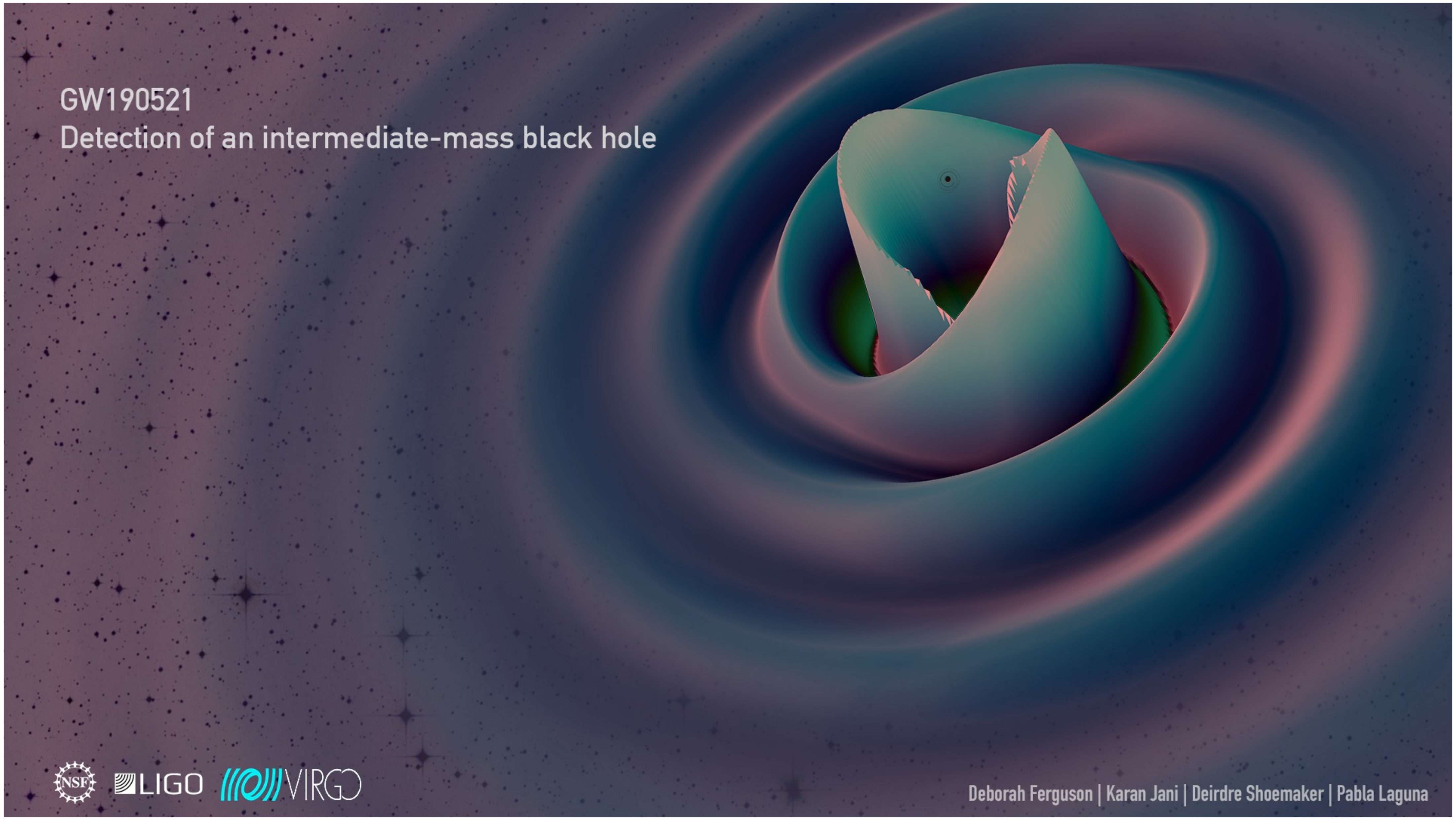
NUMERICAL RELATIVITY AND THE NEXT GENERATION OF GRAVITATIONAL WAVE DETECTORS

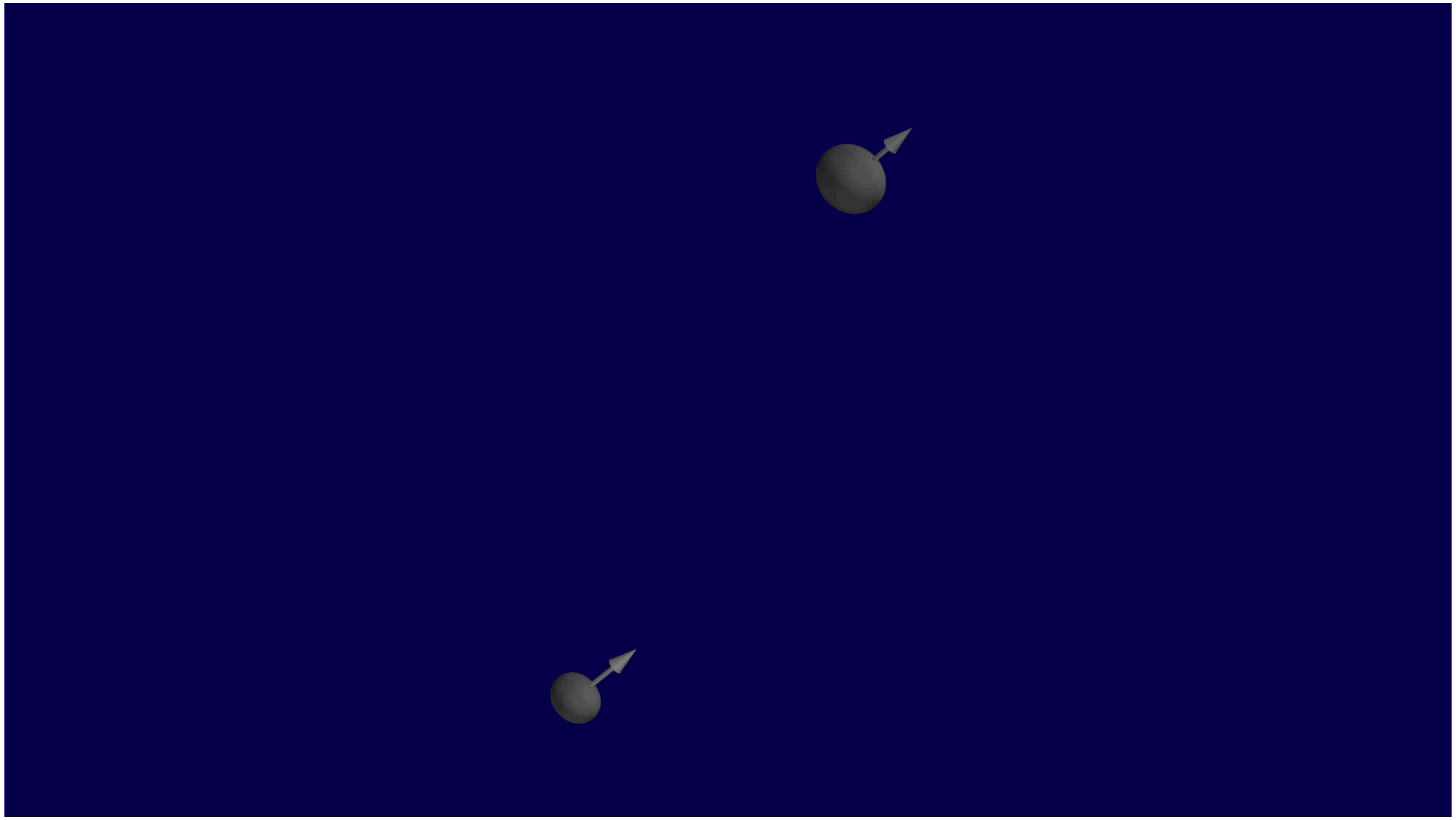


Deirdre Shoemaker
Center for gravitational physics
University of Texas at Austin

CGP
CENTER FOR GRAVITATIONAL PHYSICS

GRAVITATIONAL PHYSICS DRIVEN BY DATA

- Gravitational wave astronomy has just begun
- Future prospects of ground and space gravitational wave detectors provides incredible opportunities for astronomy and physics
- The future also places demands on the theory that predicts and interprets the waveforms
- Opportunity to use innovative data science and computing

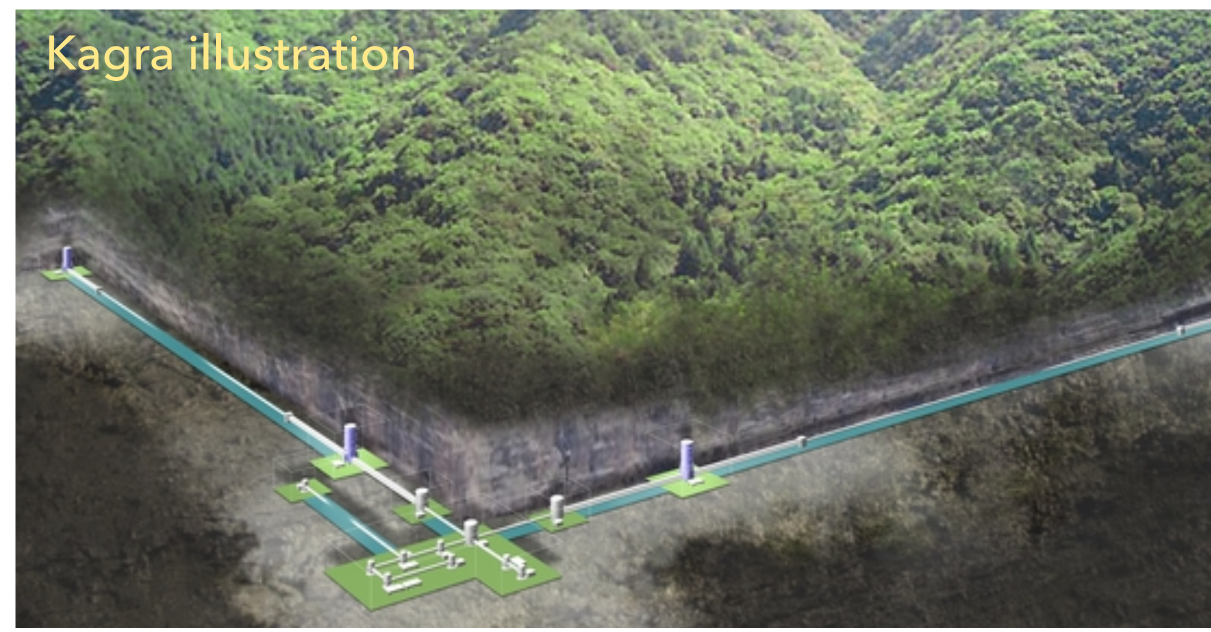


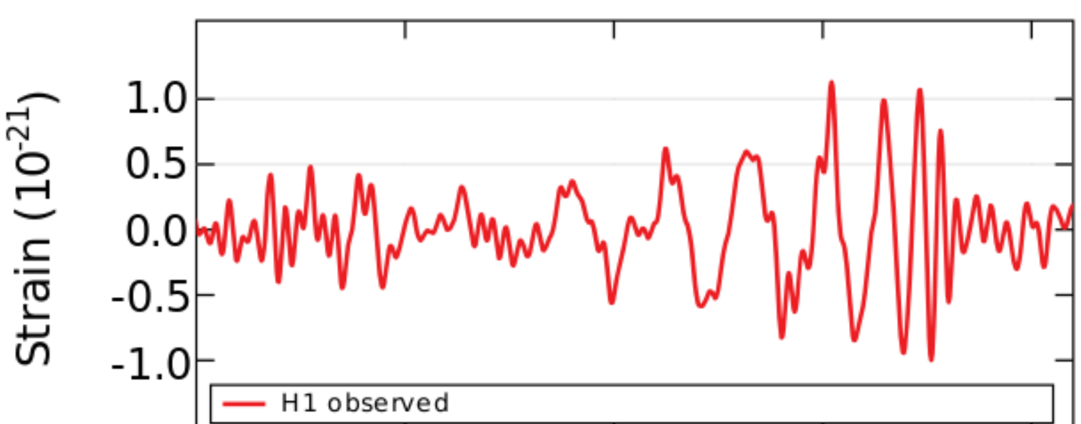
SCIENCE DRIVERS

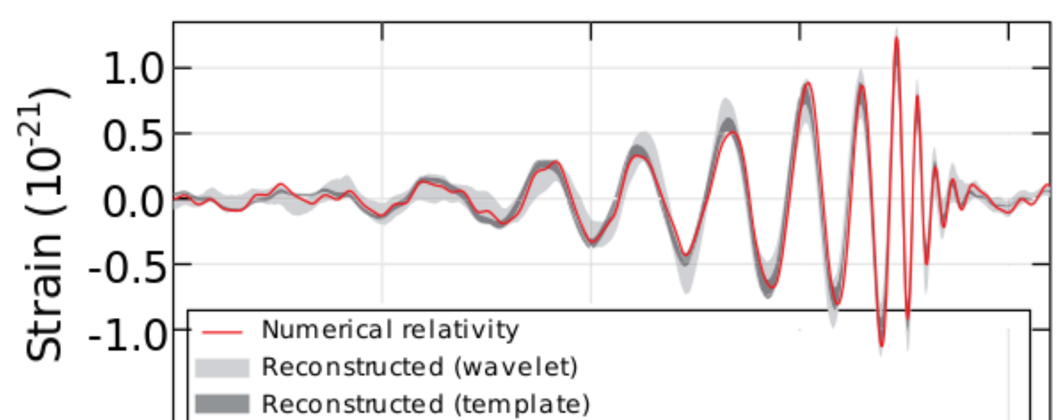
- Is Einstein’s theory the theory of gravity?
- Measure and study black holes at all mass scales
- Probe neutron stars
- Discovery engines of the universe (gamma ray bursts, active galactic nuclei)
- Formation history of black holes and galaxies
- Probe the early universe
- Measure the gravity near a black hole
- …

Discovery puts incredible demands on experiment, theory, data analytics, and computing.

TODAY'S GRAVITATIONAL WAVE LANDSCAPE







THEORETICAL LANDSCAPE

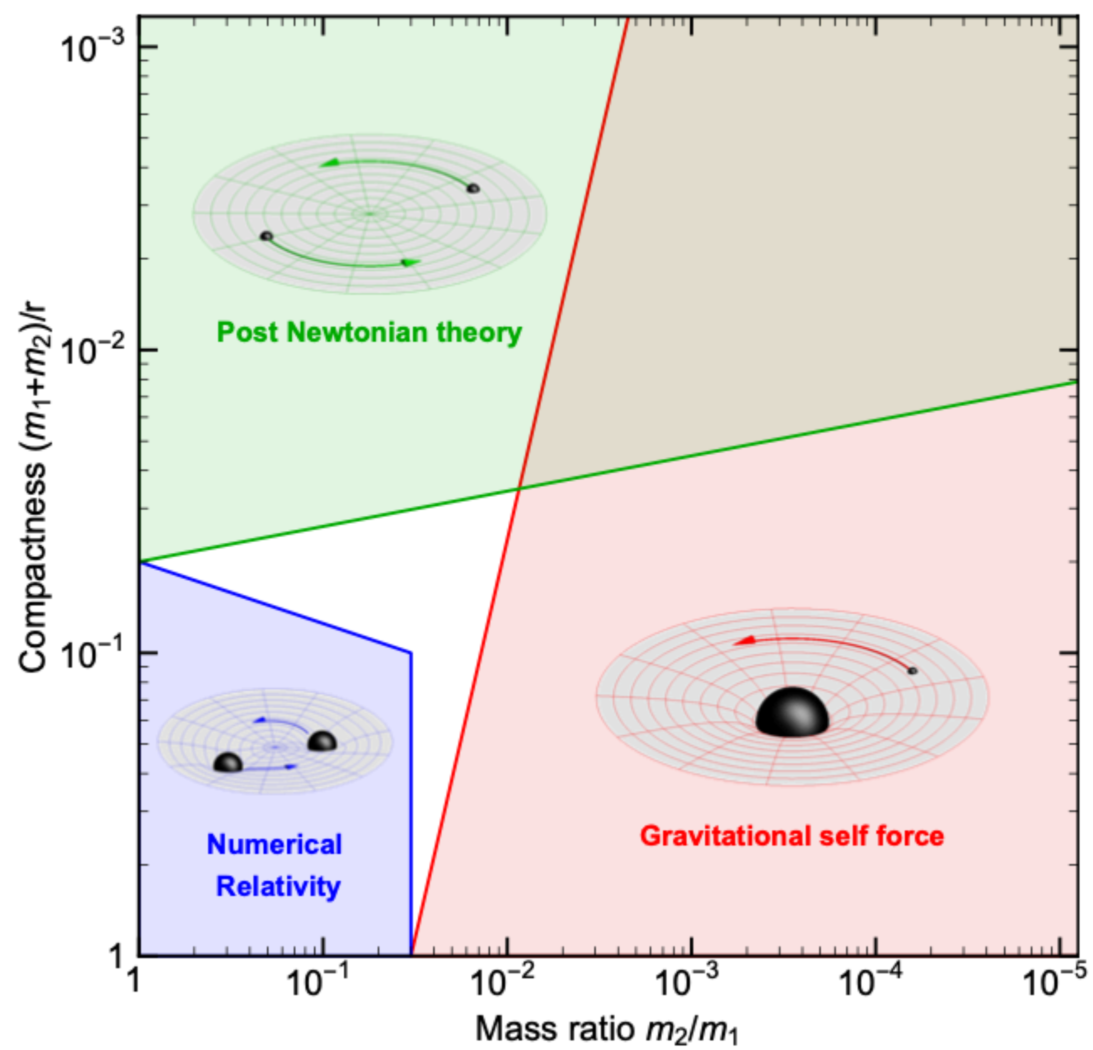
Post-Newtonian

Perturbation

SELF-FORCE NEGLIGIBLE

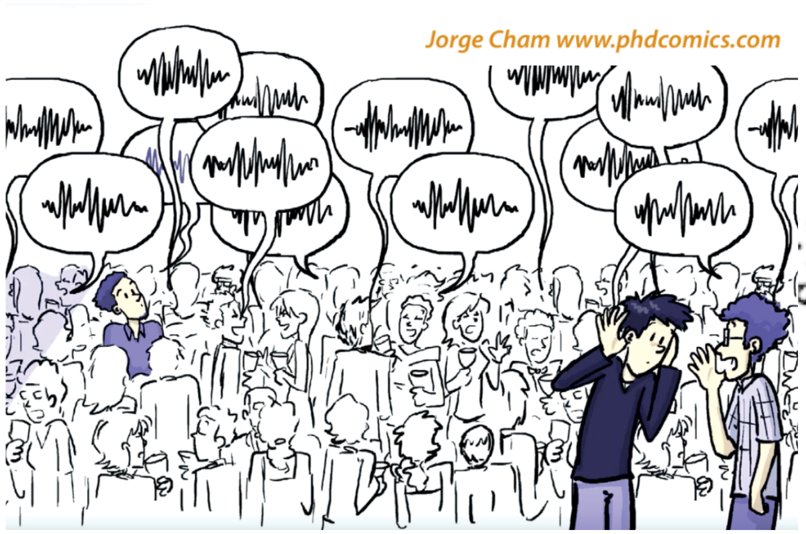
Numerical relativity

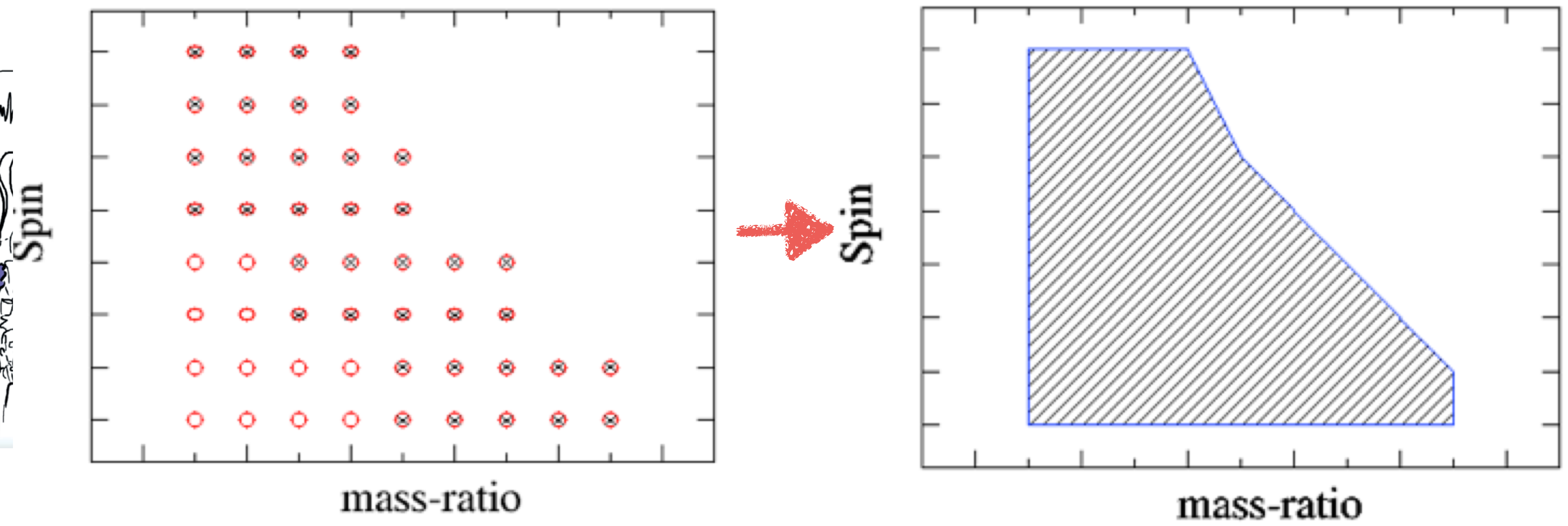
FULL GR

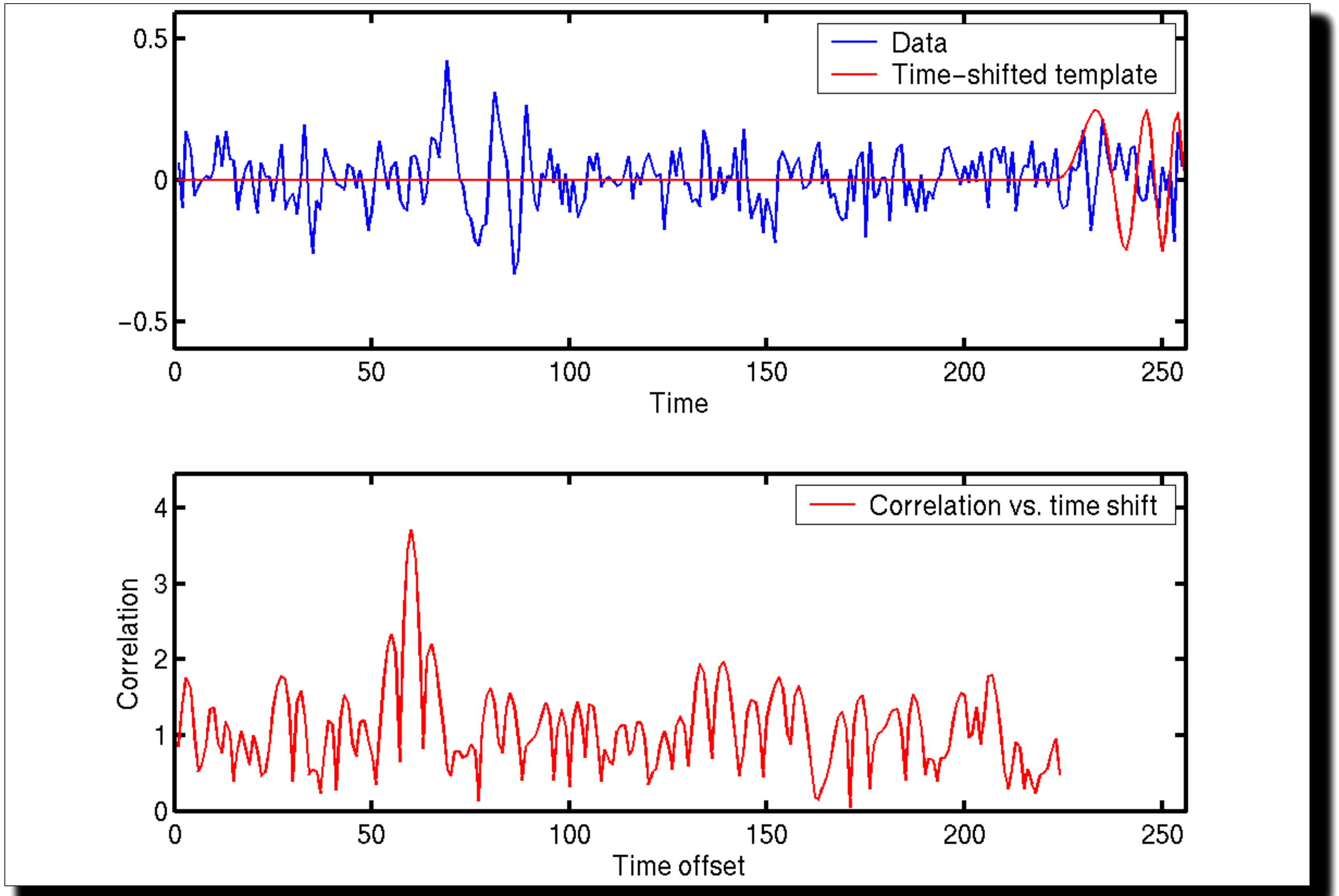


Courtesy M. van de Meent

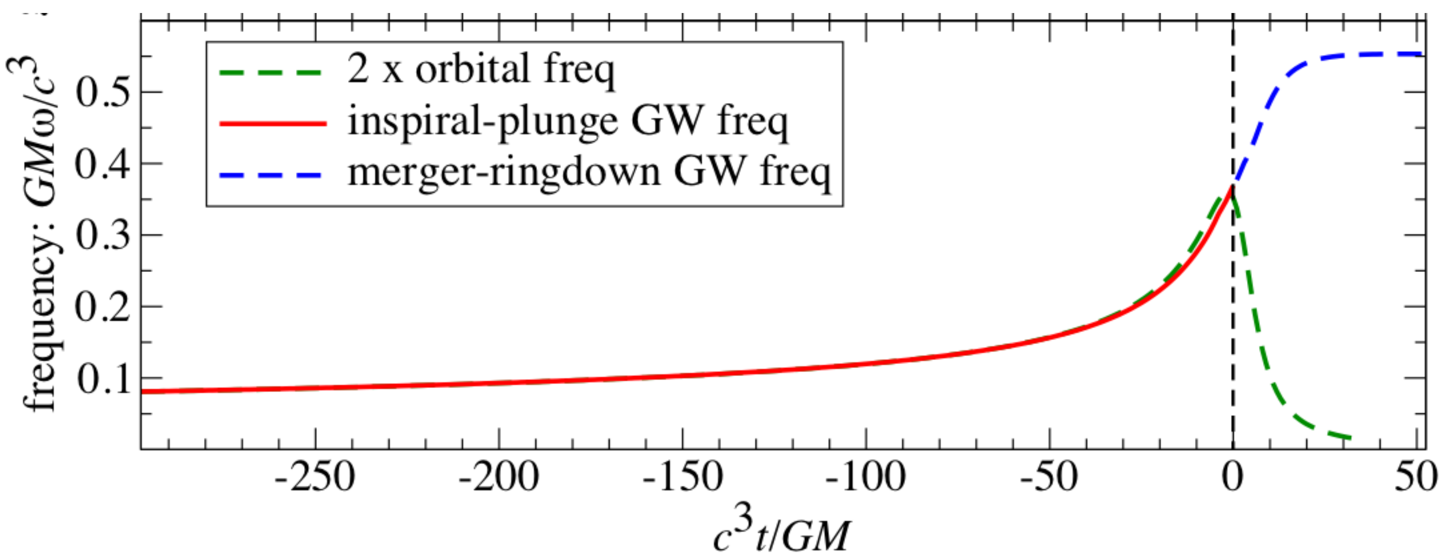
WAVEFORM TEMPLATES

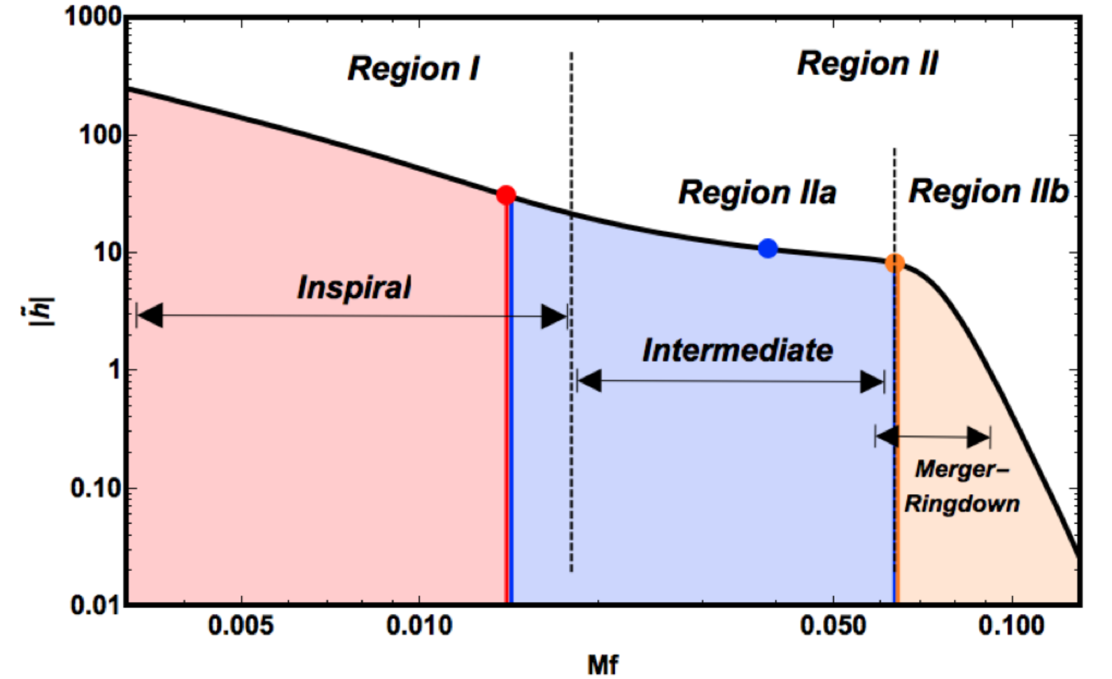






NR CONTRIBUTES TO AND GUIDES GRAVITATIONAL WAVE ASTRONOMY



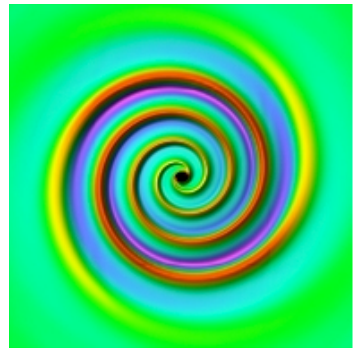


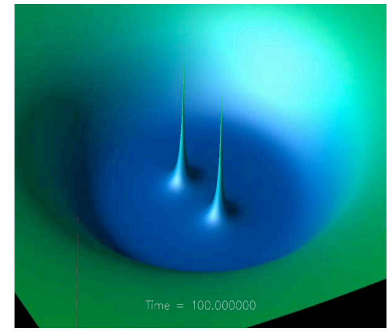
- Direct comparison to GW data (Lange et al and others)
- Modeled Waveforms of Phenom series and EOBNR series (Buonanno et al 2007, Ajith et al 2007)
- Testing GR, including fit from initial parameters to final BH parameters (Lousto et al, Rezzolla et al)
- Matter (Neutron Star equation of state, Supernova…) See almost every talk at this conference

I will focus on binary black holes

NUMERICAL RELATIVITY

2005 Pretorius
Binary inspiral and merger

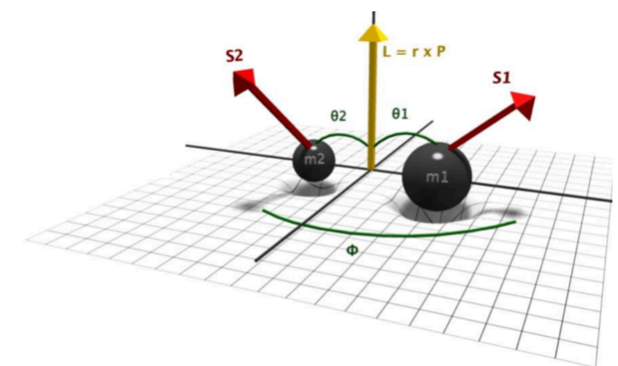




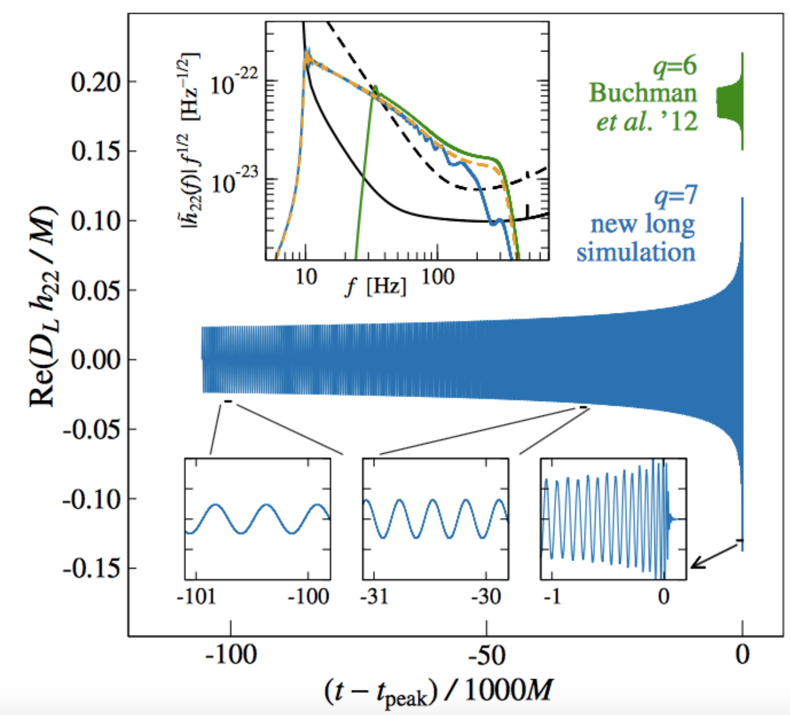
2006 RIT and NASA
Moving Punctures Method

Campanelli, Lousto, Zlochower
Phys.Rev.Lett. 96 (2006) 111101

Baker, Centrella, Choi, Koppitz, van Meter
Phys.Rev.Lett. 96 (2006) 111102



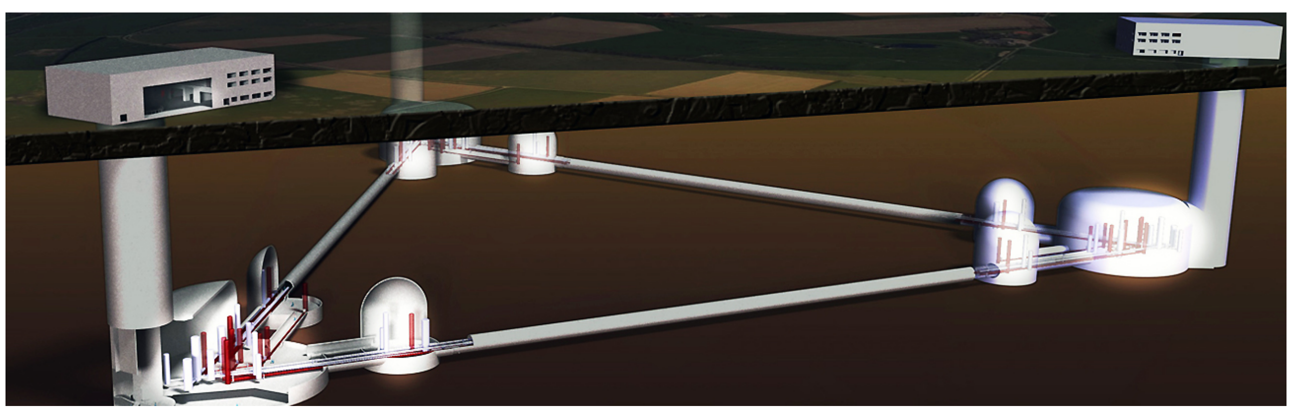
- Solves the Einstein equations - coupled, non-linear set of hyperbolic partial differential equations as initial value problem
- Solves initial data are set of elliptic equations
- Takes weeks to months on Frontera like machine, communication bound (does not scale well beyond 1000 processors)
- Several NR codes
- Many Formulations: BSSN and Generalized Harmonic and their associated gauge conditions
- 2 singularity avoidance: excision and punctures
- Public Waveform Catalogs: Maya (einstein.gatech.edu/catalog), SXS (black-hole.org), and RIT (ccrg.rit.edu)
- Waveform modeling uses fits to NR

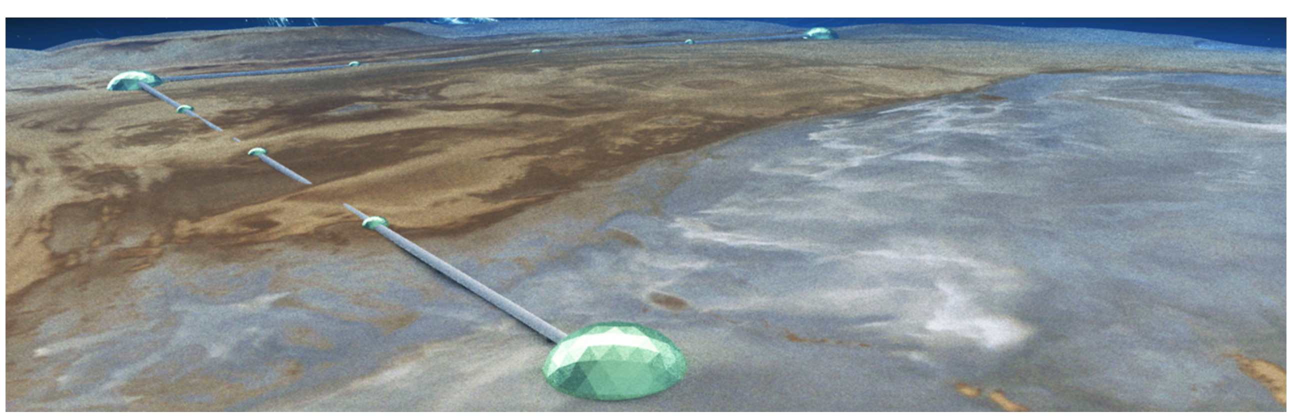


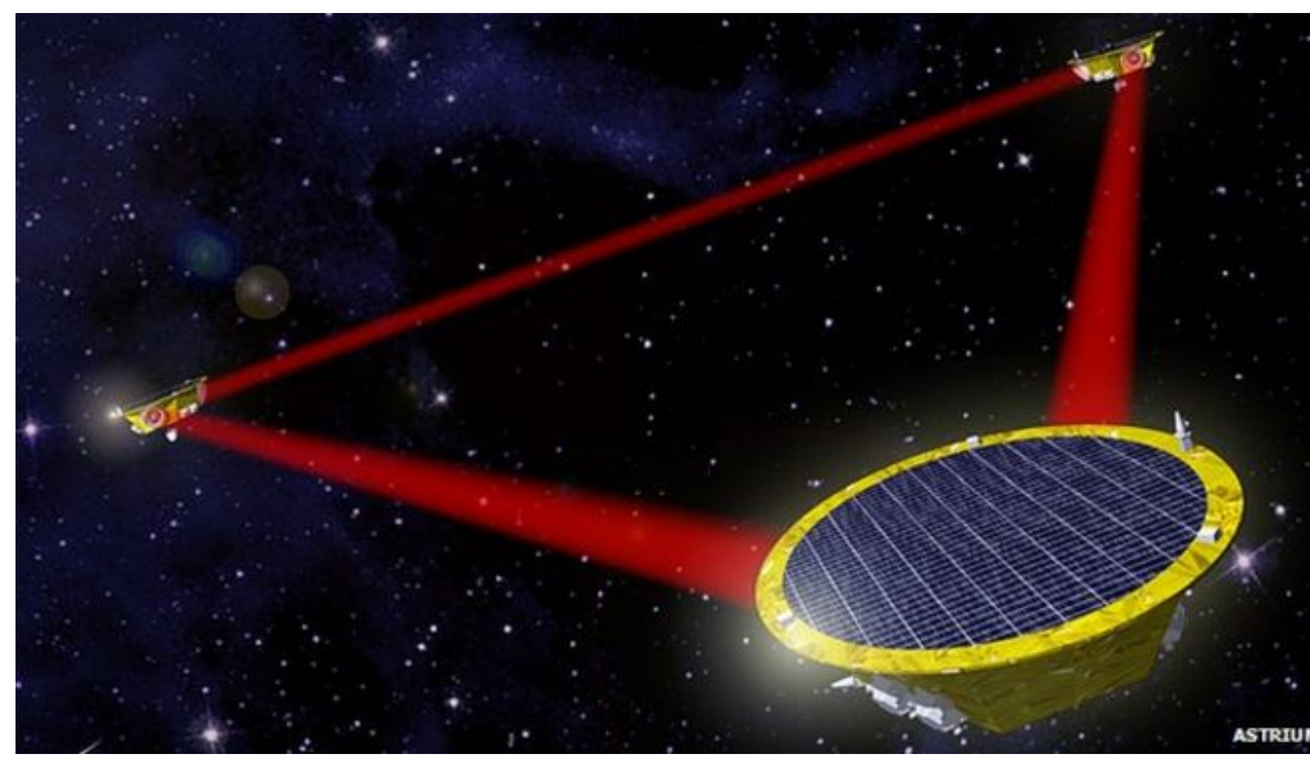
FUTURE GRAVITATIONAL WAVE DETECTORS

- Advanced LIGO Plus (A+): An incremental upgrade to aLIGO, x5 greater event rate than advLIGO
- Einstein Telescope: European, underground 10 km arm length in triangle
- Cosmic Explorer: US, LIGO Voyager technology expanded to 40 km arms
- LISA: ESA lead space mission, 2.5 million km arms triangle design

DAWN Workshop happening now





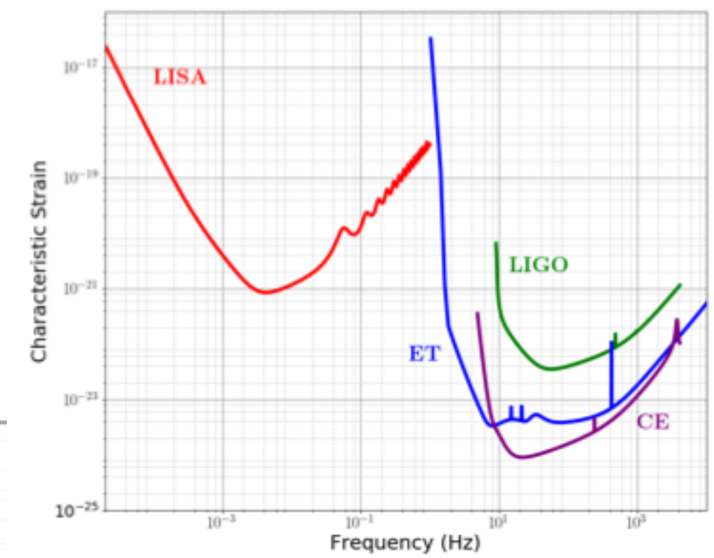


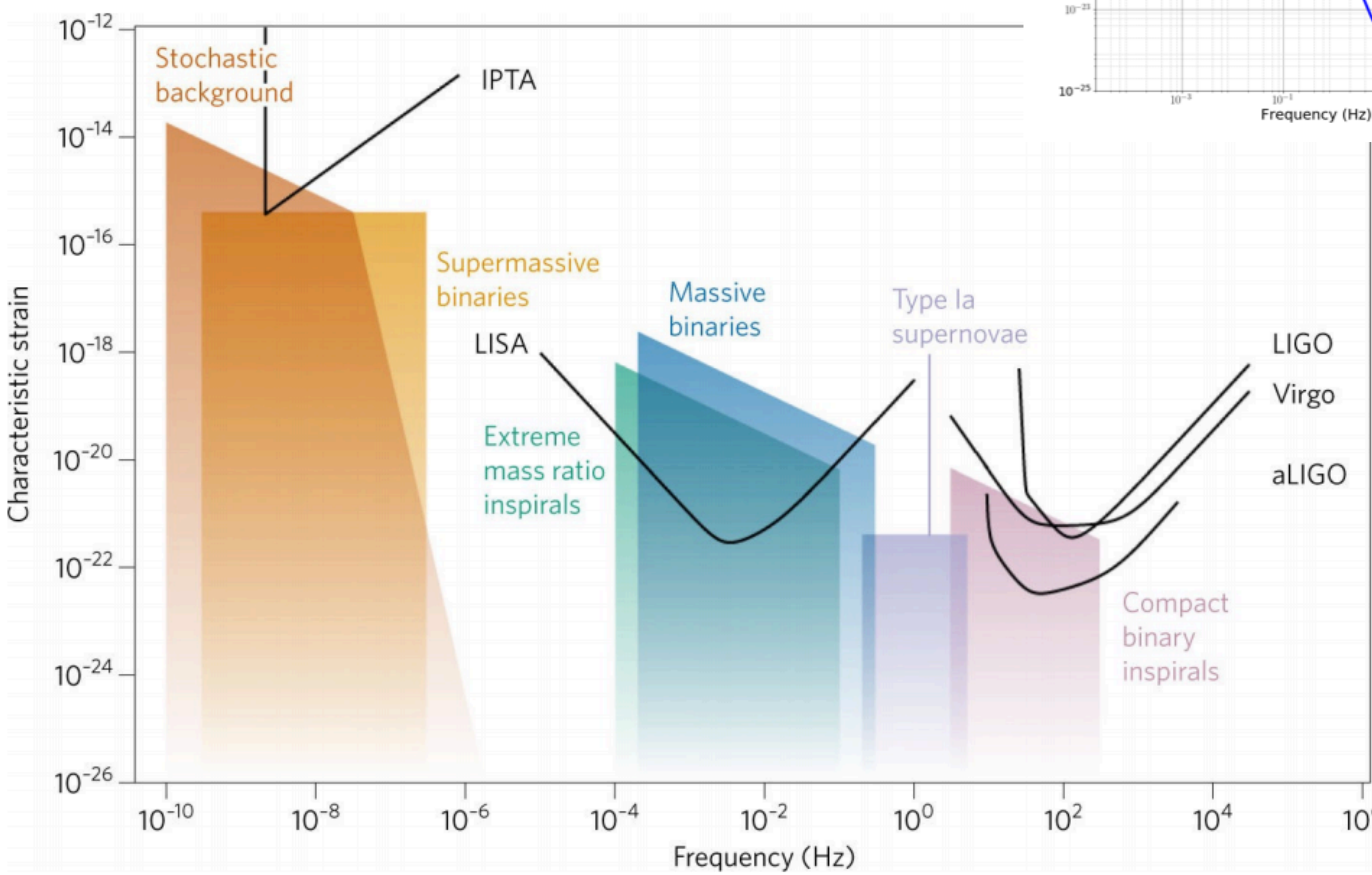
DEMANDS OF GW FUTURE

1. Different/broader frequency ranges

2. High signal-to-noise ratios

3. Multiple signals





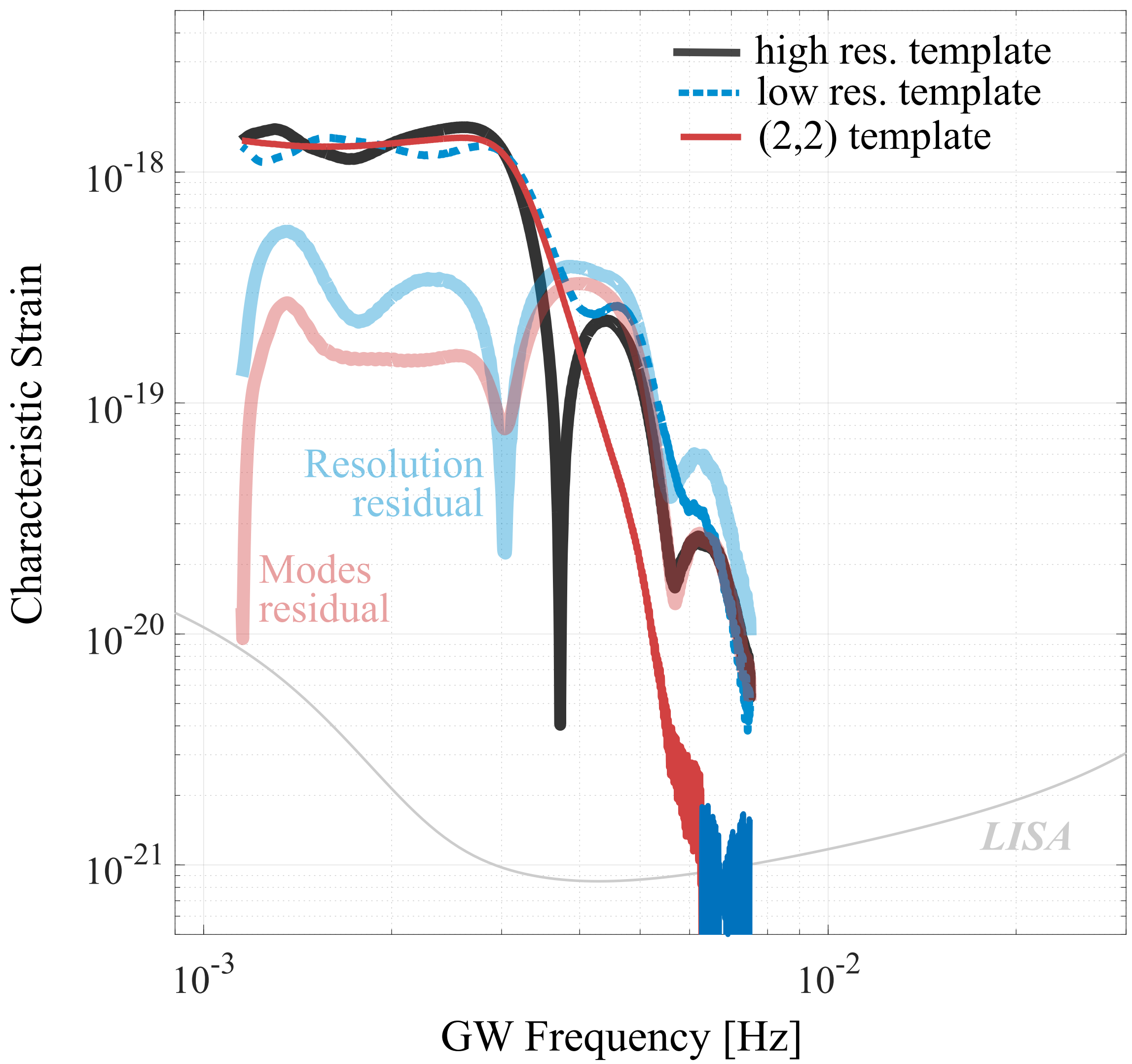
DEMANDS OF GW FUTURE

1. **Different/broader frequency ranges**
    - adds potential sources (supermassive black hole mergers, intermediate mass ratio, extreme mass ratio inspirals, galactic white dwarf binaries, …)
    - increases length of signal in band
    - observe early universe
2. **High signal-to-noise ratios**
    - game changer for precision tests of GR and accuracy of parameter estimation
    - increases the accuracy necessary from waveform models
    - increases the length of time for computing models and data analysis
3. **Multiple signals** - challenge for data analysis (global fit)

Preparing for the future

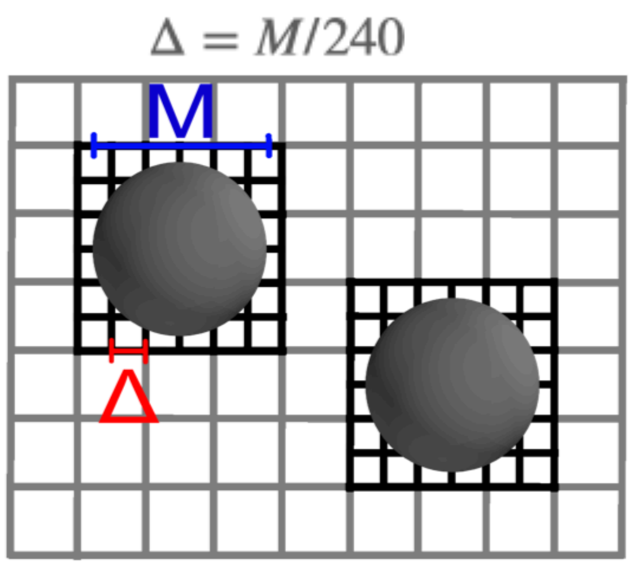
- Indistinguishable: want waveform errors to be less than the noise
- In 3G, mismatch of the models needs to be reduced by three orders of magnitude (Pürrer and Haster 2019)
- In aLIGO, 3G and LISA, NR errors are significant as SNR increases (specifically for resolution in Ferguson et al 2021)

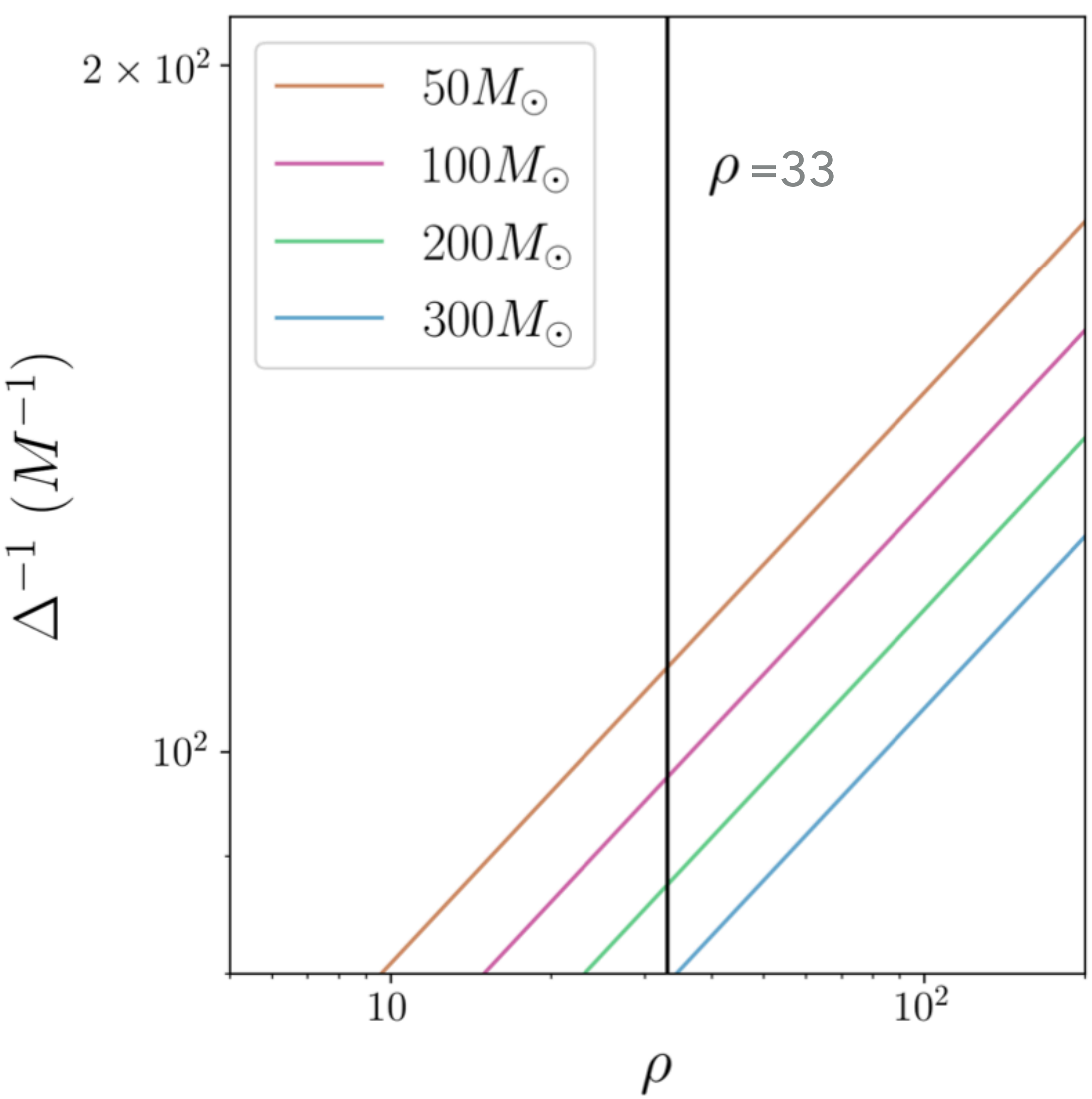
q=6, a=0.2, inclination=15



Ferguson et al 2021

HOW TO ASSESS ACCURACY





Well known criterion between two waveforms

$$\langle \delta h | \delta h \rangle < 1$$

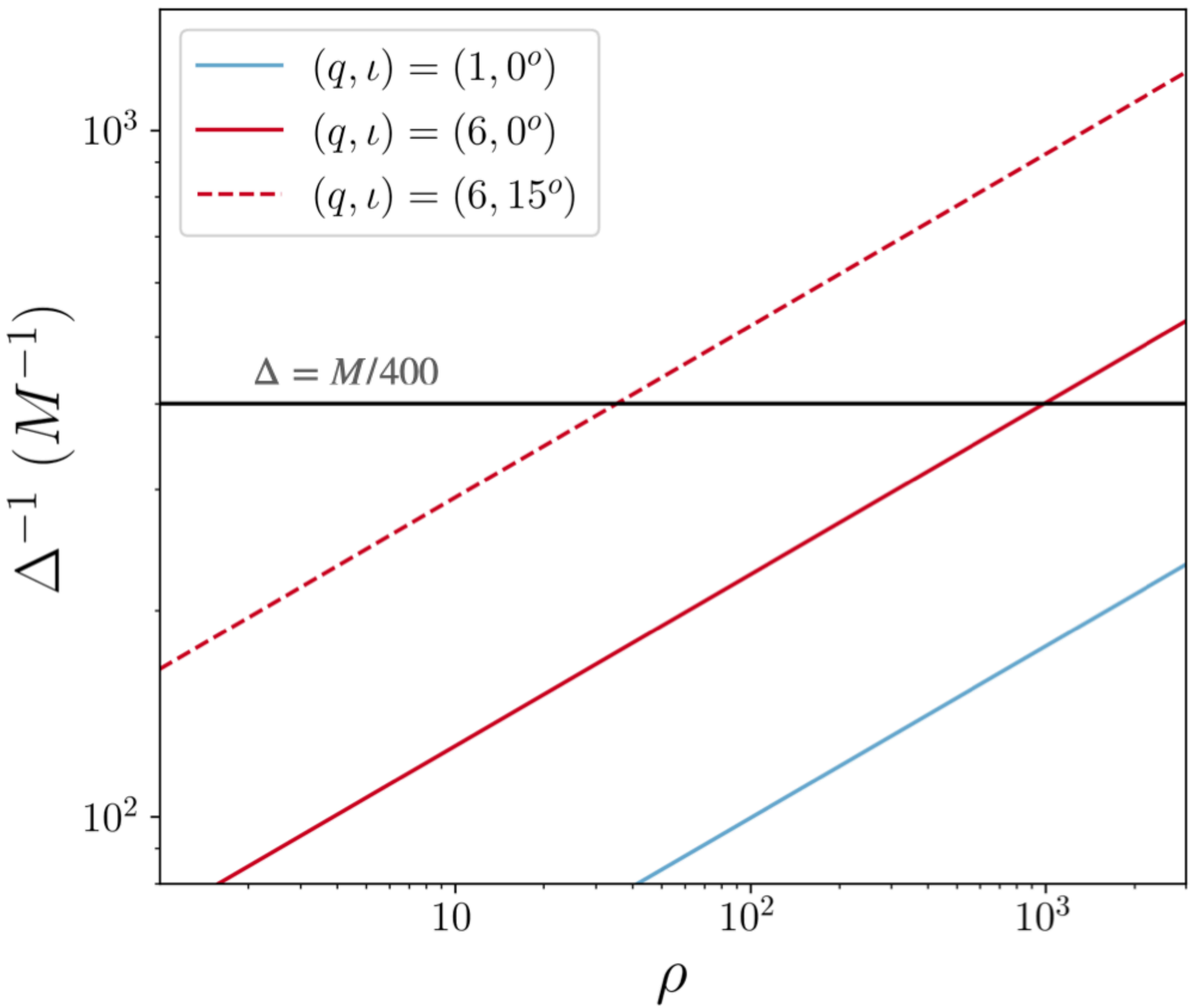
We find a new measure for indistinguishability using

- one finite resolution waveform and a Richardson extrapolated waveform with a convergence rate α
- determine β from the match between the waveforms $\epsilon[h_1, h_2] = \frac{\beta^2}{2}\left(\Delta_2^\alpha - \Delta_1^\alpha\right)^2$

$$1/\Delta < (\rho\beta)^{(1/\alpha)}$$

Ferguson et al 2021

LISA



$(q, \iota) = (1, 0^o)$
$(q, \iota) = (6, 0^o)$
$(q, \iota) = (6, 15^o)$
$\Delta = M/400$
$\Delta^{-1}\ (M^{-1})$
10^3
10^2
10
10^2
10^3
ρ

CHALLENGES FOR NUMERICAL RELATIVITY

- Faster, more efficient (scaling) codes to achieve 100s of cycles and high mass ratios
- Accuracy for high signal to noise
- Determine how to set accuracy requirements
- Go back to fundamentals to ensure no physical errors remain

EXPLORING

- GPUs
- Parallelism (task, …)
- Differencing schemes (implicit, …)
- Machine learning - noise, parameter estimation, NR?
  See Irene's talk

Challenges for BBH Numerical Relativity in future Gravitational Waves

“Solved”	Challenging
• Non-spinning, mass ratios q<15 (Jani et al, Healy et al, Mroue et al, Boyle et al, Gonzalez et al) and some up to 128 (Lousto et al)	• Faster, more efficient codes to achieve 100s of cycles and high mass ratios
• Moderate random spins for q<8 (Jani et al, Healy et al, Mroue et al) aligned spins up to 0.85, q<18 (Husa et al, Khan et al), q=1, aligned up to 0.99 (Zlochower et al, Scheel et al)	• Accuracy for high SNR and lots of harmonics
• Eccentric for q<10 (Hinder et al, Huerta et al, Gayathri et al)	• Means to set accuracy requirements
• Order tens of orbits (Szilágyi et al)	• Beyond GR to the point where we have waveforms (See Helvi’s and Luis’ talks)
• Harmonics up to ~l=6	• Eccentricity
	• Better gauge and extraction

Example from white paper
Preliminary & Incomplete Table of NR Codes

Code	Open Source	Waveform catalog	Formulation	Hydro	Beyond GR
SpEC	No	Yes	GHG	Yes	Yes
SpECTRE	Yes	No	GHG	Yes	No
LazEv	No	Yes	BSSN+CCZ4	No	No
Einstein Toolkit	Yes	Yes	BSSN	Yes	?
MAYA-ETK	Yes	Yes	BSSN	No	Yes
GR-Athena++	Yes	No	Z4c	Yes	No
SACRA-MPI	No	Yes	BSSN+Z4c	Yes	No
BAM	No	Yes	BSSN/Z4c	Yes	No
BAMPS	No	No	GHG	Yes	No
GRChombo	Yes	No	BSSN+CCZ4	No	Yes
ExaHyPE	Yes	No	CCZ4	Yes	No
Simflowny	Yes	No	CCZ4	Newtonian	No
SPHINCS_BSSN	?	No	BSSN	SPH	No
Dendro-GR	Yes	No	BSSN	No	No
NRPy+/SENR	Yes	No	BSSN	Yes	No

This PRELIMINARY Table will be published in the LISA Waveform Working Group WhitePaper

IN SUMMARY

- Gravitational wave detectors will steadily improve on the ground and will be launched in space
- Improving detectors
  - opens the door to discovery with better sensitivity and detection volume
  - increases the requirements on the waveforms
- Numerical Relativity has a pivotal role to play in the future
- We are laying the ground for achieving the science objectives now

Exciting times for NR and GW.

$$h_i = h + \delta h_i.$$

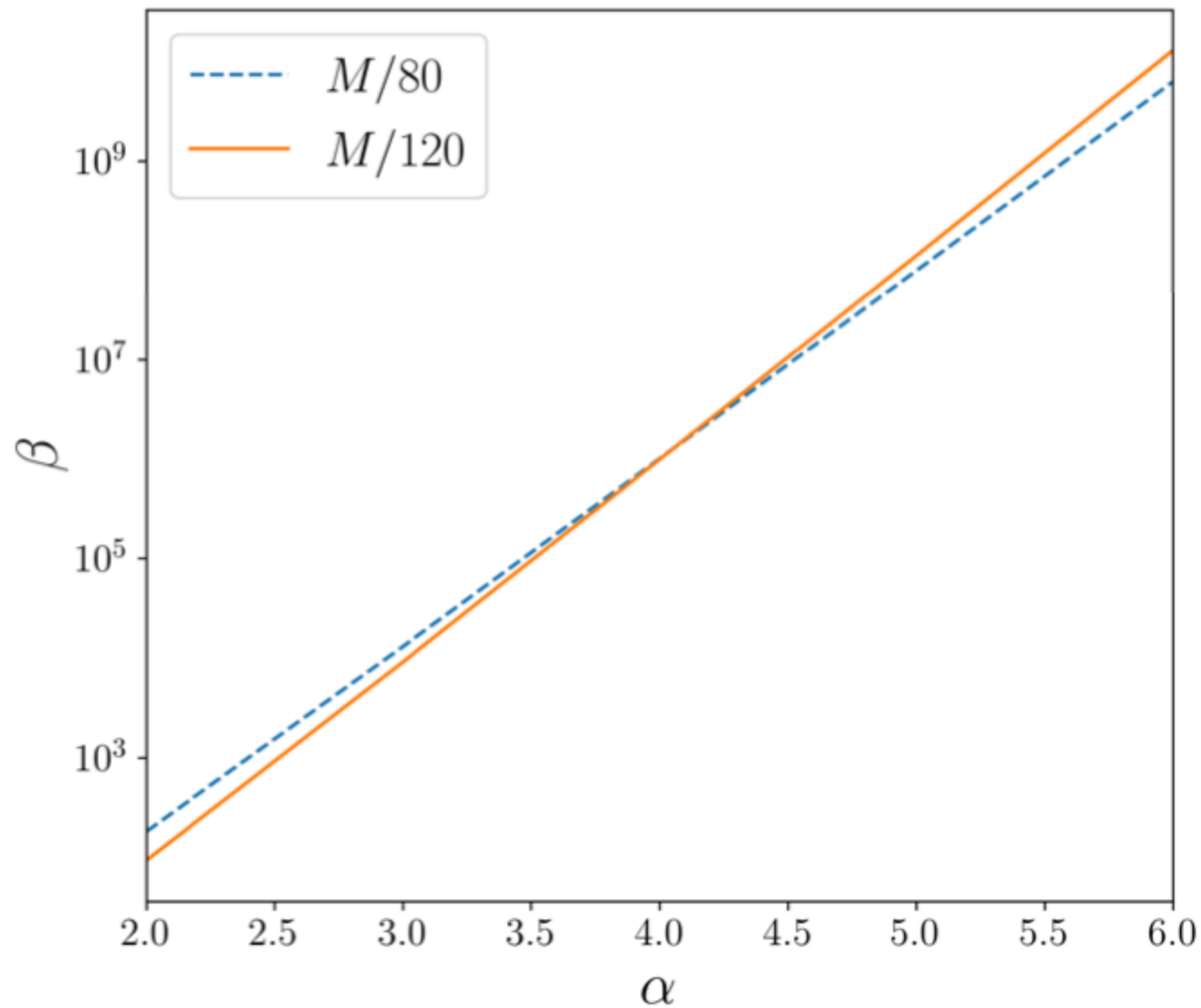
have $\delta h_i = c\,\Delta_i^\alpha$. Here α is the convergence rate of the code, c depends on derivatives of h, and Δ_i is the charac-

$$\mathcal{O}[h_1, h_2] \approx 1 - \frac{1}{2}\left(\Delta_2^\alpha - \Delta_1^\alpha\right)^2 \frac{\langle c|c\rangle}{\langle h|h\rangle}\left[1 - \mathcal{O}^2[h, c]\right]. \quad (3)$$

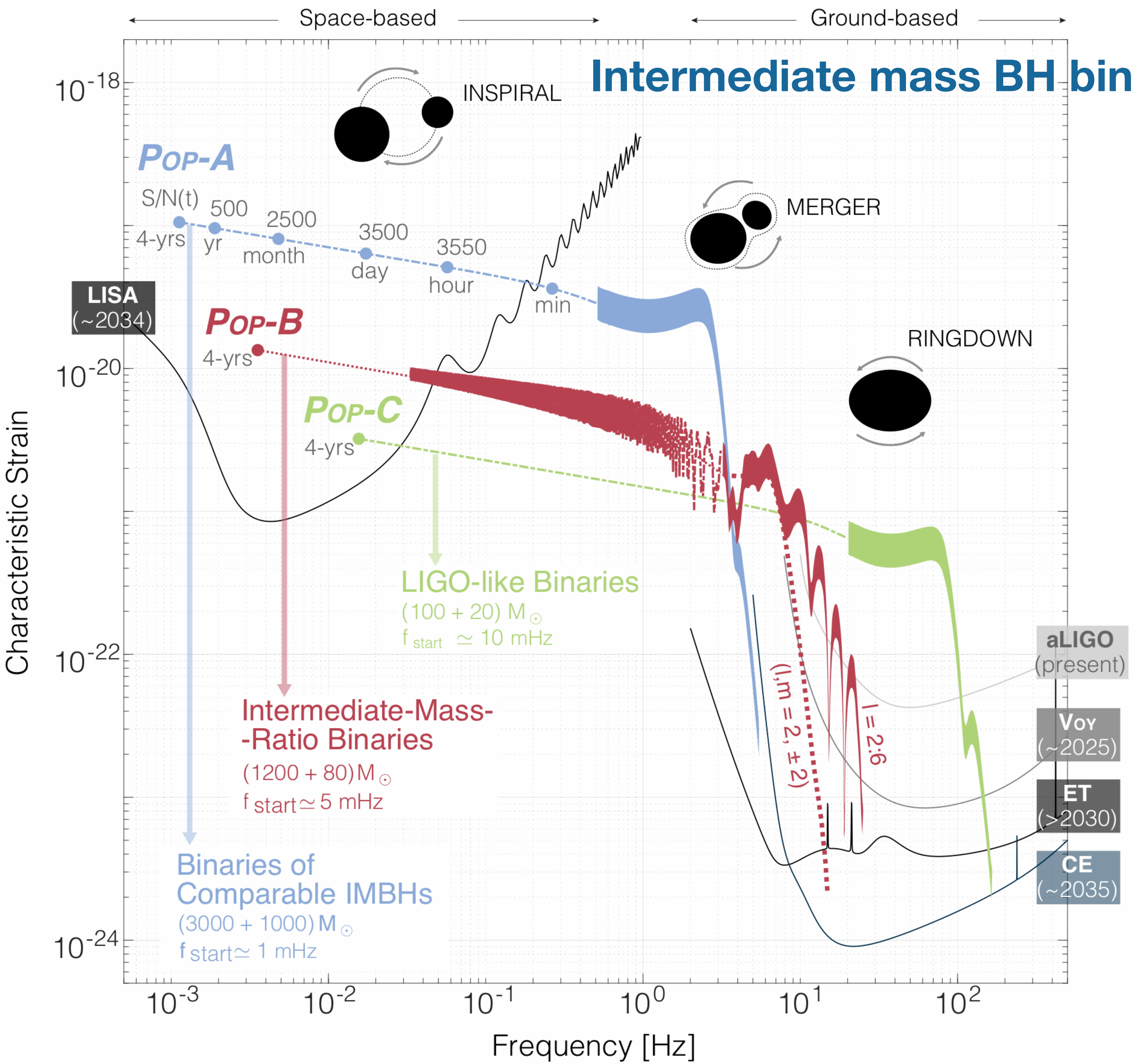
Noting that c depends on derivatives of h, we can approximate that $\mathcal{O}^2[h, c] \approx 0$ and write Eq. 3 in terms of the mismatch, $\epsilon = 1 - \max_{t_0\phi_0} \mathcal{O}$, as

$$\epsilon[h_1, h_2] = \frac{\beta^2}{2}\left(\Delta_2^\alpha - \Delta_1^\alpha\right)^2, \quad (4)$$

with $\beta^2 = \langle c|c\rangle / \langle h|h\rangle = \langle c|c\rangle/\rho^2$ and $\rho = \langle h|h\rangle^{1/2}$. The mismatch, and therefore β, depends upon the intrinsic source parameters as well as the orientation and sky position of the binary. It is independent of the distance to



Intermediate mass BH binaries



BINARY SOURCES LISA

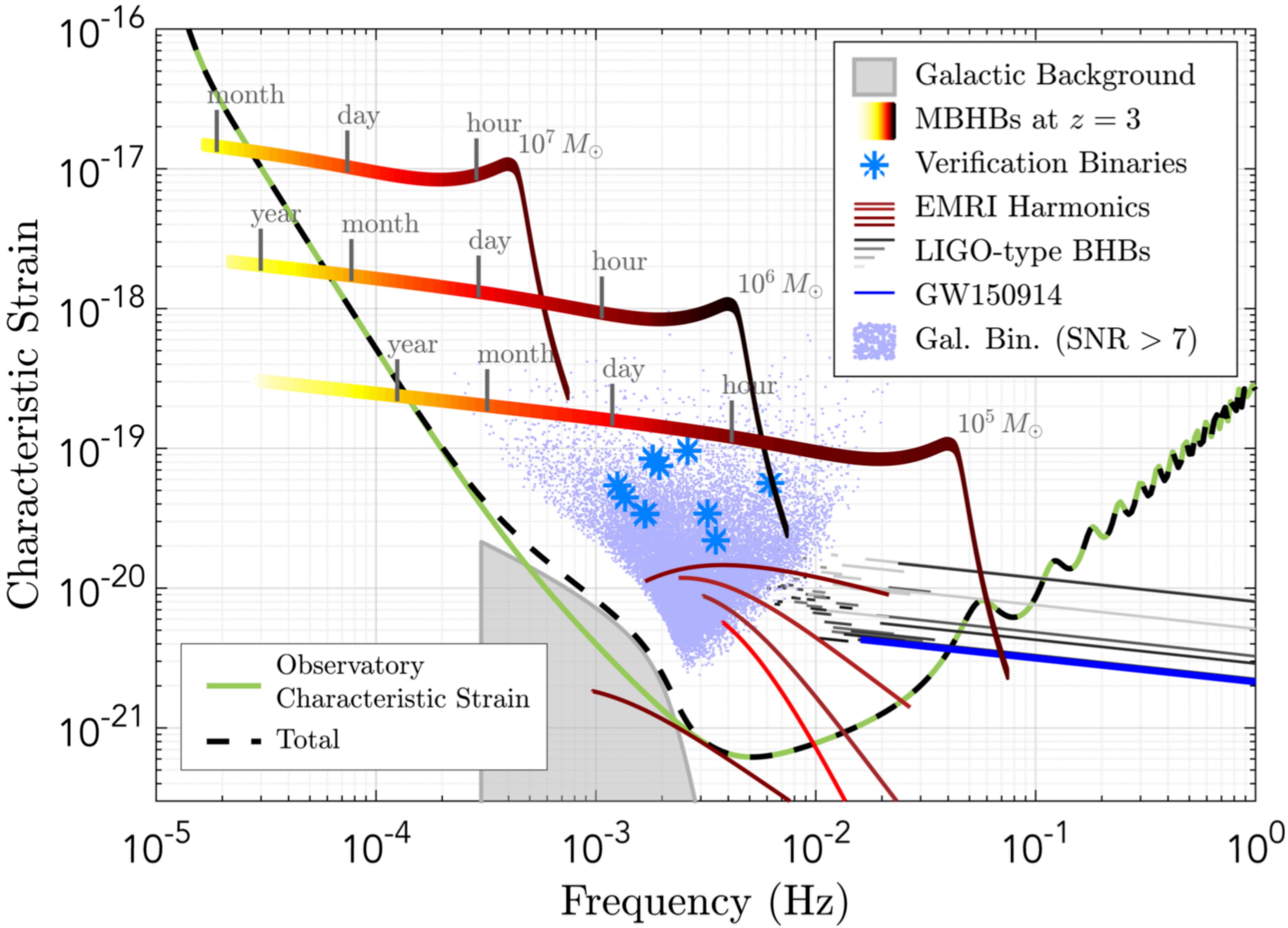
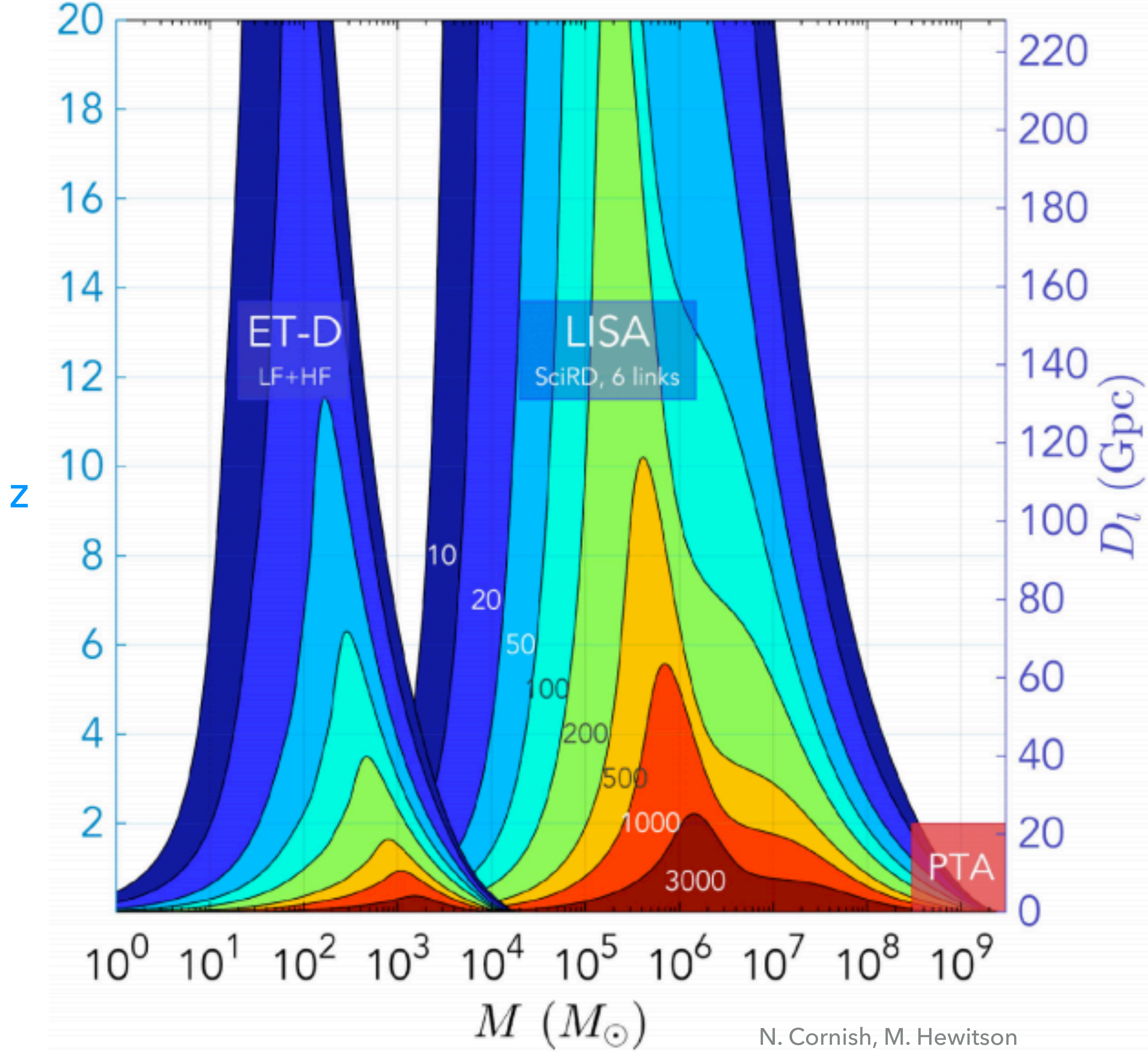


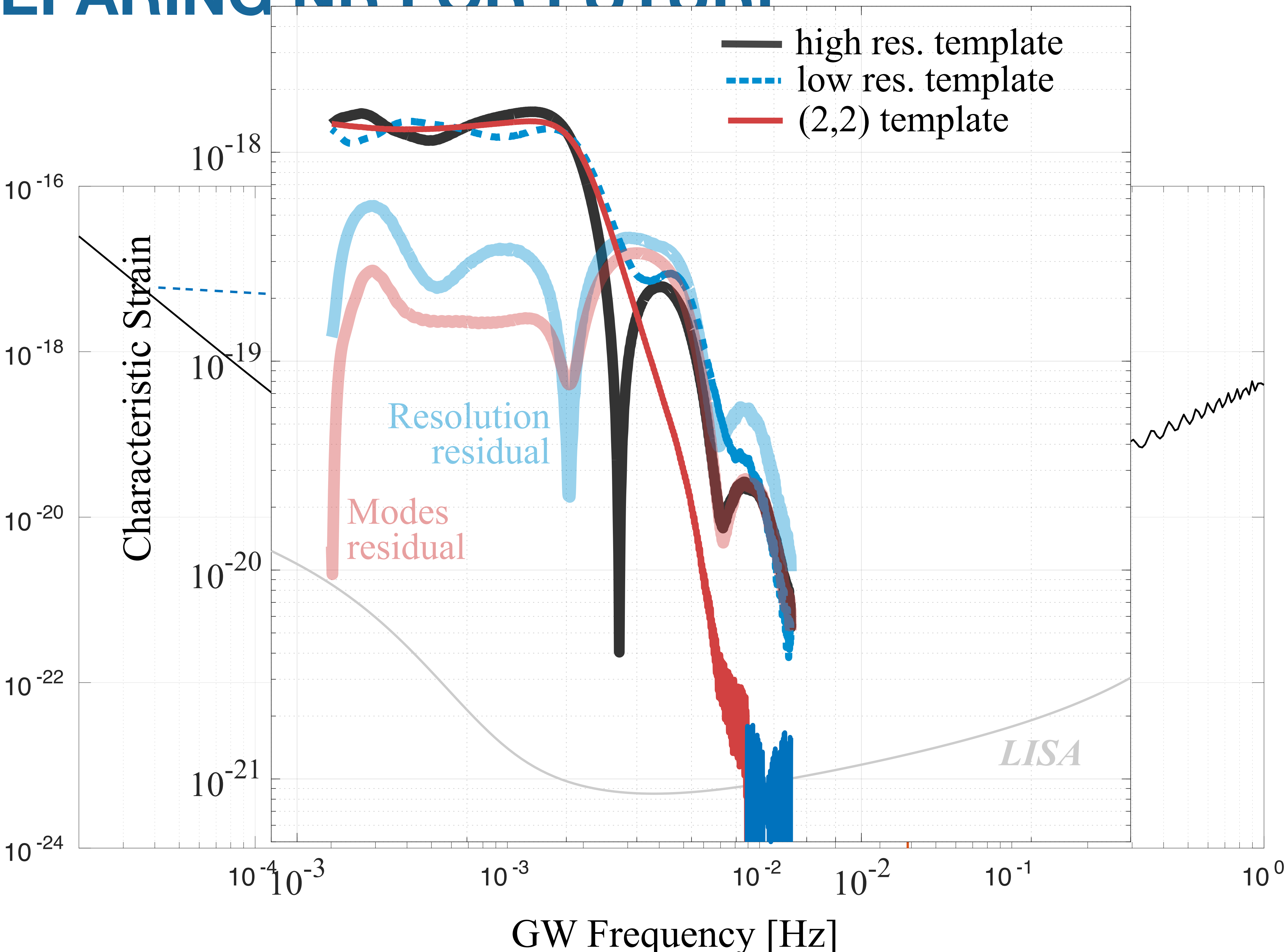
Figure 1 of LISA L3 Document

BH MASSES GROUND AND SPACE



N. Cornish, M. Hewitson

PREPARING NR FOR FUTURE



Ferguson et al 2020

IN SUMMARY

- Gravitational wave detectors will improve on the ground and be launched in space
- Black hole binaries are routinely detected
- Numerical Relativity has a pivotal role to play in these detectors
- We are laying the ground for achieving the science objectives now
- Be prepared to study the unexpected

This is the time to review gravity's role in the universe and what governs its interaction.