LISA-SKA synergies: Electromagnetic Counterparts of Massive Black Hole Binaries

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Theory/Computation in Galaxy Formation, Origin and Evolution of Massive Black Holes and Massive Black Hole Binaries

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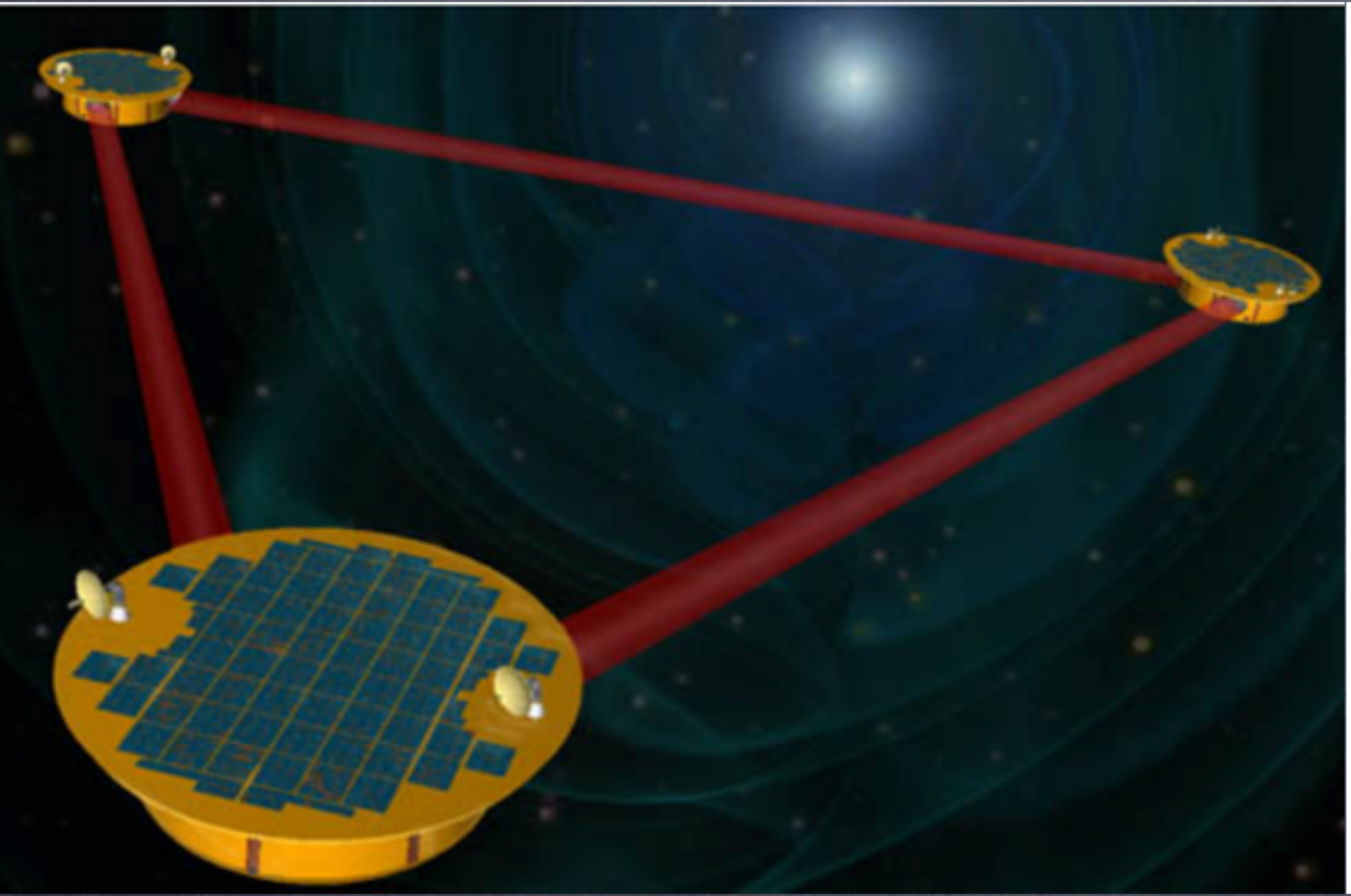
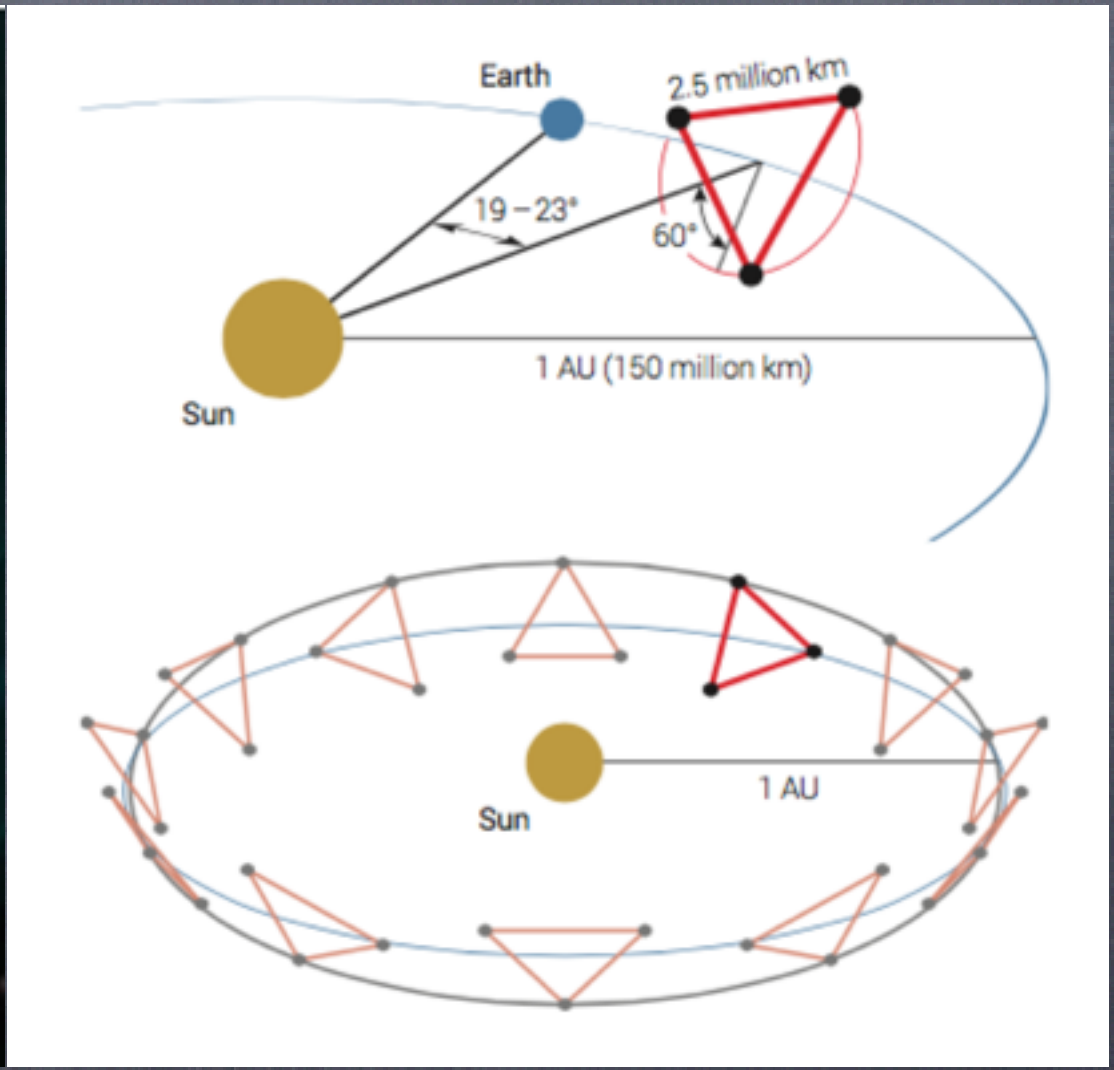
LISA

The Laser Interferometer Space Antenna (LISA)

Probing the Universe with gravitational waves

https://www.elisascience.org

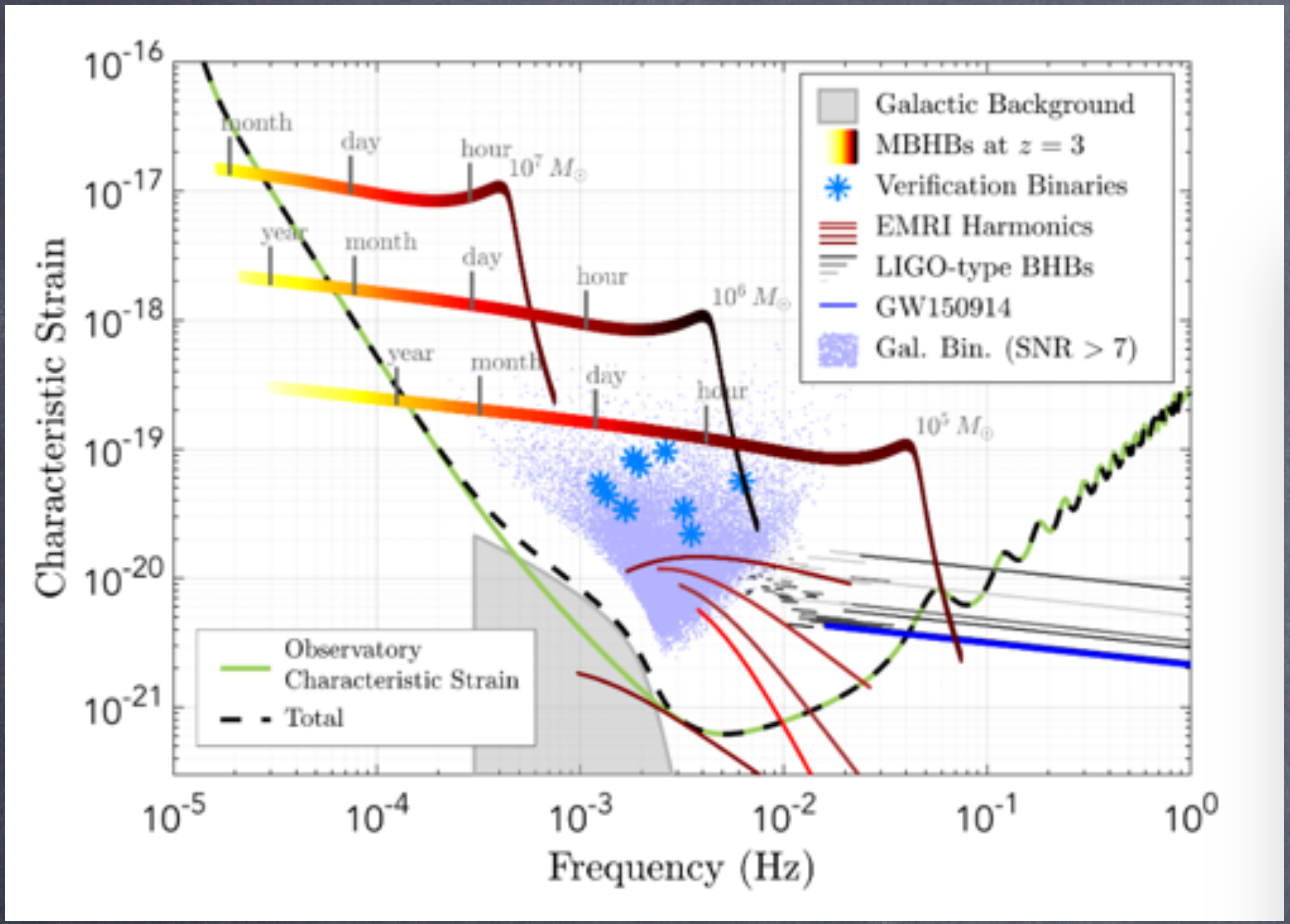




LISA is the approved next large (L3) ESA mission (2030-2034).
Three arms (six laser links) between three probes hosting test masses in free-fall will detect (low frequency) GW sources by measuring relative displacement of test masses

Merging Massive Black Hole Binaries (MBHS) in 10^4-10^8 solar mass range: the prime GW LISA sources

Other sources: extreme mass ratio inspirals (EMRIs), compact Galactic binaries, early in-spiral of stellar mass BH binaries (LIGO/VIRGO sources at later stages)



() LISA is all-sky observatory

() localisation 1-10 deg² improves towards merger time (from polarisation combined with high-frequency modulation of wave-form)

() S/N > 10 for MBH binary sources at 0 <z <10 for all detectable MBH masses

Detectable sources characterised by wave-form strain amplitude $h \sim (\mu/r)(M/R)$

M sum of BH masses, μ reduced mass of binary, r distance, R binary separation. Ultimate tests of GR (EMRIs), **cosmological probe via luminosity distance("standard sirens"),** new probe of hierarchical galaxy formation and origin of massive black holes, GW background (Amaro-Seoane et al. 2013;2017; Danzmann et al. 2017)

LISA roadmap:

- ESA L3 slot selected for a GW mission (2013)
- Pathfinder mission (2015→2017): [lisapathfinder.org]
  - Free fall and interferometric technology tested
  - **Noise tested at the LISA requirement!**
- Call for L3 mission: [arXiv:1702.00786]
  - **LISA mission selected by ESA in June 2017**
- Proposed design (result of GOAT studies with LISA WGs):
  - 3 arms + 2.5 Gm armlength + 4 years nominal duration
- Technological R&D phase (2017→2022)
  - Test laser and telescope technology (industry)
- Space system development (2022→2030)
- LAUNCH ~2030-2034

LISA Consortium: science coordination

https://lisa.pages.in2p3.fr/consortium-userguide/org.html

LISA Consortium Board and Coordination Group

LISA Science Group

Work Packages (WPs) and WP leaders

LISA Working Groups:

Astrophysics

Chairs: L. Mayer, G. Nelemans S.Larson, M. Volonteri

Cosmology

G.Nardini, C. Caprini, R.Caldwell

Fundamental Physics

P Jetzer, T.Hartog, N.Yunes

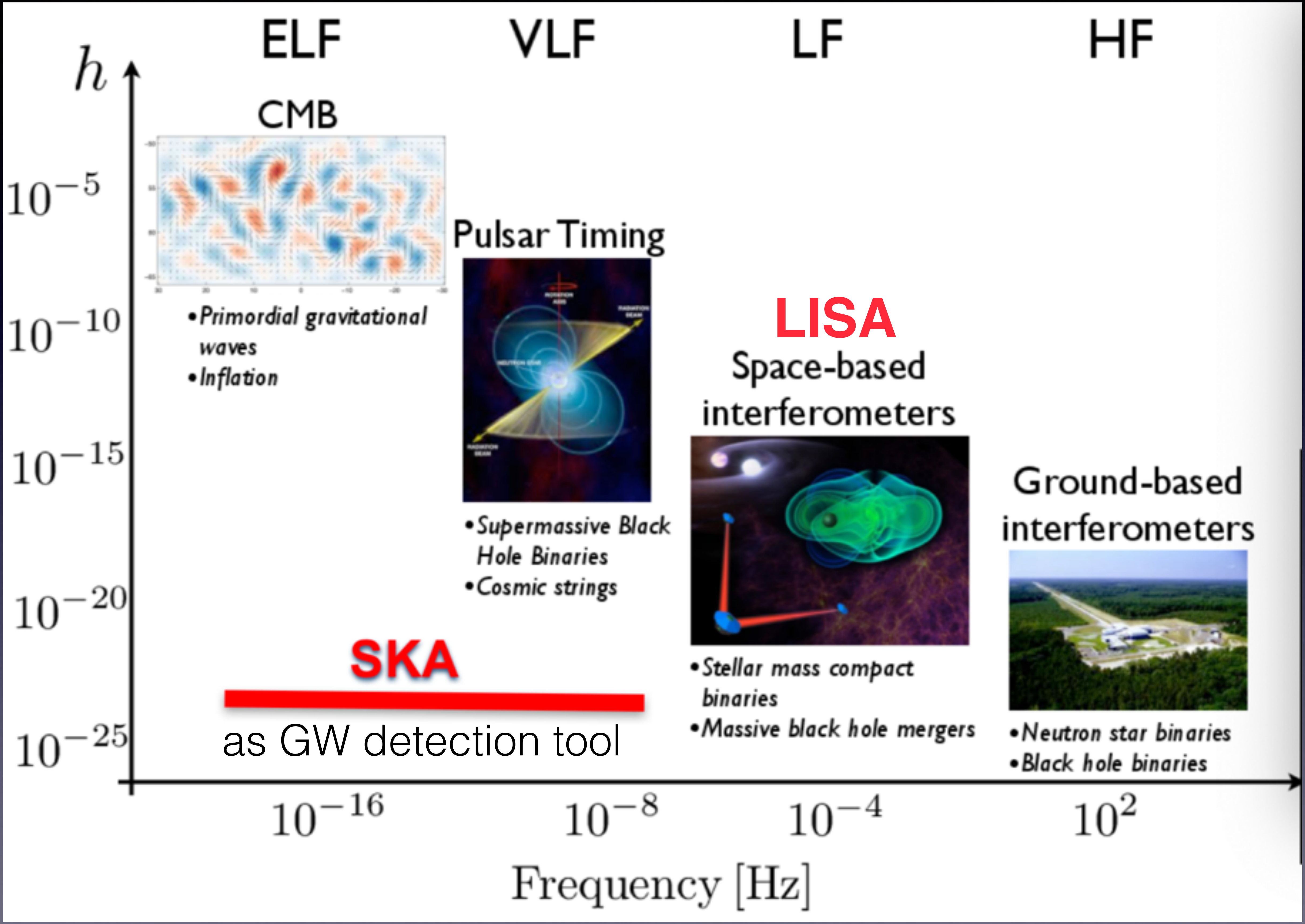
Data Challenges

Wave Form Modelling

Broad Scientific Community

Synergies with other observatories, experiments and projects (targets members and non-members of LISA Consortium)

Gravitational wave detection: regimes and probes



Credits: Tyler Bourke

A different perspective: SKA as a survey instrument to **identify and localise EM counterparts** of LISA sources

EM counterpart = EM source associated with GW source

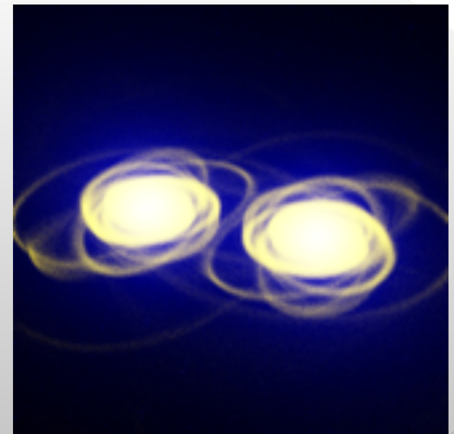
SKA could complement direct GW detection by LISA via identification of associated transient radio sources in order to:

(a) probe their astrophysical nature and environment of GW sources at different stages of MBH binary in-spiral/merger

(b)enabling identification of cosmological “standard sirens” by pinpointing GW source for optical/IR follow-up to determine redshift (LSST, ELT, JWST etc)

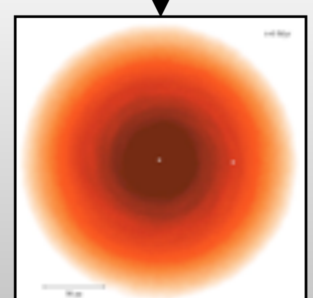
The astrophysics of MBH binary GW sources: Multi-scale journey from galaxy mergers to MBH coalescence

Stage I:
Galaxy Merger
End: coalescence of galactic nuclei and MBH pair in merger remnant



100-1 kpc scale

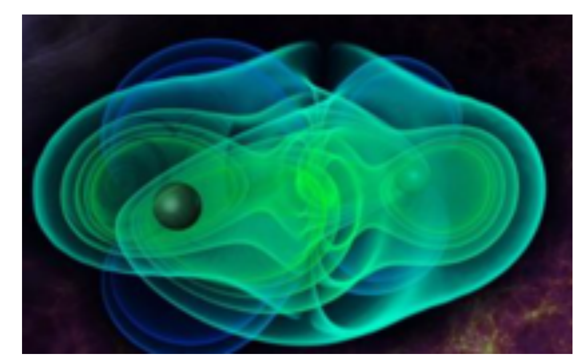
Stage II:
MBH pairing in (gas-rich) merger remnant
End: Formation of MBH binary



100 pc -1 pc scale

Stage III:
MBH binary hardening
End: GW emission-dominated phase begins
Interstellar medium/magnetized plasma surrounds binary till last phase of merger
—-> EM counterparts

1 pc -10^{-3} pc scale



Stage IV: Coalescence via GW
(< 10^{-3} pc separation)
Magnetized plasma environment

Multi-messenger astrophysics of MBH binaries: Electromagnetic (EM) Counterparts of GW sources

Three categories of EM counterparts. Different is occurrence time relative to MBH merger time

(a) Precursor; (b) Coincident;
(c) Afterglow

Recall: GW emission detectable by LISA ~year/months before merger. Initial sky localisation coarse (a few deg^2 at z=1-2) but improves near merger time

——> EM Counterparts can occur at all stages in-spiral, merger and ringdown (post-merger) always surrounded by matter
——-> Plenty of detection opportunities!

The notion of standard sirens

(slide courtesy of Nicola Tamanini)

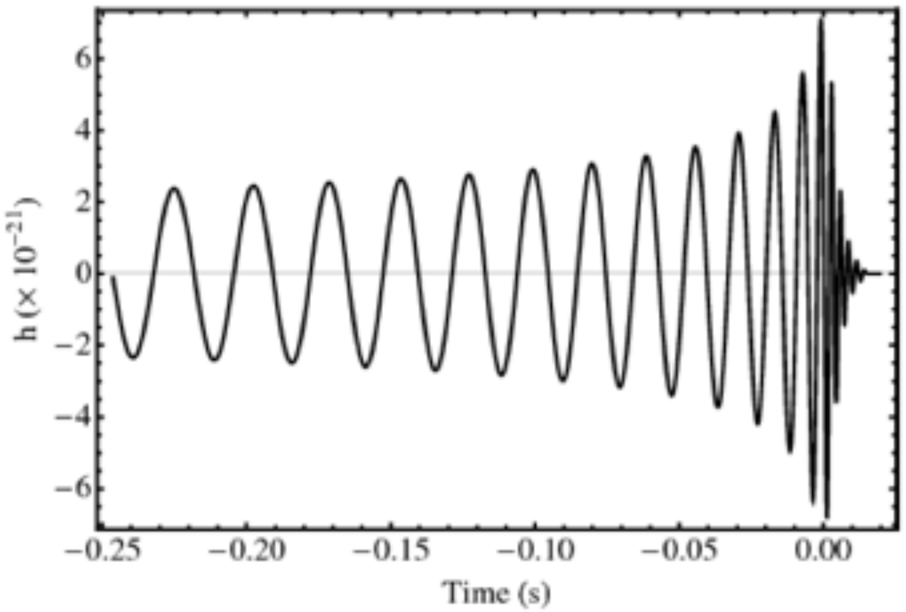
The luminosity distance can be inferred directly from the measured waveform produced by a binary system

$$\boxed{h_\times = \frac{4}{d_L}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\iota\,\sin[\Phi(t)]}$$

$\Rightarrow$ GW sources are standard distance indicator (standard sirens)

The problem with GW is to obtain the redshift of the source through the detection of an EM counterpart such as

- EM emission at merger
- Hosting galaxy



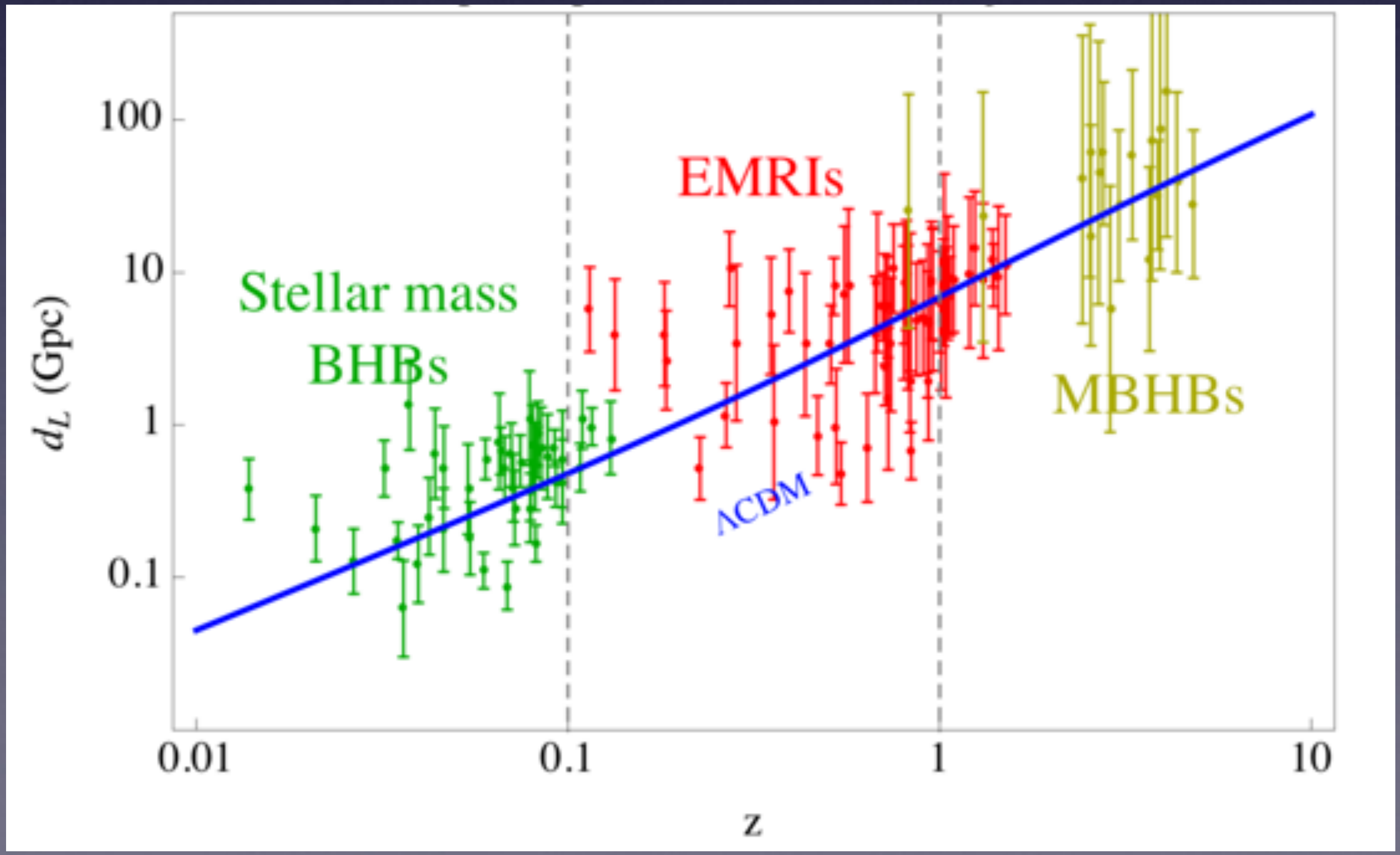
Standard sirens do not need calibration like standard candles because GR has no intrinsic scale!

First standard sirens already discovered by LIGO

Neutron star merger LIGO source GW170817 is first ever standard siren (see Abbott et al. 2017;2019).

From EM observations redshift determined: $z = 0.01006 \pm 0.00055$
From fit to Hubble law (valid at low z) ***Ho*** determined:

$$d_L = c\frac{z}{H_0} \longrightarrow H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-2}\,Mpc^{-1}}$$



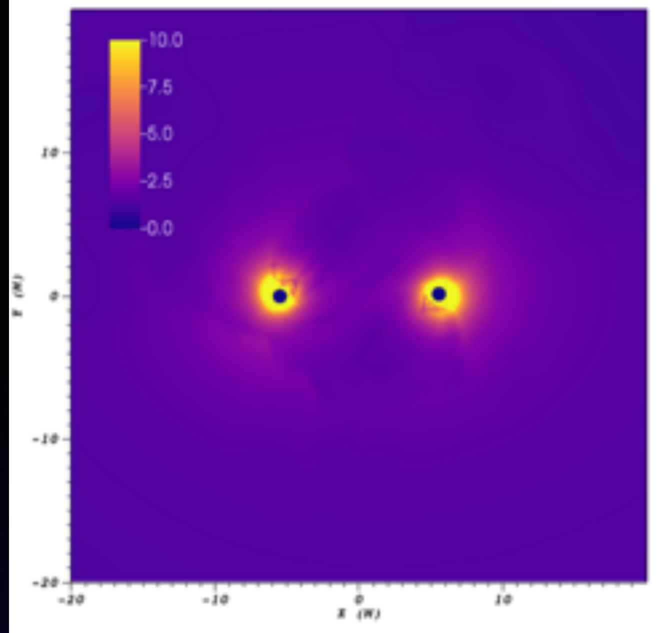
Expected distribution of LISA standard sirens.
BUT only for MBHBs EM counterparts guaranteed!

Theory of EM counterparts from hydrodynamical and MHD simulations (including GRMHD) probing different scales/stages of the MBH binary evolution (from 10^{-2} pc to a few Schwarzschild radii).

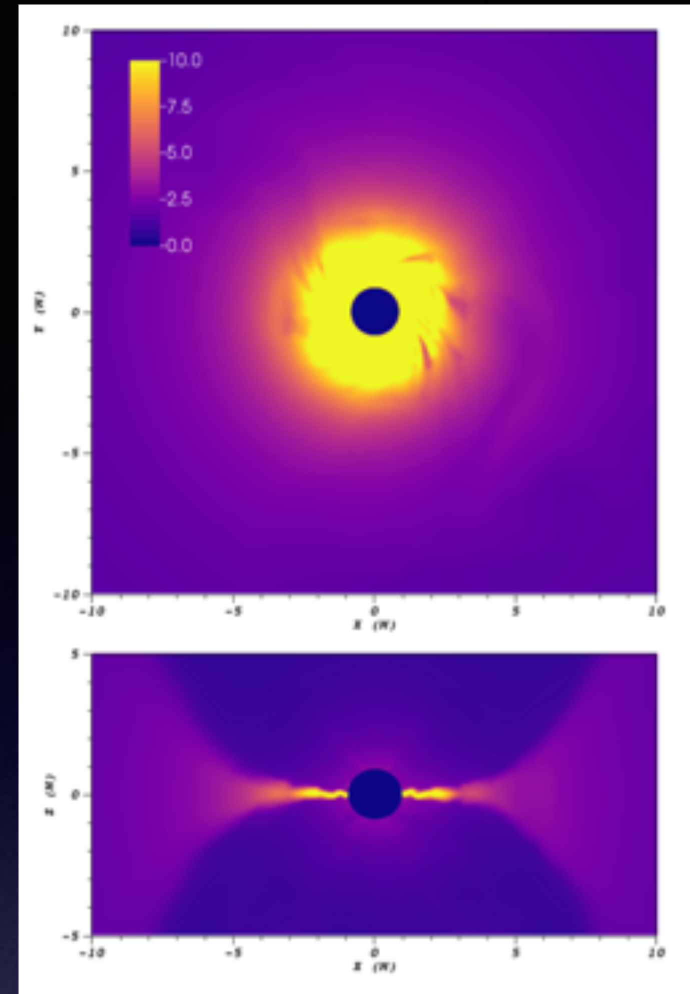
High physical complexity, plethora of models for EM counterparts proposed (White Paper by **Baker et al. .2019 - arXiv:1903:04417**)
Specific WorkPackage in LISA Science Group

Here we will focus on example most relevant to SKA —
powerful variable radio emission within hrs from BH binary merger (coincident and afterglow case). Motivation from results of GRMHD simulations (eg Palenzuela et al. 2010; Giacomazzo et al. (2012); Gold et al. 2014; Farris et al. (2015))

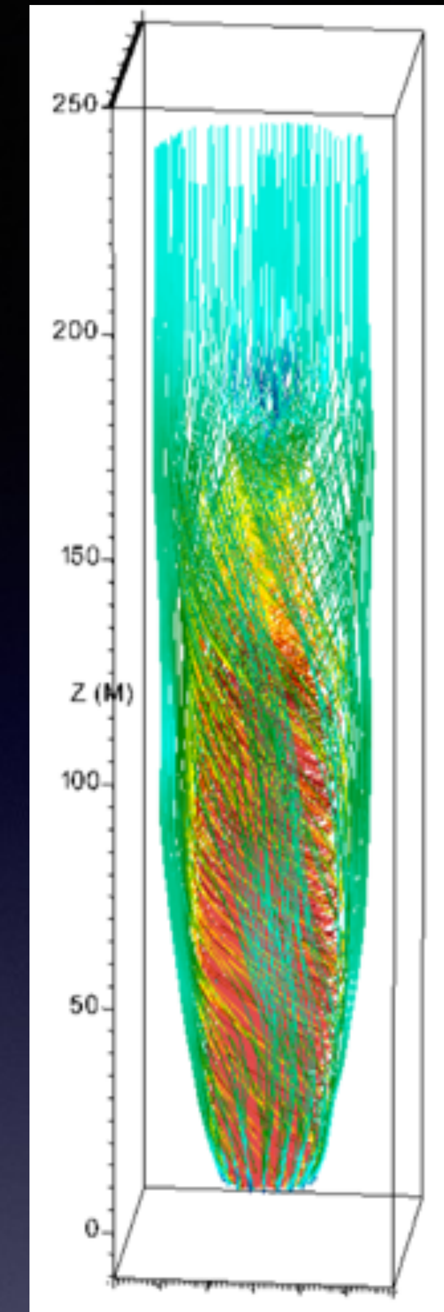
Current state-of-the-art: GRMHD AMR simulations of 10^8 Mo MBH binary starting hrs before merger by Kelly et al. (2016, PhRvD).

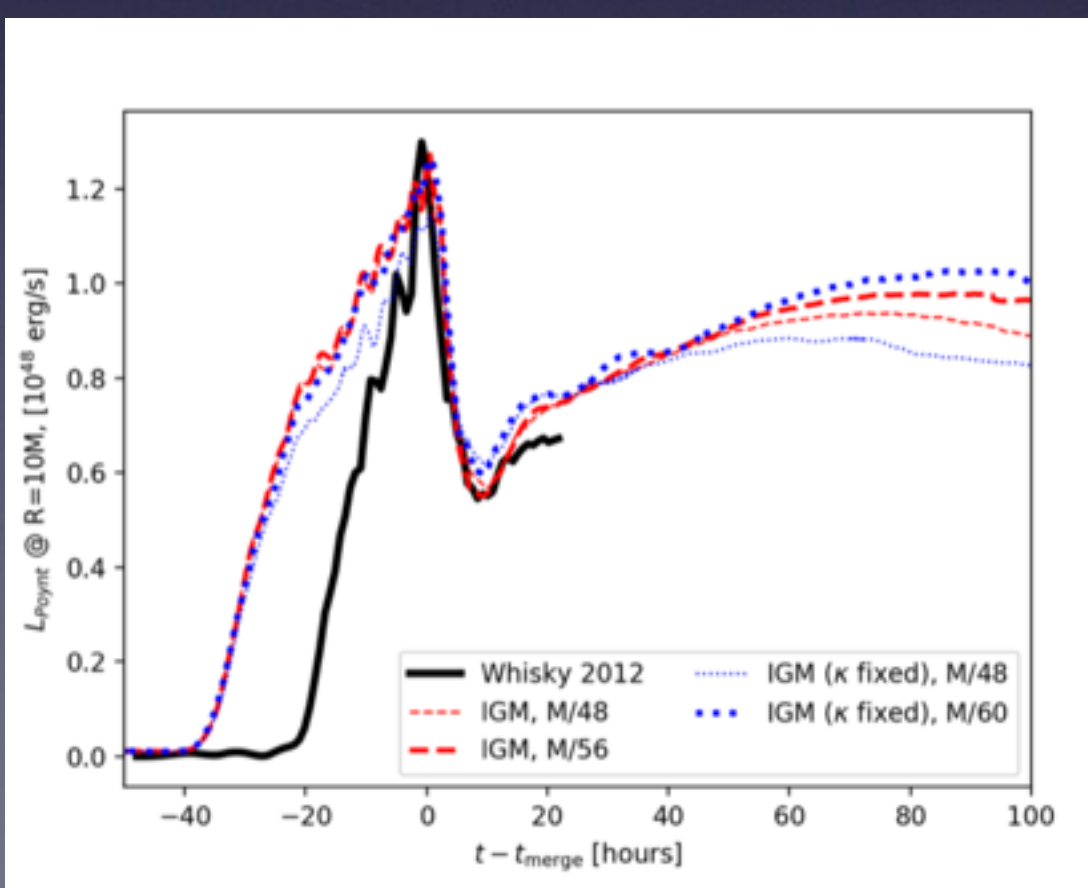


Snap at few hours
before MBH merger
(circumbinary disk,
no standard accretion disk)
Strong radial flow drives
magnetic field lines compression



few hours
after merger





Poynting flux proxy of EM counterpart "brightness":

$L_{poynt} \sim M_{BH}^2 B^2 v_{orb}^{2.7}$ ——> enormous EM energy generated compared to standard BH keplerian accretion disk from binary orbital kinetic energy

Tamanini et al. (2016): pilot study of LISA MBH population assuming SKA detection of radio flare and jet(s) at merger time.Assume bulk of (isotropic) radio emission in SKA band (characteristic frequency ~ 1.4 GHz), full-SKA configuration to reach minimum flux F_{min} ~ 1μJy for 10 minutes integration time:

$$L_{\rm radio} \geq 4\pi d_L^2 F_{\rm min}^{\rm SKA}$$

Detection requirement (d_L luminosity distance)

From population synthesis model of MBH mergers in cosmological volume select all radio sources that, within <10 deg² ,satisfy:

$$\left(\frac{L_{\rm radio}}{\rm erg/s}\right)\left(\frac{d_L}{\rm cm}\right)^{-2} \geq 4\pi\, 10^{-18}\left(\frac{F_{\nu,\rm min}^{\rm SKA}}{\mu{\rm Jy}}\right)\left(\frac{\nu_{\rm SKA}}{\rm GHz}\right)$$

Physical model for radio power generation from theory/simulations

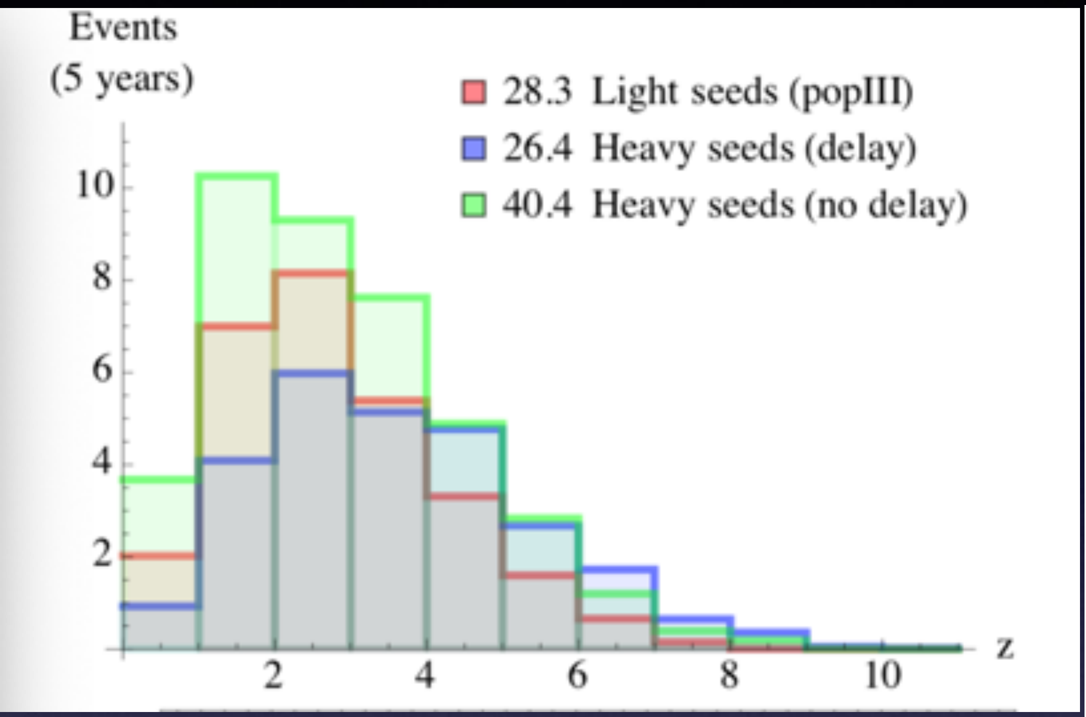
$L_{flare} \sim 10^{-2}\, v_{orb}^2\, (M_{BH1}/M_{BH2})^2 L_{edd}$ and **$L_{jet} = f(M_{dot})$**

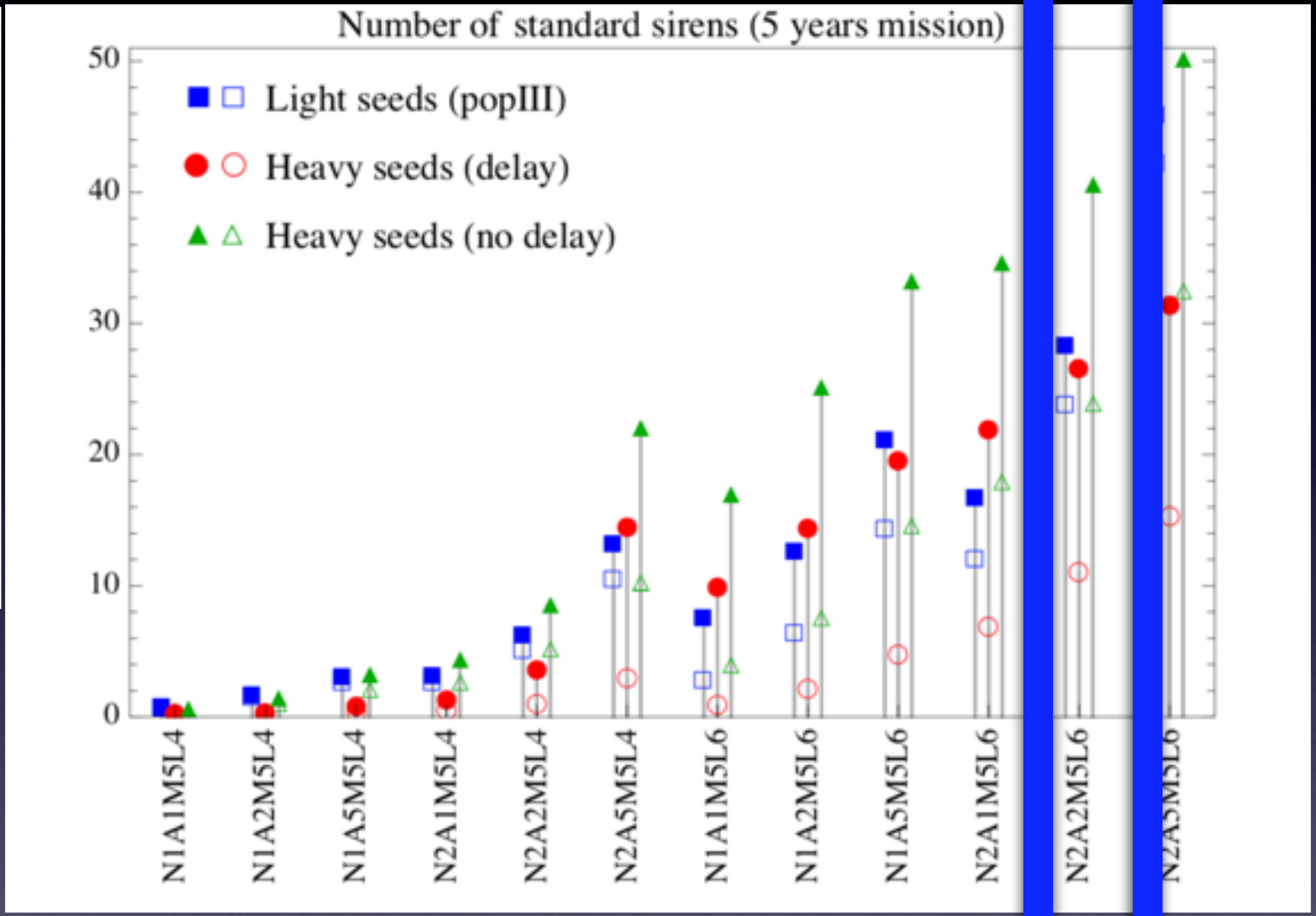
(L_{jet} functional dependence from standard Blandford-Znajeck effect)

Then obtain redshift of host galaxy from prompt optical/IR follow-up by eg ELT (spectroscopic with MICADO) and JWST

Test case: SKA + follow-up with ELT within 5 hrs

Number of standard sirens **above S/N threshold, sky-localised to better than 10 deg^2, over 5 years mission duration**





3 different MBH population synthesis models (yield different BH demographics)

Results from analysis of standard sirens at 0<z<8 (~6/yr)

Assuming mean **d_L error from wave-form** $\Delta d_L/d_L \lesssim$ few %

H_0 to $\sim 1\%$

w_0 to $\sim 15\%$