# Multimessenger opportunities with Massive Black Hole Binaries

### Alberto Sesana (Universita` di Milano Bicocca)











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.

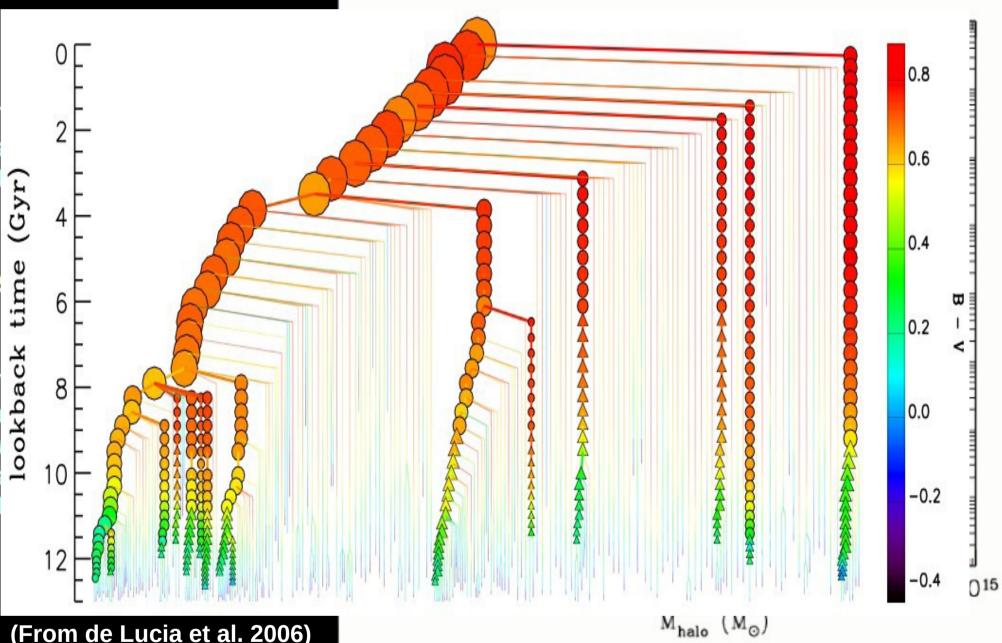
**2-** MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

**3-** Quasars have been discovered at z~7, their inferred masses are ~10<sup>9</sup> solar masses!

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

MBH formation and evolution have profound consequences for GW astronomy





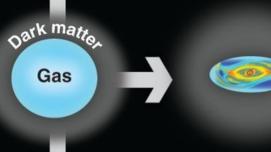
(From de Lucia et al. 2006)

# **Seed BH formation**

Gas cools very slowly forming a stable disc First stars: maybe one star per galaxy, up to several hundred times larger than the sun

mes

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun



Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms



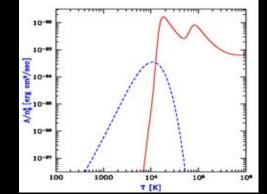
The stellar core collapses into a small black hole, embedded in what is left of the star The black hole swallows the envelope growing up to ~ one million solar masses

Locally unstable gas flows toward the galaxy center Gas fragments into stars, and a dense star cluster forms



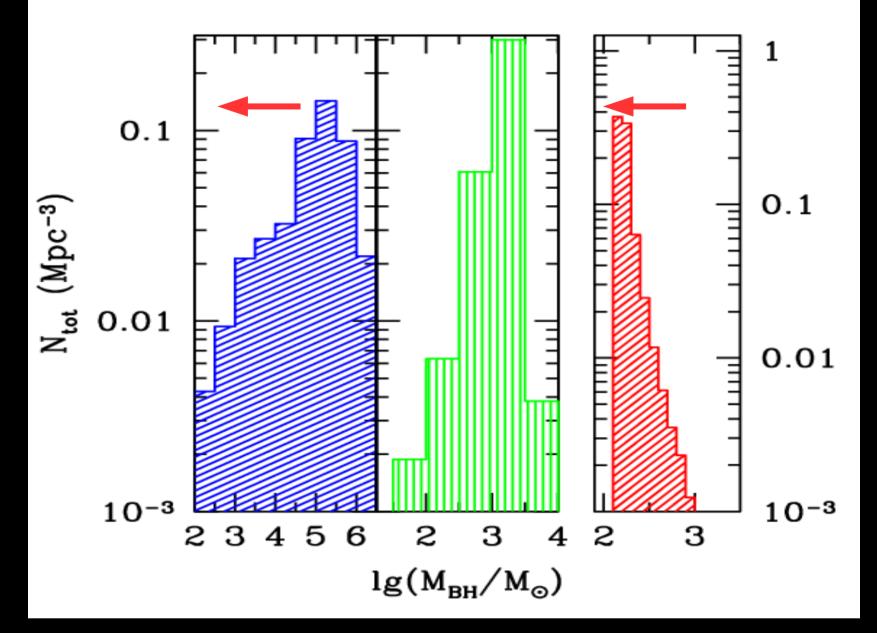
Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

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



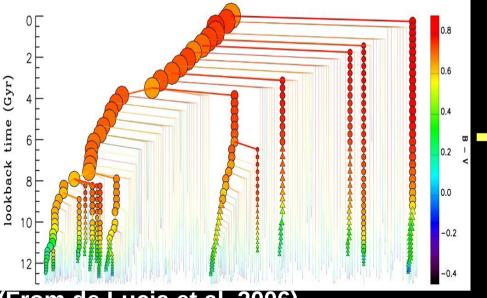
## **Seed BH mass function**

Volonteri 2010

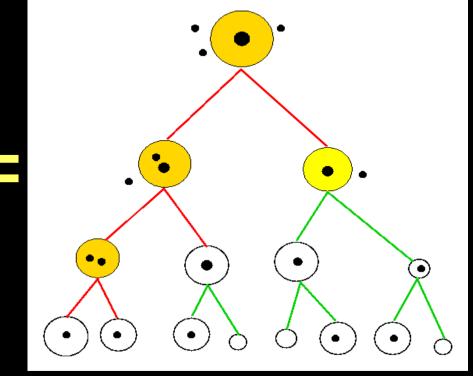


NOTE: The mass function can shift to lower values when wind mass loss and fragmentation are taken into account

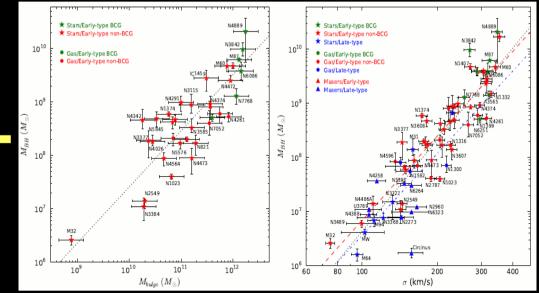
## In a nutshell



#### (From de Lucia et al. 2006)

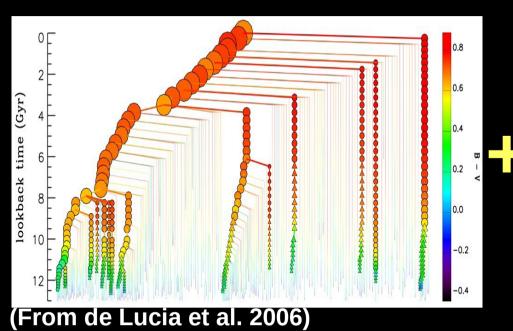


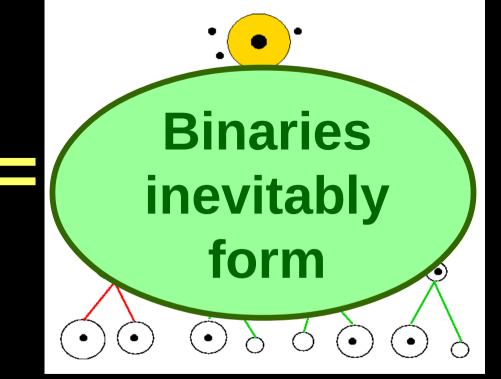
(Menou et al 2001, Volonteri et al. 2003)



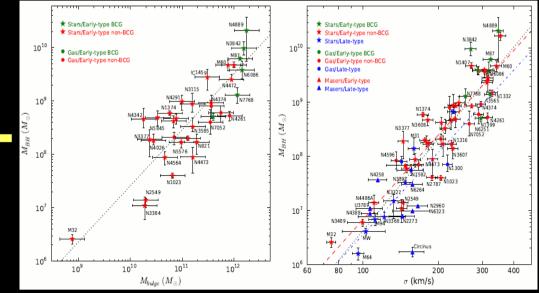
(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

## In a nutshell





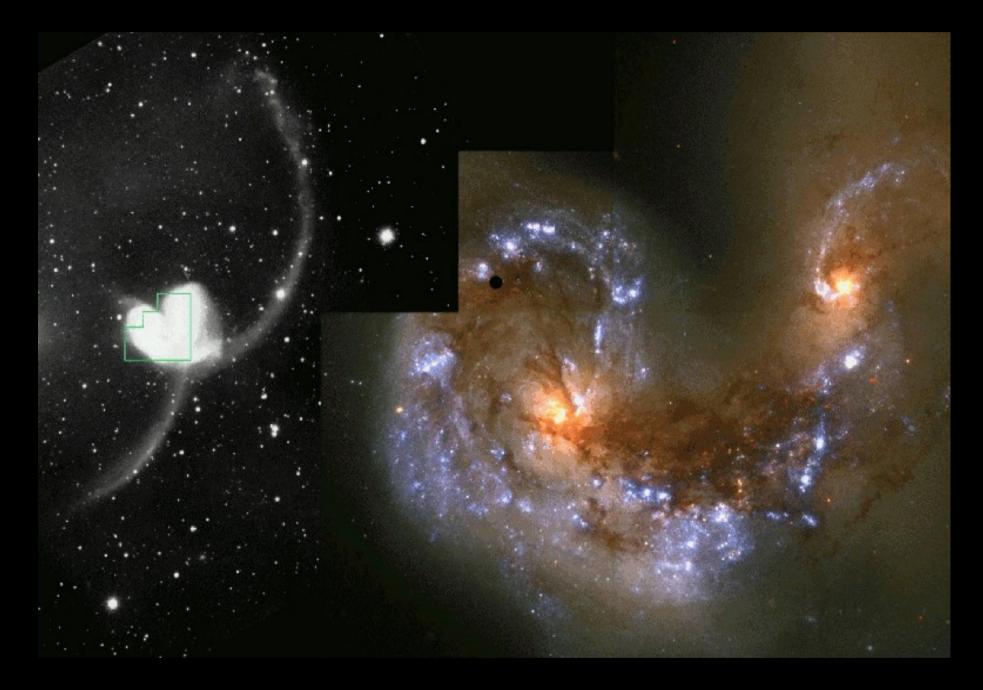
(Menou et al 2001, Volonteri et al. 2003)

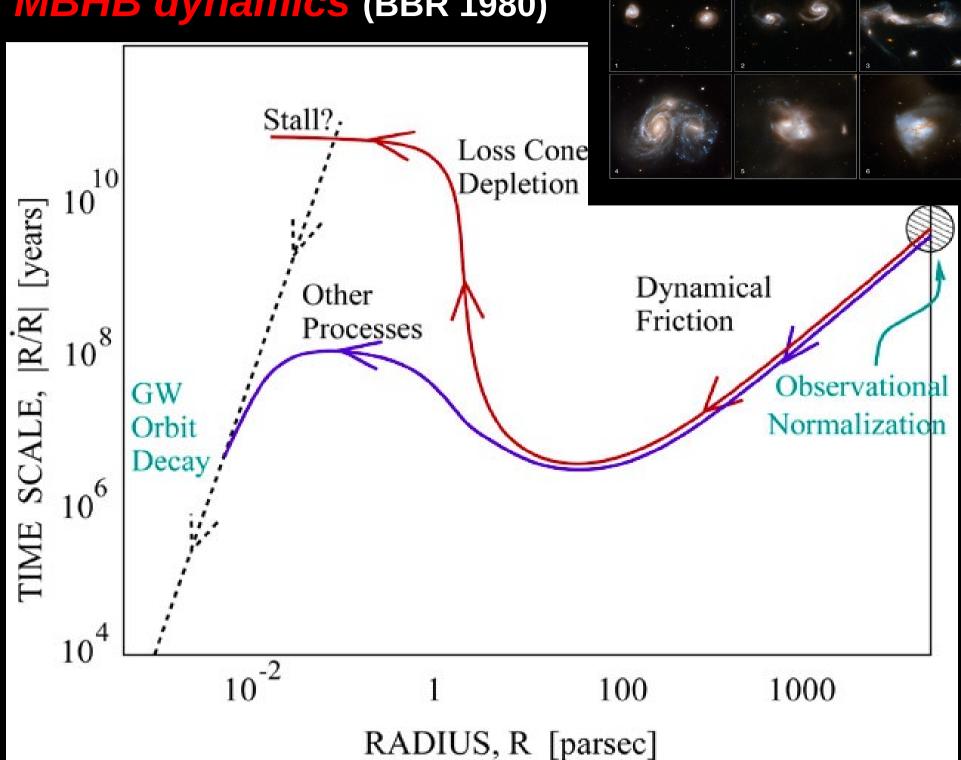


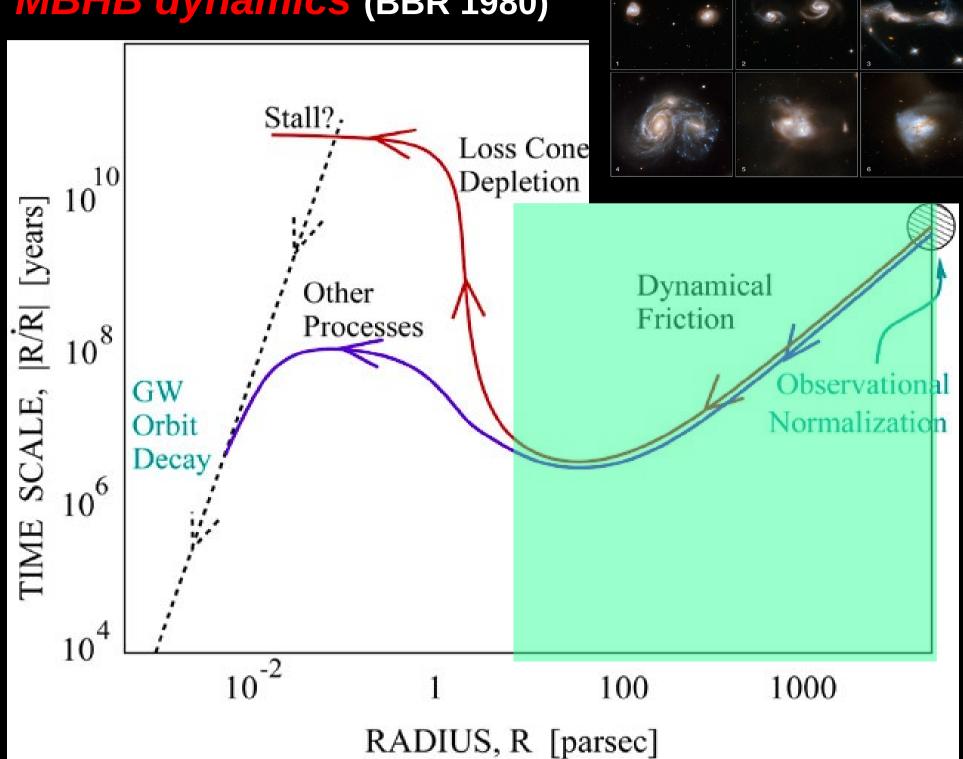
(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

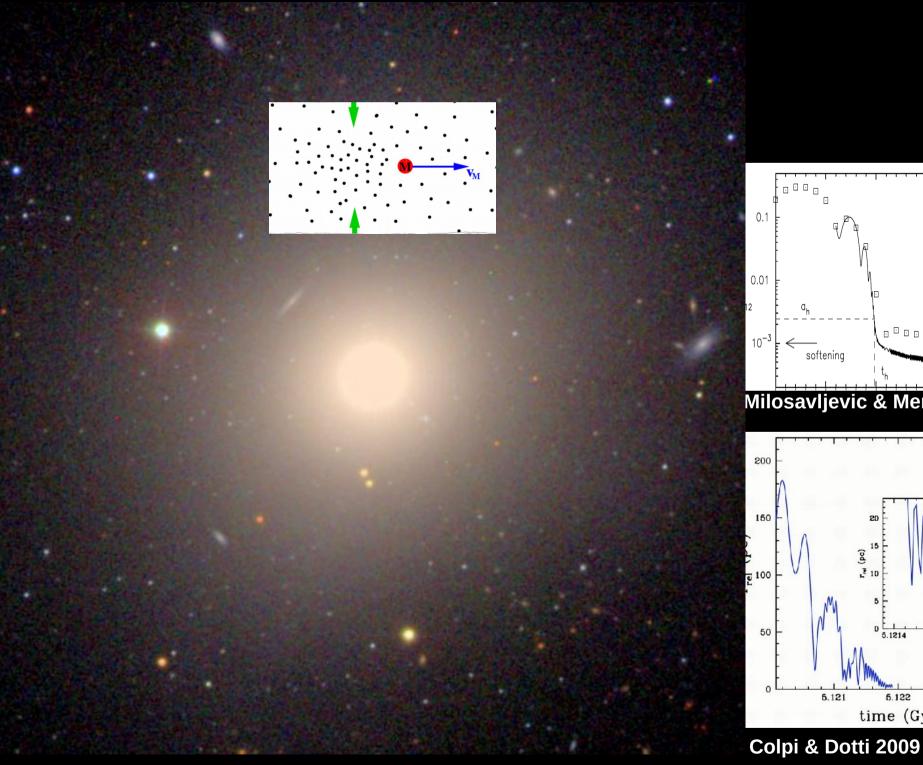
\*Where and when do the first MBH seeds form? \*How do they grow along the cosmic history? \*What is their role in galaxy evolution? \*What is their merger rate? \*How do they pair together and dynamically evolve?

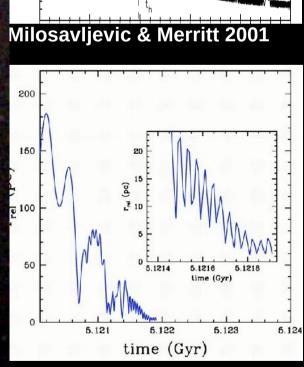
# Mergers

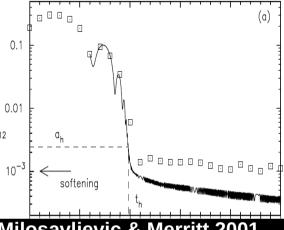


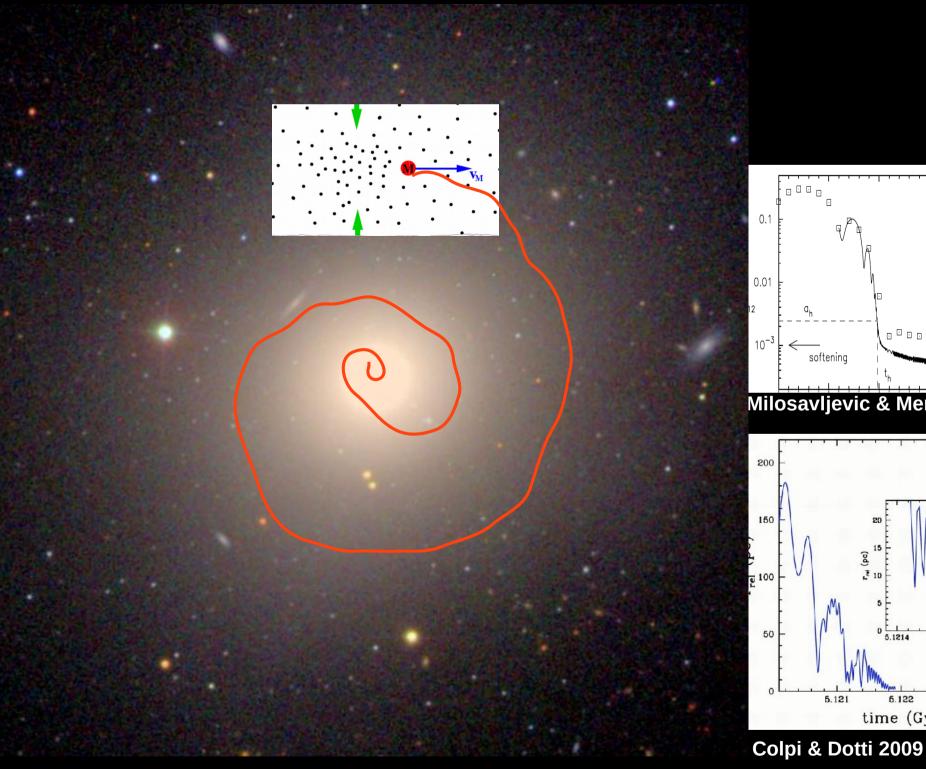


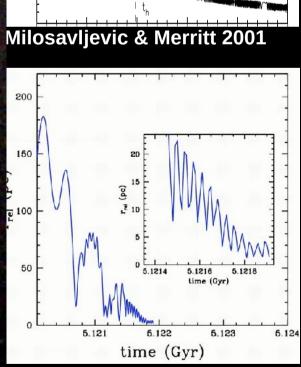


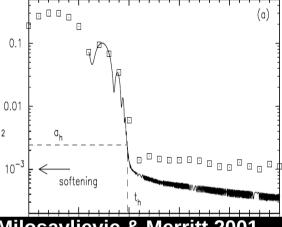


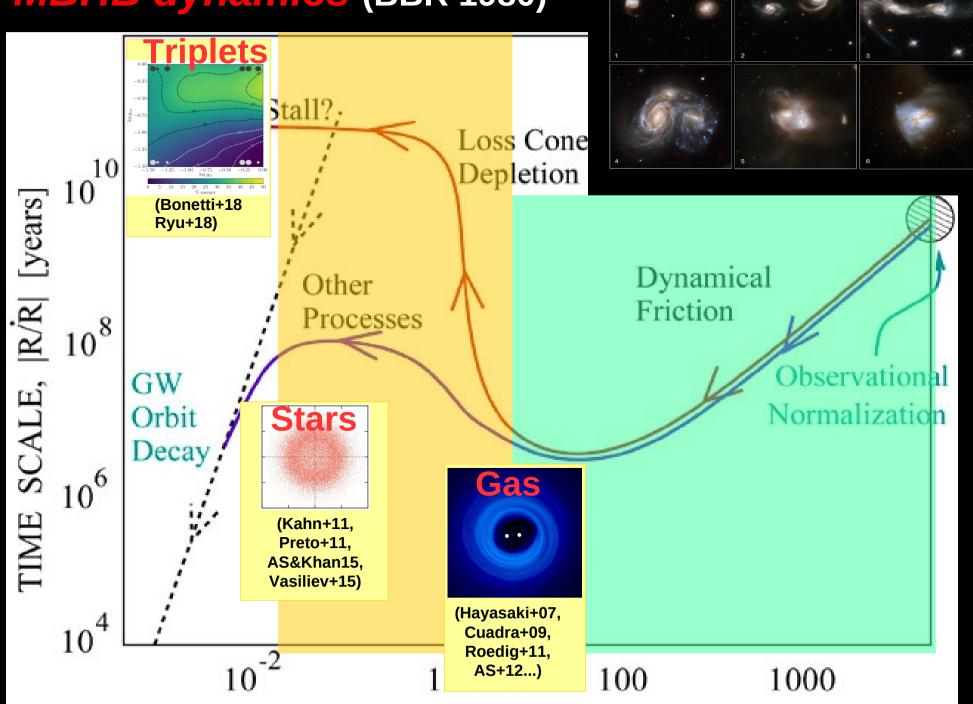






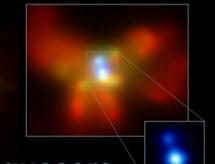




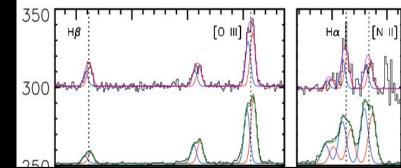


RADIUS, R [parsec]

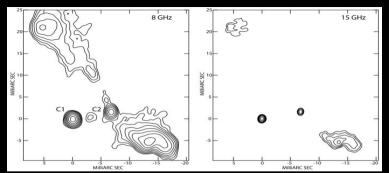
### But do we see them?



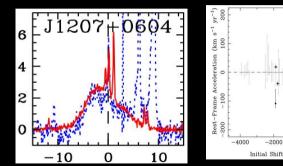
**10 kpc: double quasars** (Komossa 2003)



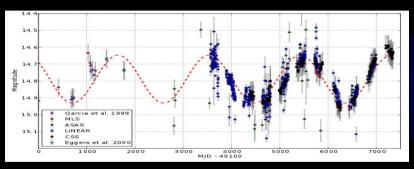
#### 1 kpc: double peaked NL (Comerford 2013)



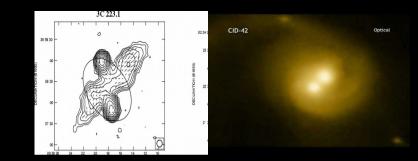
**10 pc: double radio cores** (Rodriguez 2006)



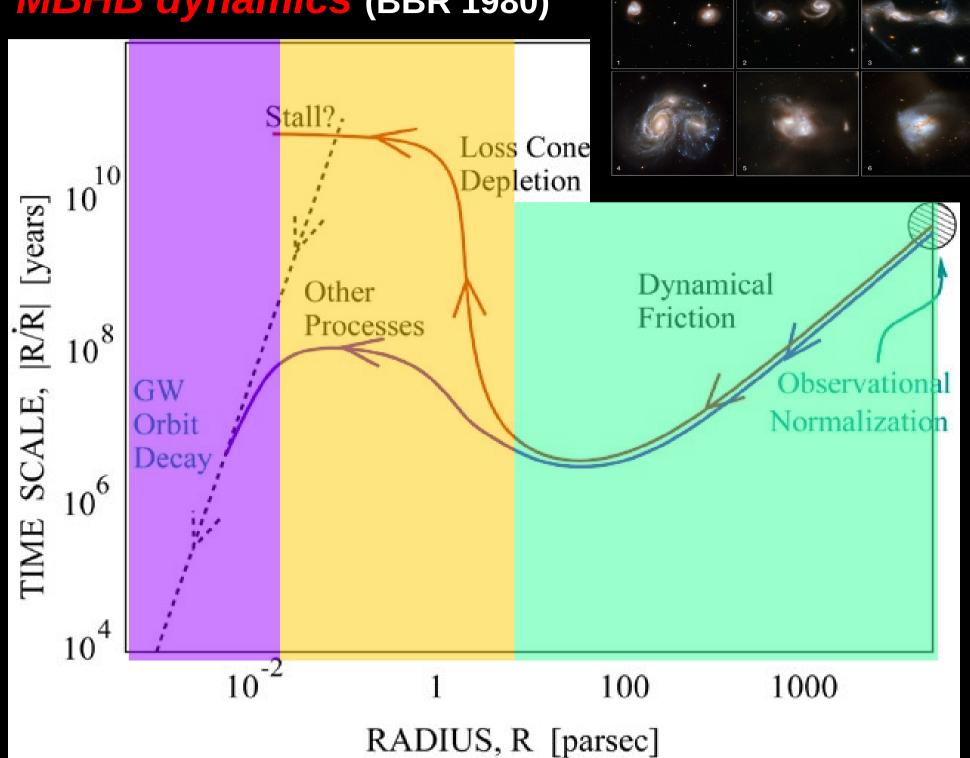
**1 pc:** -shifted BL (Tsalmatzsa 2011) -accelerating BL (Eracleous 2012)







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



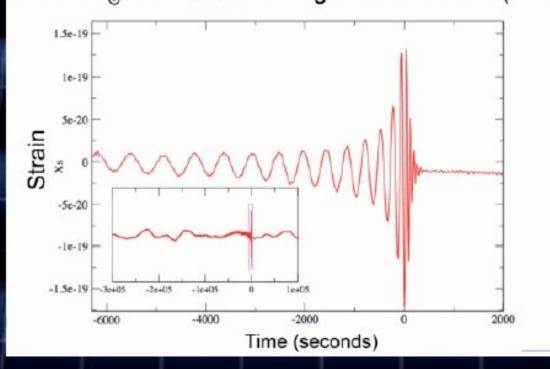
# **Gravitational waves**

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

$$t_{\rm GW} = \frac{5c^5}{256G^3} \frac{a^4}{M_1 M_2 MF(e)} \approx 0.25 \text{Gyr} \left(\frac{MM_1 M_2}{10^{18.3} \text{ M}_{\odot}^3}\right)^{-1} F(e)^{-1} \left(\frac{a}{0.001 \text{ pc}}\right)^4$$

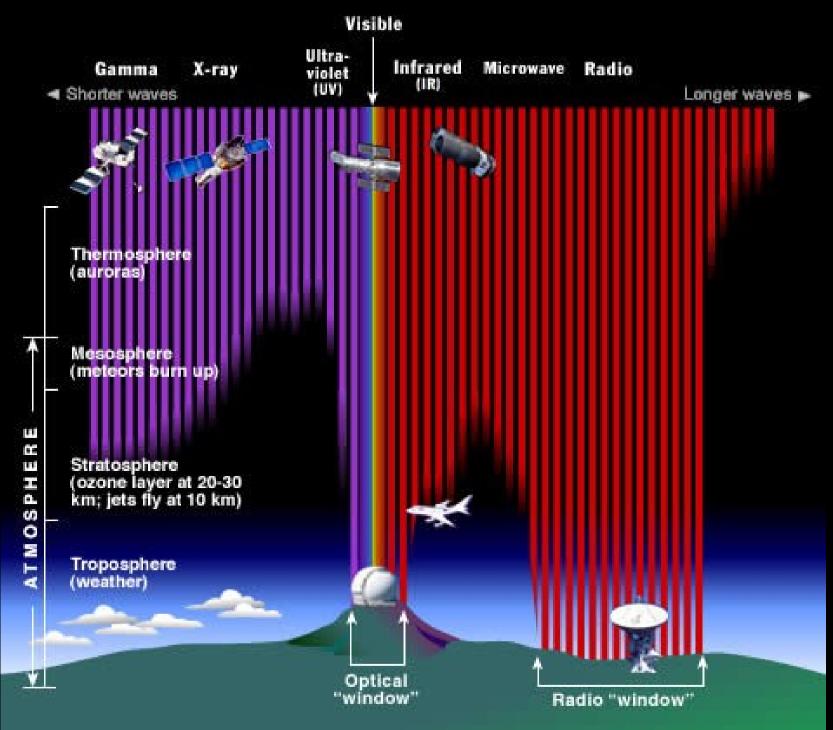
### producing the loudest gravitational wave signals in the Universe!

Simulated LISA data stream at merger event, two 10<sup>5</sup>M<sub>☉</sub> BH at z=5 including simulated noise (S/N~500)



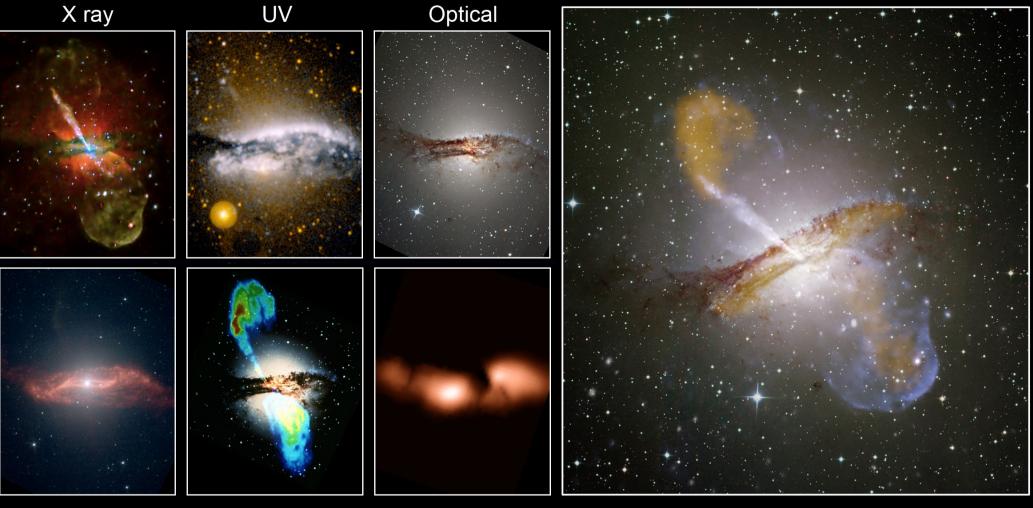


### **Electromagnetic radiation spectrum**



#### 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



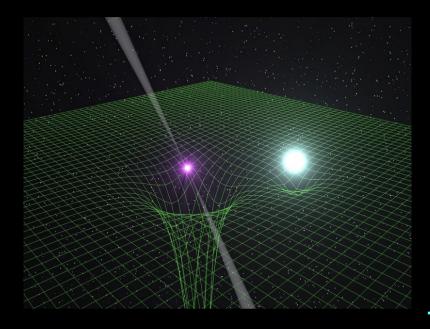
MIR

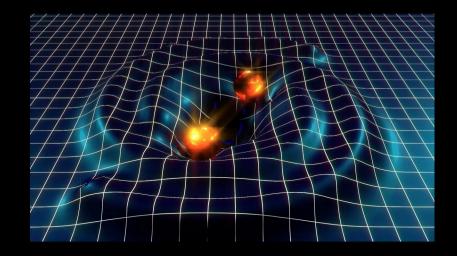
Radiocontinuum

ΗI

X ray + Optical + Submillimetre + Radio Composition

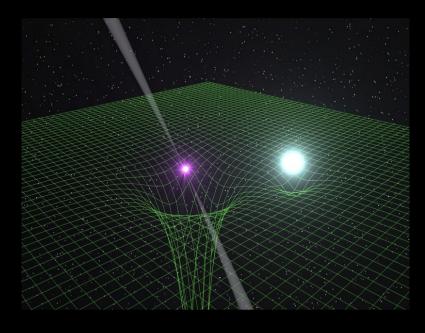
#### What happens if two compact objects (e.g. black holes) orbit each other?

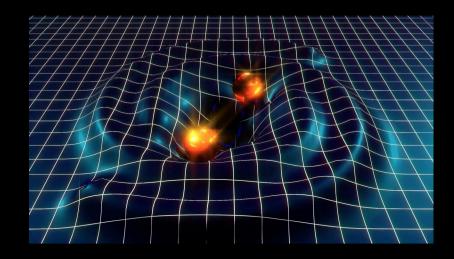




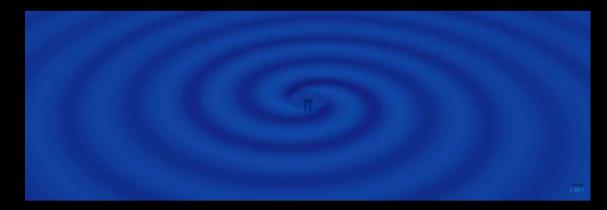
# The space distortion changes in time, following the motion of the two objects

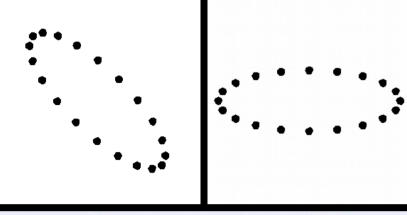
#### What happens if two compact objects (e.g. black holes) orbit each other?



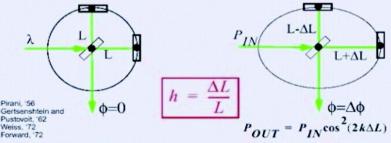


# The space distortion changes in time, following the motion of the two objects





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

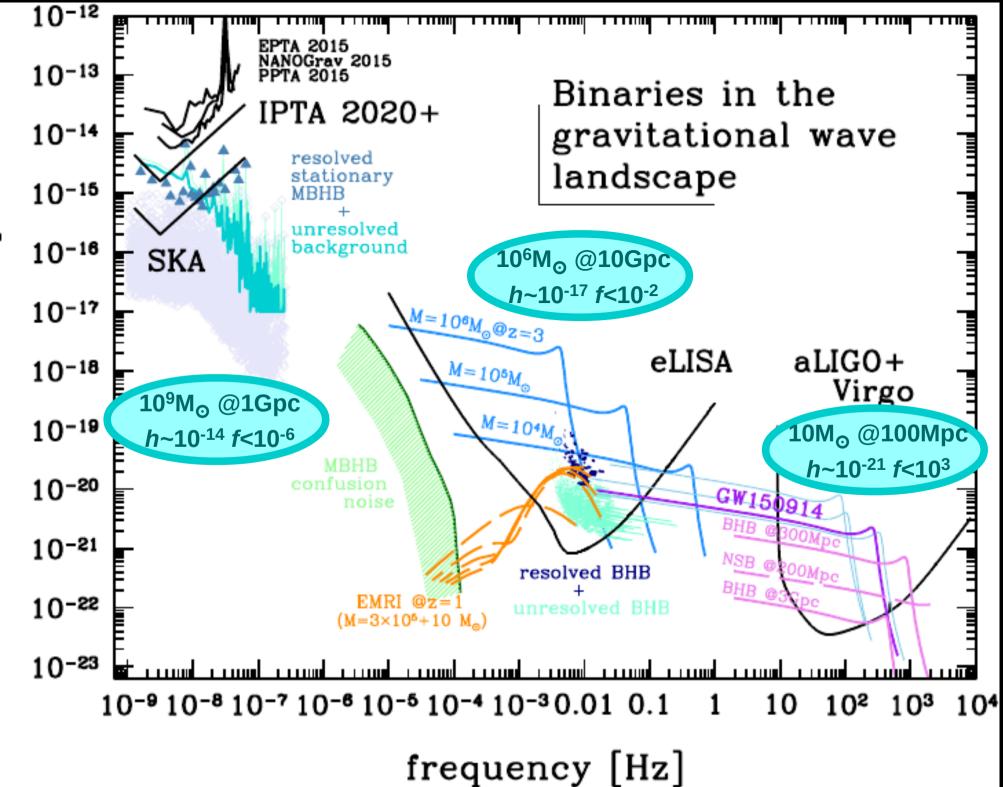
$$h \sim \frac{R_S}{a} \frac{R_S}{r} \sim \frac{(GM)^{5/3} (\pi f)^{2/3}}{c^4 r}$$

#### 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<sub>o</sub> binary at 100 Mpc: *h*~10<sup>-21</sup>, *f*<10<sup>3</sup> 10<sup>6</sup> M<sub>o</sub> binary at 10 Gpc: *h*~10<sup>-18</sup>, *f*<10<sup>-2</sup> 10<sup>9</sup> M<sub>o</sub> binary at 1Gpc: <u>*h*~10<sup>-14</sup></u>, *f*<10<sup>-5</sup>



characteristic amplitude

## **The Laser Interferometer Space Antenna**

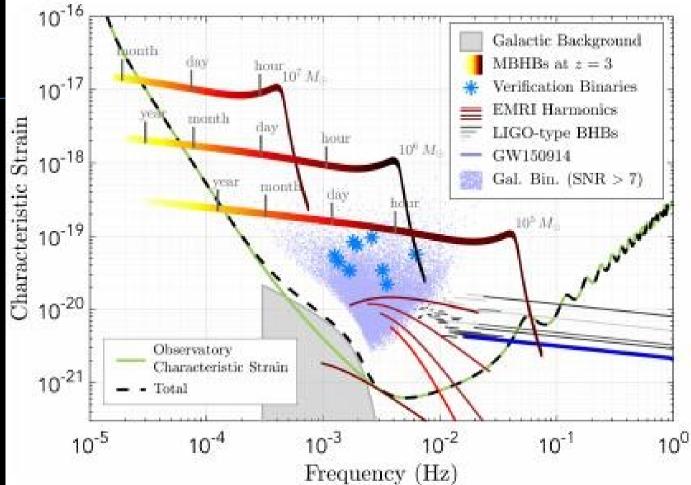
Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

### **Observes the full** inspiral/merger/ringdown

Nicolas Douillet - ARTEMIS

#### 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 News Multimedia Conferences Positions Papers Code of Conduct Cor LISA

#### https://www.lisamission.org/

LISA Consortium User Guide User guide 
Groups 
Getting help 
Contributing

#### LISA Consortium User Guide

#### Key information Collaborative tools

- Development tools and guidelines
- Sharing data tools
- Computing resources

#### LISA Consortium User Guide

This User Guide goal is to gather all the information related to the LISA Consortium tools. Users are more than welcome to contribute to its improvement. To do so, see the HowToContribute page.

#### **Key information**

- LISA Consortium website
- Sign-up for the LISA Consortium
- Organisation
- LISA websites
- Key documents
- Next meetings (need to be logged to the wiki see LISA wiki)
- Acronyms
- Publication and Presentation Committee
- Inclusion and Diversity Committee
- Positions related to LISA

#### Collaborative tools

- LISA wiki
- LISA Document Management Sytem (DMS) Atrium
- Mailing lists
- Messaging on slack channels
- Audio / Video teleconferences

#### Development tools and guidelines



holes

#### **Mailing lists**

Consortium:consortium@lisamission.org

#### Management

- Consortium Lead : consortiumlead@lisamission.org
- Exec Board : exec\_board@lisamission.org
- Board Member: board@lisamission.org
- Coordinator:coord@lisamission.org
- Coordination Group : coordination@lisamission.org
- Publication Committee : pubcom@lisamission.org
- Publication Committee Chairs: pubcom-chairs@lisamission.org

ESA: A unique experiment to explore black

What happens when two supermassive black holes collide? Combining the observing power of two future ESA missions, Athena and LISA, would allow us to study these cosmic clashes and their mysterious aftermath for the first time. 100

Search

LISA Consortium Internal

LISA Consortium Reboot

Portal here: https://signup.lisamission.org

We are now ready to reboot the Consortium and ask you to

apply. You will find all necessar information on the Application

#### Full Member Groups

#### LISA Instrument Group

- LISA Instrument Group : lig@lisamission.org
- LIG Core:lig-core@lisamission.org
- LIG Performance Modelling WG: lig-pmwg@lisamission.org
- LIG-OB:lig-ob@lisamission.org
- LIG-PMS:lig-pms@lisamission.org
- LIG-GRS:lig-grs@lisamission.org
- LIG-OMS:lig-oms@lisamission.org
- LIG-Chairs: lig-chairs@lisamission.org
- LIG SLWG Chairs: lig-slwg-chairs@lisamission.org
- LIG Performance Modelling WG Chairs: lig-pmwg-chairs@lisamission.org

Simulation Working Groups Associate and Full Members Groups LISA Data Challenge Working Groups Astrophysics Working Groups Cosmology Working Groups Eundamental Physics Working Groups Waveform Working Groups Advocacy and Outreach Working Groups

Mailing lists

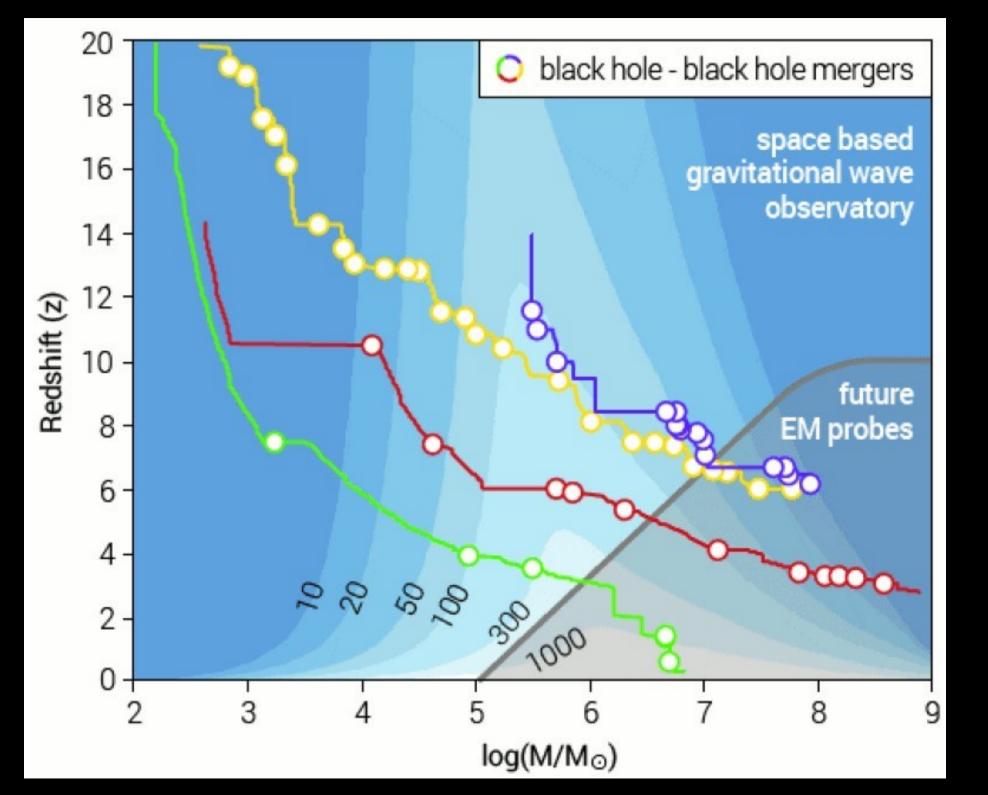
Managemen

Full Member Groups

LISA Instrument Group

LISA Science Group

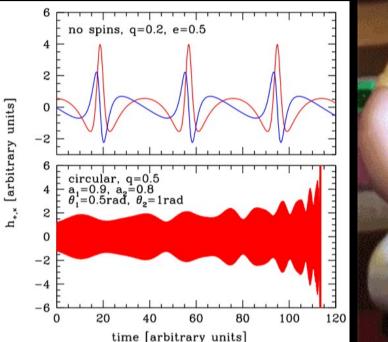
LISA Data Processing Group



# What LISA will measure

Assuming 4 years of operation:

- ~100+ detections
- ~100+ systems with sky localization to 10 deg2

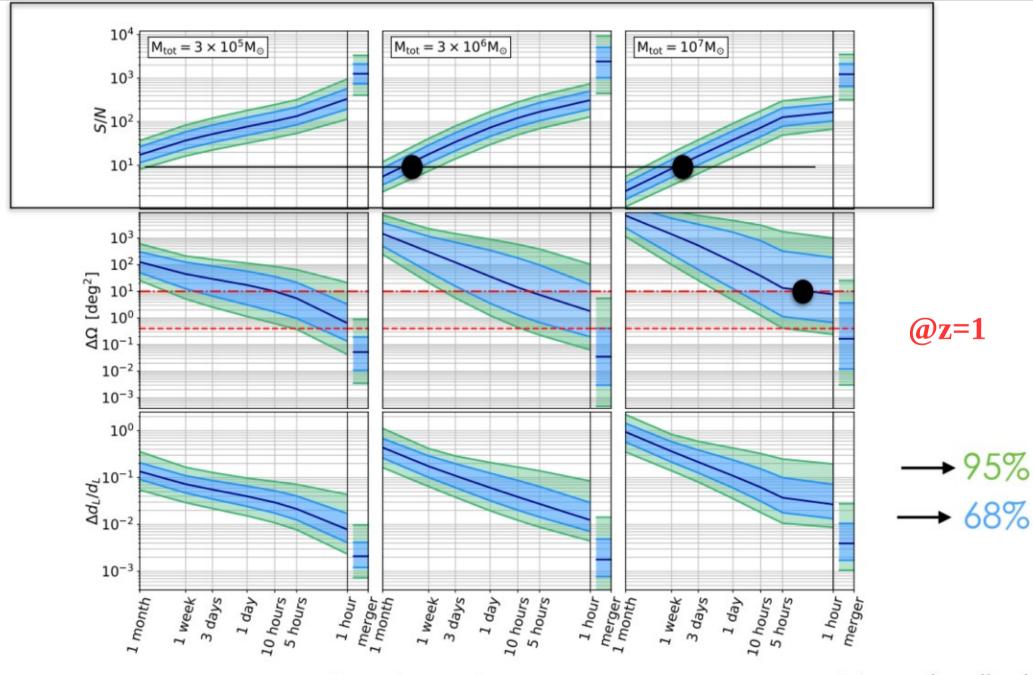




~100+ systems with individual masses determined to 1%

- ~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

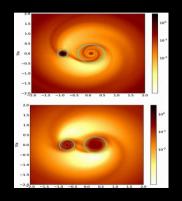


time to coalescence

Mangiagli et

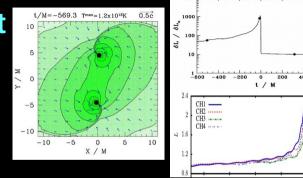
# Associated electromagnetic signatures

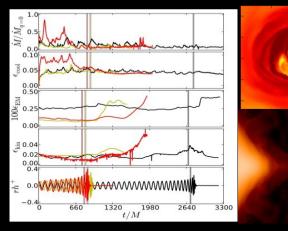
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005). However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014, Tang et al. 2018...)



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

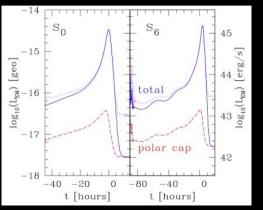
t=0M

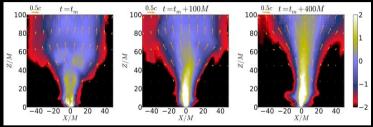


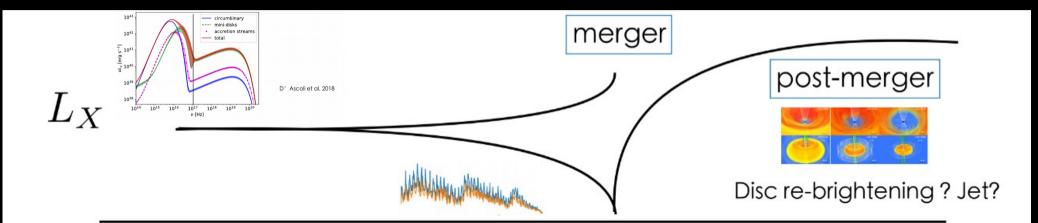


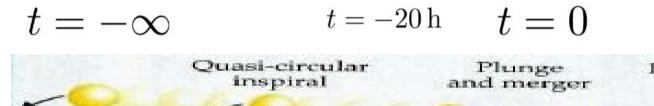
Simulations in disk-like geometry. Variability, but much weaker and unclear signatures (Bode et al. 2012, Gold et al. 2014)

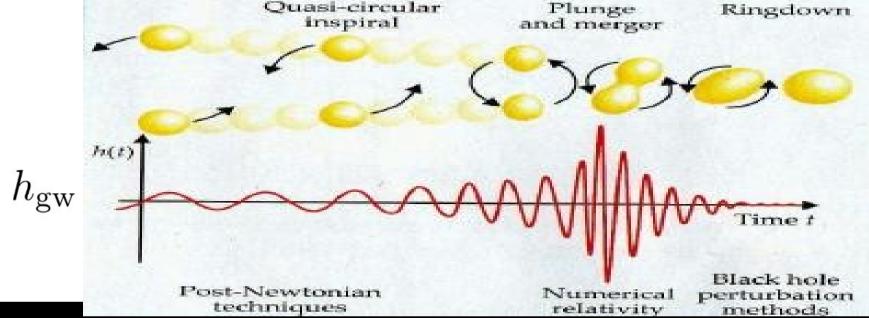
Full GR force free electrodynamics (Palenzuela et al. 2010, 2012)











# Opportunities for LISA-Athena (LSST/Rubin) synergies

#### THE ATHENA MISSION



Large Synoptic Survey Telescope

# Athena Wide Field Imager (WFI)

Parameter Characteristic 0.1-15 keV **Energy Range** Field of View ca. 40' x 40' (baseline)  $(10^6 M_{\odot}, 10^6 M_{\odot})$  @z = 1 $(10^6 M_{\odot}, 10^6 M_{\odot})$  @z = 2FOV-averaged flux limit 10-15 Da WEI 1.4m2 5" keV flux limit [erg s<sup>-1</sup> cm<sup>-2</sup>] Athena WFI 1.4m<sup>2</sup> 10<sup>-16</sup> Athena WFI 2m<sup>2</sup>, 5" 5-2  $L_{\rm X} = 10^{43} {\rm ~erg~s^{-1}}$ 10-17 AGN at z = 61000 10 10 ks~3 hours 100 Exposure time [ks]

10000 10000 10000 WFI mirror area 0.2 0.5 1 2 5 10 Photon Energy [keV]

(Rau+ 2015)

-X-ray telescope

-L2 ESA mission (~2030)

### LSST : Vera Rubin observatory



-2022+

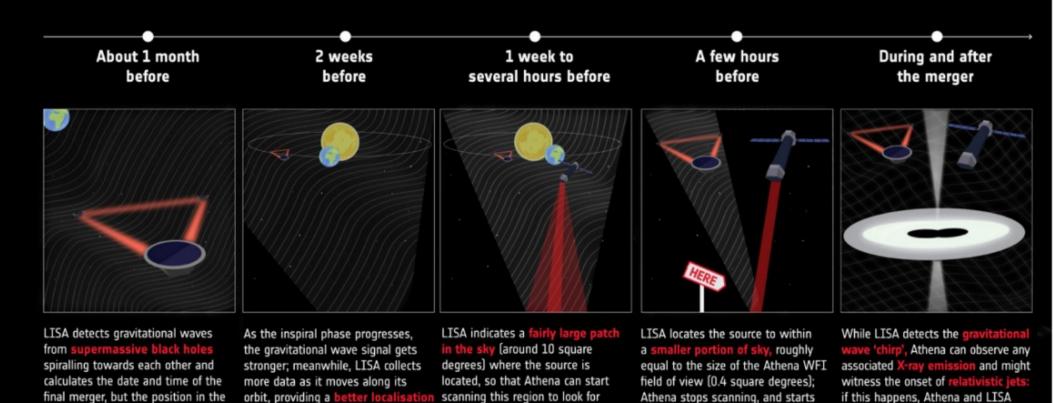
-Optical telescope

-9.6 square degree FoV

-m~24 within 30s pointings in several different filters

#### → HOW CAN LISA AND ATHENA WORK TOGETHER?

of the source in the sky



the source with its Wide Field

Imager (WFI)

staring at the most likely position of

and merger of the black holes

the source, witnessing the final inspiral

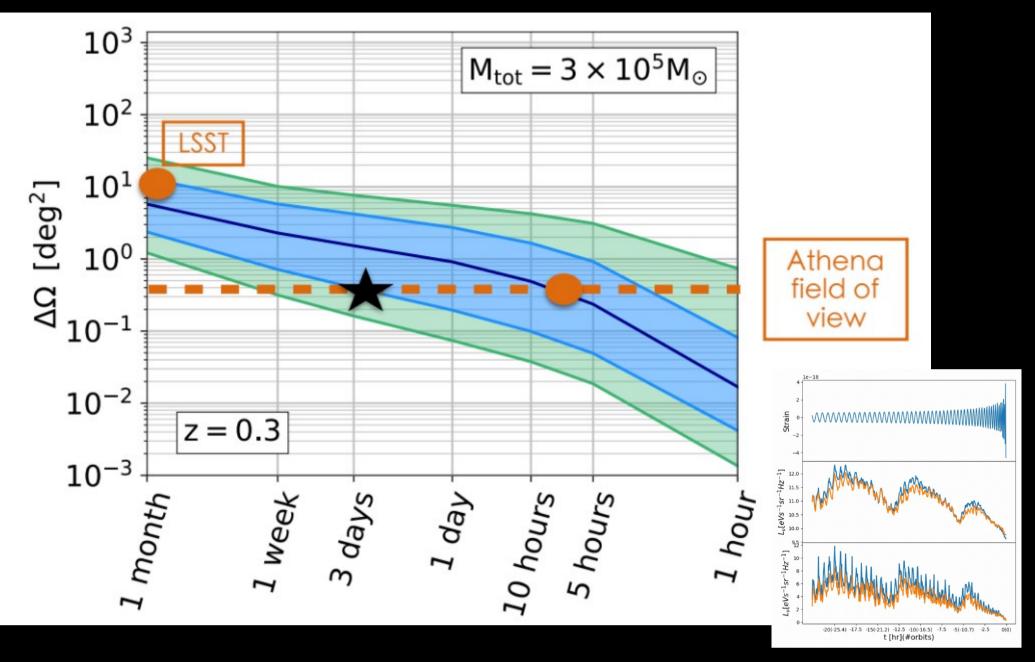
sky is unknown

Space19 🞯

may witness the birth of a new

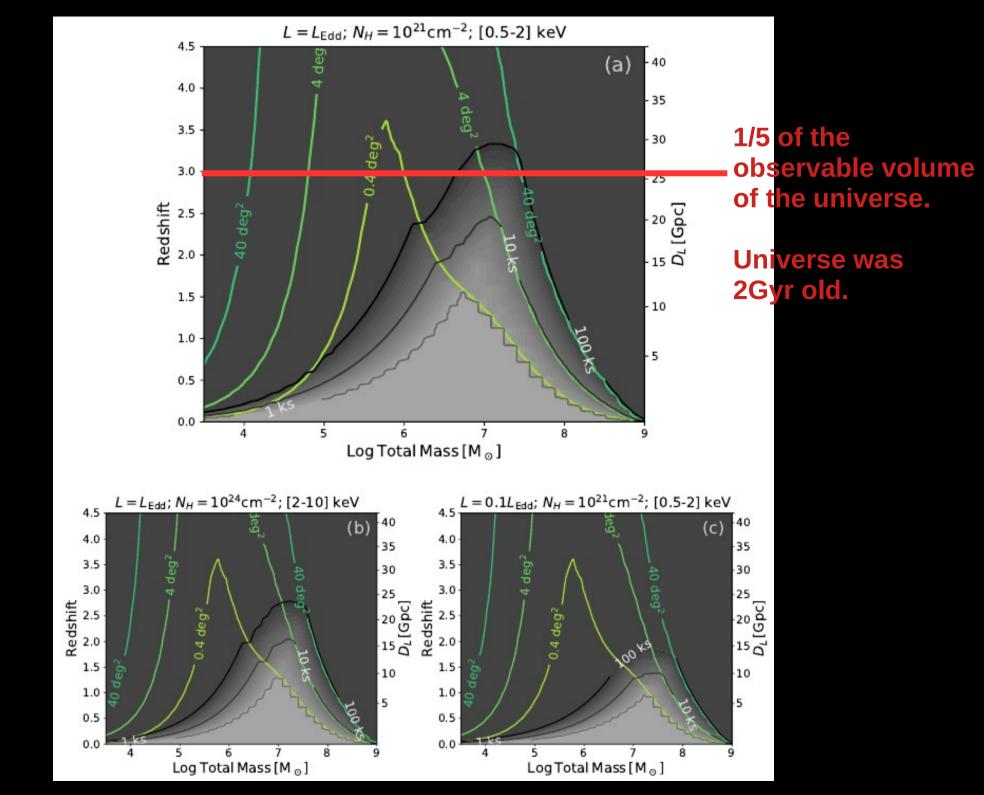
'active galaxy'

· eesa



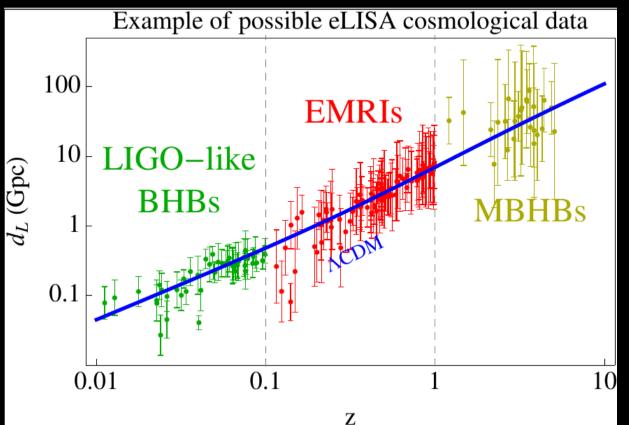
-Athena pre-pointing only possible for very low z sources

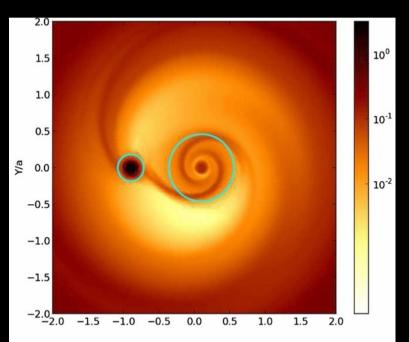
-LSST/Rubin more suitable for tracking inspiral periodicity (but optical)

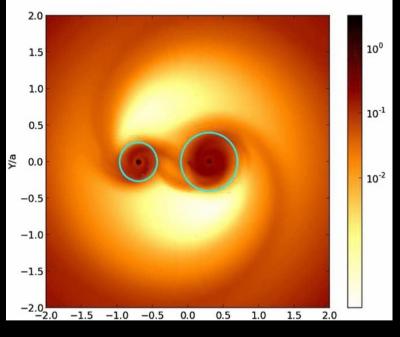


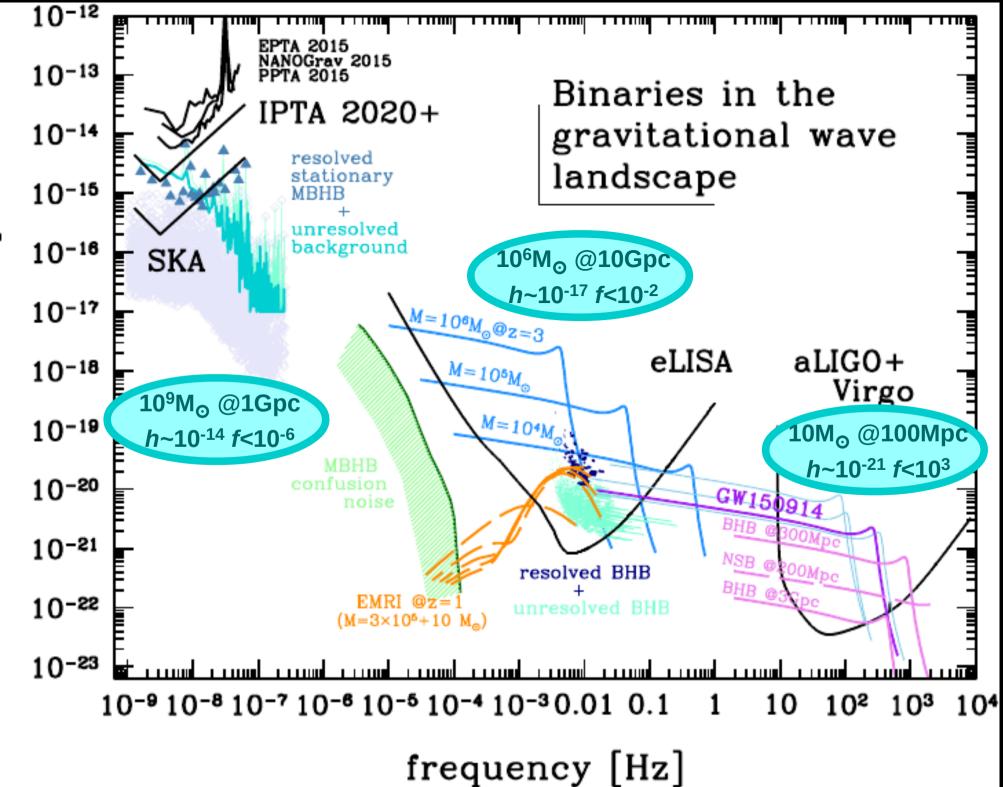
### Why multimessenger?

- 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 ...









characteristic amplitude

## **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** 

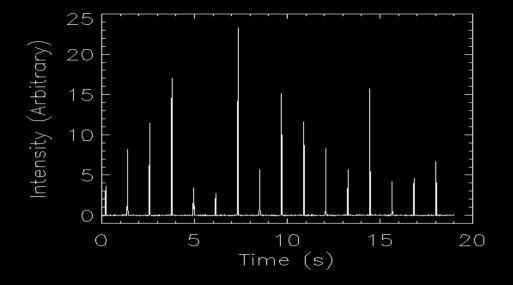
**2-Find the model which best fits the ToAs** 

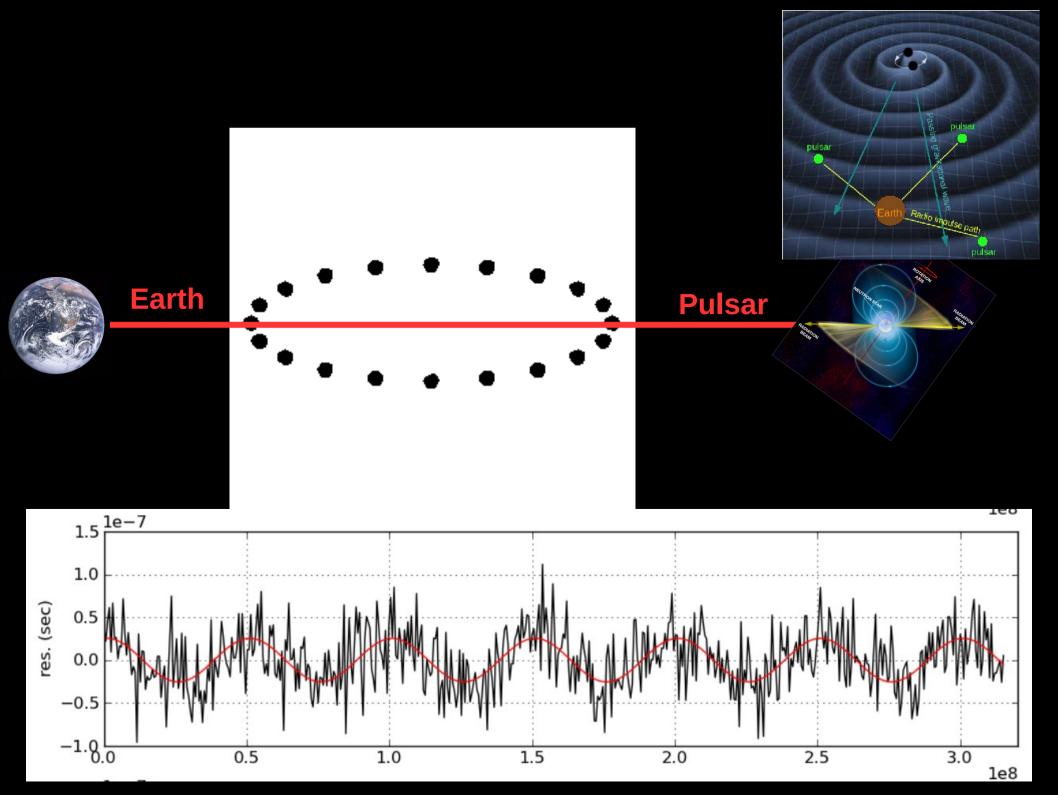
**3-Compute the timing residual R** 

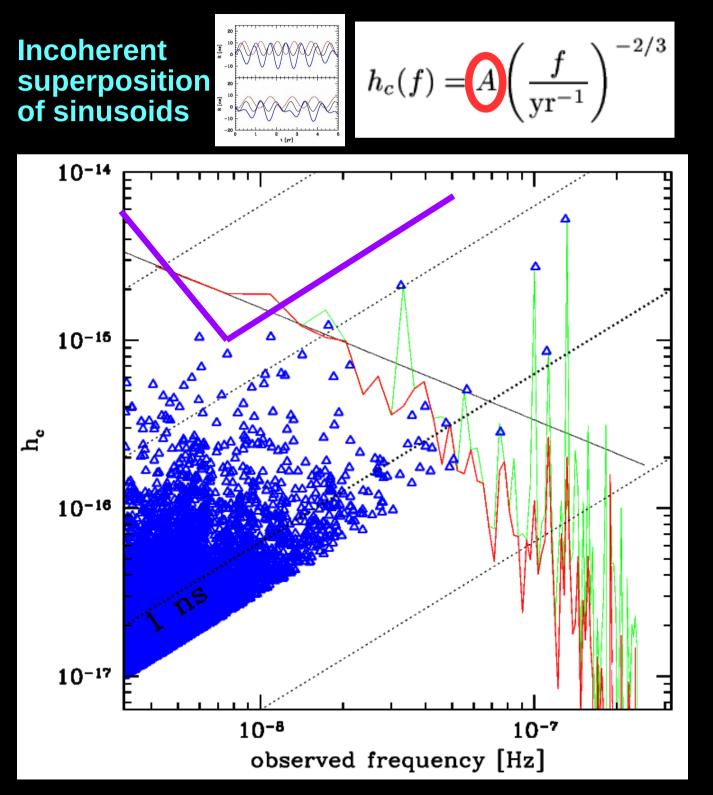
# **R**=ToA-ToA<sub>m</sub>

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

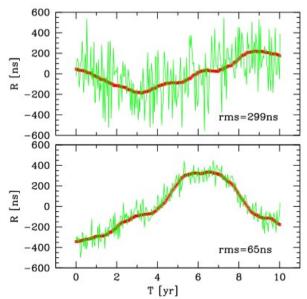








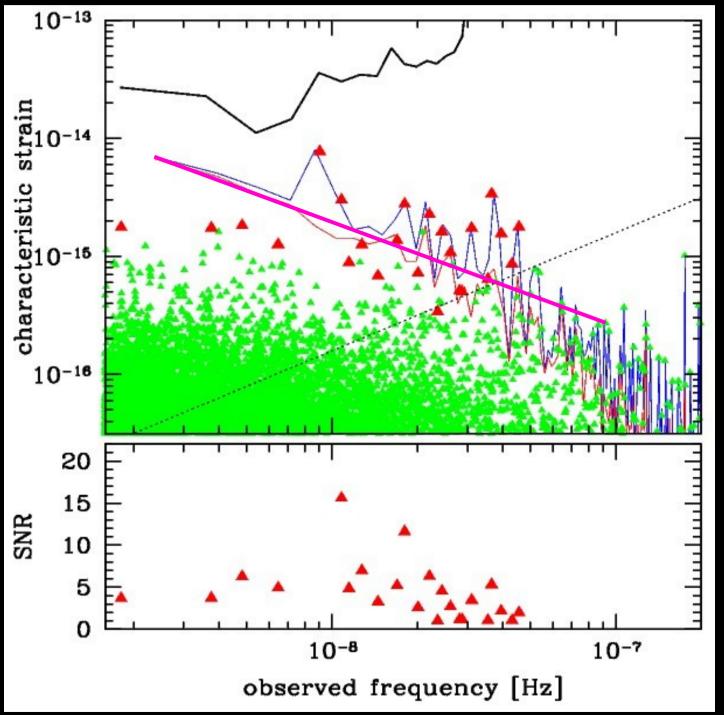
#### Simulated signal



#### **Actual data**

in the part of the same the second	J0437-4715
Bill an al selects, stands income, oft-	0.49 µs
. اس میں جمع ہے جاتے ہو گاہ جمعہ است اگر ، جمع کو تاریخ	J0613-0200
and the state of t	8.20 µs
. تحسب المحد المراقب بالفراج معالم المحرب المحديق وألف	J0711-6830
	39.03 µs
المحاجب ومأورعته المبتر متألفة بالحقاق بأجاب فستشعا عروراتهم	J1022+1001
and the summary of the state of	23.90 µs
القد بالموجد بعجموب ألك في الجوابية سلم وحواجاتهم القوم	J1024-0719
	22.24 µs
المؤاد ومندونا وماسراتهم والمتقار أبأوا فتحقيه والرجوا لأعيته وتحتر وورد والتقار	J1045-4509
aber attalite entreter and ble and been atte	24.02 µs
And the second state of th	J1600-3053
and the second s	7.62 µs
A second s	J1603-7202
	13.08 µs
and the second state of th	J1643-1224
	13.32 µs
······································	J1713+0747
	2.47 µs
٠ - نې د <sup>6</sup> د مرحيه موني ( ، لې ، دو يو لو ، و استور و <mark>م</mark> تر و <mark>م</mark> ر يو يو و و و و و و و و و و و و و و و و	J1730-2304
	16.09 µs
······································	J1732-5049
	25.10 µs
The second s	J1744-1134
All and a second se	9.79 µs
A CONTRACTOR OF	J1824-2452A
	16.63 µs
ڰؘۅۅڰۅ؋؋ۅۼڰۿۅؾۼؚڂڡ؇ؖ؋؆ڛؾڐۣ؞ڵڡ؋ڰ۠ٳۅڟڐؾ؇ڡ؆ڡڰڡڰؚۄۅڟٵۅۅ؇	J1857+0943
	8.63 µs J1909-3744
······································	J1909—3744 2.32 для
	2.32 µs J1939+2134
The second se	5.02 µs
allalis, or a fam. a flag a she will be a strong to	J2124-3358
A WARD IN TRANSPORT IN THE ADDRESS OF A DESCRIPTION OF A	28.01 µs
	J2129-5721
· · · · · · · · · · · · · · · · · · ·	35.46 µs
. حديد موجود موجود المراجع المراجع المرجوع المرجوع المرجوع المرجوع	J2145-0750
	38.15 µs
2006 2008 2010	par
0102 0003 0003	

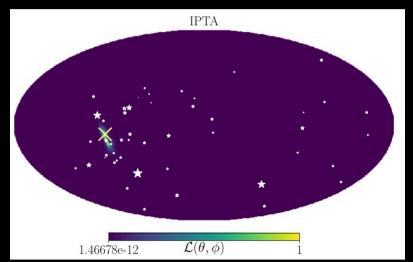
#### **Resolvable sources** (AS et al 2009)



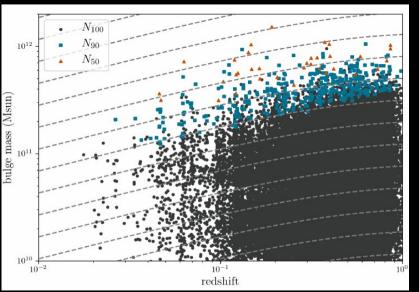
\*It is not Gaussian
\*Single sources might pop-up
\*The distribution of the brightest sources might well be anisotropic

\*It is not smooth

## Finding the right galaxy



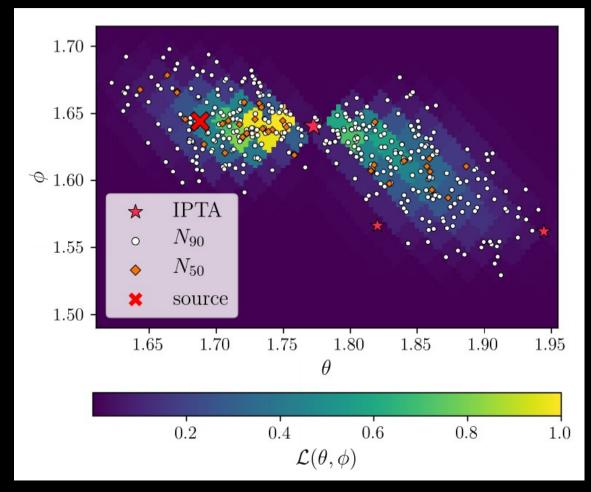
An individual PTA source must be massive and/or nearby → Only several tens of credible candidates (Goldestein et al 2019)



In general, PTA cannot break the distance-mass degeneracy (*A~M<sup>5/3</sup>/D*)

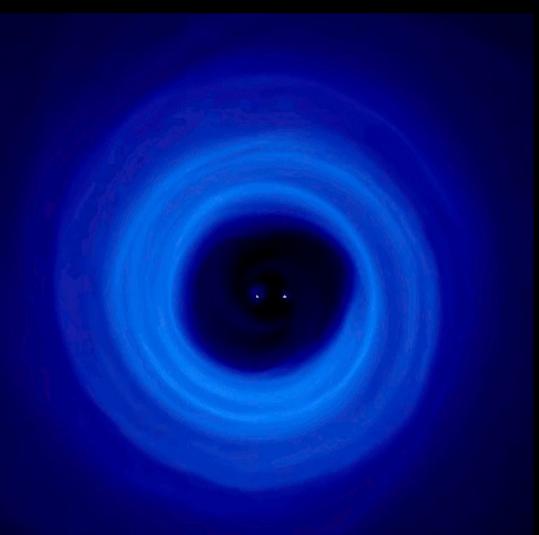
$$A = 4 \frac{(G\mathcal{M}_z)^{5/3} (\pi f)^{2/3}}{D_l}$$

Sky localization is tens of deg<sup>2</sup> so tens of thousands of potential host galaxies



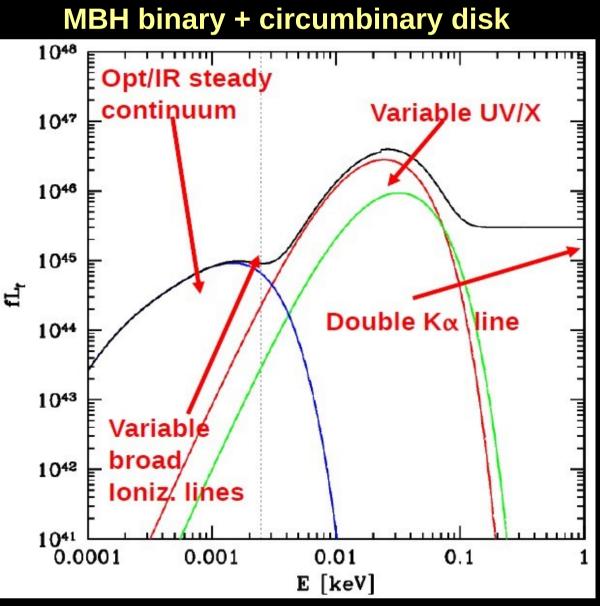
#### **Associated electromagnetic signatures PTA**

#### **MBH binary + circumbinary disk**



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

### **Associated electromagnetic signatures PTA**



(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?

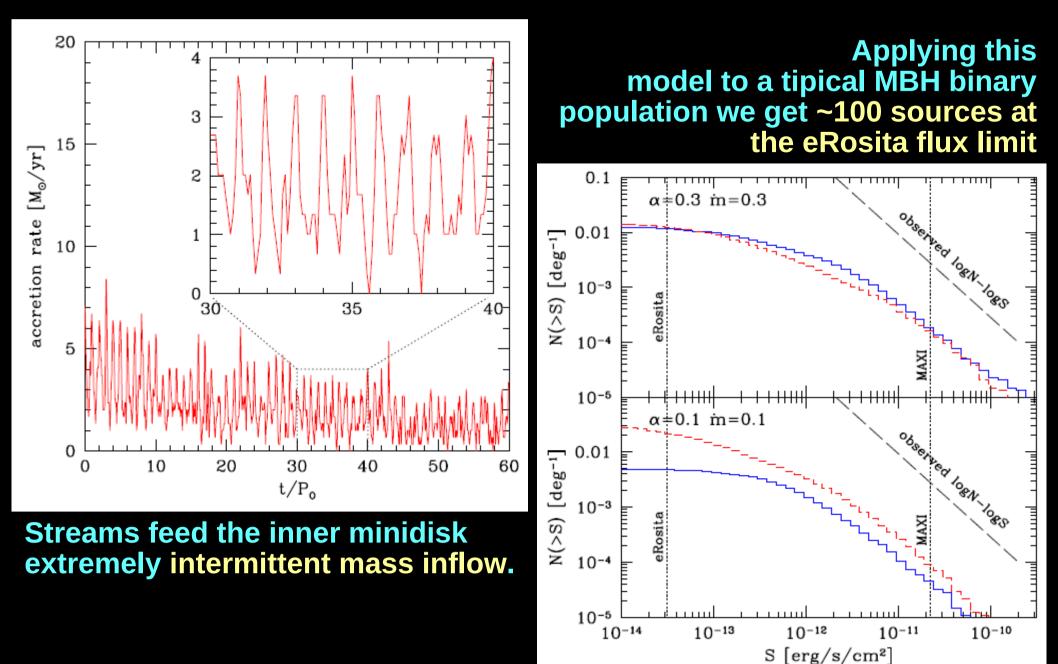
UV generated by inner streams/minidisk: periodic variability?

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



# 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