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Echoes from Fundamental Physics with LISA

IPhU Gravitational Waves days

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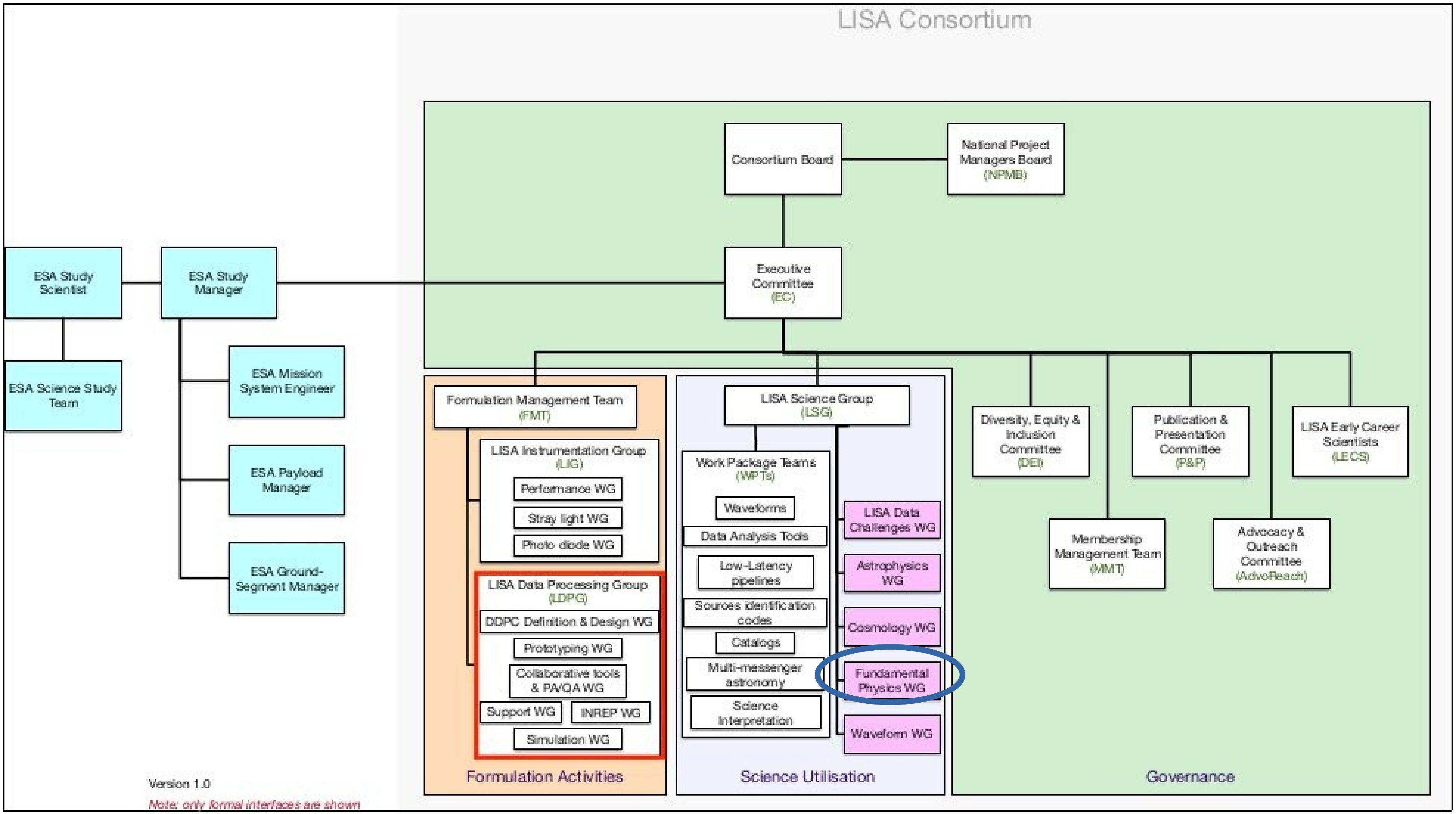
Based on E. Barausse etal. Gen.Rel.Grav. 52 (2020) 8, 81

and FP WG white paper in preparation (to be submitted to LRR in Sep)

Fundamental Physics WG

In the LISA Consortium



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Fundamental Physics WG

In the LISA Consortium

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General Relativity and Gravitation (2020) 52:81
https://doi.org/10.1007/s10714-020-02691-1

INVITED REPORT: INTRODUCTION TO CURRENT RESEARCH

Prospects for fundamental physics with LISA

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Abstract
In this paper, which is of programmatic rather than quantitative nature, we aim to further delineate and sharpen the future potential of the LISA mission in the area of fundamental physics. Given the very broad range of topics that might be relevant to LISA, we present here a sample of what we view as particularly promising fundamental physics directions. We organize these directions through a "science-first" approach that allows us to classify how LISA data can inform theoretical physics in a variety of areas. For each of these theoretical physics classes, we identify the sources that are currently expected to provide the principal contribution to our knowledge, and the areas that need further development. The classification presented here should not be thought of as cast in stone, but rather as a fluid framework that is amenable to change with the flow of new insights in theoretical physics.

Keywords Gravitational waves · LISA · Fundamental physics

Contents

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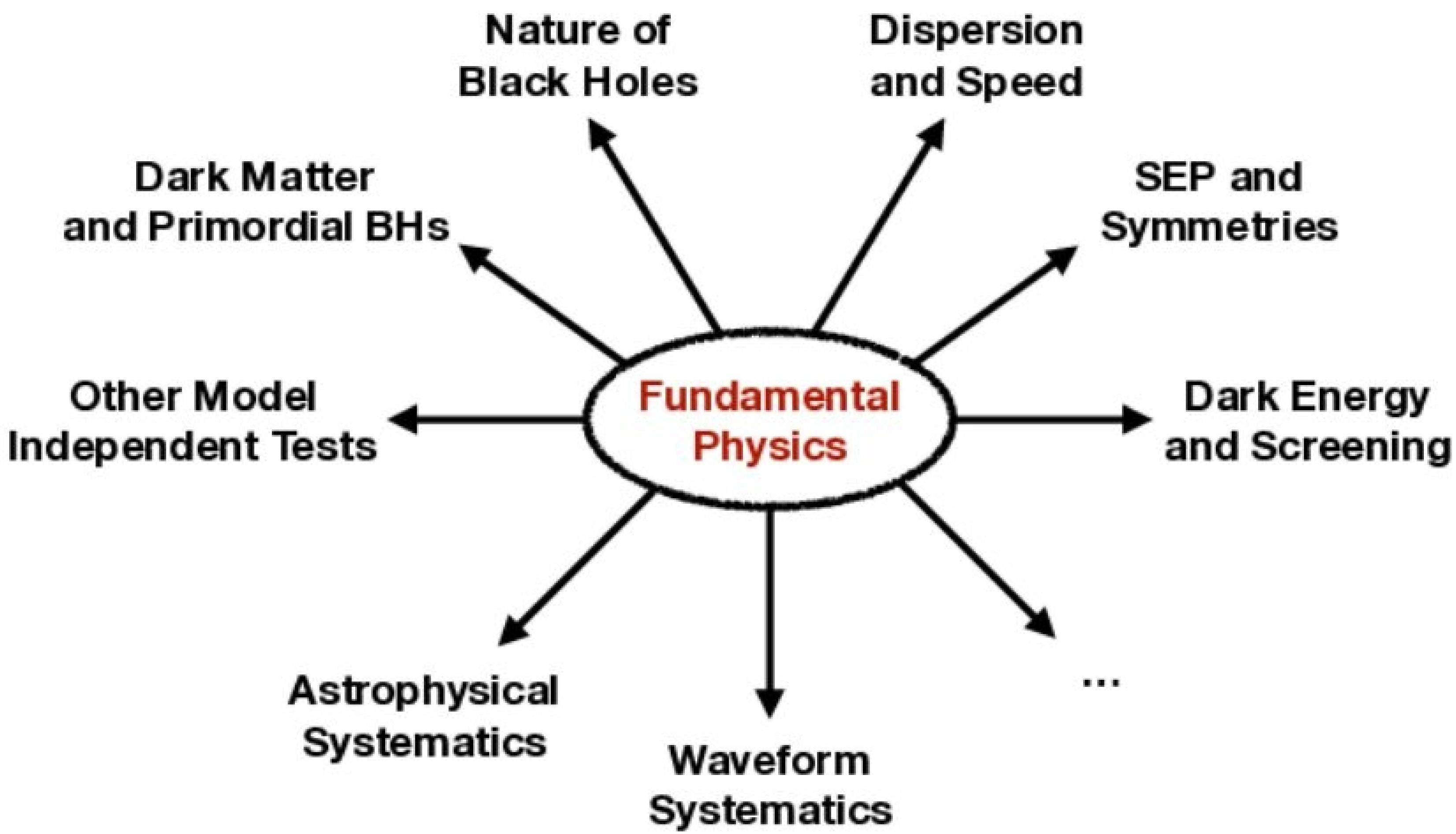
Fundamental Physics WG - White Paper

November 27, 2020

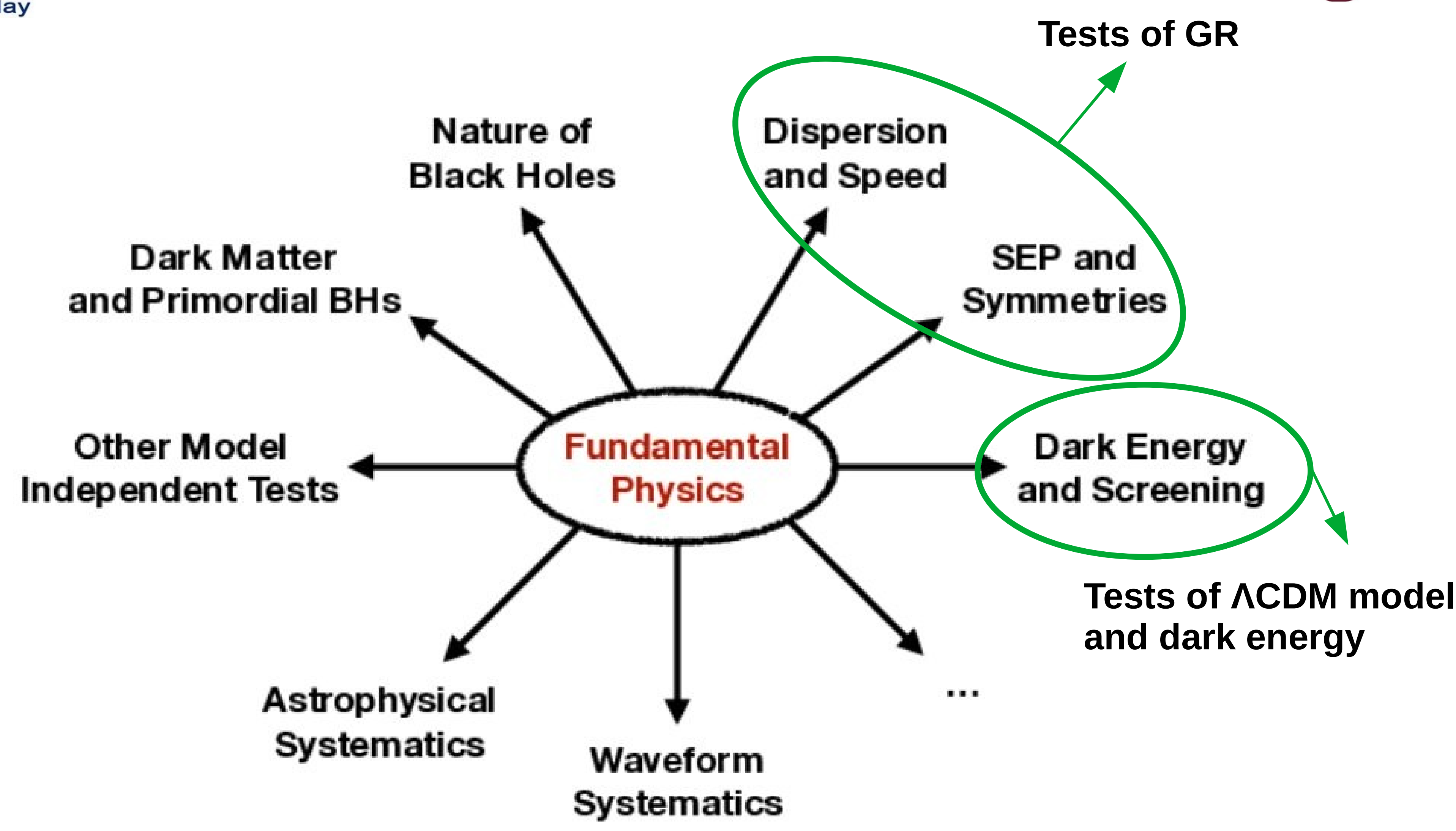
Contents

Next meeting (in person) of the FPWG
should take place: 11-14 January 2022
at the Solvay-Institute in Brussels (Belgium)
(as part of the 'Cosmological Frontiers' Series)

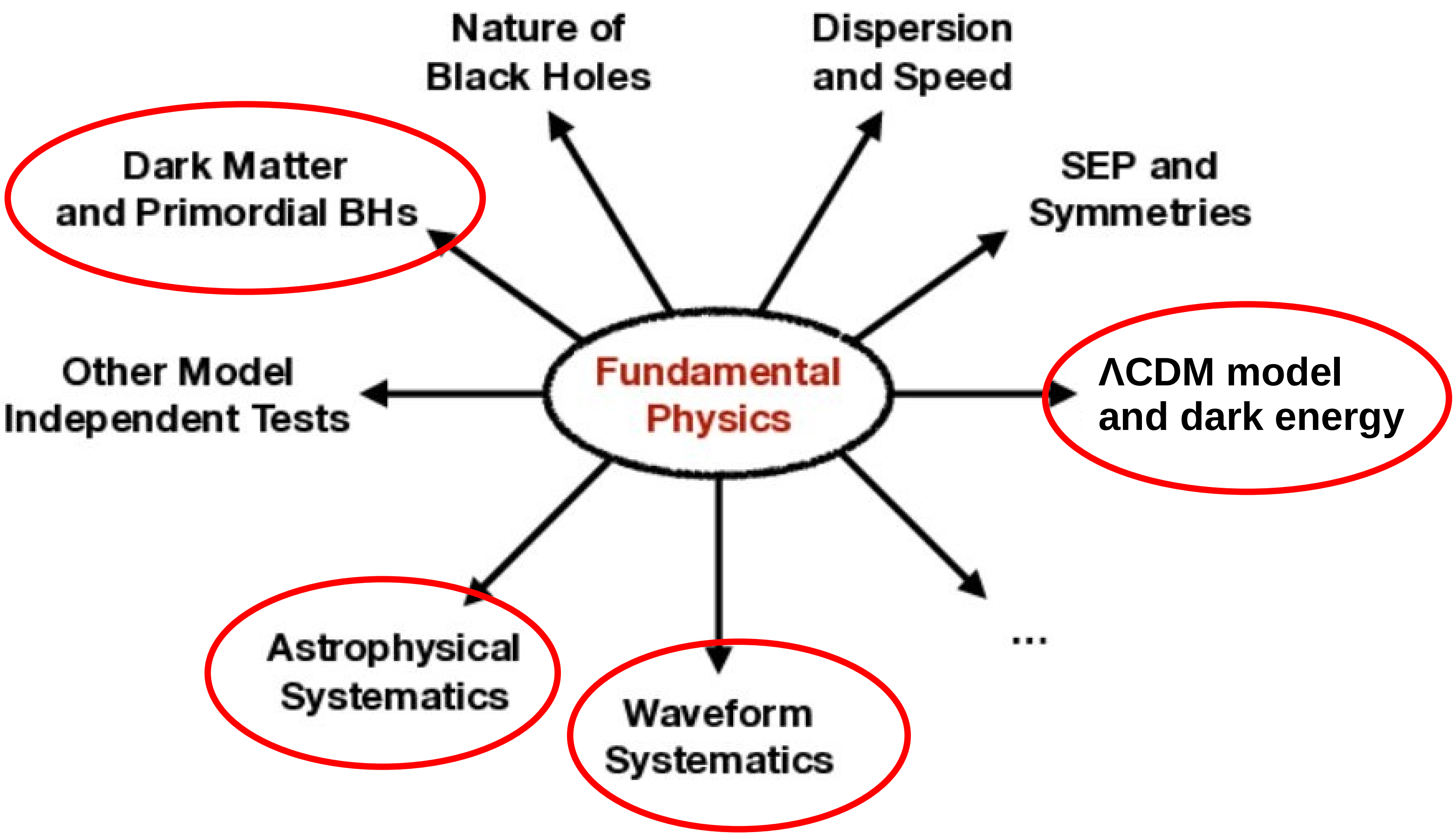
From Gen.Rel.Grav. 52 (2020) 8, 81 ….



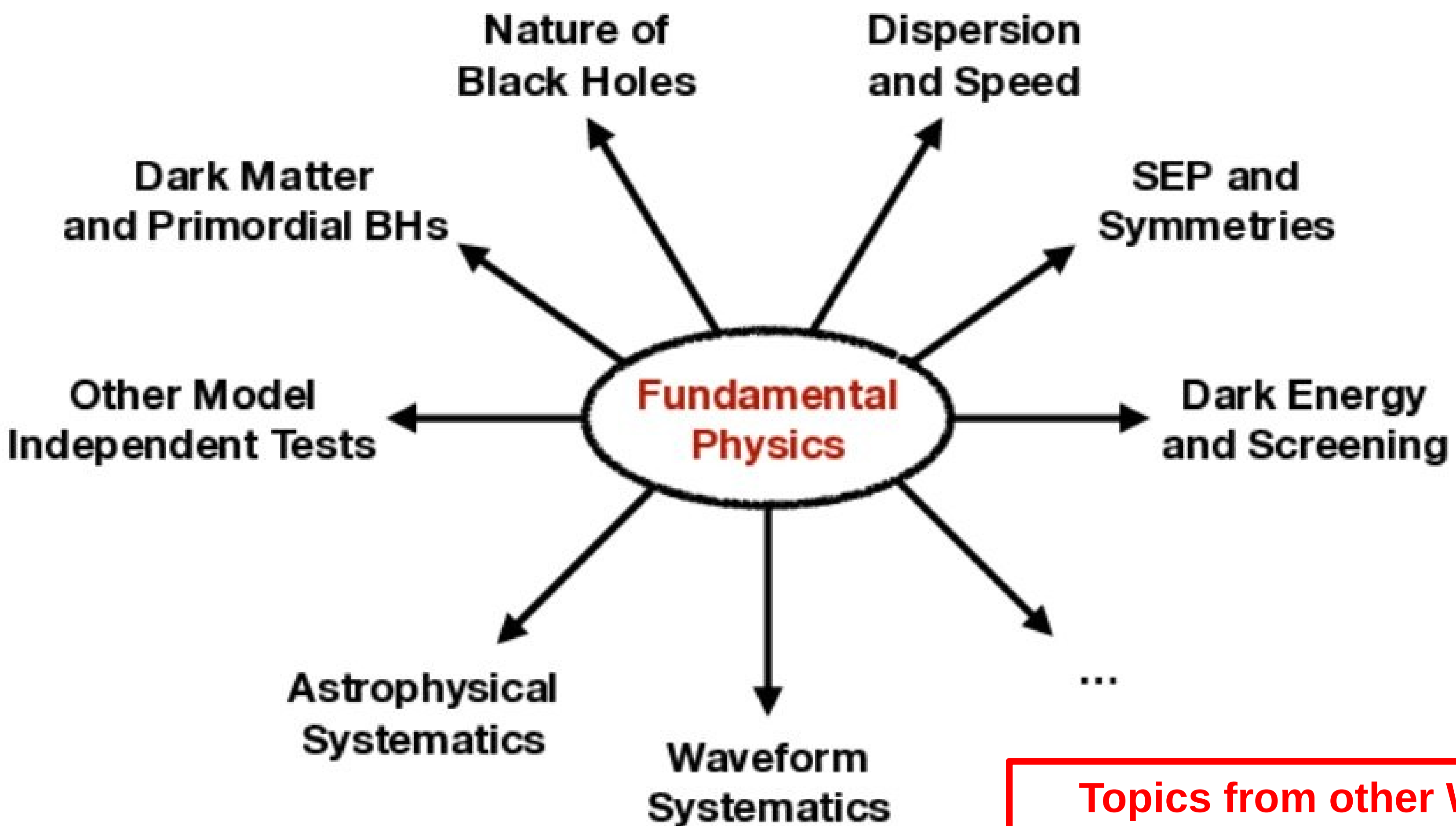
… to the Fundamental Physics WP



Also in other LISA LSG WGs



Borrowing from other WGs ?



Topics from other WGs could also appear here : e.g. 1st order PT → SGWB BSM of particle physics (presently in cosmo WG)

Selected topics on

Tests of GR

Tests of the nature of Black Holes

Dark matter and primordial Black Holes

ΛCDM model and dark energy

summary

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Tests of GR

Selected topics on

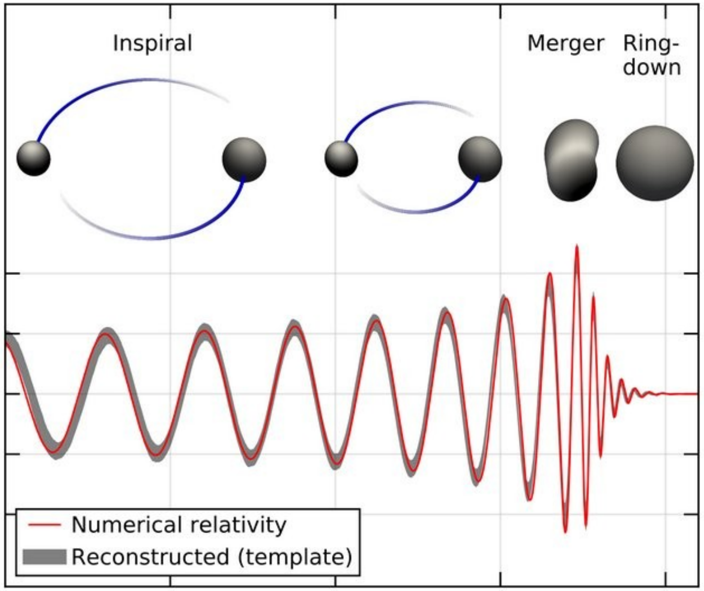
- Inspiral – Merger – Ringdown tests
- test of GR with Extreme Mass Ratio Inspirals (EMRIs)
- Modified dispersion relations and speed of gravity
- Memory effect

Tests of GR

- **inspiral :** LISA will observe very long inspiral phases

  → allow for high precision tests of gravity

  → improve the constraints on different non-GR predictions

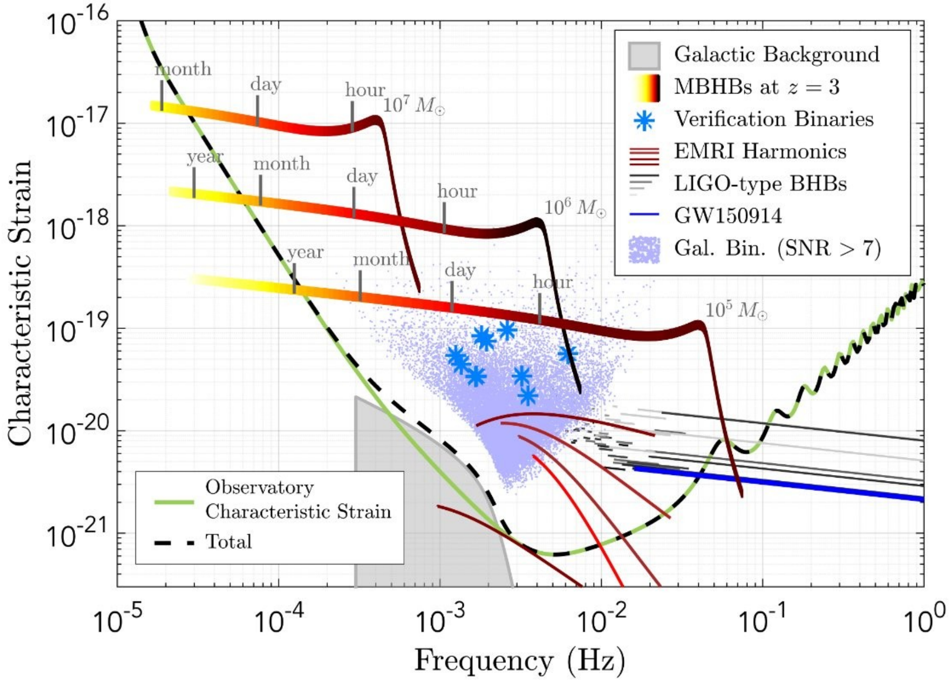


- possibility for multiband GW observations

  (with ground base detectors)

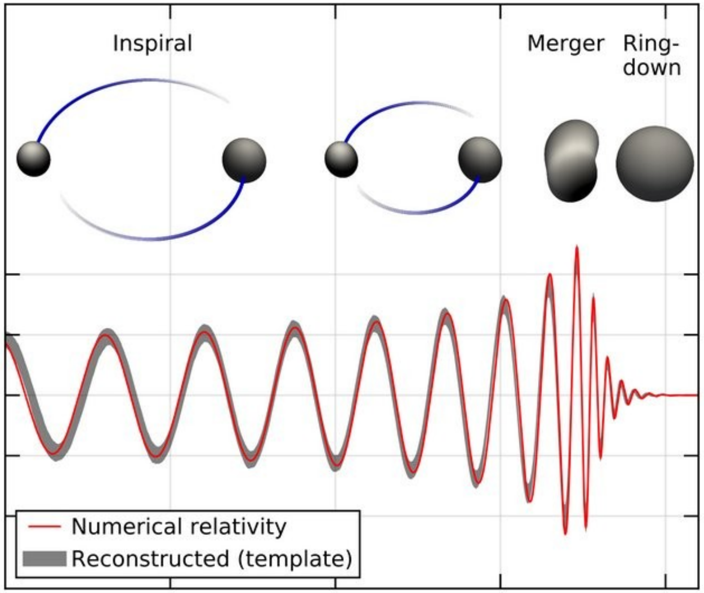
  using the LISA observations and assuming GR

  → obtain high-accuracy prediction of the time when the binary will become observable by ground-based detectors



Tests of GR

- **Merger**
  - → non linear effects of gravity truly manifest themselves
  - → very challenging regime to model,
    requiring full nonlinear evolutions of the field equations
  - → model-independent, self-consistency test could be used
    e.g the inspiral-merger-ringdown consistency test
  - → but theory-specific waveforms also seen as essential
    - can provide stringent constraints,
      and are useful for interpreting them physically
    - can be used to quantitatively explore deviations from GR
      that do not affect other parts of the waveform
      e.g. new fields that are highly excited by nonlinear effects
      and decay rapidly)
    - guide and calibrate parametrizations



- **Ringdown** → see also few slides later
  - → in GR the end state of a BBH merger is a Kerr BH
  - → before reaching the final Kerr state the BH emits GWs in quasinormal modes (QNMs see later)

Tests of GR

- **Test of GR with Extreme Mass Ratio Inspirals (EMRIs)**

  → opportunity to probe gravity in a mass range unique to LISA

  → stellar mass object orbits around a more massive one with typical mass ratios of the order of $q \sim 10^{-5} - 10^{-7}$

  → large number of accumulated cycles before the merger proportional to $\sim 1/q$

  → slow inspiral provides a detailed map of the spacetime

  → look for deviations from GR predictions (if any)

  → requires detailed knowledge of the emitted waveform to avoid spurious systematics

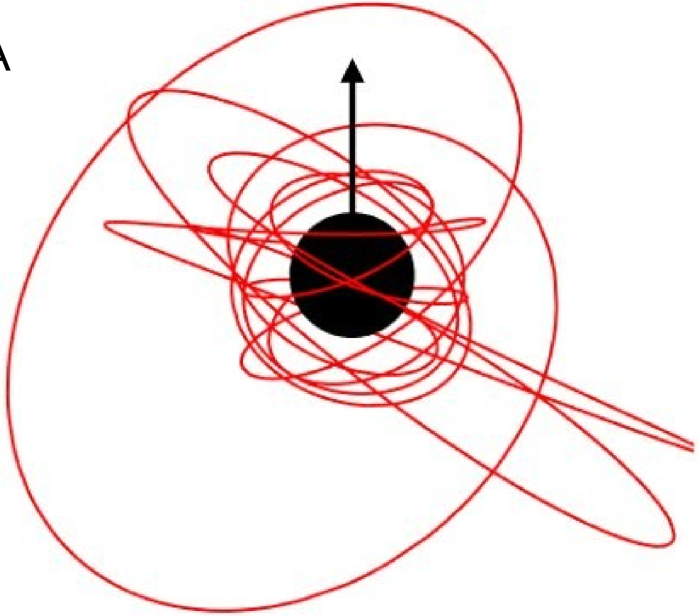


Figure from Larry Kidder, Harald Pfeiffer, Barry Wardell

Tests of GR

Modified dispersion relations and speed of gravity

- according to GR → group and phase velocity of GWs = speed of light

- Modified theories of gravity can lead to different dispersion relations (see backup) allowing :

  → either to constrain a hypothetical graviton mass ($m_g \leq 1.76\ 10^{-23}$ eV/c^2 from LIGO/Virgo)

  → or test the rate of GW dissipation

- best systems to constrain these modifications → those as far away as possible from Earth

  → because modifications to propagation of GWs accumulate with distance traveled

  → because corrections scale with the chirp mass (constraints on m_g enhanced for supermassive systems)

  → but depending on the type of modification constraints deteriorating as an inverse power of the chirp mass

- confirmation of dispersion relation of GR could place constraints on (for example) :

  → theories with extra dimensions or quantum-inspired Lorentz violation

  → modified gravity models to explain late-time acceleration of the universe

Tests of GR

Modified dispersion relations and speed of gravity

- speed of gravity in GR

  → cannot be measured precisely with **only** GWs detected with a space-based instrument or multiple ground-based detectors

  → its precise determination **requires an electromagnetic coincident observation**

- constraints on the speed of gravity are typically possible with

  → NS binaries or BH-NS binaries inducing an e.m. signal when considering ground-based detectors

  → SMBHB mergers when considering space-based detectors

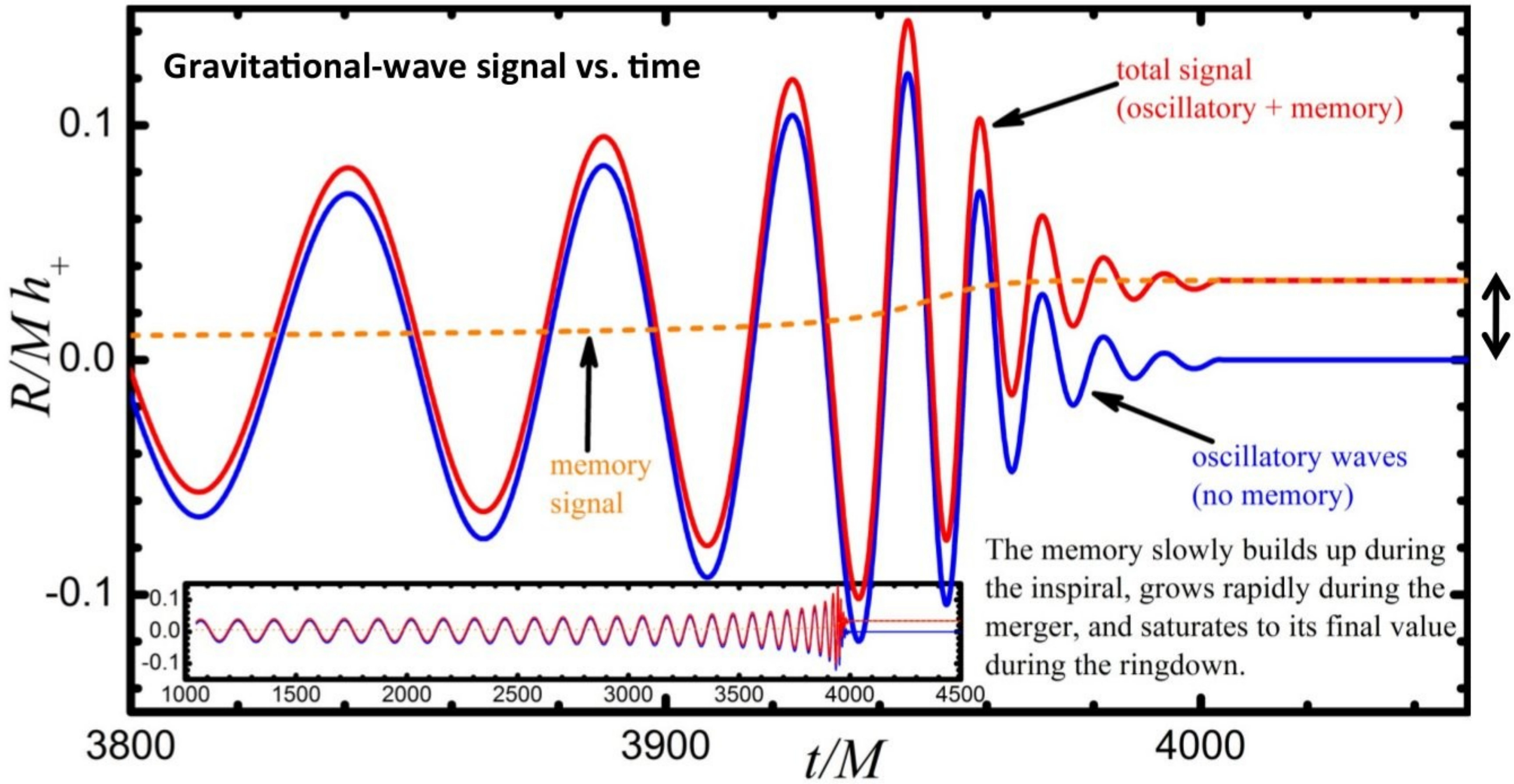
  EMRIs in which a neutron star falls into SMBH will not lead to tidal disruption outside the horizon of a SMBH due to the latter's mass, thereby decreasing the chances to generate detectable electromagnetic signals

- **LIGO-Virgo observations have already constrained the speed of gravity to better than one part in 10^{15}**

Tests of GR

Gravitational Wave memory

GW passing through a system of 2 isolated free-falling test masses would permanently stretch or compress the distance between them



example: nonlinear memory from binary black-hole mergers

from M. Favata

Tests of GR

GW memory with SMBHBs

- for a supermassive black hole binary (SMBHB) undergoing coalescence :

  - memory signal initially displays negligible growth corresponding to the slow time evolution of the binary's inspiral

  - during binary coalescence (most dynamic phase), system emits a burst of memory signal

- observations of SMBHB coalescence memory events could :

  - shed light on strong-field effects of General Relativity (GR)

  - provide information about SMBHB properties In addition from the one obtained from the oscillatory components

  - hints for **fundamental symmetries in GR** such as **asymptotic symmetries (e.g BMS) ?**

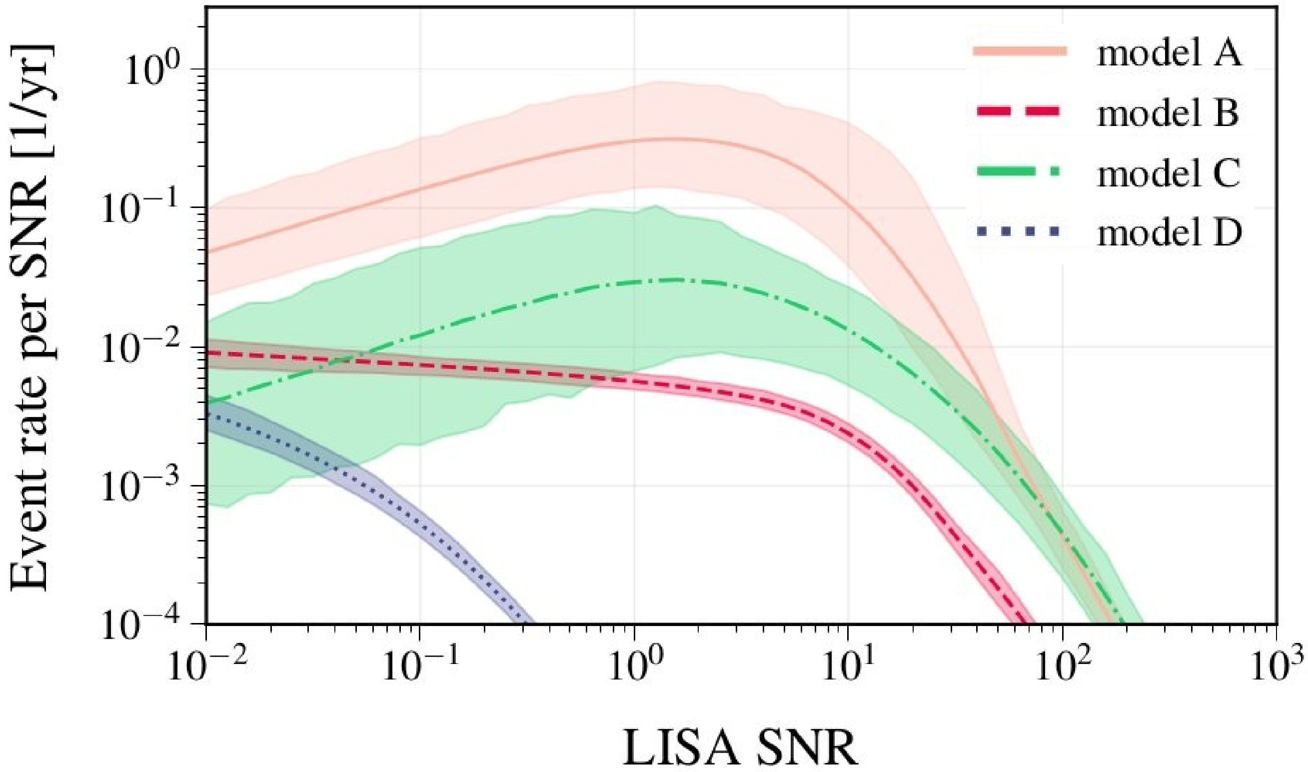
Tests of GR

Memory event rates

- LISA prospects for
  SNR ≥ 5 events :

→ occurring 0.3 − 2.8 times / year
  in the most optimistic model

→ less than 1 per million years
  in the most pessimistic



simple model for the binary evolution
due to environmental interactions

Table 1. Glossary of decoupling models

Model	GSMF	$M-M_{\rm bulge}$	Orbital Decay	Power-law parameters
A	Ilbert+Baldry	McConnell & Ma	replenished loss-cone; gas-driven	$1.0 \leq \alpha \leq 3.0$, $a_8 = 0.01$ pc
B	Ilbert+Baldry	Shankar	replenished loss-cone; gas-driven	$1.0 \leq \alpha \leq 3.0$, $a_8 = 0.01$ pc
C	Ilbert+Baldry	McConnell & Ma	no loss-cone refilling, no gas	$\alpha = 1.0$, $a_8 = 1.3$ pc
D	Ilbert+Baldry	Shankar	no loss-cone refilling, no gas	$\alpha = 1.0$, $a_8 = 1.3$ pc

K. Islo, J. Simon, S. Burke-Spolaor, X. Siemens, arXiv:1906.11936

Selected topics on

Tests of GR

Tests of the nature of Black Holes

Dark matter and primordial Black Holes

ΛCDM model and dark energy

summary

Tests of the nature of Black Holes

- **Kerr hypothesis**

  - deviations from the Kerr hypothesis

  - Exotic Compact Objects (ECOs)

- **Observables and tests (→ see backup)**

  - inspiral-based test with MBHBs, IMBHBs, and EMRIs

  - Tidal heating

  - Tidal deformability

- **Ringdown tests**

  - Quasi Normal Modes (QNMs)

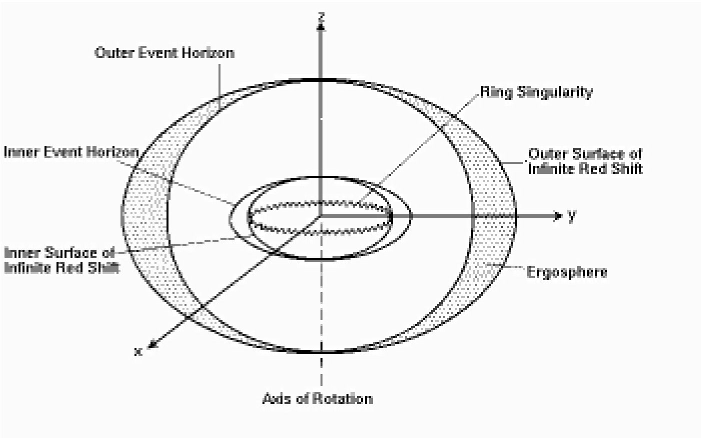
  - Echoes

Tests of the nature of Black Holes

deviations from the Kerr hypothesis

- deviations from the Kerr hypothesis

→ Kerr geometry : unique physically acceptable equilibrium, asymptotically flat BH solution
(Carter-Robinson uniqueness theorem in vacuum GR)



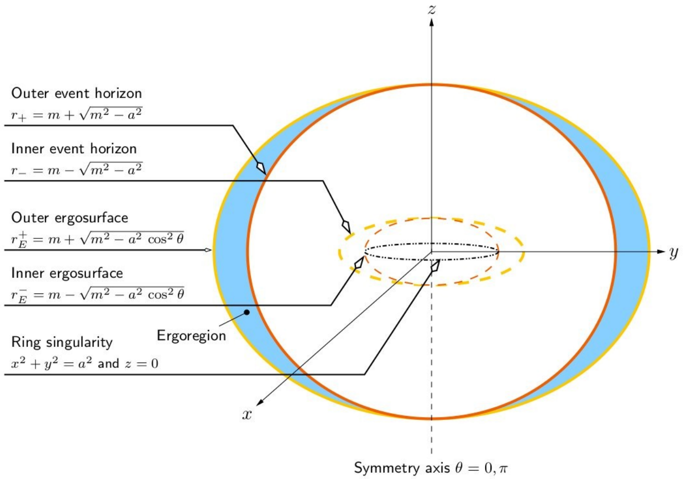


Fig from M. Visser arXiv:0706.0622

→ deviations from Kerr hypothesis require either non vacuum GR or modified gravity

- Black holes in non-vacuum GR

- Exotic Compact Objects (ECOs): deviations from (or absence of) a classical horizon

Tests of the nature of Black Holes

deviations from the Kerr hypothesis

- non vacuum GR

- adding minimally coupled matter fields (with standard kinetic terms and obeying some energy conditions) prevents the existence of non-Kerr BH in many models

→ model-specific no-hair theorems

- but several models with non-standard kinetic terms and with interacting real scalar hair and Yang Mills hair

→ allow existence of new families of BHs with hair co-existing with the vacuum Kerr solution

- astrophysical relevant hairy BHs in GR could occur in the presence of hypothetical ultra-light massive bosonic fields (e.g. QCD axion), axion-like particles, dark photons … etc

→ could be a significant component of the dark matter

→ predicted in a multitude of scenarios beyond the Standard Model of particle physics (including extra dimensions and string theories)

→ check for superradiance instabilities of Kerr BH
superradiance → SGWB, continuous GW sources, effect on EMRIs

Tests of the nature of Black Holes

deviations from the Kerr hypothesis

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- Exotic Compact Objects (ECOs)

→ hypothetical dark compact objects without a classical BH horizon

Penrose's theorem → apparent horizon hides a curvature singularity where Einstein's theory breaks down

in semi-classical approximation BHs are thermodynamically unstable and have entropy far in excess of a typical stellar progenitor

ECO trying to overcome conceptual issues associated to BHs (inner structure and information loss paradox)

→ can mimic the phenomenology of BHs at the classical level

→ may be described by their compactness, reflectivity
and possible extra degrees of freedom related to additional fields

→ absence of (or deviations from) a classical horizon
could circumvent the singularity problem

→ quantum corrections may be relevant at the horizon scale
(even for small-curvature supermassive objects)

Tests of the nature of Black Holes

deviations from the Kerr hypothesis

- examples of ECOs

→ bosonic stars (one of the most studied) :

- self-gravitating solitons, composed of either scalar or vector massive complex fields, minimally coupled to Einstein's gravity

- arise in families of models with different classes of self-interactions of the bosonic fields (may also be generalized to modified gravity)

- could in principle "co-exist" with BH and be exotic sources for LISA

→ more ambitious 1^{st}-principle model of ECO aiming instead at replacing the classical horizon completely :

- fuzzball proposal : classical horizon replaced by smooth horizonless geometries with same mass, charges, and angular momentum as the corresponding BH

- these geometries represent some of the microstates in the low-energy (super)gravity description, (microstate geometries can emerge from low-energy truncation of string theory)

- for special classes of extremal charged BHs, one can precisely count the microstates accounting for the BH entropy → thus providing a microscopic description of a classical horizon

→ and many other examples including gravastars (dark energy stars), wormholes ...

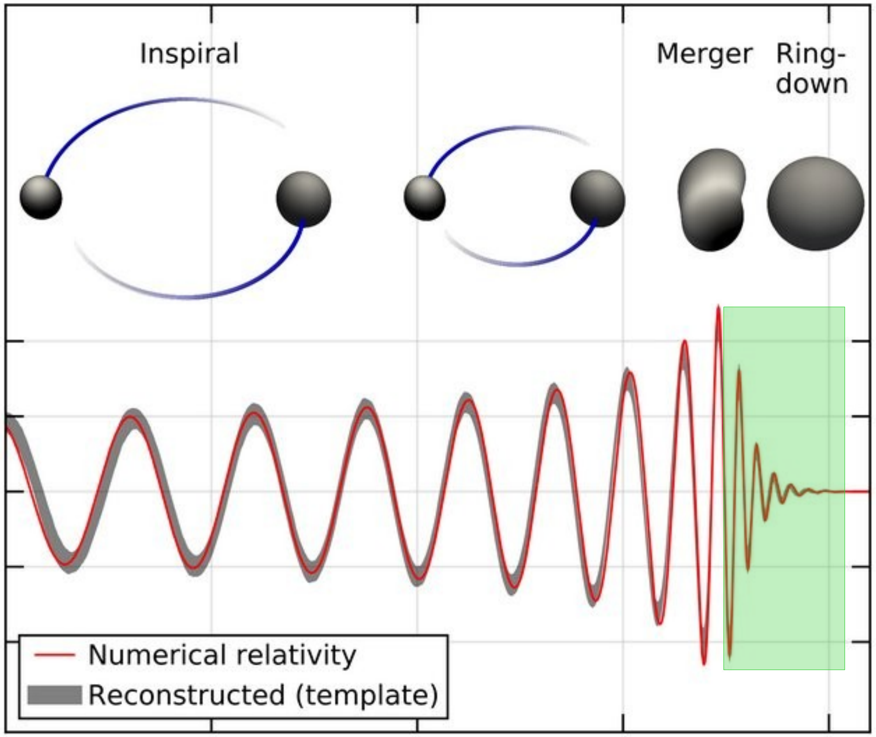
Tests of the nature of Black Holes

Ringdown tests : Quasi Normal modes

- ringdown GW dominated by superposition of damped modes of the remnant → **Quasi Normal Modes** → **BH spectroscopy**

$$h = \sum_{lmn} h_{lmn} \propto \frac{M}{r} \sum_{lmn} A_{lmn} \quad e^{-t/\tau_{lmn}} \cos\left(\omega_{lmn}\, t\right)$$

h strain of GW, M mass of BH,
A_{lmn} mode amplitude, τ_{lmn} mode damping time
l=2, m= 2, n = 0 → least damped mode



- only depend on the parameters describing a Kerr BH

  - mass M

  - dimensionless spin a (a = Jc/GM^2)

  → no-hair theorem (with non charged BH)

- testing the no-hair theorem

  → identification of at least 2 QNM frequencies in the ringdown

  → identifying 3 QNM frequencies in the ringdown would even be better

QNMs
Constraints from LIGO-Virgo

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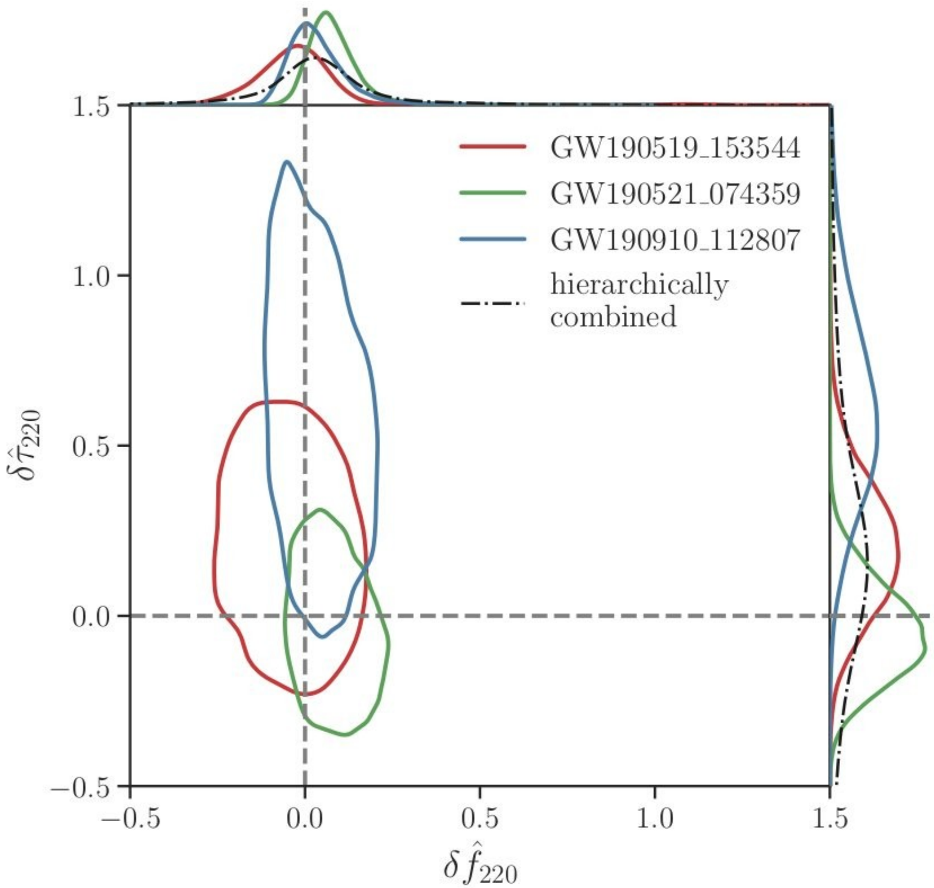
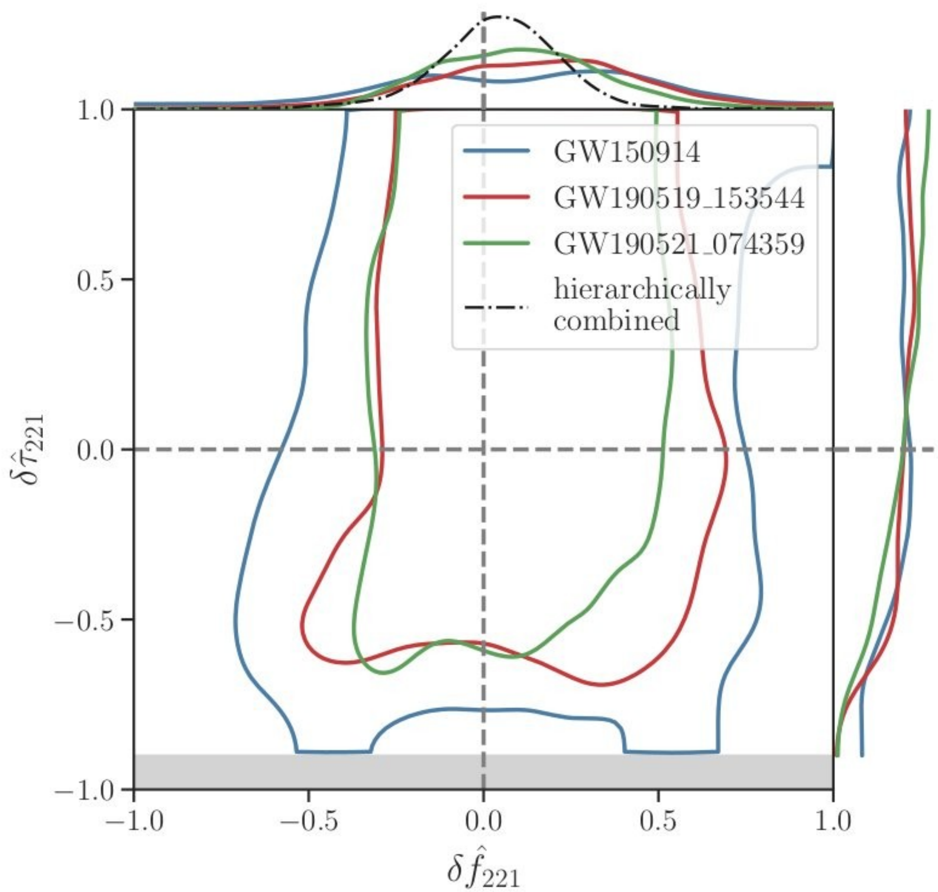
90% credible regions of the joint posterior distribution of fractional deviations of the frequency δf_{lmn} and the damping time $\delta \tau_{lmn}$





parametrized wafeform model (pSEOBNRv4HM) analysis :

→ consistent with GR

pyRing analysis (time domain) :

→ consistent with GR for the frequency mostly unconstrained for the damping time

B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations) arXiv :2010.14529

Tests of the nature of Black Holes

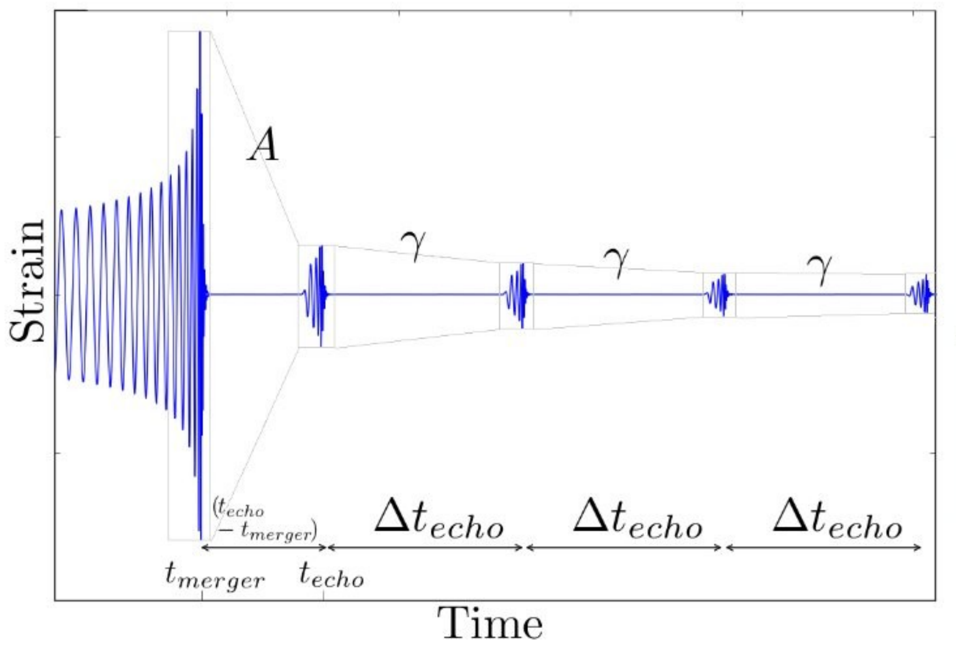
GW Echoes

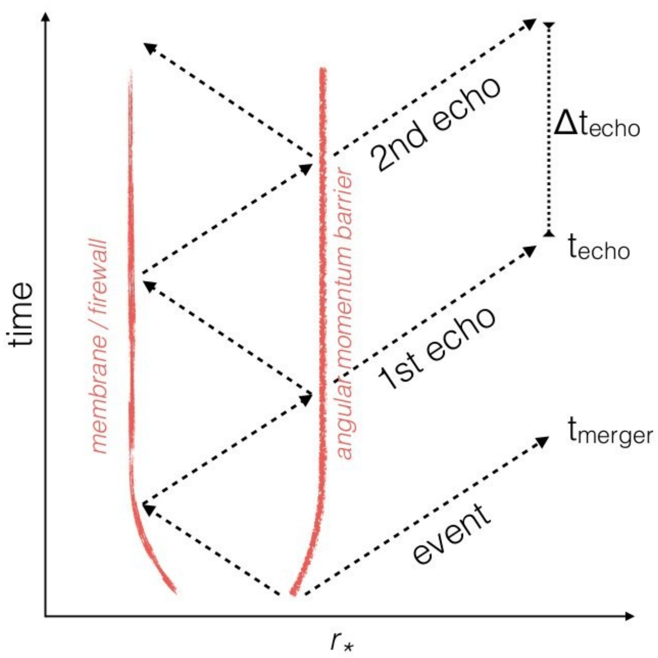
- possible GW echoes during ringdown phase of a spinning BH from postmerger coalescence

→ multiple reflections of the GW wave between BH horizon and BH angular momentum potential barrier and transmission properties of the latter

→ astrophysical signals could be a smoking gun to explore near-horizon quantum structures, ultracompact objects exotic states of matter in ultracompact stars and of modified theories of gravity

→ hope to shed light on BH horizon quantum properties





Tests of the nature of Black Holes

GW Echoes

- independent searches found evidence for GW echoes in postmerger phase of O1 and O2 events from LIGO/Virgo data

  → low statistical significance

  → recently negative searches from O3a (B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations) arXiv :2010.14529)

- excluding or detecting GW echoes from partially absorbing compact objects requires SNRs of O(100) in the post-merger phase

  → LISA will allow to place strong constraints on the reflectivity and the compactness of ECO

Selected topics on

Tests of GR

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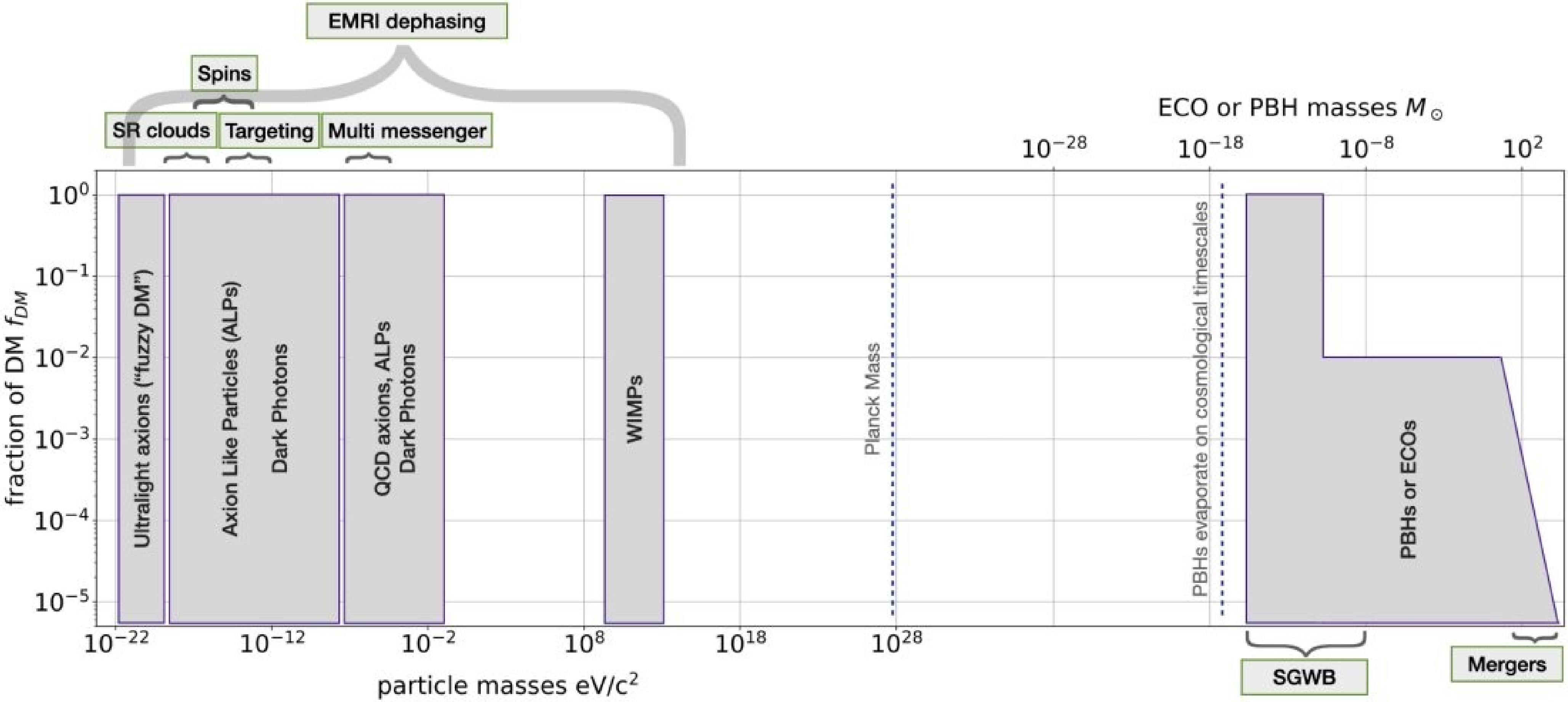
Dark matter and primordial Black Holes

ΛCDM model and dark energy

summary

Dark Matter and Primordial BH

- LISA observations may provide constraints on a large spectrum of key DM candidates and regions



Dark Matter and Primordial BH

ultralight DM bosons with 10^{-22} eV < m < 1 eV

- QCD axion, axion-like particles, dark photons, fuzzy dark matter ….

- superradiant scattering of massive bosonic fields off a rotating BH → BH can become unstable frequency waves off a rotating BH is amplified
  - → energy transfer i.e. BH's mass and angular momentum to bosonic field
  - → BH spins down
  - → formation of a long-lived bosonic "cloud" outside the horizon

- could be observable individually or as a very strong stochastic GW background

- LISA could be sensitive to bosons of mass m $\sim 10^{-19} - 10^{-15}$ eV

Dark Matter and Primordial BH

ultralight DM bosons with 10^{-22} eV < m < 1 eV

- More phenomena could leave imprints in GW signal from the binary system

  - presence of a cloud through spin-induced multiple moment(s) and tidal Love number(s)

  - presence of a companion can result into

    resonant transitions between energy levels of the cloud

    or complete tidal disruption
    → significant dephasing of the binary's GW signal

  - ultralight scalars can also form self-gravitating structures

- in the case of EMRIs

  - dynamical friction and gravitational pull from the cloud
    → sizable imprints on the GW waveform

  - for sources in the LISA band
    → more work is needed in order to build waveforms accurate enough for data analysis

Dark Matter and Primordial BH

Higher mass particles m > eV

- if a SMBH, IMBH, EMRI or IMRI merges when surrounded by a dense distribution of dark matter
  → binary's inspiral driven by both dynamical friction and GW emission

- densities required to produce an effect observable by LISA
  → typically higher than the characteristic DM densities in most galaxies

- but possible to enhanced DM density to much higher levels
  → when a smaller seed black hole grows in mass adiabatically in a DM halo
  to produce a DM "mini-spike" surviving disruption leading to a residual overdensity

- the faster rate of inspiral in the presence of DM can be distinguished from the slower inspiral in vacuum → allowing LISA to infer the presence of DM around the binary

- waveform modeling for IMRIs and EMRIs with surrounding DM spikes coupled to their evolution

  → just beginning

  → more complete modeling of these systems will be necessary to produce waveforms

Dark Matter and **Primordial BH**

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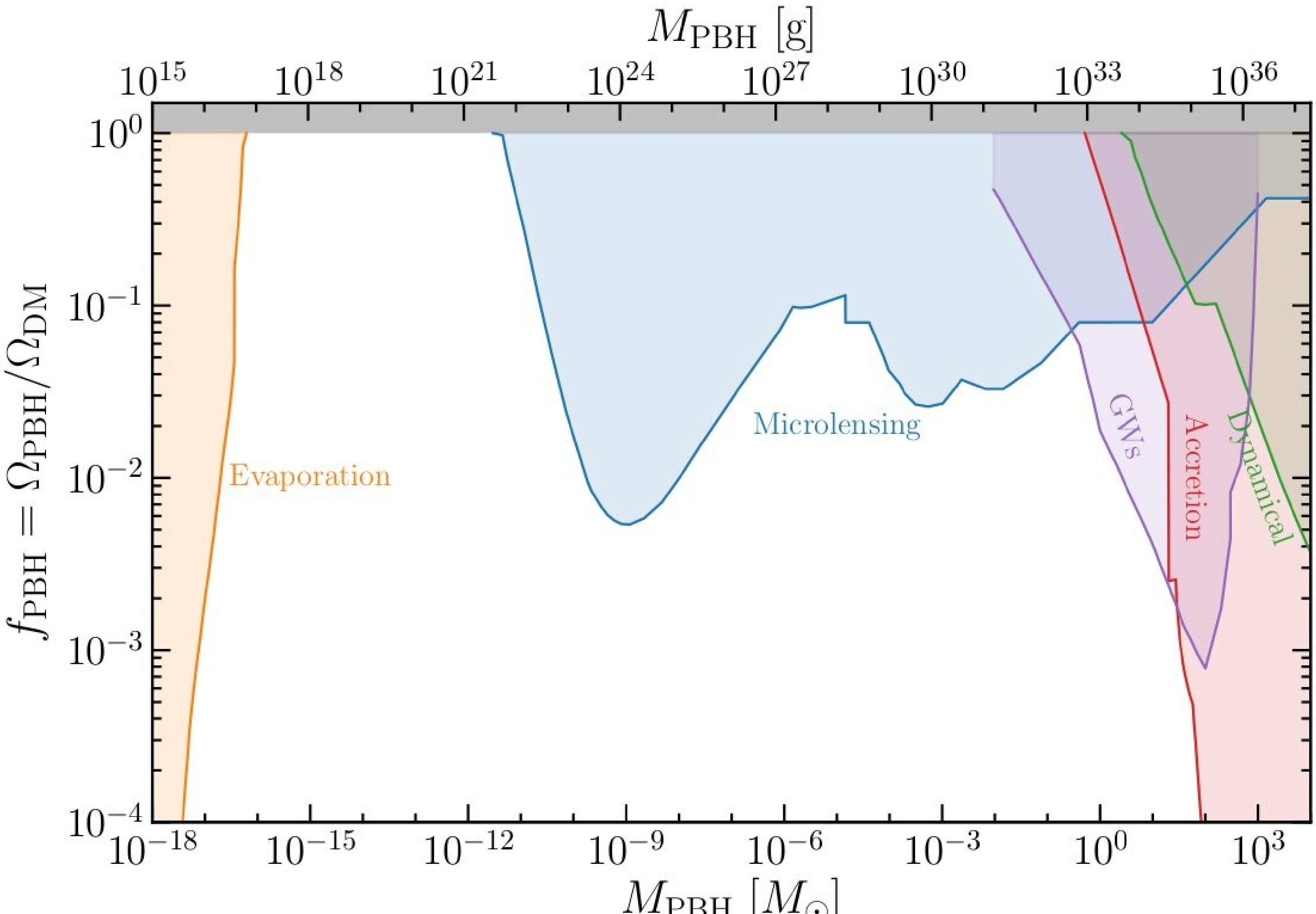
existing open window for PBHs with masses in the range $10^{-16} - 10^{-11}\ M_\odot$ to account for the totality of the dark matter in the universe



Green and Kavanagh 2007.10722

Dark Matter and Primordial BH

$M_{PBH} < M_\odot$

- $10^{-16} - 10^{-11}\ M_\odot$ mass range difficult to probe with lensing observations

- GWs from mergers of sub-solar mass PBHs
  peak at much higher frequencies compared to the ones testable by LISA

- but LISA can search for SGWB signatures of the PBH formation in that window

  → testing the possible nature of dark matter as asteroidal-mass PBHs

- curvature perturbations responsible for the PBH production would also
  lead to the emission of (second-order induced) SGWB

  → production of PBHs with masses around $M_{PBH} \sim O(10^{-15} - 10^{-8})\ M_\odot$
  associated to GW signals with peak frequencies within the LISA sensitivity band

Dark Matter and **Primordial BH**

$$M_{PBH} > M_{\odot}$$

- LISA should be able to detect merger events of resolved sources and unresolved signals in the form of a SGWB

- PBH abundance in various mass ranges → merger rate

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Dark energy and the ΛCDM model

- test models of dark energy **through the distance-redshift relation**

- GW sources at cosmological distances as reliable and independent distance indicators

  → yield a direct measurement of the luminosity distance

  → for cosmological applications they need a corresponding redshift measurement

  joint detection of an EM counterpart to infer the GW source redshift

  without any EM counterpart identification use "statistical method" on galaxy catalogues
  to infer redshift information

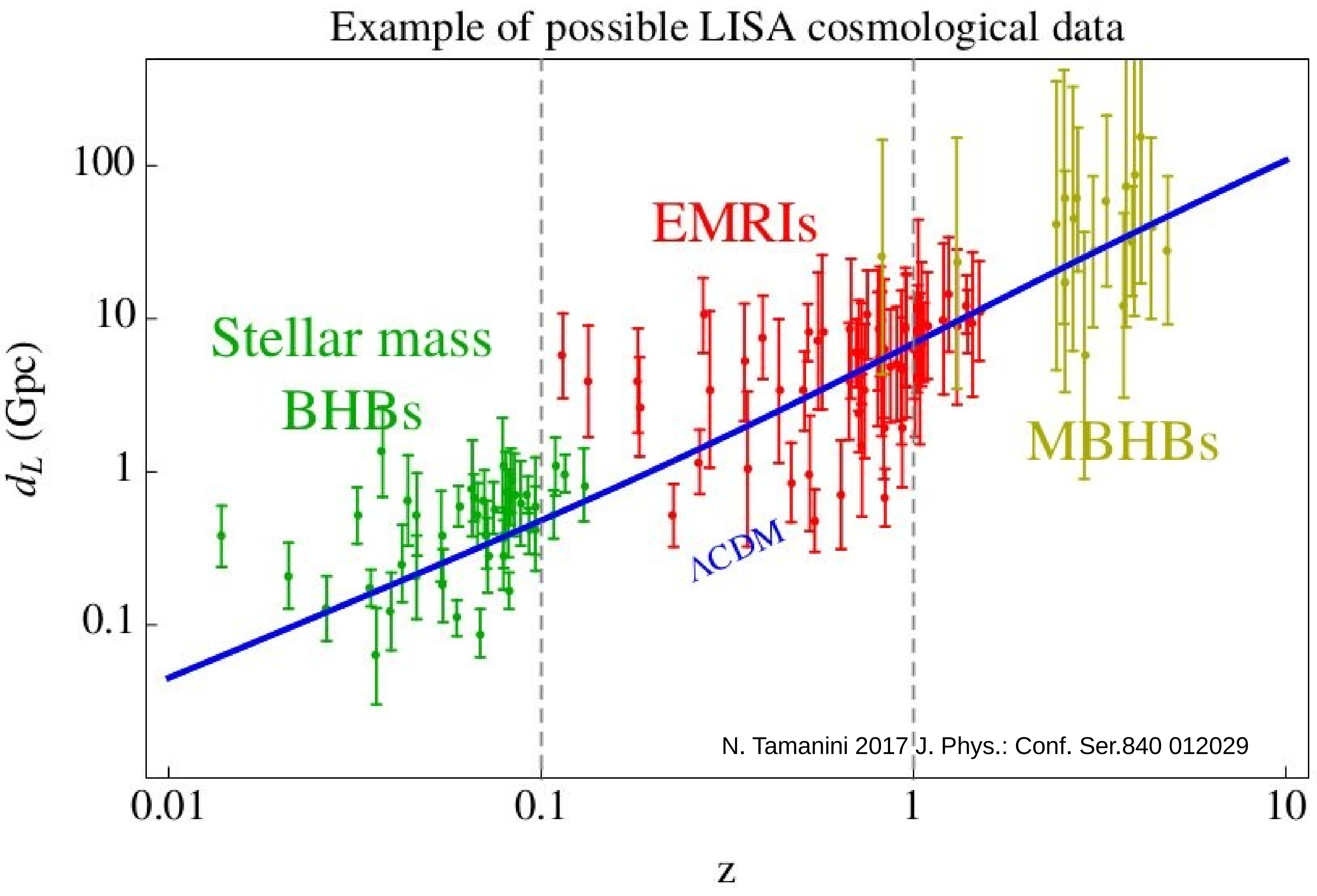
- LISA will detect mainly 3 types of GW sources at cosmological distances : SMBHBs, EMRIs, and SOBHBs

  → these sources to be observed at different redshift ranges:

  SOBHBs at $z < 0.1$
  EMRIs at $0.1 < z < 1$
  SMBHBs at $1 < z < 10$

  → **SMBHBs are expected to provide observable EM counterparts**

Dark energy and the ΛCDM model



- measurement of Hubble parameter can reach a precision of 1-3% depending on the MBHB formation model in the ΛCDM scenario (N. Tamanini et al. JCAP 04 (2016) 002)

Tests of GR : beyond GR ?

Luminosity distance ratio parametrization

simple parametrization that catches the main features of a large class of models in terms of a small number of parameters

$$\frac{d_L^{\mathrm{gw}}(z)}{d_L^{\mathrm{em}}(z)} = \Xi_0 + \frac{1 - \Xi_0}{(1+z)^n}$$

which depends on the parameters Ξ_0 and n (both taken to be positive) : in GR $\Xi_0 = 1$

Model	$\Xi_0 - 1$	n	Refs.
HS $f(R)$ gravity	$\frac{1}{2} f_{R0}$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[68]
Designer $f(R)$ gravity	$-0.24\Omega_m^{0.76} B_0$	$3.1\Omega_m^{0.24}$	[69]
Jordan–Brans–Dicke	$\frac{1}{2}\delta\phi_0$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[70]
Galileon cosmology	$\frac{\beta\phi_0}{2M_{\mathrm{Pl}}}$	$\frac{\dot{\phi}_0}{H_0\phi}$	[71]
$\alpha_M = \alpha_{M0} a^{\tilde{n}}$	$\frac{\alpha_{M0}}{2\tilde{n}}$	$\tilde{n}$	[67]
$\alpha_M = \alpha_{M0}\frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$	$-\frac{\alpha_{M0}}{6\Omega_\Lambda}\ln\Omega_m$	$-\frac{3\Omega_\Lambda}{\ln\Omega_m}$	[67, 72]
$\Omega = 1 + \Omega_+ a^{\tilde{n}}$	$\frac{1}{2}\Omega_+$	$\tilde{n}$	[6]
Minimal self-acceleration	$\lambda\left(\ln a_{acc} + \frac{C}{2}\chi_{acc}\right)$	$\frac{C/H_0-2}{\ln a_{acc}^2 - C\chi_{acc}}$	[66]

E.Belgacem etal. JCAP 1907, 024 (2019)

Tests of GR : beyond GR ?

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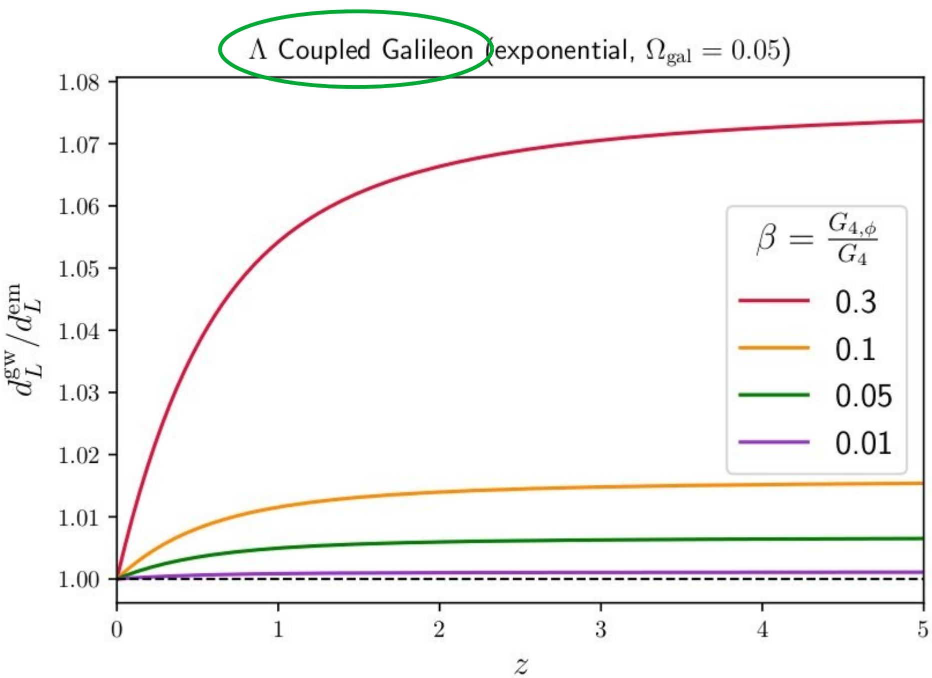
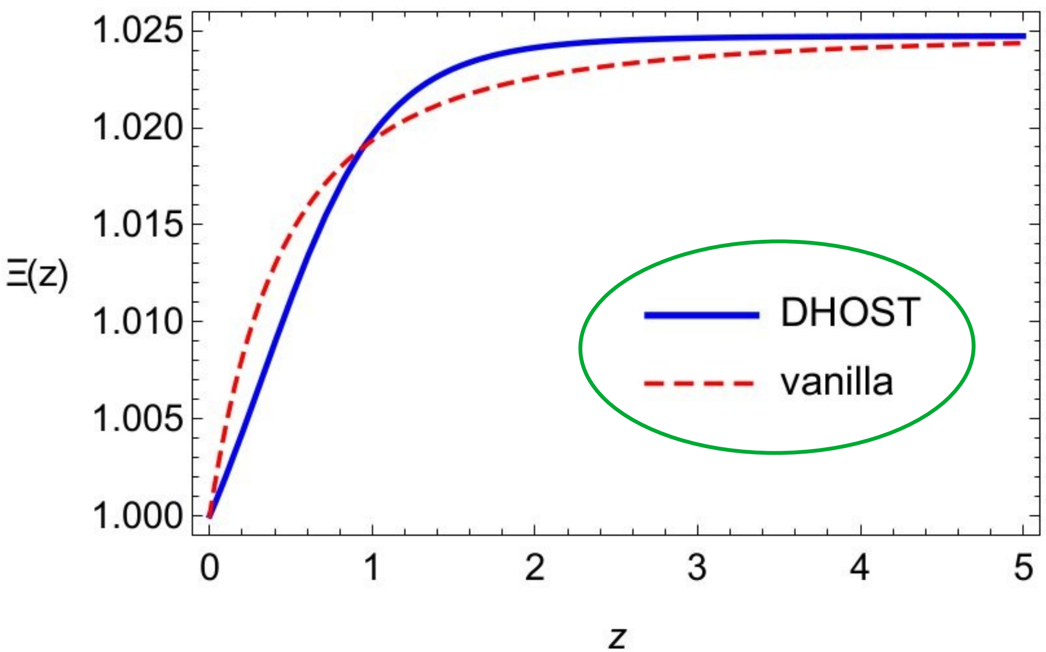
$$\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \Xi_0 + \frac{1 - \Xi_0}{(1 + z)^n}$$

which depends on the parameters Ξ_0 and n (both taken to be positive) : in GR $\Xi_0 = 1$



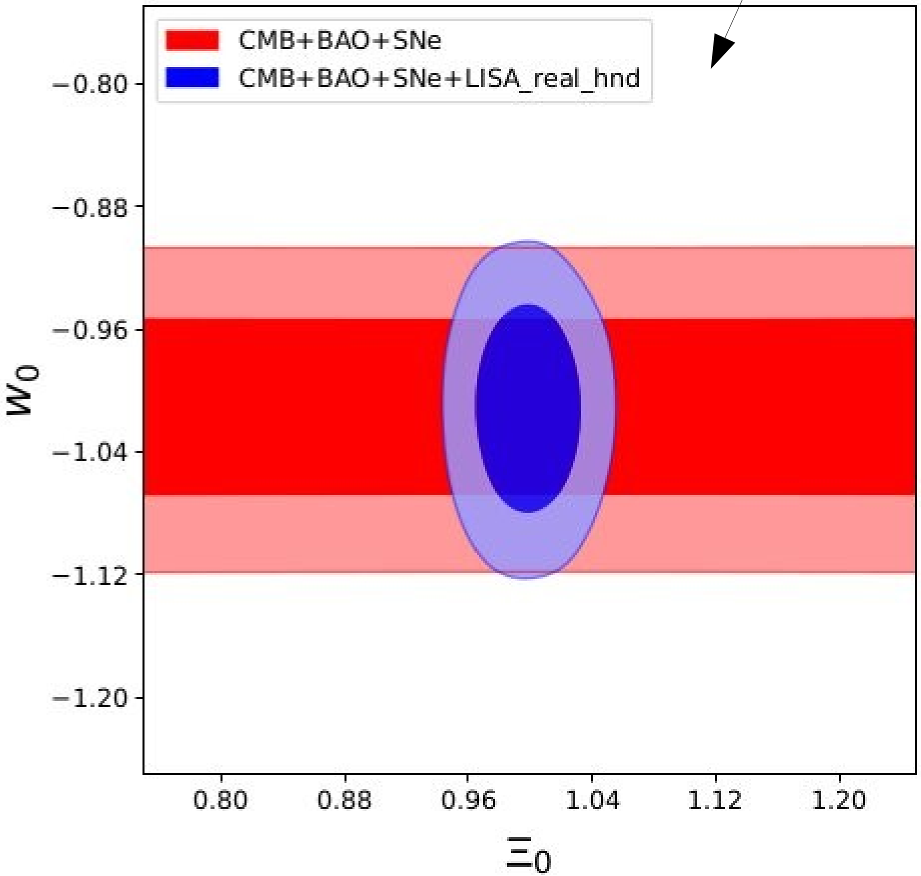


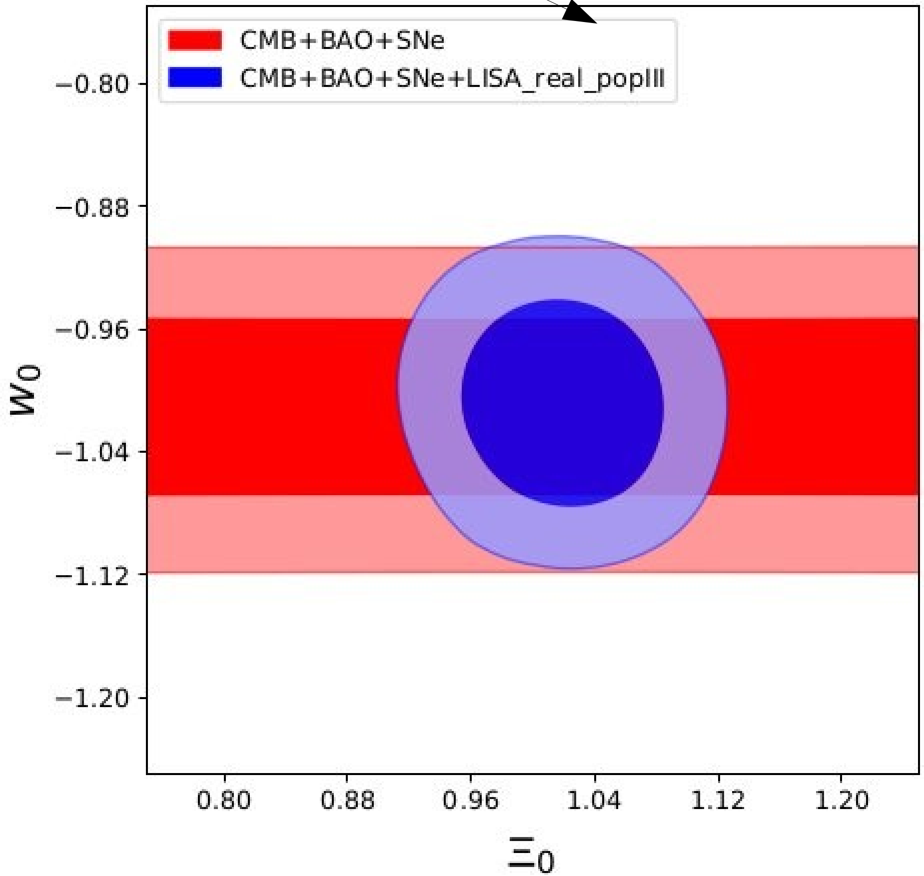
E.Belgacem etal. JCAP 1907, 024 (2019)

Tests of GR : beyond GR ?

LISA sensittivity forecasts to Ξ_0 using SMBHB coalescence (with em counterparts)

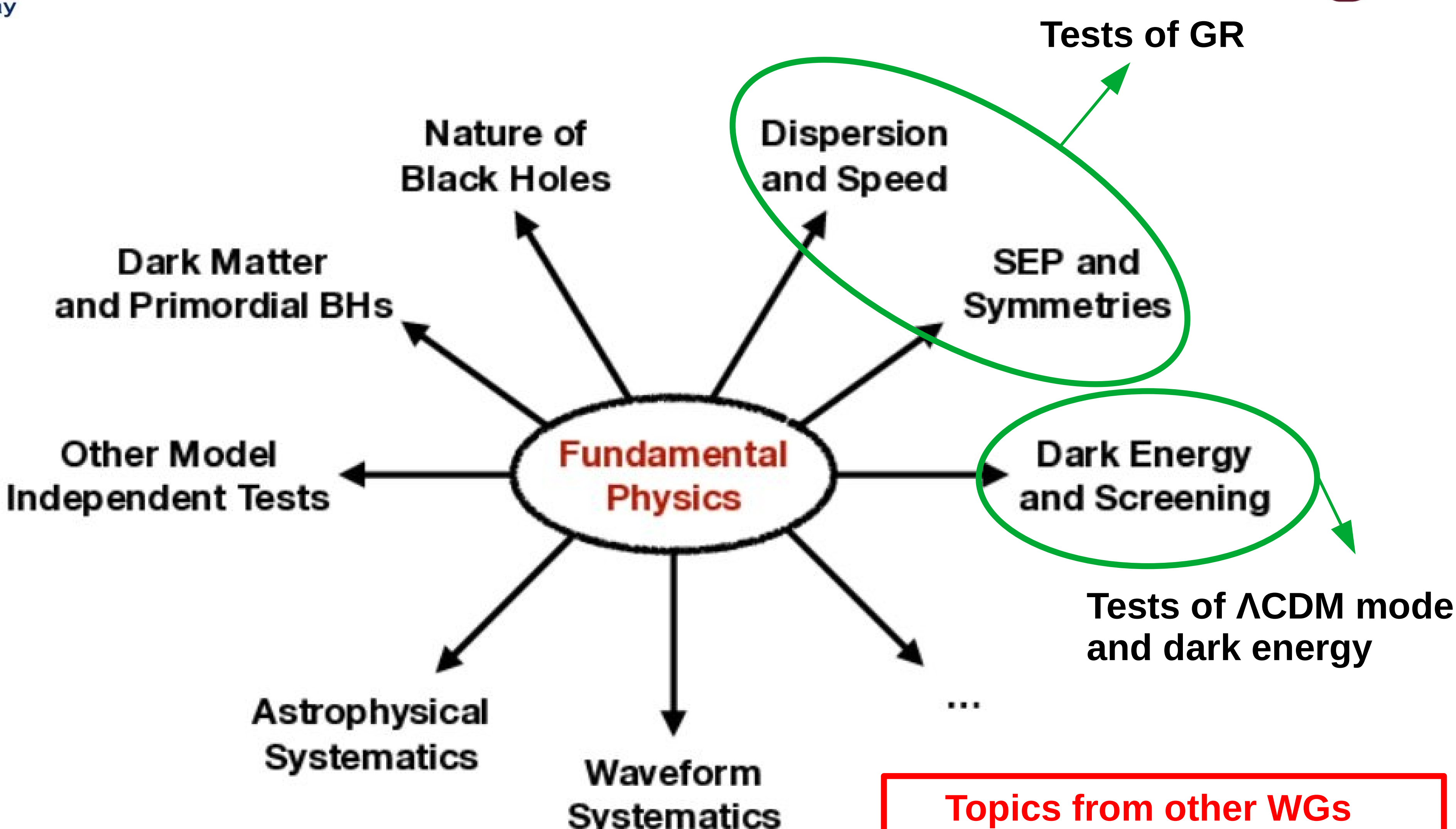
for 2 astrophysical scenarii :
heavy seads and no-delay (“hnd”) scenario and “pop III” seeds





E.Belgacem etal. JCAP 1907, 024 (2019)

… to the Fundamental Physics WP



Topics from other WGs could also appear here : e.g. 1st order PT → SGWB BSM of particle physics

LISA Fundamental Physics WG

Summary

- addresses a very large spectrum of fundamental physics topics and questions

  - GR and maybe beyond GR

  - Dark matter and dark energy

  - Black hole physics

    LISA witnessing GR meeting the quantum world ?

  - Connections with High Energy Physics

    BSM of particle physics, LHC experiments ...

  - more new ideas … ?

- connection with many other WG in LISA

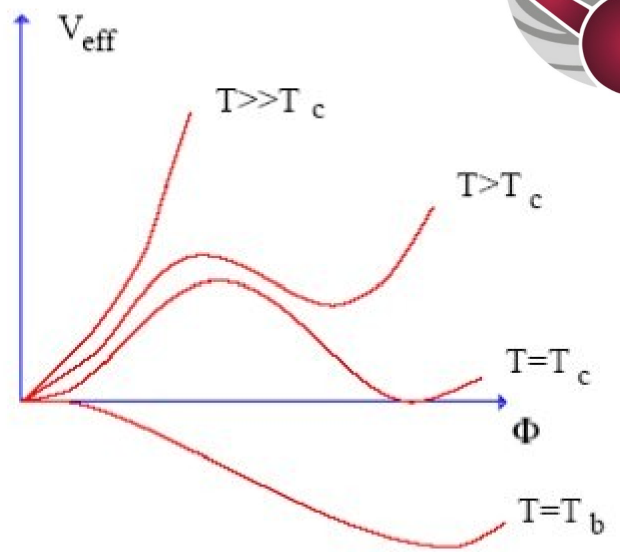
- utter importance of astrophysics inputs and waveforms developments

BACKUP

1st order Phase Transition (PT)

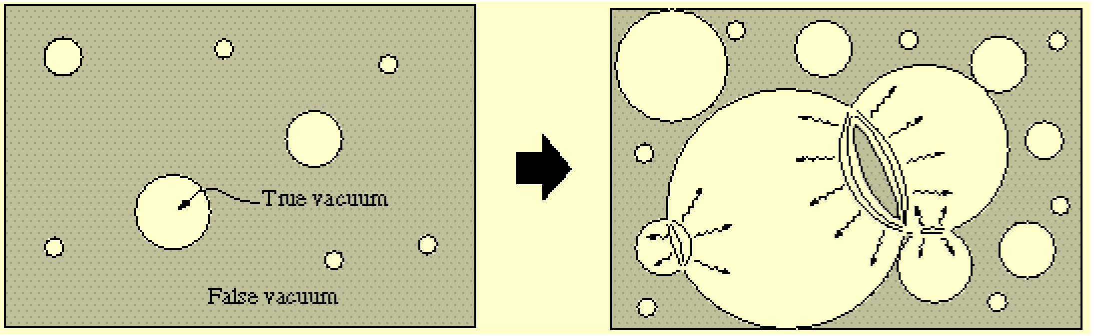
- 1st order PT can occur when 2 local minima co-exist for some range of temperatures

  → a barrier separates two degenerate minima



- relevant scalar field can quantum mechanically 'tunnel' or thermally fluctuate into the new phase

  → these processes proceed via **nucleation of bubbles** in a sea of metastable phase



- Bubble dynamics (expansion, collisions, turbulent cascade) give rise to a significant stochastic background of GW (SGWB)

1^{st} order Phase Transition (PT)

- PT characterised by few parameters:

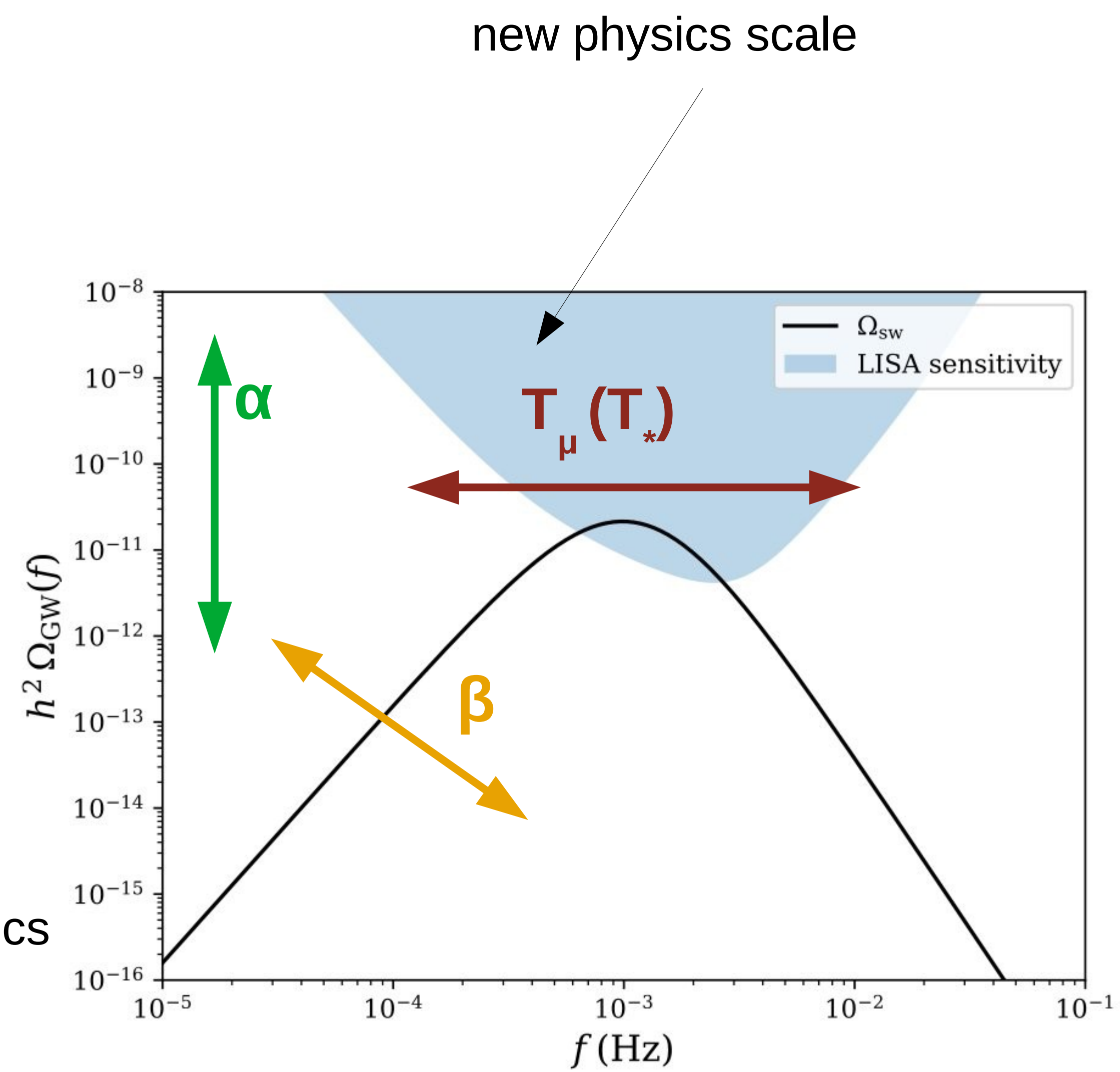
  → latent heat : **α**

  → bubble nucleation rate : **β**

  (length of time of the PT)

  → PT temperature : T_*

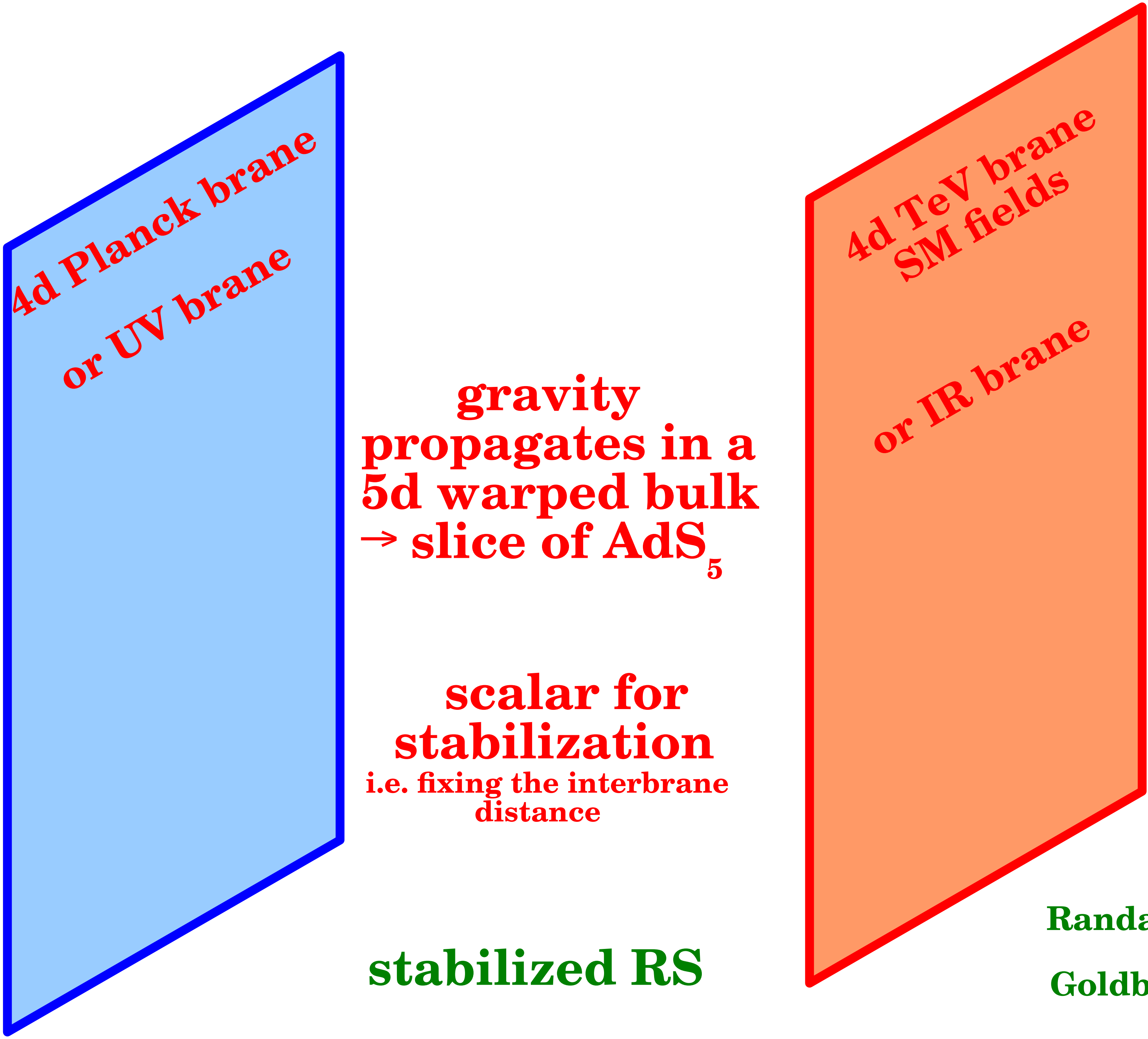
  → bubble wall velocity



- 1^{st} order PT in many BSM of particle physics

- LISA able to explore new physics scales in the few tens TeV ranges

One specific example : GW from warped spacetime

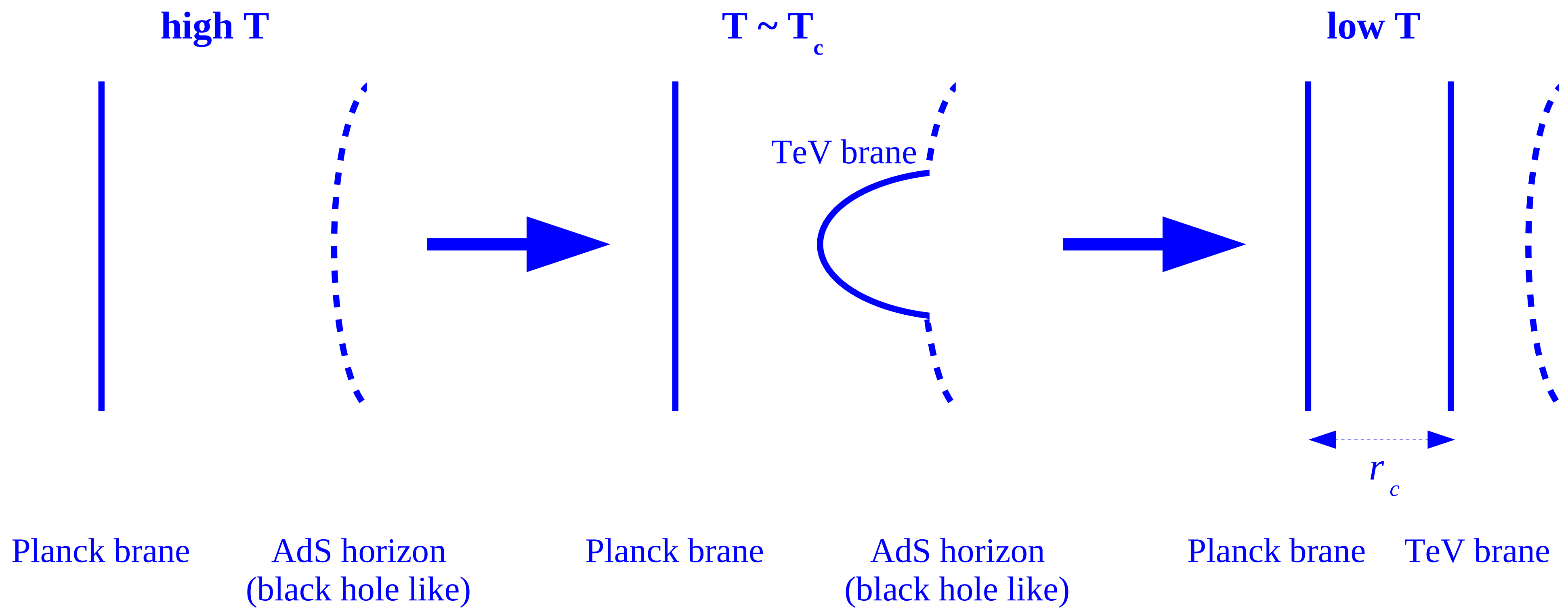


Randall Sundrum (RS)

Goldberger Wise

1st order Phase Transition (PT)

Example of PT in RS context

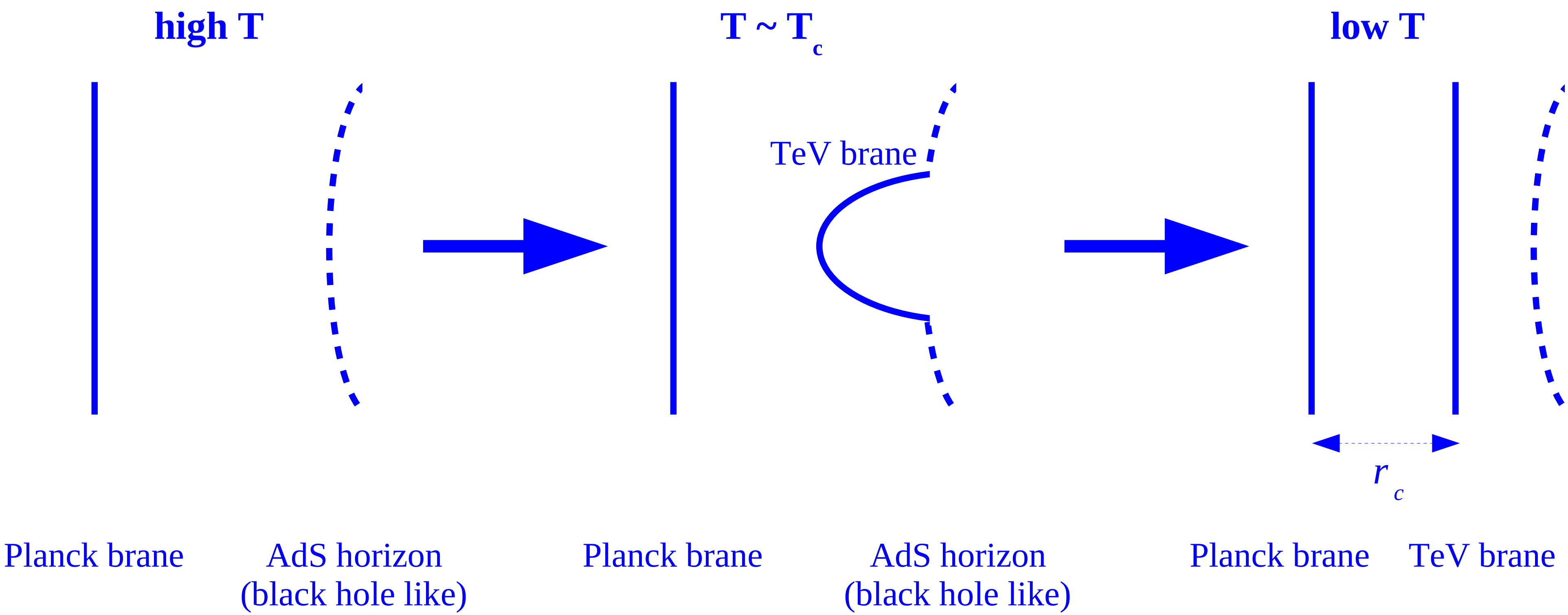


- first order phase transition from a 5D perspective :
  - formation of spherical brane patches on the horizon
  - these expand and eventually coalesce to form a complete 3-brane

- from a 4D perspective → through bubble nucleation :
  - bubble will interpolate between the unbroken hot CFT at infinity and the broken phase inside (using AdS/CFT)

1^{st} order Phase Transition (PT)

Example of PT in RS context



- in 4D, using the AdS-CFT correspondence, both phases correspond to confined and deconfined strongly interacting gauge theory respectively
- in the AdS-S phase the Higgs is deconfined → from an effective theory point of view it can be described as being in the symmetric phase
- in the RS phase the Higgs field appears i.e. confines → the possibility of having a broken symmetry opens up

1st order Phase Transition (PT)

Example of PT in RS context

- stabilized RS provides in a natural way a supercooled 1st order EW phase transition

  - radion delays the electroweak phase transition till temperatures much lower than the EW one where the order parameter of the Higgs effective potential is large

  - radion supercooling prevents then the Higgs phase transition to proceed at typical EW temperatures

- recent developments in practice (e.g. E.Megias, G. Nardini, M. Quiros, arXiv:2103.02705) :

  - compute the radion effective potential in the presence of large backreactions of the radion to the metric

  - in the resulting potential → the radion undergoes a 1st order phase transition during which it acquires a vev

  - this transition generates a SGWB

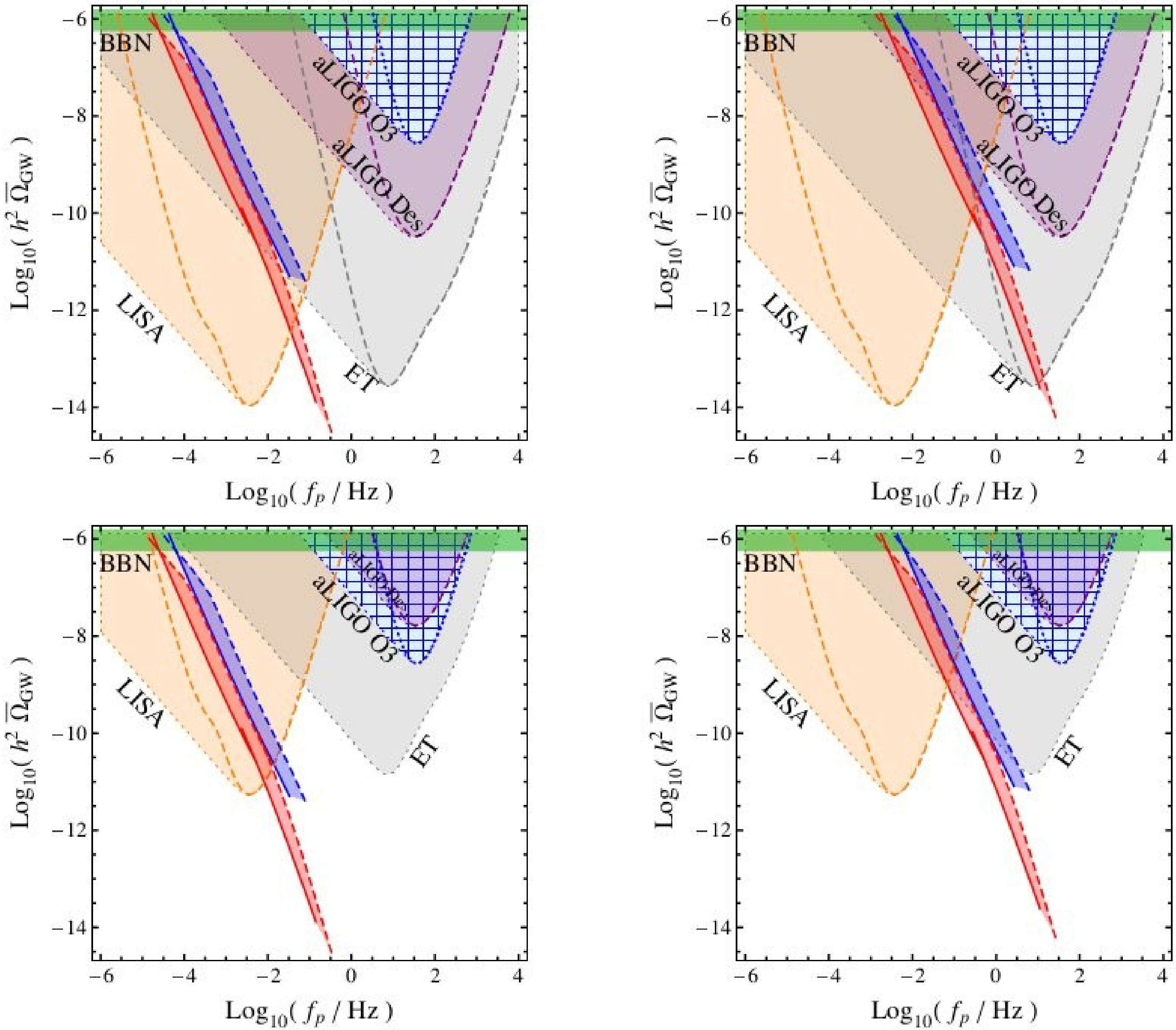
One specific example : GW from warped spacetime

CEA - Saclay

$m_{KK} \sim \rho = 1$ TeV | $m_{KK} \sim \rho = 100$ TeV

SNR ≥ 2

SNR ≥ 1000



regions inside dotted borders :
→ negligible plasma effects

regions inside dashed borders :
→ coherent motion of plasma taken into account

red diagonal strip :
→ N = 10

blue diagonal strip :
→ N = 25

with :
$N^2 = (M_5\, l\,)^3\, 16\, \pi^2$

E.Megias, G. Nardini, M. Quiros, arXiv:2103.02705

Sources

- **Supermassive Black Hole Binaries (SMBHBs): ~ 10^3**
  Coalescences with mass ratio larger than 10^{-1} and total masses in $(10^5, 10^7)\ M_\odot$
- **Intermediate-Mass Black Hole Binaries (IMBHBs):**
  Coalescences with mass ratio larger than 10^{-1} and total masses in $(10^2, 10^5)\ M_\odot$
- **Extreme mass-ratio and intermediate mass-ratio inspirals (EMRIs and IMRIs):**
  Coalescences with mass ratios in $(10^{-6}, 10^{-3})$ and $(10^{-3}, 10^{-1})$
  and total masses in $(10^3, 10^7)\ M_\odot$: **~10^3 EMRIs**
- **Stellar origin BH binaries (SOBHBs):**
  Inspirals with sufficiently low total mass e.g. in (50, 500) $M_\odot$
  such that they could be detected both by LISA and 2nd or 3rd generation ground-based detectors
- **Galactic Binaries: ~10^5**
  White dwarf or neutron star binary inspirals within the Milky Way that produce nearly monochromatic signals
- **Stochastic Backgrounds:**
  Cosmological sources of GWs that produce a stochastic background
- **…………………………………..**

Tests of GR

CEA - Saclay

- Weak Equivalence Principle (WEP)

  → postulates that the trajectory of a freely falling test body is independent of its structure and composition, providing the fact that there are no external forces acting on this body such as electromagnetism

- Einstein Equivalence Principle (EEP)

  → goes one step further and combines :

  - WEP

  - Local Lorentz Invariance (LLI)

    LLI is connected with the assumption that the outcome of any local non-gravitational test experiment is independent of the velocity of the freely-falling frame of reference where this experiment is performed

  - Local Position Invariance (LPI)

    LPI requires that the outcome of such an experiment is independent of where and when it is performed

Tests of GR

- Strong Equivalence Principle (SEP)
  - → is equivalent to the EEP with the WEP extended to self-gravitating bodies and the LLI and LPI to any experiment
  - → the SEP takes this even further and implies that the gravitational coupling is fixed as well
  - → testing the SEP is often considered synonymous to testing GR itself
  - → if the SEP is fulfilled, the only field that is a mediator of the gravitational interaction should be the spacetime metric
  - → conversely, the existence of new fields mediating gravity would generically lead to violations of the SEP

- Lovelock's Theorem and GR uniqueness
  - → Einstein field equations are unique, assuming that we are working in four dimensions, diffeomorphism invariance is respected, the metric is the only field mediating gravity, and the equations are second-order differential equations
  - → violating any of these assumption can circumvent Lovelock's theorem and lead to distinct alternative theories of gravity. However, the vast majority of them will share one property: they will contain one or more additional fields

Tests of GR

Modified dispersion relations and speed of gravity

- according to GR GWs obey dispersion relation $\omega^2 = k_i k^i$ (contraction done with flat Euclidean metric)

  → group and phase velocity of GWs = speed of light

- Modified theories of gravity can lead to different dispersion relations of some form e.g. :

1) $\omega^2 = k_i k^i + \frac{m_g^2}{\hbar^2} + A\left(k_i k^i\right)^\alpha$ in the limit $m_g^2 / h^2 \ll k^2$ and $A \ll k^{2-\alpha}$

   m_g is a hypothetical mass for the graviton, $\alpha \neq 0$ determines the type of modification introduced and A controls its magnitude

2) $\omega^2 + iH\omega\left(3 + \alpha_M\right) = \left(1 + \alpha_T\right) k_i k^i$ in the context of cosmology

   parameter α_M controls the rate of dissipation of Gws and $\alpha_T = | c_T^2 - 1 |$

- both parameterizations have advantages and disadvantages

  e.g. → 1) allows one to constrain a kinematical graviton mass while 2) does not

  2) allows one to test the rate of GW dissipation while 1) does not

Tests of GR

Modified dispersion relations and speed of gravity

- best systems to constrain these modifications → those as far away as possible from Earth

  - because modifications to propagation of GWs accumulate with distance traveled

  - because correction scales with the chirp mass
    constraints on m_g enhanced for supermassive systems

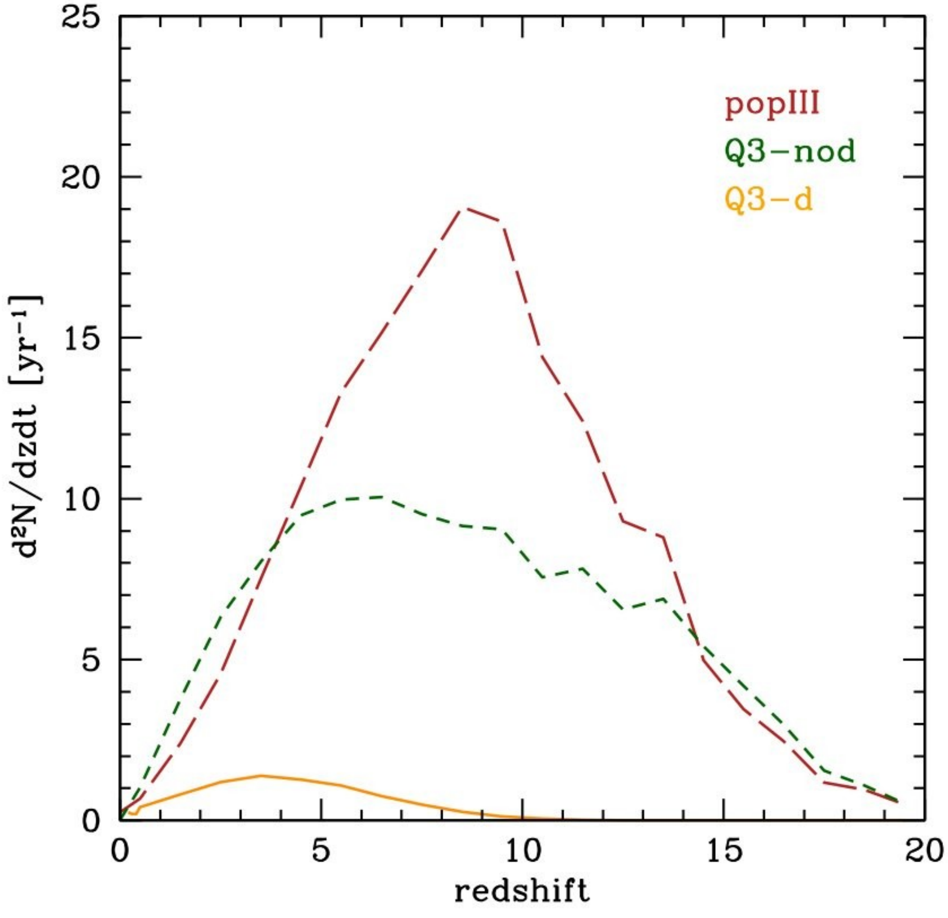
  - however for $\alpha > 1$ opposite is true
    with constraints deteriorating as an inverse power of the chirp mass

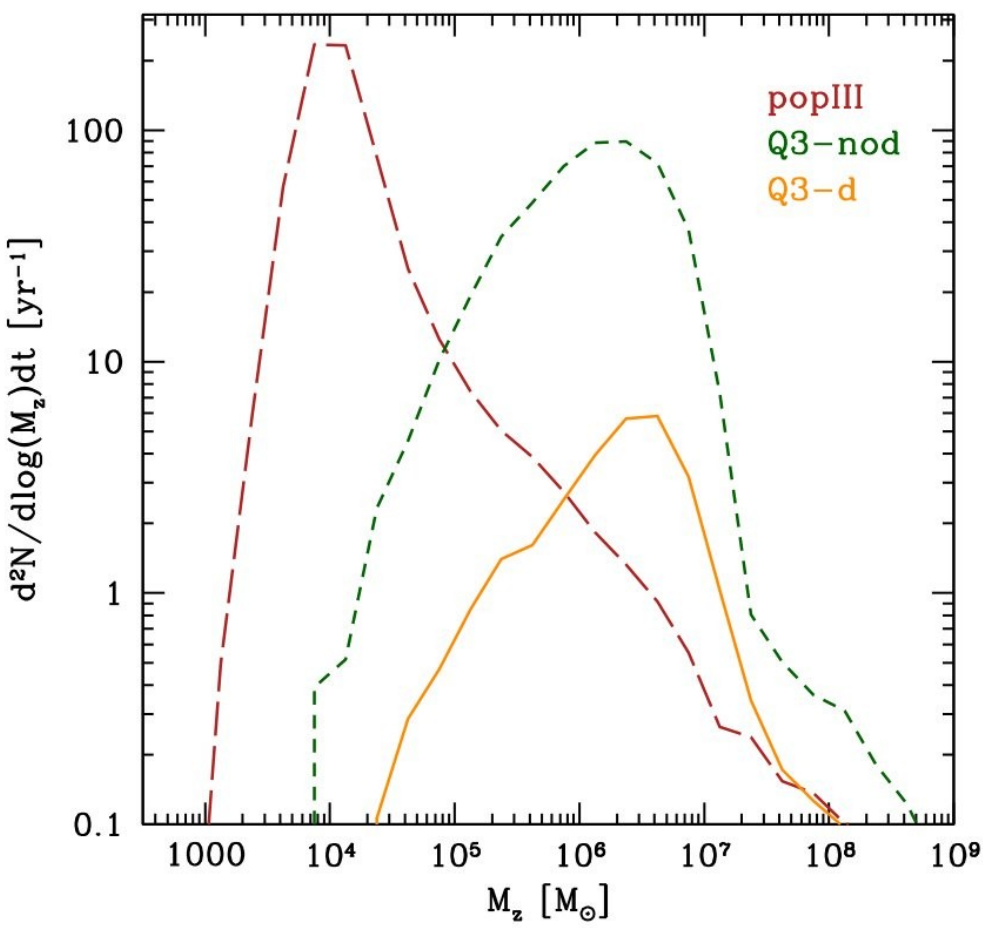
- confirmation of dispersion relation of GR could place constraints on (for example) :

  - theories with extra dimensions or quantum-inspired Lorentz violation

  - modified gravity models to explain late-time acceleration of the universe

SMBHB event rates for LISA are uncertain





Klein et al. PRD 93, 024003 (2016)

Evolution of SMBHBs

- at early stages of galaxy merger

  → dynamical friction to reduce the orbital angular momentum of the individual black holes until they sink to the center of the merger remnant forming a SMBHB

- **dominant mode of energy loss below ~10 pc binary separation is not yet understood**
  many environmental interactions potentially contribute (Merritt & Milosavljević 2005)

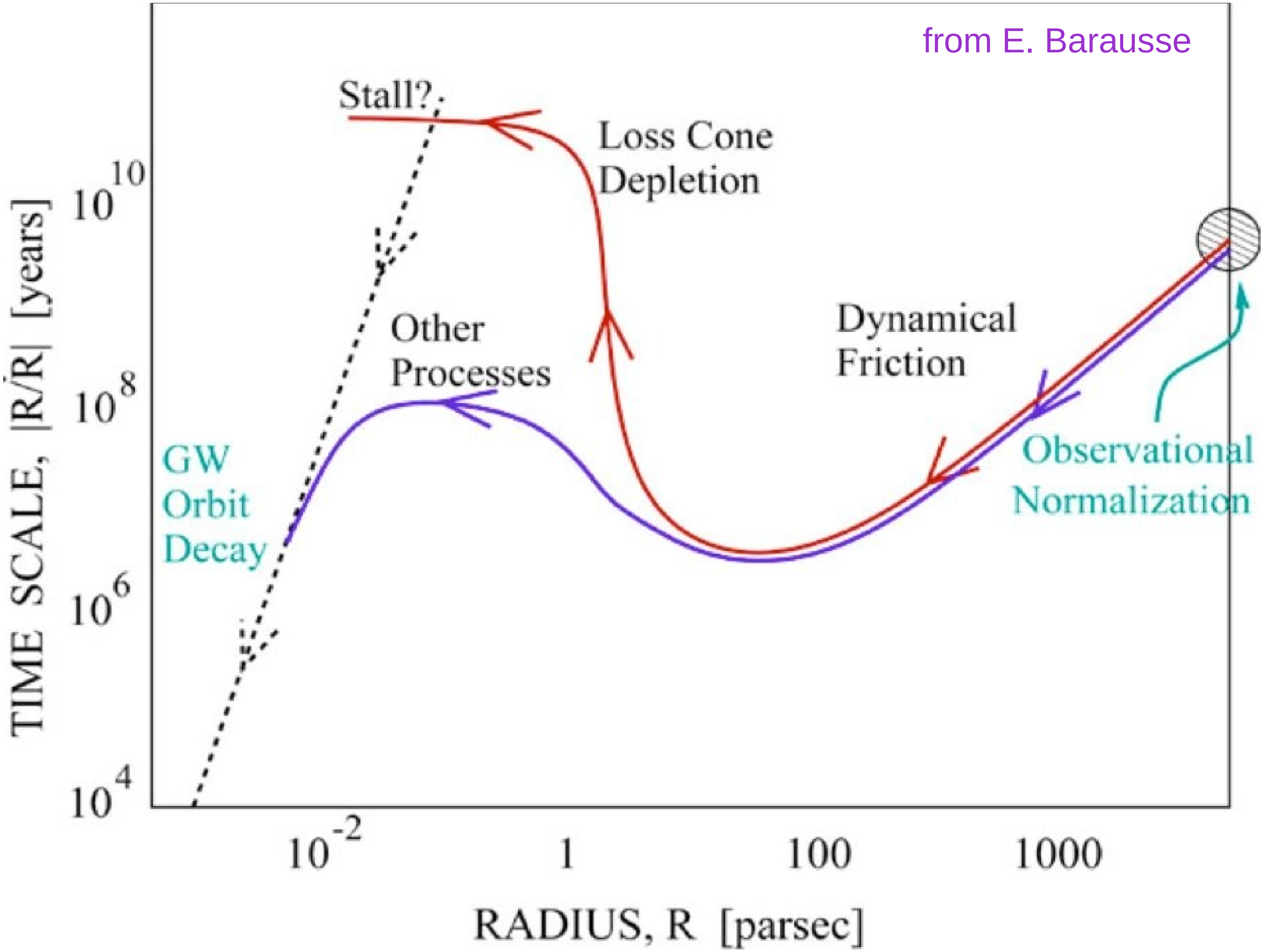
- **unclear when the environment decouples from the binary**
  after which GW emission dominates

- what is the upper limit to how fast the binary BH can merge ?

  → final parsec question ?

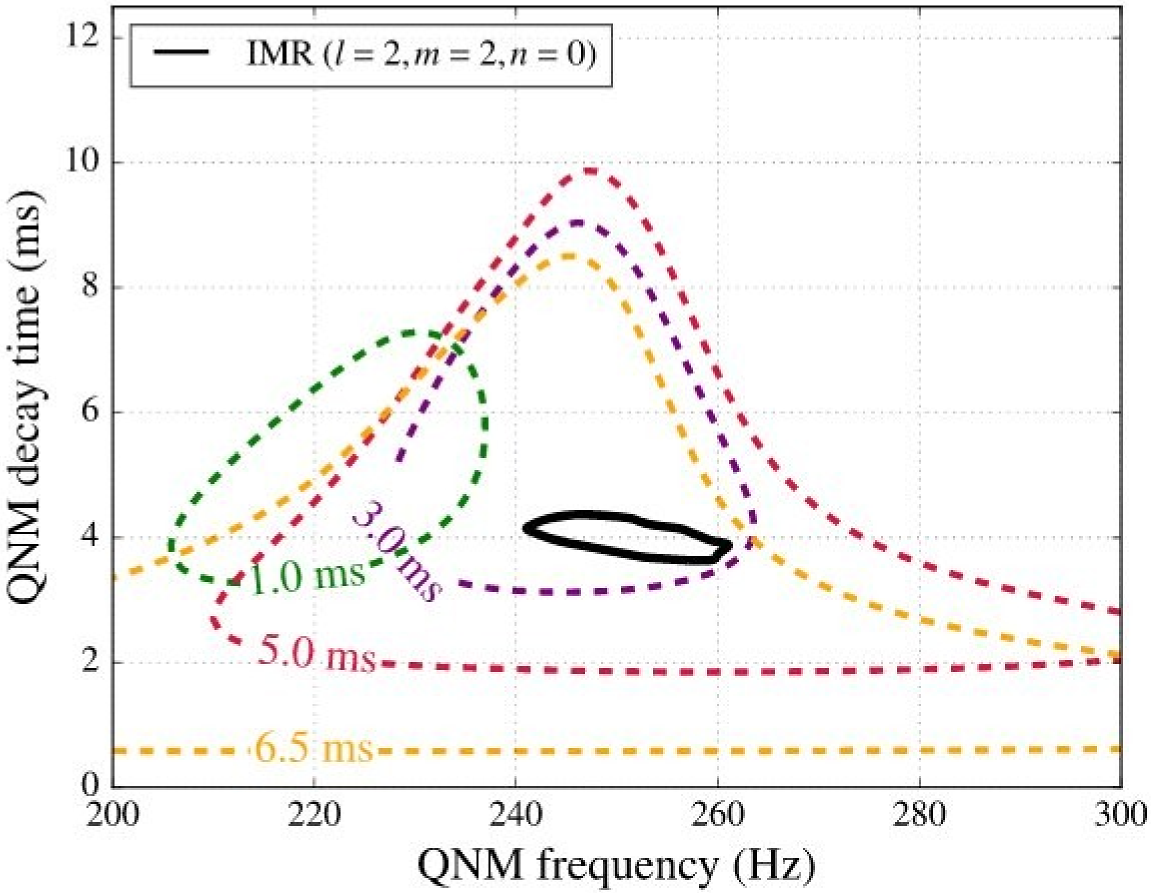
  interactions with stars can lead to binary BH merger
  but only over times exceeding 1 Gyr and only if all conditions are favorable (Ostriker) ?

The final parsec problem ?



there are ~ 1-2 orders of magnitude in radius between 10 pc and 0.01 pc
in which orbital decay time exceeds the Hubble time (the “bottleneck”)

QNMs
Constraints from LIGO-Virgo



blacksolid line shows the 90% credible region for the frequency and decay time of the l=2, m=2, n= 0 QNM as derived from the posterior distributions of the remnant mass and spin parameters

B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations) prl116,221101 (2016) and Erratum Phys. Rev. Lett. 121, 129902 (2018)

Tests of the nature of Black Holes

more observables and tests

Inspiral-based test with MBHBs, IMBHBs, and EMRIs

- Multipolar structure
- Tidal heating and tidal deformability
- Non integrability (of the e.o.m) /Chaos
- Motion within ECOs

Tests of the nature of Black Holes

more observables and tests

Inspiral-based test with MBHBs, IMBHBs, and EMRIs

- Multipolar structure

→ several gravity theories beyond GR predict deformations of the Kerr metric resulting in a different multipolar structure

$$M_l = M_l^{Kerr} + \delta M_l$$

$$S_l = S_l^{Kerr} + \delta S_l$$

M_l and S_l are the mass and current multipole moments, δM_l and δS_l are theory-dependent corrections to the Kerr moments (which might even include cases in which the geometry breaks the equatorial symmetry)

→ leaves a footprint in the GW signal emitted during the coalescence of binary system

→ modify the structure the waveform at different orders

Tests of the nature of Black Holes

more observables and tests

Inspiral-based test with MBHBs, IMBHBs, and EMRIs

- Tidal heating

  → orbit backreaction of the growing tidal field of each objects of the coalescing binary

  → rotational energy transfer from their spin into the orbit

  → stronger for highly spinning objects and for binaries with large mass ratio

- Tidal deformability

  → tidal effects in compact binaries modifying the dynamical evolution of the system accelerating the coalescence and then in turn the GW emission

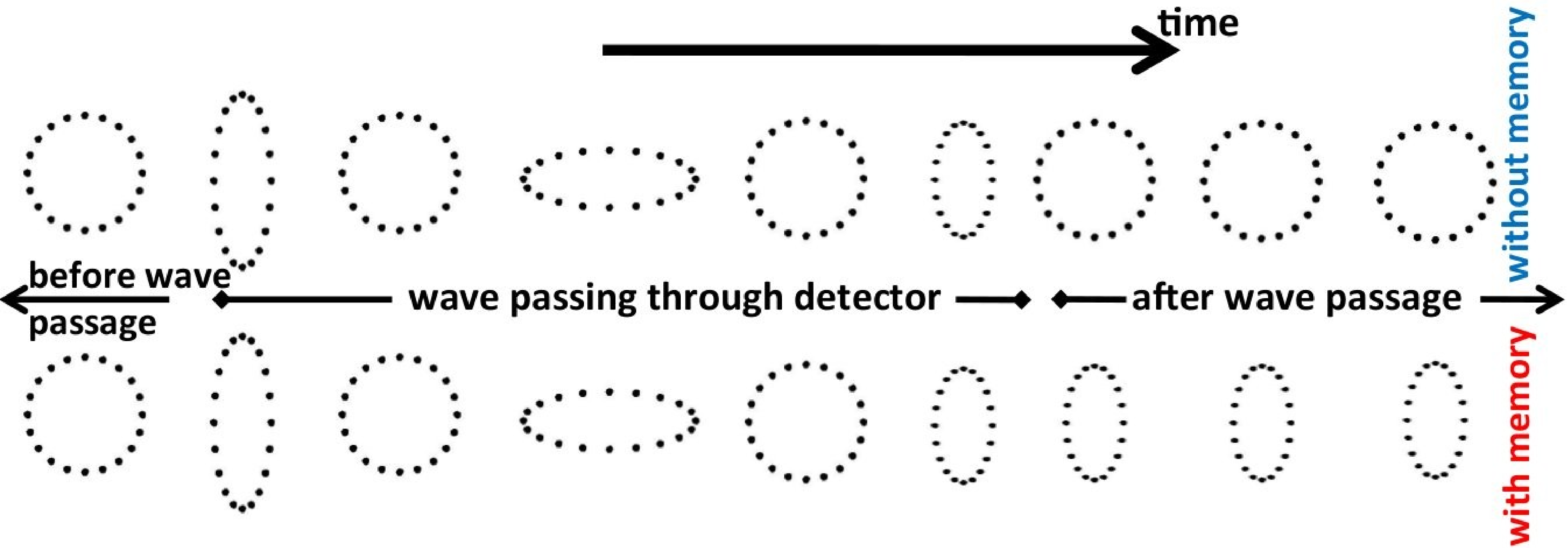
  → imprint on the waveform encoded in Tidal Love number

  tidal Love numbers of a BH in GR are precisely zero.

  tidal Love numbers are generically different from zero for ECOs

Tests of GR

Gravitational Wave memory



(gravitational-waves propagating into the screen)

from M. Favata

Gravitational Wave memory

CEA - Saclay

- GW passing through a system of 2 isolated free-falling test masses would **permanently stretch or compress the comoving distance** between them

- memory is sourced by a changing time derivative of the system's mass multipoles
(like the oscillatory component of a GW)

- it grows through the cumulative history of GW emission

- memory signal inherits the radiating system's evolving past:
its strength at any time is the result of the integrated history of the system

- can be generalized i.e.not only displacement memory effect but also (subdominant) :

  - spin memory
  - center of mass memory

  } motivated by / associated to a symmetry (as for the displacement memory effect)

  - relative proper time, relative velocity, relative rotation memories

- focus here on the permanent displacement memory effect

Asymptotic symmetries : BMS group

asymptotically flat spacetimes → metric becoming flat as one approaches ∞

asymptotic symmetries :

- ordinary 4-dimensional Minkowski spacetime has a 10-parameter group of isometries → Poincaré group

  this isometry group plays an important role in the analysis of the behavior of physical fields on Minkowski spacetime, in particular in the proof of conservation laws

  In a general curved spacetime one would not expect any exact isometries to be present

- possible to define the notion of an asymptotic symmetry

  but group of asymptotic symmetries is not the Poincaré group

  it is a much larger group containing an infinite-dimensional subgroup of "angle dependent translations" called supertranslations → BMS group

  BMS from Bondi, Van der Burg, Metzner, Sachs (1962)

Asymptotic symmetries : BMS group

- **supertranslations → angle dependent translations**

  → associated conserved charges are the supermomenta

  → non-trivial diffeomorphisms acting on the asymptotically flat phase space
  transforming a geometry into another one - physically inequivalent

  → supertranslations have a relationship with gravitational radiation

- supertranslations commute with the time translation

  → their associated charges will commute with the Hamiltonian

  → **all these degenerate states have the same energy**

- BMS group : BMS_4 = Lorentz x Supertranslations

  → reproducing the semi-direct structure of the Poincaré group

  → only difference is that the translational part is enhanced,
  implying **degeneracy of the gravitational Poincaré vacua**

  → **change in the vacuum state is detected by a net permanent displacement**
  i.e. passage of GW radiation changes the vacuum by a BMS transformation

Dark Matter and Primordial BH

$$M_{PBH} > M_{\odot}$$

- LISA should be able to detect merger events of resolved sources and unresolved signals in the form of a SGWB

- PBH abundance in various mass ranges → merger rate

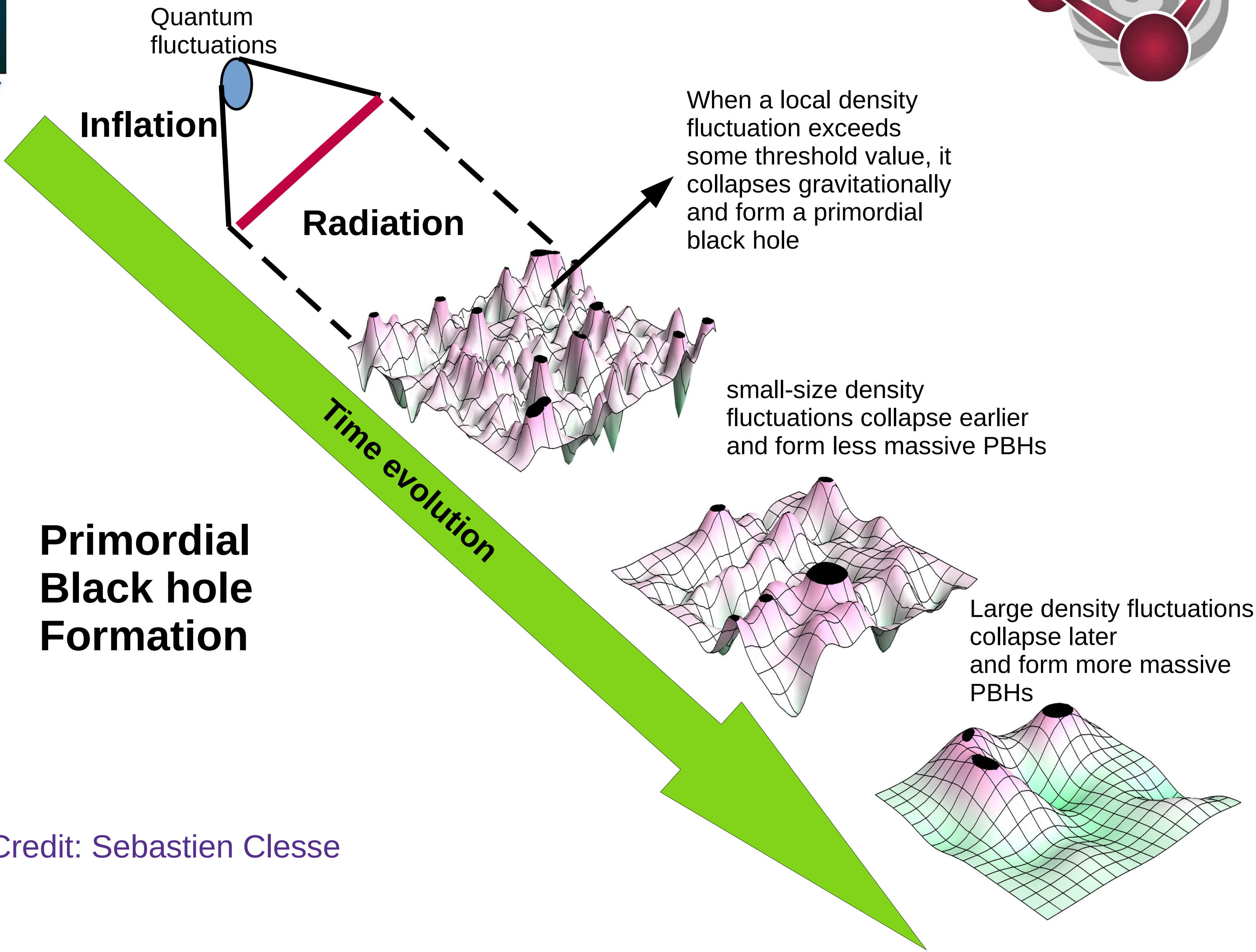
- PBH and astrophysical BHs

  - PBHs expected to form with small spins but for PBH binaries in mass range observable by LISA
    → baryonic mass accretion leads to spin growth
    → predicting extremal spins at the merger time

  - although only accounting for a small fraction of the dark matter in the universe
    → PBH still acting as progenitors of SMBH ?
    → observation of events at high z redshift would help in understanding SMBH physical origin

  - massive binary BH merger population currently observed at LIGO/Virgo expected to give rise to SGWB of unresolved sources with a tail at low frequencies detectable by LISA
    → primordial scenario expected to give a stronger contribution to SGWB w.r.t. the astrophysical one (due to the additional contribution given by PBH mergers happening at higher redshift
    → PBHs merger rate expected to increase with redshift
    stellar BHs rate first increases and peaks at redshift around $z \sim (1-2)$, and then rapidly decreases

Dark Matter and Primordial BH

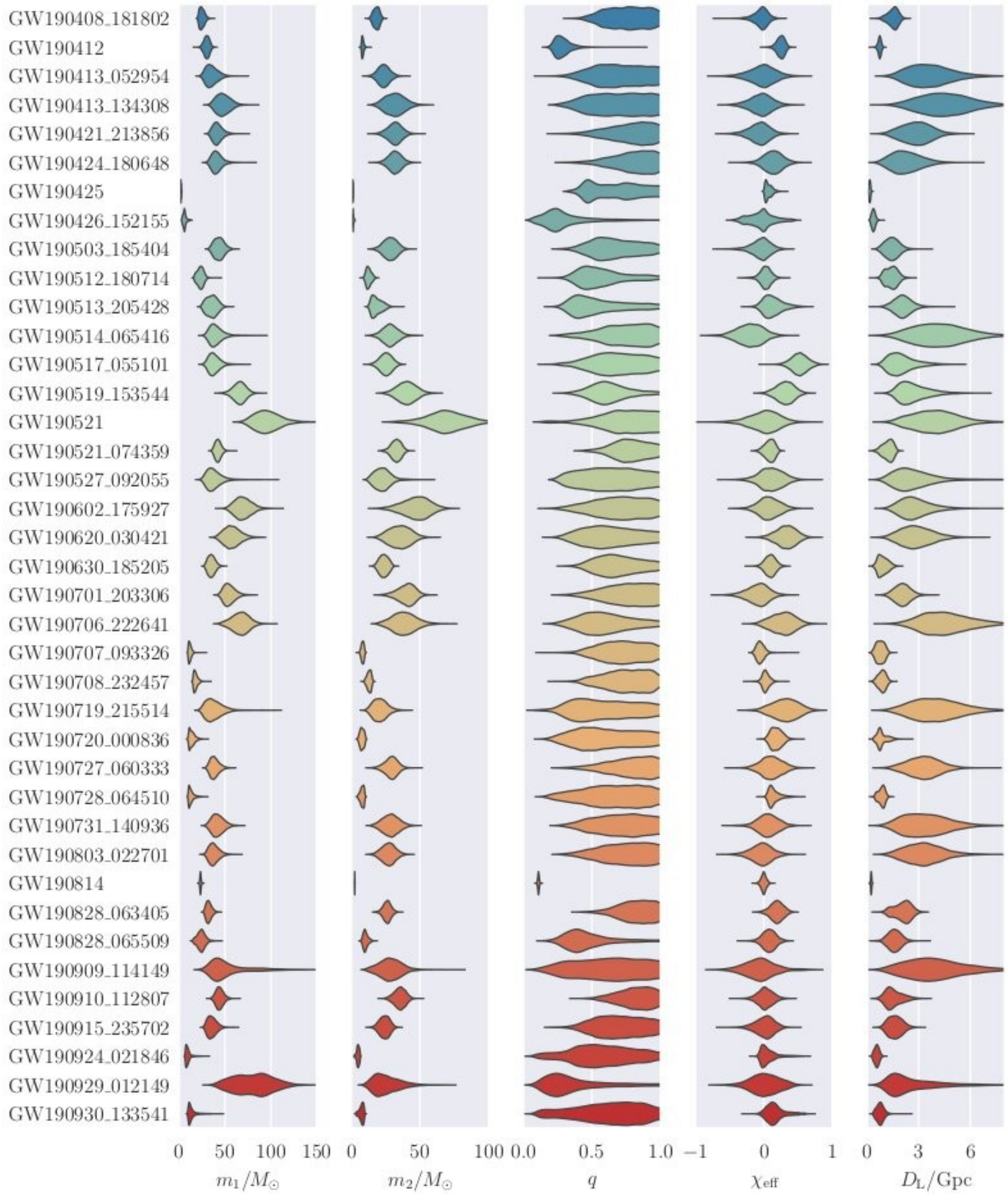


Primordial Black hole Formation

Credit: Sebastien Clesse

Dark Matter and Primordial BH

Black Hole effective spins $\chi_{eff} = [m_1 S_1 \cos(\theta_{LS1}) + m_2 S_2 \cos(\theta_{LS2})] / (m_1 + m_2)$



PBH at formation have zero spins

Open question: impact of secondary mergers?

of accretion?

B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations) arXiv :2010.14527

3 model examples

aimed at explaining late-time cosmic acceleration

- most well-known scalar-tensor theories of gravity (Brans–Dicke,f(R) , covariant Galileon models) belong to the wide class of Horndeski theories

  - most general covariant scalar- tensor theories of gravity leading to 2nd order eq. of motion

- Degenerate Higher Order Scalar-Tensor (DHOST) theories

  - Horndeski action is built on the requirement of second order field equations

  - although sufficient, this requirement is not necessary in order to avoid dangerous Ostrogradsky instabilities

  - higher order field equations are actually harmless provided that the Lagrangian is degenerate, i.e. there exists an extra primary constraint that removes the Ostrogradsky mode → DHOST theorie

  - DHOST theories represent (so far) the most general scalar-tensor theories that propagate a single scalar degree of freedom in addition to the helicity-2 mode of a massless graviton

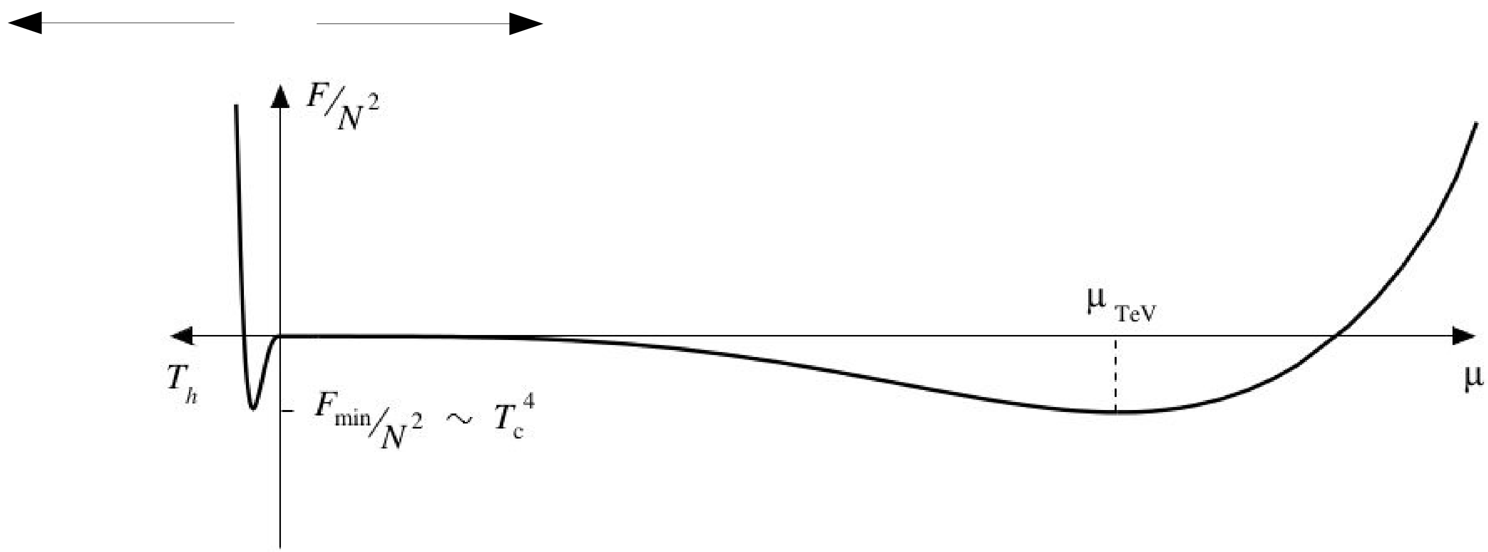
- Bi-gravity theory (Hassan Rosen)

  - consistent theory of bigravity, free of Ostrogradsky instabilities adding an Einstein-Hilbert term for the reference metric of the so-called dRGT theory of massive gravity

One specific example : phase transition in RS context

free energy for the Black Hole like solution (AdS-S)

free energy for the RS solution



AdS-S model parametrized by the Hawking temperature T_h

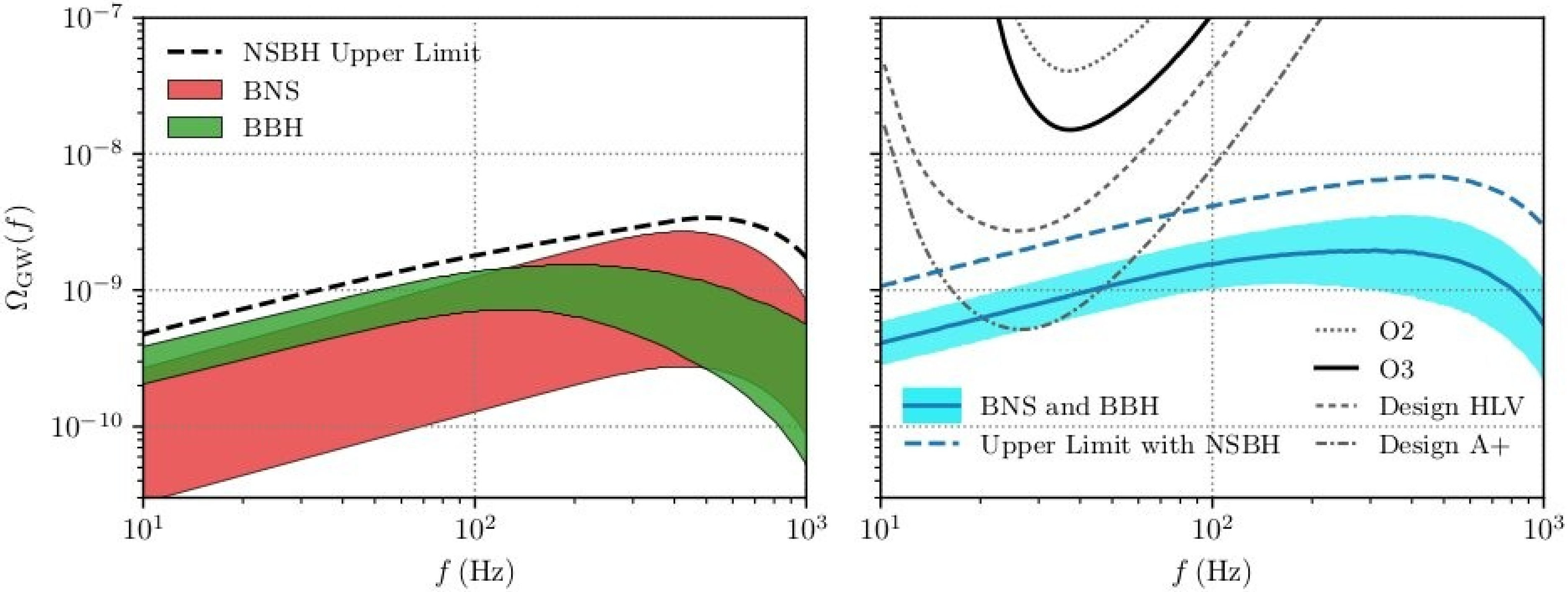
RS model parametrized by the radion VEV μ

the two classes of solutions coincide at $\mu = T_h = 0$

Upper Limit on SGWB from LIGO/Virgo

dimensionless energy density $\Omega_{GW} \leq 5.8 \; 10^{-9}$ at 95 % C.L

for flat (frequency-independent) GW background



B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations) arXiv :2101.12130