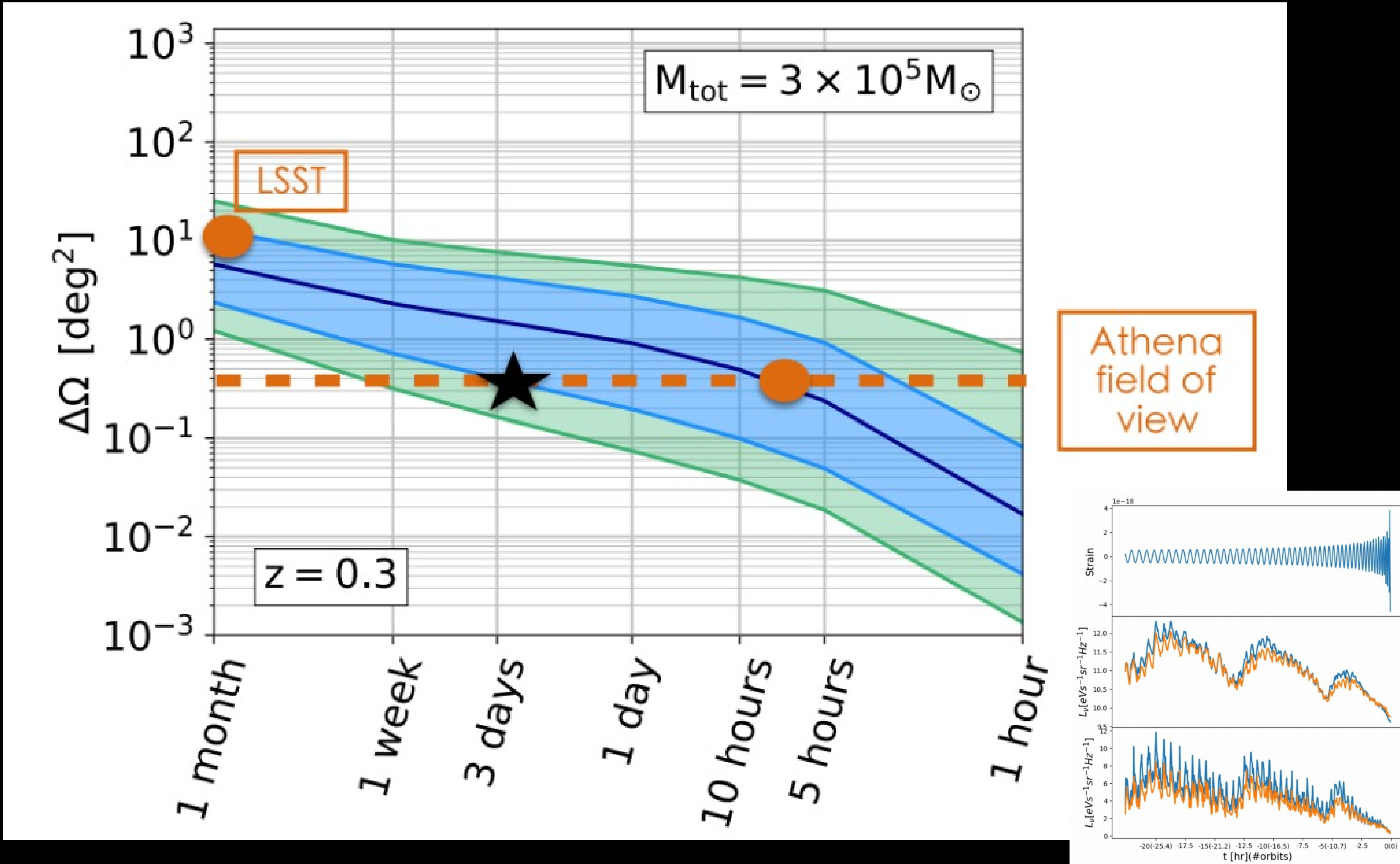


LISA locates the source to within a **smaller portion of sky,** roughly equal to the size of the Athena WFI field of view (0.4 square degrees); Athena stops scanning, and starts staring at the most likely position of the source, witnessing the final inspiral and merger of the black holes

During and after the merger

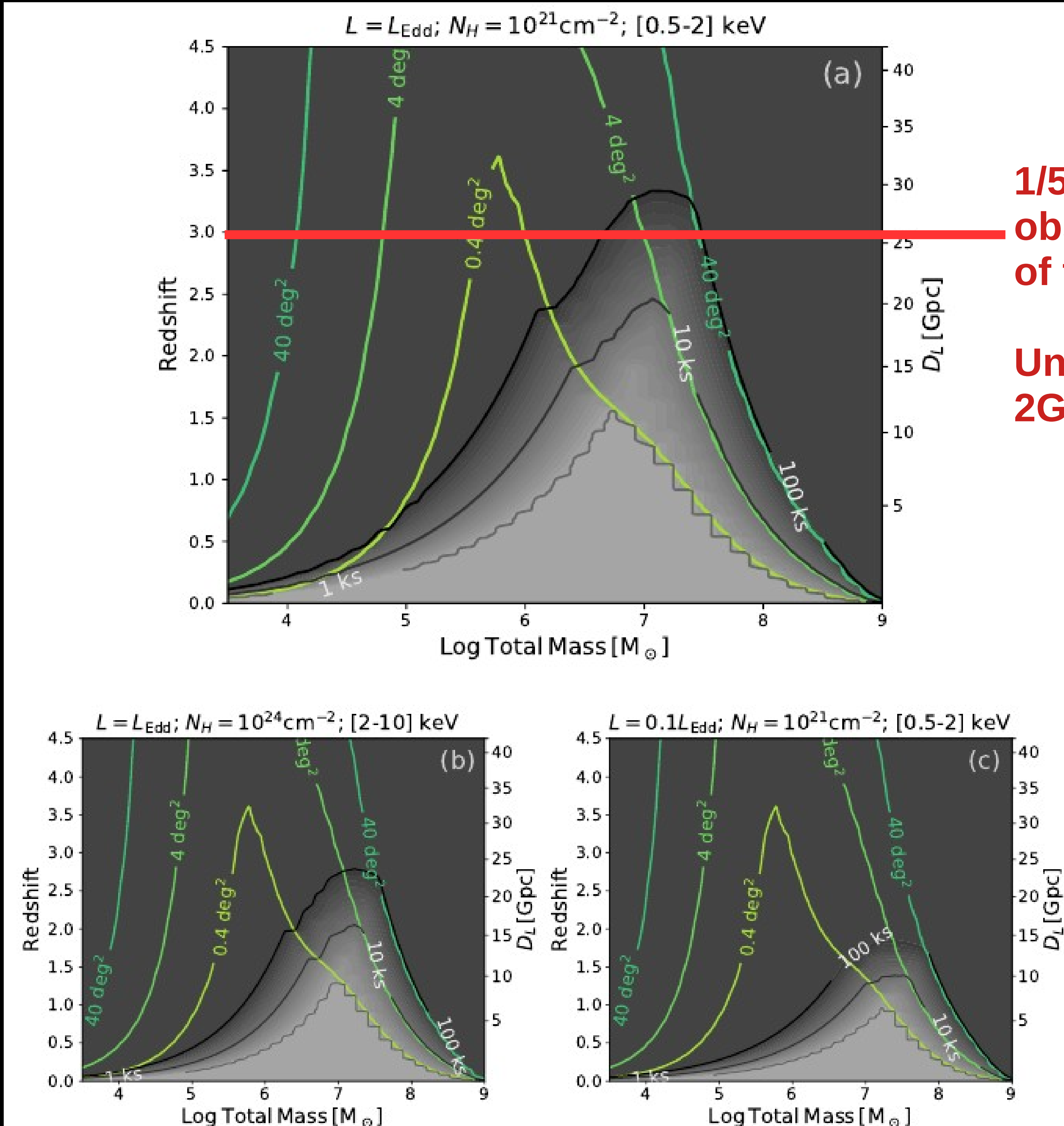


While LISA detects the **gravitational wave 'chirp',** Athena can observe any associated **X-ray emission** and might witness the onset of **relativistic jets:** if this happens, Athena and LISA may witness the birth of a new 'active galaxy'



-Athena pre-pointing only possible for very low z sources

-LSST/Rubin more suitable for tracking inspiral periodicity (but optical)



1/5 of the observable volume of the universe.

Universe was 2Gyr old.

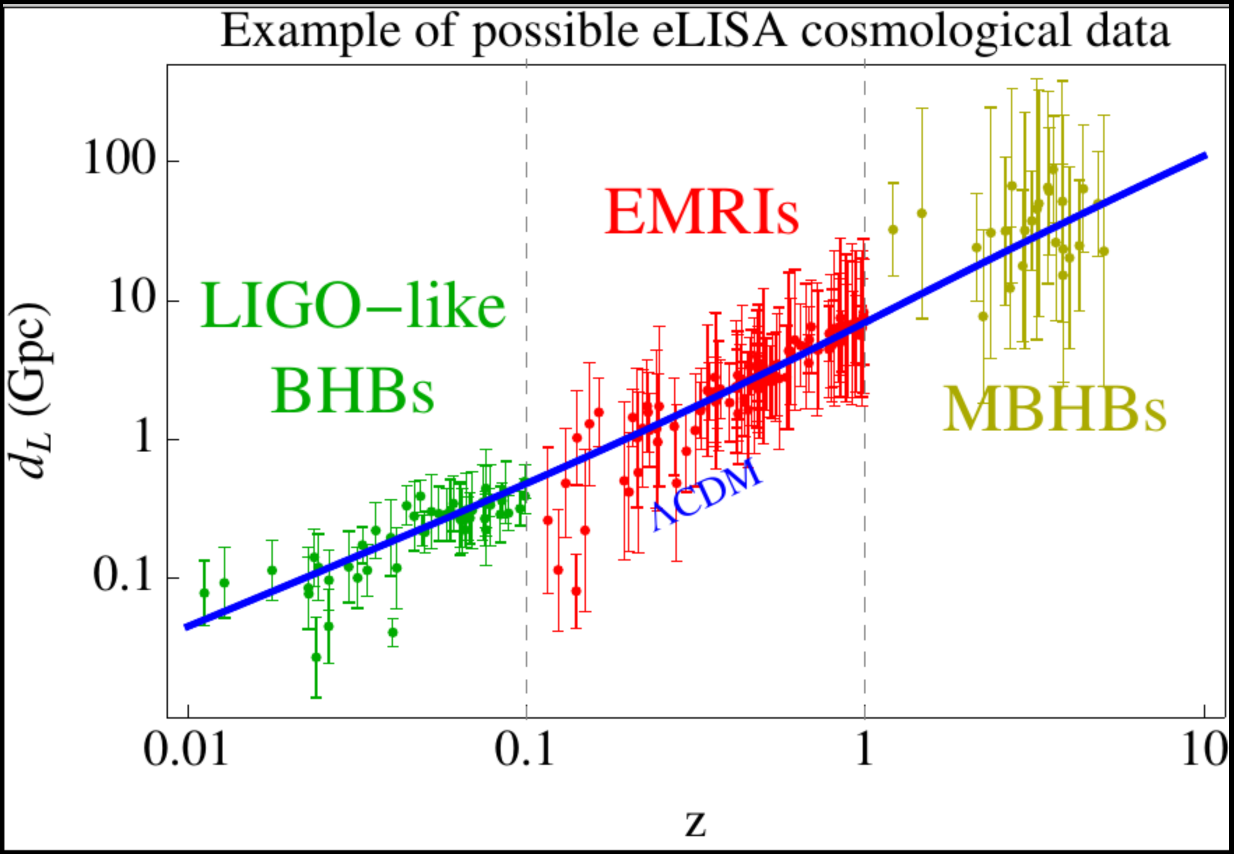
Why multimessenger?

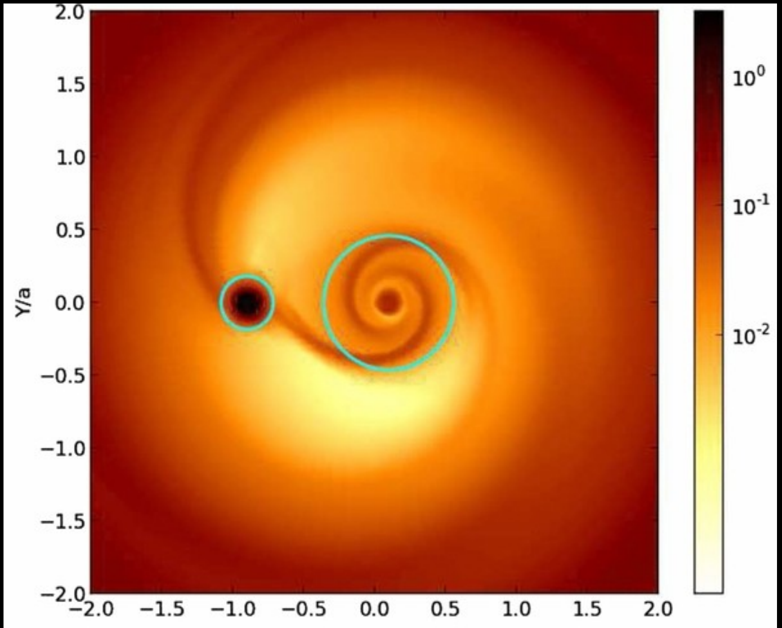
- Cosmology and cosmography at high *z*

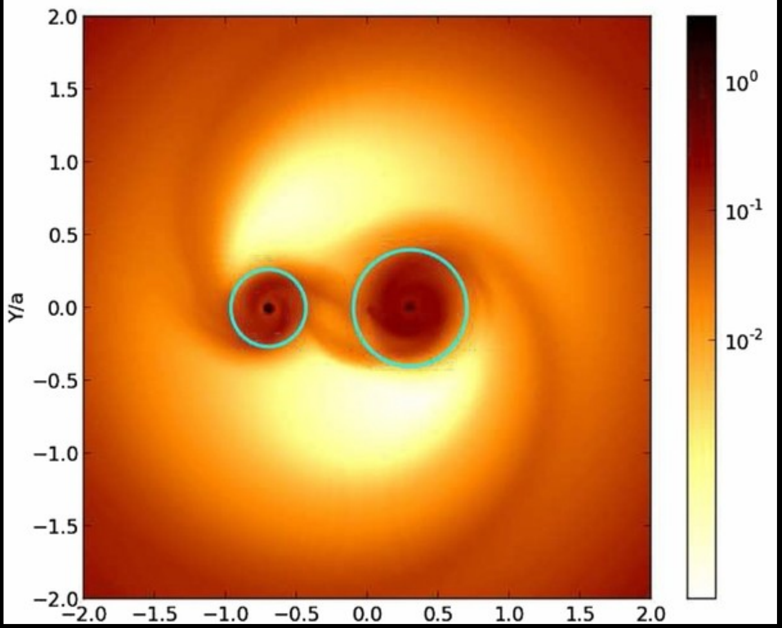
- Study of accretion on MBHs with known mass and spins

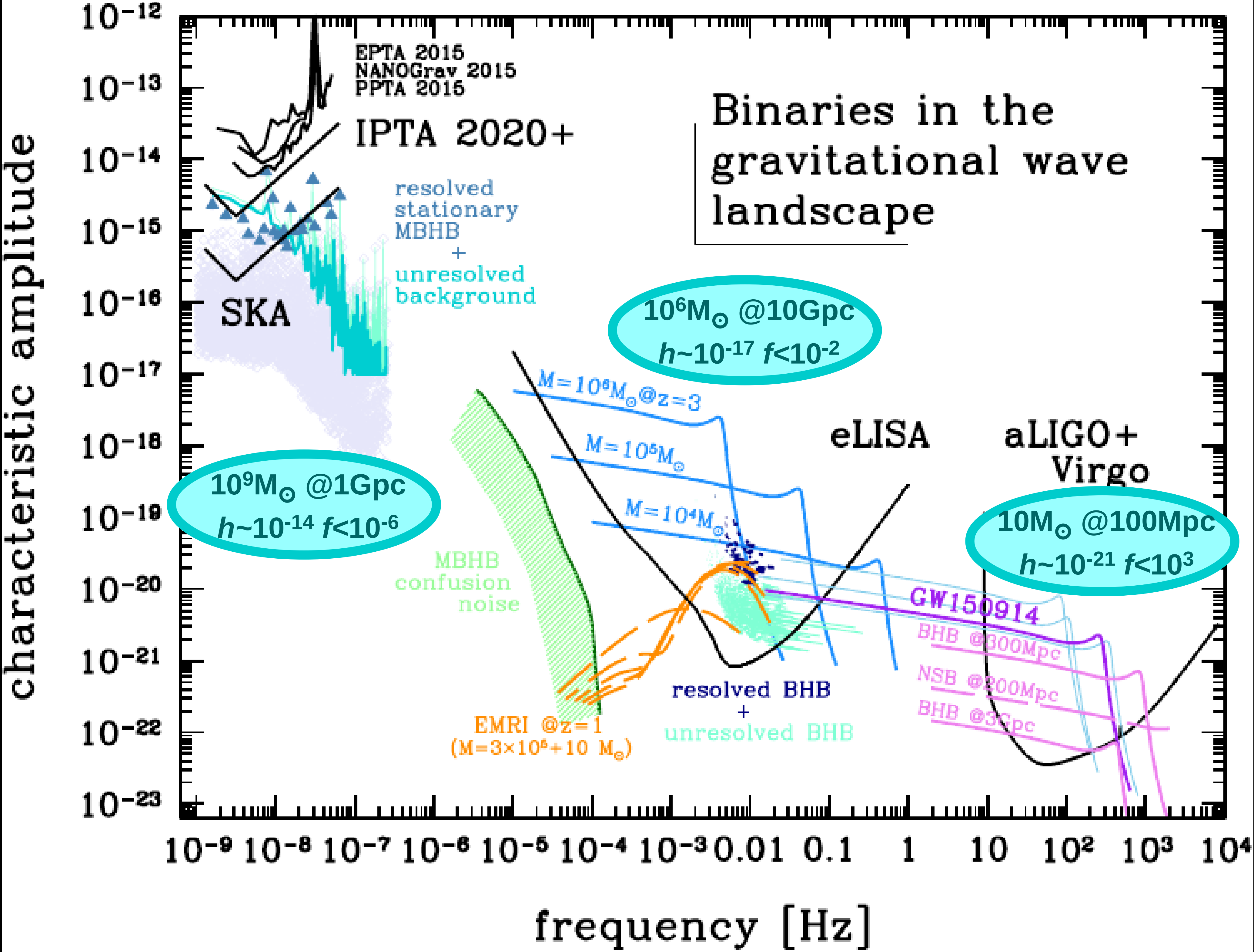
- Study of the interplay between MBHs and gas (torques, disk structure, disk models)

- Host galaxy, Jet launches, Quasar birth ...









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

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

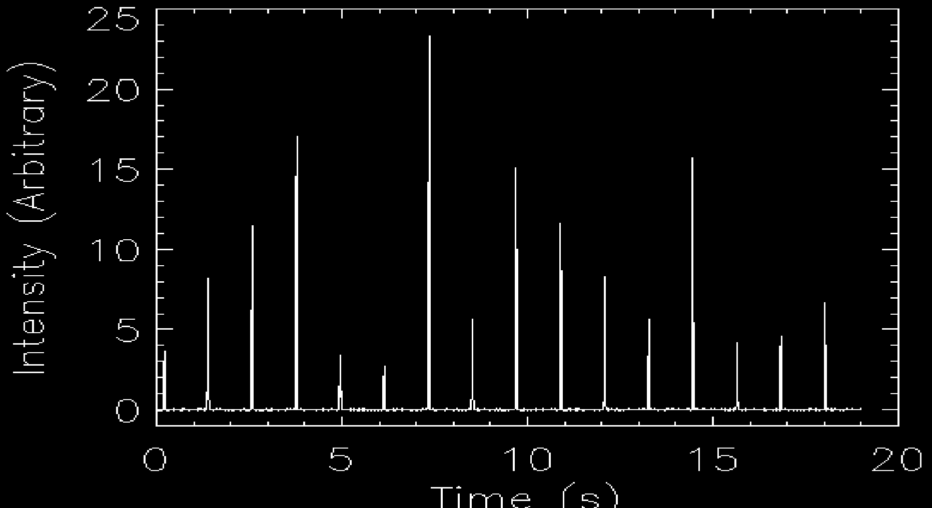
1-Observe a pulsar and measure the ToAs

2-Find the model which best fits the ToAs

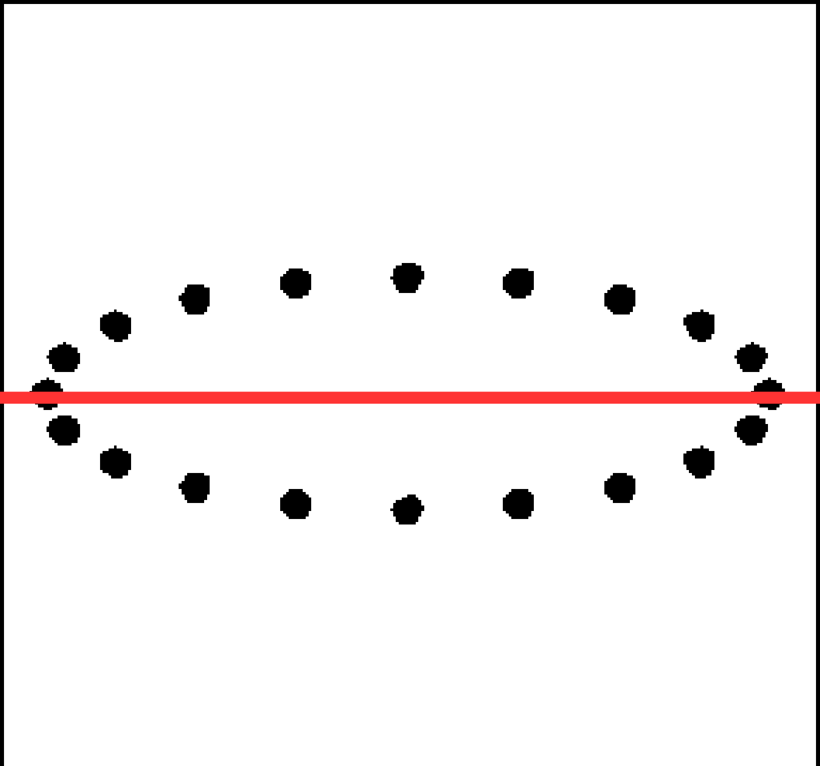
3-Compute the timing residual R

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

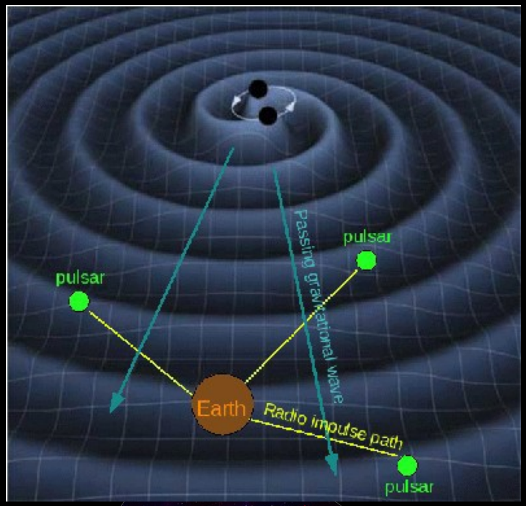
If the timing solution is perfect (and observations noiseless), then *R*=0. *R* contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) *gravitational waves*

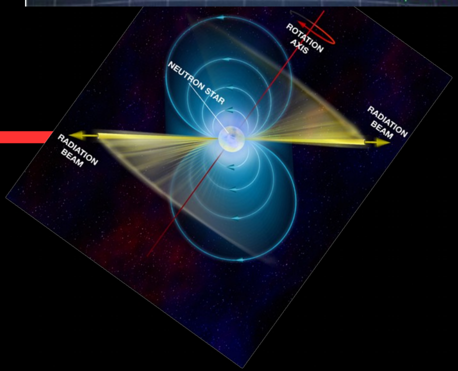


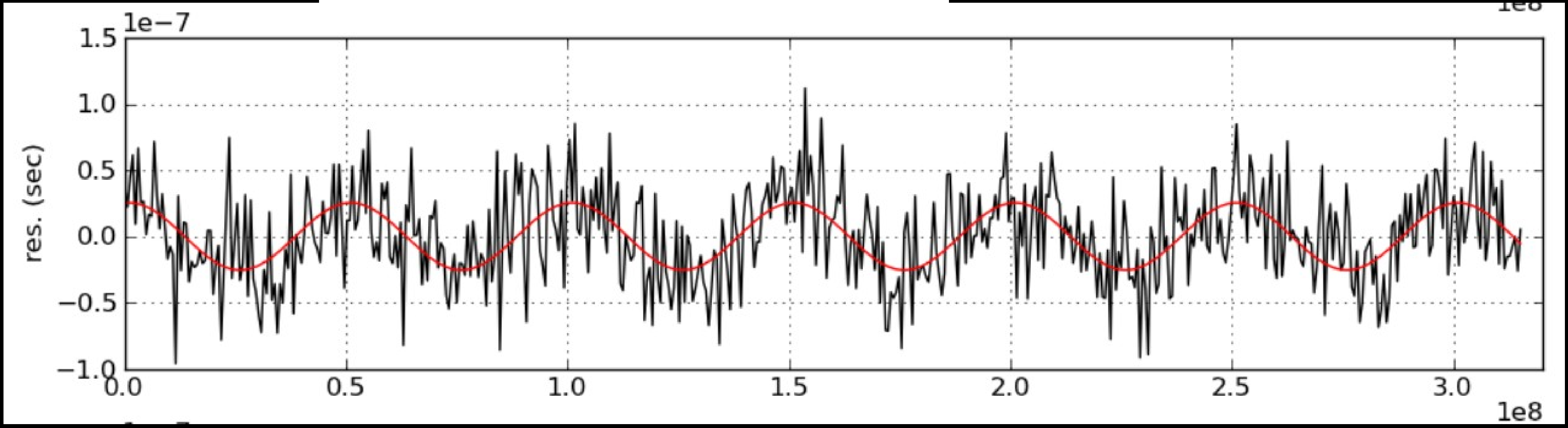
Earth



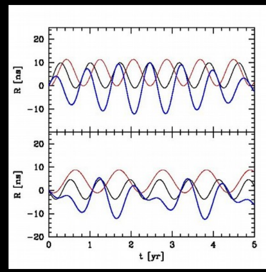
Pulsar



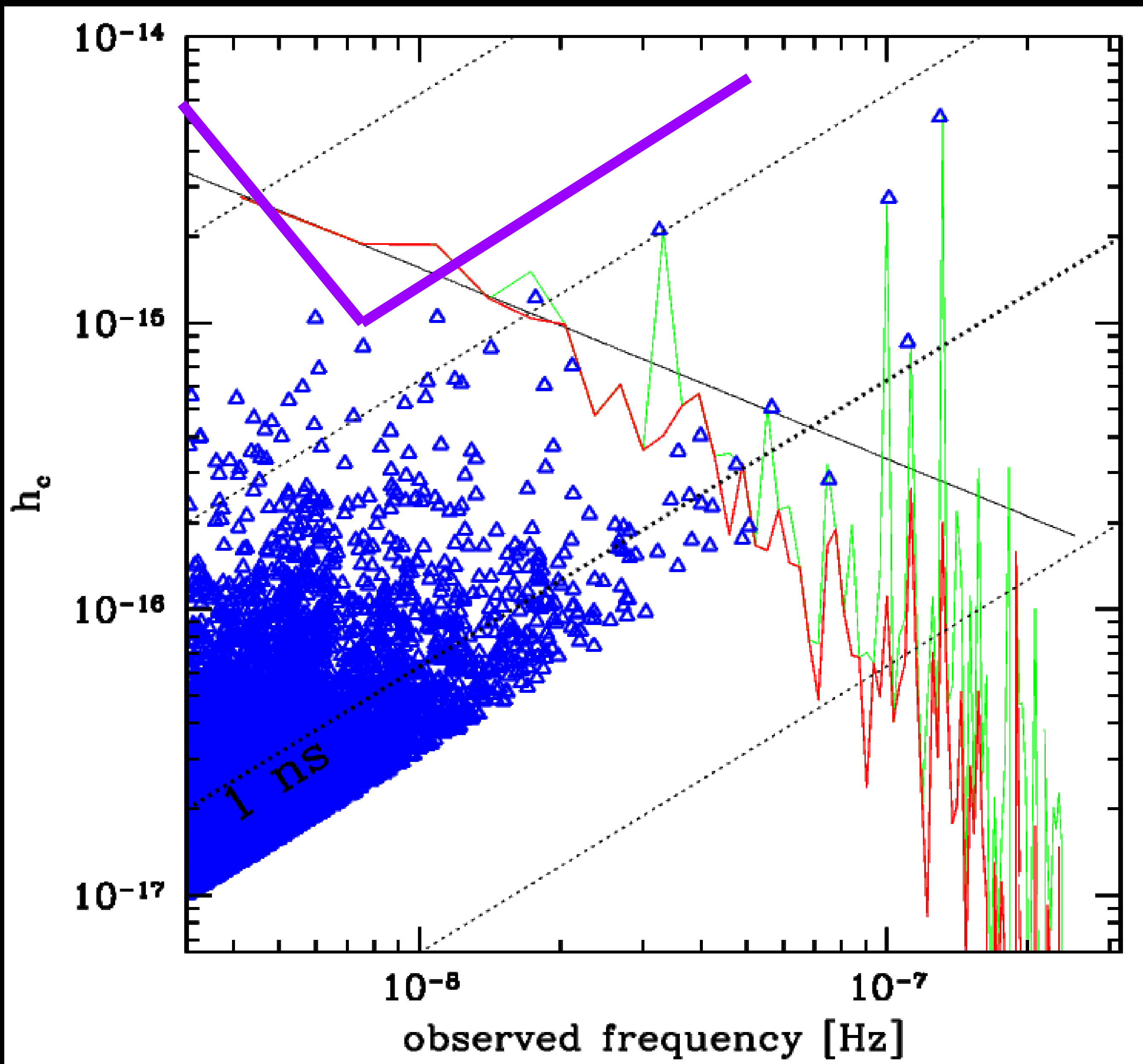




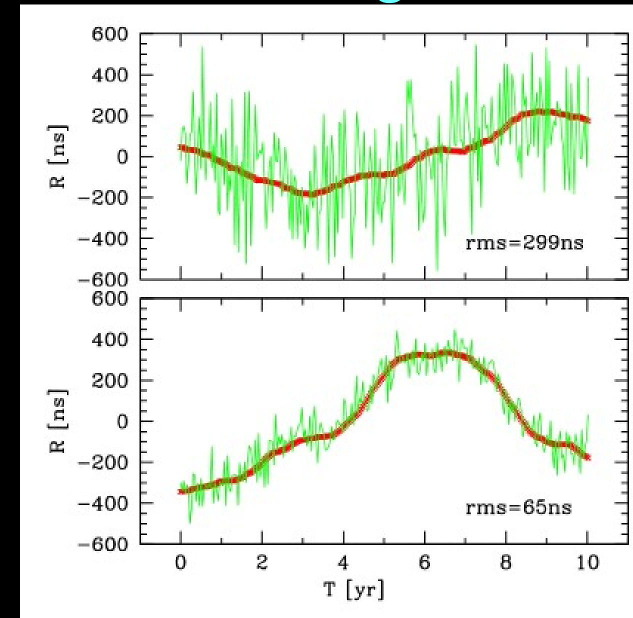
Incoherent superposition of sinusoids



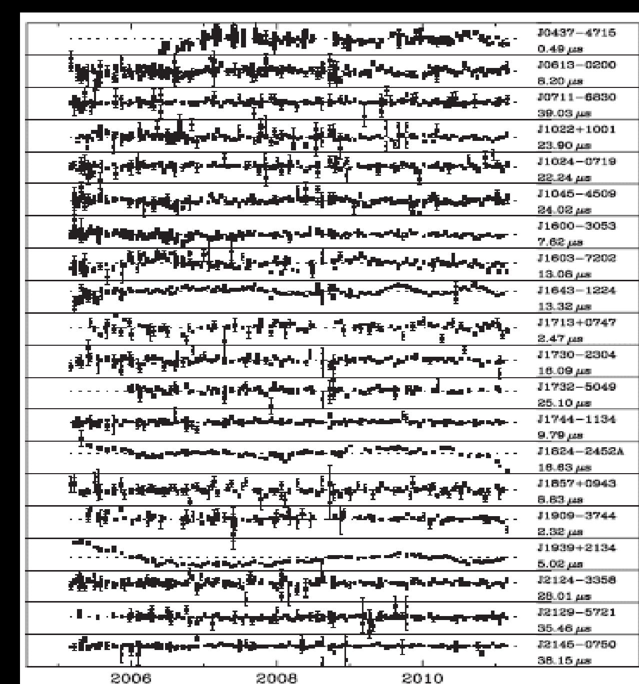
$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$



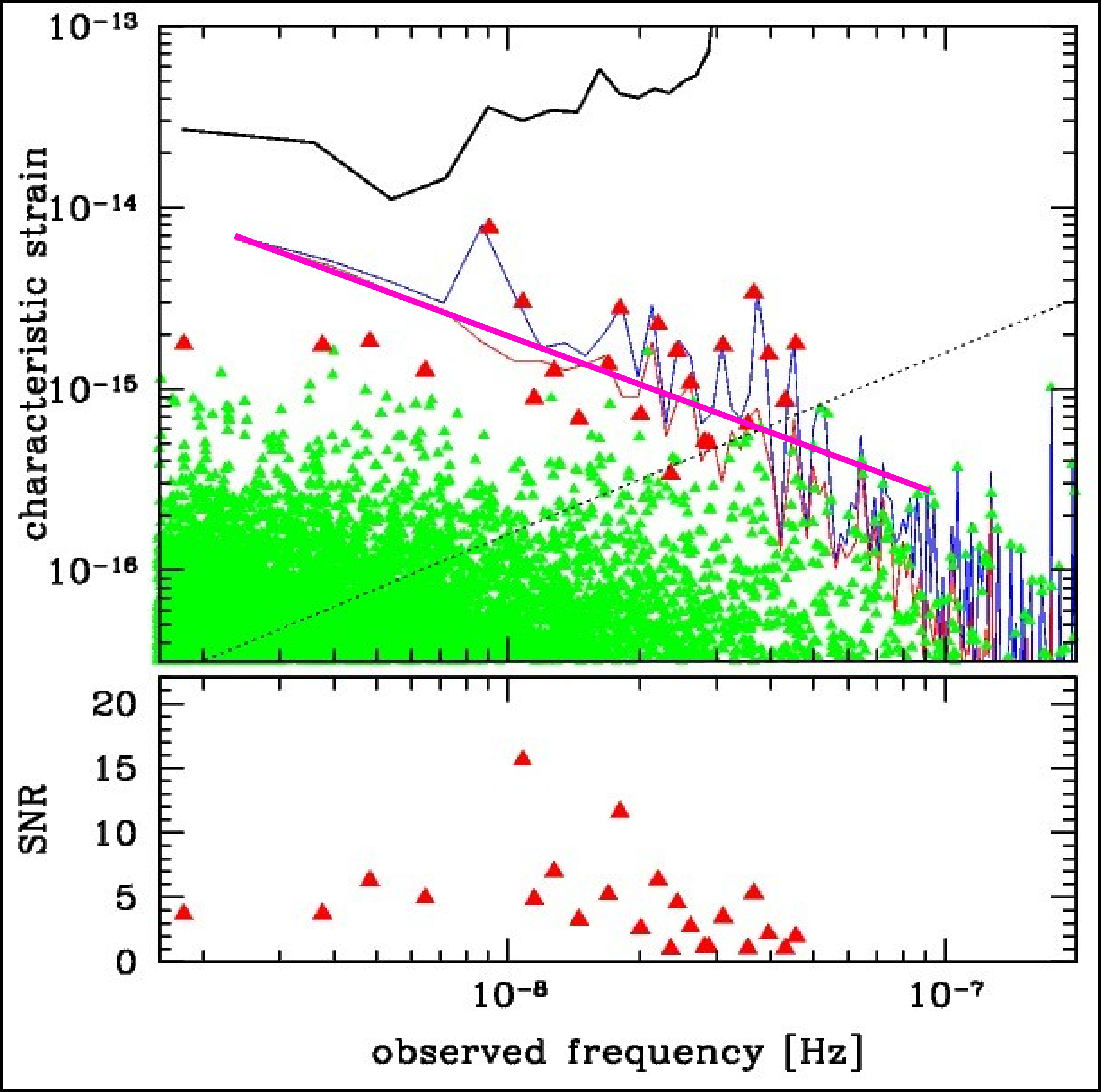
Simulated signal



Actual data



Resolvable sources (AS et al 2009)



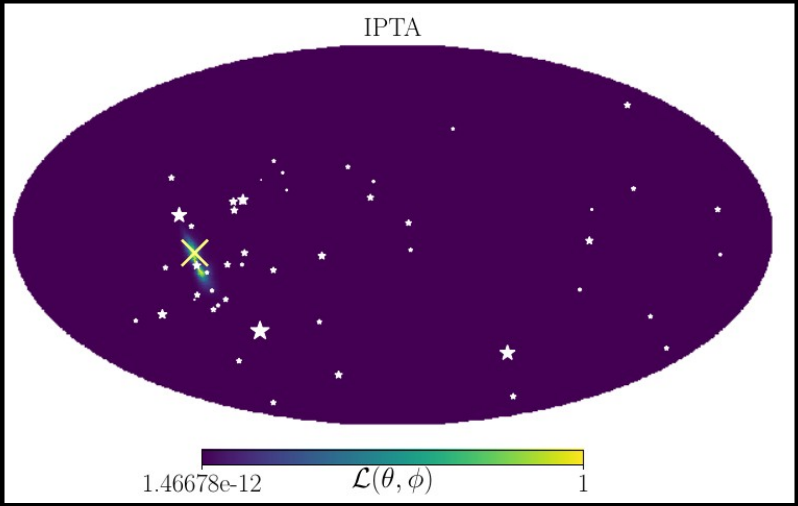
*It is not smooth

*It is not Gaussian

*Single sources might pop-up

*The distribution of the brightest sources might well be anisotropic

Finding the right galaxy



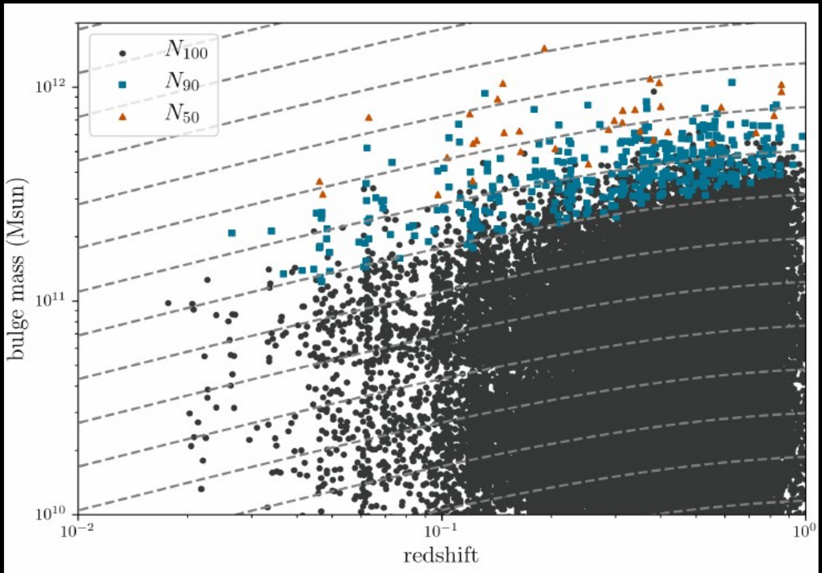
In general, PTA cannot break the distance-mass degeneracy (*$A \sim M^{5/3}/D$*)

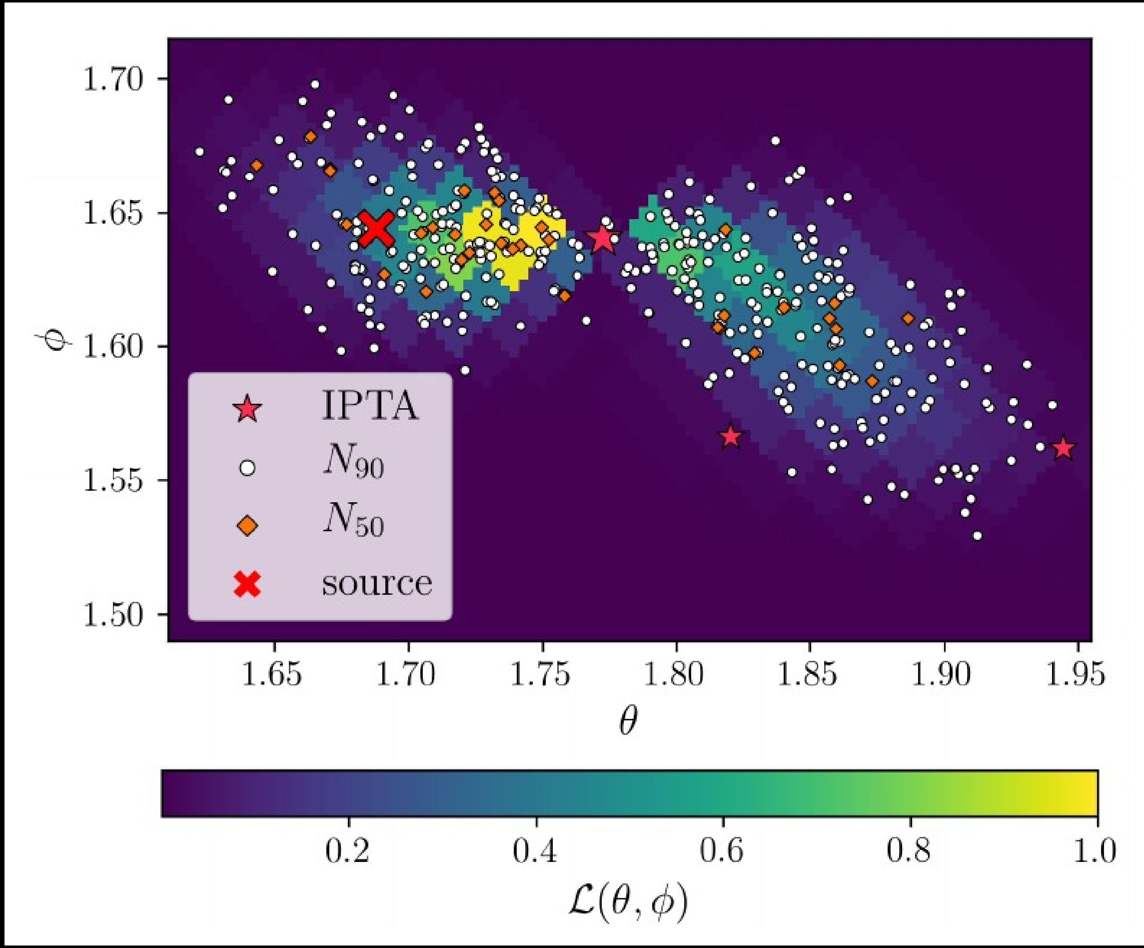
$$A = 4\,\frac{(G\mathscr{M}_z)^{5/3}(\pi f)^{2/3}}{D_l}$$

Sky localization is tens of deg² so tens of thousands of potential host galaxies

An individual PTA source must be massive and/or nearby → Only several tens of credible candidates

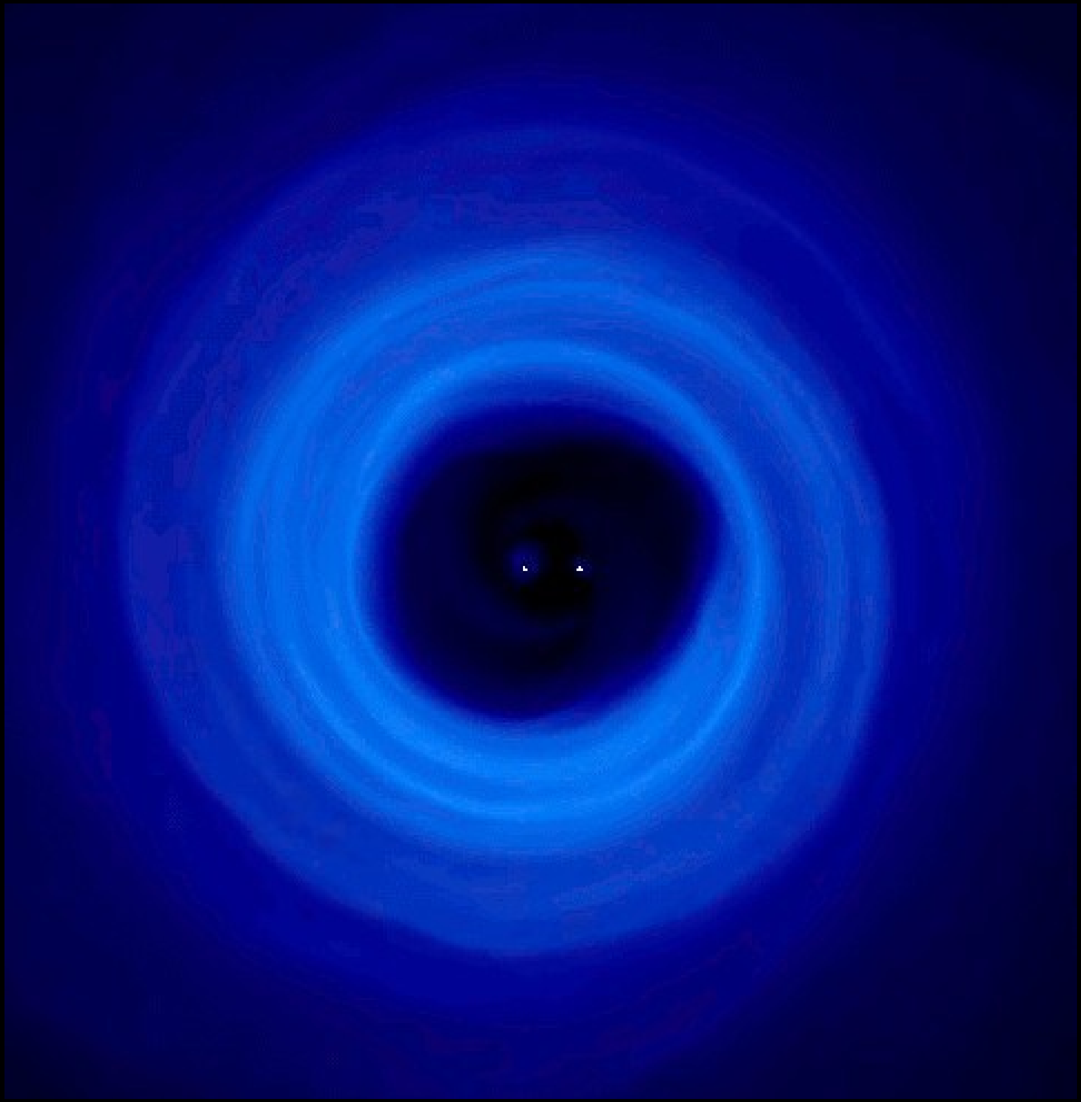
(Goldestein et al 2019)





Associated electromagnetic signatures PTA

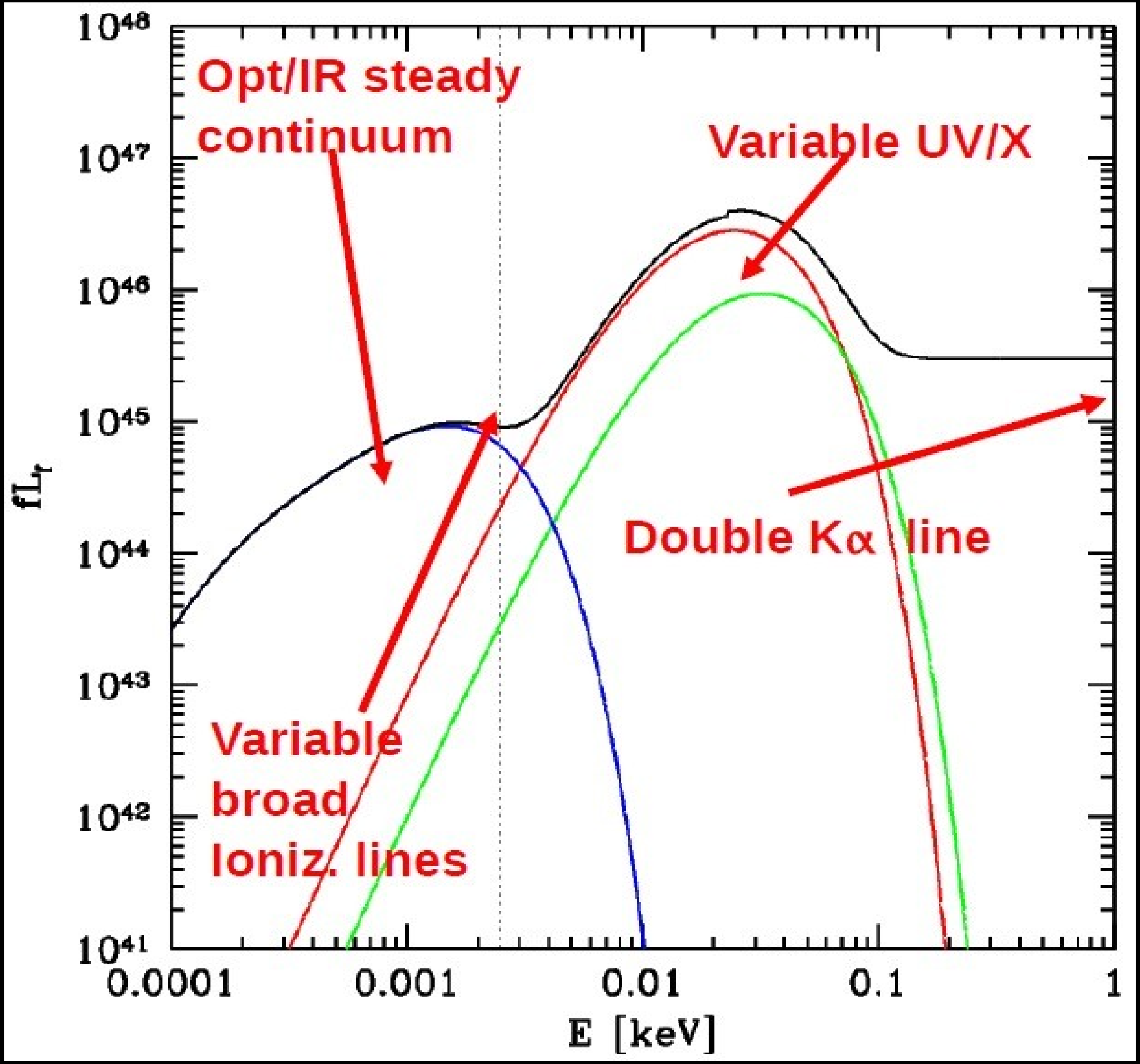
MBH binary + circumbinary disk



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

Associated electromagnetic signatures PTA

MBH binary + circumbinary disk



(Roedig et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013, Farris+, D'Orazio+, Haiman+, Tang+,...)

A variety of possibilities:

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

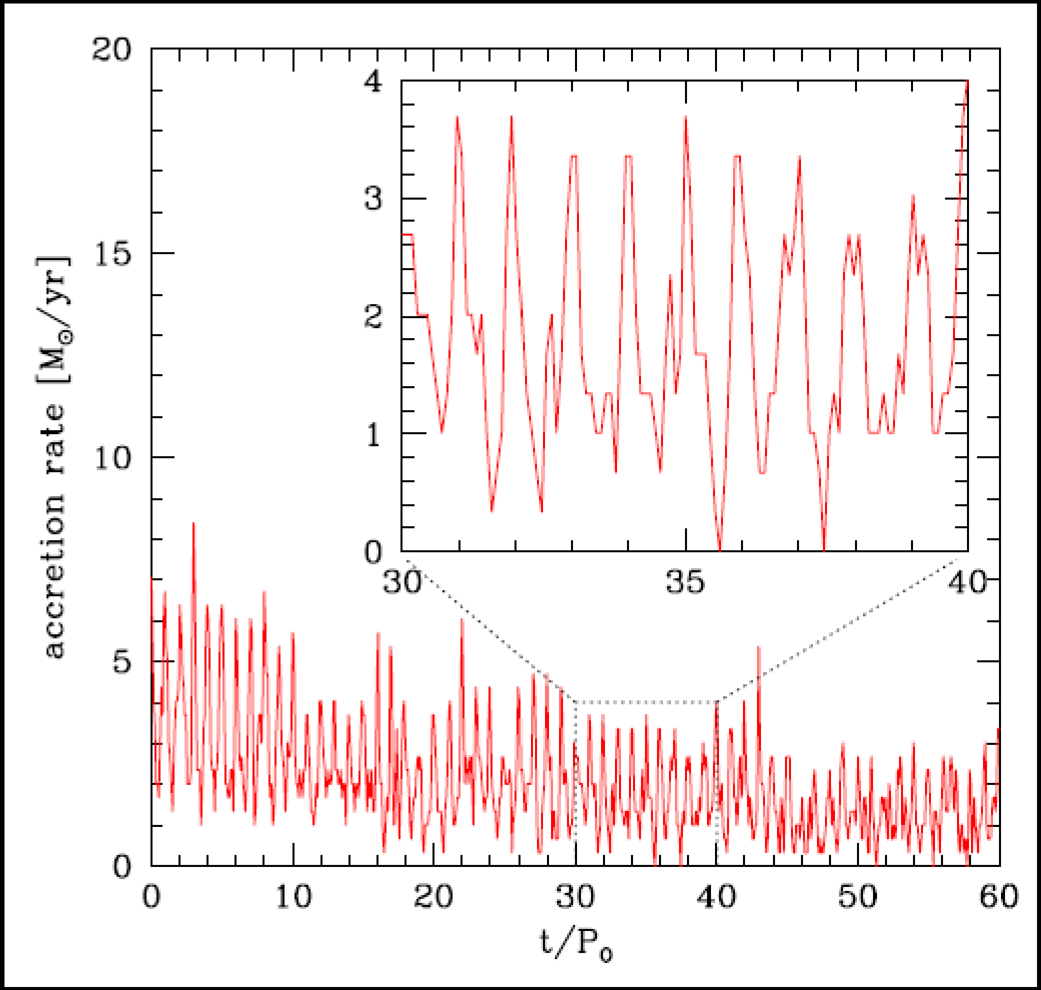
UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

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

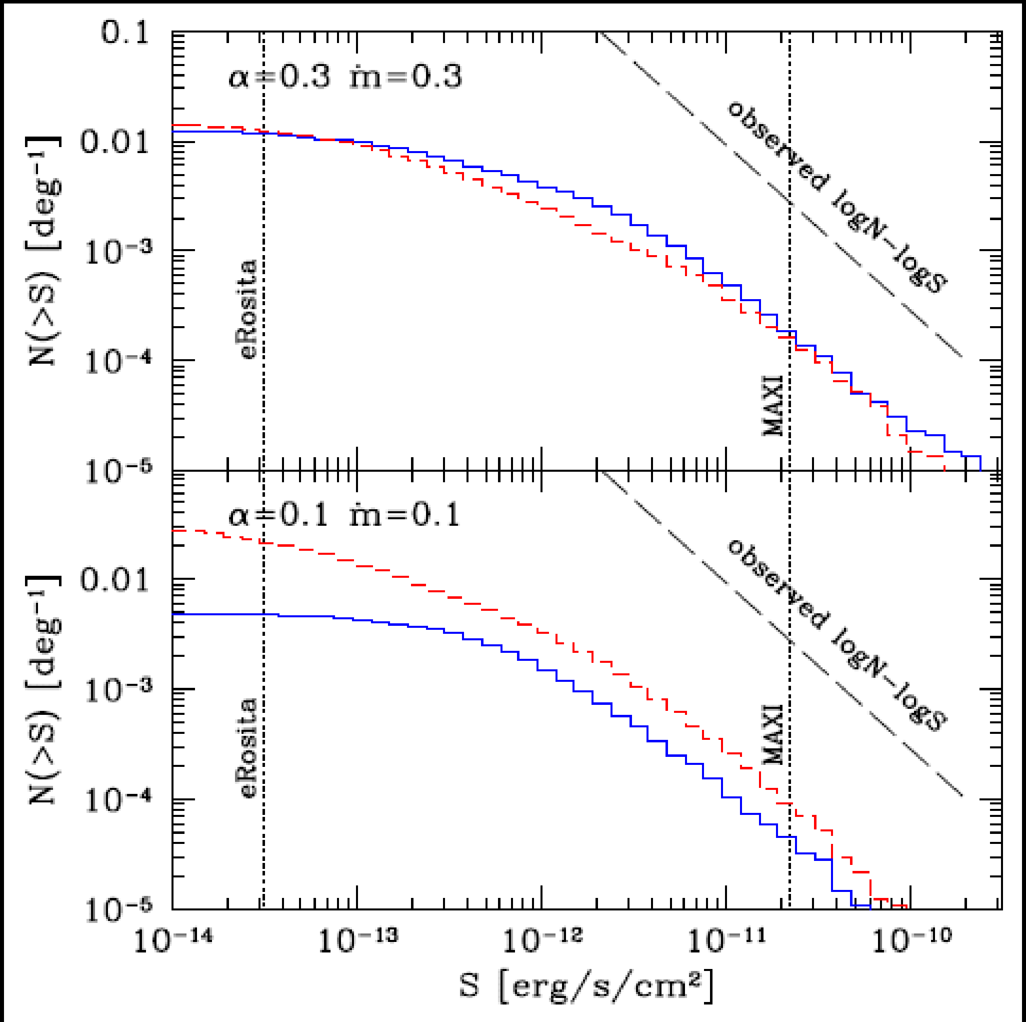
Double fluorescence lines?

Example: variability



Streams feed the inner minidisk extremely intermittent mass inflow.

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



The future

MeerKAT, South Africa (2017)

The future

FAST, China (2017)

The future

Square Kilometre Array (SKA, 2021+)

Doggybag

MBHBs:

-are expected to form In the aftermath of galaxy mergers

-their dynamics is still a matter of active research, but binaries should form and coalesce within an hubble time (reference figure: 10/yr)

-are the loudest GW sources in the Universe

-are expected to have an extravaganza of EM counterparts (but signatures?)

Joint GW-EM observations provide a number of benefits:

- **-Accretion physics**
- **-Cosmography**

LISA + Athena and/or LSST/Rubin might observe up to tens MBHBs in both GW and EM

PTA sources are massive and nearby, they might be 'easily' identified in the EM window