Unveiling the Gravitational Wave Universe at *μ*-frequencies

White paper submission for Voyage 2050

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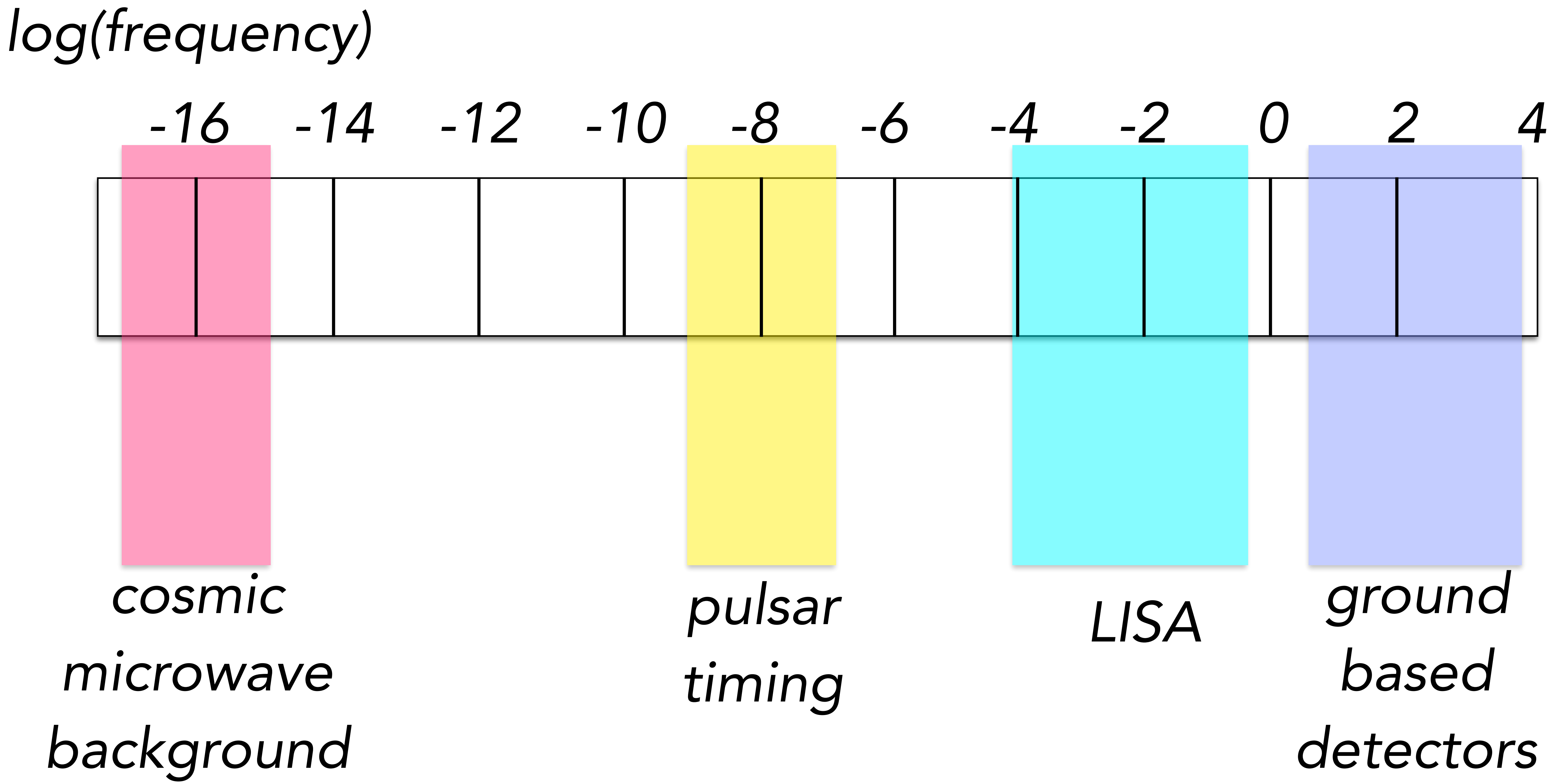
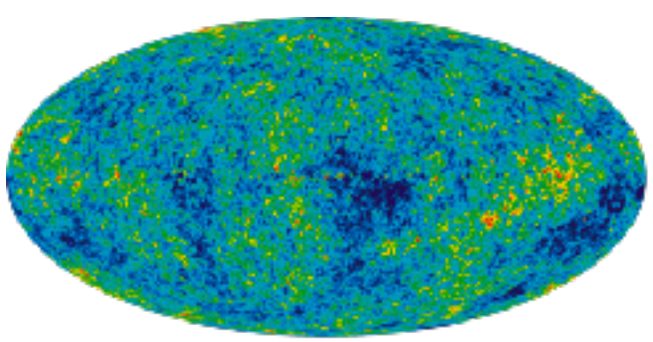
on behalf of Alberto Sesana and
the writing team

Image credit: Simon Barke

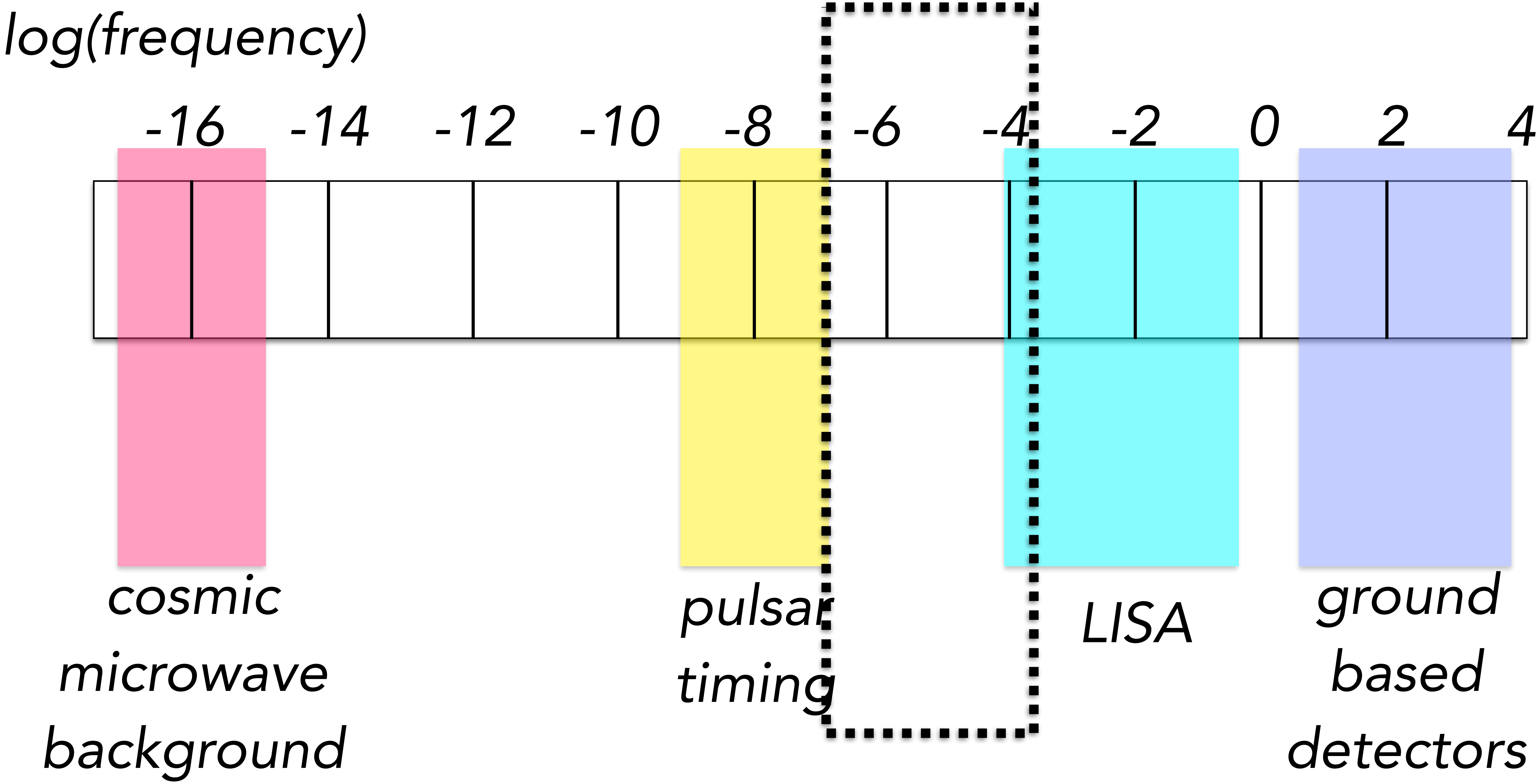
31 October 2019 *Madrid Voyage 2050 Workshop*

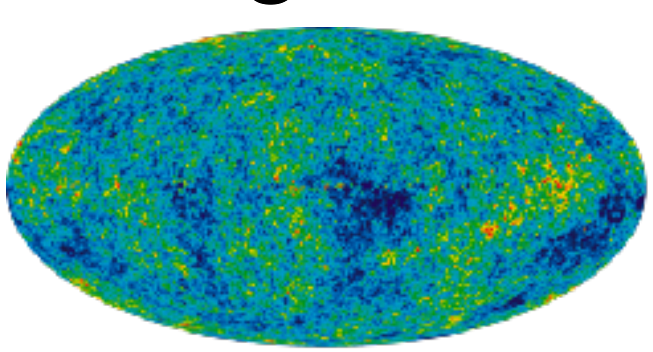
Gravitational wave spectrum

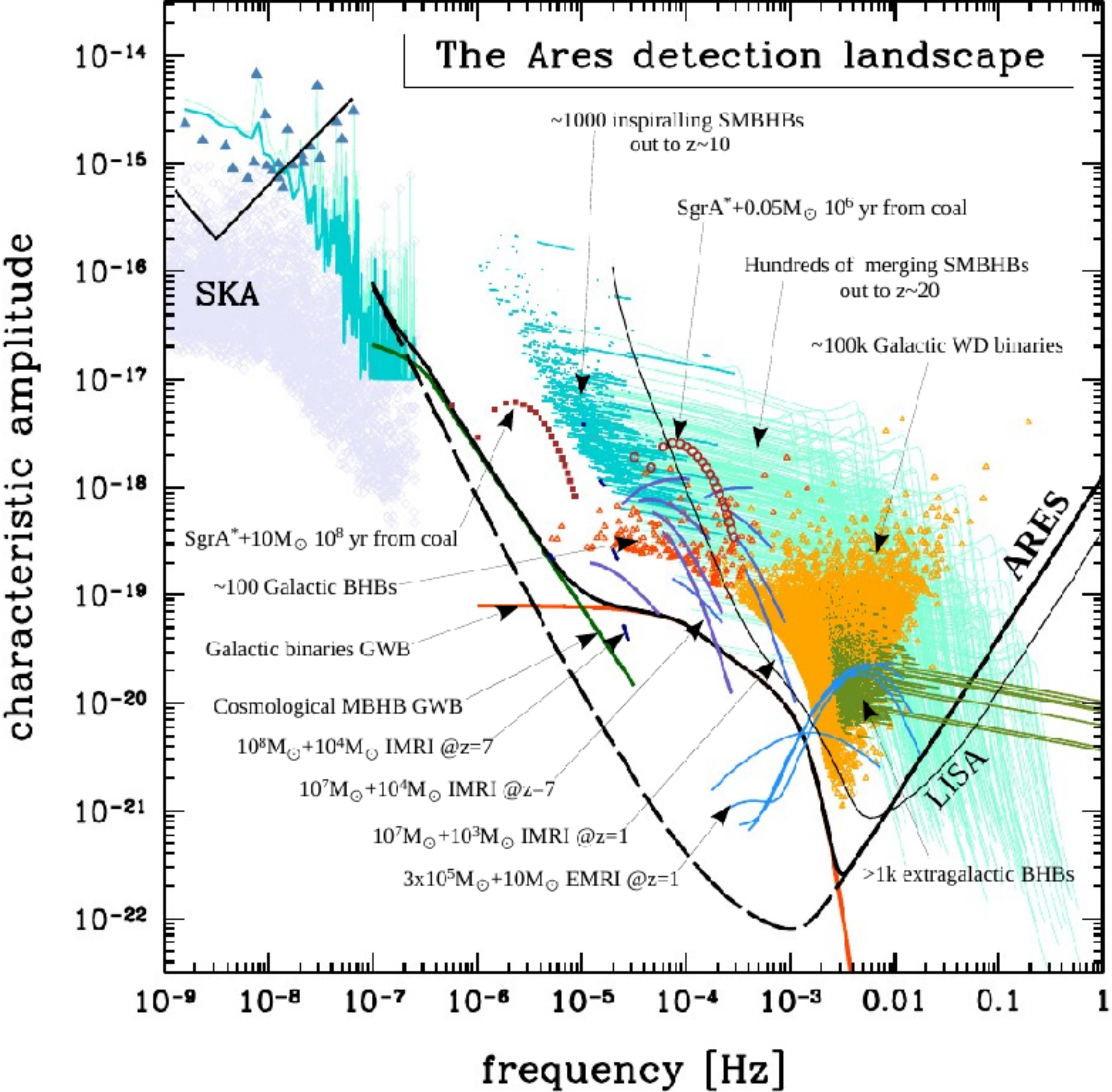




Gravitational wave spectrum






The Ares detection landscape
characteristic amplitude
frequency [Hz]
SKA
~1000 inspiralling SMBHBs out to z~10
SgrA*+0.05M⊙ 10^6 yr from coal
Hundreds of merging SMBHBs out to z~20
~100k Galactic WD binaries
SgrA*+10M⊙ 10^8 yr from coal
~100 Galactic BHBs
Galactic binaries GWB
Cosmological MBHB GWB
10^8M⊙+10^4M⊙ IMRI @z=7
10^7M⊙+10^4M⊙ IMRI @z=7
10^7M⊙+10^3M⊙ IMRI @z=1
3x10^5M⊙+10M⊙ EMRI @z=1
>1k extragalactic BHBs
ARES
LISA

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Science goals

1. *Massive Black Hole Binaries*
2. *Multimessenger and Multiband*
3. *General relativity and beyond*
4. *Cosmology and cosmography*
5. *Milky Way Science*

① Massive Black Hole Binaries Science

probe the emergence of the high-redshift quasars

establish the relative importance of accretion vs mergers in growing MBHs

disentangle seed formation models at the high-mass end of the seed spectrum

probe the population of inspiralling MBHs in low-redshift dwarf galaxies

pin down the physics of MBHB dynamics, including stellar hardening, gaseous drag, triples and multiple MBH interactions

probe the formation and dynamics of IMBHs in galactic nuclei

Probe the emergence of the high-redshift quasars

quasars are observed as far as z = 7.54

powered by SMBHs with the masses ~ 10^9 -10^{10} solar masses

how does it happen that such massive black holes are formed so early?

- *seeding*
- *accretion*
- *merger*

some or all of these mechanisms have to be enhanced

contribution to accretion can be tracked by EM observations

GWs can detect mergers

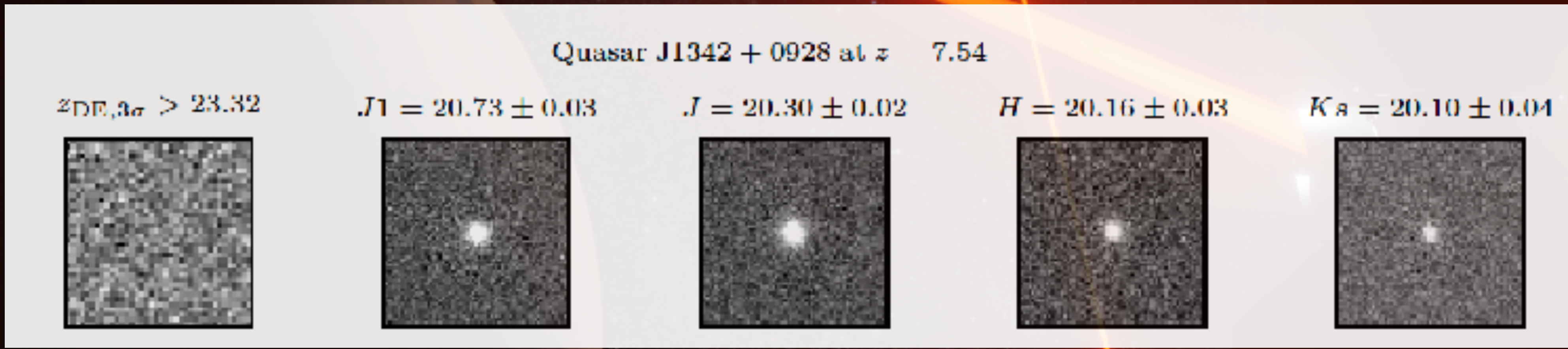


Image from Bañados et al "An 800-million-solar-mass black hole in a significantly neutral Universe at redshift 7.5"

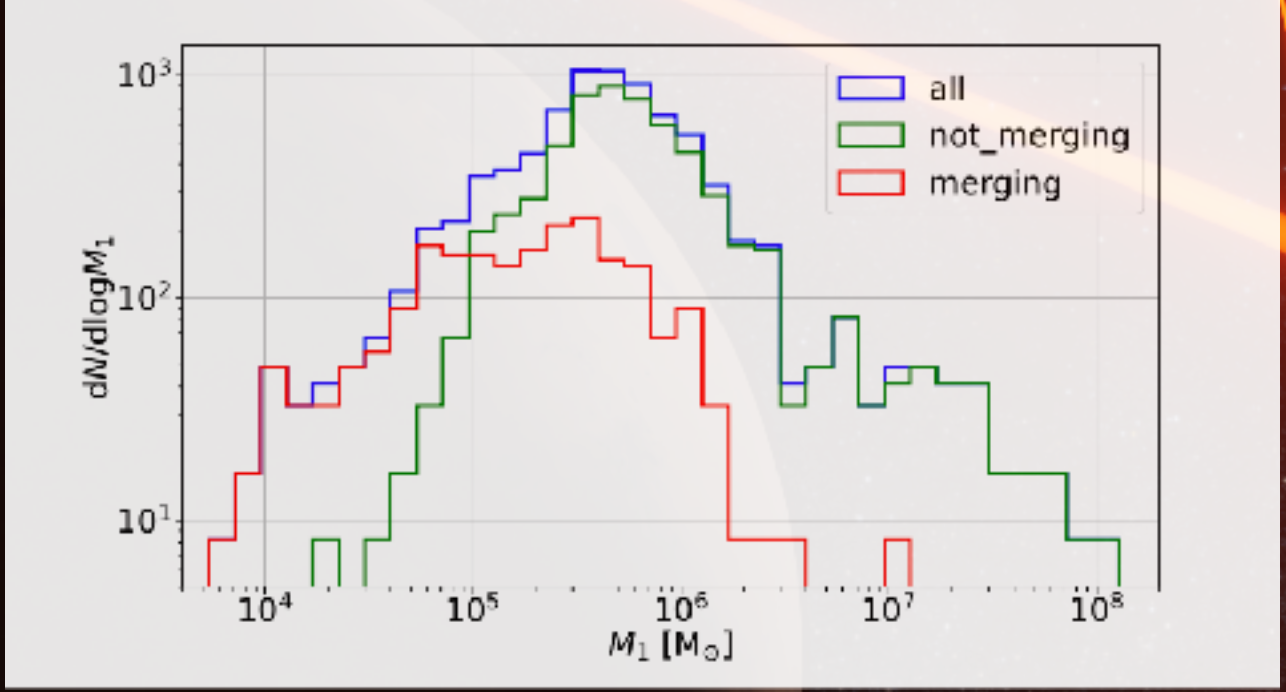
Probe the emergence of the high-redshift quasars

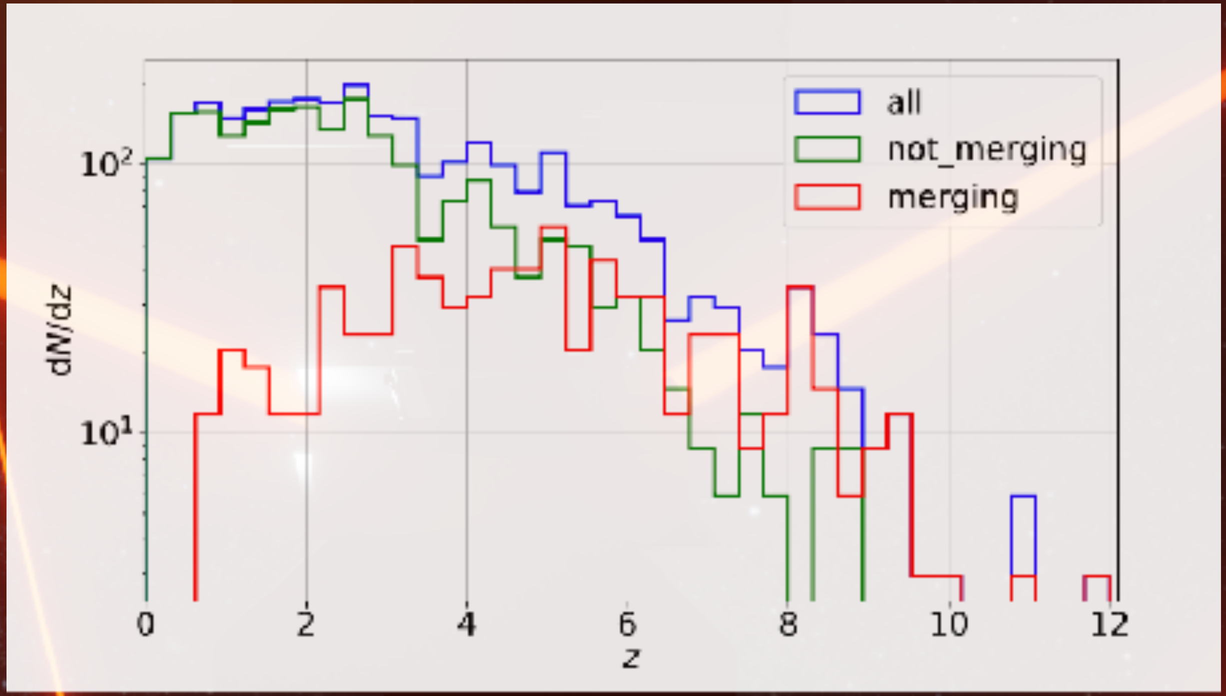
Going to μHz with GWs

detect mergers at high SNR with z = 7 - 15

large statistical sample of inspiralling MBHBs up to z ~ 10

not possible to observe in higher frequencies





Probe the population of inspiralling MBHs in low-redshift dwarf galaxies

Presence of MBH in dwarf galaxies have not been directly confirmed

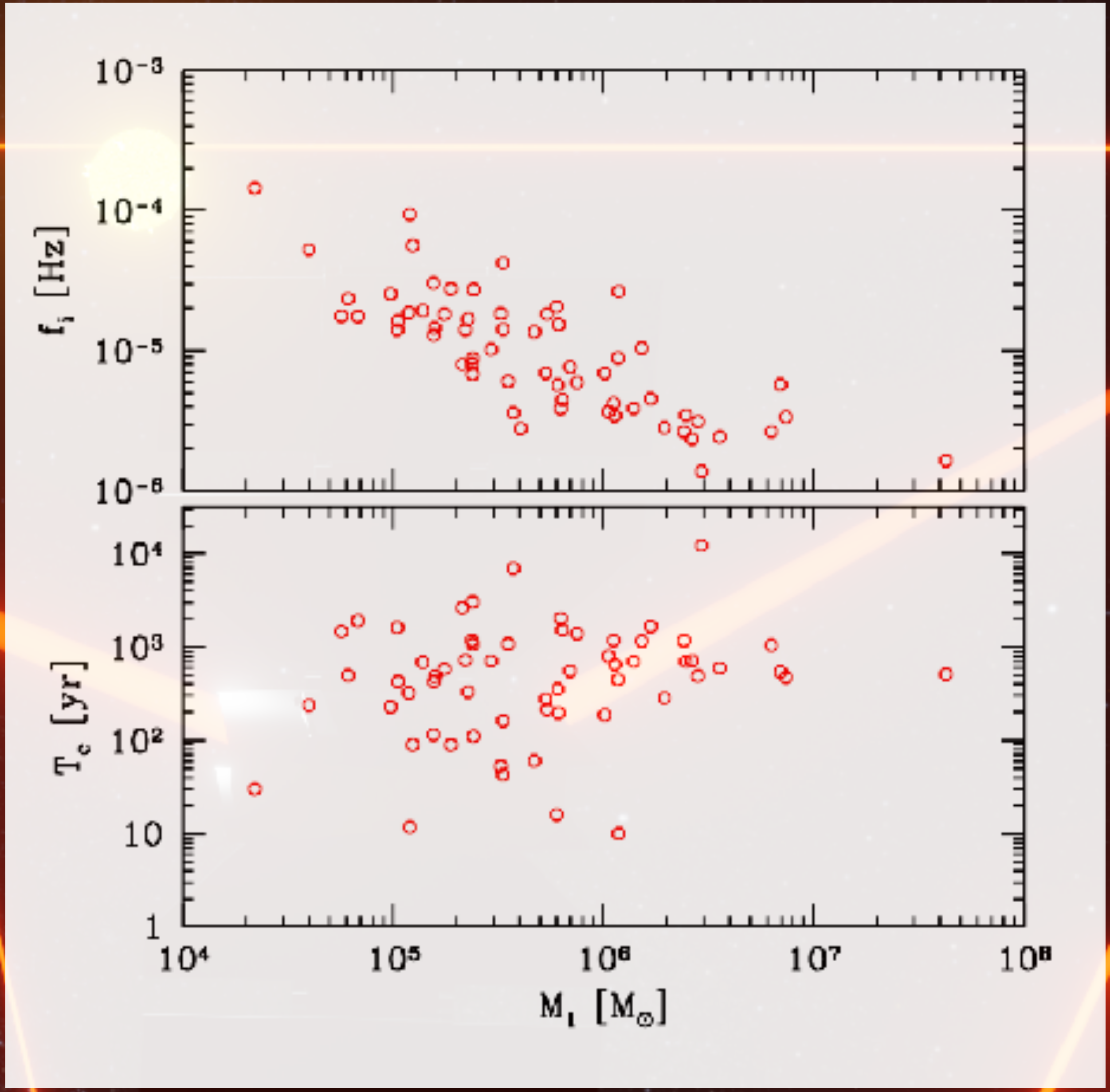
Candidates low-luminosity active galactic nuclei

Merger rate is much less than 1 per year

The inspiral can be observed in μHz

Such MBHBs will likely keep the memory of the initial seeding process.

Time to coalescence as a function of mass



2 Multimessenger astronomy

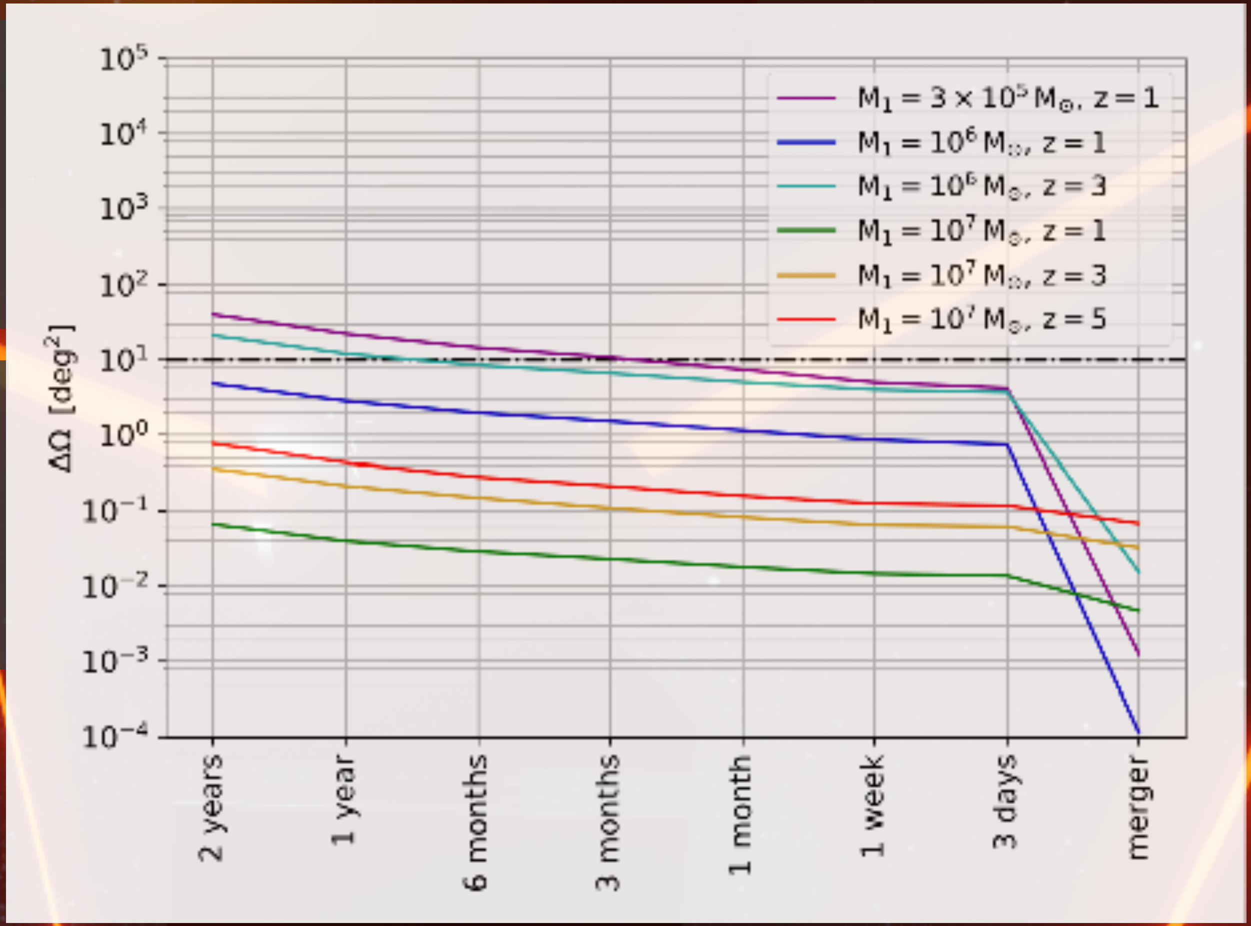
MBHBs are expected to occur in the gas-rich central regions of galaxy mergers

Together with the hosts, the GWs and EM observations can give insight to co-evolution of MBHs and galaxies

This requires unique identification of the host galaxy for a large population of mergers, which is unlikely to be fully accomplished by LISA

Merging MBHs can have several distinct EM signatures, before, during, and after the merger

Understanding binary accretion and the corresponding spectral evolution properties of the above signatures



Multimessenger astronomy

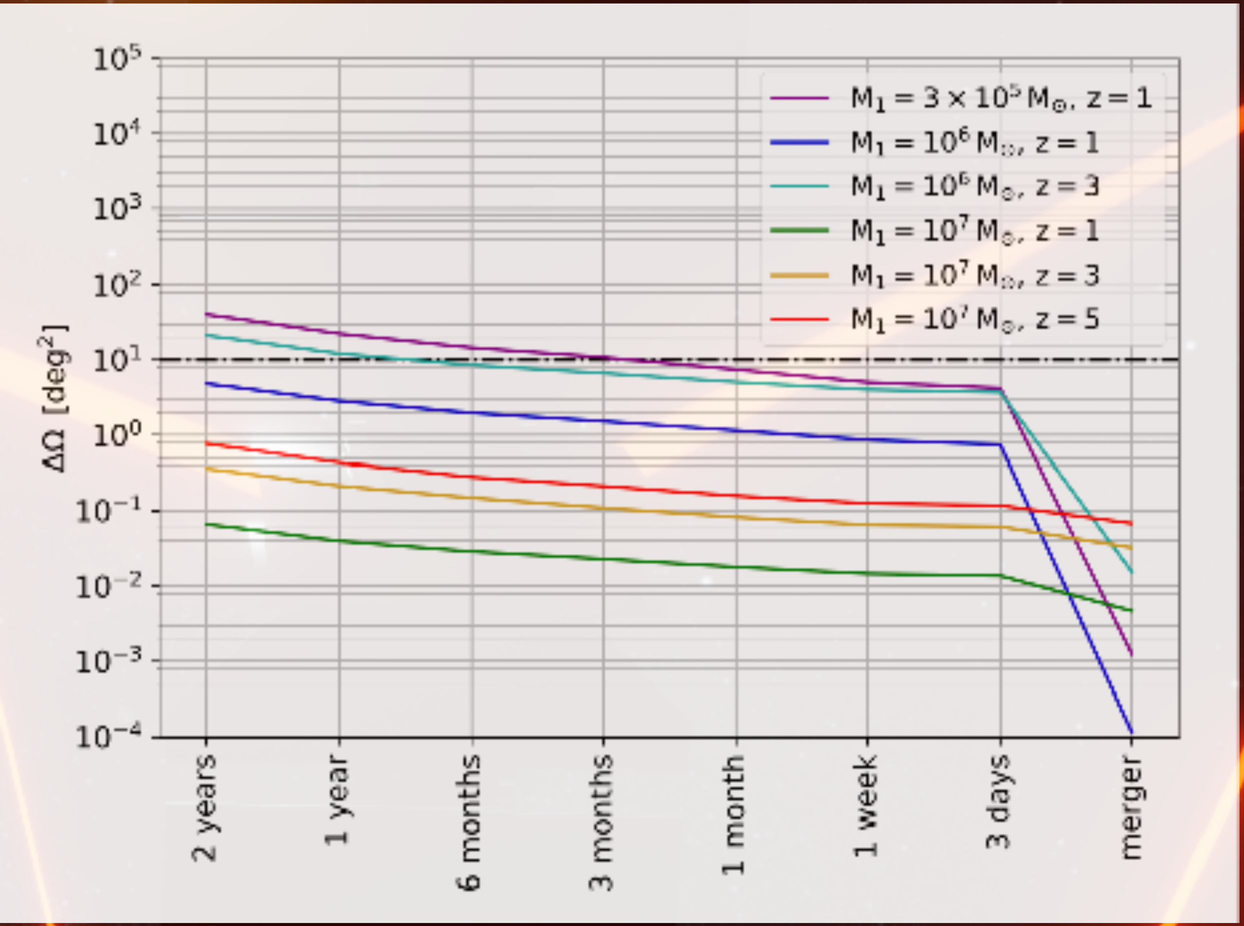
Measure the coincident EM chirp and phase it with GW over several hundred cycles the sources need to be localised on the sky weeks to months prior to merger (depending on the chirp mass)

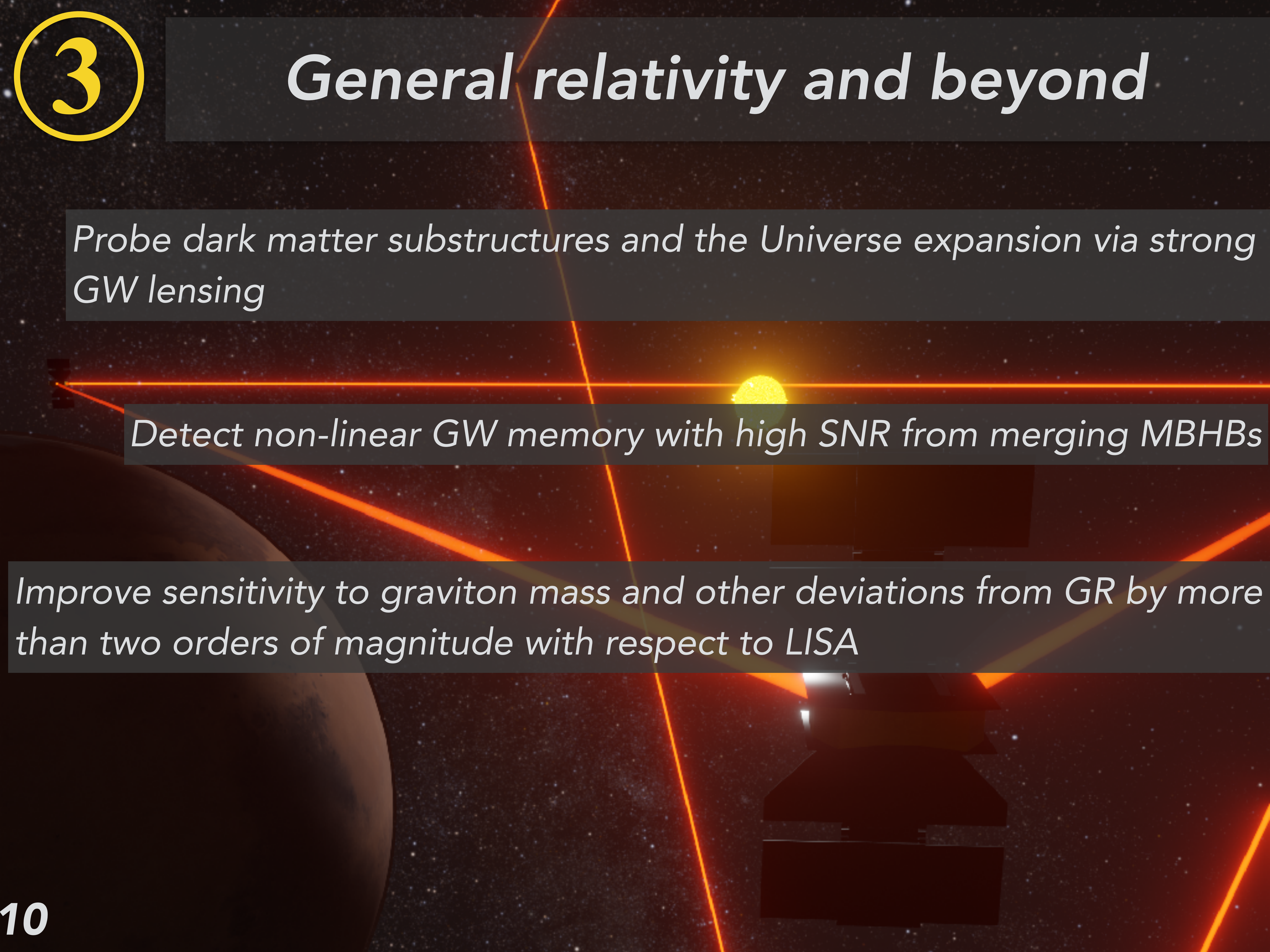
Identification of a counterpart

Extract the typical signatures of accreting binaries

Search for them in available EM data

Redshift from the EM observations will enable the cosmological use of chirping MBHBs as standard sirens




③
General relativity and beyond
Probe dark matter substructures and the Universe expansion via strong GW lensing
Detect non-linear GW memory with high SNR from merging MBHBs
Improve sensitivity to graviton mass and other deviations from GR by more than two orders of magnitude with respect to LISA
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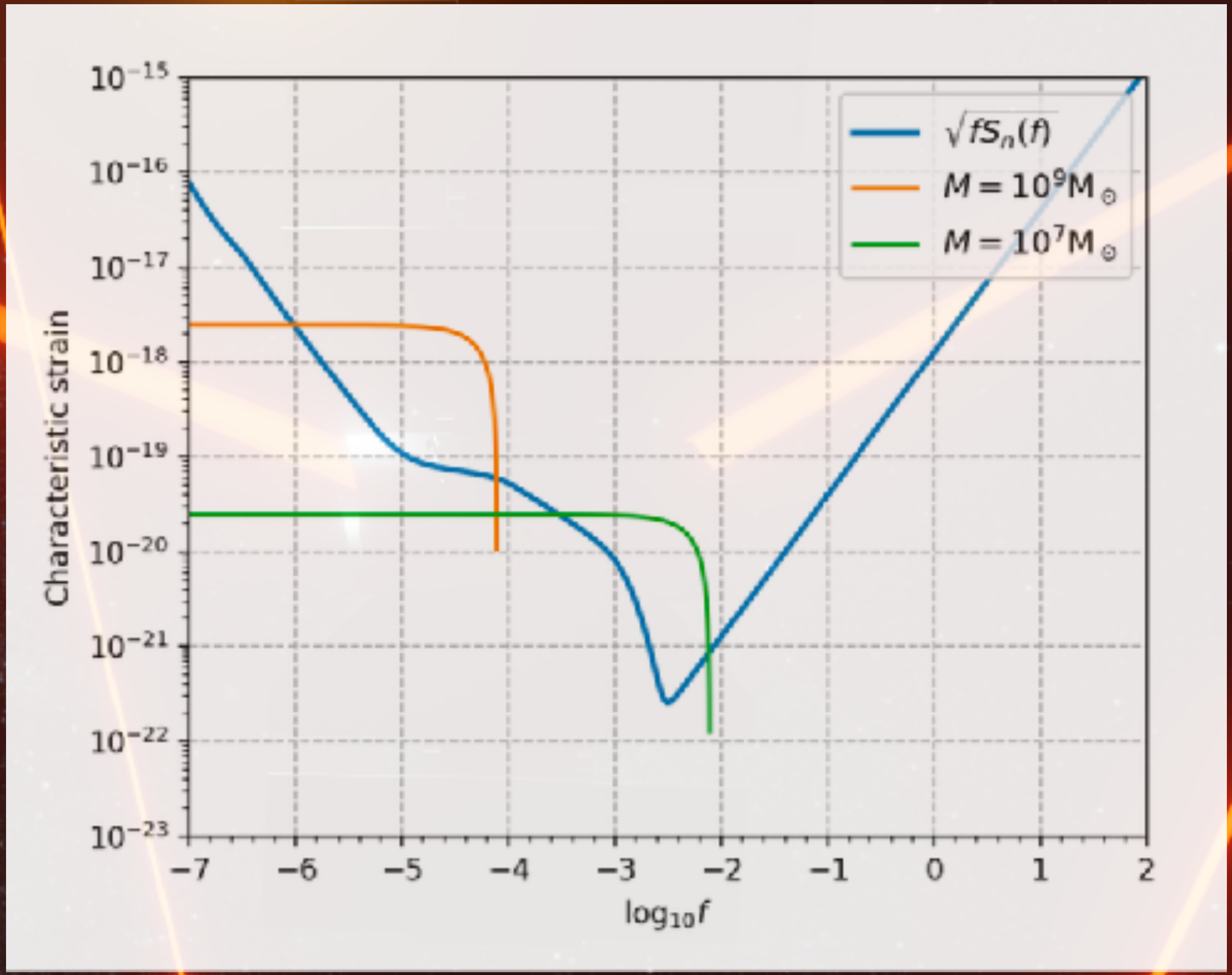
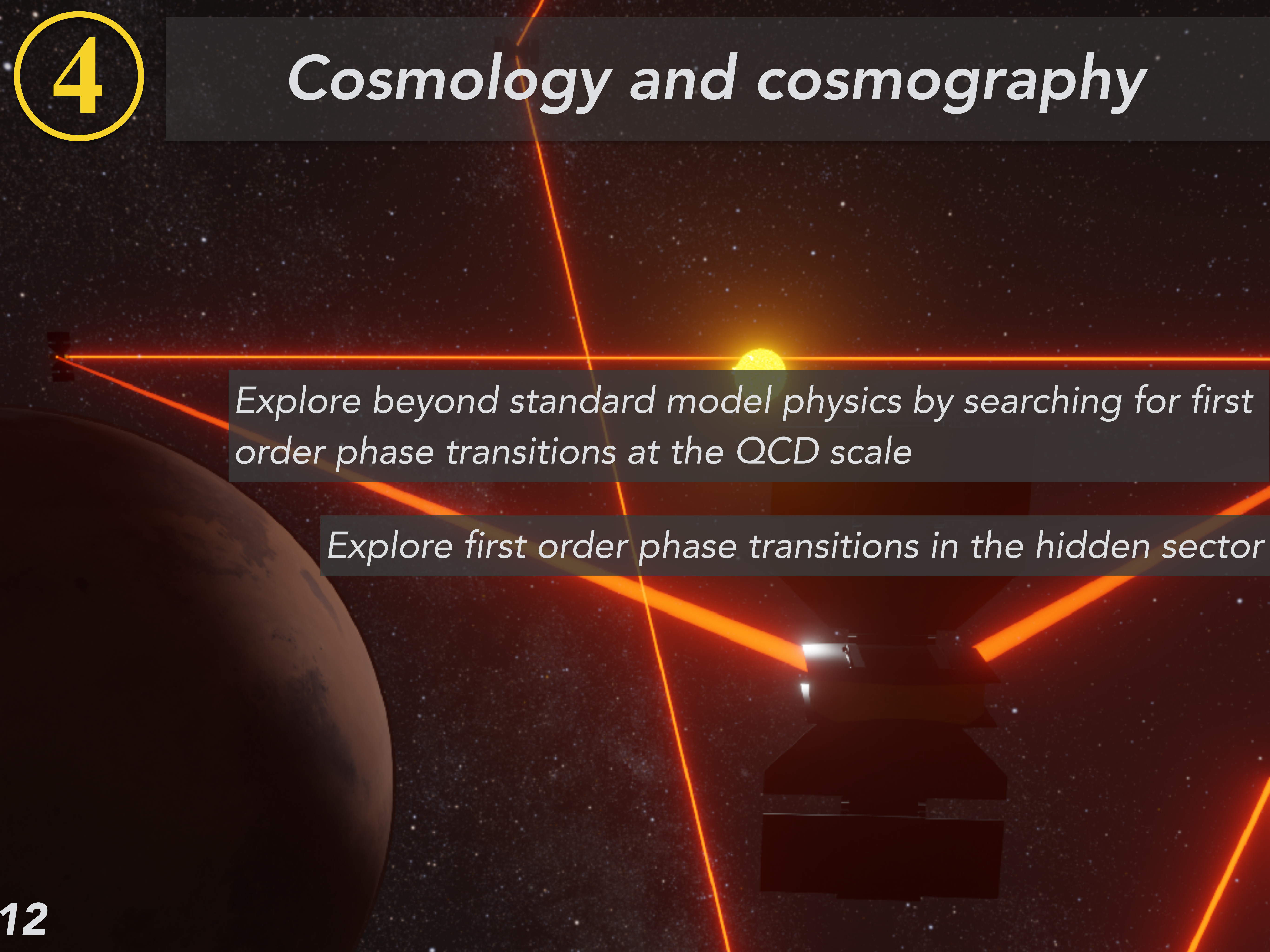
Detection of non-linear GW memory

Memory effect is the permanent relative displacement between two probe masses following the passage of GWs

Originates from the non-linearities in the Einstein field equations and therefore provides a direct test of GR in the strong regime

It is possible to detect the build-up of memory during the evolution of MBHB





④ Cosmology and cosmography

Explore beyond standard model physics by searching for first order phase transitions at the QCD scale

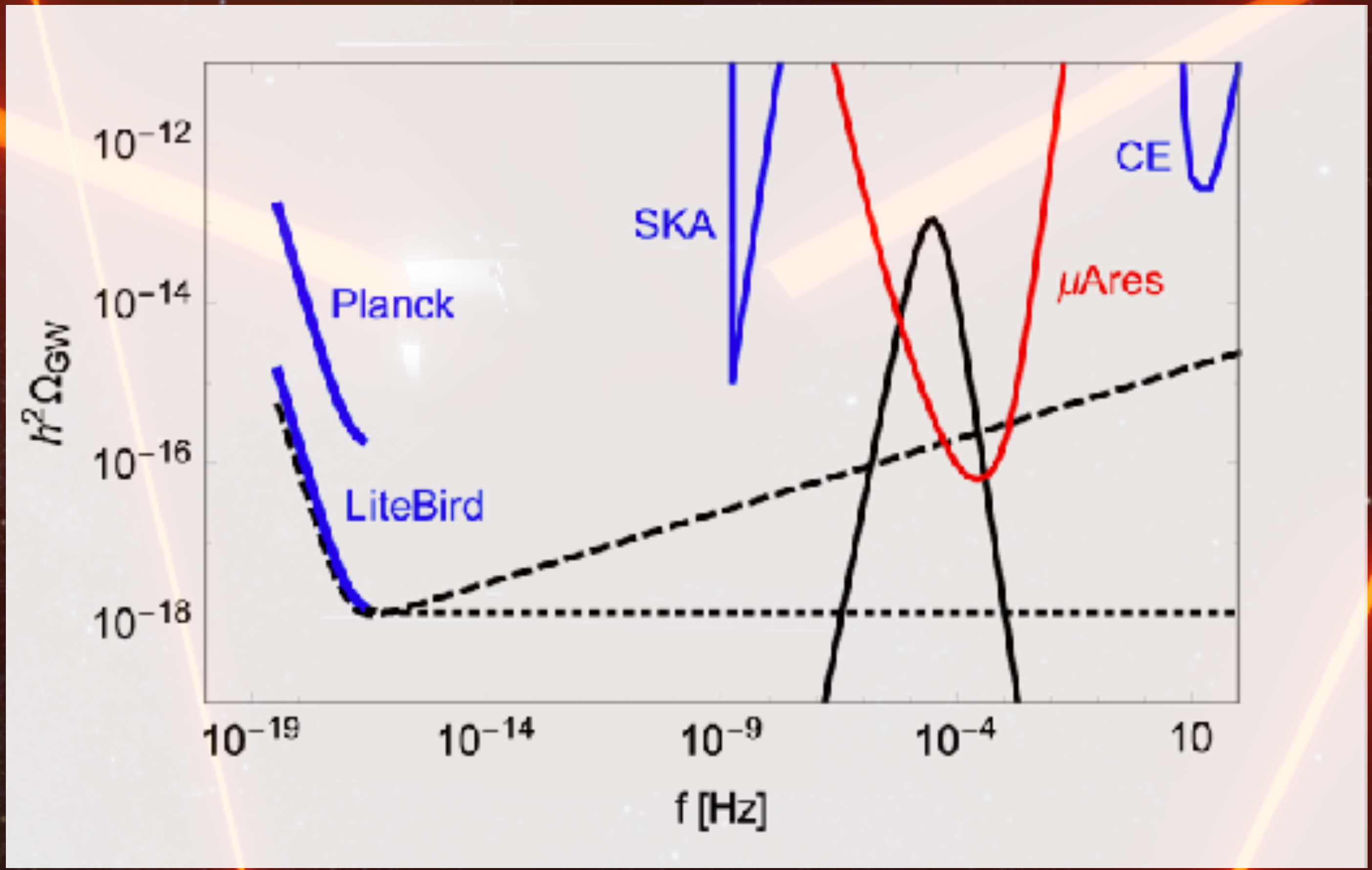
Explore first order phase transitions in the hidden sector

QCD phase transition

The main processes that can generate a SGWB in the early universe are connected either to inflation or to a primordial phase transition

By the early 2030', the LiteBird satellite will probe the signal from inflation at low frequencies and down to an amplitude of $\Omega_{GW} \sim 10^{-18}$

Complement the detection at higher frequencies -> study inflationary models beyond the standard slow roll scenario



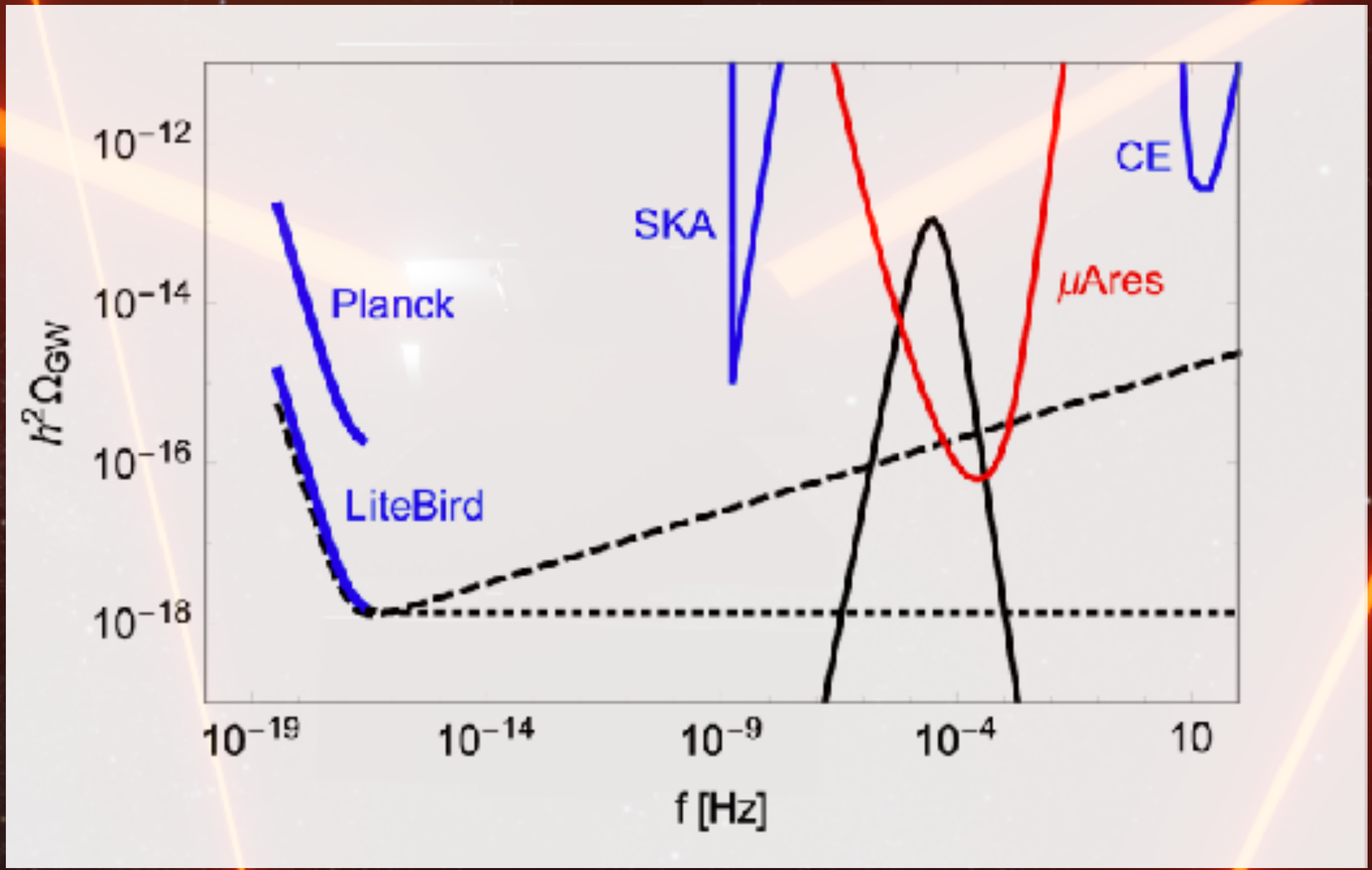
QCD phase transition

μAres is potentially sensitive to the signal from a first order QCD phase transition

For example, when a sterile neutrino is the Dark Matter

The discovery space of μAres for the occurrence of a first order QCDPT is vastly larger than the one of PTA

muAres is also potentially sensitive to phase transition occurring in dark sectors (not coupled to the standard model), which provide Dark Matter candidates



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Milky Way science

Understand common envelope physics via detection of mixed (compact objects + MS star) binaries and the distribution of DWD at $f < 10^{-4}$ Hz

Physics of contact and over-contact binaries via joint GW + EM detection

Characterization of BBH, BNS and BH-NS population in the Galaxy, synergies with PTAs and SKA

*Unveil the dynamics of stars and compact objects around SgrA**

Understanding common envelope physics

In low GW frequency we can observe CO with a non-degenerate (main sequence or brown dwarf) star

Bright EM counterparts

These studies can constrain binary evolution models and pin down the formation of rare binary systems

Will help to understanding the formation and evolution of COs and binaries in the global context of the evolution of galaxies

The period and mass distributions of WD+MS binaries provides the most direct link to common-envelope evolution

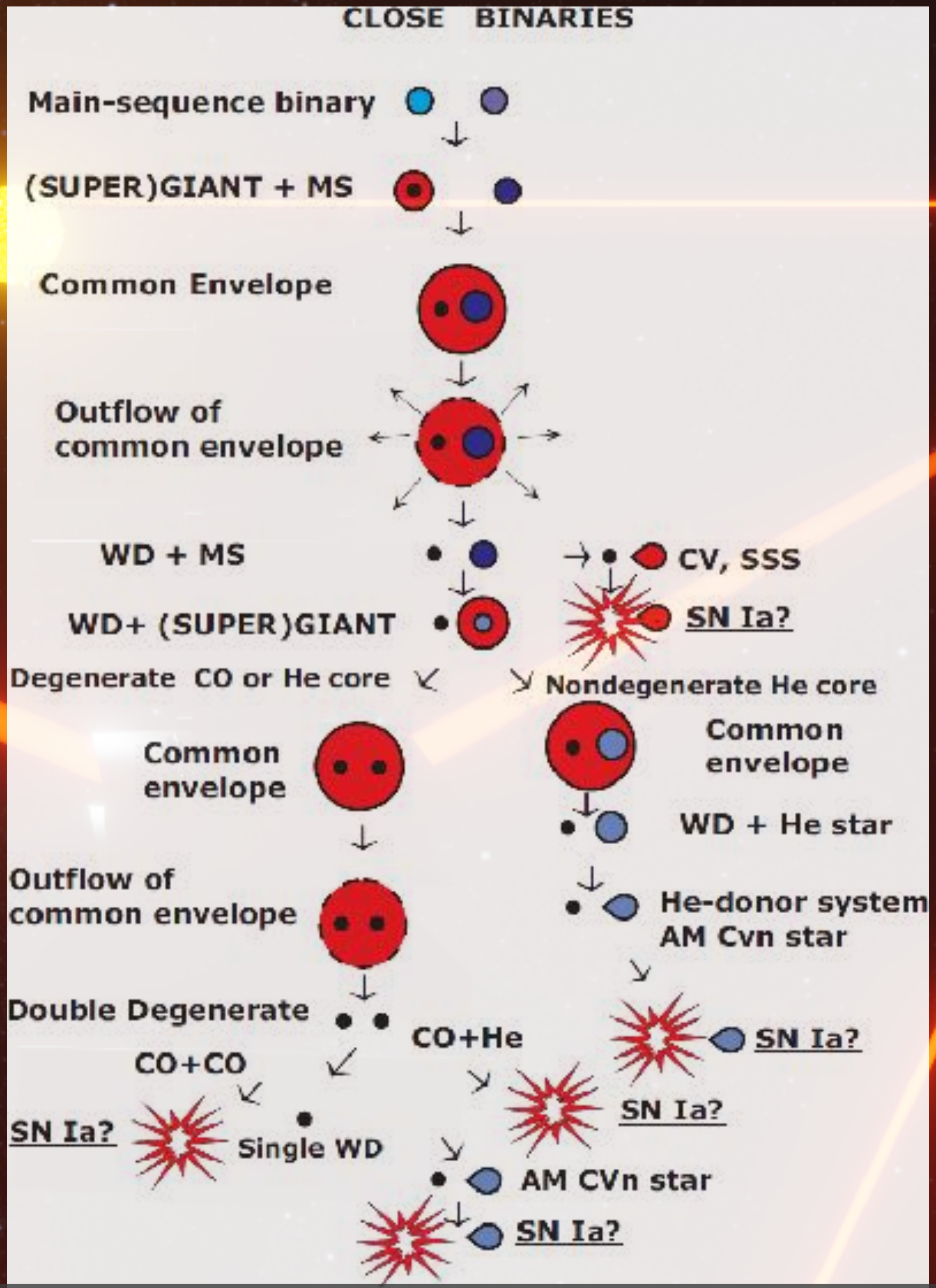


Image from Postnov and Yungelson "The Evolution of Compact Binary Star Systems" Living Reviews in Relativity

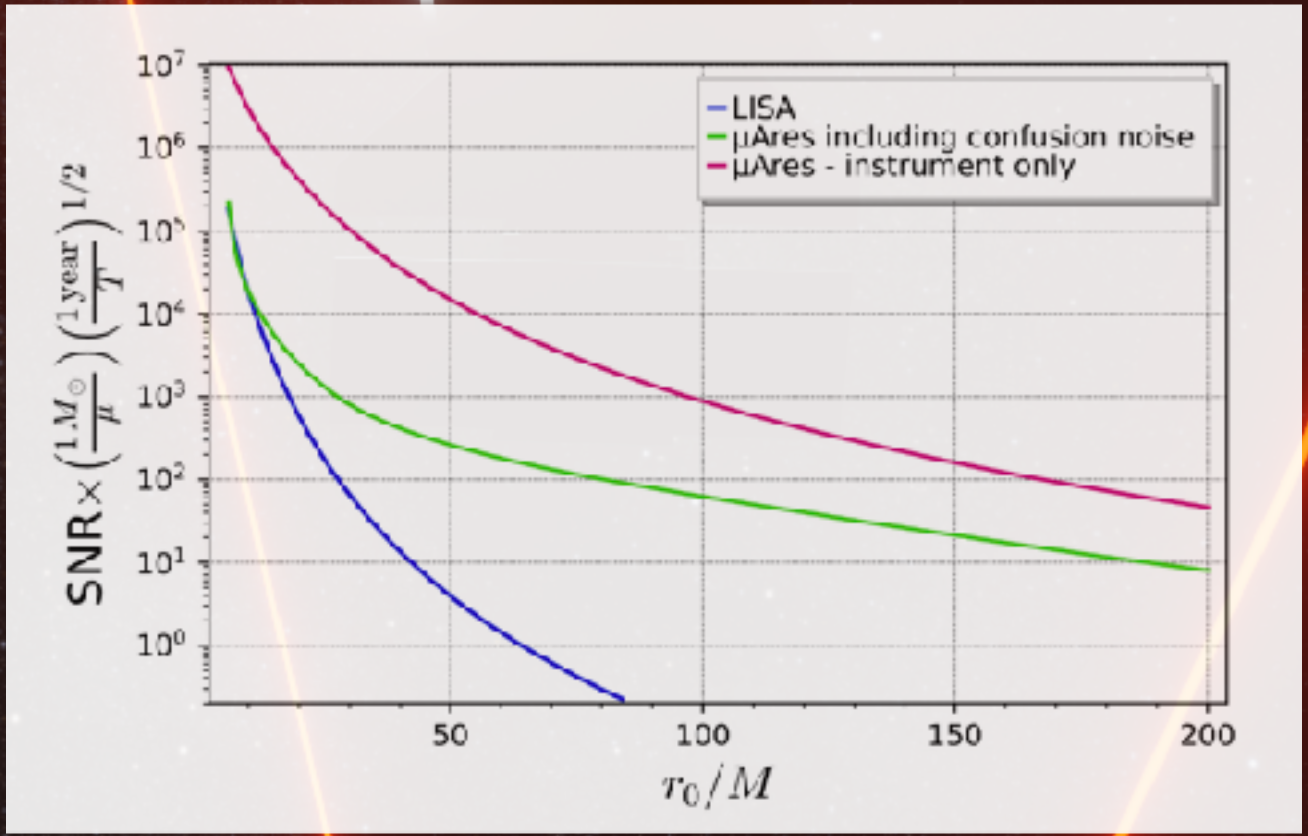
Dynamics of stars and COs around SgrA*

Theoretical models suggest that the inner 0.04 parsecs surrounding SgrA* should have a 'dark cluster' of compact remnants and faint low-mass stars

Many of low-mass stars, in the form of brown dwarfs, could be on highly relativistic orbits

The mass of SgrA* is such that if these bodies orbit sufficiently close to it they will emit GWs in μHz band

One solar mass object could be detected with an SNR 10 as far out as 8 AU from the black hole with 1 year of observing time

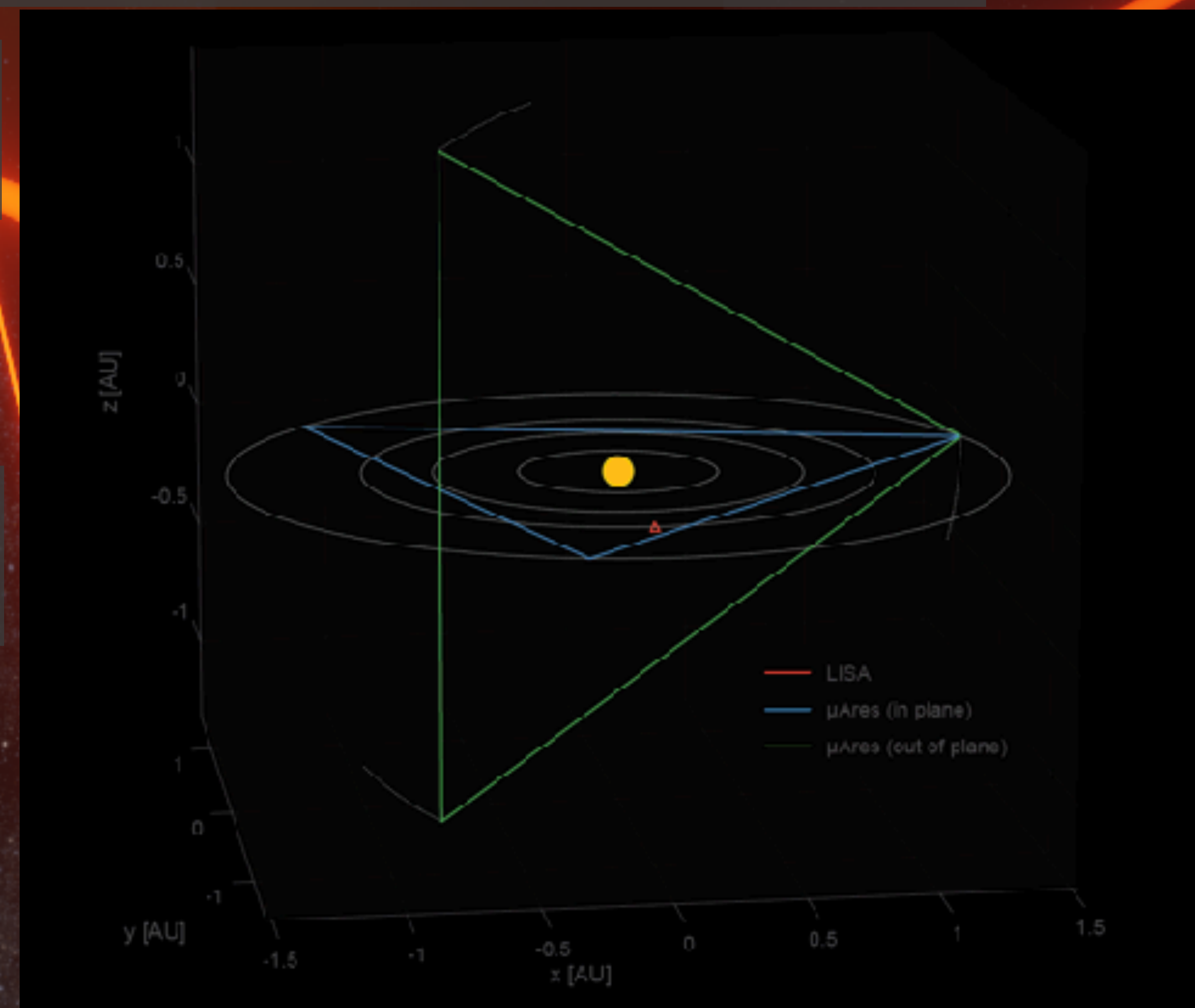


Strawman Mission Concept

Feasible with technology realistically available within the next decades!

Arm length on the order of 100 million kilometres. For the Mars orbit 395 million km

Within 10 years the spacecraft will complete 5.3 revolutions around the Sun



Heterodyne frequency range: 2…10 MHz (line-of-sight velocity < 10 m/s)

1 meter telescope diameter, 10 watts laser output power: 35 pm read-out noise limit

Acceleration noise: 2 times lower than the one demonstrated with LISA Pathfinder

UPDATE:

It is possible to have a constellation of the three spacecrafts with the arm length on the order of 100 million kilometres, which will precess with the prior less than a year

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