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 ~10⁹ solar masses!

THERE WERE 10⁹ SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy



Structure formation in a nutshell



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



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

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*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?















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)



characteristic amplitude

The Laser Interferometer Space Antenna (LISA Consortium 2017)

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

Mailing lists

Managemen

Groups

Groups

Full Member Groups

LISA Instrument Group

LISA Science Group

LISA Data Processing Group

Simulation Working Groups

Associate and Full Members Groups

Astrophysics Working Groups

Cosmology Working Groups

Waveform Working Groups

Advocacy and Outreach Working

Eundamental Physics Working

LISA Data Challenge Working Groups

https://www.lisamission.org/

LISA Consortium User Guide User guide
Groups
Getting help
Contributing

LISA Consortium User Guide

Key information

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 mosterious 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

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



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)







(Palenzuela+ 2010, Gold+ 2014, Farris+ 2014, Tang+ 2017, 2018, D'Ascoli+ 2018, ...)

Opportunities for LISA-Athena (LSST/Rubin) synergies

THE ATHENA MISSION



Large Synoptic Survey Telescope

Athena Wide Field Imager (WFI)

Parameter Characteristic **Energy Range** 0.1-15 keV 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 Na WEI 1.4m2 5" keV flux limit [erg s⁻¹ cm⁻²] Athena WFI 1.4m² 10-16 Athena WFI 2m², 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 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 (Abell+ 2009)



-Optical telescope

-2022+

-9.6 square degree FoV

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

→ HOW CAN LISA AND ATHENA WORK TOGETHER?



calculates the date and time of the final merger, but the position in the sky is unknown

more data as it moves along its orbit, providing a better localisation of the source in the sky

located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (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

witness the onset of relativistic jets if this happens, Athena and LISA may witness the birth of a new 'active galaxy'

#Space19plus #AnsweringTheBigQuestions

Space19 🙆

· eesa



(Mangiagli+ 2020, Piro+ in prep.)

-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 ... Example of possible eLISA cosmological data 100 **EMRIs** 10-LIGO-like $d_L \text{ (Gpc)}$ BHBs 0.1 0.01 0.1 10

Ζ

Courtesy of N. Tamanini



-0.5

-1.0

-1.5

-2.0

-1.5

10-2

1.5

0.5

1.0

2.0



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_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







Simulated signal



Actual data

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(Courtesy of PPTA)

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^{5/3}/D*)

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

Sky localization is tens of deg² 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 (AS+ 2012)



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