Inferences in theoretical physics

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Fundamental Physics with LISA
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JOHNS HOPKINS
UNIVERSITY

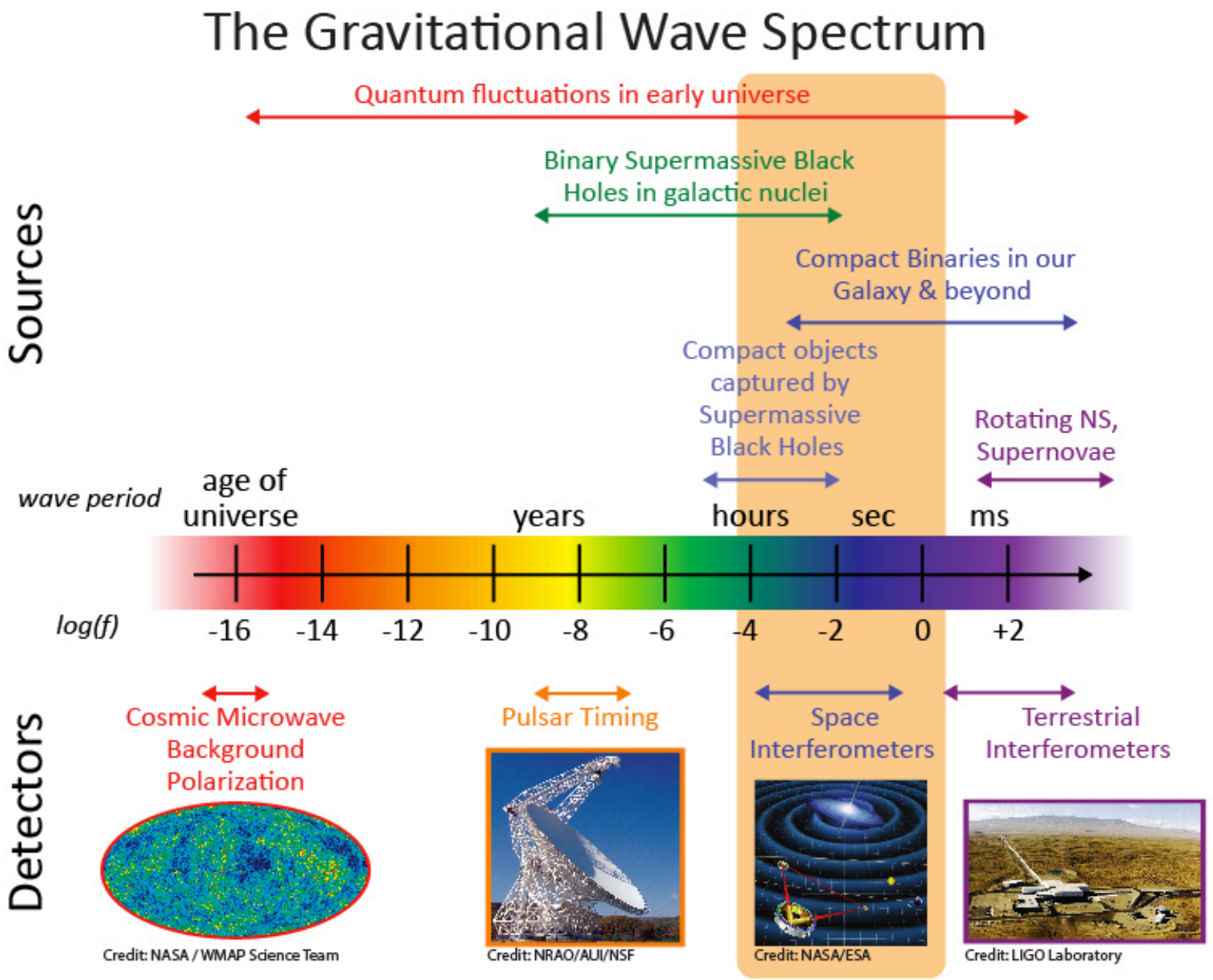
Inferences in theoretical physics: outline

- **The NASA and ESA views: what is "fundamental" physics?**
  Are astrophysics and cosmology "less fundamental"?
- **Building the science case for a mission on a 15-20 year timescale: need to rank "fundamental" topics in theoretical physics**
- **The issue of bias**

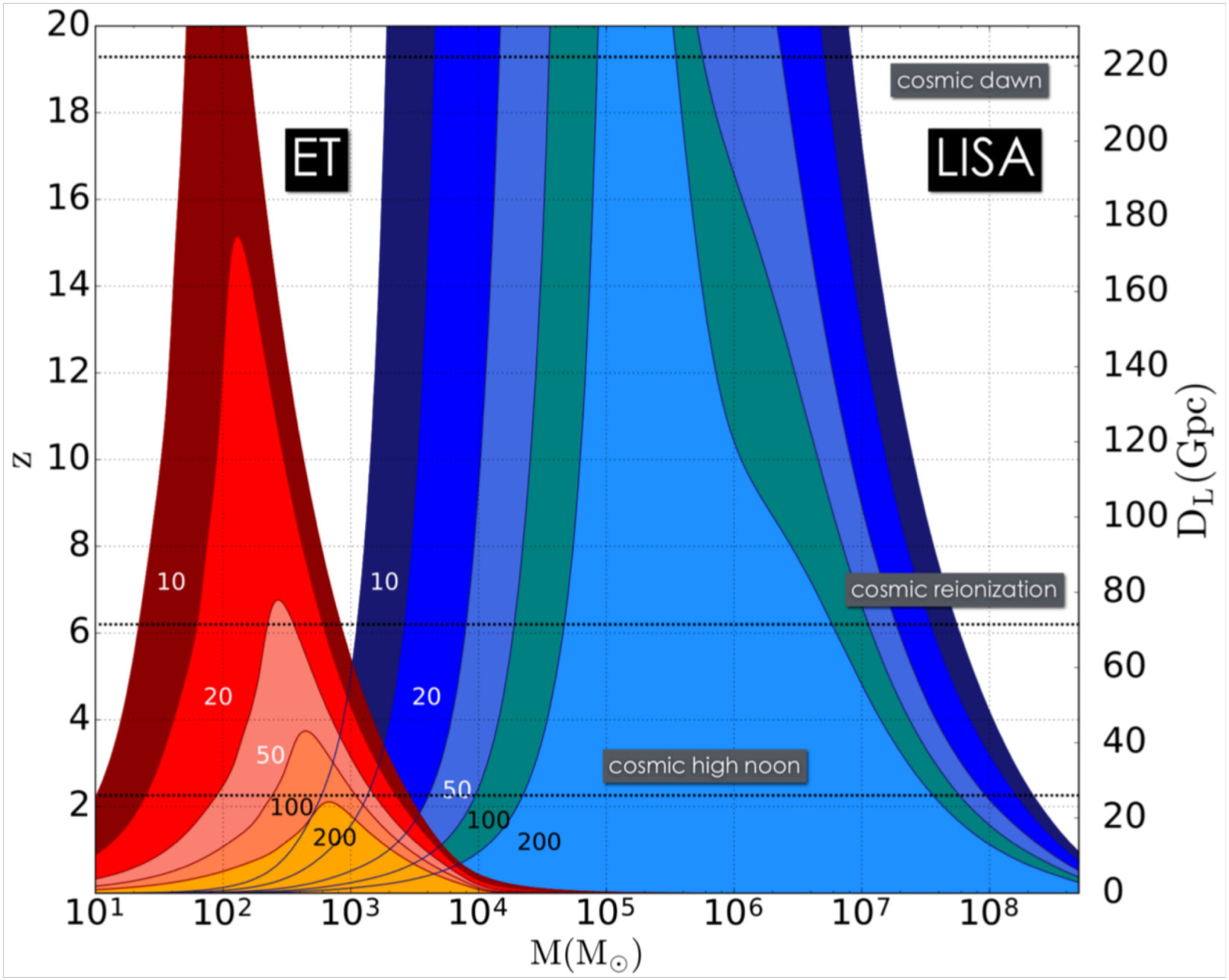
- **Parametrized vs. model-specific tests**
- **Landscape of physics/astrophysics in the LISA age: Multiband/multimessenger/statistical tests**

- **Classifying tests of theoretical physics:**
  - **Gravitational wave generation/propagation**
  - **Black hole spacetimes/dynamics**
  - **New physics/cosmology (dark matter, primordial BHs…)**
  - **"Discovery space"**

What LISA sources are best to test GR/fundamental physics?
What GR foundations/physics are tested by each source class?



LISA in the 2030s: multiband, multimessenger



fundamental

adjective • UK /ˌfʌn.dəˈmen.tᵊl/ US /ˌfʌn.dəˈmen.ţᵊl/

C2 forming the base, from which everything else develops:

*We need to make fundamental **changes** to the way in which we treat our environment.*

*It's one of the fundamental **differences** between men and women.*

*The school is based on the fundamental **principle** that all children should reach their full potential.*

*Diversity is **of** fundamental **importance** to all ecosystems and all economies.*

C2 more important than anything else:

*Some understanding of grammar is fundamental **to** learning a language.*

− More examples

A fair justice system is a fundamental part of a civilized society.

Peaceful demonstrations that do not cause a public nuisance are a fundamental right in any truly democratic country.

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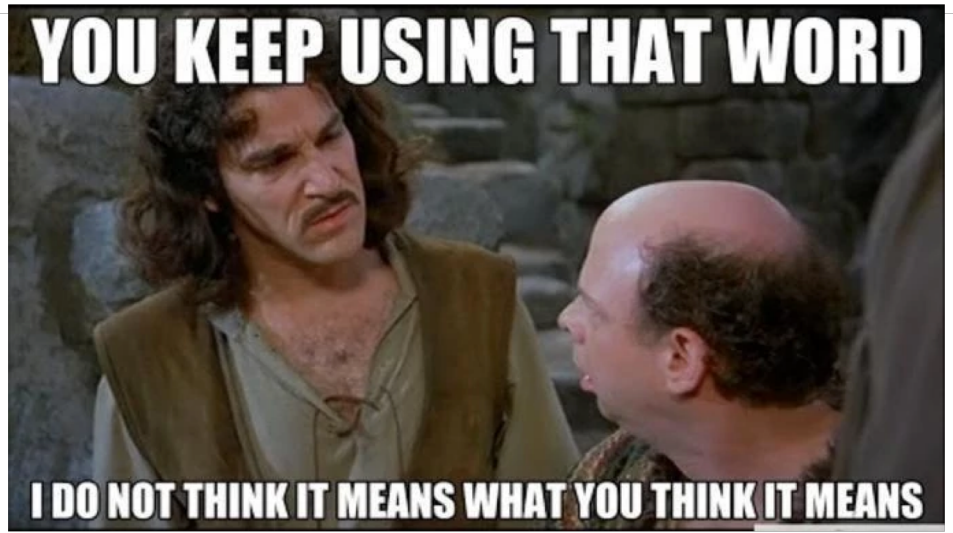


LISA and fundamental physics: the NASA and ESA views

- **Decadal Survey**

Tests of General Relativity and Fundamental Physics with Space-based Gravitational Wave Detectors

Emanuele Berti,[1,*] Deirdre Shoemaker,[2] Ilias Cholis,[3] Bernard Kelly,[4,5,6] Ely D. Kovetz,[1] Tyson B. Littenberg,[7] Jeffrey Livas,[4] Jeremy Schnittman,[4,6] and Nicolás Yunes[8]

- **One of about ~15 white papers:**
  SMBHs, IMBHs, EMRIs, UCBs, cosmology, discovery space, multiband, multimessenger, science case, community building, technological readiness…

- **Feedback/help is needed and welcome!**

First joint meeting of NLST/ESA Study Team in preparation for Decadal:
http://sites.krieger.jhu.edu/lisa/

What is the nature of gravity?

- **Is general relativity correct in the strong-field regime?**
  BH-BH, BH-NS, NS-NS, bursts, continuous GWs (ground, space)
  astrophysical and cosmological stochastic backgrounds
  (ground, space, PTAs, CMB)

- **Is general relativity correct on cosmological scales?**
  BH-BH, BH-NS, NS-NS, bursts, continuous GWs (ground, space)
  astrophysical and cosmological stochastic backgrounds
  (ground, space, PTAs, CMB)

- **What is the nature of dark matter and dark energy?**
  BH-BH, BH-NS, NS-NS, bursts, continuous GWs (ground, space)
  astrophysical and cosmological stochastic backgrounds
  (ground, space, PTAs, CMB)

What are the end states of stellar evolution, in isolation and in dynamical environments?

- **What is the equation of state of matter at high density?**
  NS-NS, NS-BH mergers, collapse (ground)

- **Are "black holes" the Kerr solutions of general relativity?**
  merger/ringdown (ground, space)
  BH/NS capture by massive BHs in nearby galaxies (space)

- **How do stellar mass binaries form?**
  Field, clusters, triples, AGN disks, primordial BHs…
  BH-BH, BH-NS, NS-NS mergers (ground, space)
  mHz GW binaries in the Milky way: WDs, NSs, BHs (space)
  BH/NS capture by massive BHs in nearby galaxies (space)

- **Where are the IMBHs?**
  (ground, space)

How do massive black holes and galaxies co-evolve over cosmic time?

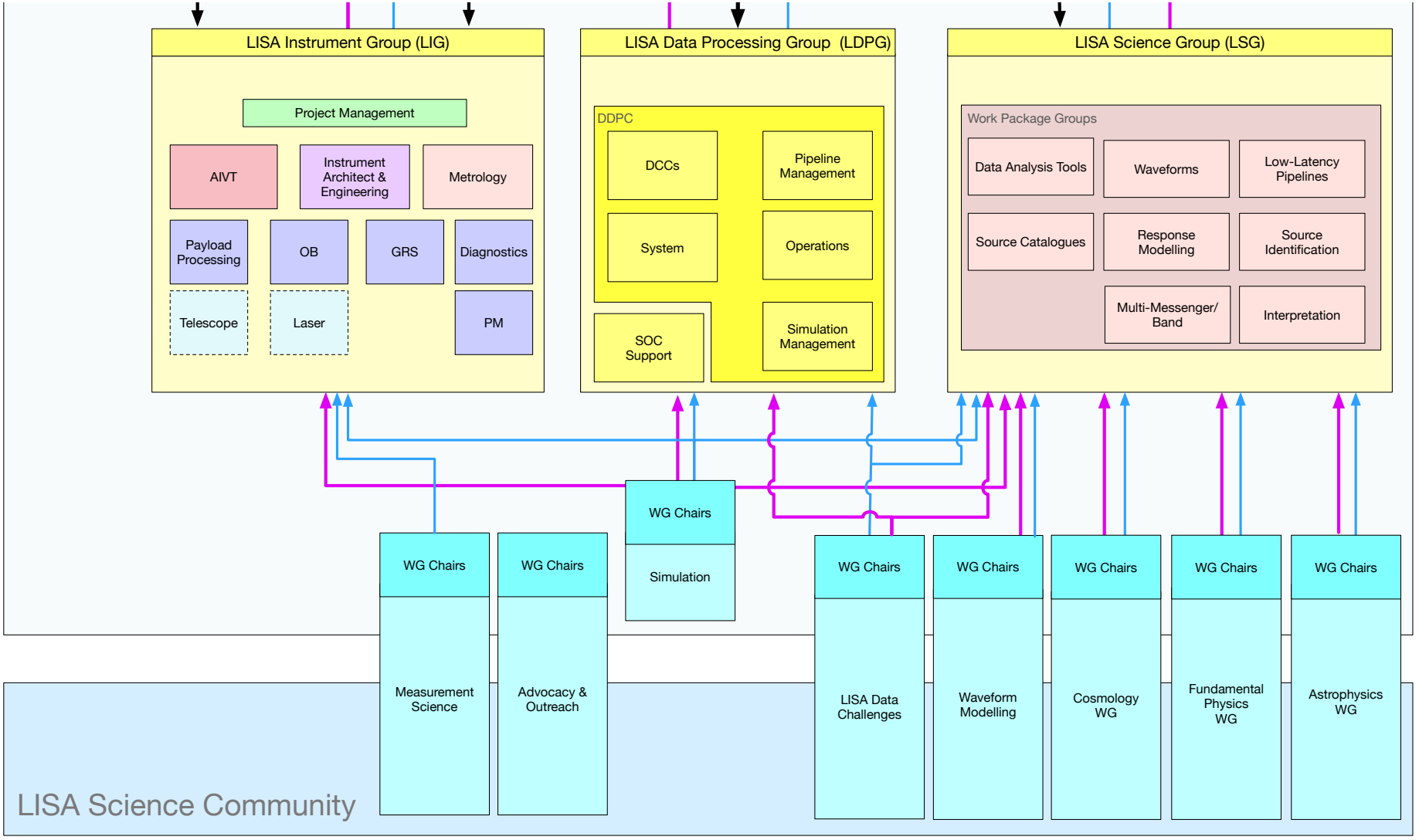
- **What are the seeds of massive BHs?**
  BH-BH mergers (ground, space, PTAs)

- **How do massive BHs interact with their galactic hosts?**
  BH-BH mergers (space, PTAs)

- **What are the relationships between these black holes and their hosts, how have these relationships evolved and what processes drive them?**
  BH-BH mergers (space, PTAs)

- **How do black holes and galaxies participate in the process that formed the structure of the universe we observe today?**
  BH-BH mergers (space, PTAs)

LSG and working groups



An experiment on bias: possible routes to new (theoretical) physics

Table 1: Ideas underlying possible routes to new physics. Grades indicate the relative importance of searching for evidence of the idea (higher grade = more important). The first column indicates whether there is a viable theory supporting the idea. Column two ranks the theoretical motivation for the idea, and column three asks whether we know where in parameter space to look for signals of this physics.

	Theoretically Sound?	Why?	Where?	Net Grade
Gravitational Waves	10	20*	10	40
Near weak-scale physics (e.g. EDMs, Flavor, g-2)	10	10	5	25
Neutrino masses (neutrinoless double beta decay)	10	10	5	25
QCD axion	10	15*	5	30
Axiverse, Photiverse	10	5	0	15
Moduli, Extra Dimensions	10	5	0	15
Lorentz, CPT Violation	5	0	0	5
Gravitational Decoherence	-5	-10	0	-15
Quintessence, Chameleons, Galileons	-5	-10	0	-15
Vacuum Energy, Holography	-10	-10	0	-20

"Opportunities in fundamental physics", Gordon & Betty Moore Foundation

The matrix: fundamental physics and LISA sources

The goal of this document is to come up with a classification of the sub-items that will be studied within the LISA Fundamental Physics Working group. There is clearly a very large number of ways to classify this work, so we have here made a choice based on current research interests. This choice classifies interests based on 2 dimensions (type of fundamental physics and source used). Ideally, different members of the working group will populate the cells of this table, with one or two people identified per cell as "captains" of the respective topic. Members of the working group are encouraged to opulate multiple cells of the table.

Fundamental Physics / Source Type	**Modified Dispersion Relations and the Speed of Gravity**	**Violations of the Equivalence Principle and Fundamental Symmetries**	**Tests of the Nature of Black Holes**	**Dark Energy Candidates and Screening**	**Dark Matter Candidates and Primordial Black Holes**	**Other Model Independent Tests**	**Stacking and Astrophysical Systematics**	**Waveform Systematics**
SMBH Binaries								
EMRIs and IMRIs								
Multi-Band Sources								
Galactic Binaries								
Stochastic Backgrounds								

Notes:
The classification above implicitly assumes that one work on theoretical development, waveform generation or data analysis within any of these topics.
"Tests of the Nature of Black Holes" includes ringdown "no-hair" tests, quadrupolar deformation tests and chaos tests
"Tests with tidal deformabilities" can be included in the "Tests of the Nature of BHs" column
"Violations of Equivalence Principle, etc" can include theories like EdGB or quadratic gravity, as well as theories that have Kerr as a solution but with other degrees of freedom that modify the dissipative sector.
"Astrophysical Systematics" and "Waveform Systematics" are about how astrophysical effects or incorrect modeling of GR waveforms can impact test GR
"Astrophysical Systematics" also includes stacking ideas
"Other model-independent tests" includes things like residual tests, tests of waveform consistency, and ppE tests
"Violations of Fundamental Symmetries" includes violations of gravitational parity and violations of Lorentz symmetry and other violations of SEP
"Tests of the BH Nature" incldues tests of the Kerr hypothesis, sesarch for ECOs and echoes
"Dark Energy Candidates and Screening" includes massive gravity, and other Horndeski theories
"Cosmic strings" is already included in another cosmology work-package.
"Primordial BHs" is probably also already in another cosmology work-package, also they would already be under SMBHs or as EMRIs or as other Multi-band sources (a small mass BH wouldn't be visible in LISA, unless it's an EMRI)
Is guess "candidates" can be
deleted from header of DE and
DM
Does multiband include EM?

https://pollev.com/surveys/fWVj2jogj/web

Classification of tests of gravity and fundamental physics

- **Tests of gravity and fundamental physics white paper [EB+]**
  - **Tests of gravitational wave generation/propagation**
  - **Tests of black hole spacetimes/dynamics**
  - **Joint electromagnetic/gravitational tests**
  - **Dark matter / primordial black hole searches**

The known unknown

- **Tests of gravity and fundamental physics white paper [EB+]**
  - **Tests of gravitational wave generation/propagation**
  - **Tests of black hole spacetimes/dynamics**
  - **Joint electromagnetic/gravitational tests**
  - **Dark matter / primordial black hole searches**

…and the unknown unknown

- **Tests of gravity and fundamental physics white paper [EB+]**
  - **Tests of gravitational wave generation/propagation**
  - **Tests of black hole spacetimes/dynamics**
  - **Joint electromagnetic/gravitational tests**
  - **Dark matter / primordial black hole searches**

- **“Discovery space” white paper [Cornish+]**
  - **Cosmic strings**
  - **Warped extra dimensions**
  - **First order phase transitions**
  - **Properties of neutrinos**
  - **Antimatter and gravitation**
  - **Collapse of supermassive stars**
  - **Boson condensates & stars / self-interacting dark matter**
  - **Black holes and information paradox**
  - **…**

“No matter what, we need to be crazy to solve the information paradox”

Tests of gravitational wave generation

- **EFT or specific theories?**
  - **EFT and black hole physics:**
    - **Tattersall-Ferreira 1711.01992 [GR background]**
    - **Burgess+ 1808.00847 [echoes]**
    - **Franciolini+ 1810.07706 [hairy BHs]**

- **Which theories? "Foils" to test foundations of GR**
  - **massive gravity**
  - **scalar-tensor**
  - **Einstein-Maxwell-dilaton**
  - **Horndeski (galileons, EsGB…)**
  - **dynamical Chern Simons**
  - **Einstein-Aether/Khronometric**
  - **extra dimensions (ADD/RS)**

Tests of gravitational wave generation

- **Inspiral:**

  post-Newtonian works ok…mostly (screening)

  test PN coefficients (Arun/Sathya)

  generalizations:

    parametrized post-Einsteinian (allows mapping to theories)

    quadrupole tests

    tidal Love numbers

Mapping ppE to specific theories

$$\tilde{h}(f) = \tilde{A}_{\rm GR}(f)\left[1 + \alpha_{\rm ppE}\, v(f)^a\right] e^{i\Psi_{\rm GR}(f) + i\beta_{\rm ppE}\, v(f)^b}$$

Table 2 Mapping of ppE parameters to those in each theory for a black hole binary

Theory	$\beta_{\rm ppE}$	b
Scalar–tensor [36,179,180]	$-\frac{5}{1792}\dot{\phi}^2\eta^{2/5}\left(m_1 s_1^{\rm ST} - m_2 s_2^{\rm ST}\right)^2$	-7
EdGB, D^{2}GB [23]	$-\frac{5}{7168}\zeta_{\rm GB}\frac{\left(m_1^2 s_2^{\rm GB} - m_2^2 s_1^{\rm GB}\right)^2}{m^4\eta^{18/5}}$	-7
dCS [181]	$\frac{1549225}{11812864}\frac{\zeta_{\rm CS}}{\eta^{14/5}}\left[\left(1-\frac{231808}{61969}\eta\right)\chi_s^2 + \left(1-\frac{16068}{61969}\eta\right)\chi_a^2 - 2\delta_m\chi_s\chi_a\right]$	-1
EA [182]	$-\frac{3}{128}\left[\left(1-\frac{c_{14}}{2}\right)\left(\frac{1}{w_2^{Æ}} + \frac{2c_{14}c_+^2}{(c_+ + c_- - c_- c_+)^2 w_1^{Æ}} + \frac{3c_{14}}{2w_0^{Æ}(2-c_{14})}\right) - 1\right]$	-5
Khronometric [182]	$-\frac{3}{128}\left[(1-\beta_{\rm KG})\left(\frac{1}{w_2^{\rm KG}}\frac{3\beta_{\rm KG}}{2w_0^{\rm KG}(1-\beta_{\rm KG})}\right) - 1\right]$	-5
Extra dimension [183]	$\frac{25}{851968}\left(\frac{dm}{dt}\right)\frac{3-26\eta+34\eta^2}{\eta^{2/5}(1-2\eta)}$	-13
Varying G [151]	$-\frac{25}{65536}\dot{G}\mathcal{M}$	-13
Mod. disp. rel. [184]	$\frac{\pi^{2-\alpha_{\rm MDR}}}{(1-\alpha_{\rm MDR})}\frac{D_{\alpha_{\rm MDR}}}{\lambda_{\mathbb{A}}^{2-\alpha_{\rm MDR}}}\frac{\mathcal{M}^{1-\alpha_{\rm MDR}}}{(1+z)^{1-\alpha_{\rm MDR}}}$	$3(\alpha_{\rm MDR}-1)$

Tests of gravitational wave propagation

- **Varying G**

- **Modified dispersion relations.**

$$E^2 = (pc)^2 + \mathbb{A}\,(pc)^{\alpha_{\rm MDR}}$$

Map to, e.g.:

Massive gravity
Multifractional spacetime
Doubly special relativity
Extra dimensions
Standard Model Extension (Kostelecky)
Horava

Mapping ppE to specific theories

$$E^2 = (pc)^2 + \mathbb{A}\,(pc)^{\alpha_{\rm MDR}}$$

Table 3 Mapping between modified dispersion relation parameters for the graviton in Eq. (20) and the parameters of each theory

Theory	$\mathbb{A}$	$\alpha_{\rm MDR}$
Massive gravity [198–201]	m_g^2	0
multifractional spacetime [202–205]	$\frac{2}{3-\alpha_{\rm MDR}} E_*^{2-\alpha_{\rm MDR}}$ (timelike spacetime)	2–3
	$-\frac{2\cdot 3^{1-\alpha_{\rm MDR}/2}}{3-\alpha_{\rm MDR}} E_*^{2-\alpha_{\rm MDR}}$ (spacelike spacetime)	
Double special relativity [206–209]	$\eta_{\rm dsrt}$	3
Extra dimension [210]	$-\alpha_{\rm edt}$	4
SME [211]	$-2\mathring{k}_{(I)}^{(d)}$ (even $d \geq 4$)	$d-2$
	$\pm 2\mathring{k}_{(V)}^{(d)}$ (odd $d \geq 5$)	
Hořava [108,136,212,213]	$\kappa_{\rm hl}^4 \mu_{\rm hl}^2/16$	4

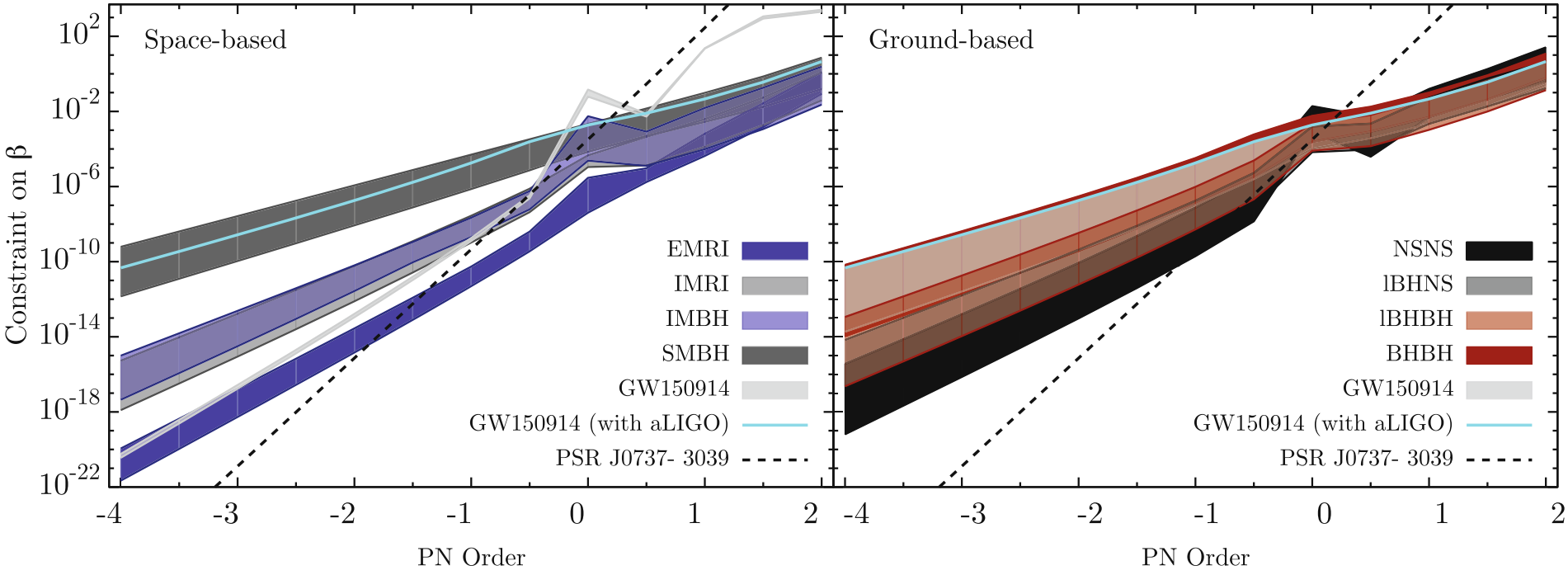
The meaning of the parameters is as follows. m_g: the graviton mass; E_*: the characteristic length scale above which spacetime is discrete; $\eta_{\rm dsrt}$: the characteristic observer-independent length scale; $\alpha_{\rm edt}$: the square of the Planck length in extra dimensional theories; $\mathring{k}_{(I)}^{(d)}$ and $\mathring{k}_{(V)}^{(d)}$: parameters controlling the Lorentz-violation operators in SME in the rotation-invariant limit; $\kappa_{\rm hl}$: a parameter related to the bare gravitational constant; $\mu_{\rm hl}$: a parameter related to the deformation in the "detailed balance" conditions in Hořava gravity

Mapping ppE to specific theories

Table 4 Various bounds on example theories that violate certain fundamental pillars in GR

Theory	GR pillar	PN	Repr. parameters	GW150914	Other bounds
EdGB, D^{2}GB	SEP	-1	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	–	10^7 [218], 2 [65,66,68]
Scalar–tensor			$\lvert\dot{\phi}\rvert$ [1/sec]	–	10^{-6} [180]
dCS	SEP, PI	$+2$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	–	10^8 [100,106]
Einstein-Æther	SEP, LI	0	(c_+, c_-)	(0.9, 2.1)	(0.03, 0.003) [126,127]
Khronometric			$(\beta_{\rm KG}, \lambda_{\rm KG})$	(0.42, $-$)	(0.005, 0.1) [126,127]
Extra dimensions	4D	-4	ℓ [μm]	8.6×10^9	10–10^3 [140,219–222]
Time-varying G	SEP	-4	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	5.4×10^{18}	0.1–1 [223–227]
Massive graviton	$m_g = 0$	$+1$	m_g [eV]	10^{-22} [214]	10^{-29}–10^{-18} [228–232]
Multifractional	LI	$+4.75$	E_*^{-1} [eV^{-1}] (time)	5.8×10^{-27}	–
			E_*^{-1} [eV^{-1}] (space)	1.0×10^{-26}	3.9×10^{-53} [233]
Double special rel.	LI	$+5.5$	$\eta_{\rm dsrt}/L_{\rm Pl} > 0$	1.3×10^{22}	–
			$\eta_{\rm dsrt}/L_{\rm Pl} < 0$		2.1×10^{-7} [233]
Extra dimensions	4D	$+7$	$\alpha_{\rm edt}/L_{\rm Pl}^2 > 0$	5.5×10^{62}	2.7×10^2 [233]
			$\alpha_{\rm edt}/L_{\rm Pl}^2 < 0$		–
Stand. model ext.	LI	$+4$	$\mathring{k}^{(4)}_{(I)} > 0$	–	6.1×10^{-17} [117,233]
			$\mathring{k}^{(4)}_{(I)} < 0$	0.64	–
		$+5.5$	$\mathring{k}^{(5)}_{(V)} > 0$ [cm]	1.7×10^{-12} [211]	1.7×10^{-40} [117,233]
			$\mathring{k}^{(5)}_{(V)} < 0$ [cm]		–
		$+7$	$\mathring{k}^{(6)}_{(I)} > 0$ [cm^2]	7.2×10^{-4}	3.5×10^{-64} [117,233]
			$\mathring{k}^{(6)}_{(I)} < 0$ [cm^2]		–
Hořava–Lifshitz	LI	$+7$	$\kappa_{\rm hl}^4 \mu_{\rm hl}^2$ [1/eV^2]	1.5×10^6	–
Einstein-Æther	LI	$+4$	c_+	0.7 [234]	0.03 [126,127]

LISA vs. ground-based tests



Tests of gravitational wave generation

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  post-Newtonian works ok…mostly (screening)

  test PN coefficients (Arun/Sathya)

  generalizations:

  parametrized post-Einsteinian (allows mapping to theories)

  quadrupole tests

  tidal Love numbers

- **Merger:**

  well posedness? stability?

  what can be simulated?

  what is worth simulating?

  So far: scalar-tensor: dynamical scalarization

  Einstein-Maxwell-dilaton: dynamical (de)scalarization?

  dynamical Chern Simons (EFT)

  Einstein-dilaton-Gauss-Bonnet (EFT)

Tests of black hole spacetimes

- **BH "charges":**
  scalar monopole (e.g. Einstein-dilaton Gauss-Bonnet)
  scalar dipole (e.g. dynamical Chern-Simons)
  electric charges (astrophysically unrealistic? minicharged DM)
  magnetic charges (e.g. heterotic string)

- **EMRIs and multipolar structure of compact objects**

- **Tidal Love numbers: do they test Planck-scale physics?**

- **Axion cloud mapping**

- **Inspiral resonances (if central object is not a black hole)**

Tests of black hole dynamics

- **Area theorem and golden binaries**
- **Ringdown "no-hair" tests**
- **Black hole echoes**
- **Parametrized tests:**
  - **EFT? Only nonrotating**
  - **Specific theories (few: no-hair theorems…)**
    - **Einstein-dilaton-Gauss-Bonnet (nonrotating only)**
    - **dynamical Chern-Simons**
    - **Einstein-Maxwell-dilaton (slowly rotating)**
  - **Kerr is special! separability in modified gravity is an issue**
  - **post-Kerr: when/how much does the geodesic/WKB approximation break down?**
- **Dark matter**

Multiband / multimessenger / statistical tests

- **Tests of GR via synergy of LISA and 3G detectors?**
  (Multiband)

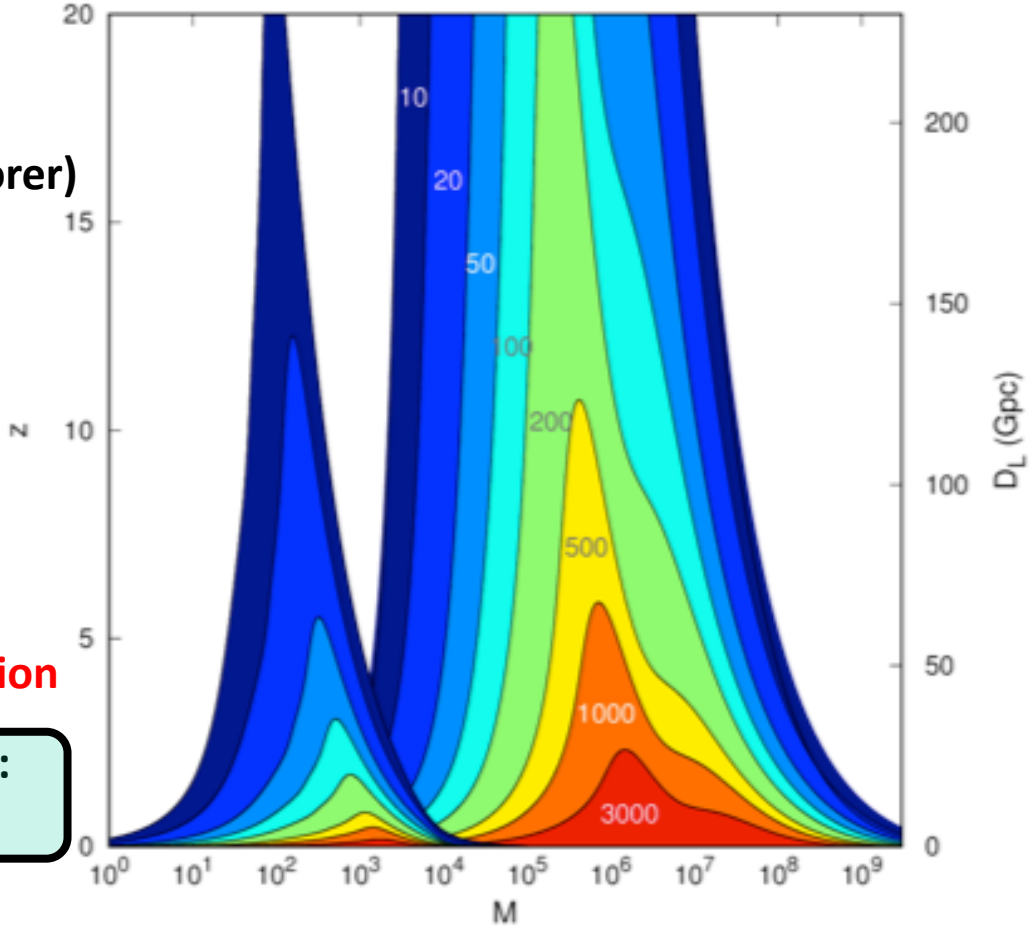
- **Test of GR via synergy of LISA and EM/neutrino counterparts?**
  (Multimessenger)

  What are the possible counterparts?
  What kind of tests can we do?
  How much do we suffer from/care about:
  uncertainties in astrophysical source modeling
  uncertainties in the EM emission mechanism

- **What can we do with source populations that we cannot do with single sources?**

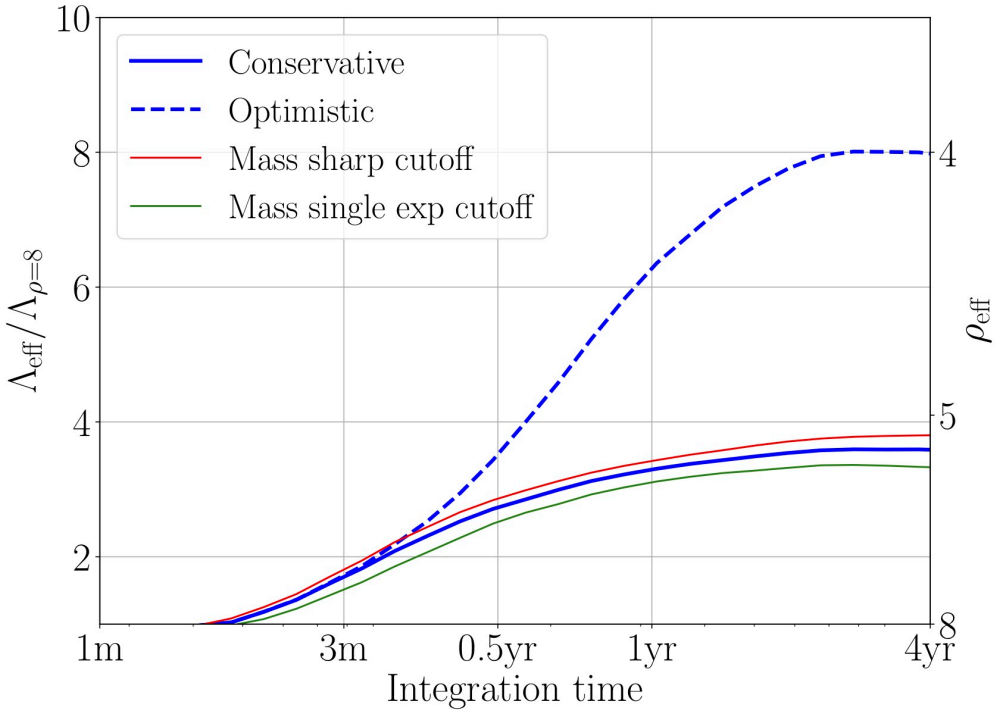
Multiband observations in the 3G era

- **Limited improvements on 3G PE**
  GW150914:
  SNR~700 (2000) in Voyager (Cosmic Explorer)
  [cf. Vitale 1605.01037]
- **However LISA will break degeneracies:**
  (χ_1, χ_2) from LISA, χ_{eff} and χ_f from LIGO
  M_{chirp} from LISA, M from LIGO
- **Use 3G detections to remove foreground and go after stochastic backgrounds**
- **Use LISA for 3G phase/amplitude calibration**
- **Post-process LISA data after 3G detection: boost LISA multiband event rates**

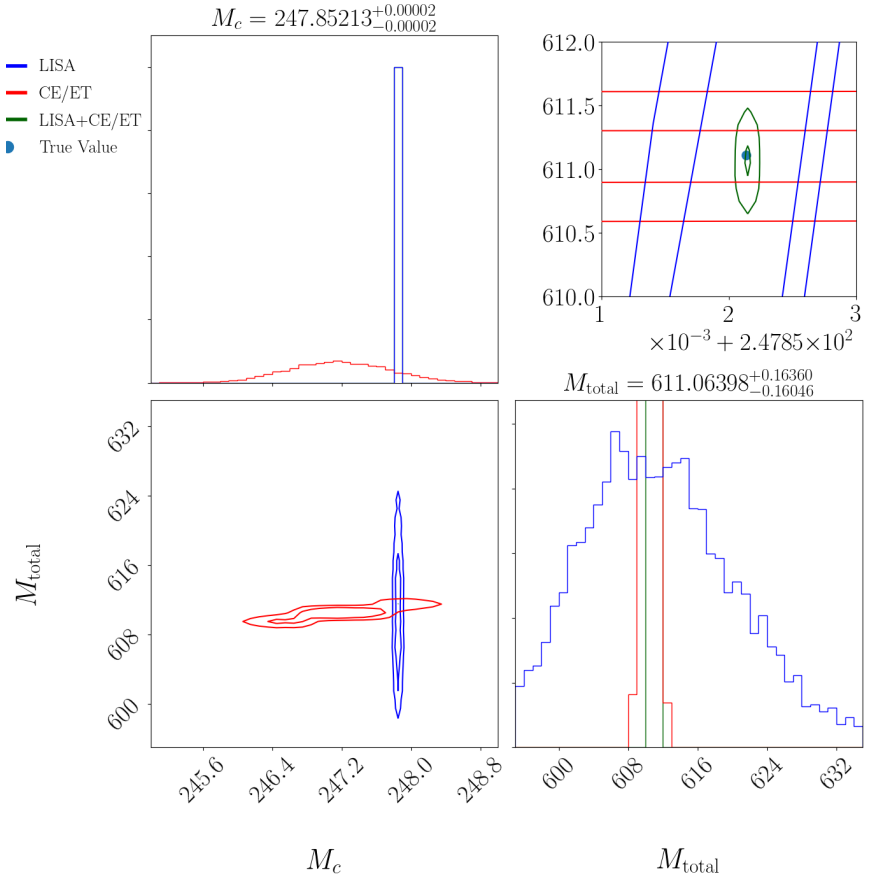


[Figure courtesy of Neil Cornish]

LISA/3G complementarity



[Wong, Kovetz, Cutler, EB, 1808.08247]



[Cutler+, multiband WP]

Dark matter / Beyond the Standard Model

- **Superradiance**
- **Stochastic backgrounds**
- **Primordial black holes**
- **First order phase transitions in the early Universe?**
  Can LISA see the resulting gravitational waves?
  Connections to theories of baryo- and lepto- genesis

Matter at high density/pressure

- **NS-NS generate conditions that may probe new physics**
- **QCD phase transition and axions?**
- **Any other properties of physics may be relevant? (EDMs?)**
- **New forces (modification of gravity at short distances)?**
- **New forces at the scale of the binary (new radiation channels too)**
- **New radiation channels in general will cool NS-NS faster**

- **Is all of this relevant to LISA?**

Inferences in theoretical physics: outline

- **The NASA and ESA views: what is "fundamental" physics?**
  Are astrophysics and cosmology "less fundamental"?

- **Building the science case for a mission on a 15-20 year timescale: need to rank "fundamental" topics in theoretical physics**
- **The issue of bias**

- **Parametrized vs. model-specific tests**
- **Physics/astrophysics landscape in the LISA age: Multiband / multimessenger / statistical tests**

- **Classifying tests of theoretical physics:**
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