Fundamental Physics from the Work Package Perspective

Science Investigation Work Package

Current chairs (since Aug 2022): Stas Babak, Tessa Baker, Chiara Caprini, Alberto Sesana

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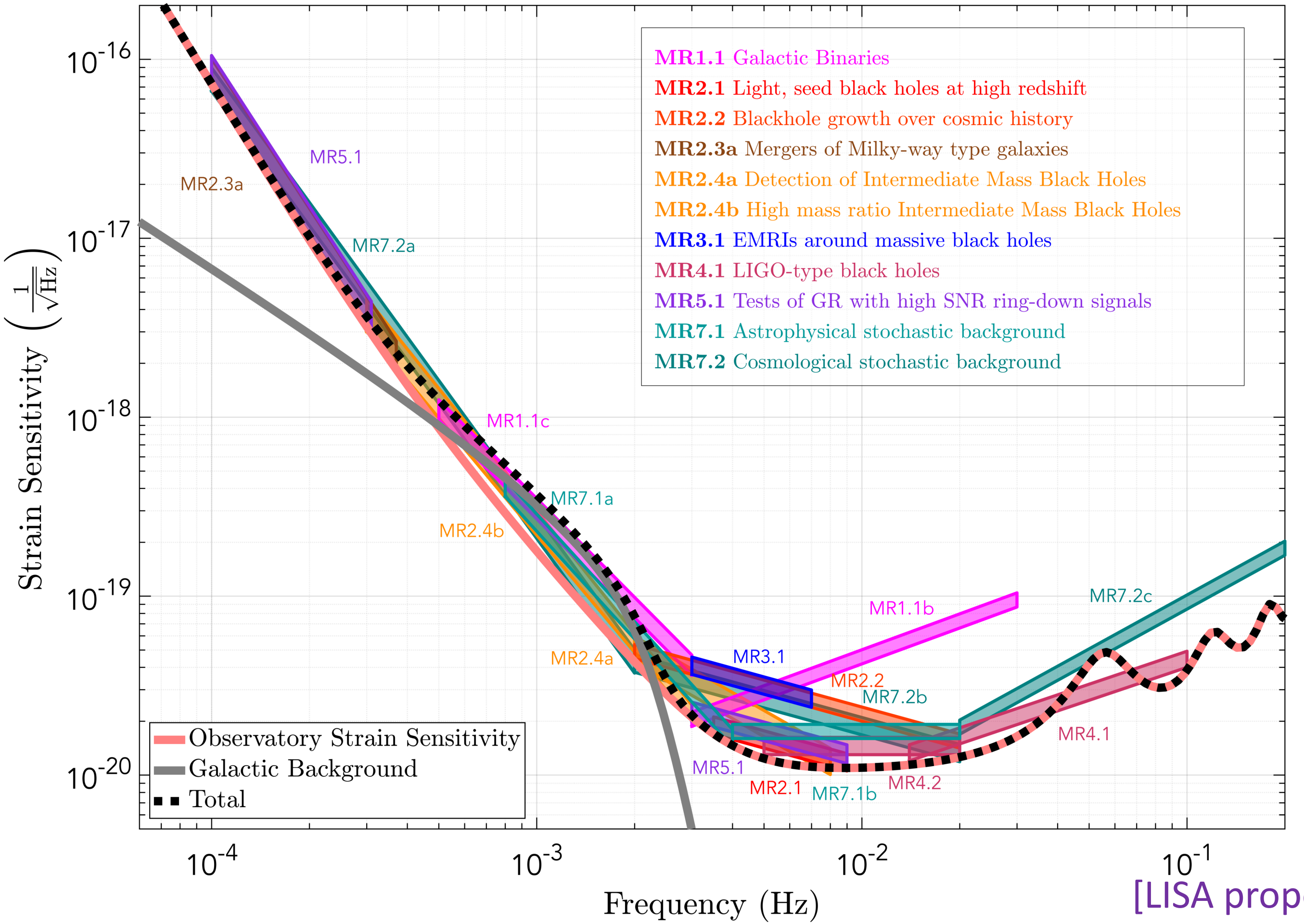
LISA in Copenhagen

August 9 2023

Johns Hopkins University

Please consider that Copenhagen is a very enjoyable and beautiful city,
and as the capital of Denmark has plenty of wonderful things to do and is easy to reach. […]
If you're planning on coming with the family, please remember also that
the entire Nordic region has plenty to offer and is a remarkable place for summer vacations.

The Work Package Perspective: Mission Requirements



[LISA proposal, 1702.00786]

LISA Consortium: Working Groups vs. Work Packages

- Starting point: Science Requirements Document (SciRD)
  https://www.cosmos.esa.int/documents/678316/1700384/SciRD.pdf

- Difference between WGs / WPs
  WGs: community (three broad areas: astrophysics, cosmology, fundamental physics)
  WPs: "core group" actively involved in mission development (WP on Science Investigation: WPSI)
  https://wiki-lisa.in2p3.fr/LSG/WP7

- Broader framework (Gair's and Petiteau's talks):
  ongoing discussion at ESA/NASA on open data policy, science ground segment(s)
  role of the Consortium within the mission and in relation with ESA/NASA

- WP work usually needs additional involvement from the WG members

- Four concrete examples of WP (but not WG) work, which can and often does lead to publications:
  - Mission duration study (arXiv:2107.09665, published in GERG)
  - Low-f study (GERG paper in preparation)
  - FoM development and application: SciRD vs. "Current Best Estimate" (CBE)
  - Definition of data products
  - Preparation of the Red Book for mission adoption (tentatively, September 2023)

Fundamental physics: what is in the Red Book now?

SO5: Explore the fundamental nature of gravity and black holes (Carlos Sopuerta, Philippe Jetzer)

The nature of black holes, strong gravity, and physics beyond the standard model

LISA is likely to detect loud, transient sources as coalescing MBHBs or sources with thousands of cycles in band such as EMRIs and IMRIs. Both allow us to test with high precision the nature of BHs and the validity of GR in the strong-field regime in the range of $10^5\,M_\odot$ to $10^7\,M_\odot$. LISA may also allow us to detect new fundamental fields, constrain extensions of GR and the standard model of particle physics, and probe the properties of a variety of dark matter models.

Section 3.5, SO5:	3.5.1 Ringdown
	3.5.2 EMRIs, multipolar structure of MBHs, new light fields
	3.5.3 Beyond-GR emission channels
	3.5.4 Propagation of GWs
	3.5.5 Test massive fields around MBHs
Also relevant:	
Section 3.6, SO6:	Probe the rate of expansion of the Universe with standard sirens
Section 3.7, SO7:	Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
Section 3.8, SO8:	Search for GW bursts (cosmic strings) and unforeseen sources

Fundamental physics: what is in the Red Book now?

3.5.1 Use **ringdown** characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR

- Are the massive objects that merge and their remnants consistent with being rotating Kerr MBHs?
- If not, are they horizonless ultracompact objects?

SI 5.1 aims at detecting multiple ringdown “spectral lines” in the post-merger signal of MBHBs and put limits on GW echoes.

3.5.2 Use **EMRIs** to explore the multipolar structure of MBHs and search for the presence of new light fields

- Are the massive objects observed at centres of galaxies consistent with the rotating Kerr MBHs predicted by GR?
- Are there new fundamental fields leading to hairy BHs?

SI 5.2 LISA aims to observe small objects spiralling into putative MBHs for thousands of cycles, with SNR in excess of 50, thus testing the structure of the spacetime around these objects, probing the presence of dark matter, and potentially measuring charges on the orbiting body associated with new fundamental fields.

SI 5.5 also uses EMRIs and has the potential to reveal [...] black hole hair, dark matter in the form of a light boson cloud, or the fact that the primary is not a BH but something more exotic.

Fundamental physics: what is in the Red Book now?

3.5.3 Test the presence of **beyond-GR emission channels**

- Are there GW emission channels beyond GR?
- Are there new physical degrees of freedom and extra GW polarizations, as predicted by some extensions of the standard model and of GR? Are the massive objects that merge and their remnants consistent with being rotating Kerr MBHs?

SI 5.3 LISA aims to probe the existence of dynamical fields by searching for additional radiation channels and polarizations that would be a smoking gun for non-GR theories.

MBHBs and EMRIs will allow to test beyond GR theories by looking into possible effects of new radiation channels in the gravitational emission.

3.5.4 Test the **propagation properties of GWs**

- Does the fundamental theory of gravity respect Lorentz symmetry and parity invariance?
- How do GWs propagate over cosmological scales?

SI 5.4 aims at detecting GWs from golden MBHB coalescences or/and from EMRIs, all with SNR > 200 to probe the propagation of GWs over very large distances, imposing new stringent constraints on dark energy models, modified graviton dispersion relations, and theories of gravity beyond GR.

Contributors: Vishal Baibhav, Tessa Baker, Emanuele Berti, Daniela Doneva, Paolo Pani, Mairi Sakellariadou, Thomas Sotiriou, Gianmassimo Tasinato, Kent Yagi…and many others I probably forgot

Defining success: what is a figure of merit (FoM)?

- WGs are a way of gathering expertise from the community
- WPs are concerned with the mission's success. How do we define success?

  "Figure of Merit" (FoM)

  FoM implementation:
  Maude Le Jeune, Stas Babak, Antoine Petiteau, Etienne Savalle, Sylvain Marsat, Alexandre Toubiana
  and many others, with input from WPSI/WFWG…

- To be blunt: in this context, fundamental physics is almost an afterthought!
  - Mission Requirements (MRs) focused on astrophysical sources (and SGWBs)
  - Only ringdown tests were listed among the original Mission Requirements (MR5.1)

- Why are fundamental physics FoMs different from those based on astrophysical sources?

What is a figure of merit (FoM)?

- Starting point: Science Requirements Document (SciRD, May 14 2018) https://www.cosmos.esa.int/documents/678316/1700384/SciRD.pdf
- FoM is a **number** translated into a "traffic light" color: red (mission is a no-go)
  yellow (careful)
  green (ok)
  blue (better than expected)
- FoMs are necessary to test instrumental configurations against their performance on the mission Science objectives (SOs) and Science investigations (SIs)
- FoM development by WPSI: https://www.overleaf.com/read/qgftztjxfbwb
- FoMs were implemented and results collected on the LISA wiki (Maude Le Jeune, Stas Babak, Antoine Petiteau, Etienne Savalle, Sylvain Marsat, Alex Toubiana, using also WPSI- and WFWG-provided tools)
- Requirements: Fix a reference LISA configuration
  Reproducibility, version tracking, constants, orbits, conventions
- Complexity: astrophysical uncertainties, waveform systematics, limited parameter estimation

Caveats: simple waveform models

- **GBs:** phenomenological model $A \exp\left[\phi_0 + \omega t + \frac{1}{2}\dot{\omega} t^2\right]$

  Frequency derivative can have either sign

- **MBHs:** PhenomD and PhenomHM (nonprecessing, circular)
  Plans: precessing binaries with higher order modes
  eccentricity (harder)

- **SOBHs:** PhenomD
  Current f-domain implementation not good if binary does not evolve much in frequency
  Plans: at least eccentricity

- **EMRIs:** Barack-Cutler analytic kludge (AK) model. Recently, relativistic Schwarzschild model
  Plans: AAK augmented kludge (or 5PN kludge) for generic orbits around Kerr
  Issue: need cutoff on number of harmonics
  (based on their amplitude and desired precision)

More caveats

- LISA Science Interpretation Work Package completed two studies before the FoM study:
  Impact of **low-f sensitivity** (< 0.1mHz)
  Impact of **mission duration (and gaps)**

- Both issues (especially gaps) have an impact on waveform modelling requirements

- FoM definitions "independent" of astrophysical modeling, but models did inform definitions

- Interface takes noise matrix as input - needs performance working group output (noise/data artifacts)

- **Most current FoMs are based (for simplicity) on SNR thresholds – not good when PE should be used**
  Some exceptions (e.g. sky localization and luminosity distance errors for MBHBs as standard sirens)

- **Note: modest target. Not "real" data analysis, "only" quantify FoM definition uncertainties**

What is a figure of merit (FoM) in the context of fundamental physics?

- FP-related FoMs introduced by WP SI:
  - WP SI.6: elucidating dark matter
    Diego Blas, Maximiliano Isi (Nichols, Brito on Thu)
  - WP SI.7: foundations of gravitational interaction (ppE/memory)
    Tessa Baker, Gianmassimo Tasinato, Kent Yagi, Lavinia Heisenberg (Nichols, Brito on Thu)
  - WP SI.8: testing the nature of BHs (spectroscopy, tidal deformability/heating, ECO binaries, echoes)
    Paolo Pani, Aaron Zimmerman (Mayerson, Maggio, Zimmerman's talks on Wed)

- Also relevant to FP:
  - EMRIs (WP SI.3: related to Kerr tests, XMRIs, DM spikes)
    Pau Amaro-Seoane, Christopher Berry, Alvin Chua
  - Estimation of cosmological parameters (WP SI.4)
    Hsin-Yu Chen, Nicola Tamanini (Tamanini, Chen, Baker/Tasinato on Thu)
  - SGWBs (WP SI.5)
    Irina Dvorkin, Valerie Domcke, Marco Peloso, Germano Nardini

    …and many others that I have probably forgotten (Richard Brito, Andrea Maselli…) - with apologies!

What is a figure of merit (FoM)?

- Examples of interplay between mission design and FoMs in the context of tests of FP:
  - Effect of mission duration
  - Effect of low-f sensitivity

Example: the mission duration study

LISA proposal: Science Objectives (SOs) and Science Investigation (SIs) in the Science Requirements Document (SciRD) based on a 4-year mission with no gaps

LISA Pathfinder: 75% duty cycle, T_{data} = 0.75 $T_{elapsed}$

Consider various mission durations (4 to 6 years) with 75% duty cycle and three scenarios:

1) a single continuous gap (T4C/T5C/T6C)
2) 5-day gaps (T4G5, T6G5)
3) 1-day gaps (T4G1, T6G1)

How does this affect SOs? "Traffic light" answer broken down by science themes

Astrophysics:	**Massive black hole binaries**
	Stellar-mass compact objects (incl. galactic binaries, **SOBHs**)
	Extreme mass-ratio inspirals (EMRIs)
Cosmology:	H_0 and cosmological parameters via standard sirens
	Stochastic gravitational wave backgrounds
Fundamental physics:	Dark matter
	Tests of general relativity
	Nature of black holes

Top: SNR with/without gaps

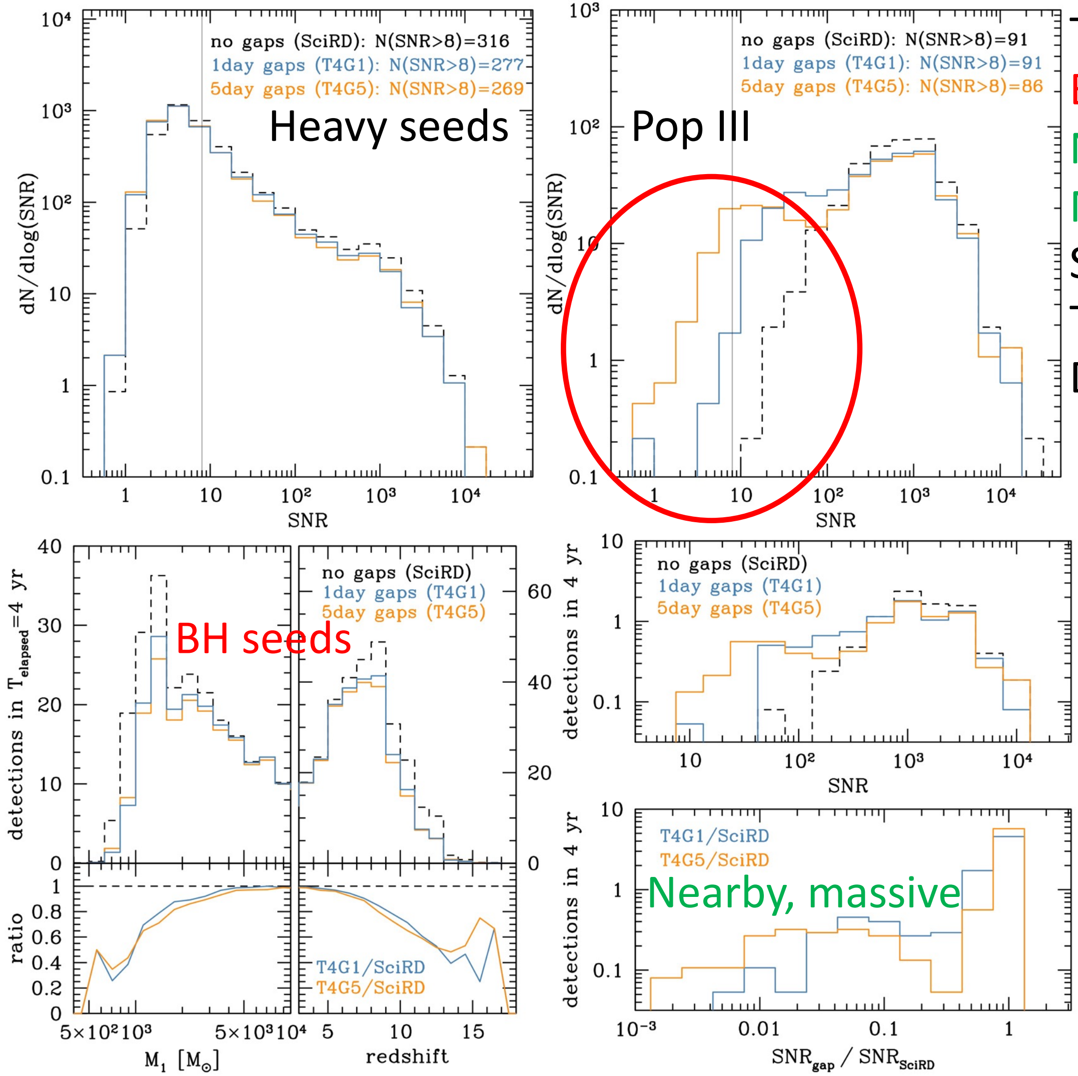
BH seeds: 25->10 with $M<10^3 M_{sun}$, $z>10$

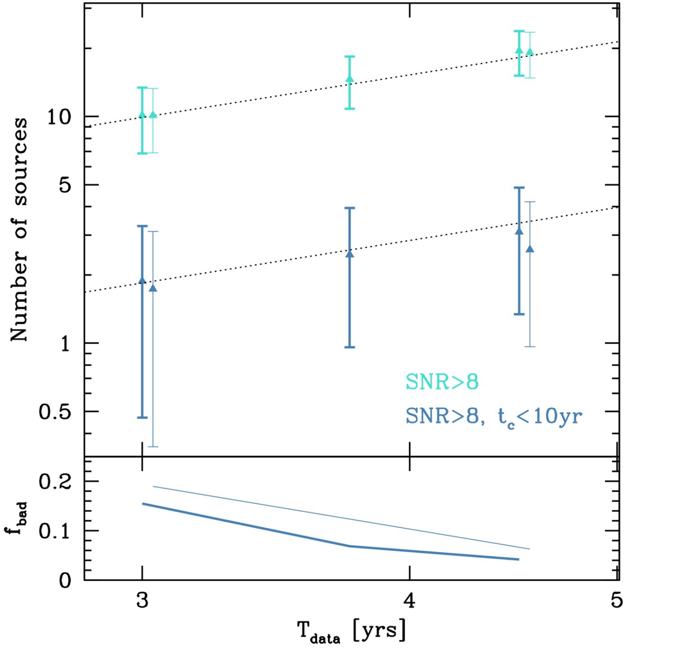
Nearby, massive: 1/3 of MBHBs with $M>10^5 M_{sun}$, $z<2$ drop in SNR by ~10

SOBHs: all sources and multiband subset

Thick: continuous gaps, thin: 1 or 5 days

Dotted: $N \propto T_{\rm data}^{3/2}$, bottom: $f_{\text{no-multiband}}$





Mission duration summary table

Scenario	T4C	T4G5	T4G1	T5C	T6C	T6G5	T6G1
T_{elapsed}		4 yr		5 yr		6 yr	
$T_{\mathrm{data}} = 0.75 \times T_{\mathrm{elapsed}}$		3 yr		3.75 yr		4.5 yr	
Gaps	one	5 days	1 day	one	one	5 days	1 day
Galactic binaries (SO1 SI1.2) (§3)							
Black hole seeds (SO2 SI2.1) (§2)							
EM counterparts (SO2 SI2.3) (§2, §5)							
EMRIs (SO3 SI3.1) (§4)							
Multiband SOBHs (SO4 SI4.1) (§3)							
SOBH formation (SO4 SI4.2) (§3)							
Kerr tests (SO5 SI5.1&5.2) (§9)							
Tests of GR (SO5 SI5.3&5.4) (§8)							
Ultralight bosons (SO5 SI5.5) (§7)							
H_0 via standard sirens (SO6 SI6.1) (§6)							
Cosmological parameters (SO6 SI6.2) (§6)							

SIWP also studied: low-f sensitivity
figures of merit
data products definition

arXiv:2107.09665

What’s next?

- Examples of interplay between mission design and FoMs in the context of tests of FP:

    - Effect of mission duration
    - Effect of low-f sensitivity

…but wait a minute: Red Book and mission adoption! Isn’t the mission design frozen? Aren’t we done? **no**

- Examples:

    - Comparing SciRD vs. CBE

    - Other observational facilities may change the landscape of tests of FP

    - Ever changing mission design (despite adoption, Red Book, etcetera)

    - Time to go beyond back-of-the-envelope estimates, Fishers etc. and into “real” DA:
      The fundamental physics community should contribute to LISA data challenges! (Babak’s talk)
      Time to coordinate with (NSF-funded) CE MDC
      Need to develop ET MDC

Discussion #1: Do we need to update the science case? What is missing?

Areas that have expanded/should be included (IMO):

a) WF systematics in GR to avoid "false positives" of beyond-GR effects. (Shoemaker, Maselli on Fri)
Examples:
- Higher harmonics in MBHBs within GR (Pitte+, 2304.03142)
- Nonlinearities in merger/ringdown modeling (Baibhav+, 2302.03050)

b) Model-independent IMR tests (Bernard, Yagi on Fri)
- ParSpec (Maselli+, 1910.1293; Carullo, 2102.05939)
- EOB-based (Brito+, 1805.00293; Silva+, 2205.05132; Maggio+, 2212.09655)

c) Synergies with next-gen detectors (CE/ET) - important for the science case of all three

d) Synergies with MMA, EM observations, PTAs…

e) More cosmology! (Tamanini, Chen, Baker/Tasinato on Thu)
Example: strong lensing and dark matter (sub)structures (Caliskan+, 2206.02803, 2307.06990)

Discussion #2: Do we expect new observations/experiments to reprioritize FP goals?

What will LISA be most useful for, considering that the FP landscape in 15 years will be different?

Rank these:

a) Cosmology (cosmological tensions will still be there)

b) Astrophysical/cosmological SGWBs (PTAs and LIGO/Virgo/KAGRA will not tell us enough)

c) MBH binary merger rates and black hole tests (PTAs and EM observations will be inconclusive)

d) MMA rates and EMRIs (TDEs will not reveal enough)

Discussion #3: Systematics – What should be the main priority?

a) Instrumental calibration

b) MBHBs:
  - Waveforms in GR
  - Waveforms beyond GR

c) EMRIs:
  - Self-force, resonances
  - Environmental effects (dark matter, boson clouds…)
  - Beyond-GR effects (scalar charges…)

d) GBs:
  - Astrophysical systematics

Discussion #4: More realistic data analysis

We have discussed how forecasts with fundamental physics with LISA need to be as realistic as possible. What would be most helpful to achieving this for your work?

Select the most important:

a) Tutorial on waveform systematics

b) Tutorial on modelling of other systematics (e.g. lensing)

c) Hands-on training with LISA data tools under development

d) Attempting some of the LDC challenges

e) Tutorial on including instrumental effects in forecasts (e.g. gaps in the datastream, orbital rotation)

f) Something else

Follow-up question: if something else, what? (Freeform text entry)

Discussion #5: Overlap and communication with other areas (cosmo/astro…)

Some of the FP interests discussed here overlaps or relies upon other WGs.

Where do we need to be communicating the most? (Rank from most to least)

a) Astro WG

b) Cosmo WG

c) LDC WG

d) Waveform WG

e) Other WP (e.g. Science Investigation WP, Data analysis WP etc.)

Follow-up questions:

- If other, where?

Extra slides

Science Objectives / Science Investigations (from SciRD)

SO 1 Study the formation and evolution of compact binary stars in the Milky Way Galaxy

SI 1.1 Elucidate the formation and evolution of Galactic Binaries by measuring their period, spatial and mass distributions

SI 1.2 Enable joint gravitational and electromagnetic observations of galactic binaries (GBs) to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems

SO 2 Trace the origin, growth and merger history of massive black holes across cosmic ages

SI 2.1 Search for seed black holes at cosmic dawn

SI 2.2 Study the growth mechanism of MBHs before the epoch of reionization

SI 2.3 Observation of EM counterparts to unveil the astrophysical environment around merging binaries

SI 2.4 Test the existence of intermediate-mass black holes (IMBHs)

SO 3 Probe the dynamics of dense nuclear clusters using extreme mass-ratio inspirals (EMRIs)

SI 3.1 Study the immediate environment of Milky Way like massive black holes (MBHs) at low redshift

SO 4 Understand the astrophysics of stellar origin black holes

SI 4.1 Study the close environment of Stellar Origin Black Holes (SOBHs) by enabling multi-band and multi-messenger observations at the time of coalescence

SI 4.2 Disentangle SOBHs binary formation channels

Science Objectives / Science Investigations (from SciRD)

SO 5 Explore the fundamental nature of gravity and black holes

SI 5.1 Use ring-down characteristics observed in massive black hole binary (MBHB) coalescences to test whether the post-merger objects are the black holes predicted by General Theory of Relativity (GR)

SI 5.2 Use EMRIs to explore the multipolar structure of MBHs

SI 5.3 Testing for the presence of beyond-GR emission channels

SI 5.4 Test the propagation properties of gravitational waves (GWs)

SI 5.5 Test the presence of massive fields around massive black holes with masses larger than 10^3 $M_\odot$

SO 6 Probe the rate of expansion of the Universe

SI 6.1 Measure the dimensionless Hubble parameter by means of GW observations only

SI 6.2 Constrain cosmological parameters through joint GW and electro-magnetic (EM) observations

SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

SI 7.1 Characterise the astrophysical stochastic GW background

SI7.2 Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

SO 8 Search for GW bursts and unforeseen sources

SI 8.1 Search for cusps and kinks of cosmic strings

SI 8.2 Search for unmodelled sources

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LISA wiki implementation

Index

FoM	OR	Link
Background		
Estimating the galactic background noise [1.0 yr]	1.1c	report
Estimating the galactic background noise [6.0 yr]	1.1c	report
SO1 : Study the formation and evolution of compact binary stars in the Milky Way Galaxy.		
Horizon distance of stellar-mass source 6.0 yr	1.1.a	report
Capability to detect and characterise a significantly large population of resolved detached stellar-mass binaries [6.0 yr]	1.1a	report
Capability to detect mass-transferring binaries [6.0 yr]	1.1a	report
Capability to detect and characterise a significantly large population of resolved stellar mass-binaries with accurate chirp masses. [6.0 yr]	1.1b	report
Capability to detect and characterise a significantly large population of resolved stellar mass-binaries with accurate position. [6.0 yr]	1.1b	report
Capability to detect and characterize mass-transferring binaries [6.0 yr]	1.2c	report
Capability to detect and characterize detached binaries [6.0 yr]	1.2c	report
Detectability of verification binaries and measurement of the their frequency evolution [1.0 yr]	1.2a	report

WPSI organization must be cross-matched with SOs/SIs - astro

WPSI organization must be cross-matched with SOs/SIs - cosmo

WPSI organization must be cross-matched with SOs/SIs – fundamental physics

Example. WP SI.1: formation, evolution, EM counterparts of MBH mergers (SO2)

For each requirement we defined a FoM that is evaluated as follows:

1. The FoM is summarized as the percentage of sources which can be detected at a given threshold SNR within a specified mass and redshift range.

2. Within the mass and redshift ranges defined for each FoM, the percentage is computed by drawing a population of 10,000 (with the exception of 1.5 below, which was calculated using 2000 trials) sources with the following properties:

   - random sky location, orbital orientation, polarization angle, initial orbital phase;
   - aligned spins randomly drawn in the $[-1, 1]$ range[1];
   - log-flat distribution in the primary mass m_1 (with $m_1 \geq m_2$) within the specified range;
   - log-flat distribution in mass ratio $q = m_2/m_1$ in the range $0.1 \leq q \leq 1$ (unless defined otherwise, cf. 1.8 below);
   - redshift probability proportional to dV_c/dz to ensure a uniform distribution in co-moving volume within the specified range.
   - coalescence time randomly drawn between 0.1 – 0.95 yr

3. The percentage of sources passing the FoM specifications computed in this way is compared to the "traffic light" thresholds that define the quality of the FoM.

The pass/fail criteria have been informed by the astrophysical models of MBHB formation and evolution (PopIII, Q3nod, Q3d) presented by Klein et al. in Ref. [26]. For example, the passing criterion for FoM1.1 ensures detectability of at least five mergers within the specified mass-redshift range in the models where those systems exist, which has been deemed necessary to confidently separate among them.

Galactic binaries

FoM	OR	Link
Background		
Estimating the galactic background noise [1.0 yr]	1.1c	report
Estimating the galactic background noise [6.0 yr]	1.1c	report
SO1 : Study the formation and evolution of compact binary stars in the Milky Way Galaxy.		
Horizon distance of stellar-mass source 6.0 yr	1.1.a	report
Capability to detect and characterise a significantly large population of resolved detached stellar-mass binaries [6.0 yr]	1.1a	report
Capability to detect mass-transferring binaries [6.0 yr]	1.1a	report
Capability to detect and characterise a significantly large population of resolved stellar mass-binaries with accurate chirp masses. [6.0 yr]	1.1b	report
Capability to detect and characterise a significantly large population of resolved stellar mass-binaries with accurate position. [6.0 yr]	1.1b	report
Capability to characterize mass-transferring binaries [6.0 yr]	1.2c	report
Detectability of verification binaries and measurement of the their frequency evolution [1.0 yr]	1.2a	report
Detectability of verification binaries and measurement of the their frequency evolution [6.0 yr]	1.2a	report

Massive black holes / Extreme mass ratio inspirals

SO2 : Trace the origin, growth and merger history of massive black holes across cosmic ages		
Disentangling seed formation mechanisms [1.0 yr]	2.1	report
Constraining the progenitors of luminous quasars at the peak of quasar activity (new OR low freq) [1.0 yr]	new	report
Reconstructing the cosmic history of the most common MBHs populating galaxies today [1.0 yr]	2.2a	report
Understanding MBH spin growth [1.0 yr]	2.2b	report
Multimessenger astronomy, enabling follow-ups [1.0 yr]	2.3b	report
Discovering IMBHs in the local universe [1.0 yr]	2.4a	report
Detecting intermediate mass ratio inspirals [1.0 yr]	2.4b	report
Multimessenger astronomy, enabling pre-localization [1.0 yr]	2.3a	report
SO3 : Probe the dynamics of dense nuclear clusters using EMRIs		
Detectability of $10^5 - 10M_\odot$ EMRI at redshift z=3 with eccentricity e=0.68 at plunge 2 years [1.0 yr]	3.1	report
Detectability of $10^6 - 10M_\odot$ EMRI at redshift z=3 with eccentricity e=0.25 at plunge 2 years [1.0 yr]	3.1	report

SOBHs: mostly ok, ringdown: will get back to it later

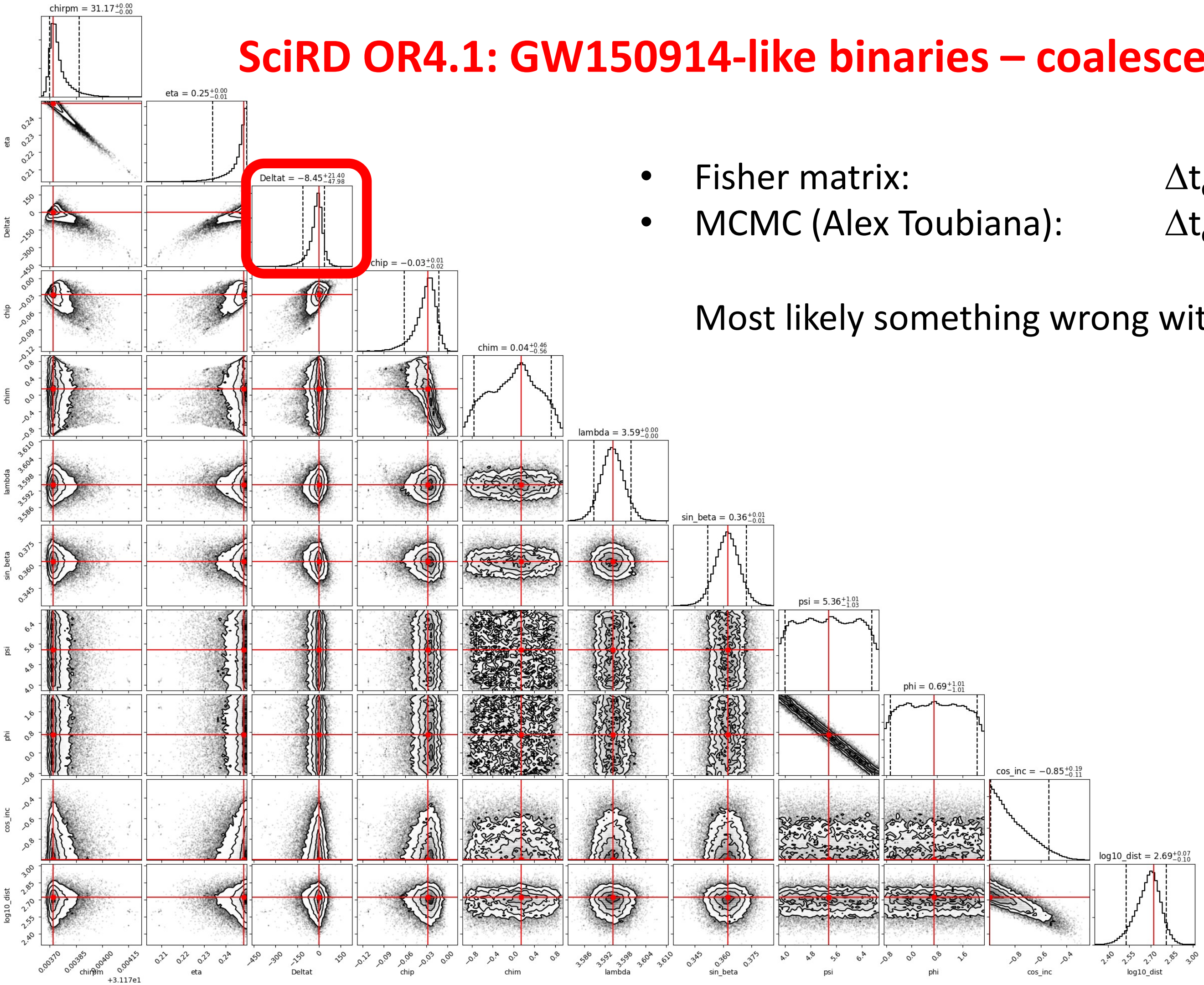
SO4 : Understand the astrophysics of stellar origin black holes		
Ability to detect GW150914-like events using optimal sky position [6.0 yr]	4.1	report
Capability to detect a 10 $M_\odot$ BH-BH source out to specific horizon distances [6.0 yr]	4.2	report
Capability to detect a GW150914 like source out to specific horizon distances [6.0 yr]	4.2	report
Capability to detect a GW190521 like source out to specific horizon distances [6.0 yr]	4.2	report
SO5 : Explore the fundamental nature of gravity and black holes		
Detectability of ringdown for high mass SMBH	5.1	report

SI4.1 Study the close environment of SOBHs by enabling multi-band and multi-messenger observations at the time of coalescence

OR4.1: Have the ability to detect the inspiral signal from GW150914-like events with SNR > 7 after 4 years of observation and estimate the sky localisation with $< 1\,\mathrm{deg}^2$ and the time of coalescence in ground-based detectors to within one minute. This will allow the triggering of alerts to ground-based detectors and to pre-point EM probes at the SOBH coalescence.

MR4.1: Detecting the inspiral of SOBHs with a mass comparable to those in the GW150914 system with SNR higher than 7, accumulated over 4 years, constrains the rising branch of the sensitivity curve by requiring a strain sensitivity of better than $1.2 \times 10^{-20}\,\mathrm{Hz}^{-1/2}$ at 14 mHz rising to $4 \times 10^{-20}\,\mathrm{Hz}^{-1/2}$ at 100 mHz.

SciRD OR4.1: GW150914-like binaries – coalescence time issue



- Fisher matrix: $\Delta t_c \sim 10$ hours
- MCMC (Alex Toubiana): $\Delta t_c \sim$ seconds

Most likely something wrong with the Fisher calculation

Cosmology: standard sirens, stochastic backgrounds

SO6 : Probe the rate of expansion of the Universe		
MBHB as standard sirens [1.0 yr]	6.2	report
SOBHB as standard sirens [6.0 yr]	None	report
SO7 : Understand stochastic GW backgrounds		
Unresolved stellar origin black holes [6.0 yr]	7.1	report
Cosmic strings beyond SKA [6.0 yr]	7.2	report
SGWB from PBH dark matter [6.0 yr]	7.2	report
Characterise representative template for SGWB power-law with n=0 [6.0 yr]	7.2	report
Characterise representative template for SGWB power-law with n=2/3 [6.0 yr]	7.2	report
Characterise representative template for SGWB power-law with n=-3 [6.0 yr]	7.2	report

SI6.1: Measure the dimensionless Hubble parameter by means of GW observations only

OR6.1a Have the ability to observe SOBH binaries with total mass $M > 50\,M_\odot$ at $z < 0.1$ with SNR higher than 7 and typical sky location of $< 1\,\mathrm{deg}^2$.

OR6.1b Have the ability to localize EMRIs with an MBH mass of $5 \times 10^5\,M_\odot$ and an SOBH of $10\,M_\odot$ at $z = 1.5$ to better than $1\,\mathrm{deg}^2$.

SI6.2: Constrain cosmological parameters through joint GW and EM observations

OR6.2 Have the capability to observe mergers of MBHBs in the mass range from 10^5 to $10^6\,M_\odot$ at $z < 5$, with accurate parameter estimation and sky error of $< 10\,\mathrm{deg}^2$ to trigger EM follow ups [19].

- **Dropped: SOBHBs as standard sirens**
  Two main reasons: degradation of high-frequency noise since [Del Pozzo-Sesana-Klein, 1703.01300]
  revision of SOBHB rates post LIGO/Virgo O1/O2/O3a runs
- **Added: FoM on EMRIs as standard sirens**

Added more FoMs related to fundamental physics - e.g. WP SI.6 (dark matter)

- Superradiant instabilities: mainly population uncertainties
  FoMs defined so they are not affected by astrophysical uncertainties

FoM: range of detectable boson masses for $M = 4 \times 10^6 M_\odot$ and $a = 0.9M$ at $z = 0.5$
$q > 110\%$
$90\% < q < 110\%$
$q < 90\%$

FoM: the range of boson masses that can be constrained for a reference BH with initial mass $M = 4 \times 10^6 M_\odot$ (i.e. SgrA*-like) and spin $a/M = 0.9$ at $z = 0.5$. For this reference source one finds $6.5 \times 10^{-18}\,\mathrm{eV} \leq m_b \leq 1.0 \times 10^{-17}\,\mathrm{eV}$, using the SciRD PSD and assuming SNR$= 10$ as the detection threshold (not accounting for the presence of the galactic binary foreground). We will take the width of this interval ($3.5 \times 10^{-18}\,\mathrm{eV}$) as a reference and define the FoM (q) as a percent with respect to this value, i.e.,

$$q \equiv \frac{\max(m_b) - \min(m_b)}{3.5 \times 10^{-18}\,\mathrm{eV}} \times 100\%\,, \tag{6}$$

where $\max(m_b)$ and $\min(m_b)$ refer to the upper and lower ends of the detectable boson mass range, respectively.

WP SI.7 (ppE tests, nonlinear GW memory)

- Christodoulou memory: not an issue
- **ppE tests: large waveform uncertainties**

PN order n or α	FoM	Binary Type
$n = -5.5$ (dark matter)	$\beta/\beta_{\mathrm{GW150914}} = 10^{-14}$	EMRI
$n = -5.5$ (dark matter)	$\beta/\beta_{\mathrm{GW150914}} = 7.2 \times 10^{-14}$	EMRI
$n = -5.5$ (dark matter)	$\beta/\beta_{\mathrm{GW150914}} = 10^{-12}$	EMRI
$n = -1$ (dipole emission)	$\beta/\beta_{\mathrm{GW150914}} = 5 \times 10^{-7}$	EMRI
$n = -1$ (dipole emission)	$\beta/\beta_{\mathrm{GW150914}} = 1.5 \times 10^{-6}$	EMRI
$n = -1$ (dipole emission)	$\beta/\beta_{\mathrm{GW150914}} = 10^{-5}$	EMRI
$\alpha = 0$ (massive graviton)	$A/A_{\mathrm{GW150914}} = 10^{-9}$	EMRI
$\alpha = 0$ (massive graviton)	$A/A_{\mathrm{GW150914}} = 9.6 \times 10^{-9}$	EMRI
$\alpha = 0$ (massive graviton)	$A/A_{\mathrm{GW150914}} = 10^{-7}$	EMRI

WP SI.8 (nature of black holes)

- **Black hole spectroscopy: some waveform uncertainties**
  Only FoM implemented so far in FoM pipeline

FoM: Maximum BH mass such that we can observe at least three ringdown modes
$M_{\max} > 10^9 M_\odot$
$5 \times 10^8 M_\odot < M_{\max} < 10^9 M_\odot$
$10^8 M_\odot < M_{\max} < 5 \times 10^8 M_\odot$

Table 3: Minimum and maximum remnant masses ($M_{\min}$, $M_{\max}$) at which different ringdown modes are observable for the merger of non-spinning BHs of $q = 2$ at $D_L = 3$Gpc.

(ℓ, m)	$M_{\min}[M_\odot]$	$M_{\max}[M_\odot]$		
		$f_{\text{low}} = 10^{-4}$Hz	$f_{\text{low}} = 2 \times 10^{-5}$Hz	$f_{\text{low}} = 10^{-5}$Hz
(2, 2)	4.6×10^4	1.1×10^8	5.4×10^8	1.1×10^9
(3, 3)	1.3×10^5	1.7×10^8	8.6×10^8	1.7×10^9
(2, 1)	1.1×10^5	9.5×10^7	4.8×10^8	7.6×10^8
(4, 4)	2.5×10^5	2.3×10^8	1.2×10^9	2.1×10^9

No-hair test accuracy with two-mode ringdown spectroscopy	
0.1%	Significant improvement wrt reference system
1%	Reference binary: source-frame $M_{\text{tot}} = 10^6 M_\odot$, $q = 2$, no spin, $d = 5$ Gpc. $\text{SNR}_{\text{ringdown}} = 476$. FoM = 1%
5%	No significant improvement wrt current LIGO IMR consistency tests and future ringdown tests at design sensitivity

WP SI.8 (nature of black holes)

- **Tidal Love numbers in the inspiral, boson stars, echoes**

Measurement accuracy on the tidal Love number, $\frac{\Delta_{k_2}}{k_2}$, for a reference object with $k_2 = 0.1$	
1%	Significant improvement wrt reference binary
10%	Reference binary: source-frame $M_{\rm tot} = 10^6 M_\odot$, $q = 2$, no spin, $d = 5\,{\rm Gpc}$. ${\rm SNR}_{\rm inspiral} = 7710$. FoM = 10%
100%	Unable to distinguish the ECO binary from a BH binary (for which $k_2 = 0$)

Measurement accuracy on the quartic coupling of a scalar field, $\Delta M_B/M_B$, forming a boson star	
1%	Significant improvement wrt reference binary
10%	Ref. binary: source-frame $M_{\rm tot} = 8 \times 10^5 M_\odot$, $q = 1.2$, $\chi_1 = 0.6$, $\chi_2 = 0.3$, $d = 5\,{\rm Gpc}$. ${\rm SNR}_{\rm inspiral} = 3719$. FoM = 10%
100%	Prevent measurement of the coupling

Measurement accuracy on the object effective reflectivity, $\Delta\mathcal{R}/\mathcal{R}$, from echo searches, assuming $\lvert\mathcal{R}\rvert^2$=0.1	
0.1%	Significant improvement wrt reference binary
1%	Reference remnant: $M_{\rm remnant} = 10^6 M_\odot$, $\chi_{\rm remnant} = 0.7$. ${\rm SNR}_{\rm ringdown} = 476$. FoM = 1%
100%	Prevent measurement of the reflectivity

Example. WP SI.1: formation, evolution, EM counterparts of MBH mergers (SO2)

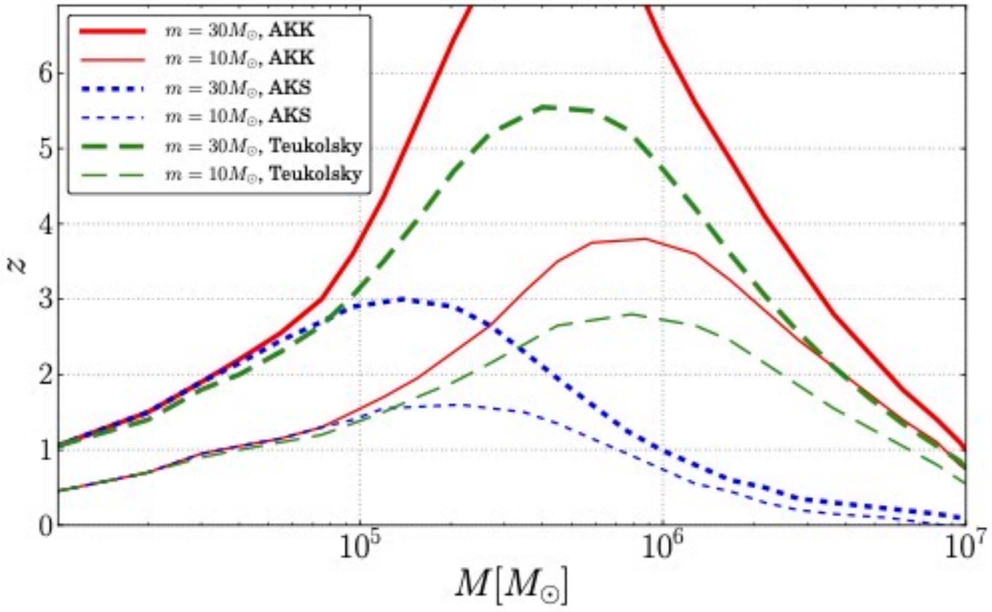
- Most affected by waveforms:

1.2 (quasar progenitors)	**Detection of MBHBs with source-frame mass in the range 10^7-10^8 $M_\odot$ and formation redshift in the range $z=2.5-3.5$ with SNR>10.**
1.4 (spin growth)	**Detection of MBHBs with source-frame mass in the range 10^5-10^6 $M_\odot$ and formation redshift in the range $z=2-3$ with SNR>300.**
1.5 (MMA, pre-localization)	**For a MBHBs with source-frame mass in the range 10^5-10^7 $M_\odot$ at $z=1$ measurement of: (i) sky localization within $100\,\mathrm{deg}^2$ 1 day before merger and (ii) time to coalescence within 4h 2 days before merger.**
1.6 (MMA, follow-ups)	**Detection of MBHBs with source-frame mass in the range 10^5-10^7 $M_\odot$ and formation redshift in the range $z=1.5-2.5$ with SNR>500.**
1.8 (IMRIs)	**Detection of MBHBs with source-frame primary mass in the range 10^4-10^6 $M_\odot$, $q=0.01$ and formation redshift in the range $z=2-3$ with SNR>30.**

WP SI.2 (stellar-mass COs)

- Waveform modeling in WP SI.2 not as critical. Most affected by waveforms:
  Tidal effects
  Eccentricity in SOBHs

…but EMRIs (WP SI.3) are a problem



WP SI.3 (EMRIs/IMRIs)

SO3 for the LISA mission calls for the detection and measurement of EMRIs involving 10–60$M_\odot$ SOBHs inspiralling into 10^5–$10^6 M_\odot$ MBHs. The original OR3.1 in the LISA mission proposal specified detectability of such EMRIs out to redshift $z = 3$, but we propose relaxing this to $z = 2$ (where star formation in galaxies is peaked).

Our proposed FoM for the detection requirements are:

1. Probability of detecting a 2-year $(10^5, 10)M_\odot$ (source-frame) Schwarzschild EMRI with eccentricity $e = 0.25$ at plunge, at redshift $z = 2$ with SNR of 20 (10%: red; 50%: yellow; 90%: green).

2. Probability of detecting a 2-year $(10^6, 10)M_\odot$ (source-frame) Schwarzschild EMRI with eccentricity $e = 0.25$ at plunge, at redshift $z = 2$ with with SNR of 20 (10%: red; 50%: yellow; 90%: green).

WP SI.4 (standard sirens)

- Important to quantify sky localization with full IMR waveforms

Events with the following characteristics must be detected with sky localisation better than 10 deg^2 and SNR ≥ 10:

- If one among these events is detected, the FoM is yellow: $M_c = 3.2 \cdot 10^4\, M_\odot$, $z = 2.5$ (popIII), $M_c = 3.0 \cdot 10^5\, M_\odot$, $z = 2.8$ (heavy delay), $M_c = 1.4 \cdot 10^5\, M_\odot$, $z = 2.7$ (heavy no delay)
- If one among these events is detected, the FoM is green: $M_c = 6.0 \cdot 10^3\, M_\odot$, $z = 4.3$ (popIII), $M_c = 1.3 \cdot 10^5\, M_\odot$, $z = 4.9$ (heavy delay), $M_c = 4.7 \cdot 10^4\, M_\odot$, $z = 4.5$ (heavy no delay)
- If one among these events is detected, the FoM is blue: $M_c = 2.5 \cdot 10^3\, M_\odot$, $z = 5.8$ (popIII), $M_c = 2.2 \cdot 10^4\, M_\odot$, $z = 7.0$ (heavy delay), $M_c = 1.4 \cdot 10^4\, M_\odot$, $z = 6.6$ (heavy no delay)

WP SI.4 (standard sirens)

- **EMRIs** that can be used for cosmology must have SNR ≥ 100. Therefore, events with the following characteristics must be detected with SNR≥ 100:
  - (detector frame) chirp mass $1250 M_\odot$, symmetric mass ratio $1.2 \cdot 10^{-5}$ and redshift 0.34: if only this event has SNR ≥ 100, the FoM is yellow
  - (detector frame) chirp mass $1100 M_\odot$, symmetric mass ratio $8.8 \cdot 10^{-6}$ or $1.8 \cdot 10^{-5}$ (to be decided) and redshift 0.4: if this event has SNR ≥ 100, the FoM is green
  - chirp mass $570 M_\odot$, symmetric mass ratio $6.0 \cdot 10^{-6}$ or $5.6 \cdot 10^{-5}$ (to be decided) and redshift 0.6: if this event has SNR ≥ 100, the FoM is blue

- **SOBHBs** that can be used for cosmology must have relative error on the luminosity distance $\Delta D_L/D_L \leq 0.2$. However, since the events below have already been taken from a catalogue that satisfies this condition, we impose the FoM in terms of sky localisation (when you run it, please check that $\Delta D_L/D_L \leq 0.2$ is indeed satisfied). We consider here equal mass binaries.
  - If an event with chirp mass 46.5 $M_\odot$ and redshift $z = 0.057$ is measured with sky localisation better than 0.46 deg^2 the FoM is yellow
  - If an event with chirp mass 38.4 $M_\odot$ and redshift $z = 0.073$ is measured with sky localisation better than 0.2 deg^2 the FoM is green
  - If an event with chirp mass 21 $M_\odot$ and redshift $z = 0.095$ is measured with sky localisation better than 0.03 deg^2 the FoM is blue

WP SI.5 (SGWBs)

- Representative templates
- Stand-alone science cases:
  - Unresolved SOBHs
  - Cosmic strings beyond SKA
  - SGWB from PBH dark matter
- **Issues: noise model/properties, but also subtraction of loud signals (e.g. SMBHs)**