Astrophysics *with*

The Laser Interferometer Space Antenna

LISA Science Group
co-chair

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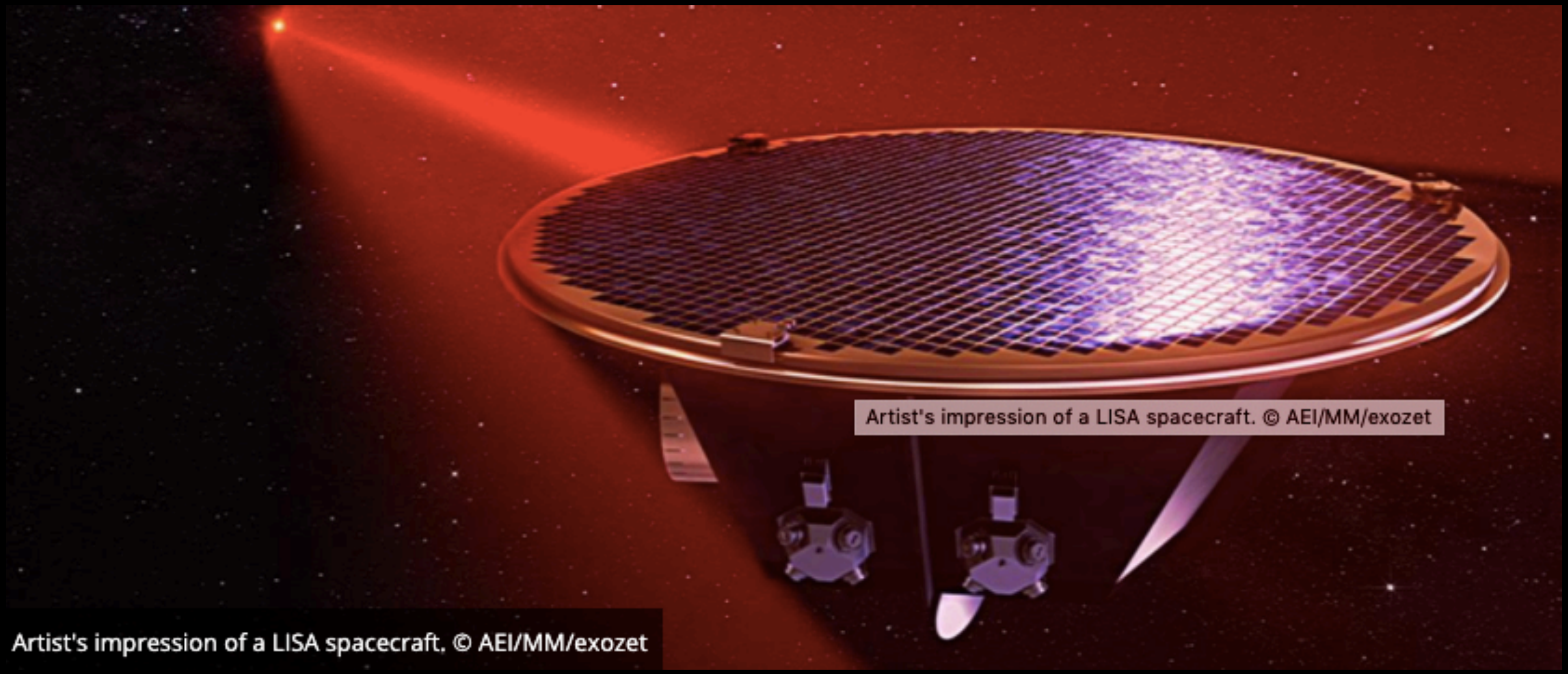
the Netherlands

LISA Dutch Community Day, Leiden 1st October 2021

Constellation of 3 satellites

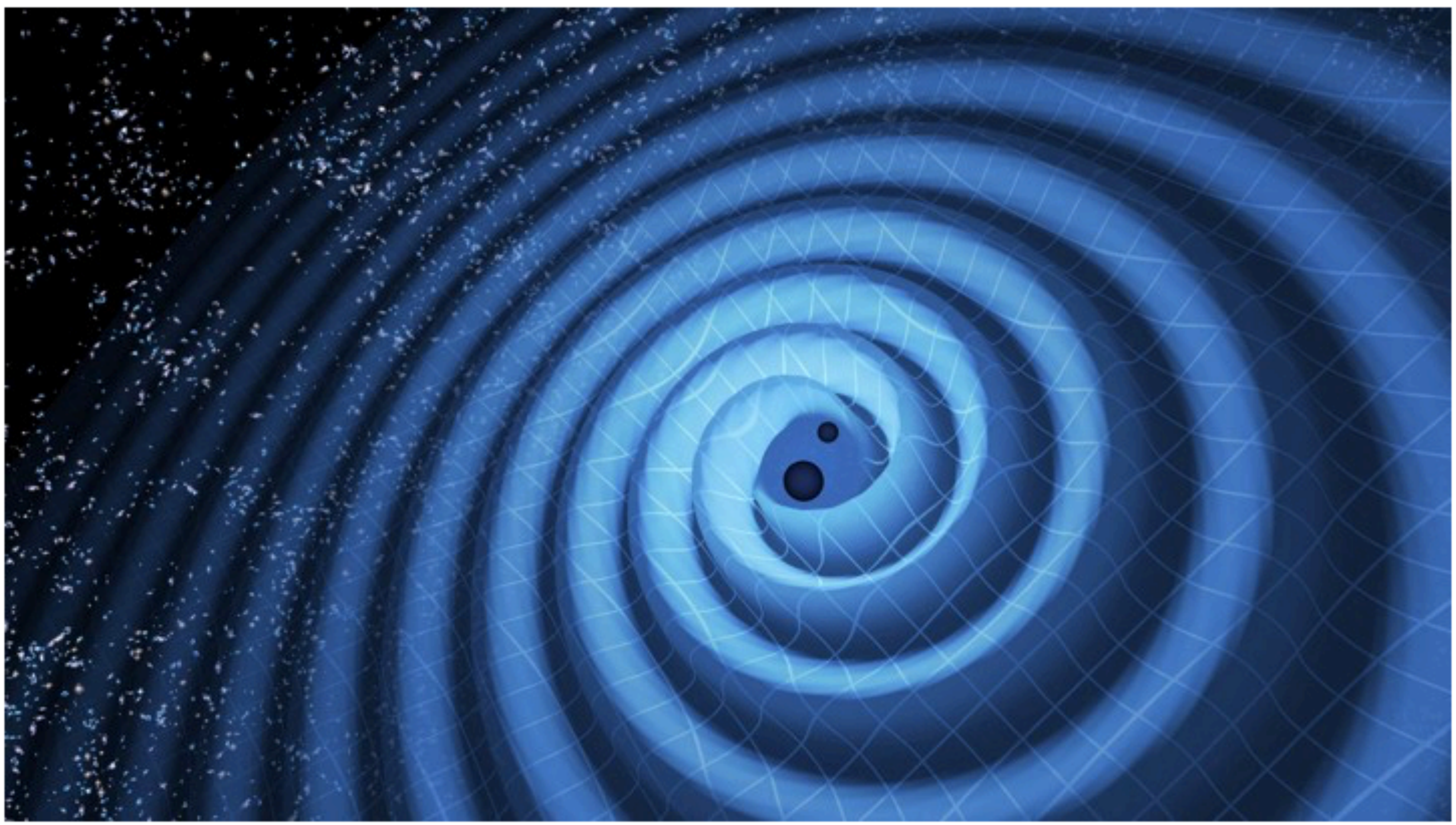
LISA current status

- NASA is minority partner
- LISA currently in Phase A (study phase, with mission formulation review this fall)
- Adoption in 2024 (consolidation of the mission design, and science management plan)
- **2034** nominal launch



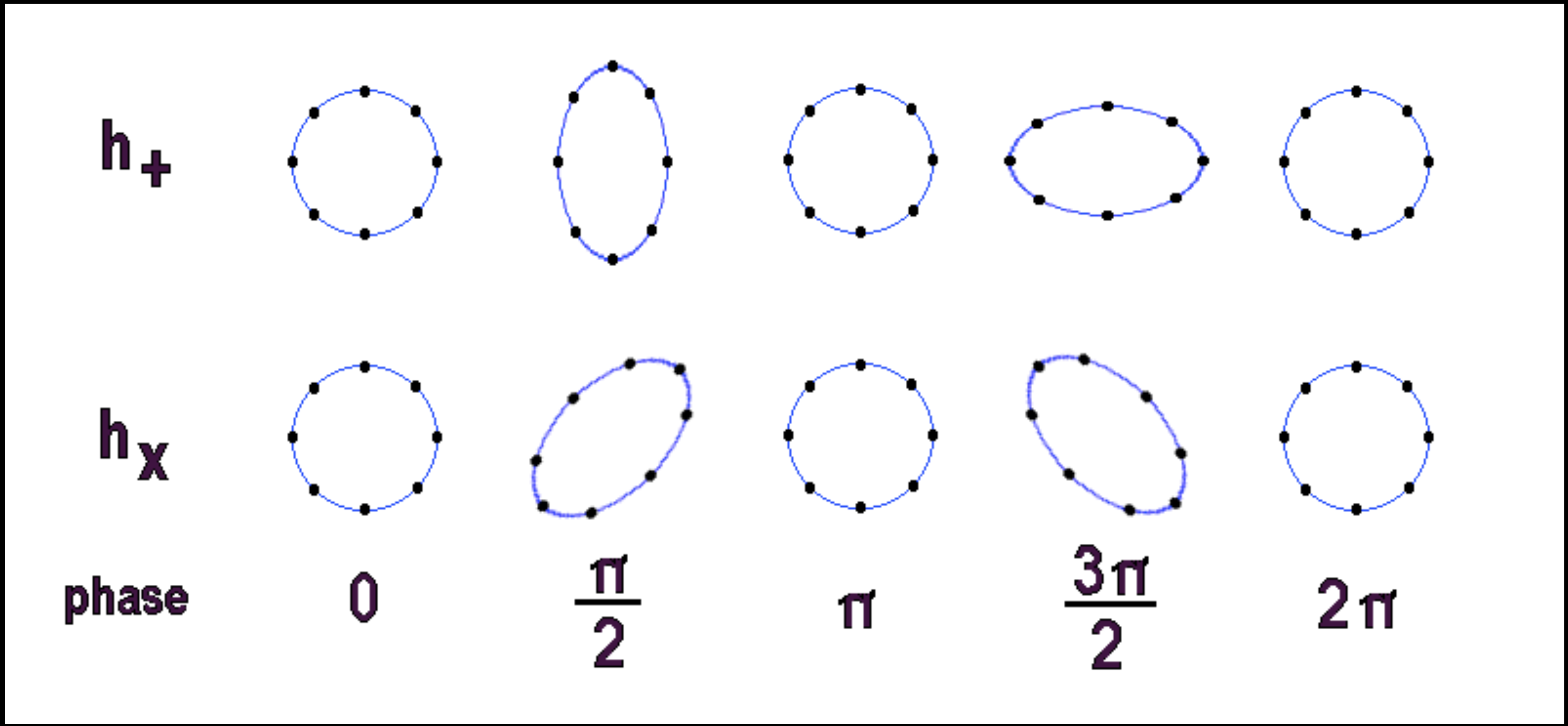
Gravitational Waves

- Mass in non spherical, nonuniform motion produces ripples of curved spacetime which propagate away from the source at the speed of light, as transverse waves



An illustration of black holes spinning so fast that they radiate gravitational waves (LIGO / T. PYLE)

- Two independent polarisations
- Deform space periodically



- Carry away energy from the source

A binary system:

$$P_{\rm GW} \sim \frac{c^5}{G}\left(\frac{GM}{c^2 L}\right)^5 < \frac{c^5}{G} \approx 3.6 \times 10^{59}\ \mathrm{erg/s}$$

When the compactness is >0.001 the Luminosity exceeds that of the Milky Way

Note: all galaxies in visible light in the visible universe emit

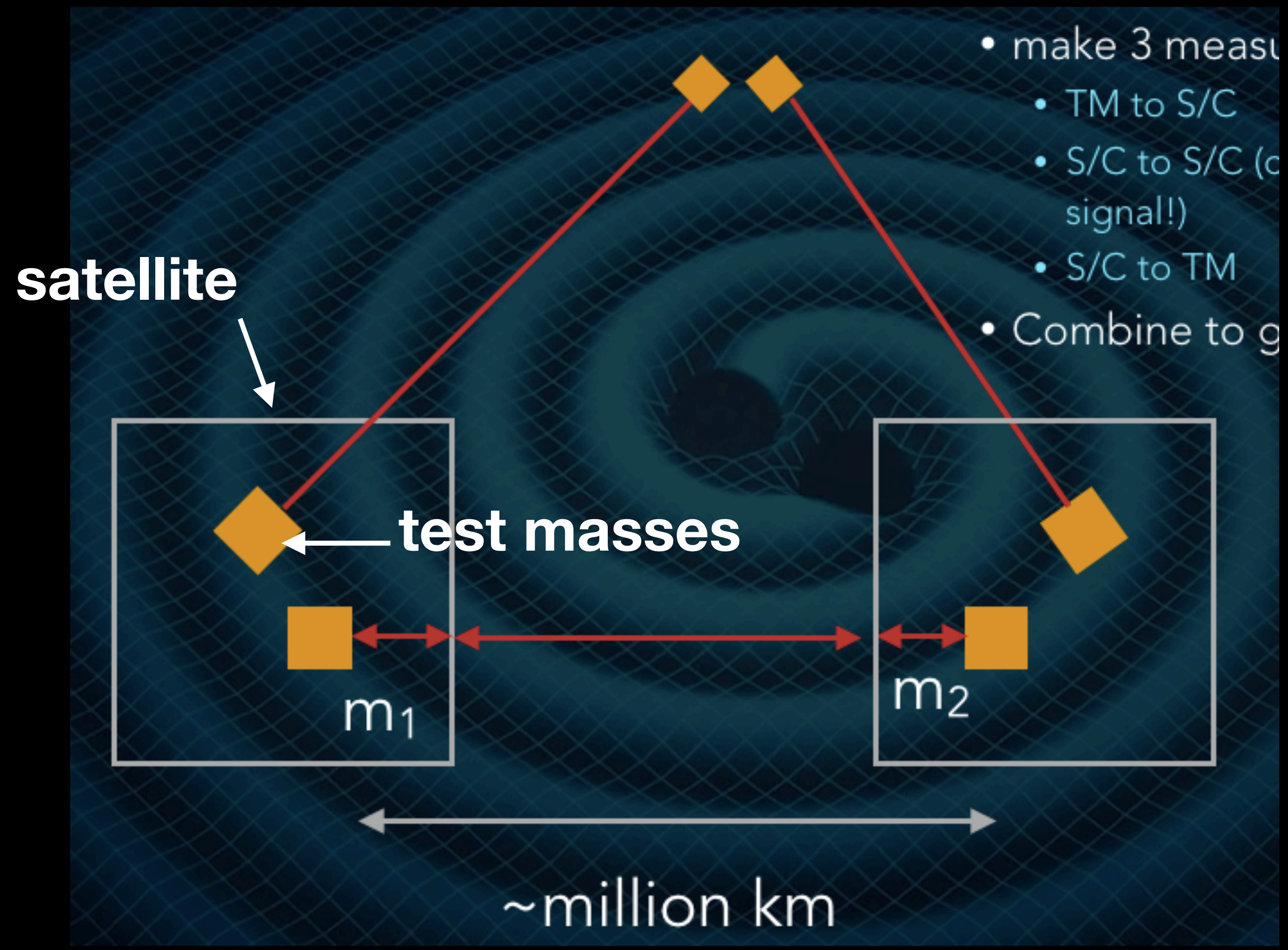
$$L_{\rm visible} \approx 10^{56}\ \mathrm{erg/s}$$

- GWs can be detected by the change in proper time between pairs of **free-falling** test masses

- These changes are inferred by the time of flight of photons exchanged between test masses

- Laser interferometry: change in the interferometric pattern

- LISA: test masses in satellites, arm of the interferometer= distance between satellites

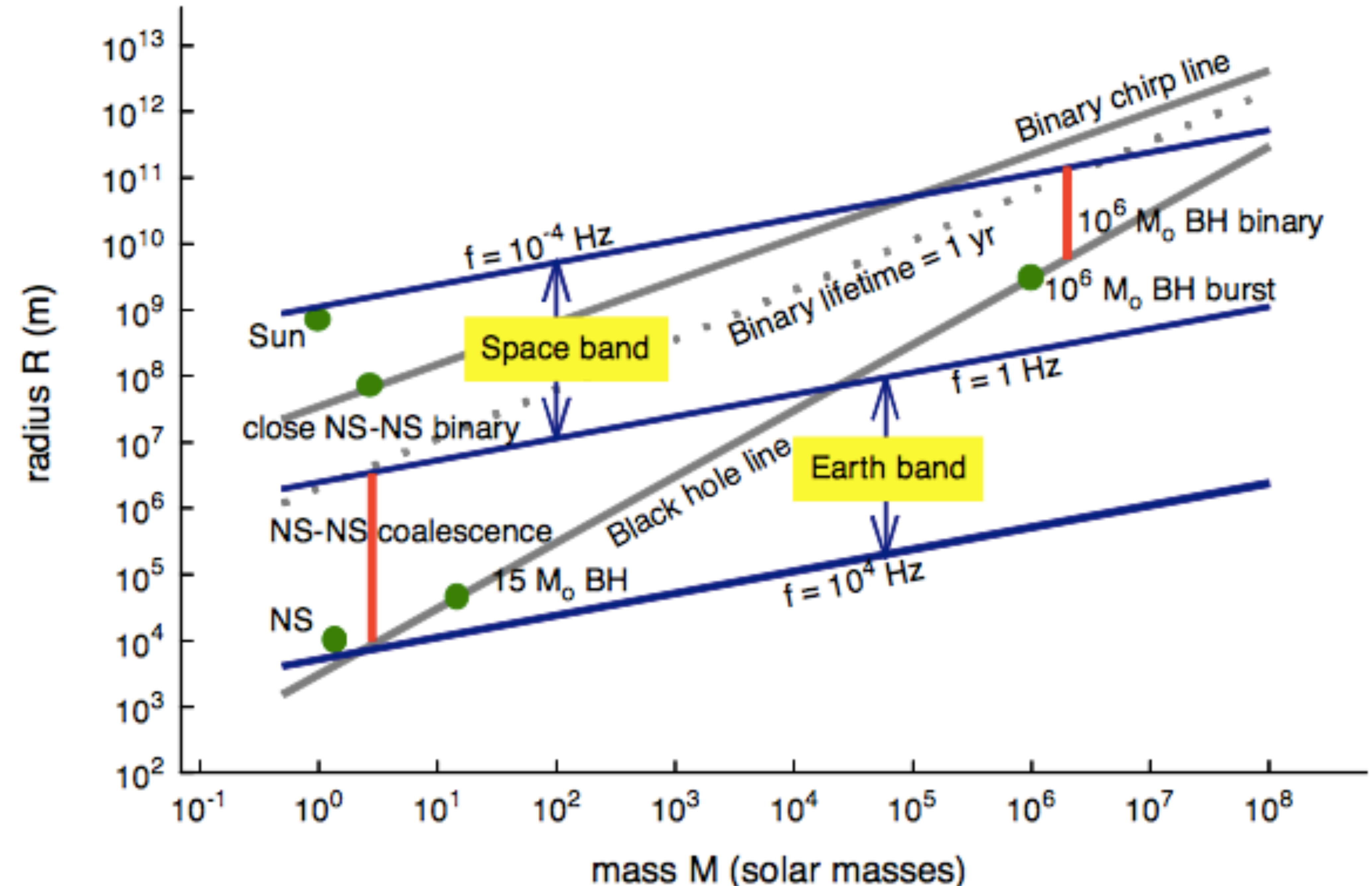


- But measurement is challenging, because the relative displacement between test masses is of the order of

$$\boxed{h \sim \frac{G}{c^4}\frac{M^{5/3} f^{2/3}}{r}} = dL/L \sim 10^{-21}$$

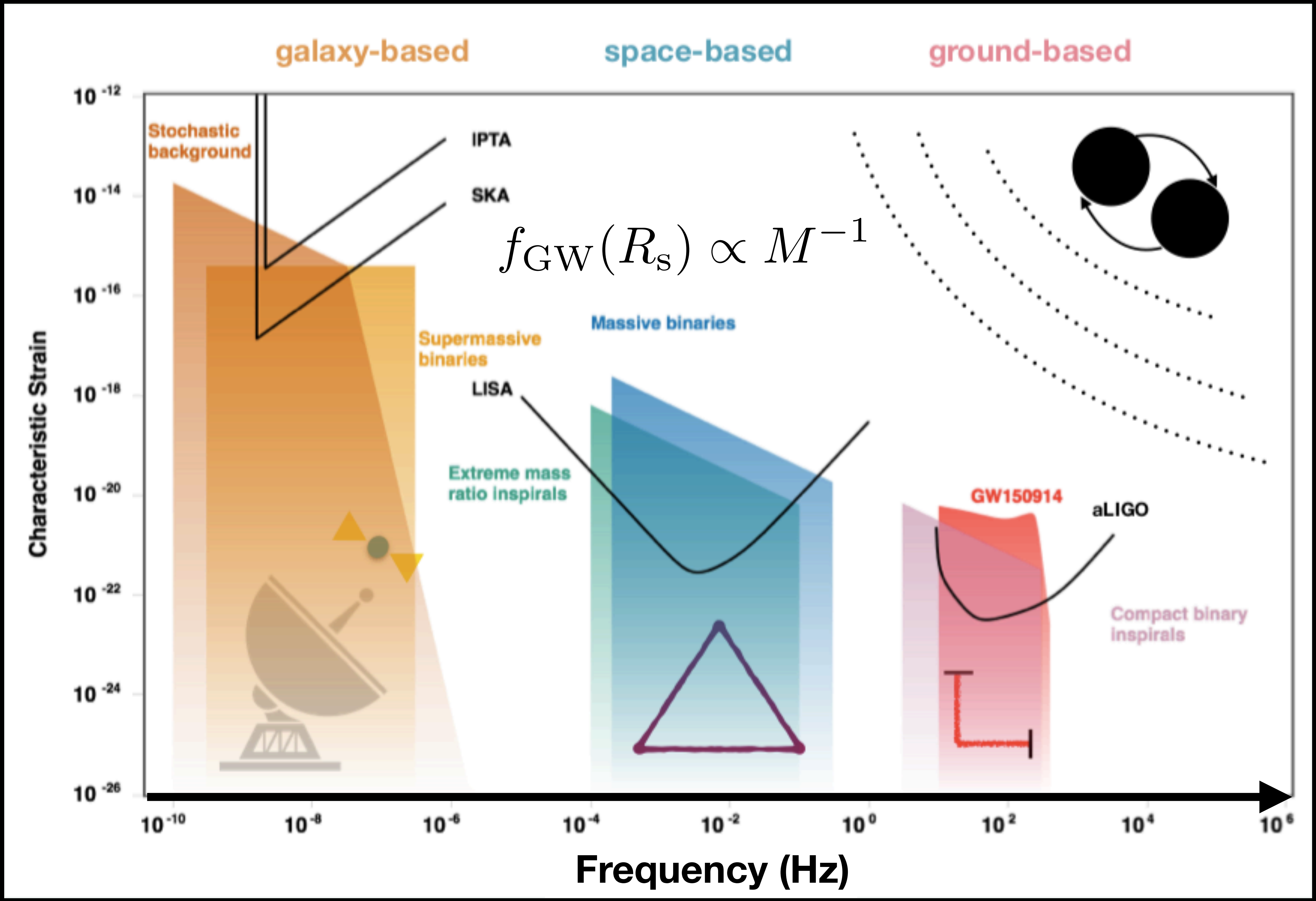
+ Noise, + source confusion…

A binary system: frequency $f_{\mathrm{GW}} \approx \left(\frac{GM}{R^3}\right)^{1/2}$



Sathyaprakash and Schutz 2009

Barack, Cardoso, Nissanke et al (inc. EMR) 2018

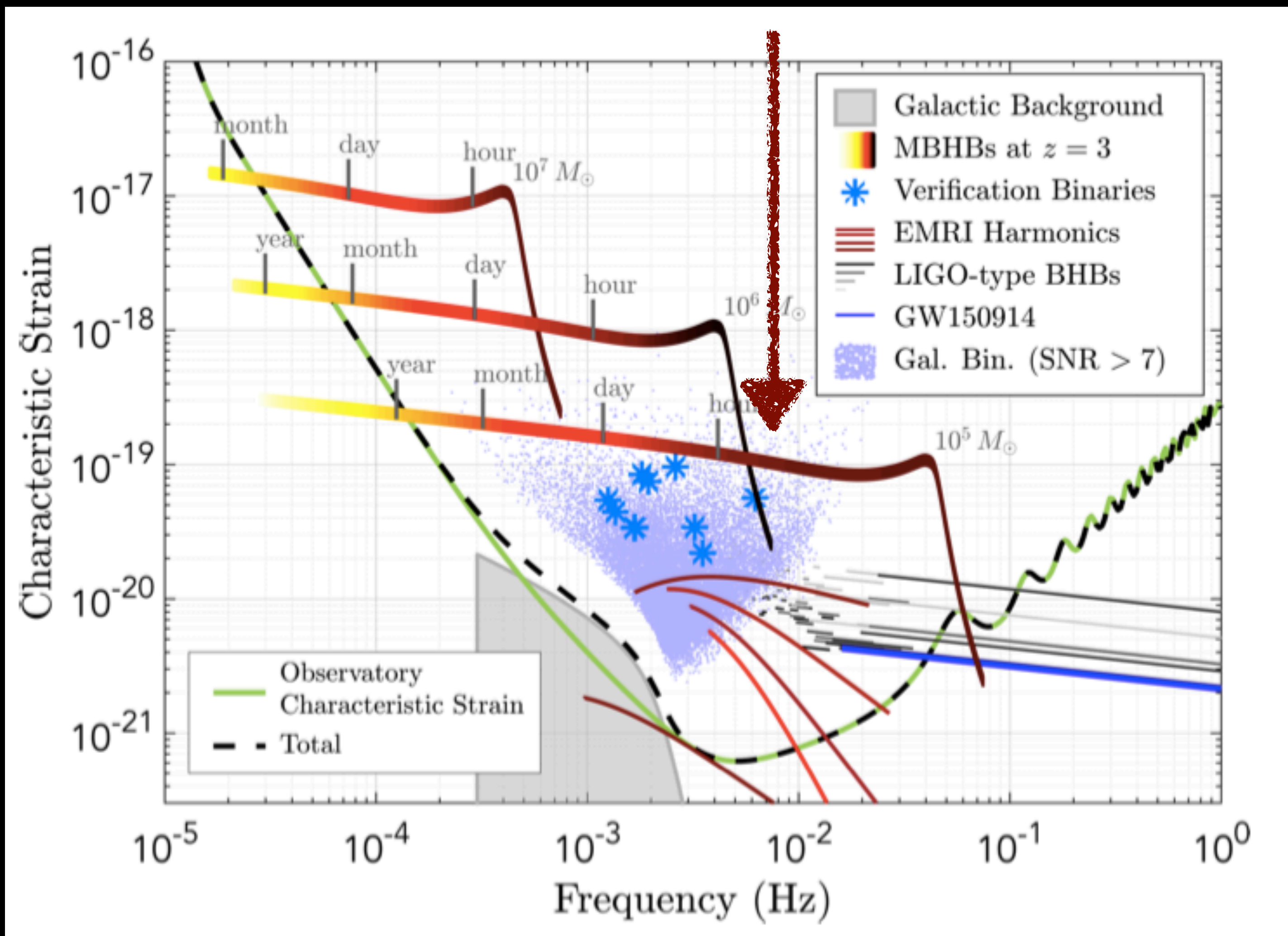


Binary system separation or Period

LISA Astro Sources

1. SMBH binaries*
2. Extreme Mass Ratio Inspirals
3. Stellar Origin Black Holes binaries
4. Stellar Mass Compact binaries (mainly white dwarfs)*
5. Planets

Supermassive black holes

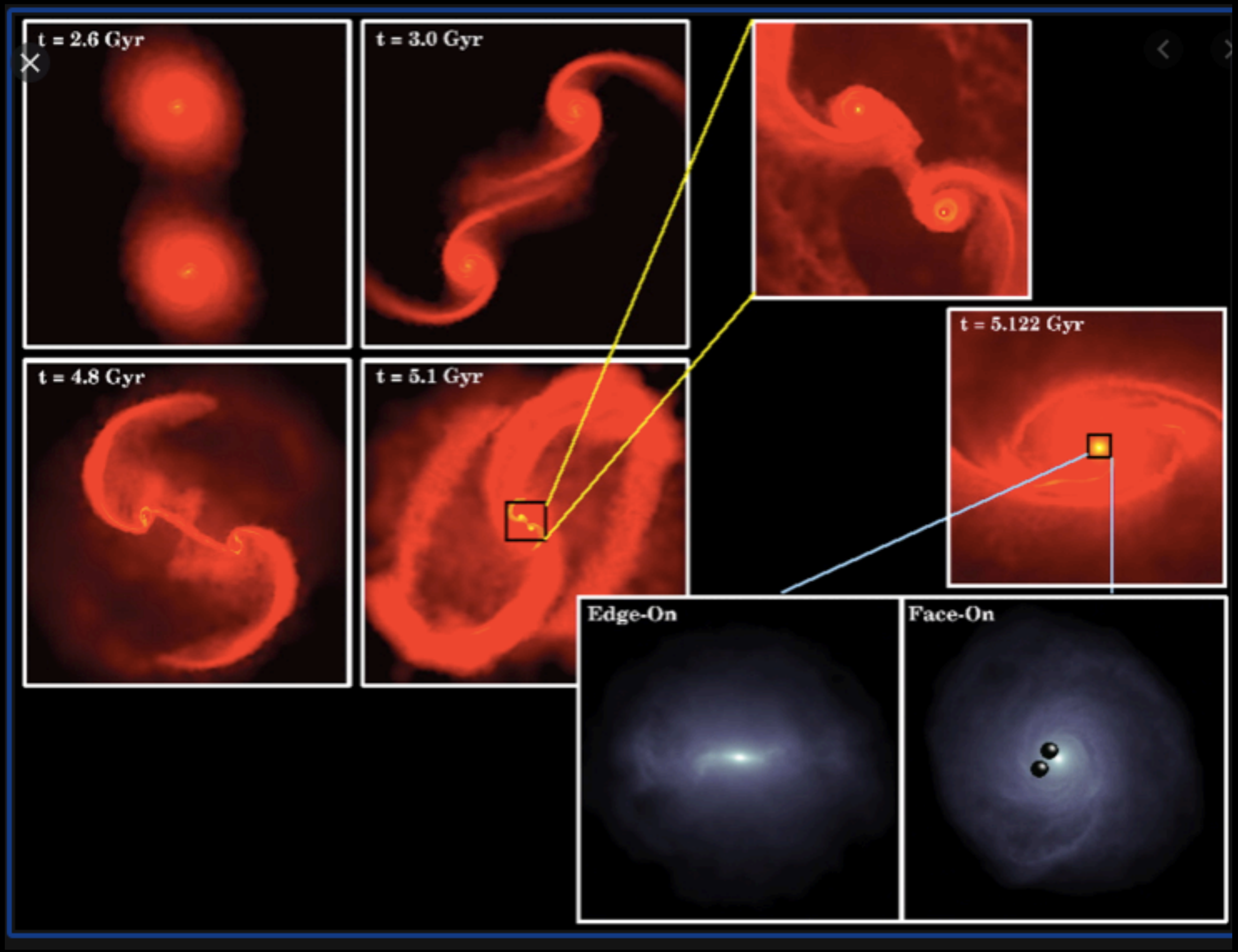


LISA team Proposal (2017)

- merging binaries*
- week to months in LISA band
- high mass/high redshift —> low f

*wave form for all merger phases is needed

Supermassive black holes



Mayer et al. 2007

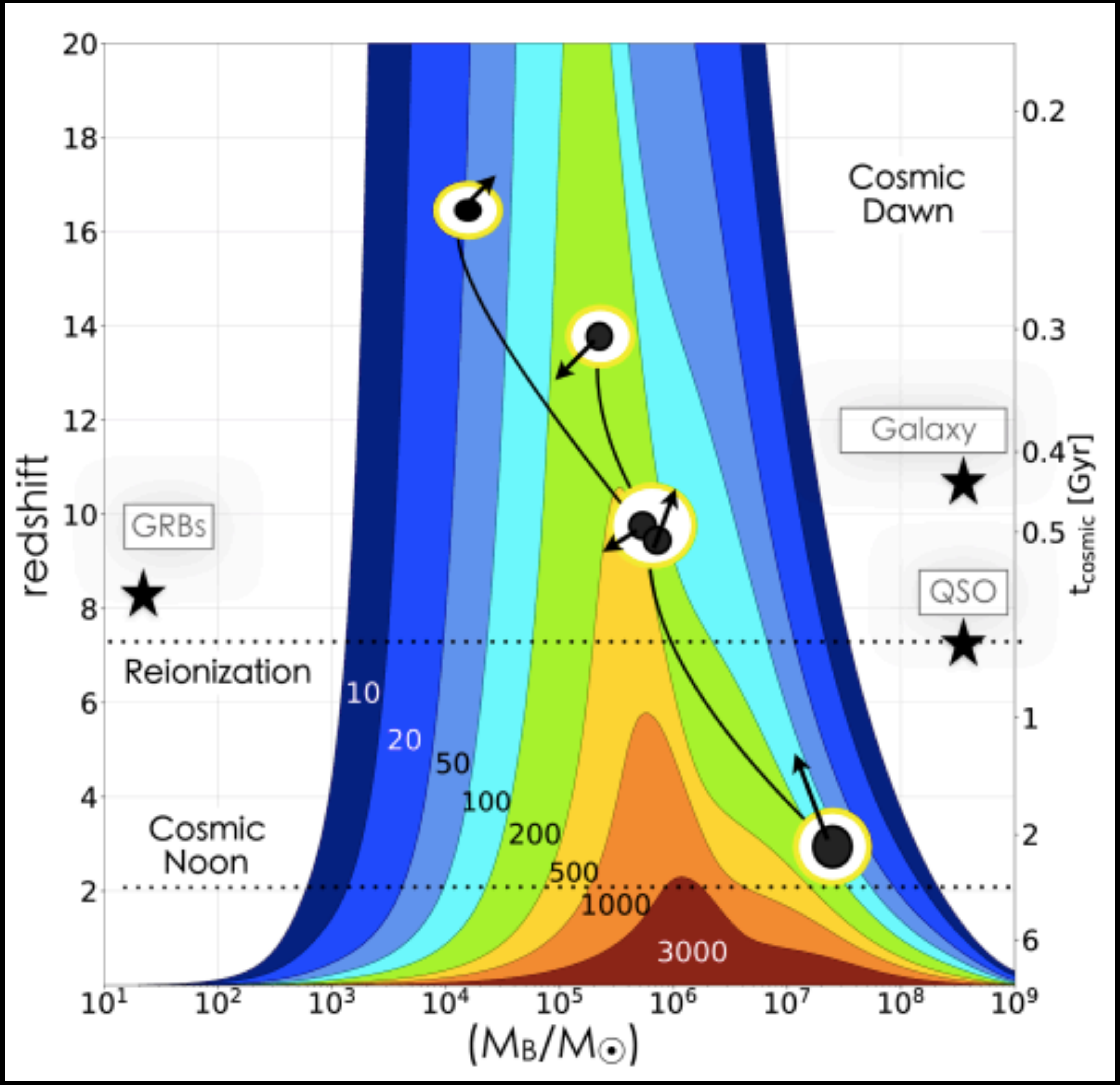
- merging binaries
- week to months in LISA band
- high mass/high redshift —> low f

- Galaxy formation and evolution through cosmic times (high z)
- Hydro-dynamics in galactic centre
- magneto-hydrodynamics in highly curved, changing space-time

NL: Joop Schaye's Group

e.g. Khan+2018; Pfister+19; Bonetti+19; Bortolas+20; Munoz+21, Cattorini+2021…

SMBHB: the loudest sources



Source-frame mass, q=0.5

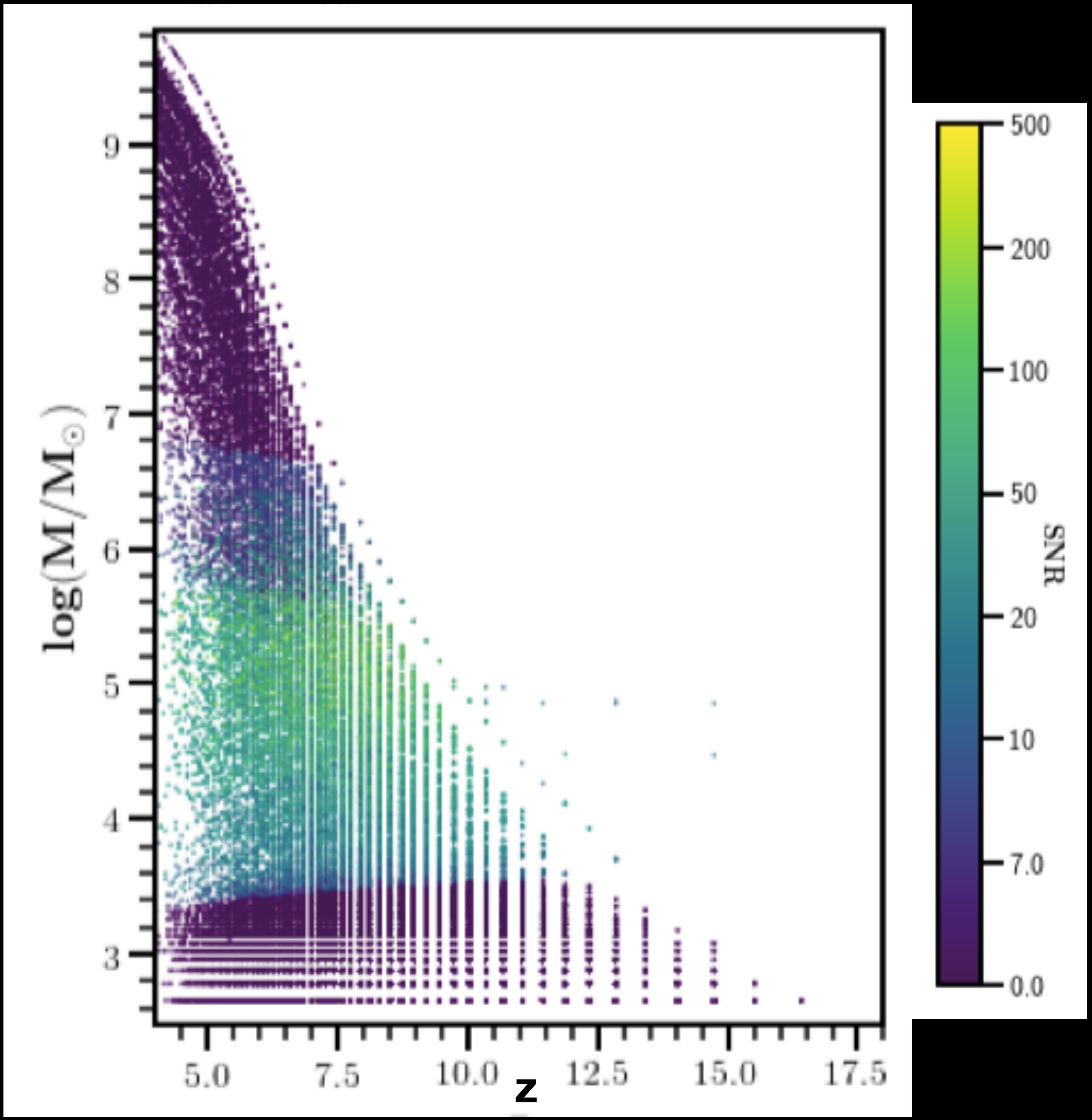
Colpi et al 2019 (Decadal survey 2020 white paper)

LISA detection rates in 4yr: ~10 to 300 yr^{-1}

- Detections peak $5<z<10$, with $10^4<M_{sun}<10^7$

- Several high SNR detections at $z<2$, with $M_{sun}> 3 \times 10^5$

e.g. Katz + 2019
Dayal+ 2019
DeGraf & Sijacki 2019
Latif et al. 2019
Bonetti et al. 2019
Ricarte & Natarajan 2018
Hartwig, Agarwal & Regan, 2018
Colpi 2018 …..



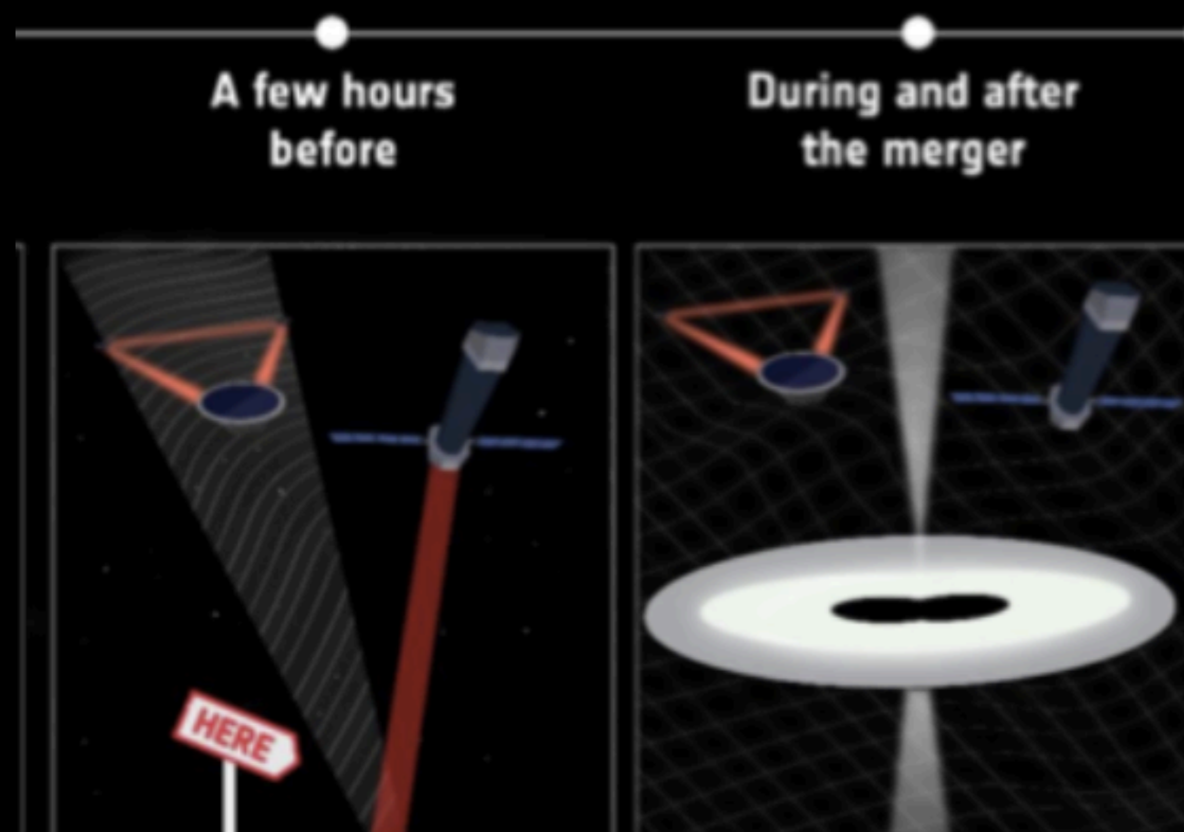
Dayal, EMR+2019

Athena-LISA

How: Athena as follow-up instrument for LISA, when source is localised down to~ Athena Wide Field Imager (0.4 deg^2);

Likely sources for joint detection:

- *pre-merger*: 3-10 x 10^5 , $z < 1$



- *post-merger:* 10^5-10^7 M_{sun}, $z < 2$

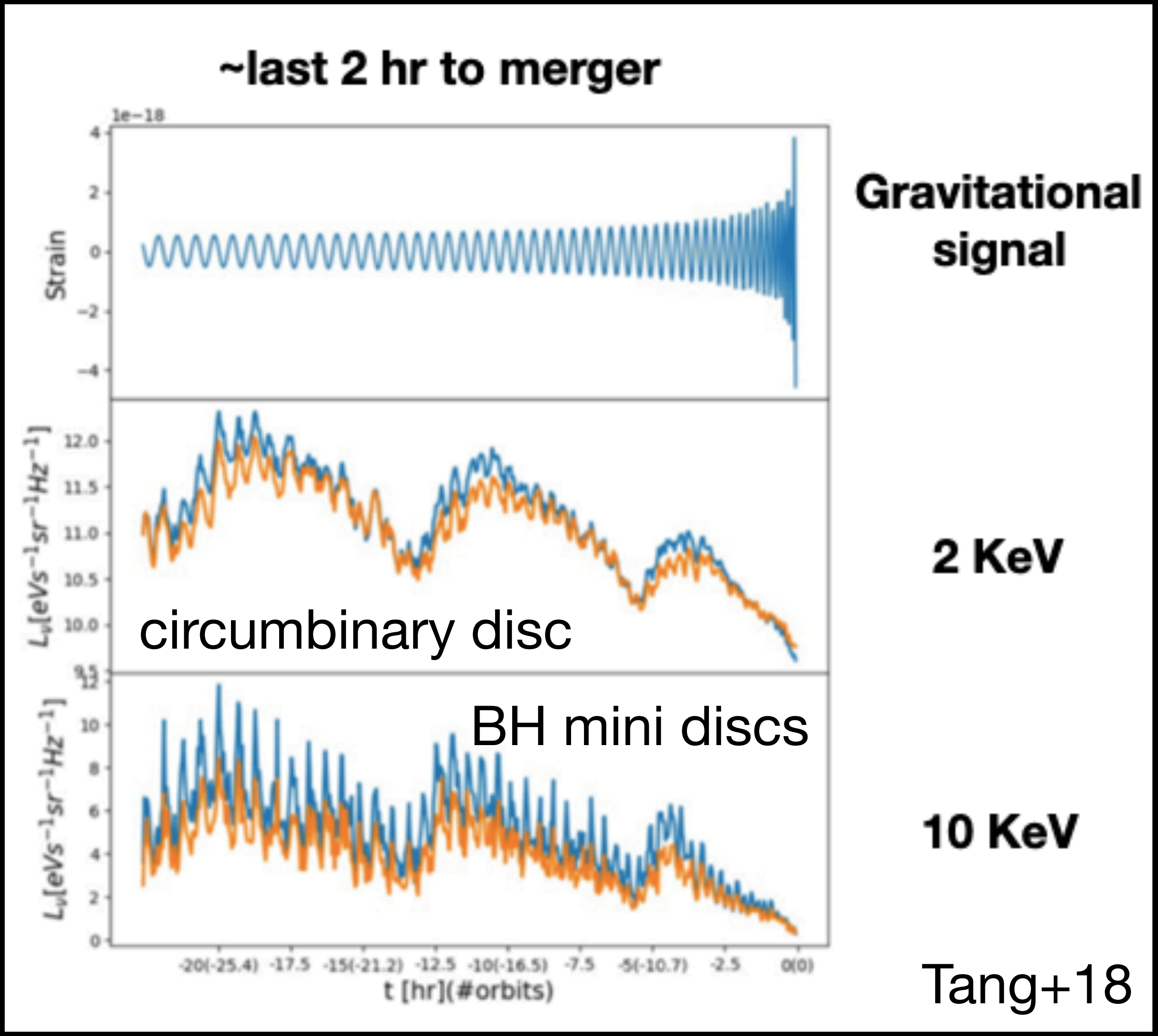
credit:ESA

Athena-LISA Synergy Working Group's paper in prep. ; McGee+20; Mangiagli + 20

Astro of pre-merger phase

We can learn: magneto-hydrodynamics in dynamic spacetimes

X-ray emission may be modulated in time with characteristic frequencies linked to orbital motion and/or surrounding fluid patterns

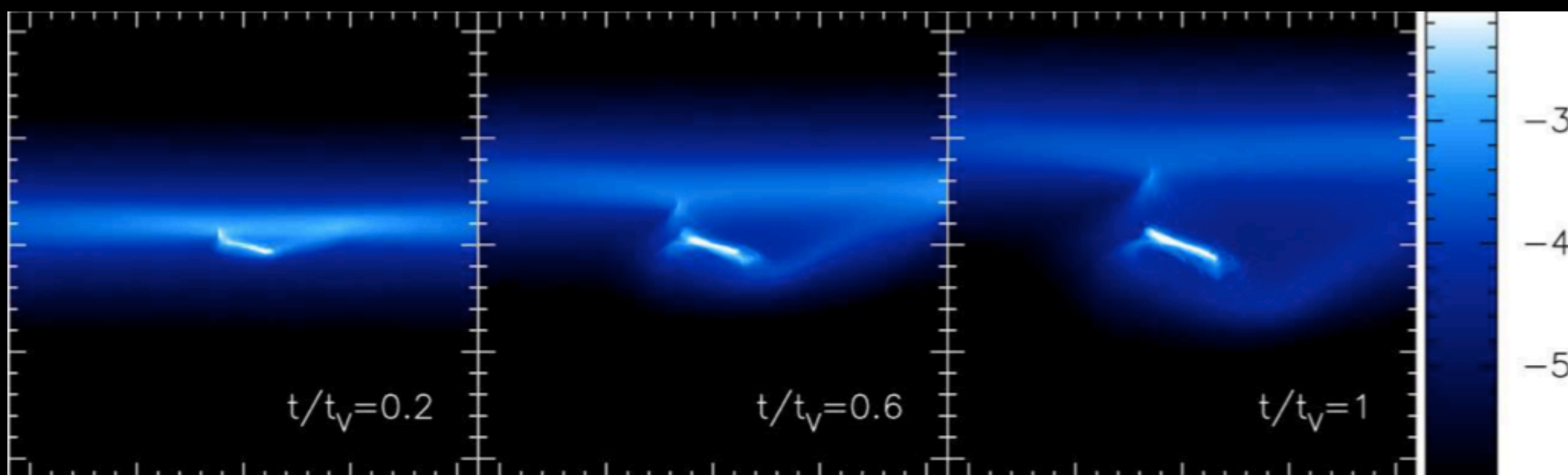


e.g. Roedig+14; Farris+ 2014; Tang + 2017; Bowen + 17,18, Yike+18; D'Ascoli+18; Kelley+19

Astro of post-merger phase

We can learn:

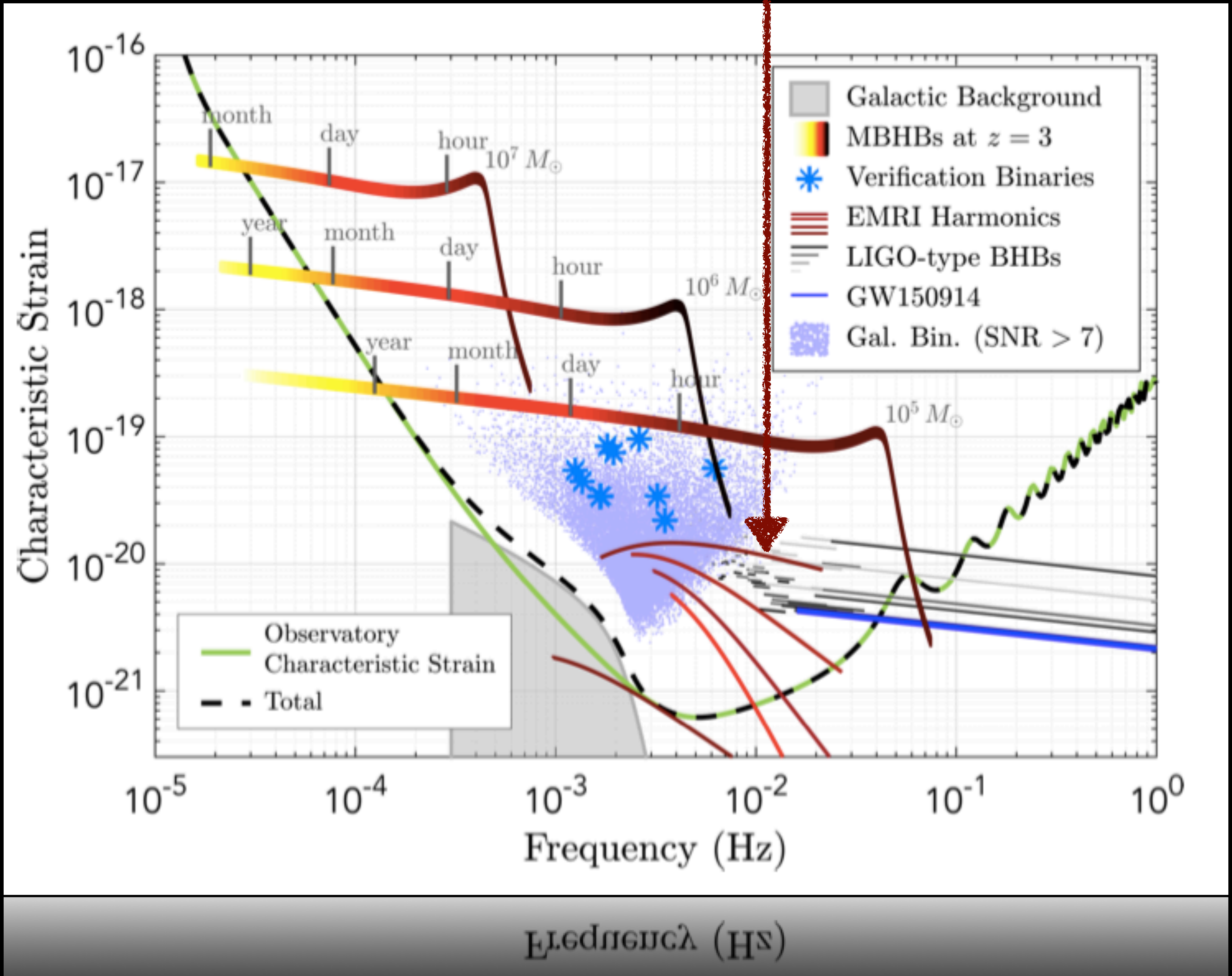
- perturbed disc dynamics
- turned-on AGN as accretion resumes
- formation of X-ray corona and jet



EMR + 2010

Lippai+ 08; Shields & Bonning 08; Schnittman & Krolik 08; Megevand+ 09; de Mink & King 17

Extreme Mass Ratio Inspirals



LISA team Proposal (2017)

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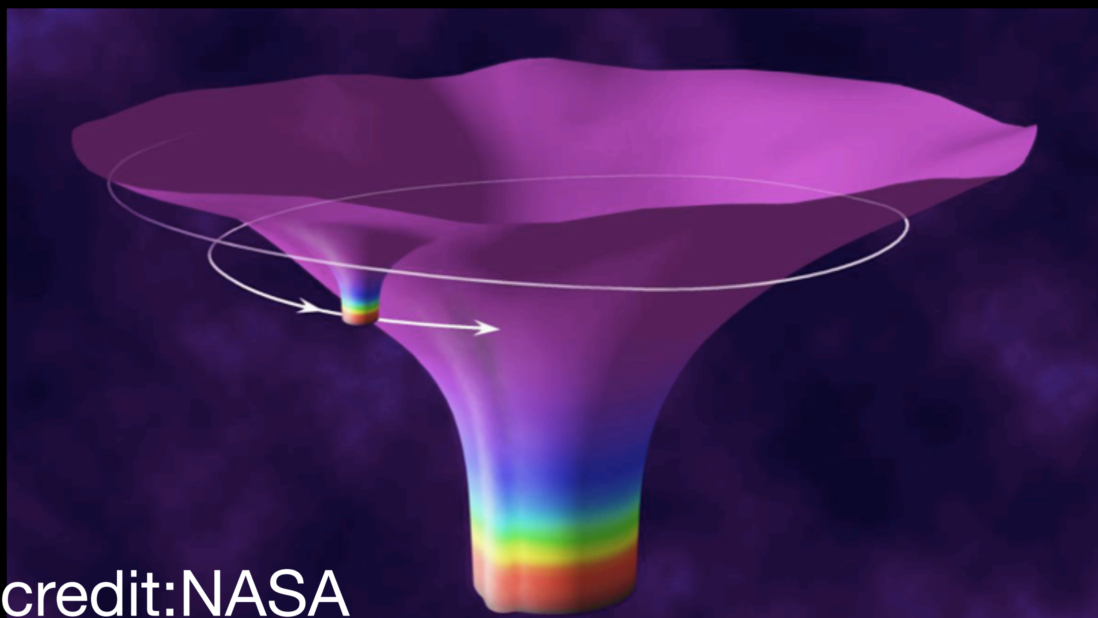
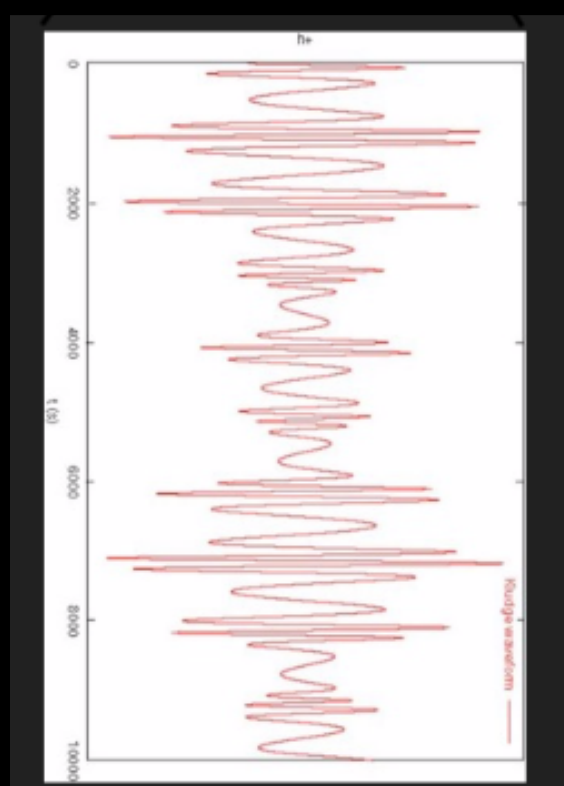


credit:NASA

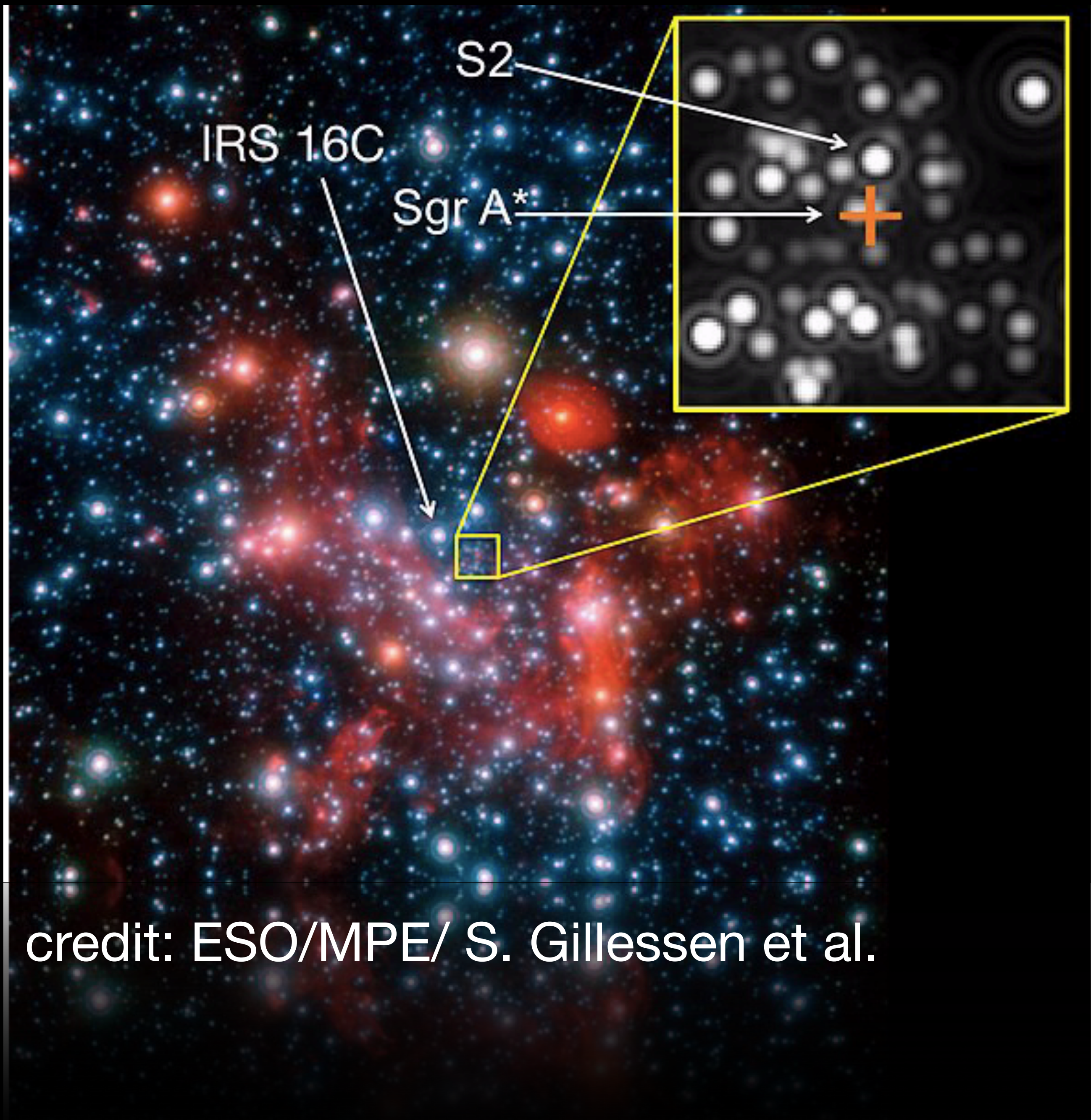


credit: J. Gair

- stellar mass object (black hole, brown dwarf) around SMBHs
- ~yrs in LISA band, 10^4-10^5 cycles
- Resolved sources + background in LISA
- complex wave form*
- Detections mainly at 0.5<z <2 around SMBHs with masses : 3 x 10^4-3 x 10^6
- Detection rate: a few to 1000s per yr
- sky loc. ~ 1 deg^2; DL/L ~1%; SMBH mass and Spin measurements < 10^{-4} !!!!

Babak+17

Extreme Mass Ratio Inspirals

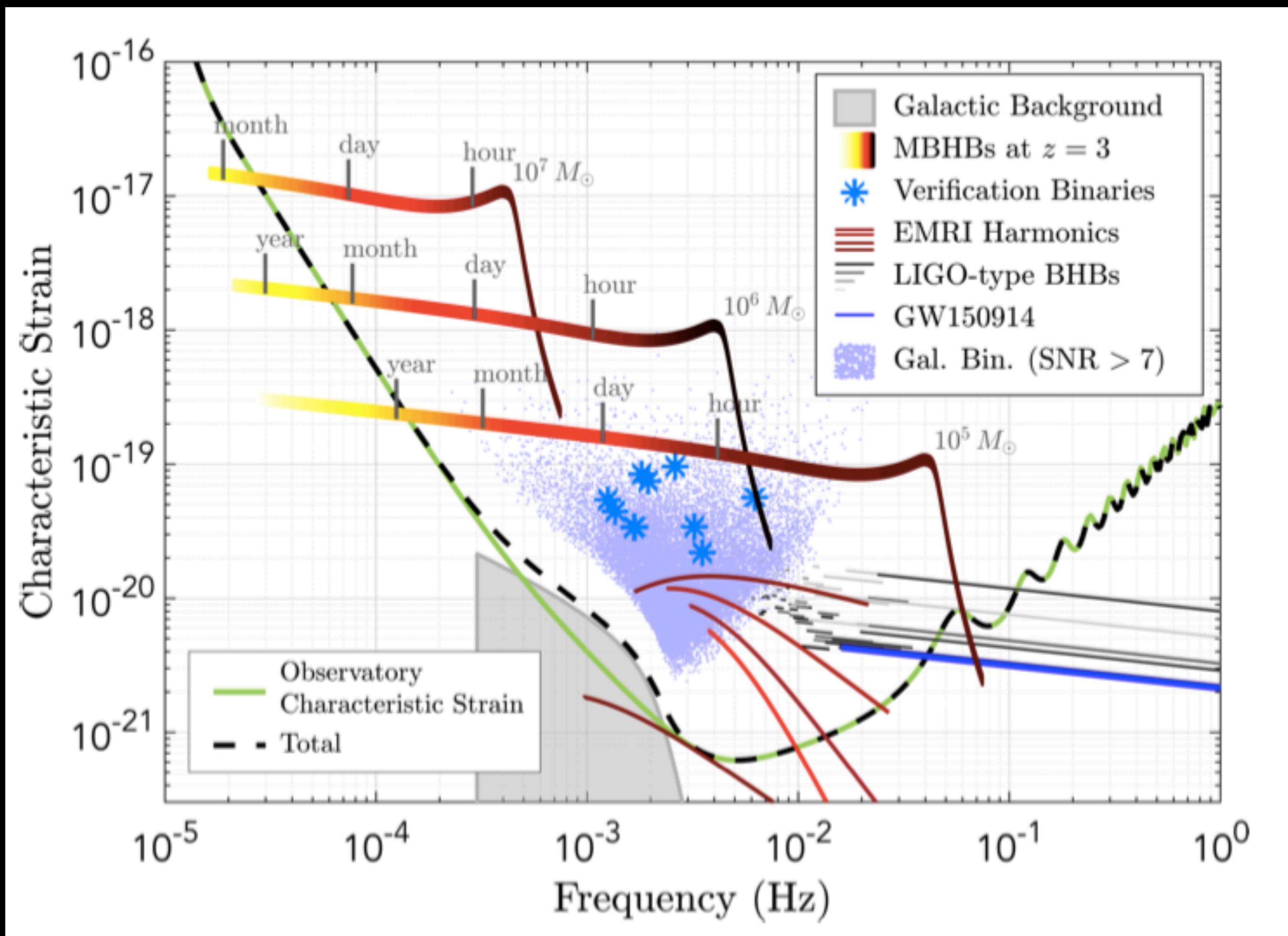


credit: ESO/MPE/ S. Gillessen et al.

- Occupation fraction of SMBH
- Stellar dynamics in galactic centre (connection to TDEs, HVSs..)
- Compact object central cusp
- Hydrodynamics of black-hole disc gas interaction (e.g. EMRIs in AGN disc)
- Galactic Center: low mass star/brown dwarf EMRIs~1-20 in LISA band

e.g. Freitag 03; Hopman&Alexander 05; Marritt +11; kocsis +11; Fouvry & Or 18; Generozov +18; Amaro-Seoane 19,20; Gourgoulhon+19; McGee +20; Bonetti & Sesana 20;Derdzinsk+21; Pan&Yan 21

Stellar Origin black hole binaries

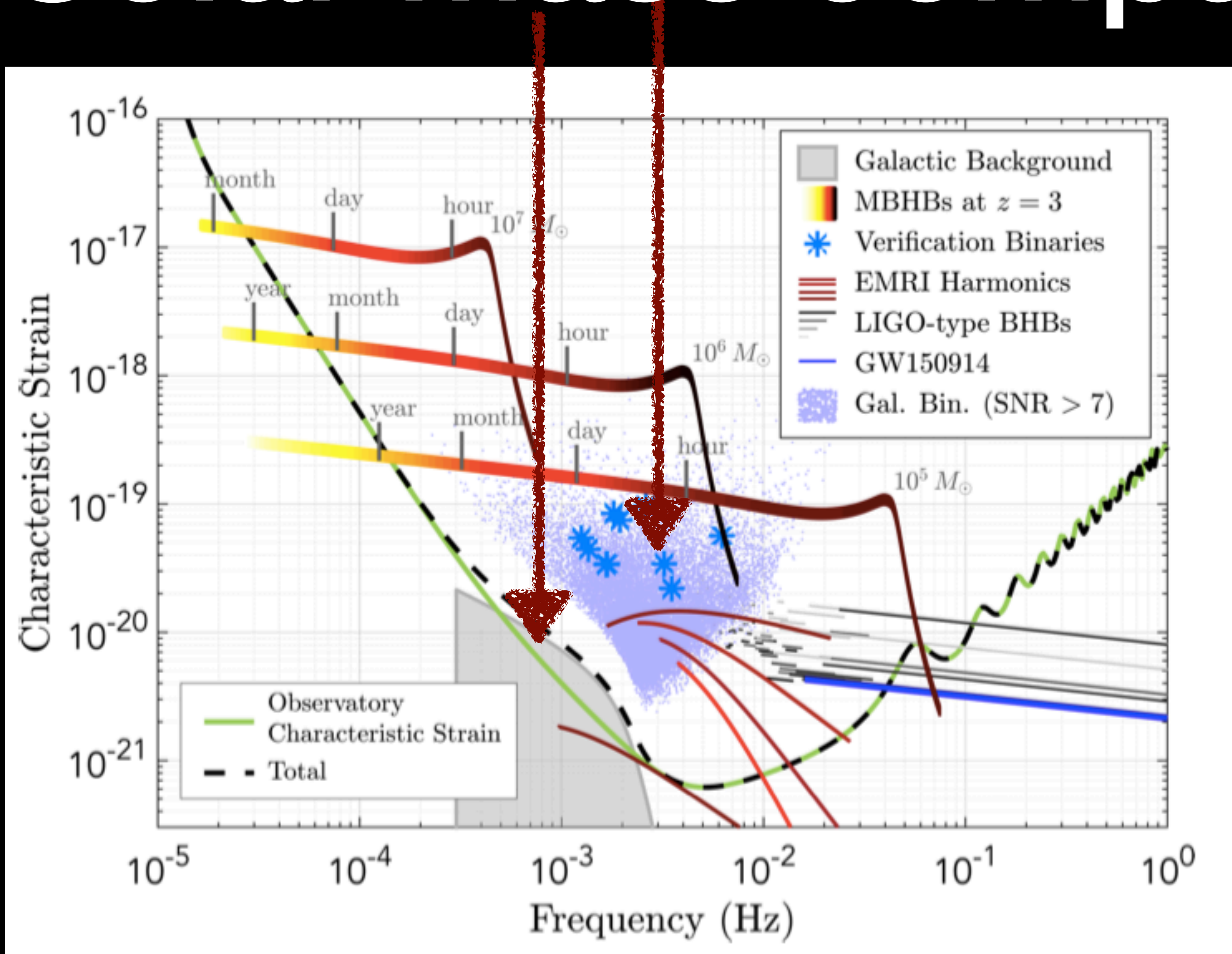


LISA team Proposal (2017)

- persistent source in LISA
- tens of events ~10 yr before merger
- high f
- GW multi-band observations
- Advanced merger localisation within 0.1 deg^2 and < 10 s
- E.M. Counterparts in LISA and LIGO/VIRGO
- Unknown Origin that can be unveiled in LISA by measuring the eccentricity

Sesana 2016

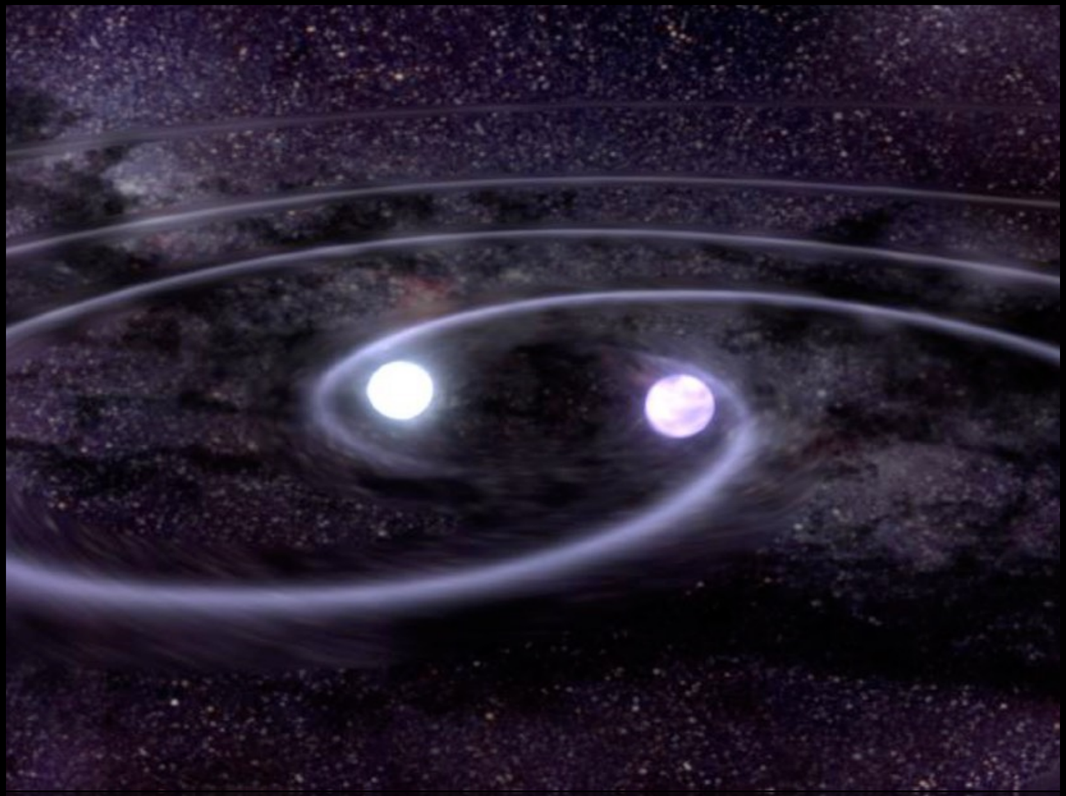
Solar mass compact object binaries



LISA team Proposal (2017)

- in spiralling binaries
- persistent source in LISA
- high f —> resolved binary
- low f—> foreground
- verification binary for instrument calibration
- simple, almost monochromatic, waveform

solar mass compact object binaries

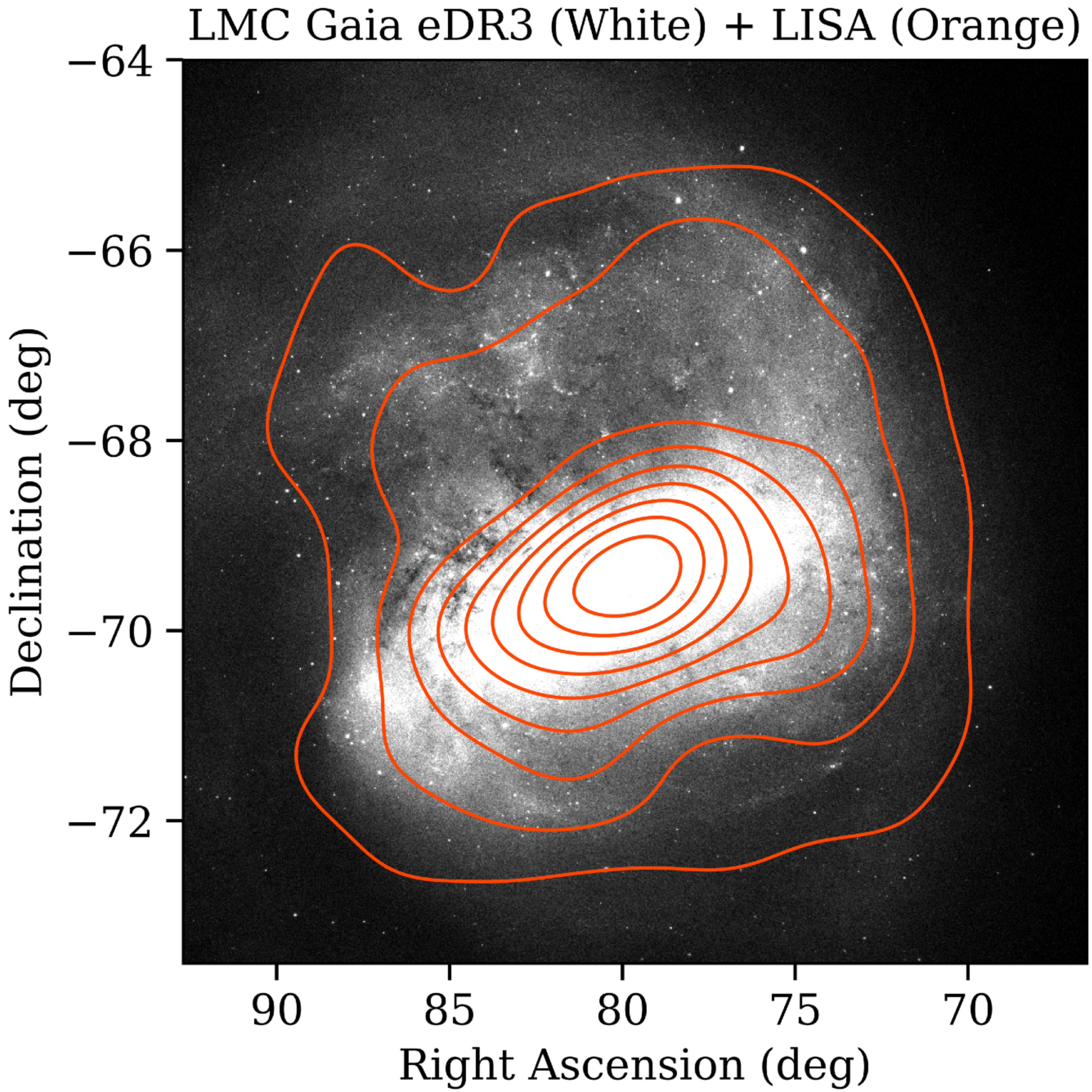


Credit: T. Strohmayer (GSFC), CXC, NASA

- White dwarf tides and internal structure (B. Bonga and T. Hinderer in NL)
- Stellar binary evolution theory (Nelemans, Toonen, Nissanke, Portegies-Zwart)
- Accretion theory in CVs (Groot)
- Stellar population studies (e.g. SN Ia progenitors)
- and…

Nelemans + 2001, 2004, Nissanke +2012, Shah et al. 2012;
Ruiter et al. 2010, Toonen + 2012, Korol, EMR et al. 2017, Breivik +17; Kremer+2017, Lamberts +2019

The Local Group's structure and properties

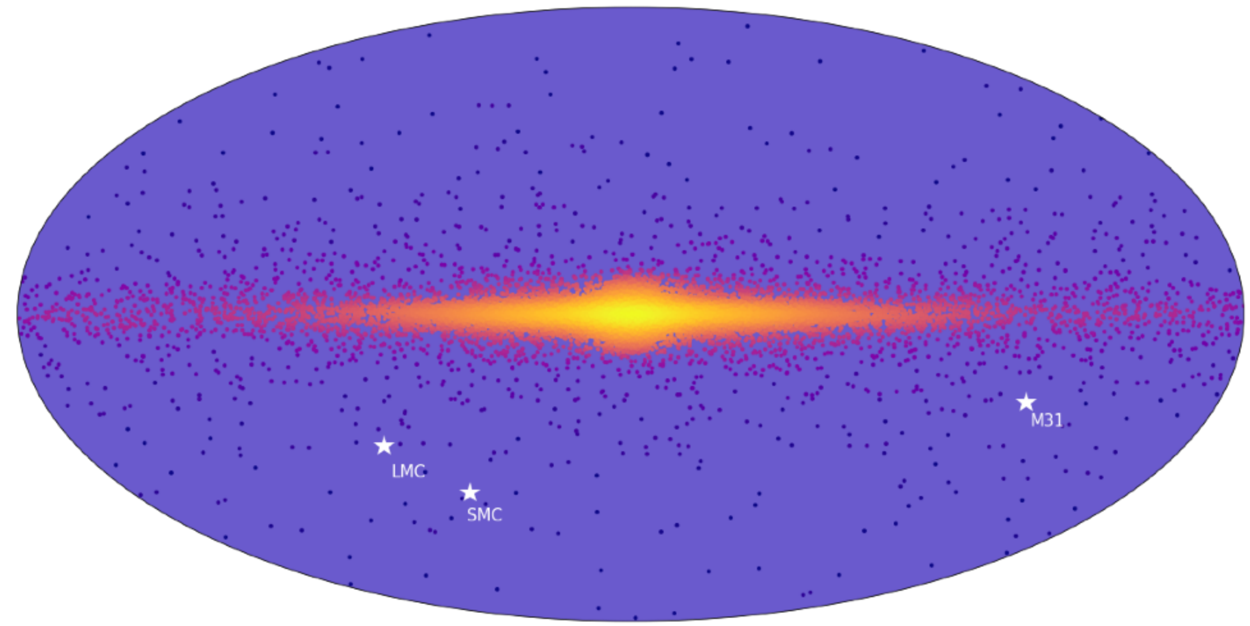


Keim, Korol & EMR in prep.

The Local Group’s structure and properties

Recovering structure <u>from GW only</u>:

- from background signal
- from resolved binaries’ signal



Korol, ERM & Barausse 2019

cit: Benacquista & Holley-Bockelmann 2006; Adams & Cornish 2012, 2014; Korol +2019; Breivik+2020

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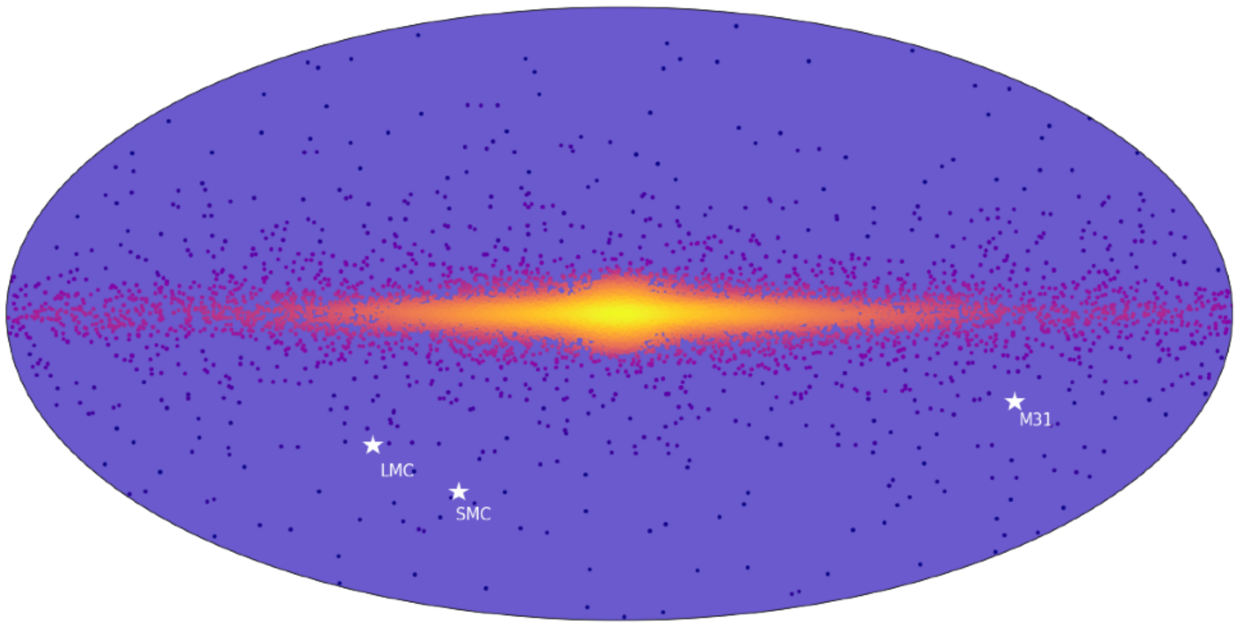


Korol, ERM & Barausse 2019

Why DW binaries are so powerful?

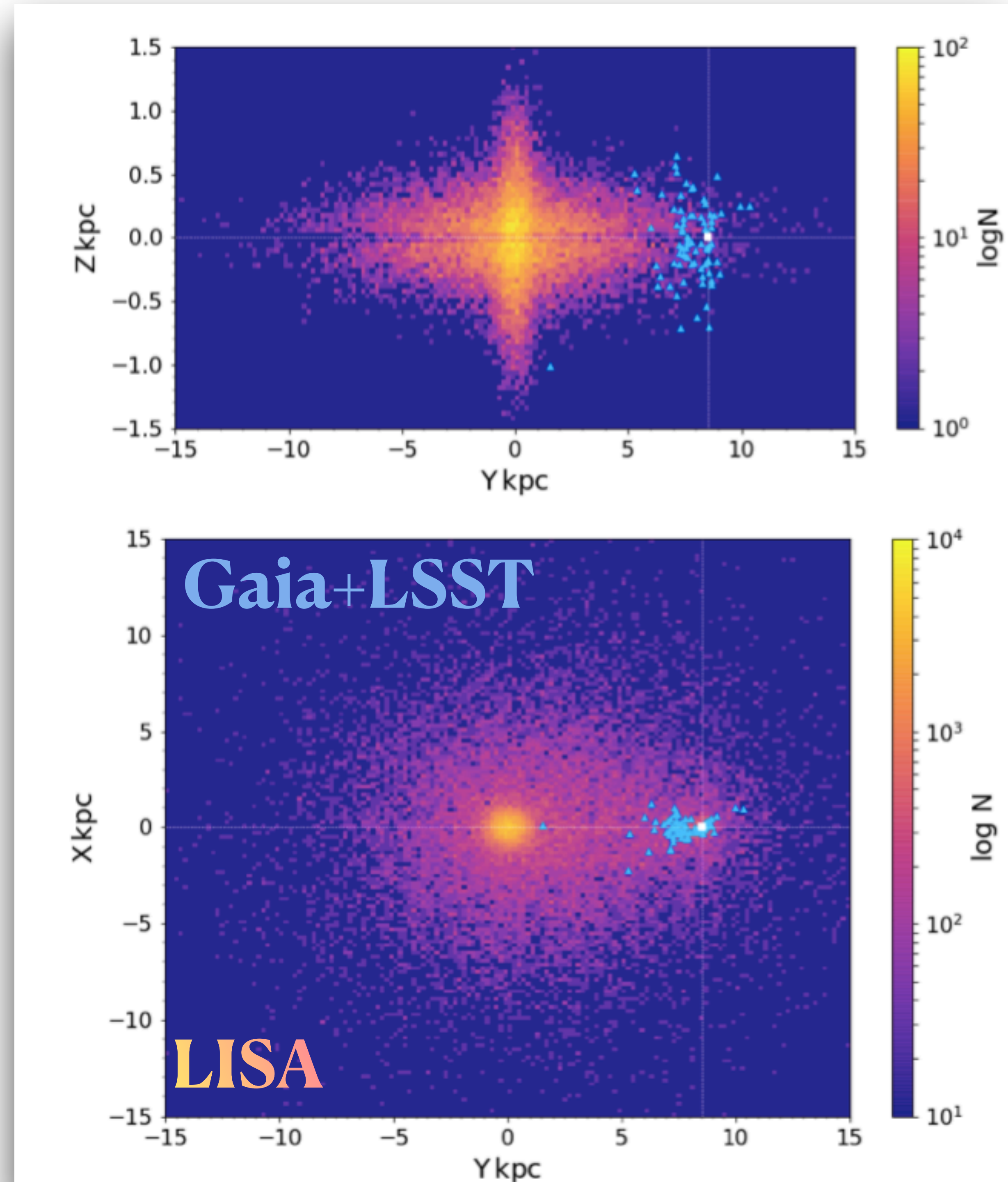
- **Abundant:** 10-40 thousands in LISA and ~200 Gaia+LSST
- **Trace parent population's position** (no-kick)
- **Trace large range of stellar ages**

cit: Benacquista & Holley-Bockelmann 2006; Adams & Cornish 2012, 2014; Korol +2019; Breivik+2020

GW+EM: excellent synergy

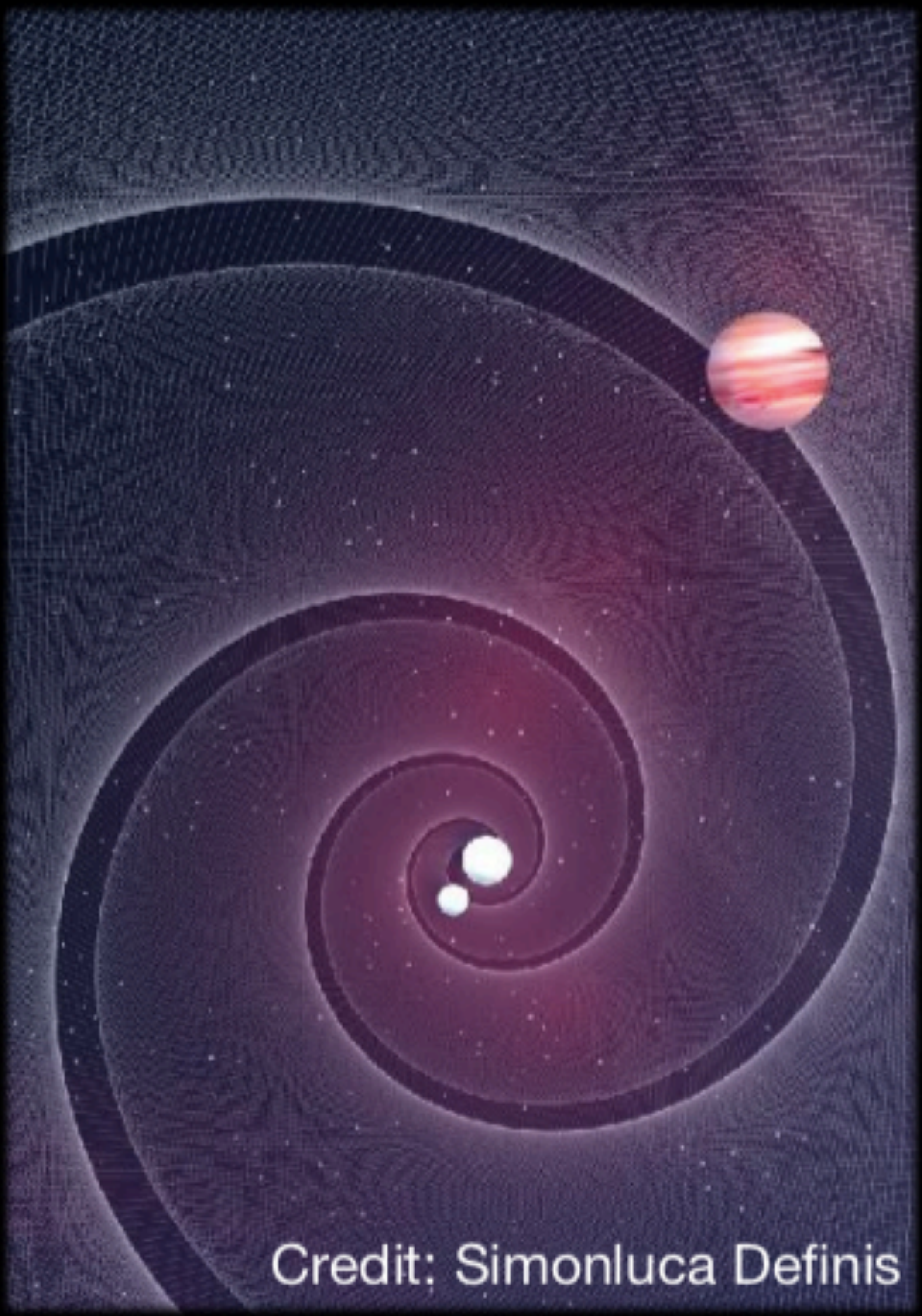
- **GW:**
  - seen through dust and stellar crowding
  - one distance measurement method
  - tracing low mass stars

- **EM:**
  - tracing motion (proper motion and radial velocity)
  - tracing stars with low (nearby) and high (out to large distances) mass
  - precise position



Korol, ERM & Barausse 2019

Planets and Brown Dwarfs around white dwarf binaries



Danielski & Tamanini 2020

Tamanini & Danielski 2019

Steffen et al. 2019

- Gravitational pull of 3rd object puts centre of mass on a Keplerian orbit
- Measuring a period Doppler modulation in signal
- frequency shift is measurable if mass> Jupiter and position < 10 au

- Learning about DDW and planet formation histories

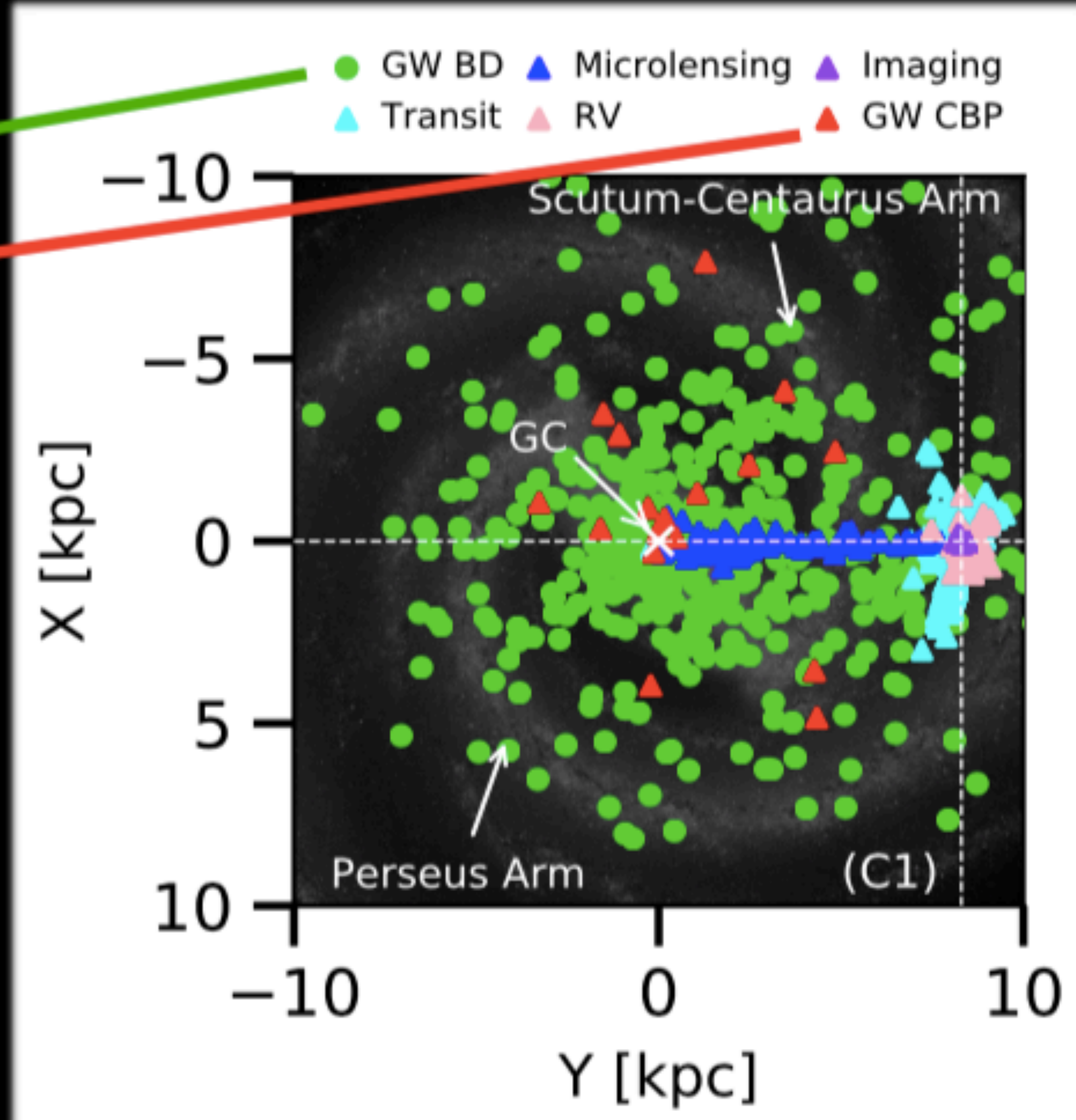
Planets and Brown Dwarfs around white dwarf binaries

In 4-yr mission:

Brown Dwarfs: ~10-2000

Circumbinary Jupiter: ~1-100

Note: Spatial distribution beyond Solar Neighbourhood

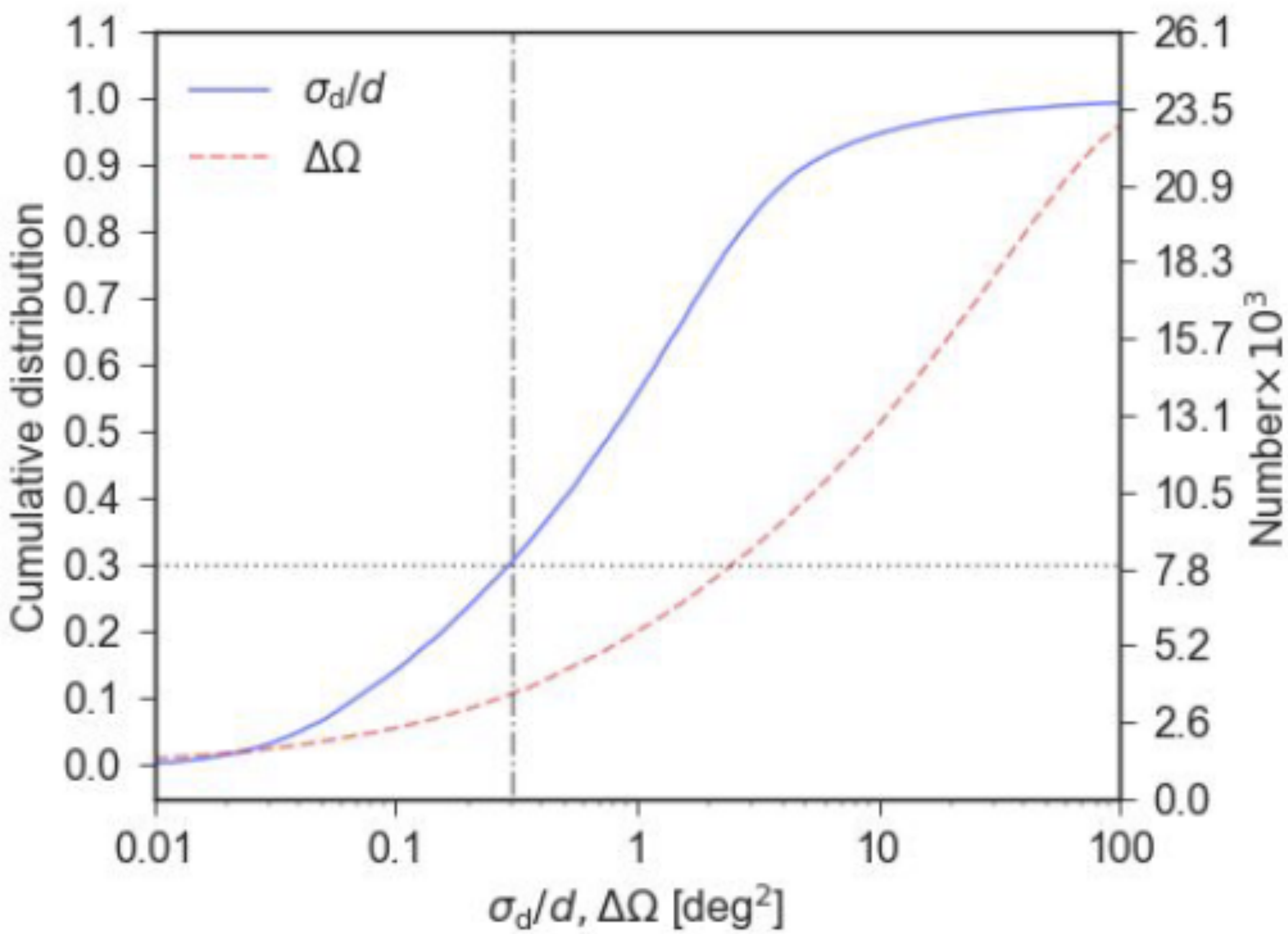


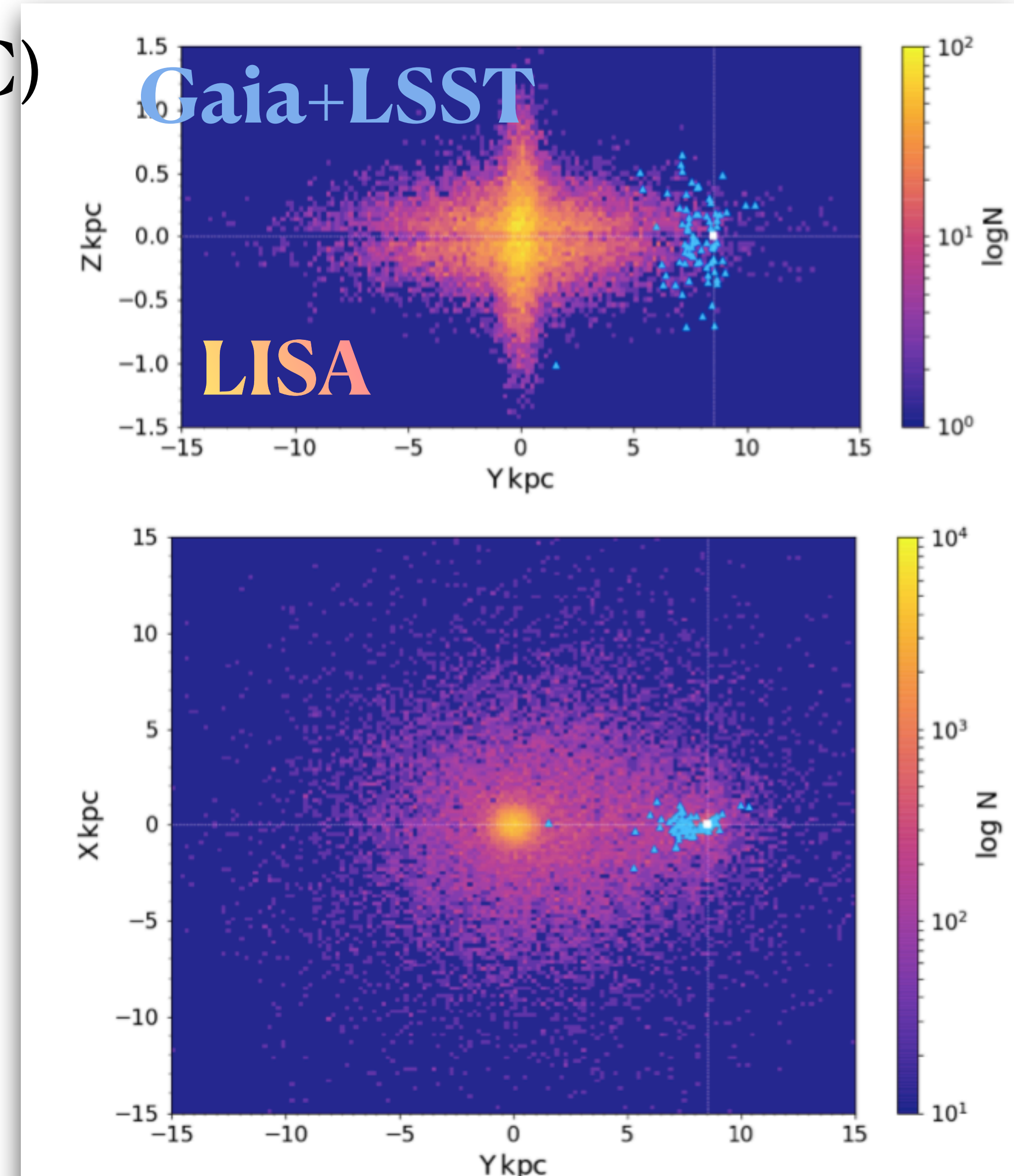
Danielski, Korol, Tamanini & EMR 2019

back-up

The Milky Way in GW

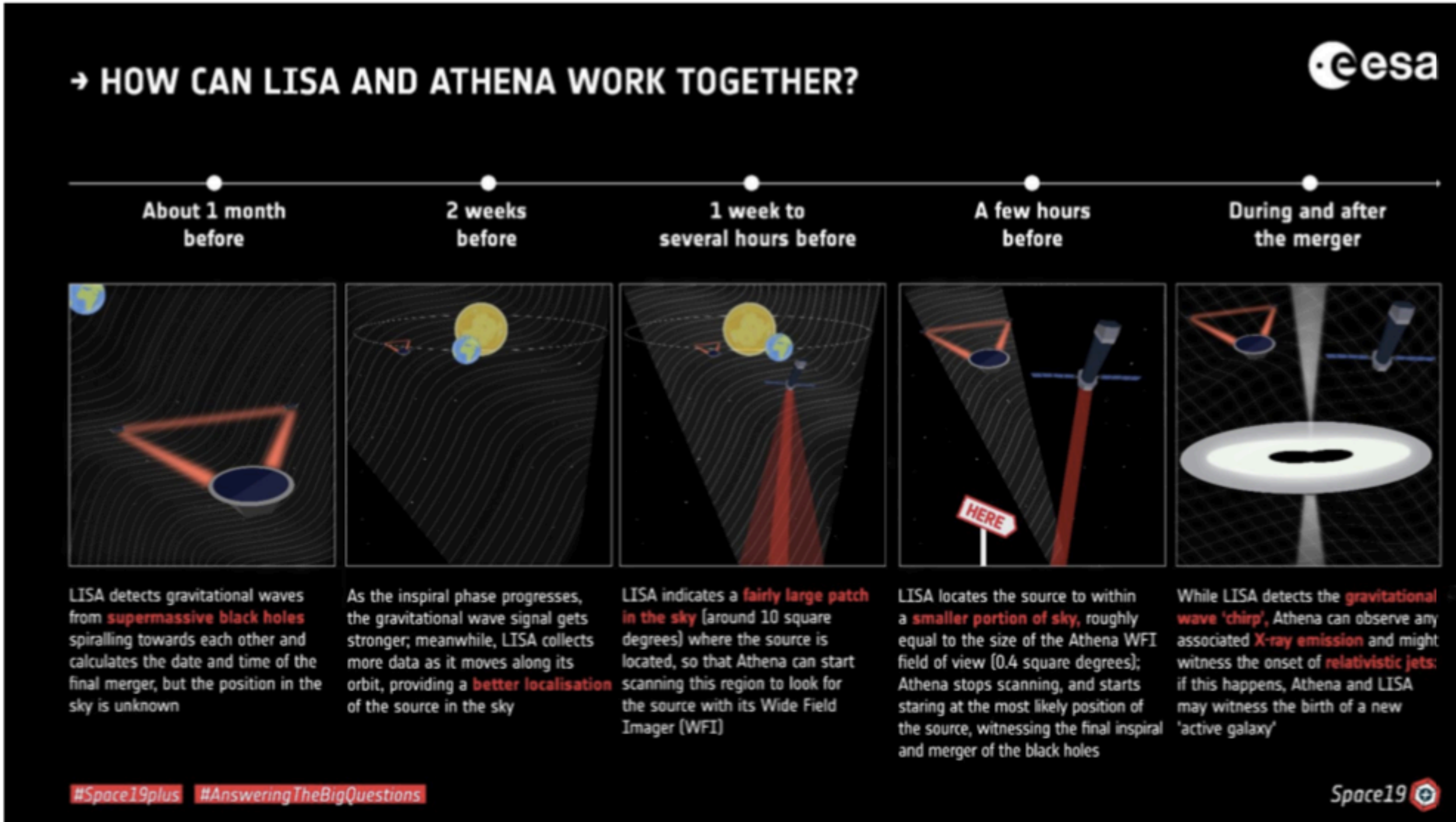
stance and Localisation errors with FIM (MLDC)



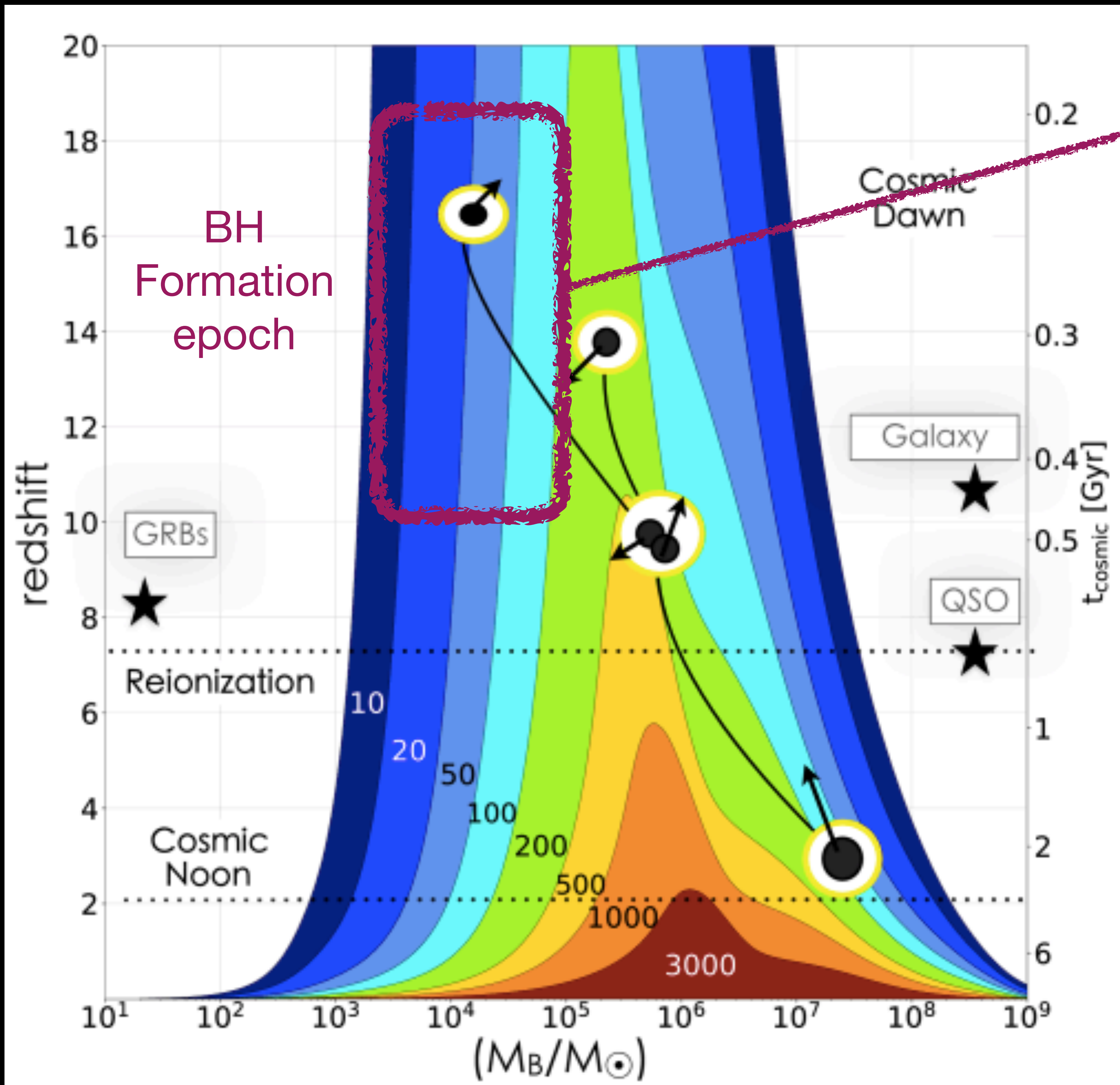


Korol, ERM &Barausse 2019

Athena-LISA

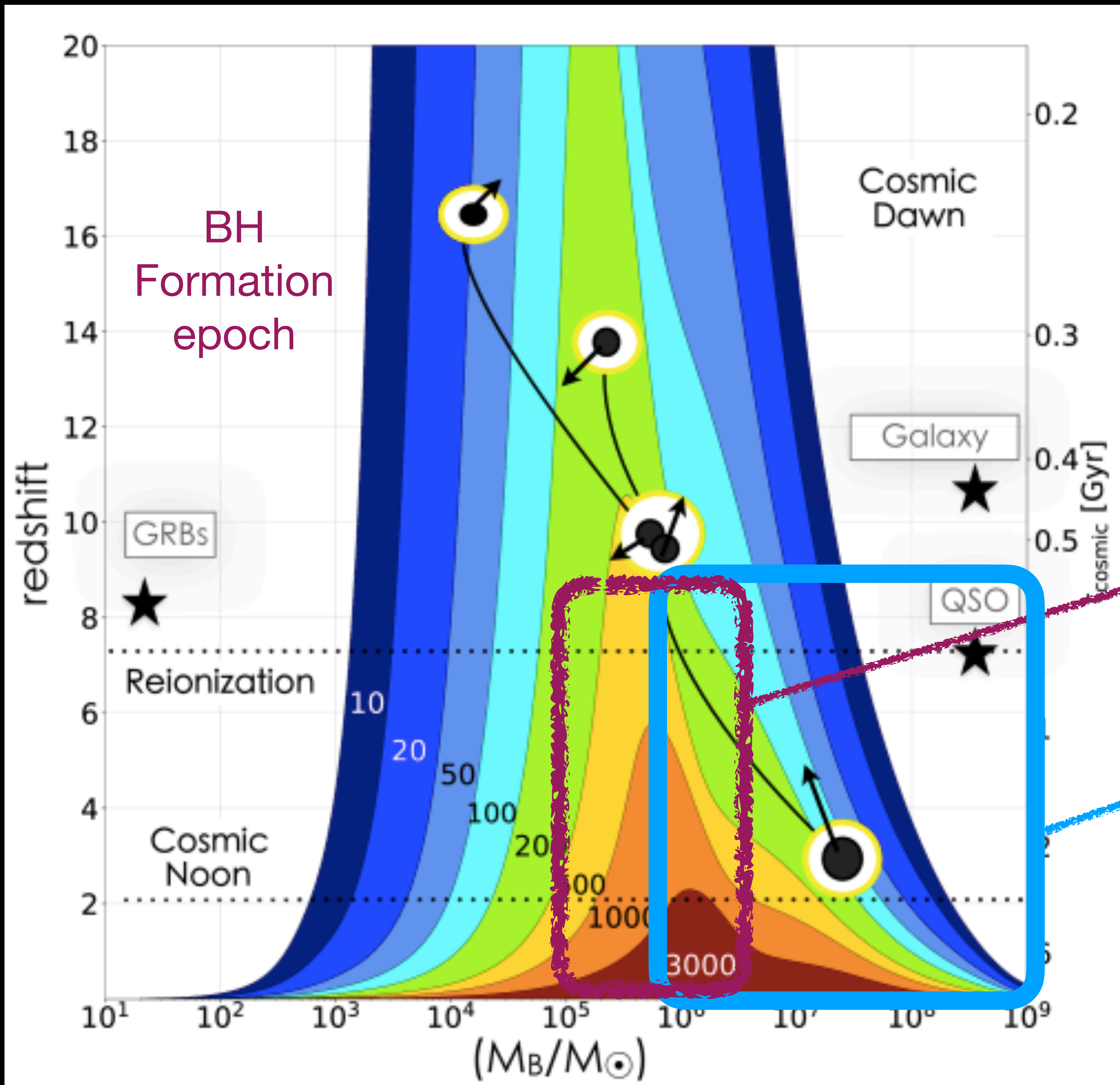


→ HOW CAN LISA AND ATHENA WORK TOGETHER?
esa
About 1 month before
2 weeks before
1 week to several hours before
A few hours before
During and after the merger
HERE
LISA detects gravitational waves from supermassive black holes spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown
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
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)
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
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'
#Space19plus
#AnsweringTheBigQuestions
Space19



Masses, Distances with fractional error< 20%

GW + EM



Masses, Distances with fractional error ~1%
Spin error <10% (SNR>200)

E.M. Counterparts

Joint detection in the "high mass tail"