LISA Science: A brief status update

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Physics of the Cosmos Minisymposium

APS Global Physics Summit

Anaheim, CA

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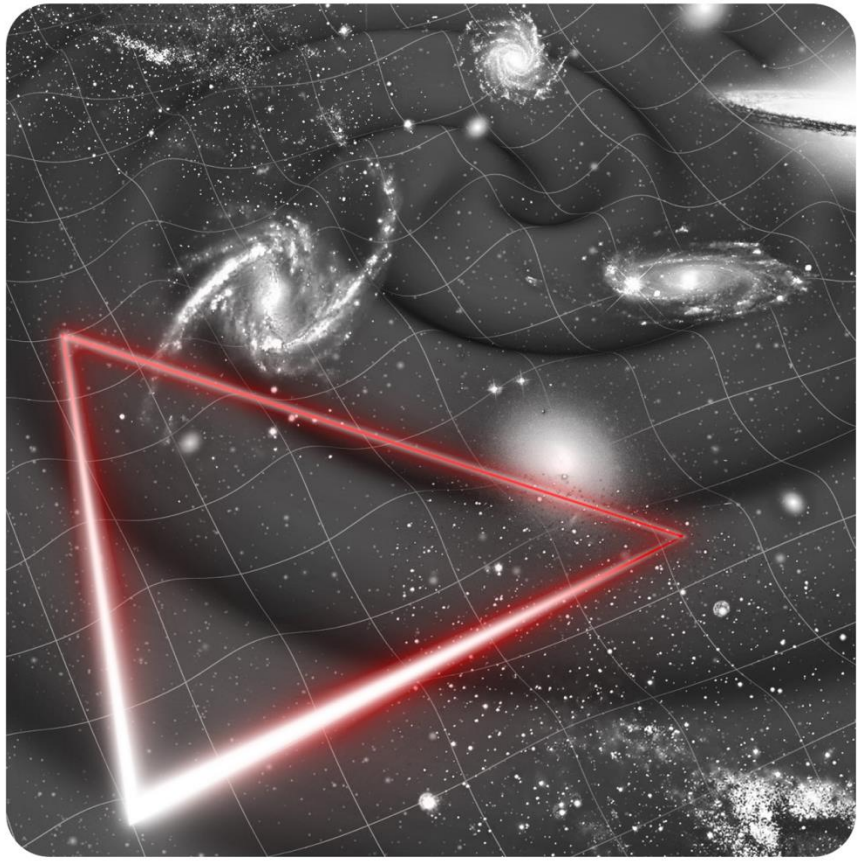
LISA

Laser Interferometer Space Antenna



Definition Study Report

LISA MISSION SUMMARY

Science Objectives

- Study the formation and evolution of **compact binary stars** and the structure of the Milky Way Galaxy
- Trace the origins, growth and merger histories of **massive Black Holes** across cosmic epochs
- Probe the properties and immediate environments of Black Holes in the local Universe using **extreme mass-ratio inspirals** and **intermediate mass-ratio inspirals**
- Understand the astrophysics of **stellar-mass Black Holes**
- Explore the **fundamental nature of gravity** and Black Holes
- Probe the rate of **expansion of the Universe** with standard sirens
- Understand **stochastic gravitational wave backgrounds** and their implications for the early Universe and TeV-scale particle physics
- Search for gravitational wave bursts and **unforeseen sources**

[LISA definition study report (Red Book), 2402.07571]

A brief history of LISA

1970s – Pete Bender (JILA): LAGOS
1990s – Six spacecraft proposal to ESA, M3, then Horizon 2000 plus

1997 – NASA/ESA **LISA** mission: three spacecraft, 5 million km
2000 – LISA final report
2003 – top ranked in terms of technological readiness in Beyond Einstein program
2005 – ESA Cosmic Vision, among top candidates for L1 launch slot

2011 – NASA pulls out: NGO, two arms

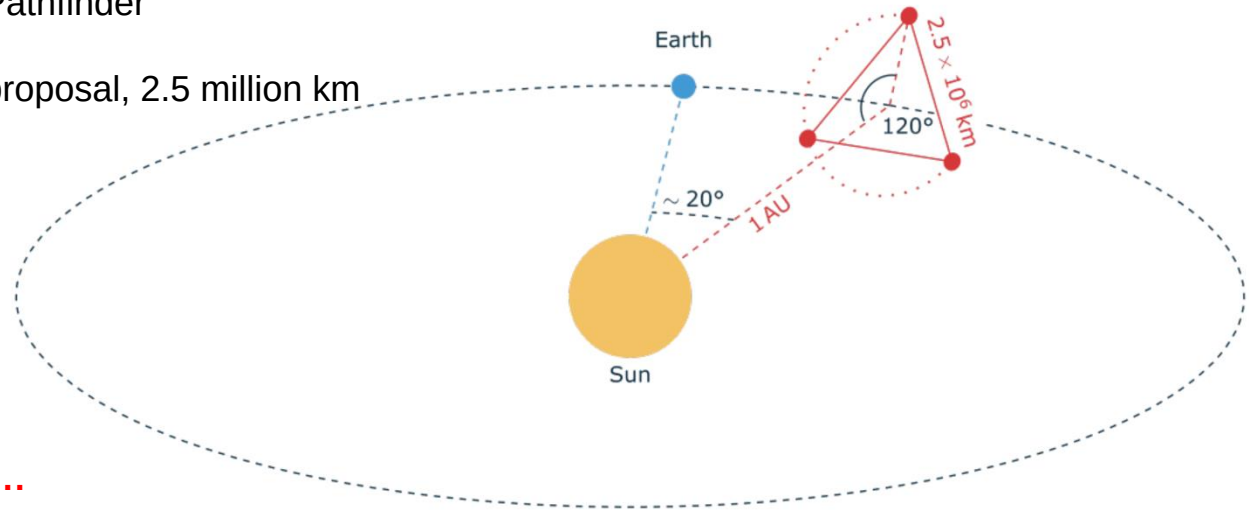
2015 – GW150914, success of LISA Pathfinder

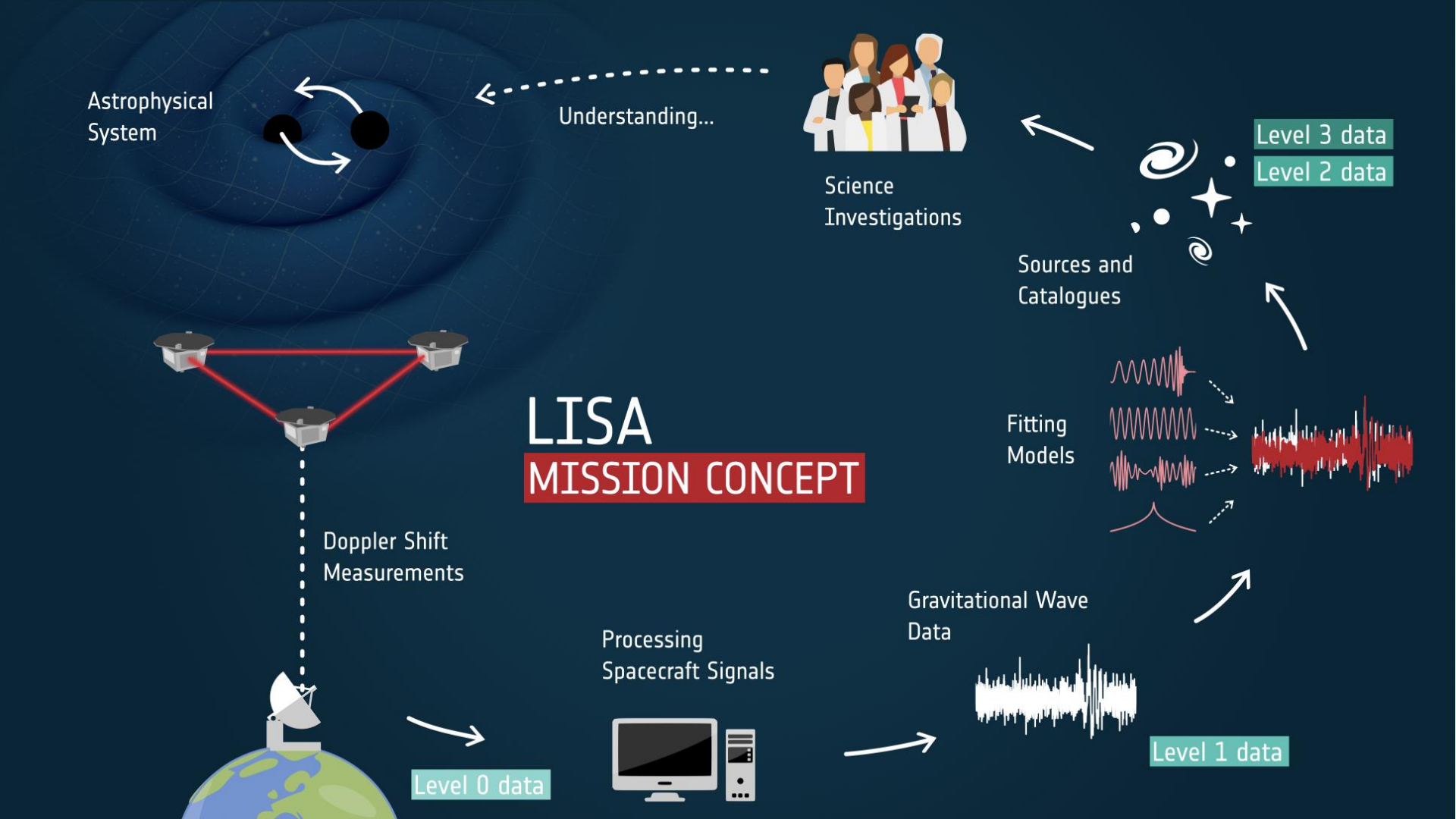
2017 – ESA/NASA LISA Consortium proposal, 2.5 million km

Phase 0
3-year Phase A
Phase B1 (2021-2023)…

2023 – Mission adoption
2035 – Launch

Mission requirements, data analysis…




Astrophysical System
Understanding...
Science Investigations
Level 3 data
Level 2 data
Sources and Catalogues
LISA
MISSION CONCEPT
Fitting Models
Doppler Shift Measurements
Gravitational Wave Data
Processing Spacecraft Signals
Level 0 data
Level 1 data

THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

Ground-based experiment

Space-based observatory

Pulsar timing array

Cosmic microwave background polarisation

Timescales

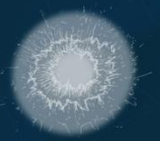
milliseconds — seconds — hours — years — billions of years

Frequency (Hz)

100 — 1 — 10^{-2} — 10^{-4} — 10^{-6} — 10^{-8} — 10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources



Supernova

Pulsar

Compact object falling onto a supermassive black hole

Merging supermassive black holes

Merging neutron stars in other galaxies

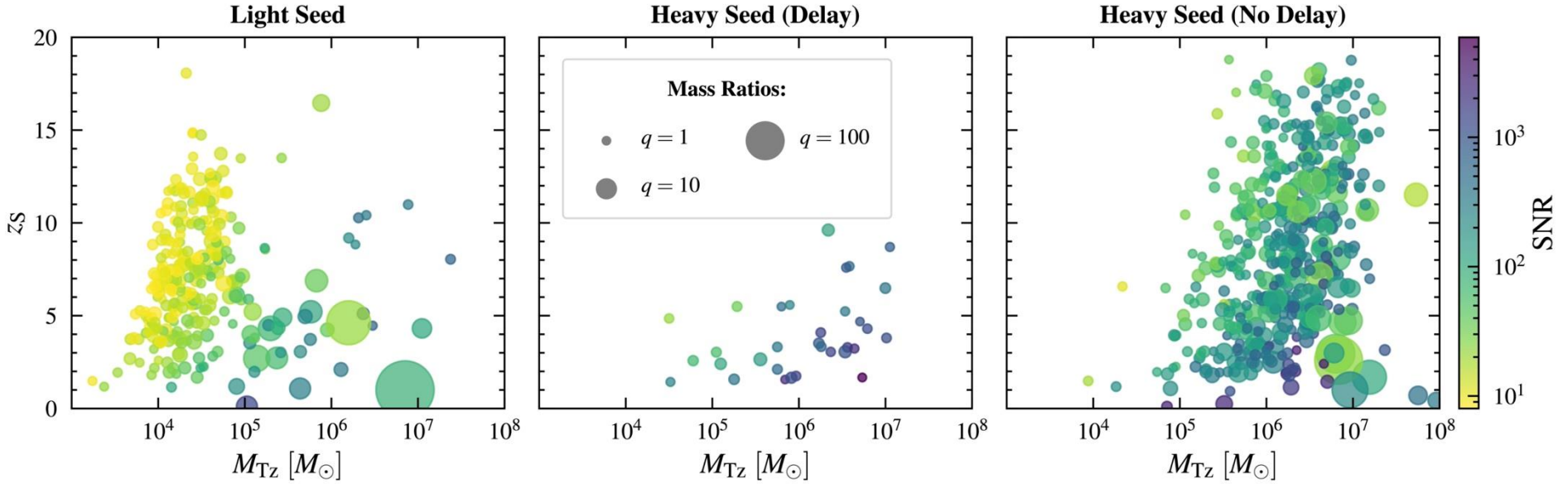
Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

ESA | NASA lisa

#lisa

SMBH rates are very uncertain

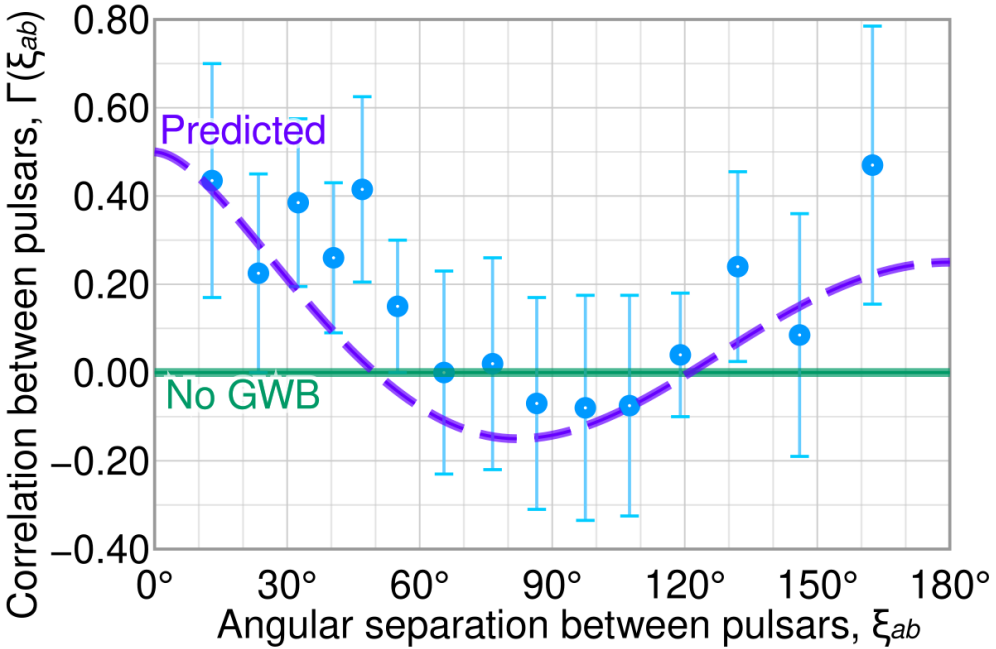


[Klein+, 1511.05581; plot from Çaliskan+, 2307.06990]

Sources: PTAs and JWST are changing our understanding of SMBHs

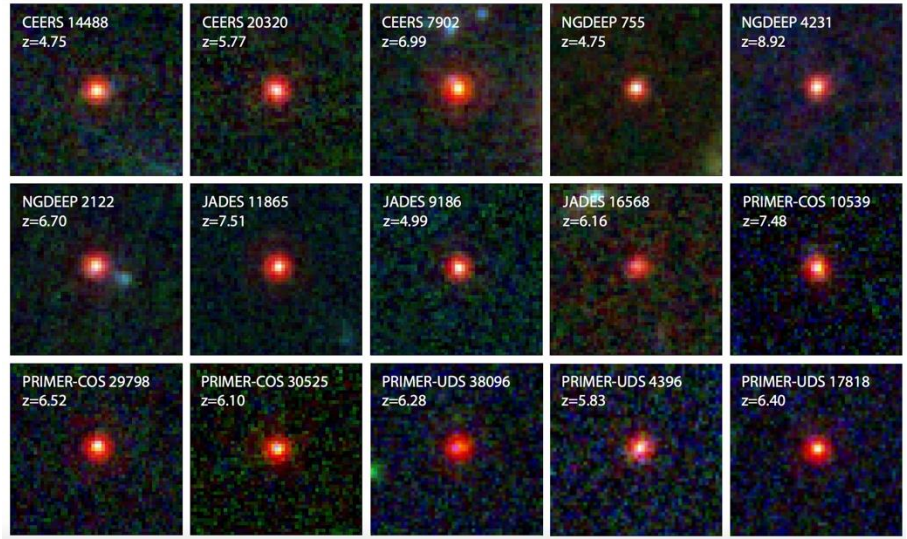
PTA implications for LISA unclear: Steinle+ 2305.05955, Barausse+ 2307.12245, Izquierdo-Villalba+ 2401.10983, Sato-Polito+ 2312.06756 and 2501.09786

High rates? Cosmological/exotic backgrounds?
Different physics driving binaries to merger?
Consistency with quasar luminosity function?



JWST: little red dots (Greene+, Maiolino+, …) and massive young star clusters at z~10 (Adamo+). Implications for seeding of LISA SMBH binaries?

Puzzling, several possible scenarios (massive seeds? Population III? Hierarchical mergers of NSCs? PBHs?)



Sources: verification binaries and WD science

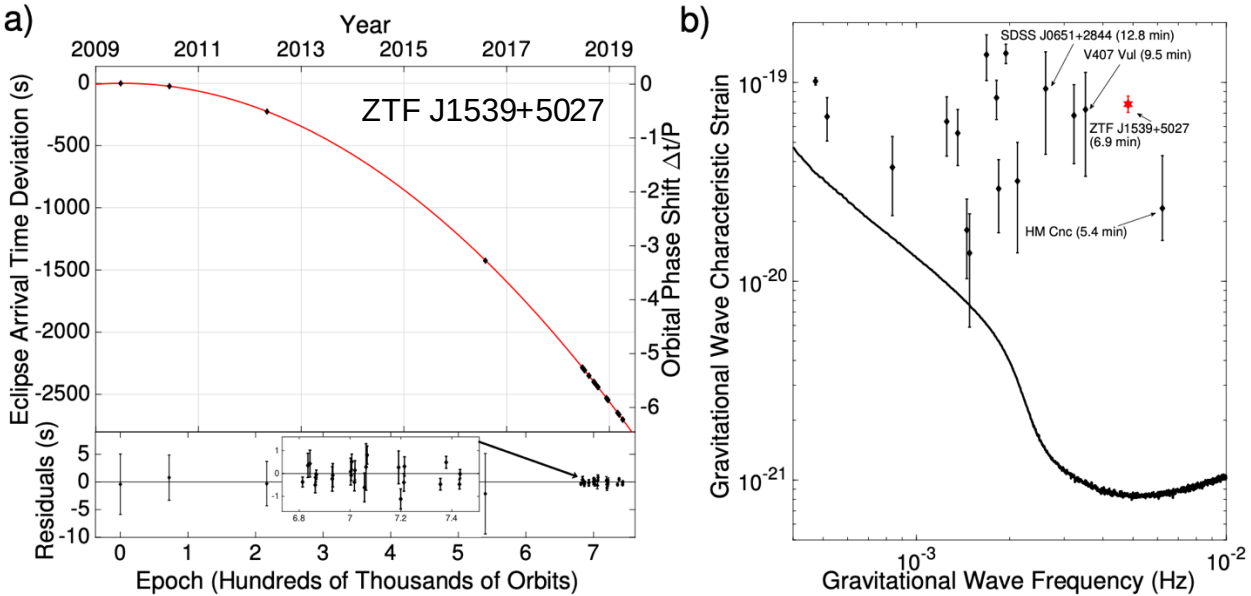
Amazing progress in finding WD verification binaries:
e.g. Burdge+ (1907.11291, *Nature,* P=7 minutes);
Finch+ (2210.10812); Gaia DR3 (Kupfer+, 2302.12719).

But see Littenberg-Lali (2404.03046): have **any** verification binaries been found? (need global fit)

Buscicchio+ (2410.08263):
DWD foreground is not Gaussian (2mHz-10mHz)

What physics/astronomy **can** we do with WD binaries?

Accretion? (Yi+, 2310.16172)
Probe Galactic potentials (Ebadi+, 2405.13109)
Milky Way Satellites? (Korol+ 2002.10462)
Fundamental physics? (Littenberg-Yunes, 1811.01093)
…



Sources: foregrounds or backgrounds? Parametrize populations?

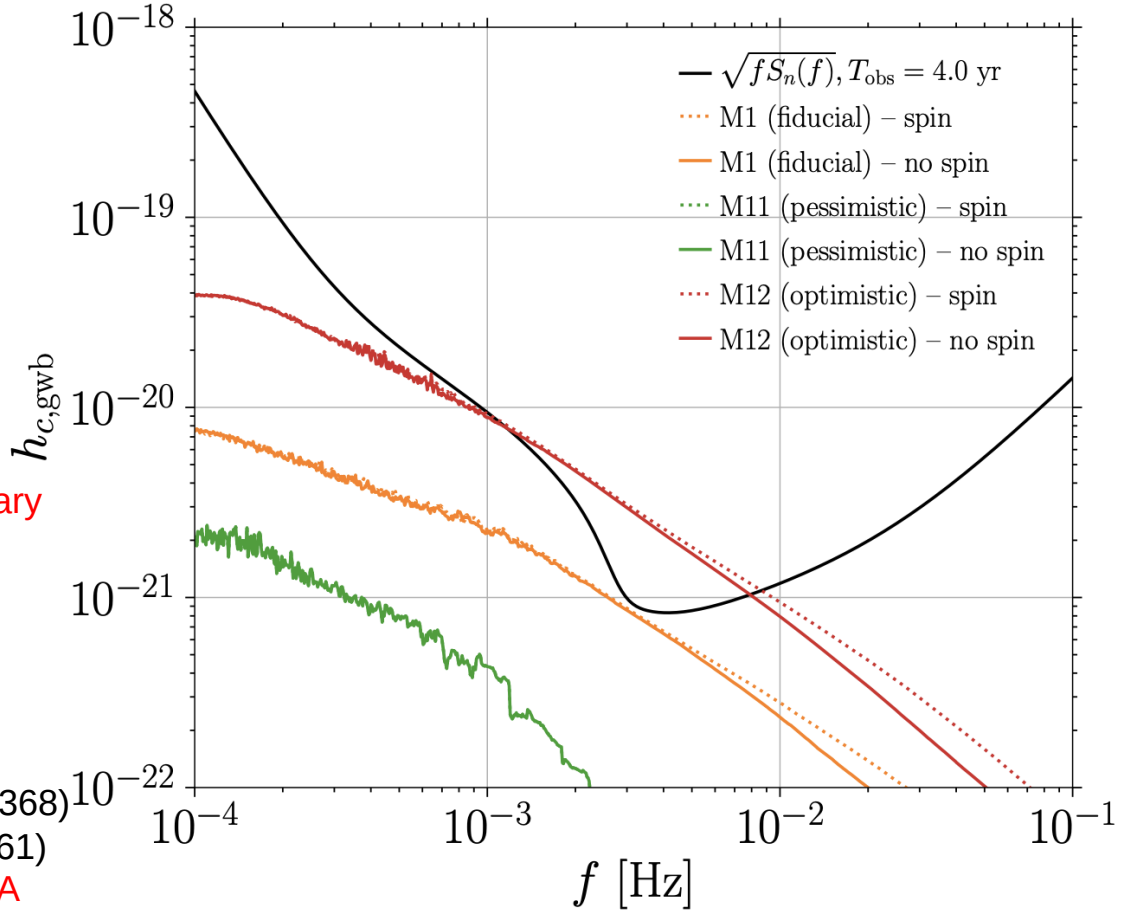
Foregrounds or backgrounds?
EMRI rates uncertain
(Babak+ 1703.09722, Rom+ 2406.19443)
New techniques in next-gen ground detectors

EMRIs:
Bonetti-Sesana (2007.14403), then
Pozzoli+ (2302.07043, 2311.12111):
EMRI SGWB estimates
Weakly parametric inference

Piarulli+ (2410.08862):
EMRI background may not be Gaussian/stationary

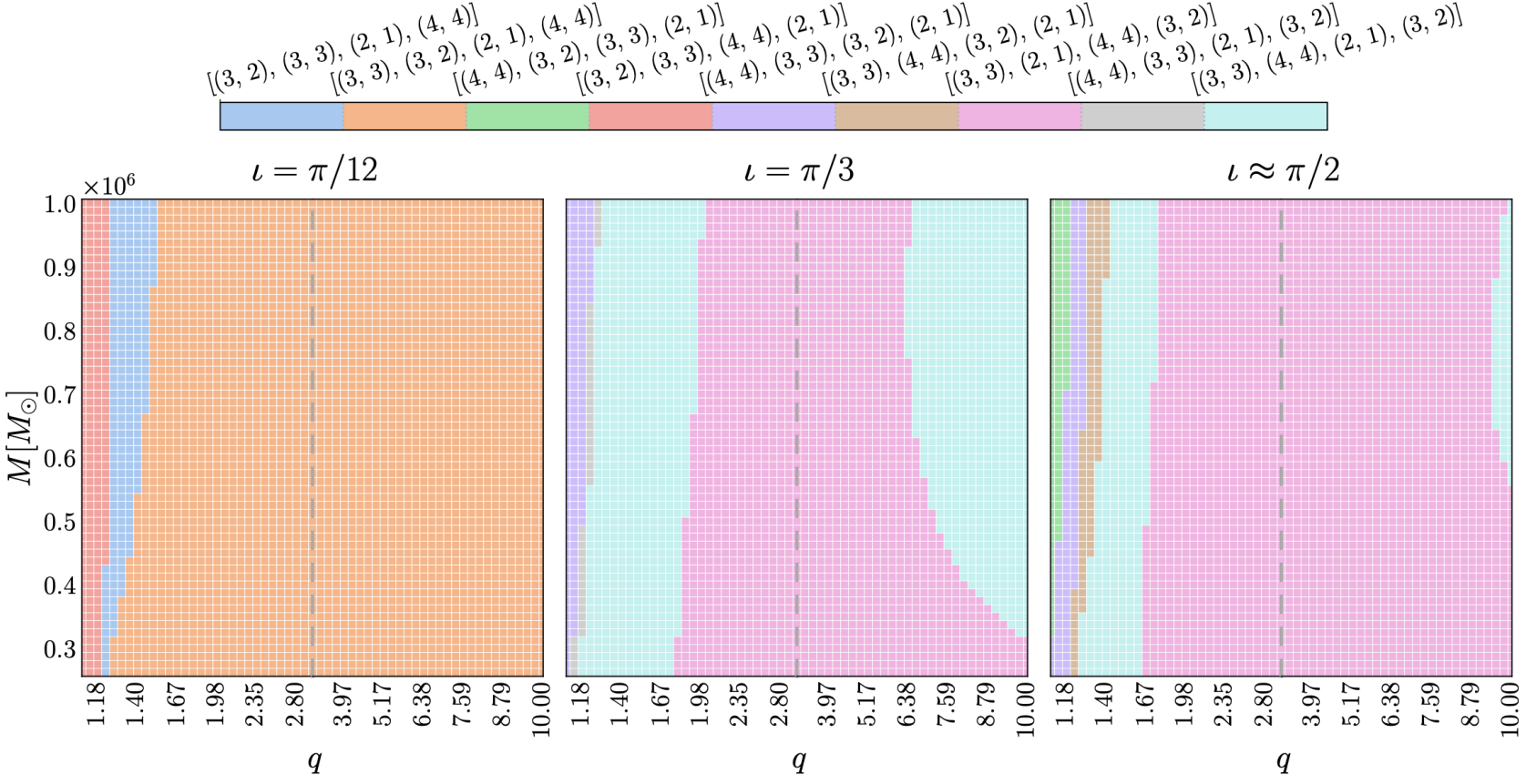
SMBHs:
PTA+JWST puzzles prompted "flexible" models
POMPOCO (Toubiana+, 2410.17916)

Stellar mass:
LIGO rate estimates of BBHs (Babak+, 2304.06368)
BBH+BNS with COMPAS (Lehoucq+, 2306.09861)
SOBBH background could be detectable by LISA



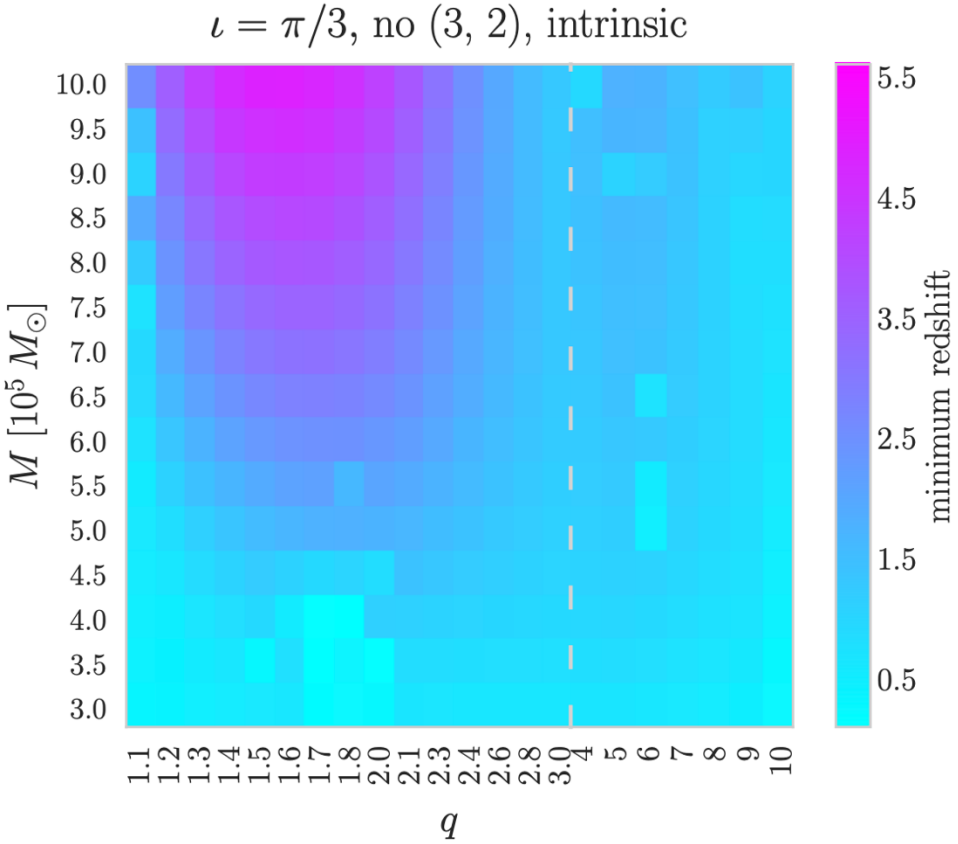
Waveform modeling: SMBHs

SMBHs: waveform systematics dominate inference! Crucial
Example: higher harmonics



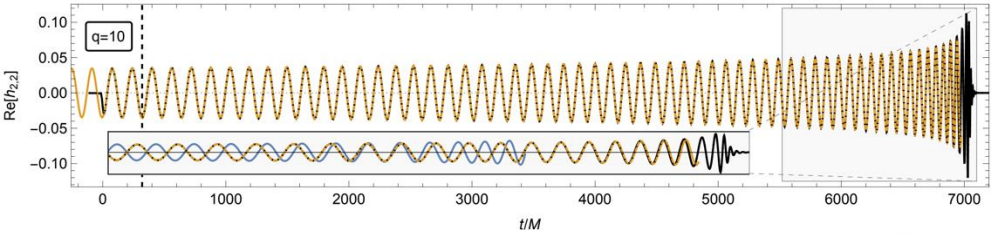
Waveform modeling: SMBHs

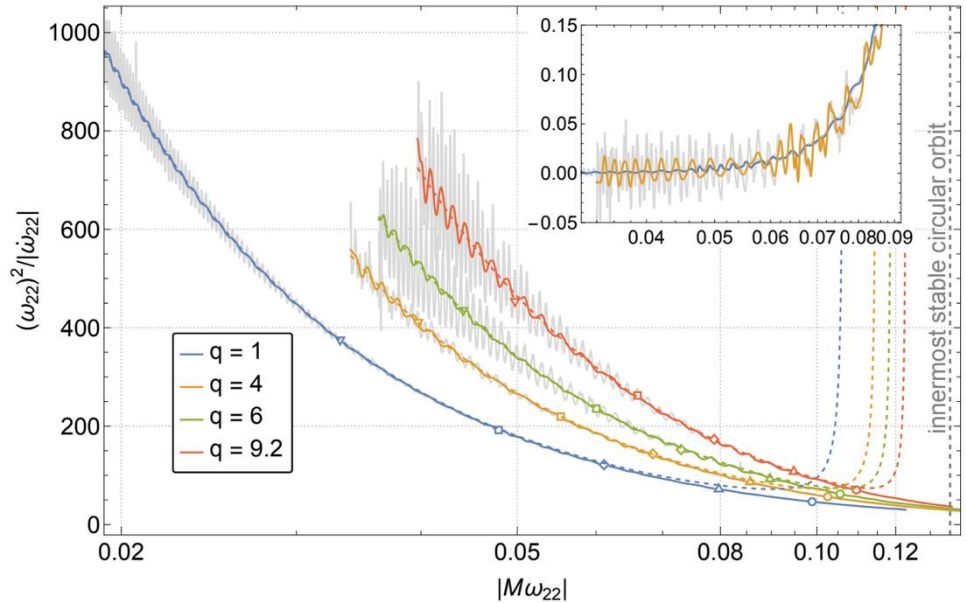
SMBHs: waveform systematics dominate inference! Crucial
See LISA Consortium Waveform Working Group White Paper (2311.01300)



Waveform modeling: EMRIs

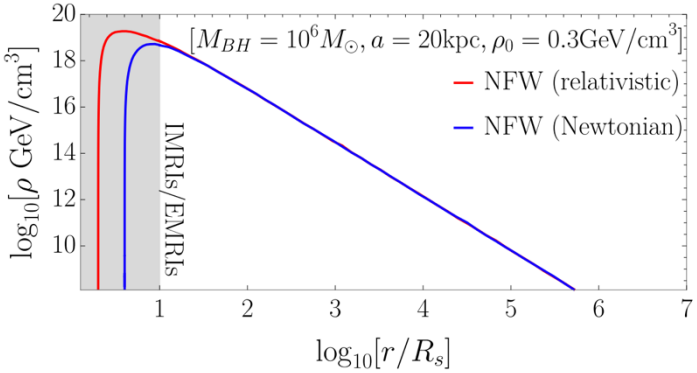
Waveform building in vacuum (CAPRA community): terrific progress on second-order self-force (e.g. Wardell+, 2112.12265)

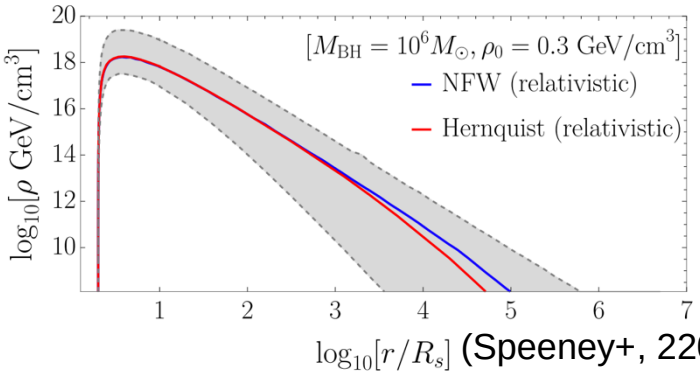




Tests of GR in environments: dark matter spikes, accretion disks, boson clouds…

Optimistic back of the envelopes, but relativistic effects matter: dynamical friction, Magnus effect…

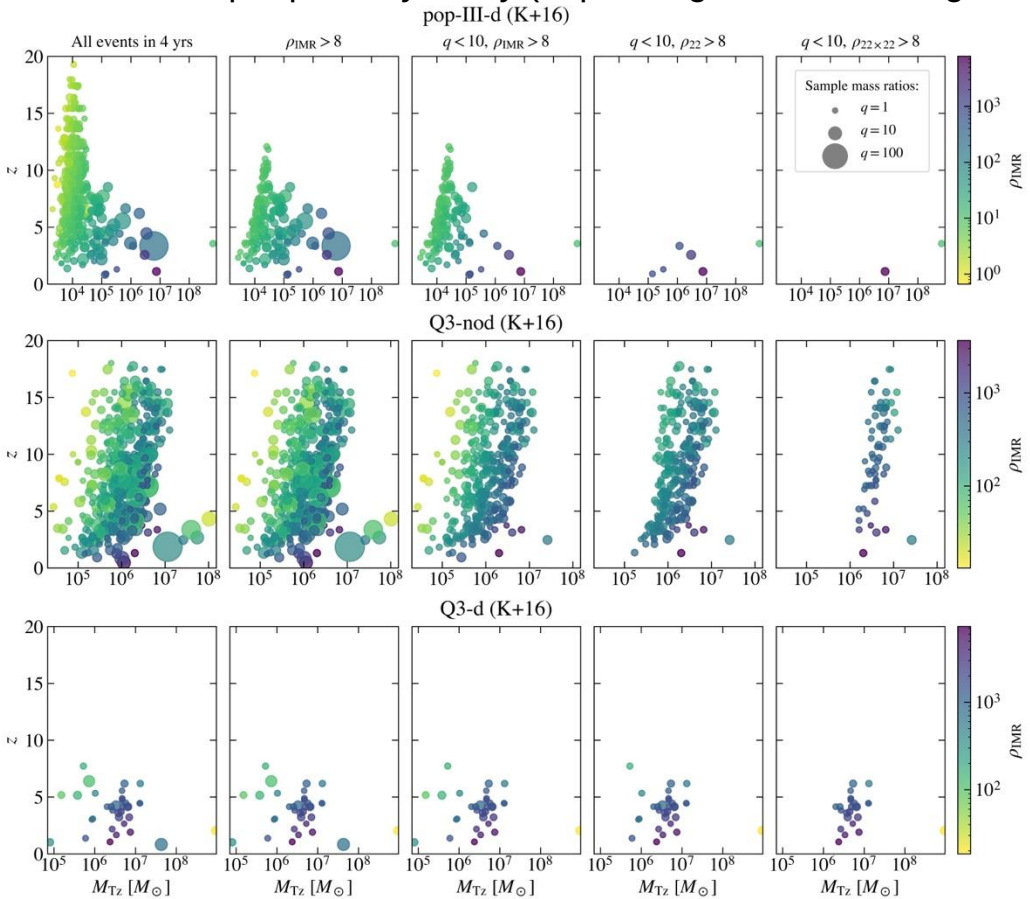




(Speeney+, 2204.12508)

Testing general relativity / fundamental physics

Nonlinear ringdown (Physics Today, big new review), gravitational memory: perhaps a few detections in Cosmic Explorer, Einstein Telescope, possibly many (depending on SMBH merger rates) in LISA



(Yi+, 2403.09767)

Data analysis / Tools

Source are dense in time and frequency: **LISA Global Fit**

Demonstrations on simulated data in LDC2A
- GLASS (Littenberg-Cornish, 2301.03673)
- Erebor (Katz+, 2405.04690, GPU accelerated MCMC)
- Modular pipeline (Deng+, 2501.10277)

SGWB recovery:
- GLASS (Rosati-Littenberg, 2410.17180)
- Saqqara (Alvey+, time-dependent noise: 2408.00832)

Software tools: **lisabeta** (Sylvain Marsat et al., upon request)
LISA Analysis Tools (Michael Katz)

LISA Figures of Merit

A very active community in Europe **and in the US.** Examples:
- 10 years to LISA @ JPL (Apr 1-3, https://science.jpl.nasa.gov/workshops/LISA/)
- LISA Sprint @ Huntsville (Apr 28-30, https://tlittenberg.github.io/lisa_sprint_2025/)
- ICERM Brown ML for GWs (Jun 2-6, https://icerm.brown.edu/program/topical_workshop/tw-25-smlgwa)
- EMRIs Global Fit (Jun 23-25, APC Paris, https://indico.in2p3.fr/event/34916/)
- …


TEN YEARS TO LISA
New Challenges and Opportunities in Multimessenger/Multiband Science
The 3rd LISA Sprint
April 28–30, 2025 | Huntsville, AL

Conclusions

Exciting times!

Sources:

SMBH mergers: major changes in our understanding from PTAs and JWST
WD binaries: ZTF/Gaia are changing our understanding of verification binaries and background
EMRIs: rates as uncertain as ever - additional background?

Theory:

SMBHs: waveform systematics dominate if we want to do test GR or do multimessenger astronomy
EMRIs: great progress on waveform modeling, possible probes of dark matter/astrophysical environments

Data analysis:

Big ongoing effort to solve the global fit/cocktail party problem, look for SGWBs
Multiple codes/tools, some public

Get involved! Join the reorganized LISA Consortium