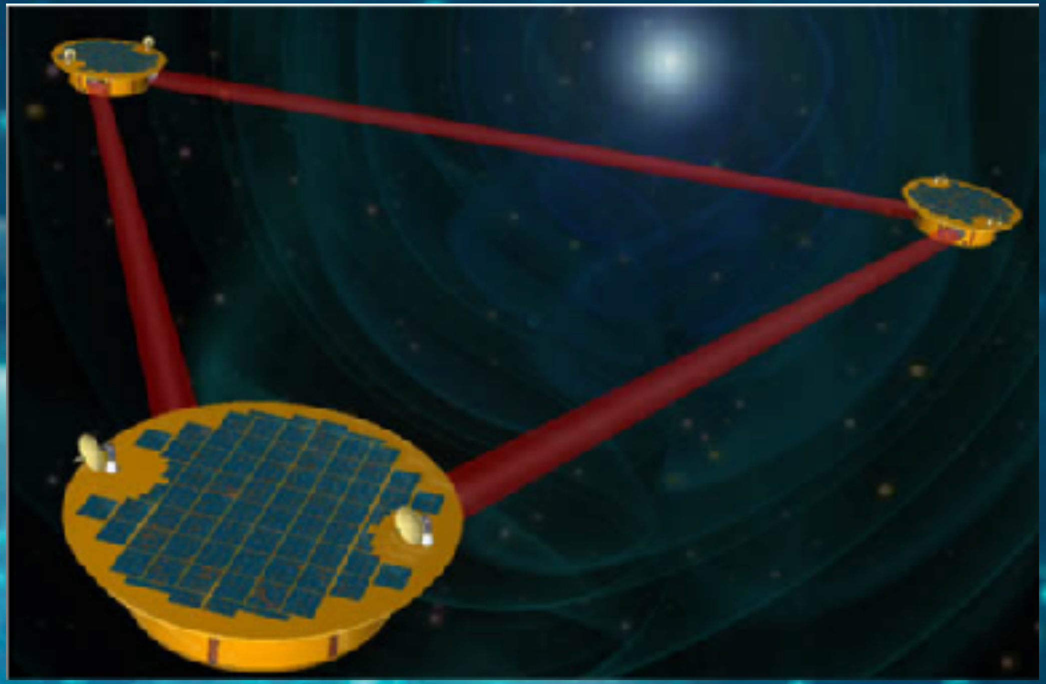
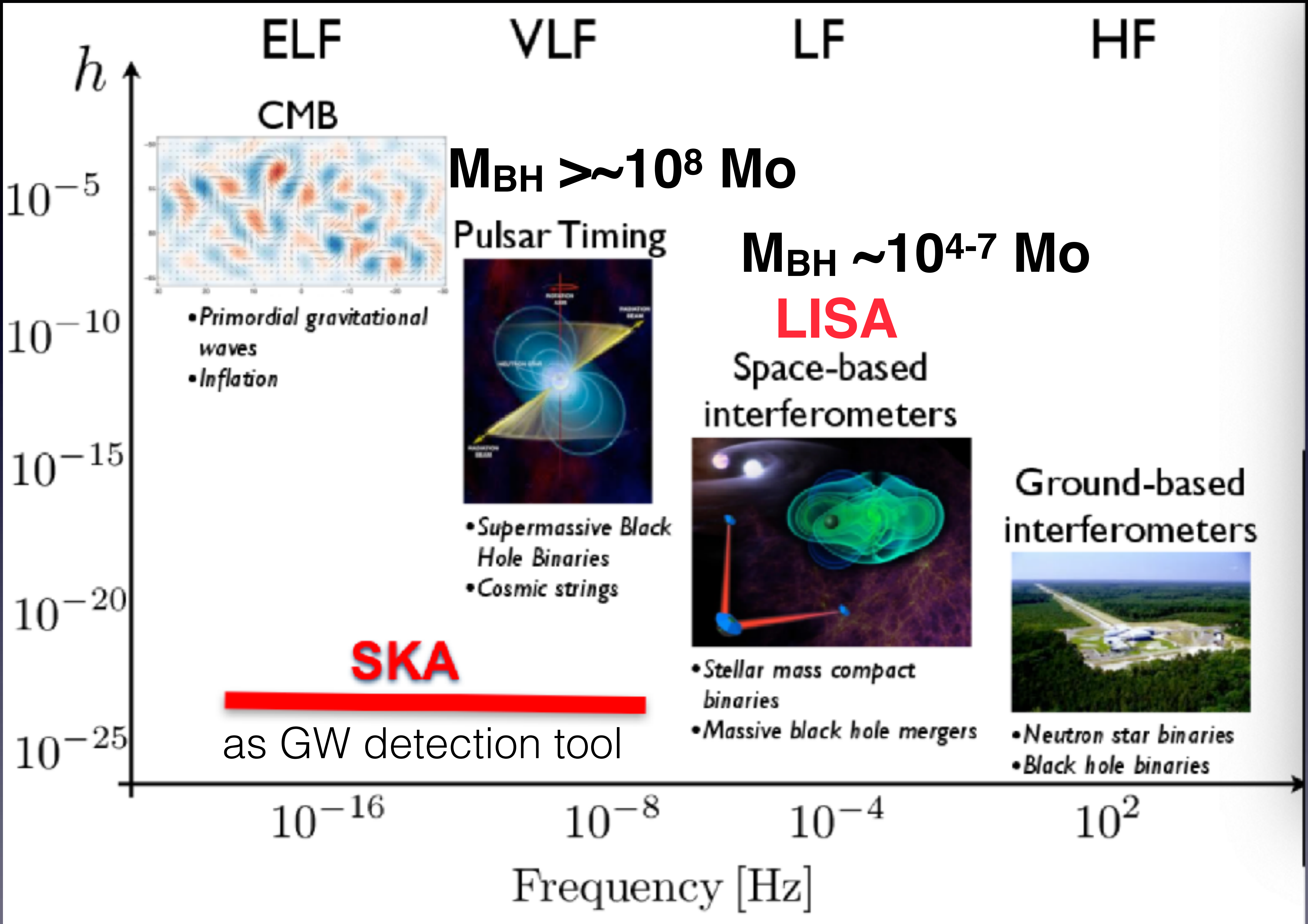
SKA-LISA synergies



Lucio Mayer
Center for Theoretical Astrophysics and Cosmology
Institute for Computational Science
University of Zurich

Gravitational wave detection: regimes and probes



$M_{BH} >\sim 10^8$ Mo

$M_{BH} \sim 10^{4-7}$ Mo

LISA

SKA

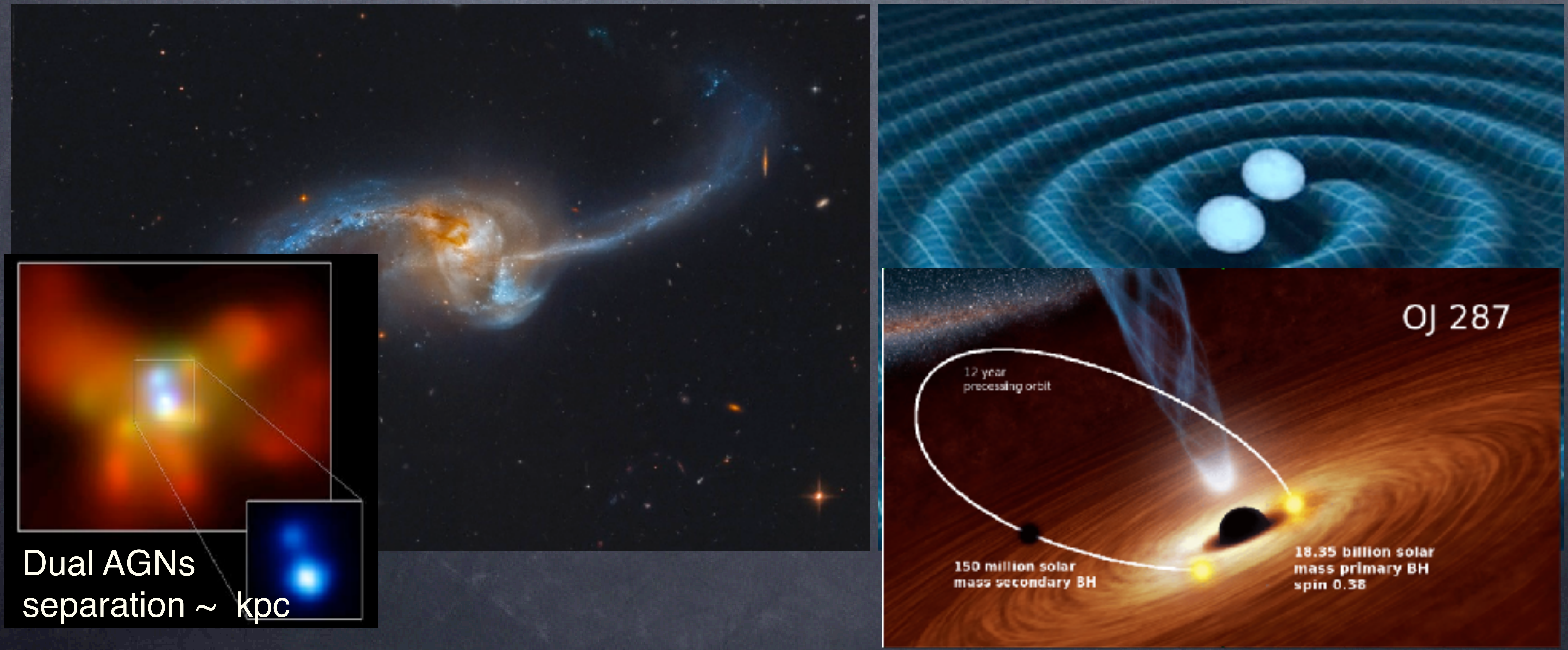
as GW detection tool

Credits: Tyler Bourke

(Super)massive Black Holes (M_{BH} >~ 10^5 Mo) in the landscape of hierarchical galaxy formation

Most galaxies host one at their center. Galaxy mergers could generate a powerful GW source if the separation between massive BHs < milliparsecs

($t_{gw} < 10^7$ yr for a binary with 10^6 Mo MBHs at separation ~ 10^{-3} pc).



SKA-LISA synergy in (at least) two ways

(1) a survey instrument to **identify and localise electromagnetic counterparts** of LISA sources
(2) a tool to discover and characterize sources whose higher frequency signature could be detected in LISA

In (1) SKA could complement direct GW detection by LISA with 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 imprint of fluctuations of orbital phase due to torques by surrounding matter: higher frequency harmonics of waveform *"DIRTY WAVEFORMS (DWs)"*

(Zwick et al. 2022)

Torque fluctuations on small mass ratio secondary → Buffet the secondary's orbit on superorbital frequencies → Quadrupole moment is affected by the acceleration

Generates high frequency harmonics *on top of the main GW*

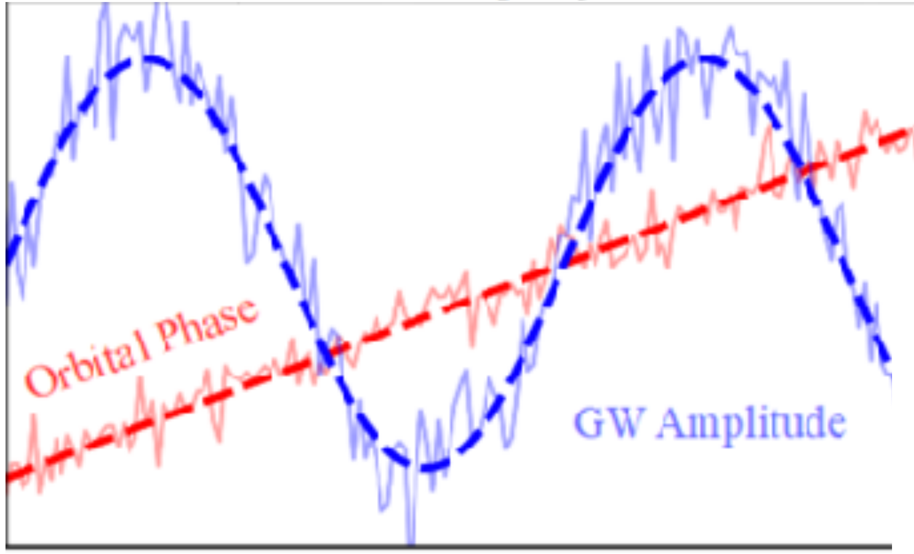
Strain of n^{th} DWF harmonic

$$|h_n^{\rm DW}| \sim \sigma_n \frac{4G\dot{L}_{\rm lin}}{c^4 D_{\rm L}}$$

Fluctuation spectrum

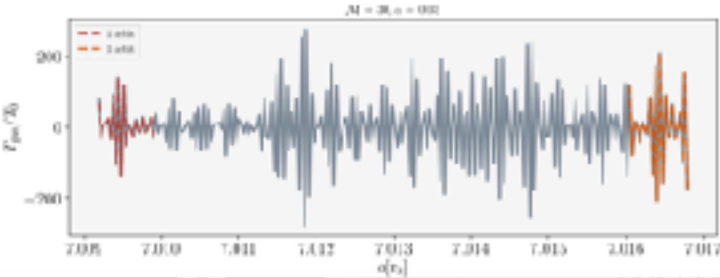
$$\sigma_n = \sigma \left(\frac{l}{n}\right)^j$$

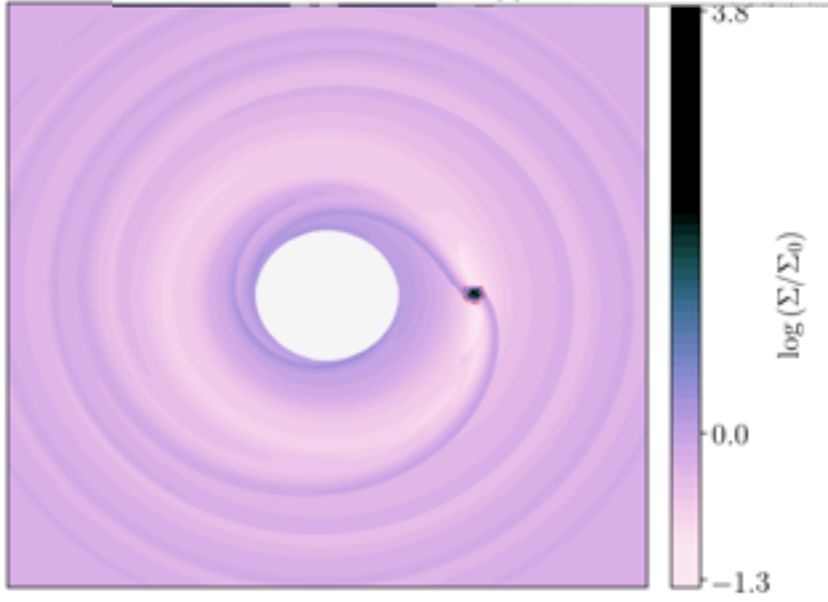
Calibrated with hydro sims + turbulence model



Typically: 10^{-5} to 10^{-3} of carrier

Typically: $10^2/q$ harmonics

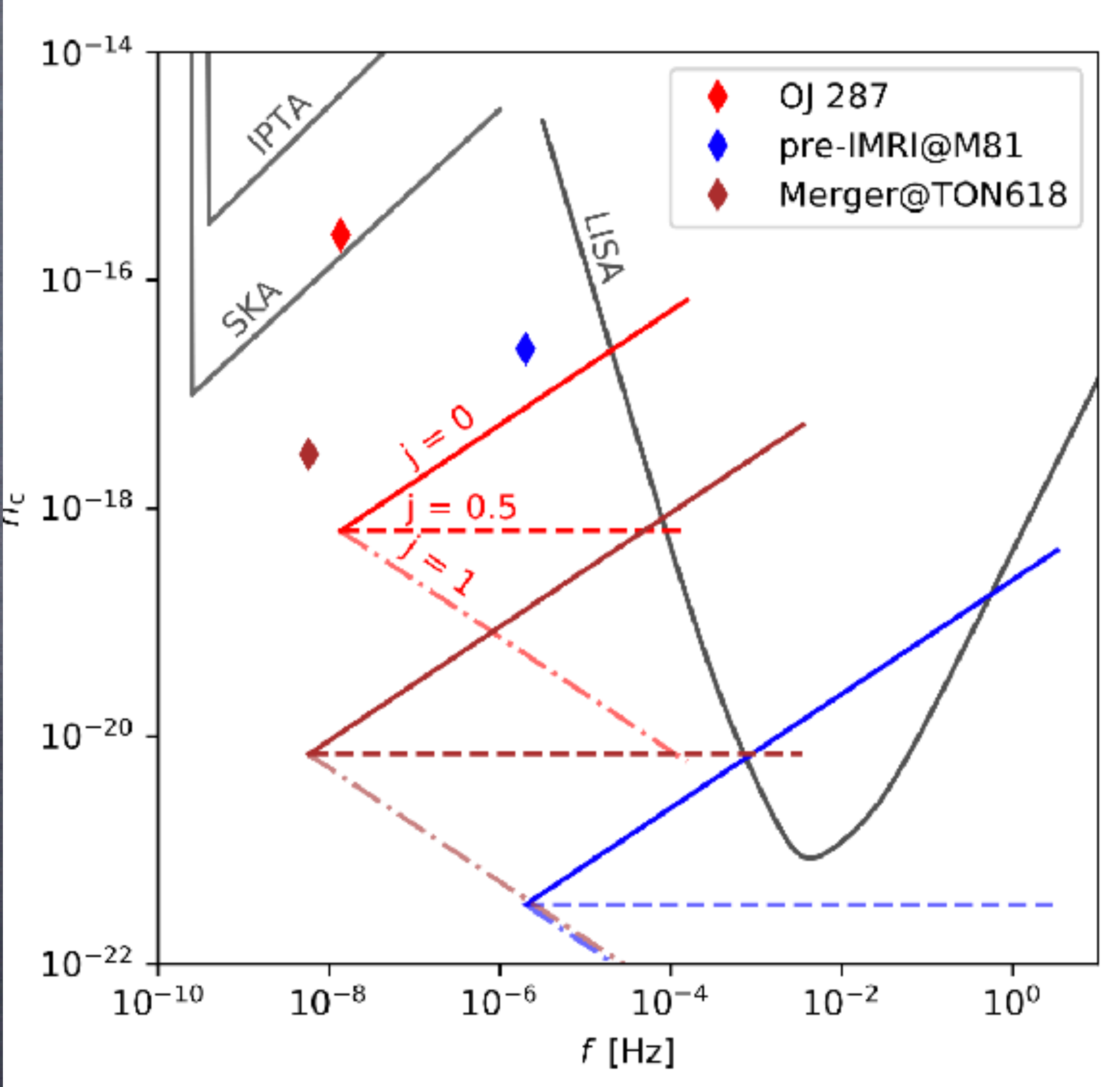




DIRTY WAVEFORMS allow to detect a loud PTA source (eg detectable With SKA) in the LISA band.

OJ287 will be a “verification binary”! The LISA high-frequency signal carries rich information on accretion disk physics, but interpretation meaningful only if main carrier signal identified with IPTA or SKA.

SKA wil be a game-changer in identification of unequal mass SMBHs which will be too faint for the current IPTA



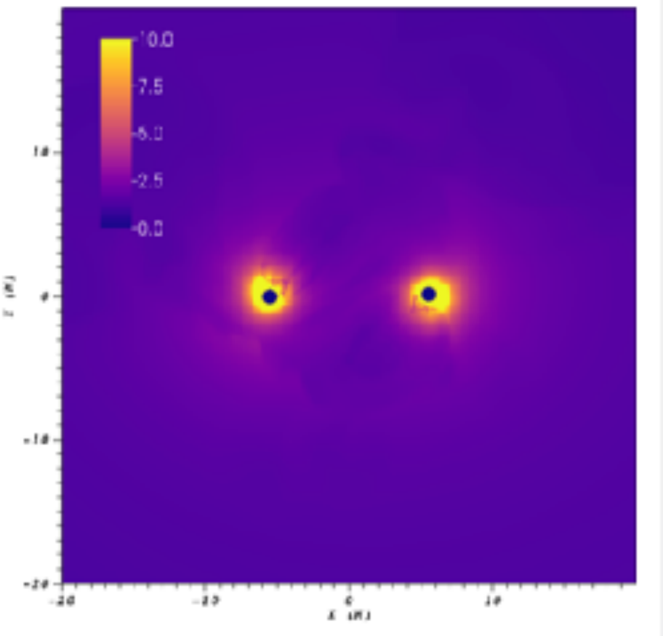
(Zwick et al. 2022)

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

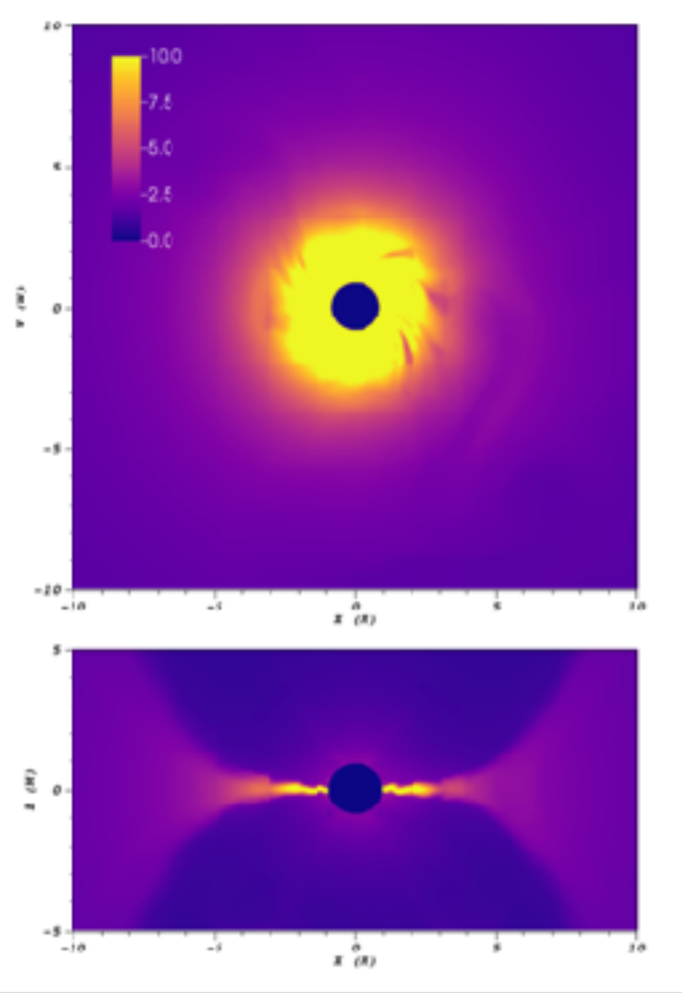
Three categories of EM counterparts. Different
is occurrence time relative to MBH merger time
(a) Precursor; (b) Coincident;
(c) Afterglow

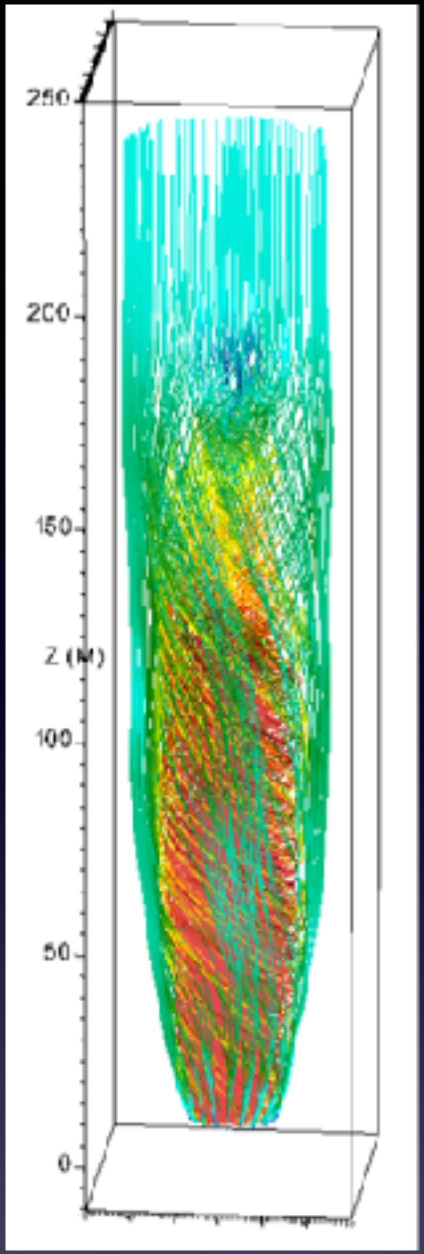
GW emission detectable by
LISA ~year/months before merger. Initial sky localisation
coarse (a few deg^2 at z=1-2) but improves near merger time

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



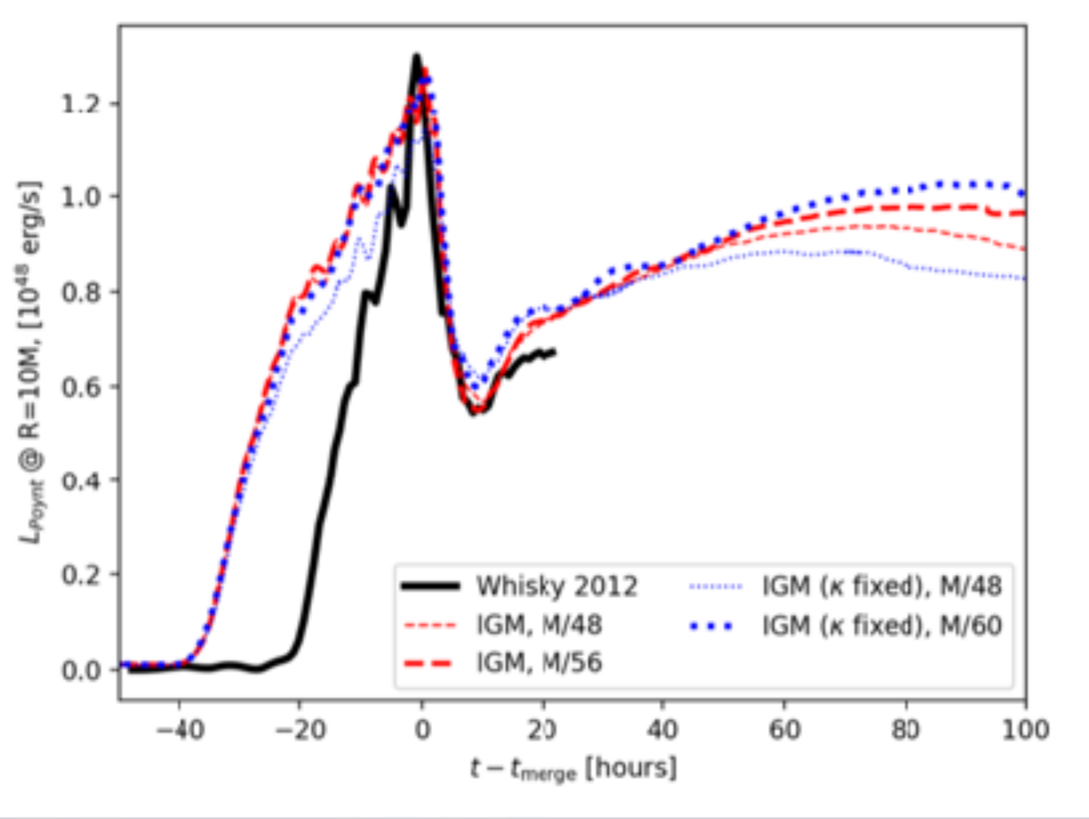
Snap at few hours
before merger of two 10^8 Mo MBHs
(circumbinary disk,
no standard accretion disk)
Strong radial flow drives
magnetic field lines compression





few hours
after merger

Kelly et al. (2016, PhRvD)

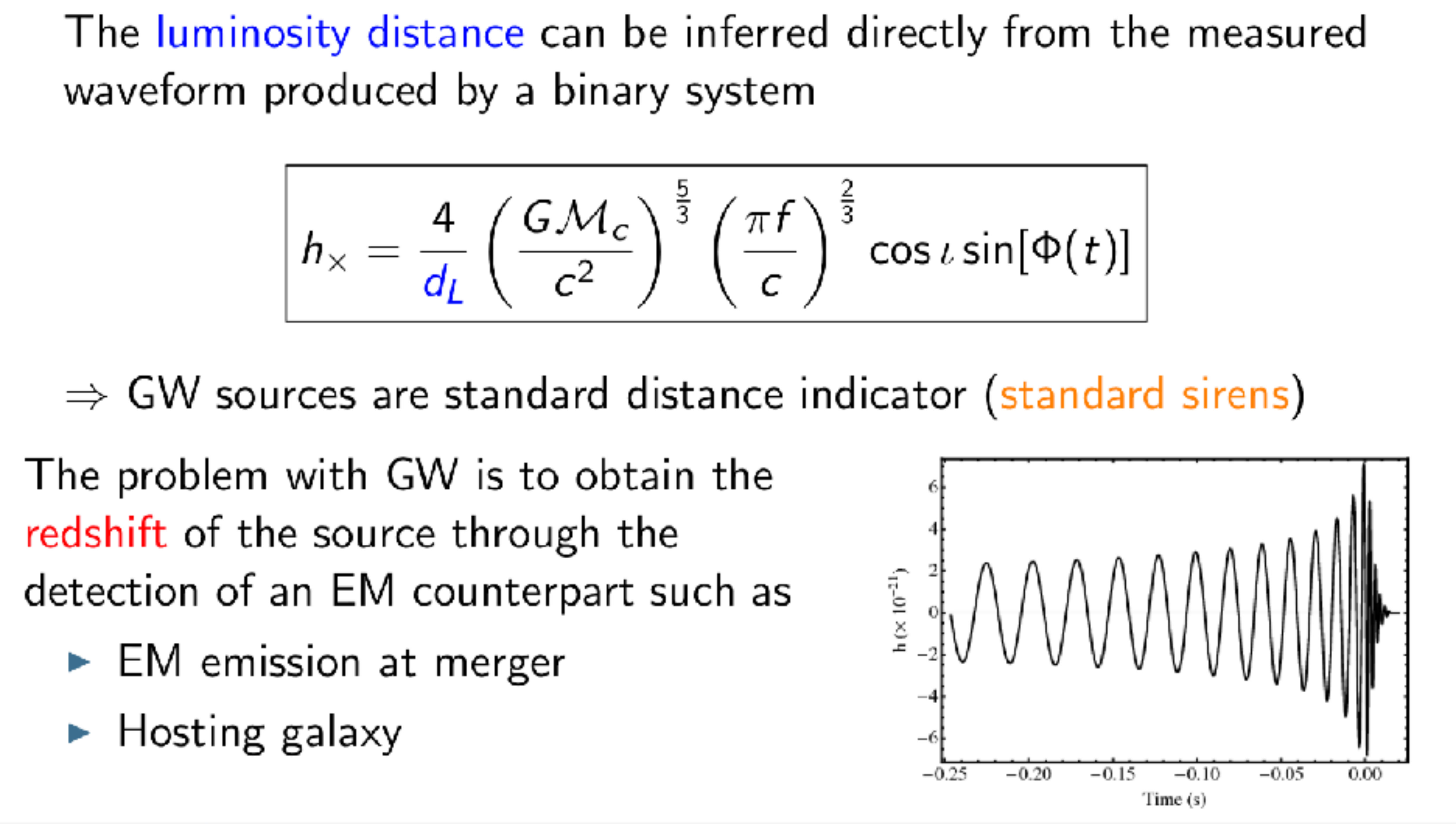


Poynting flux proxy of EM counterpart
“brightness”:

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

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

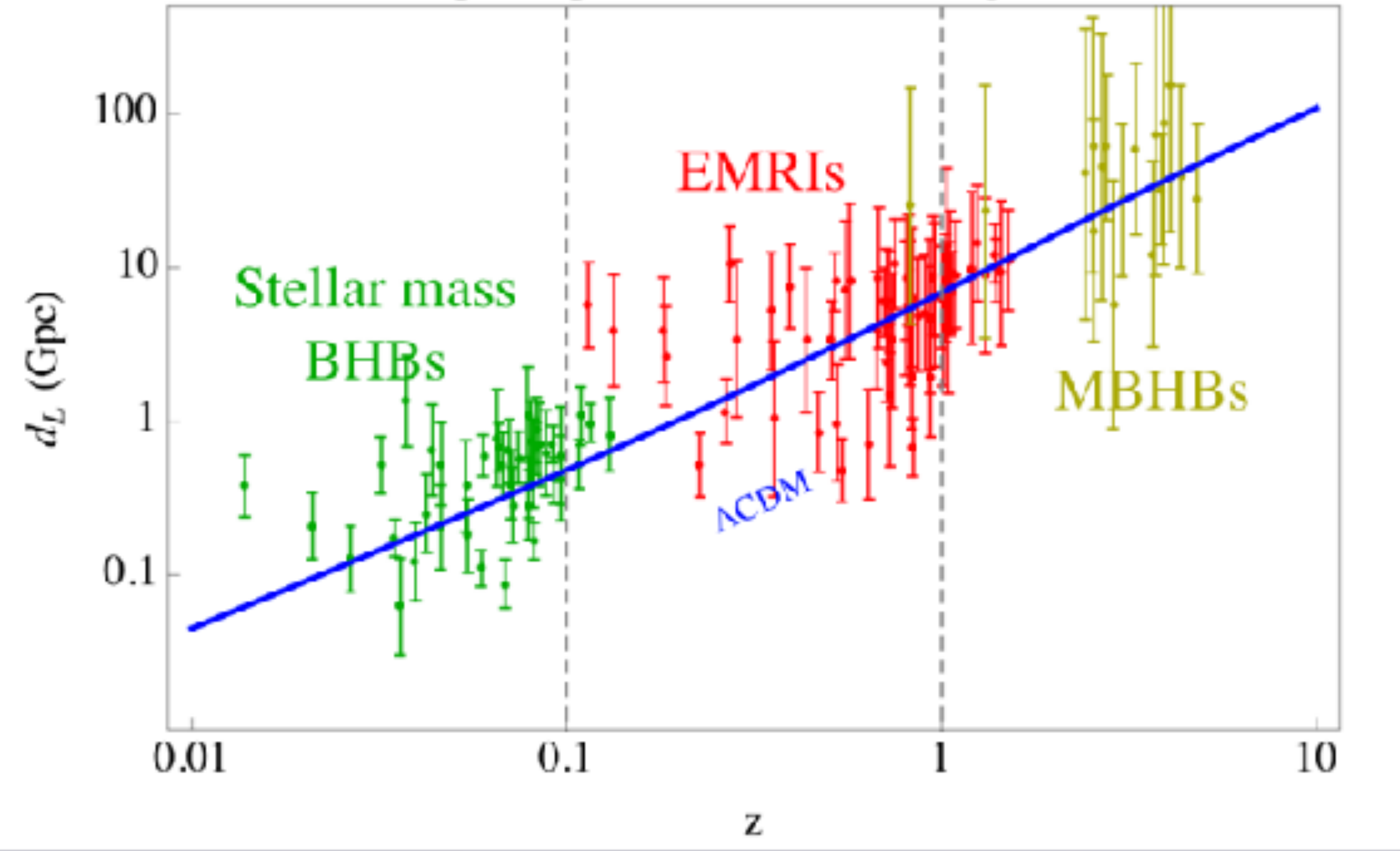
Standard sirens do not need calibration like standard candles because GR has no intrinsic scale!
First standard sirens already discovered by LIGO

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:

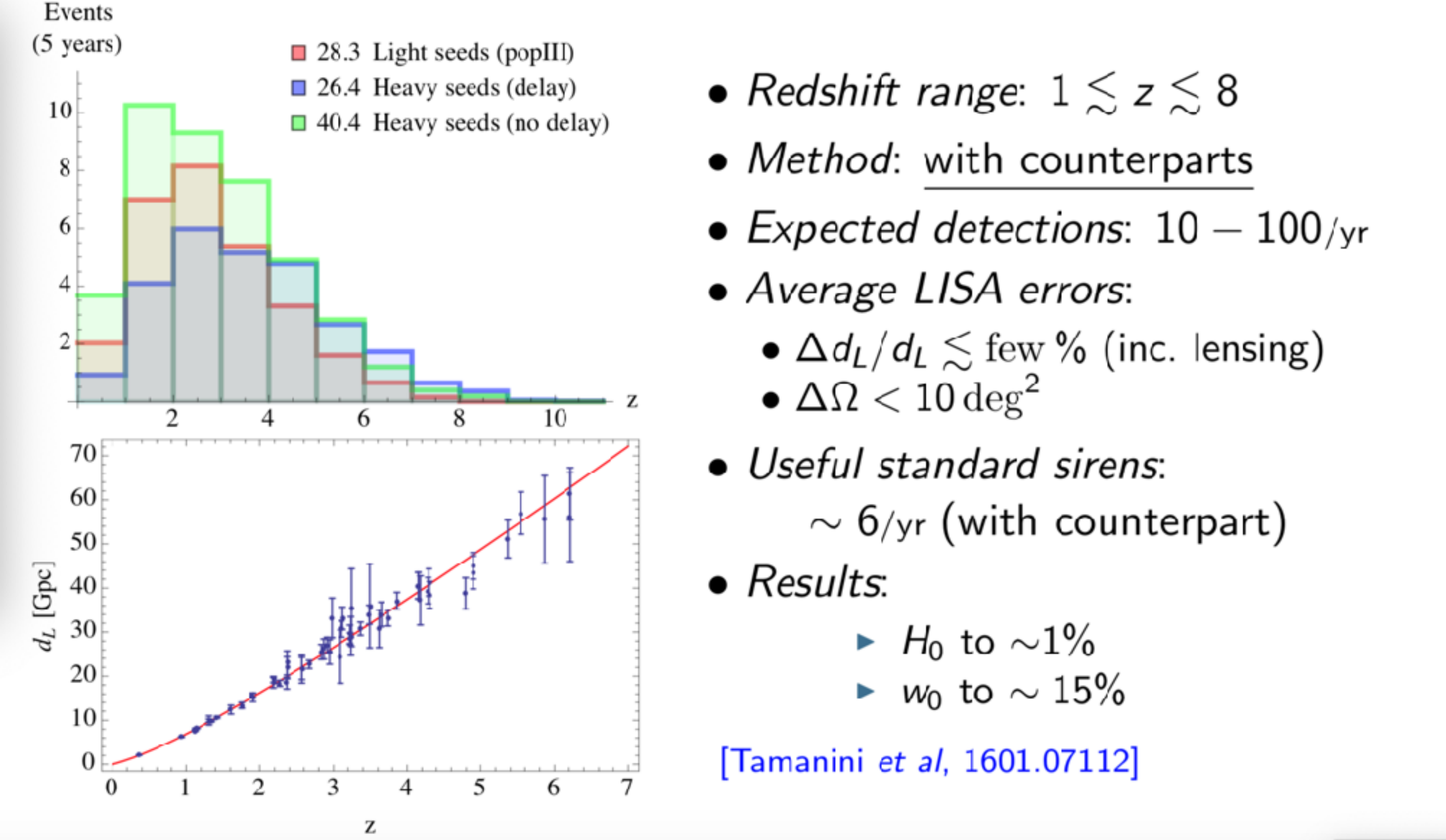
$$d_L = c\frac{z}{H_0} \longrightarrow H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-2}\,Mpc^{-1}}$$



Expected distribution of LISA standard sirens.

BUT only for MBHBs EM counterparts guaranteed, for EMRIs strongly depends on formation model

Hubble diagram from LISA standard sirens (for different population models of SMBH mergers)



- *Redshift range*: $1 \lesssim z \lesssim 8$
- *Method*: with counterparts
- *Expected detections*: $10 - 100/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few % (inc. lensing)
  - $\Delta\Omega < 10\,\mathrm{deg}^2$
- *Useful standard sirens*:

  $\sim 6/\mathrm{yr}$ (with counterpart)
- *Results*:
  - H_0 to $\sim$1%
  - w_0 to $\sim$ 15%

[Tamanini *et al*, 1601.07112]

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 deg^2 ,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

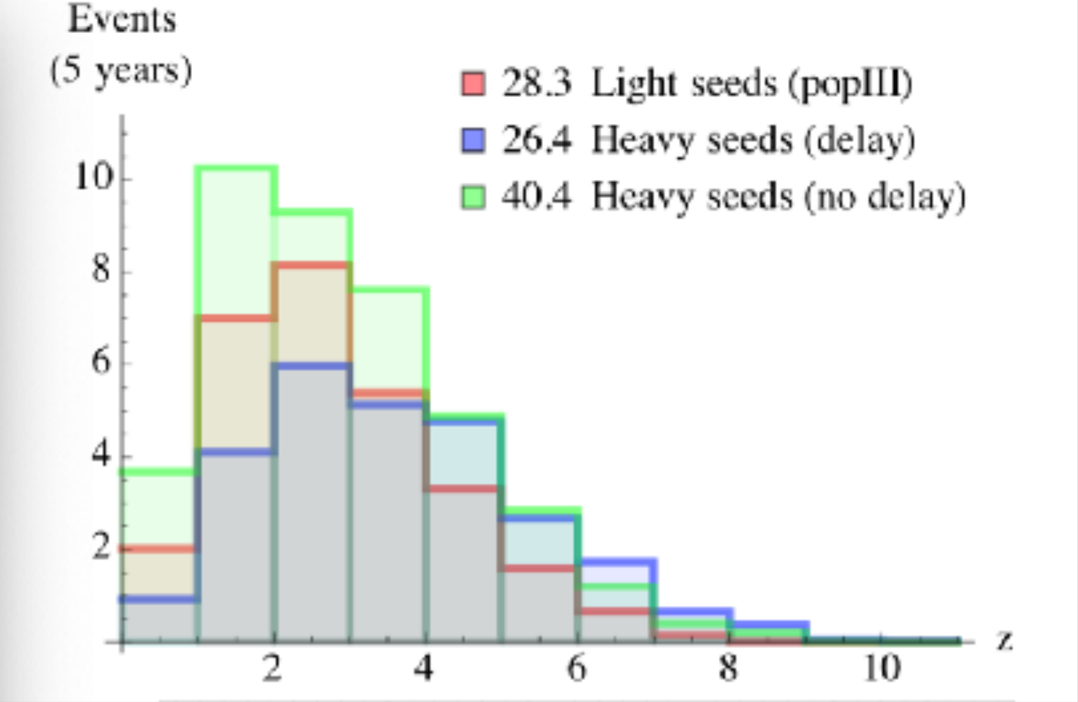
$L_{flare} \sim 10^{-2}\, v_{orb}^2\, (M_{BH1}/M_{BH2})^2 L_{edd}$ and **$L_{jet} = f(M_{dot})$**

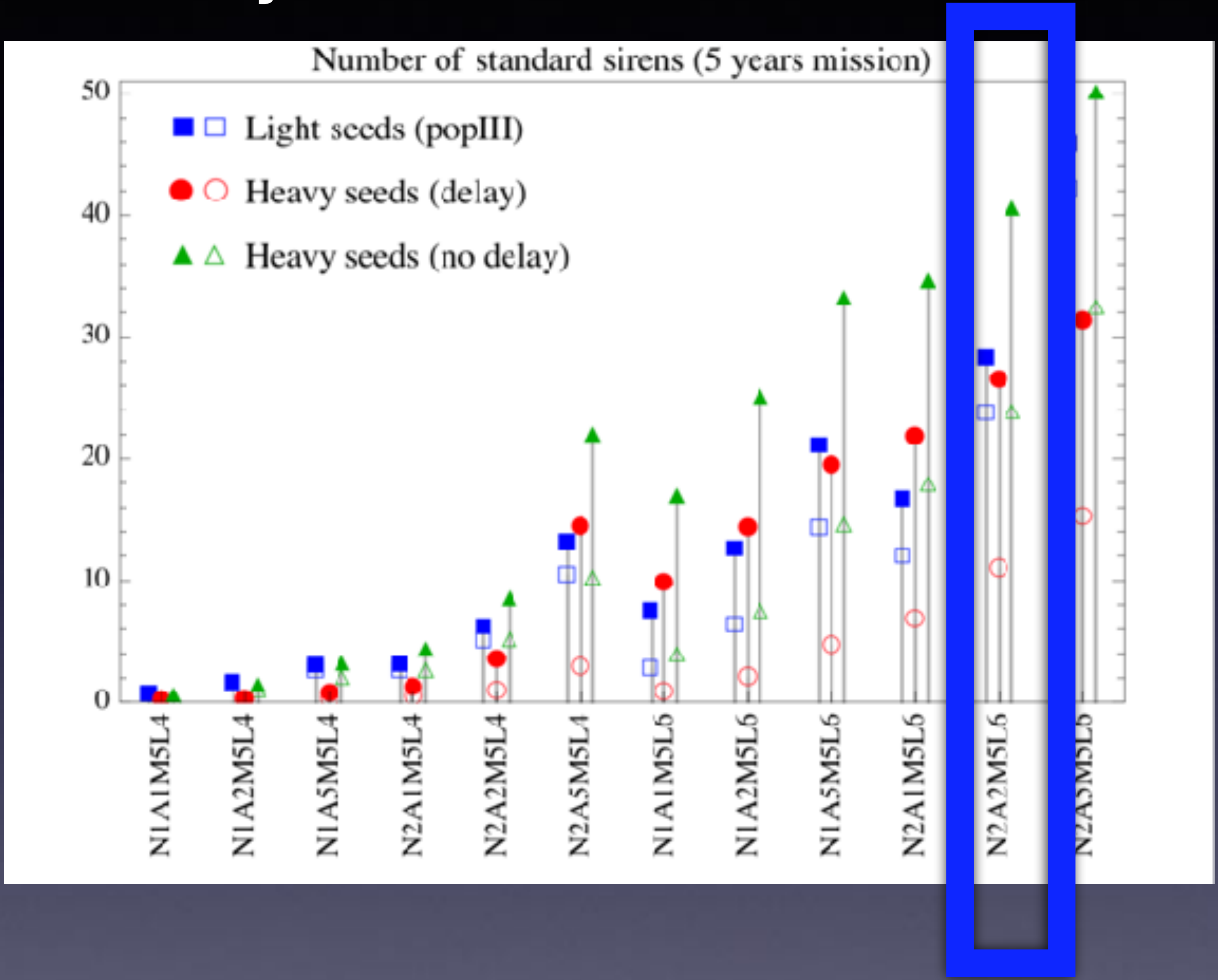
(L_{jet} functional dependence from standard Blandford-Znajeck effect)

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)

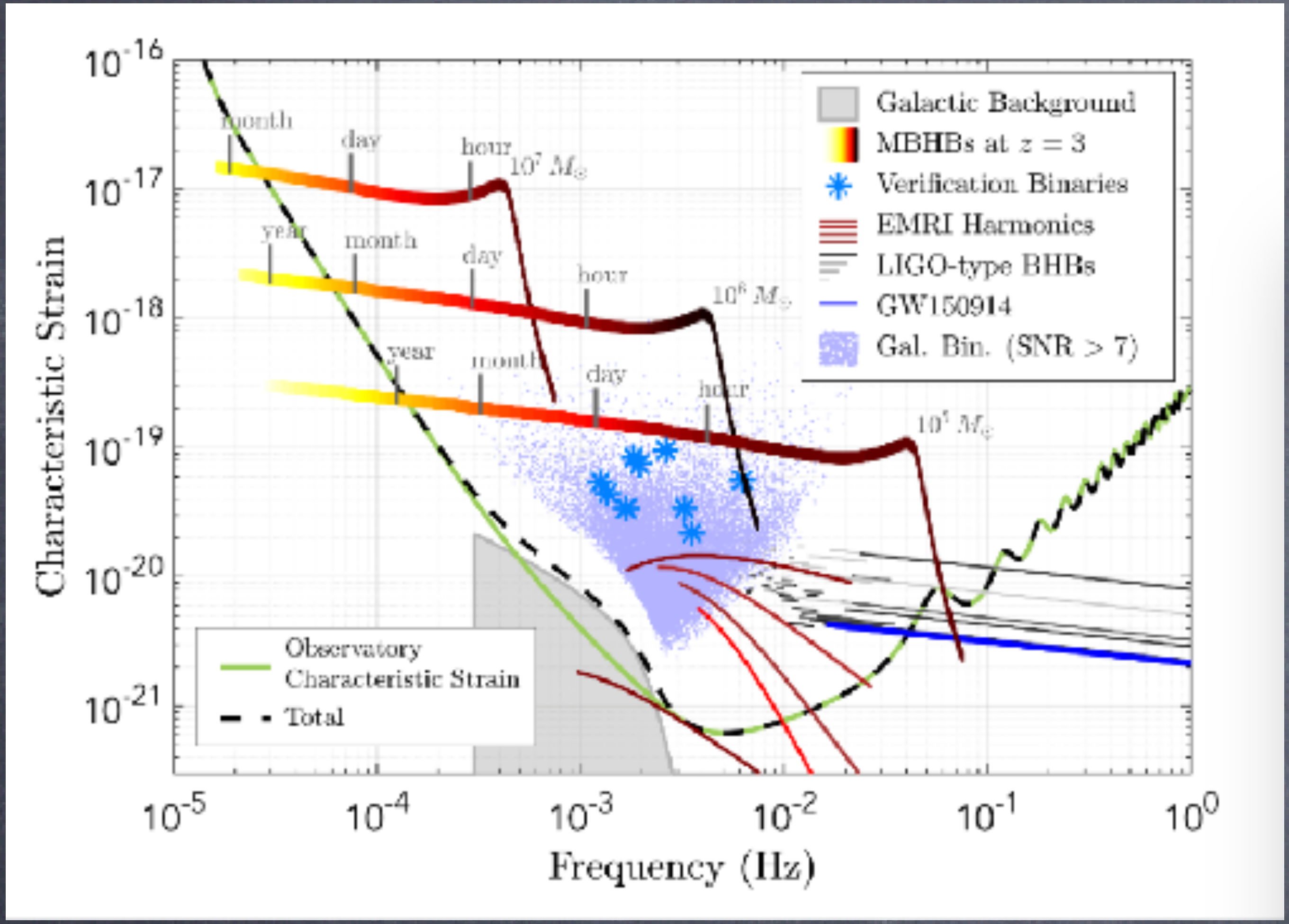
Assuming mean **d_L error from wave-form** $\Delta d_L/d_L \lesssim$ few %

H_0 to $\sim 1\%$

w_0 to $\sim 15\%$

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 deg^2 improves towards merger time (from polarisation combined with high-frequency modulation of wave-form)

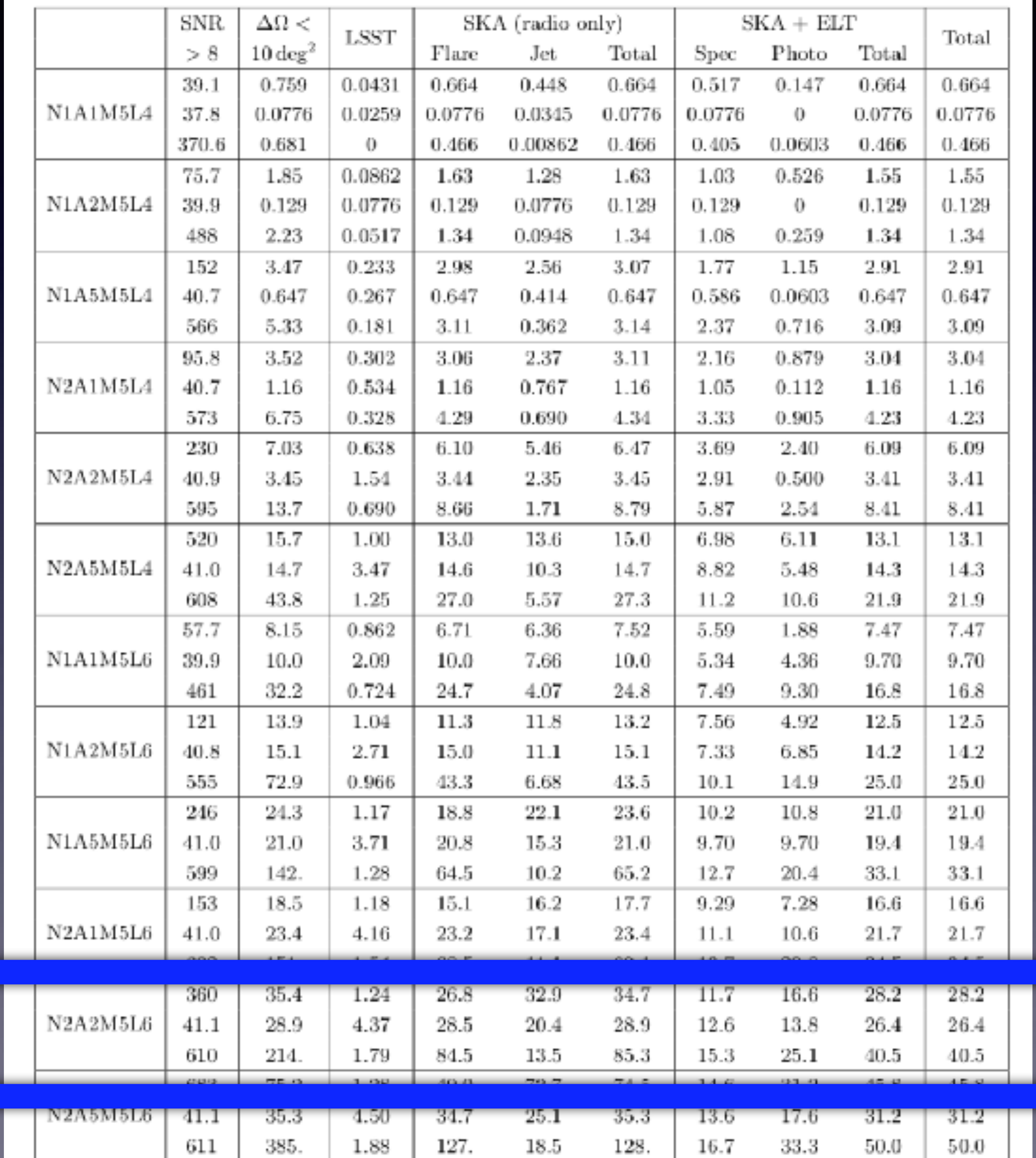
() S/N > 10 for MBH binary sources at 0 <z <10 for all detectable MBH masses

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)

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

Number of standard sirens **above S/N threshold, sky-localised to better than 10 deg² , over 5 years mission duration**



	SNR	$\Delta\Omega <$	LSST	SKA (radio only)			SKA + ELT			Total
	> 8	$10\,\mathrm{deg}^2$		Flare	Jet	Total	Spec	Photo	Total	
N1A1M5L4	39.1	0.759	0.0431	0.664	0.448	0.664	0.517	0.147	0.664	0.664
	37.8	0.0776	0.0259	0.0776	0.0345	0.0776	0.0776	0	0.0776	0.0776
	370.6	0.681	0	0.466	0.00862	0.466	0.405	0.0603	0.466	0.466
N1A2M5L4	75.7	1.85	0.0862	1.63	1.28	1.63	1.03	0.526	1.55	1.55
	39.9	0.129	0.0776	0.129	0.0776	0.129	0.129	0	0.129	0.129
	488	2.23	0.0517	1.34	0.0948	1.34	1.08	0.259	1.34	1.34
N1A5M5L4	152	3.47	0.233	2.98	2.56	3.07	1.77	1.15	2.91	2.91
	40.7	0.647	0.267	0.647	0.414	0.647	0.586	0.0603	0.647	0.647
	566	5.33	0.181	3.11	0.362	3.14	2.37	0.716	3.09	3.09
N2A1M5L4	95.8	3.52	0.302	3.06	2.37	3.11	2.16	0.879	3.04	3.04
	40.7	1.16	0.534	1.16	0.767	1.16	1.05	0.112	1.16	1.16
	573	6.75	0.328	4.29	0.690	4.34	3.33	0.905	4.23	4.23
N2A2M5L4	230	7.03	0.638	6.10	5.46	6.47	3.69	2.40	6.09	6.09
	40.9	3.45	1.54	3.44	2.35	3.45	2.91	0.500	3.41	3.41
	595	13.7	0.690	8.66	1.71	8.79	5.87	2.54	8.41	8.41
N2A5M5L4	520	15.7	1.00	13.0	13.6	15.0	6.98	6.11	13.1	13.1
	41.0	14.7	3.47	14.6	10.3	14.7	8.82	5.48	14.3	14.3
	608	43.8	1.25	27.0	5.57	27.3	11.2	10.6	21.9	21.9
N1A1M5L6	57.7	8.15	0.862	6.71	6.36	7.52	5.59	1.88	7.47	7.47
	39.9	10.0	2.09	10.0	7.66	10.0	5.34	4.36	9.70	9.70
	461	32.2	0.724	24.7	4.07	24.8	7.49	9.30	16.8	16.8
N1A2M5L6	121	13.9	1.04	11.3	11.8	13.2	7.56	4.92	12.5	12.5
	40.8	15.1	2.71	15.0	11.1	15.1	7.33	6.85	14.2	14.2
	555	72.9	0.966	43.3	6.68	43.5	10.1	14.9	25.0	25.0
N1A5M5L6	246	24.3	1.17	18.8	22.1	23.6	10.2	10.8	21.0	21.0
	41.0	21.0	3.71	20.8	15.3	21.0	9.70	9.70	19.4	19.4
	599	142.	1.28	64.5	10.2	65.2	12.7	20.4	33.1	33.1
N2A1M5L6	153	18.5	1.18	15.1	16.2	17.7	9.29	7.28	16.6	16.6
	41.0	23.4	4.16	23.2	17.1	23.4	11.1	10.6	21.7	21.7
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
N2A2M5L6	360	35.4	1.24	26.8	32.9	34.7	11.7	16.6	28.2	28.2
	41.1	28.9	4.37	28.5	20.4	28.9	12.6	13.8	26.4	26.4
	610	214.	1.79	84.5	13.5	85.3	15.3	25.1	40.5	40.5
N2A5M5L6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	41.1	35.3	4.50	34.7	25.1	35.3	13.6	17.6	31.2	31.2
	611	385.	1.88	127.	18.5	128.	16.7	33.3	50.0	50.0

Important: need to assume that radio observation allows unambiguous identification of GW source