Theory and phenomenology of gravitational physics: current status and future prospects

Leonardo Gualtieri

Sapienza University of Rome - INFN Roma1

WHY?

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- Cosmology and the early universe:

Can we explain cosmological acceleration in terms of modifications of the gravitational interaction? Which phase transitions took place in the early history of the universe? How do cosmological parameters vary with redshift? *[see Monday talks by Cardone, Piacentini etc.]*

WHO?

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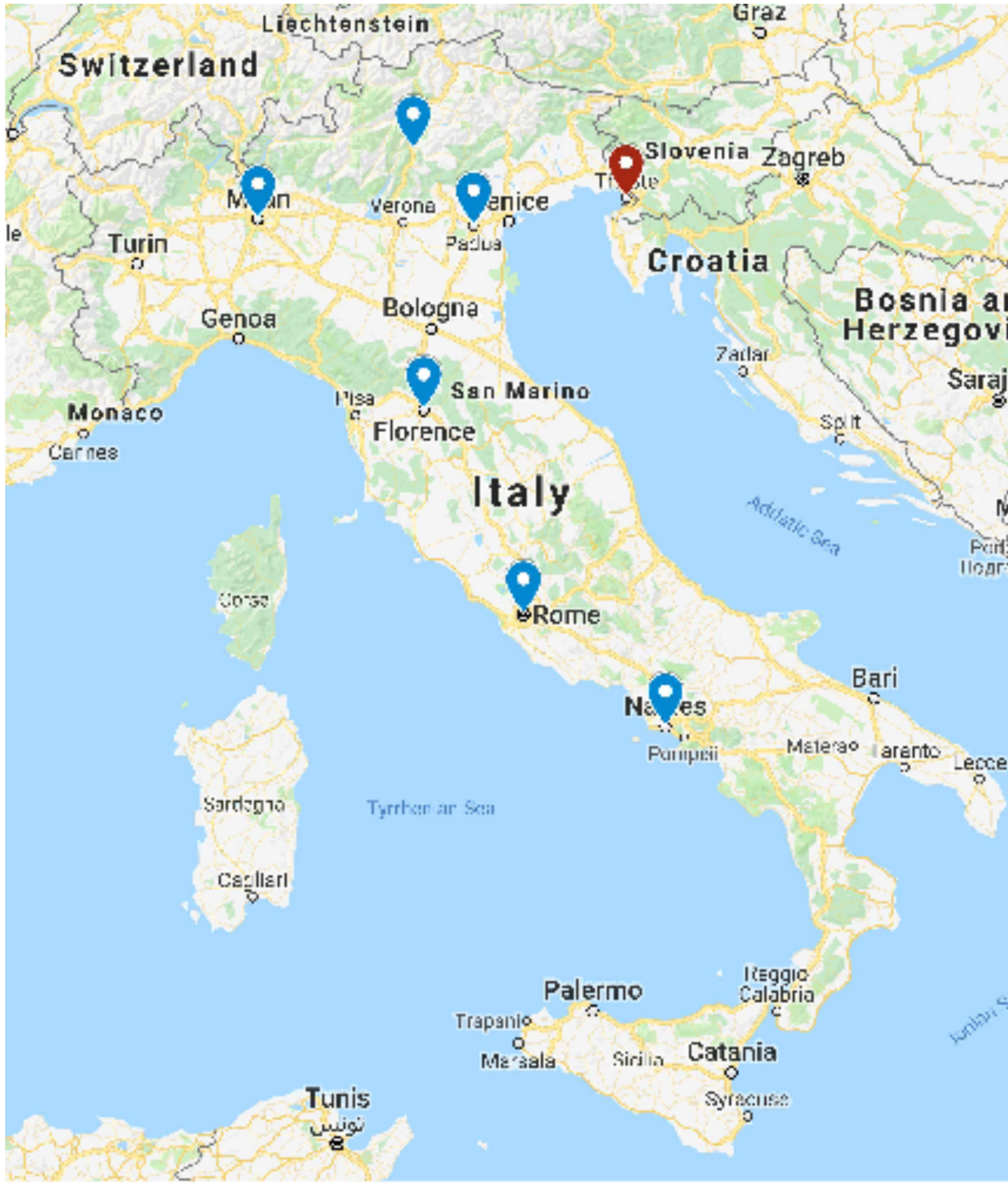

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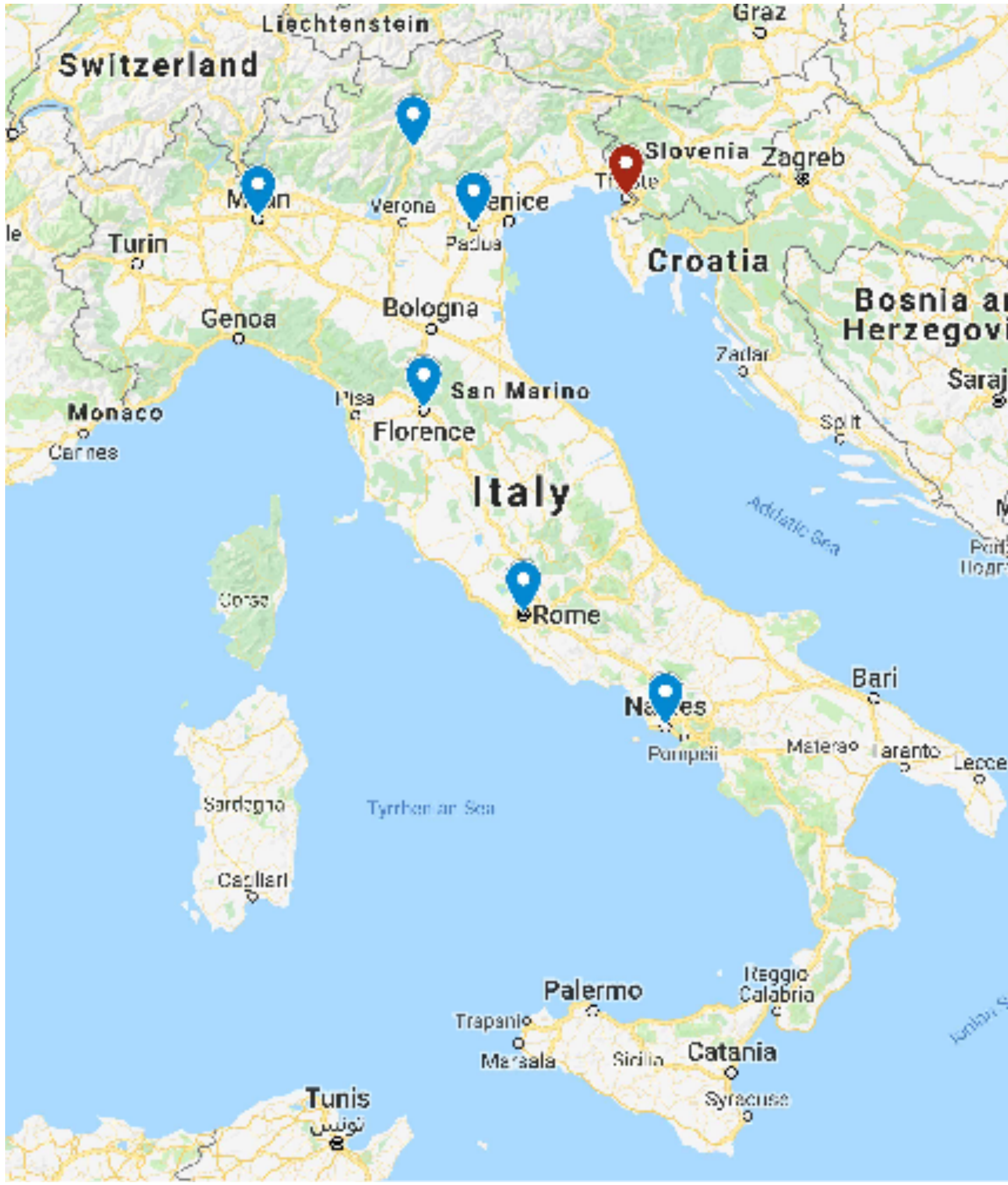
TEONGRAV is an INFN Network (belonging to the Line V (astroparticle) of GR4) including Italian groups studying theoretical gravitational physics, an in particular sources of gravitational waves

- Padova
- Milano Bicocca
- TIFPA-Trento
- SISSA-Trieste (to be included)
- Firenze
- Roma 1 (coordinator)
- Napoli



Some of these nodes (e.g. Padova and Milano Bicocca) are more focussed on the astrophysics, while others (e.g. Roma and SISSA) are mostly on theoretical physics.

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Gravity theory and gravitational wave phenomenology

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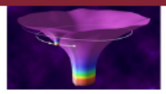
LATEST NEWS

PAX VI Meeting @ Virgo



Gravity Essay on tidal effects with EMRIs

EXTERNAL LINKS

- Amaldi Research Center
- COST Action GWverse
- Physics Dept. at Sapienza
- TEONGRAV INFN Initiative

Welcome to the gravity theory group @ Sapienza!

The landmark detection of **gravitational waves** has opened a new era in physics, giving access to the hitherto unexplored **strong-gravity regime**, where spacetime curvature is extreme and the relevant speeds are close to the speed of light. In parallel to its countless astrophysical implications, this discovery can also give important insight for fundamental physics.

We investigate various phenomena related to strong gravitational sources such as **black holes, neutron stars, and binaries thereof** - that can be used to turn these objects into cosmic labs, where matter in extreme conditions, the very foundations of Einstein's theory of gravity, and even particle physics can be put to the test.

We are exploring some outstanding, cross-cutting problems in **fundamental physics**: the physics of neutron stars, the limits of classical gravity, the nature of black holes and of spacetime singularities, the existence of extra light fields, and the effects of dark matter near compact objects.

We are members of the COST Action *"CA 16104 Gravitational waves, black holes and fundamental physics (GWverse)"*, of the *"Amaldi Research Center for gravitational physics and astrophysics"* at Sapienza, and of the INFN Specific Initiative *TEONGRAV - Gravitational Wave Sources*.

We are part of the **LISA Consortium**, the **GWIC-3G Science Case Team**, and **eXTP Science Team**.

FUNDING

We acknowledge financial support from:

- Fondi Ateneo Sapienza
- TEONGRAV INFN
- ERC-2017 StG DarkGRA
- PRIN 2017 MIUR
- H2020-MSCA-RISE-2015 StronGrHEP
- H2020-MSCA-IF-2017 FunGraW

webpage:
https://web.uniroma1.it/gmunu

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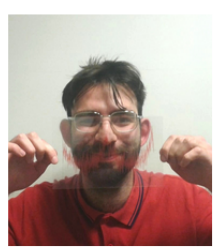

Gabriel Piovano
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mail - website

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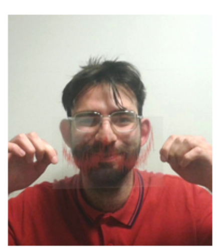

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+ other TEONGRAV-ROMA1 members:

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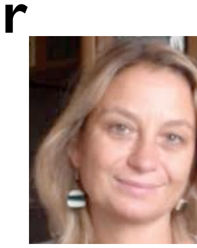
- **Francesco Pannarale** (RTDB Researcher, RLM Fellow, Virgo Group)

- **Raffaella Schneider** (Ass. Professor, Astrophysicist)



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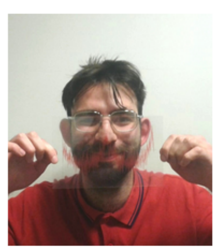
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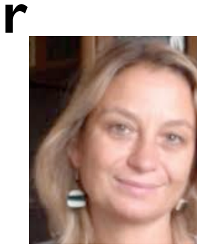

We also collaborate:

- in Rome, with other members of Virgo and with astrophysicists of Monte Porzio Observatory
- in Italy, with the other TEONGRAV nodes (presently, we have a PRIN with some of them)
- worldwide, with several groups in JHU (US), Lisbon Univ. (PT), King's College Lond. (UK), Nottingham Univ. (UK), DAMPT (UK), Aveiro Univ. (UK), Barcelona Univ. (SP), etc.

WHICH RESEARCH TOPICS?

1. Modelling sources of Gravitational Waves

2. Test the gravitational interaction, looking for general relativity deviations in the strong-field regime

3. Determine the equation of state of nuclear matter in the inner core of neutron stars

4. Test the nature of compact objects

5. Search for dark matter candidates looking at its strong gravity interaction with compact objects

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but it's also the *fundamental tool for all other* research lines in gravity:

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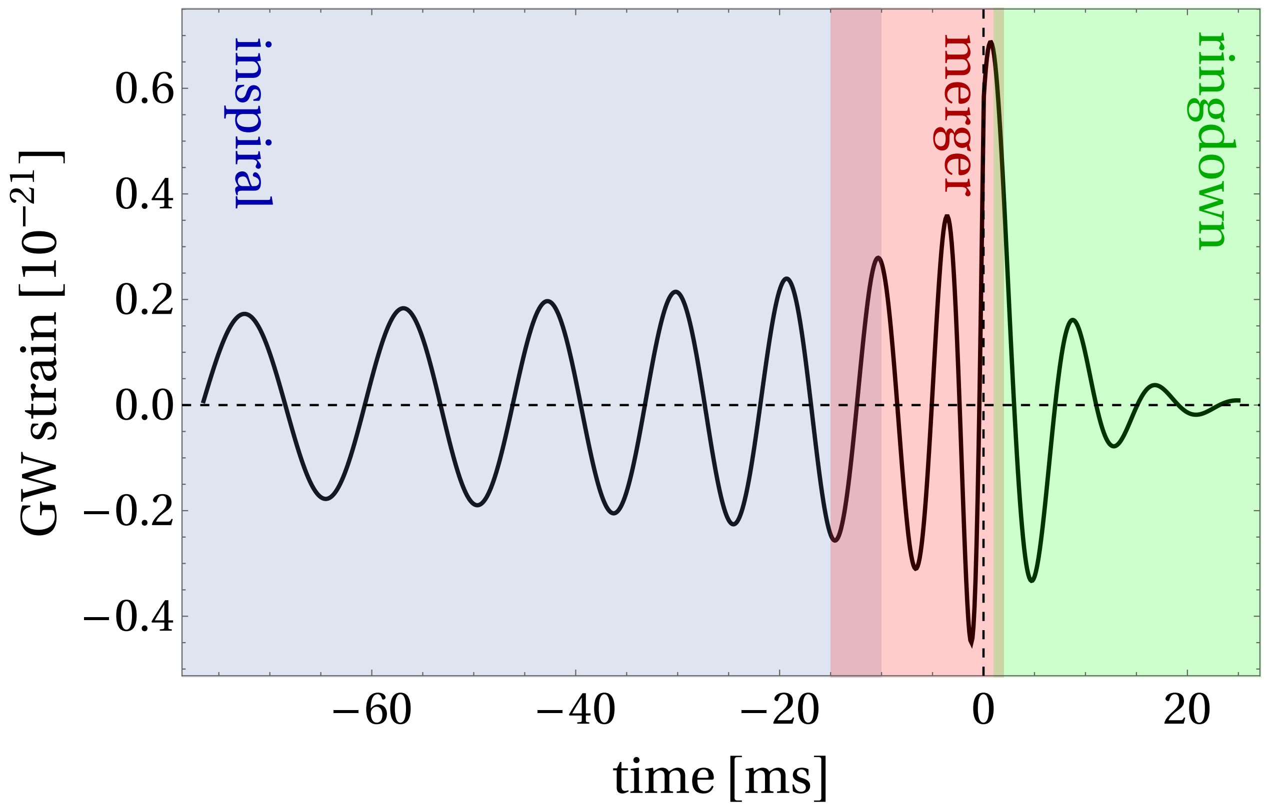
Most interesting kind of source (the one which has been detected):

coalescence of binary systems composed of BHs and/or NSs



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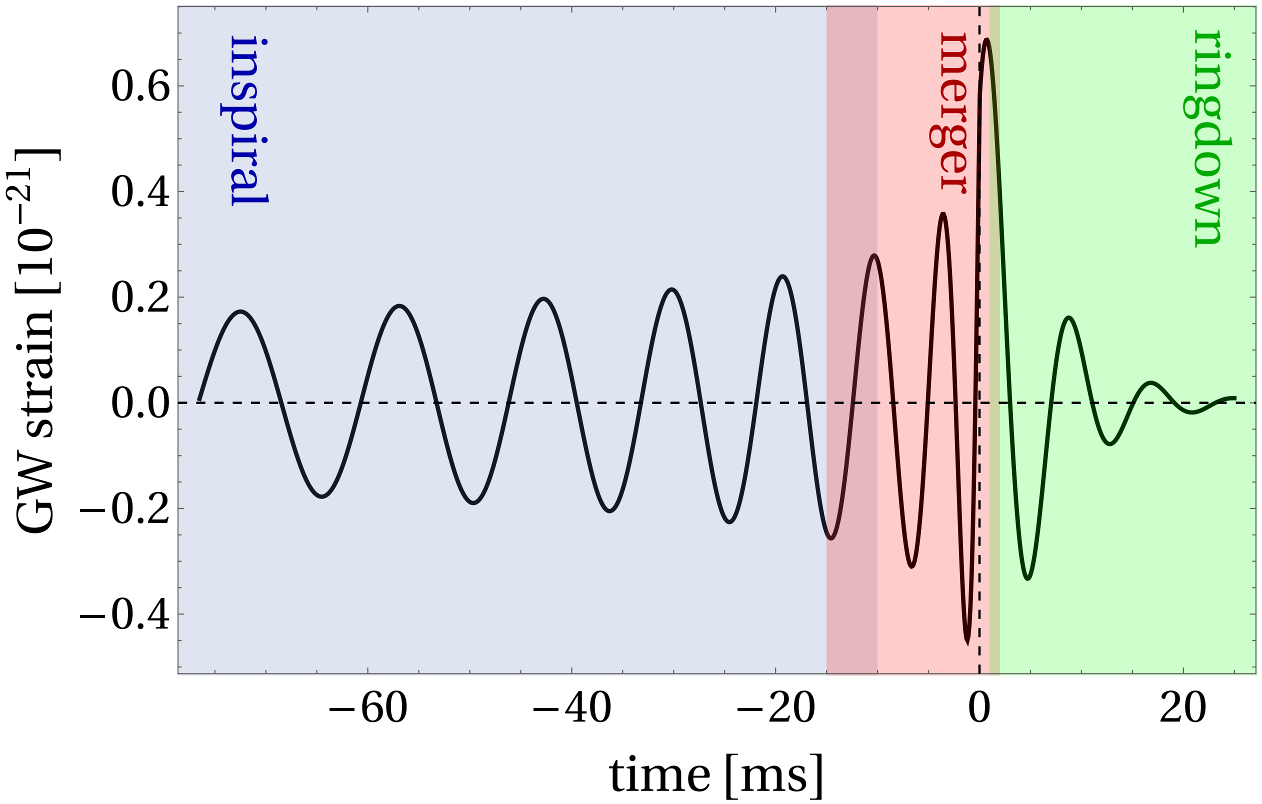

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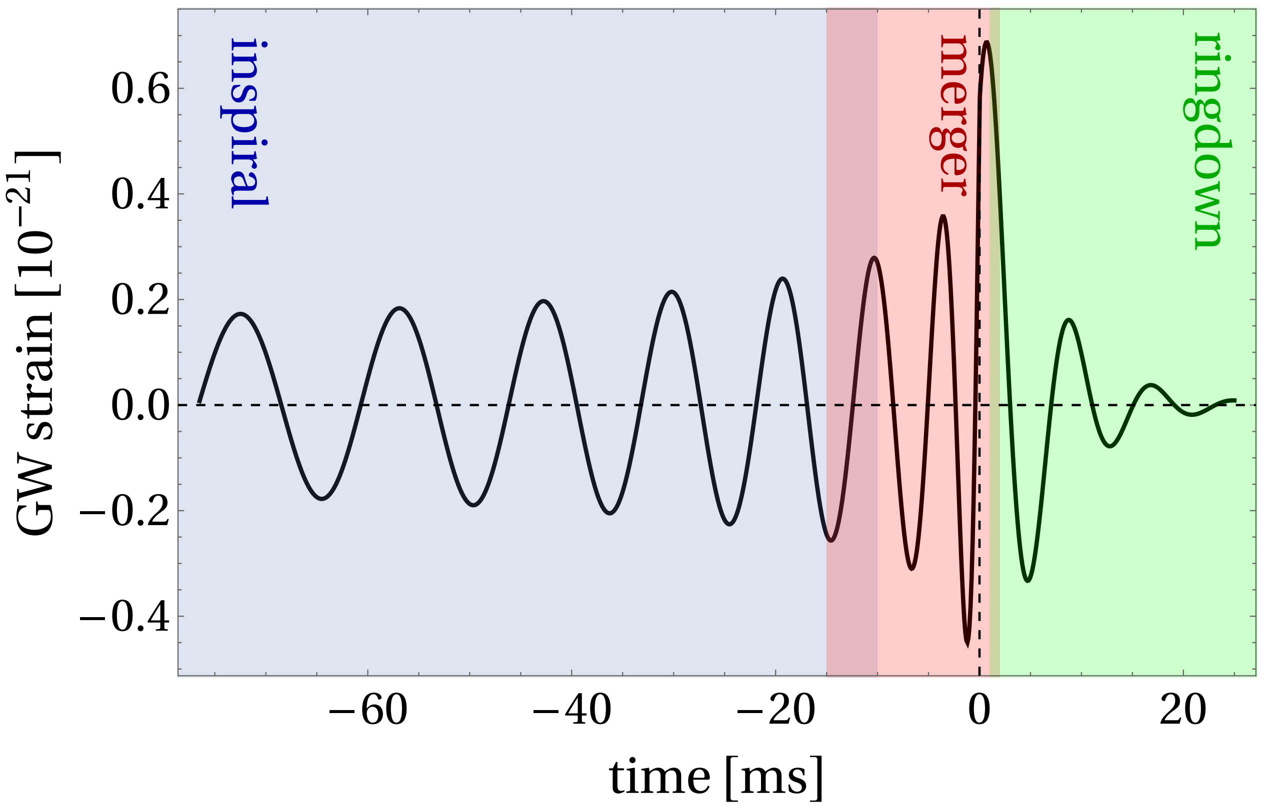

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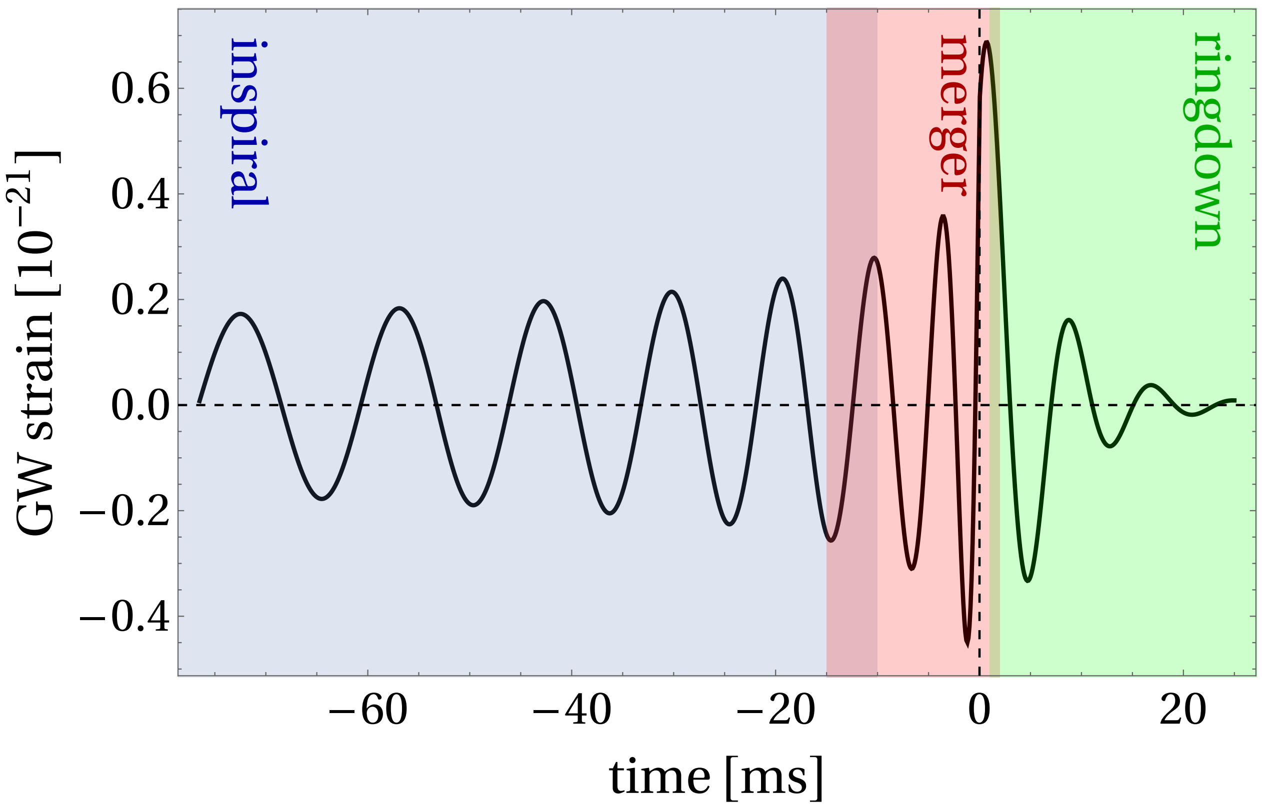

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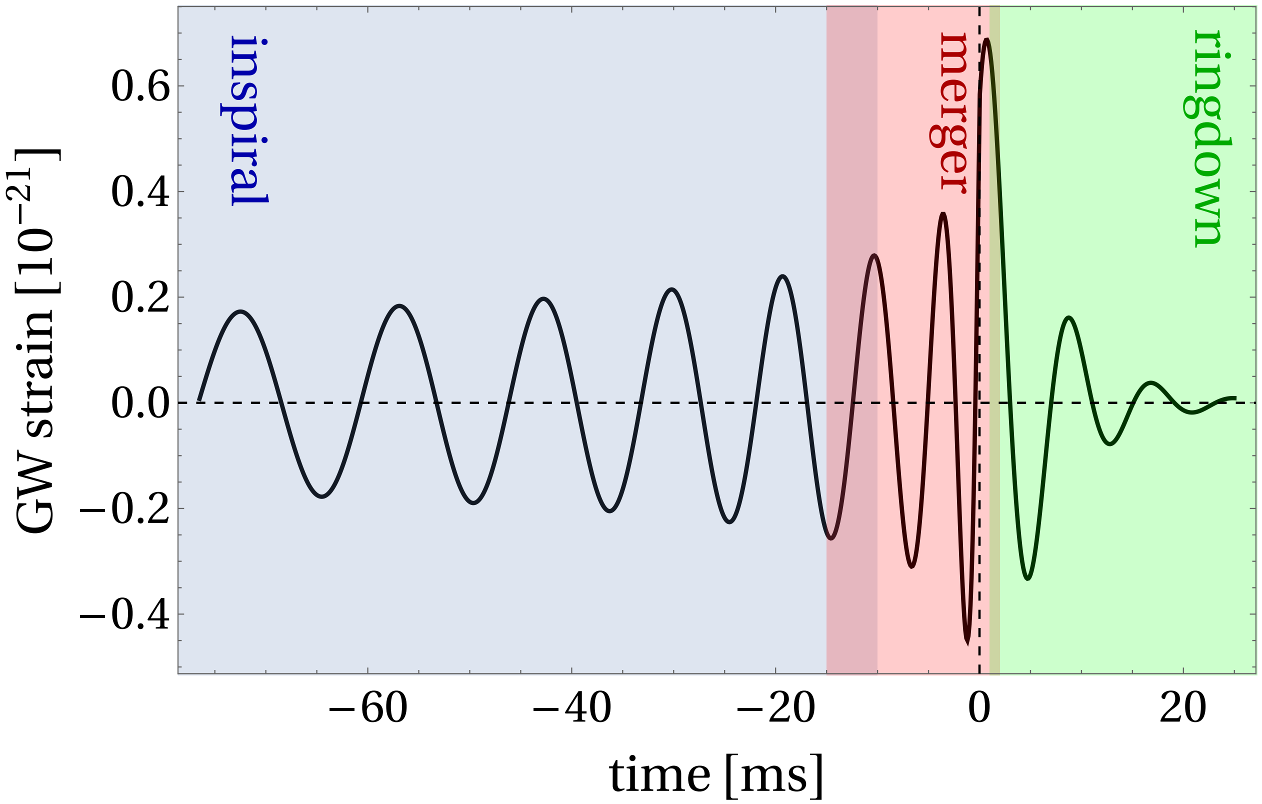

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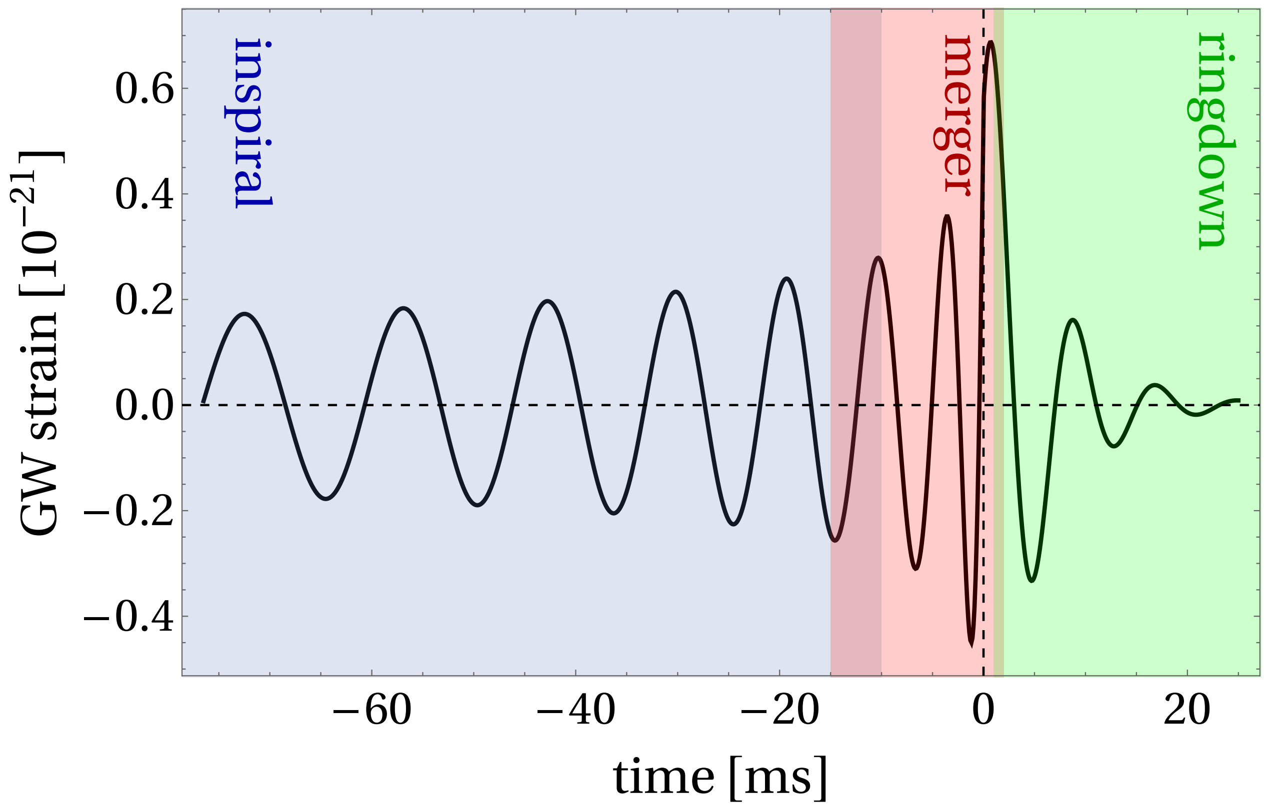

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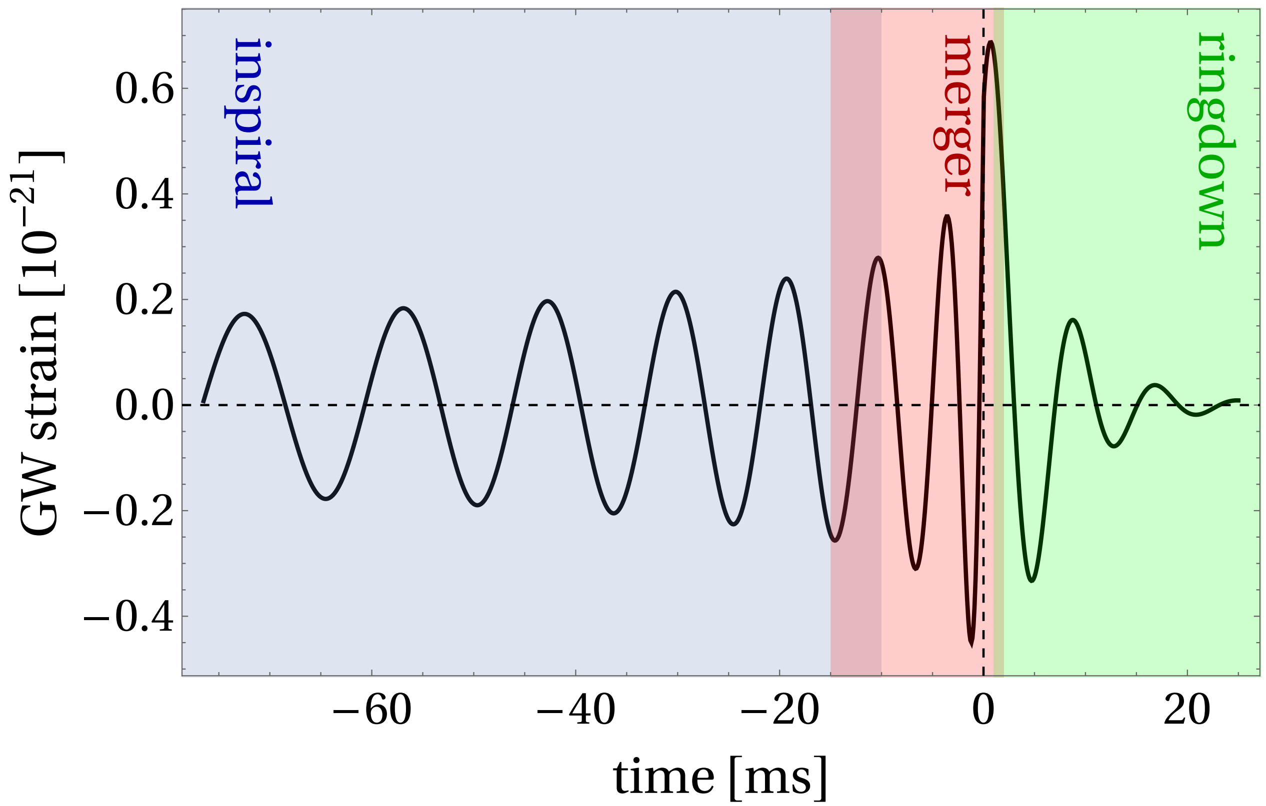

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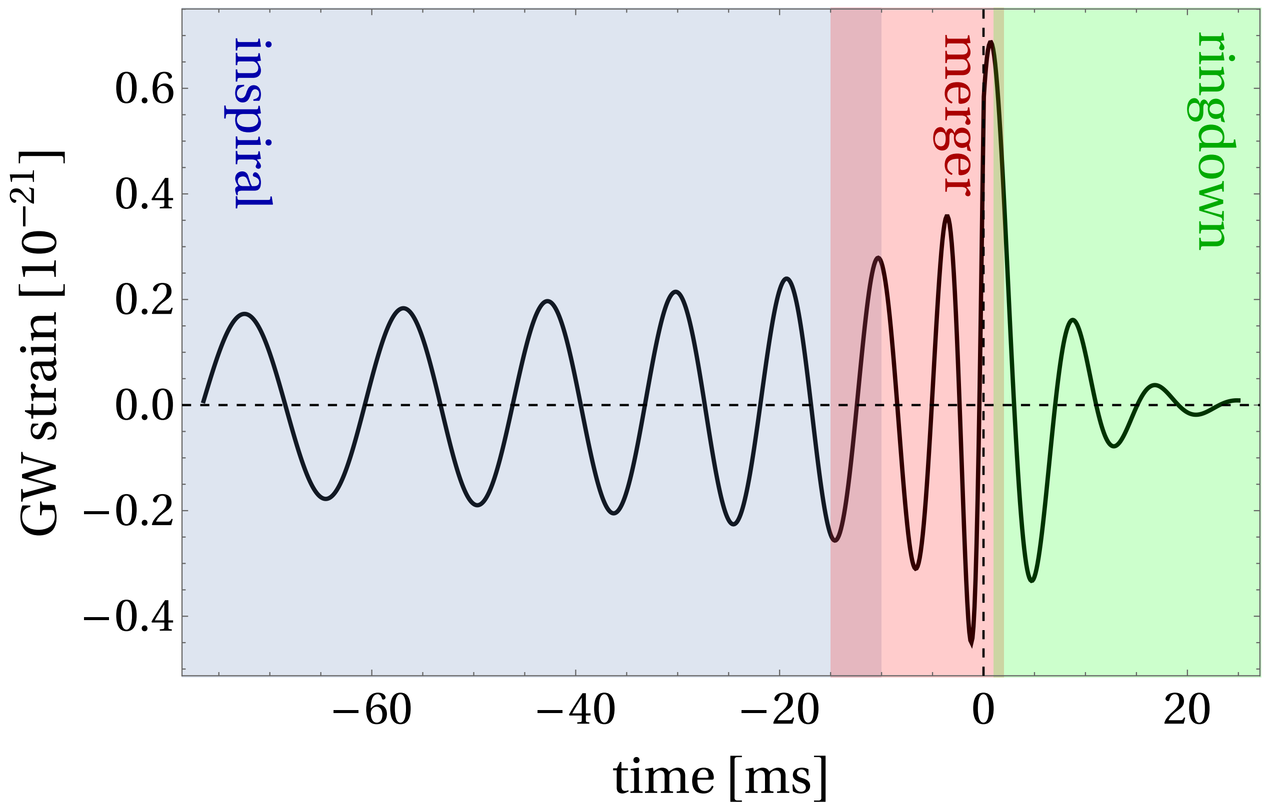

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- Stochastic background of gravitational waves

(e.g. *Marassi et al. MNRAS '09, Schneider et al. MNRAS'10, Marassi et al. PRD '11, MNRAS '11, Maselli et al. PRL '16*)

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Just a mention to other sources which - although not detected yet - deserve investigation:

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Further information can be extracted by combining gravitational wave observations with astrophysical observations, as the X-ray emission from accreting neutron stars, or gamma-ray bursts

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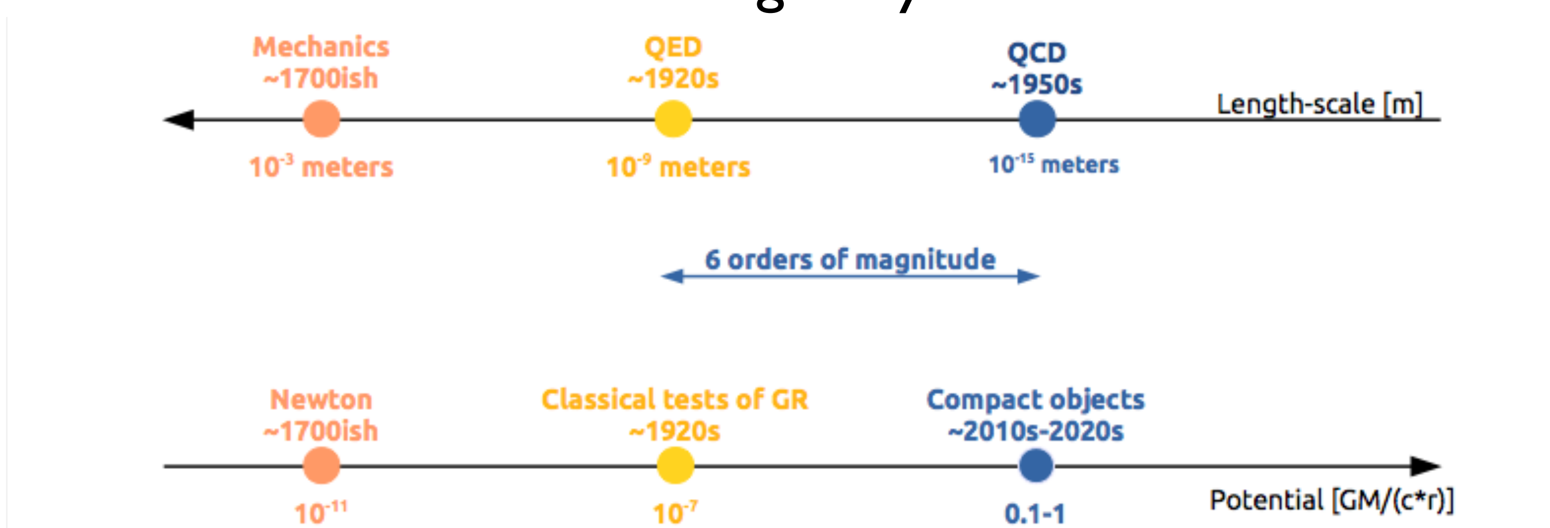

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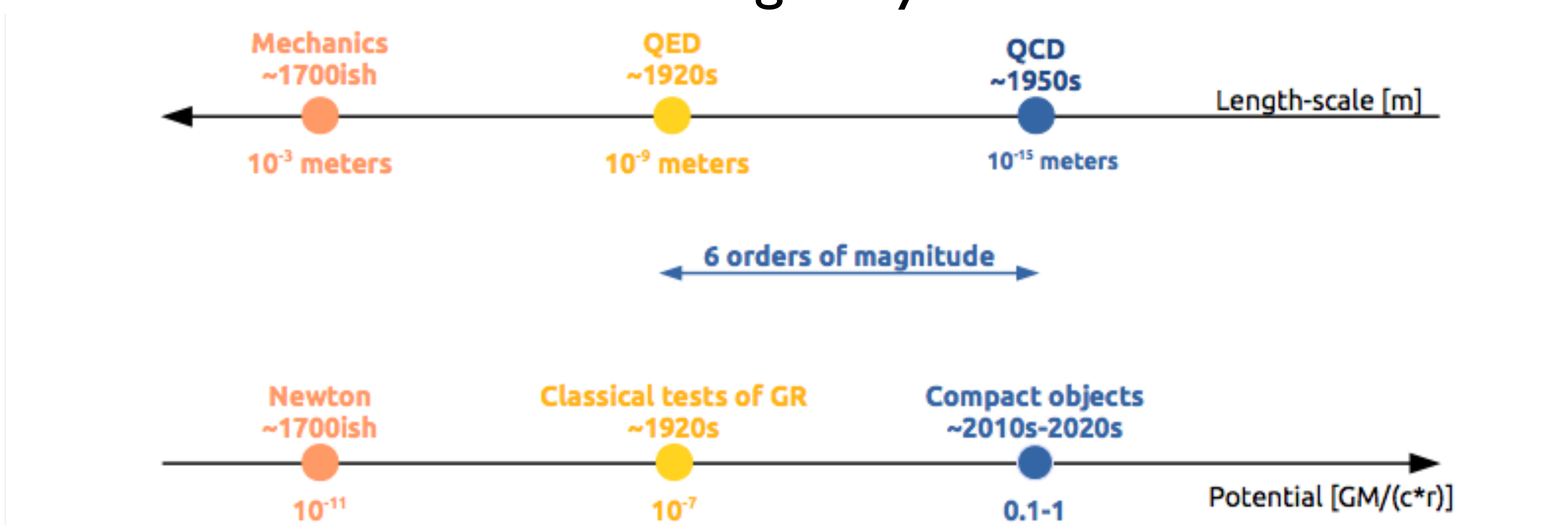

Moreover:

- we already know that *some deviation* has to occur (although at a much smaller lengthscale): all tentatives to unify GR with the quantum world have failed
- the theory of GR contains its own pathologies (singularities, causality violations)
- dark matter, dark energy are still not fully understood, GR deviations may provide alternative explanations to observations

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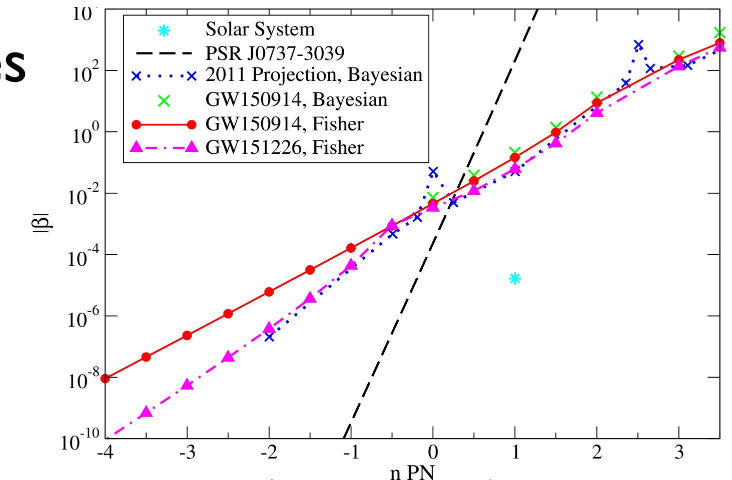

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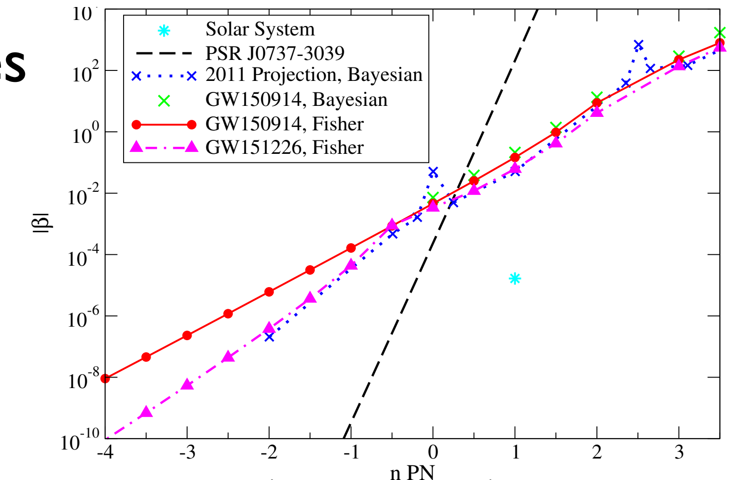

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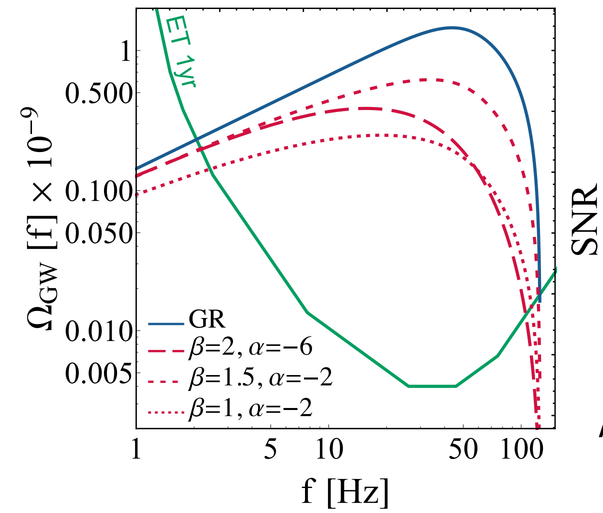

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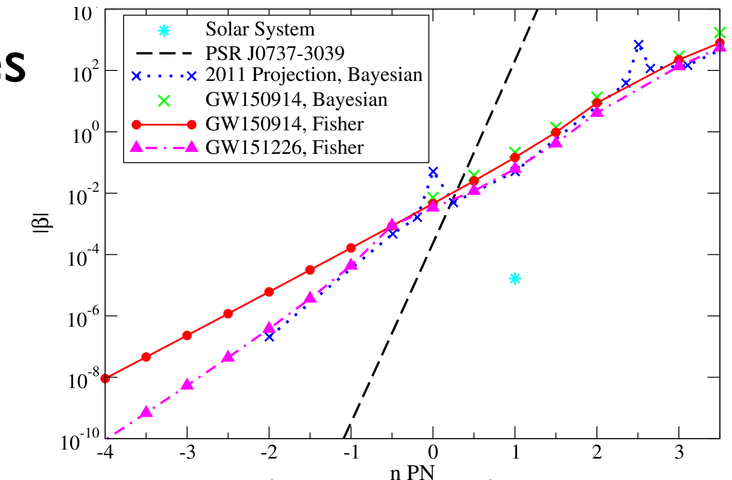

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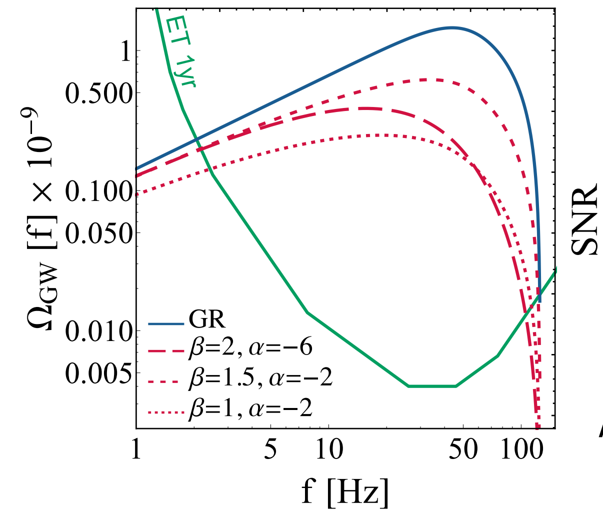

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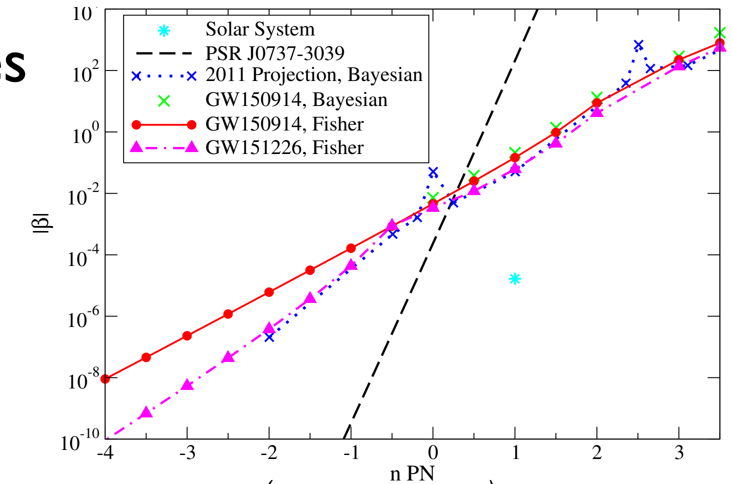

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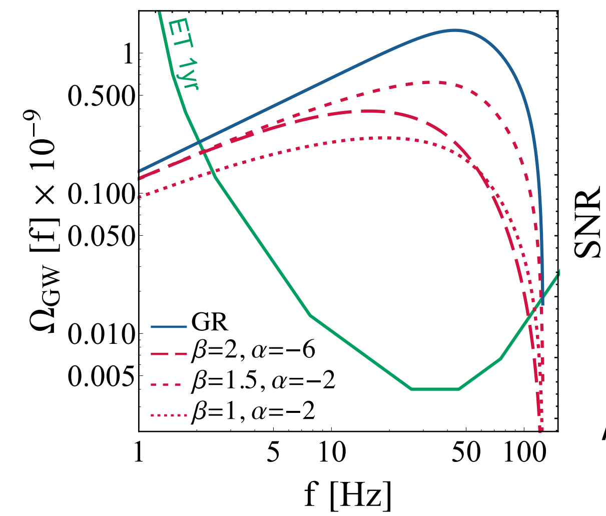

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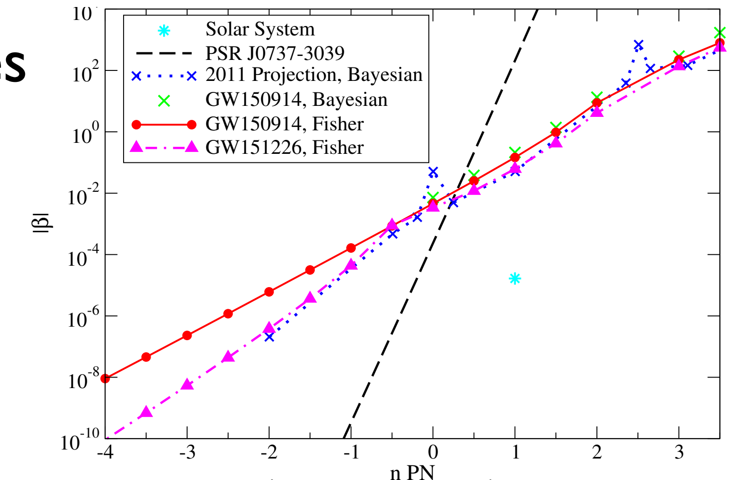

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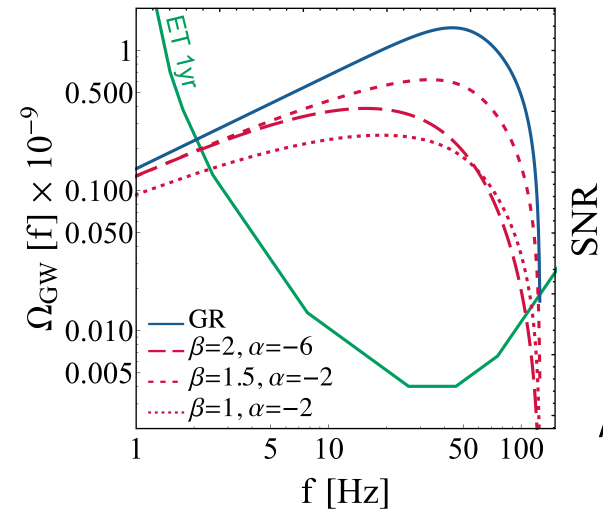

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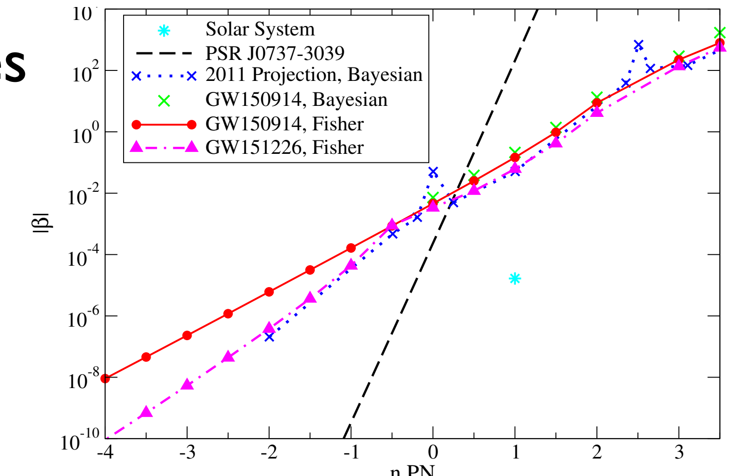

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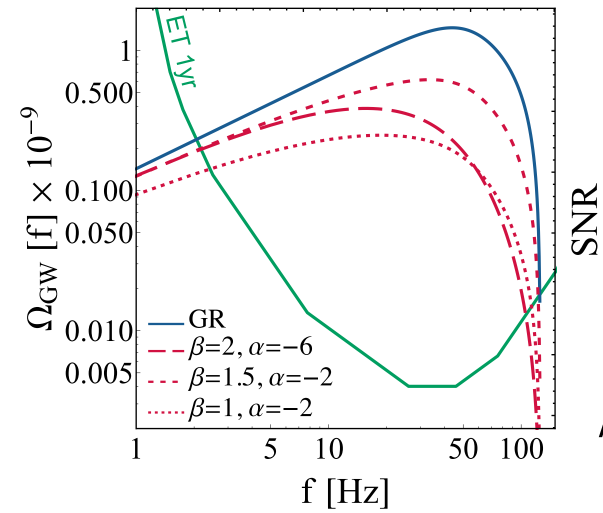

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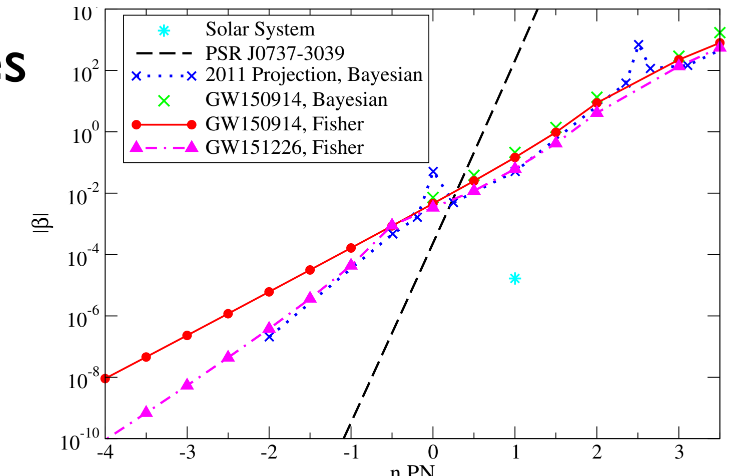

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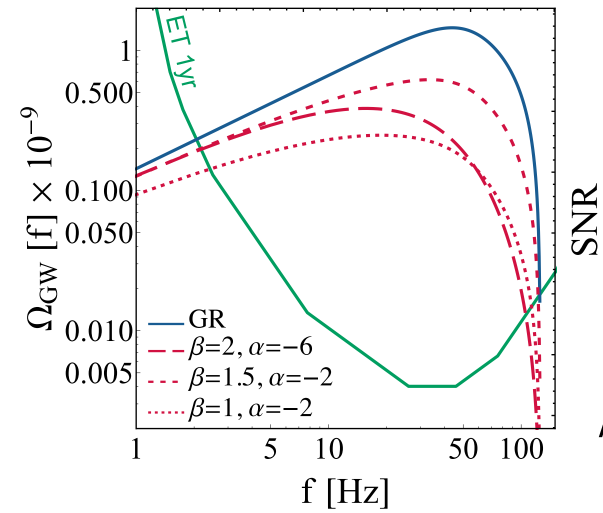

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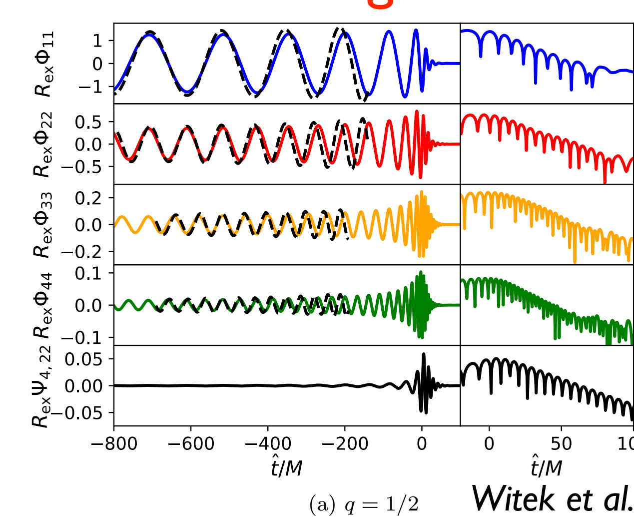

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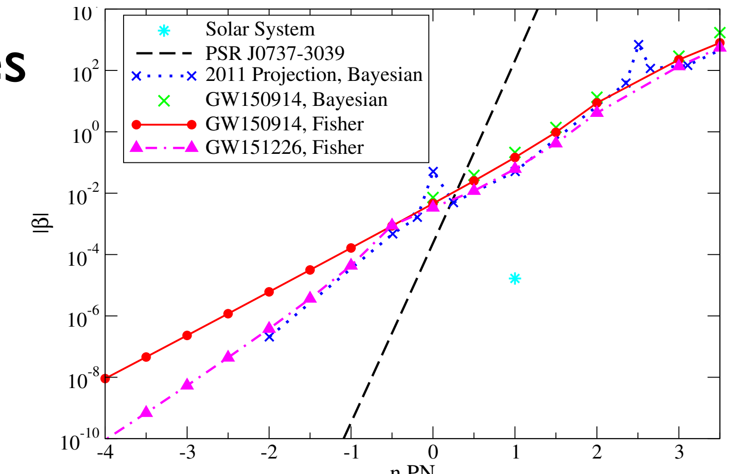

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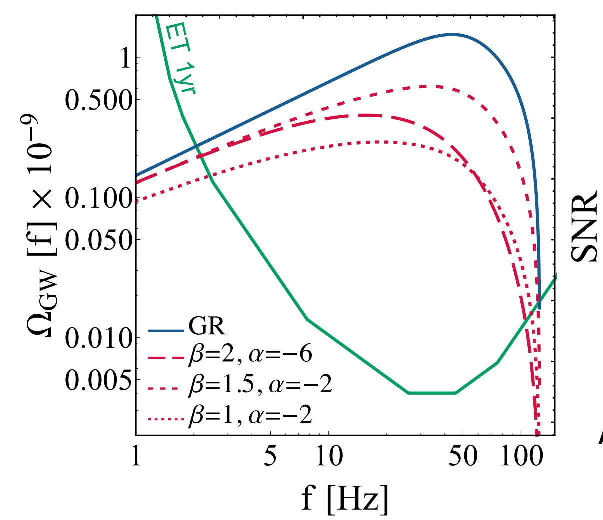

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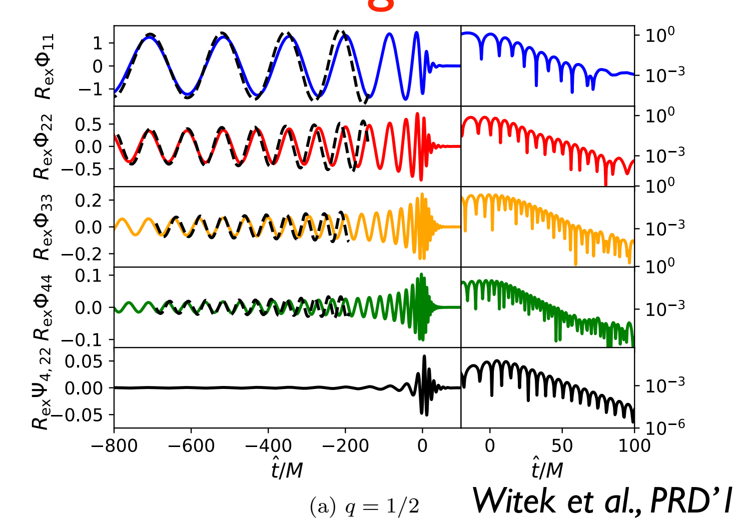

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See also the review "**Testing GR with astrophysical observations**", *Berti, Barausse, Cardoso, Gualtieri, Pani et al., CQG '15*

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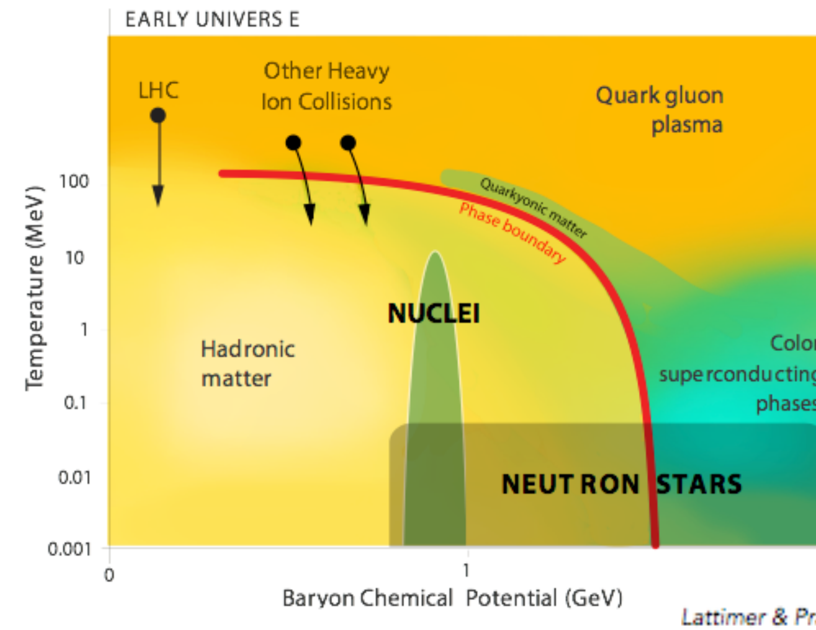

Lattimer & Prakash, 2007
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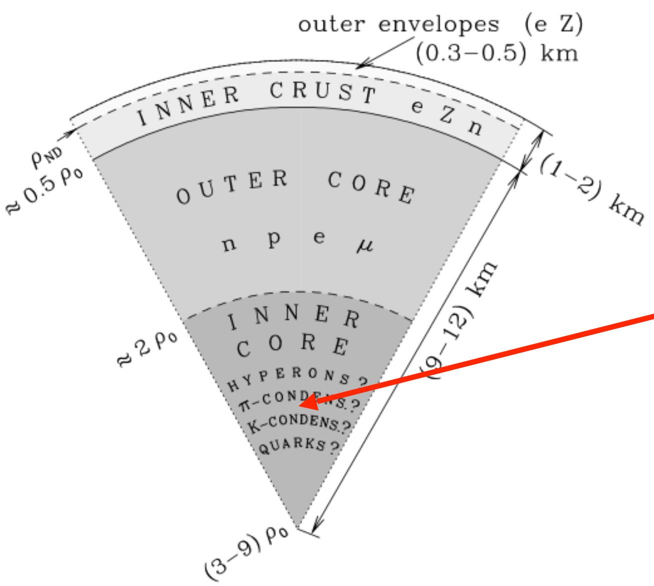

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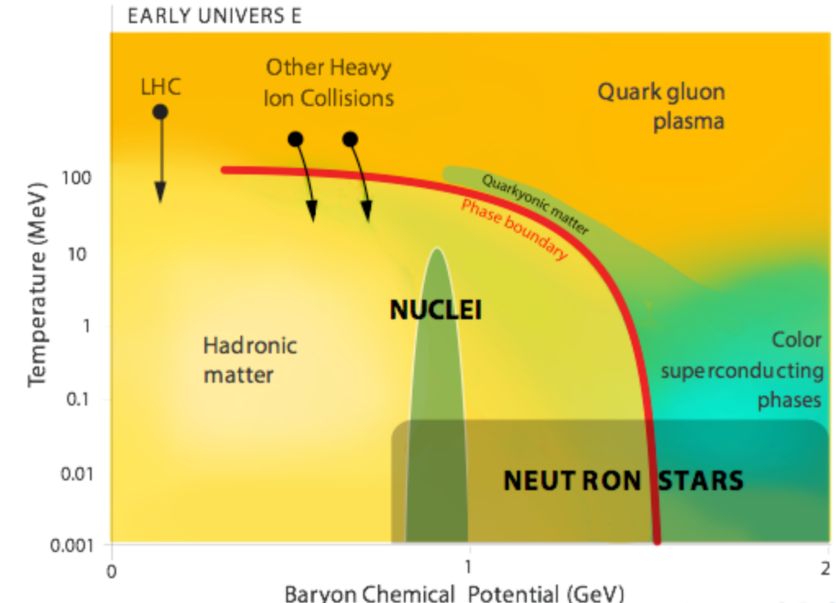

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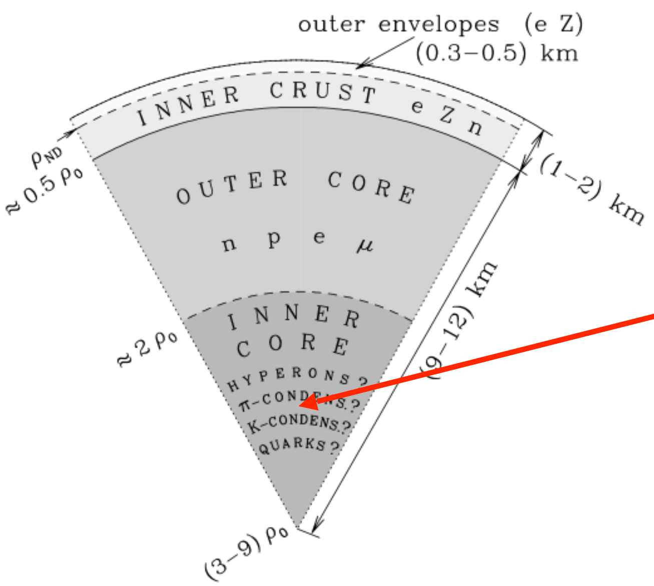

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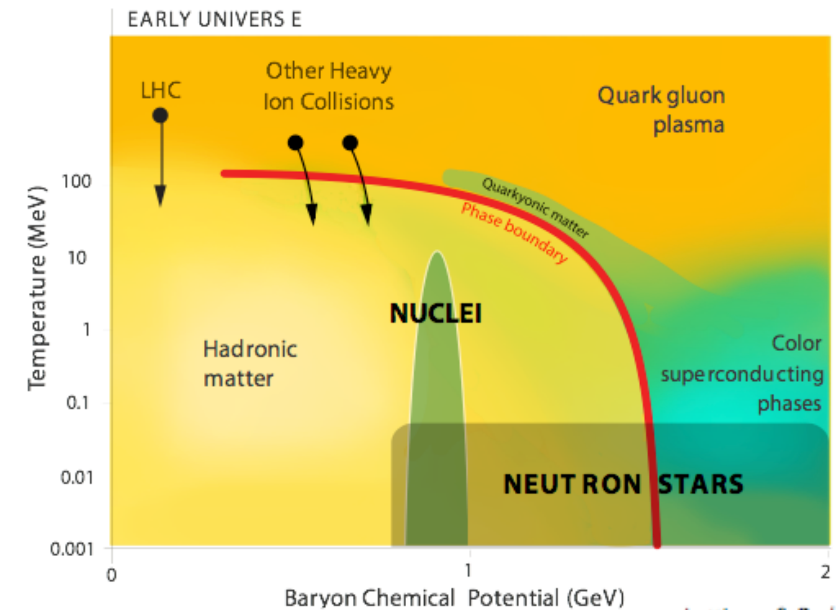

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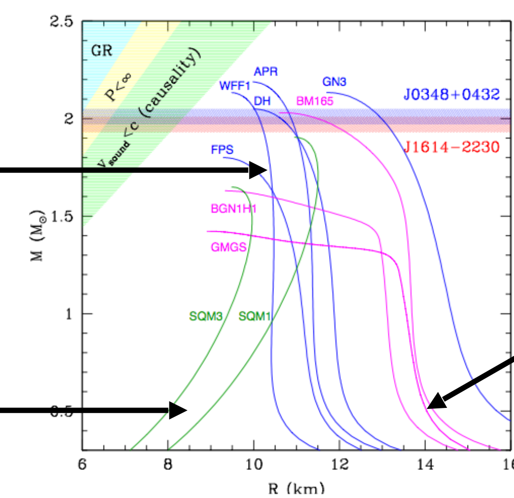
The proposed EoSs are different in *physical assumptions*, *particle content* and *computational approaches*

normal matter

exotic matter



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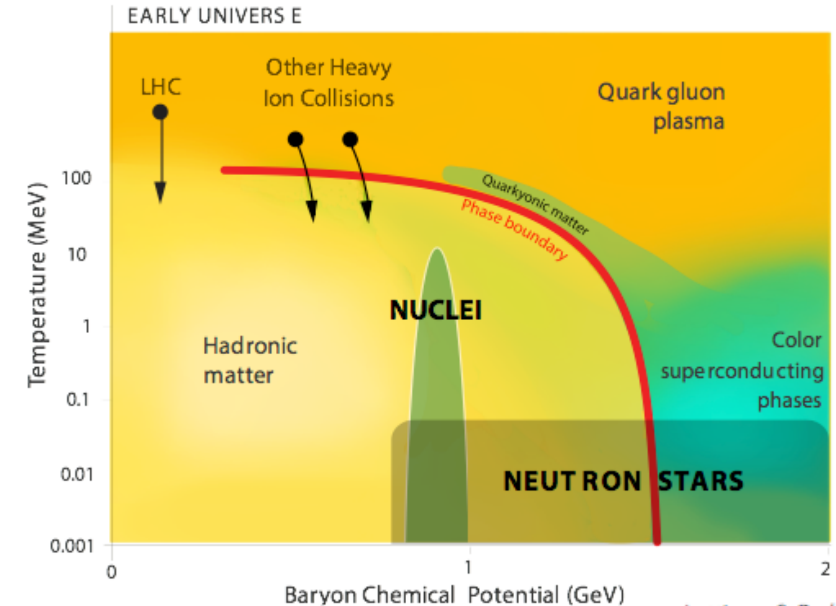

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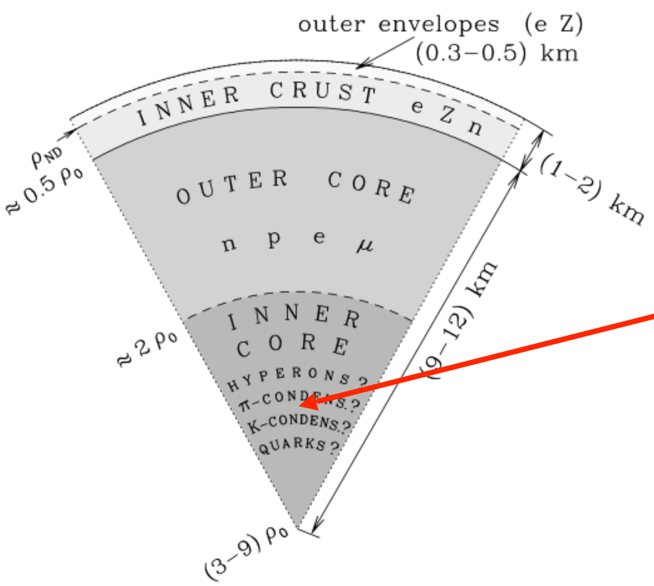

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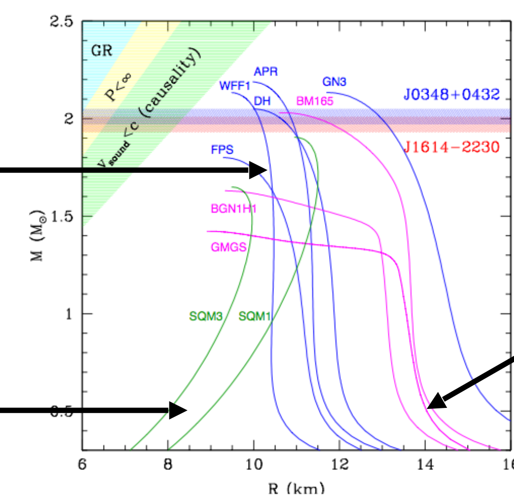

The most promising probe of the NS EoS is the tidal deformability, measured through GWs!

$$Q_{ab} = \lambda\, G_{ab}$$

quadrupole tensor induced by the tidal field

tidal deformability ("Love number")

tidal tensor

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During the late inspiral and merger of a neutron star binary,
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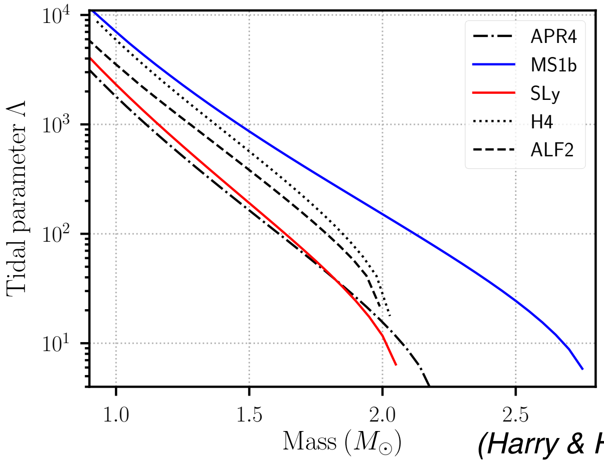

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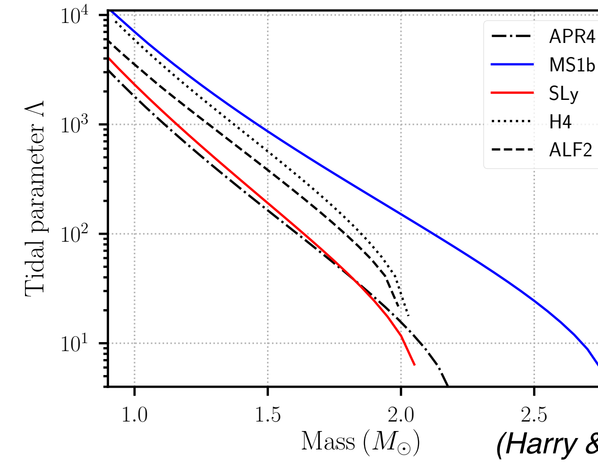

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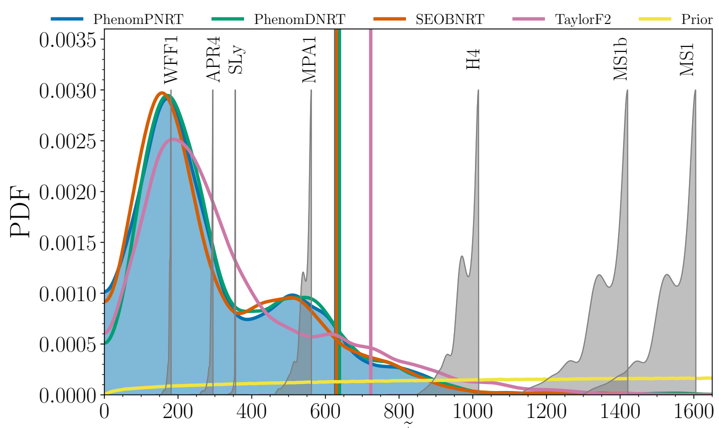
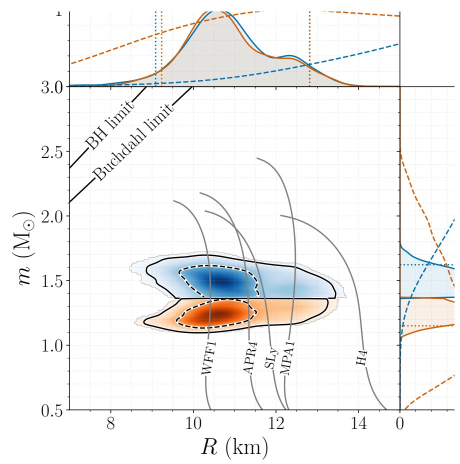


LIGO-Virgo collaboration, '18



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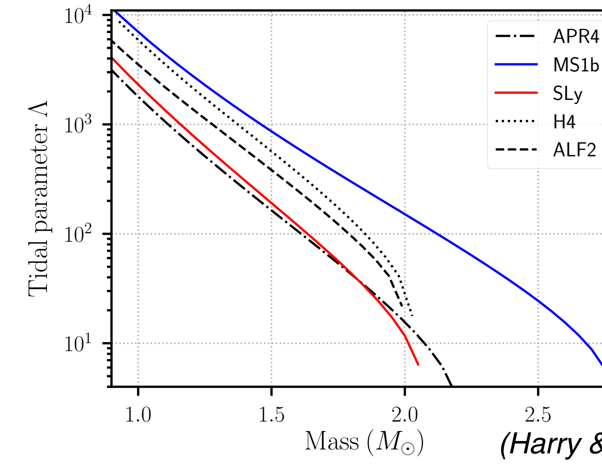

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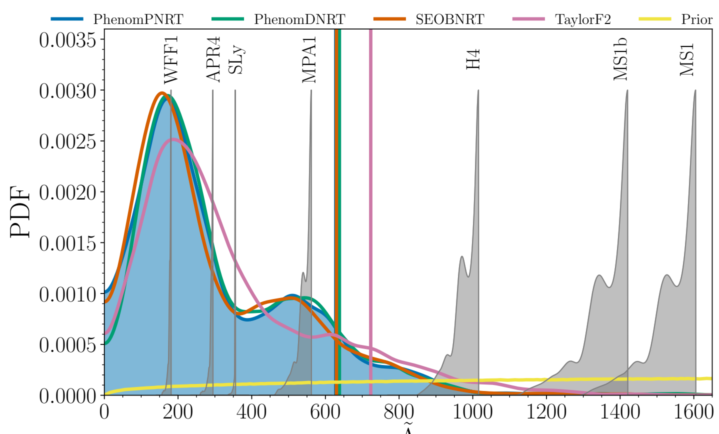

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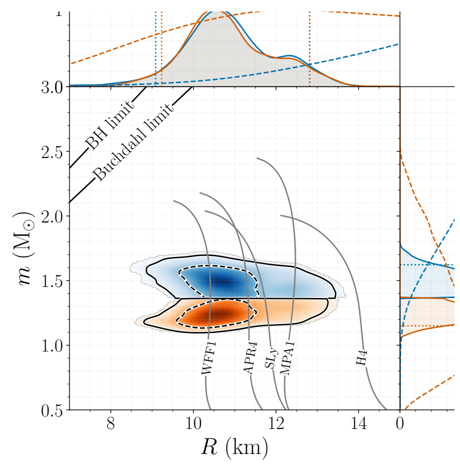

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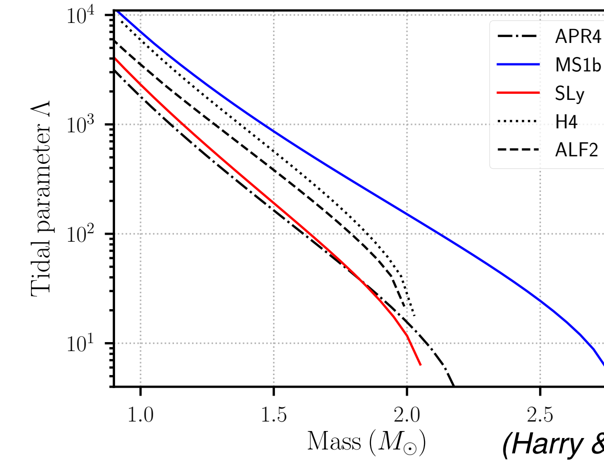

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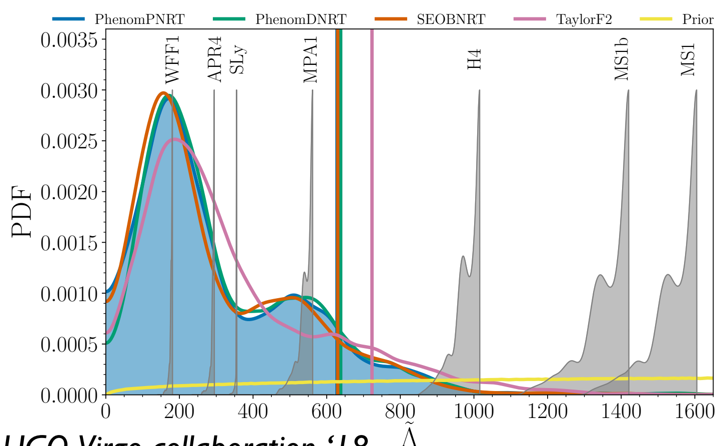

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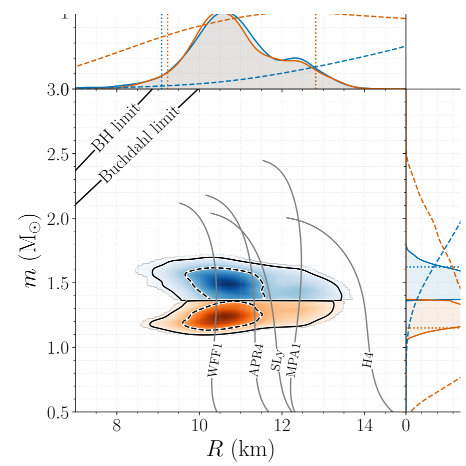

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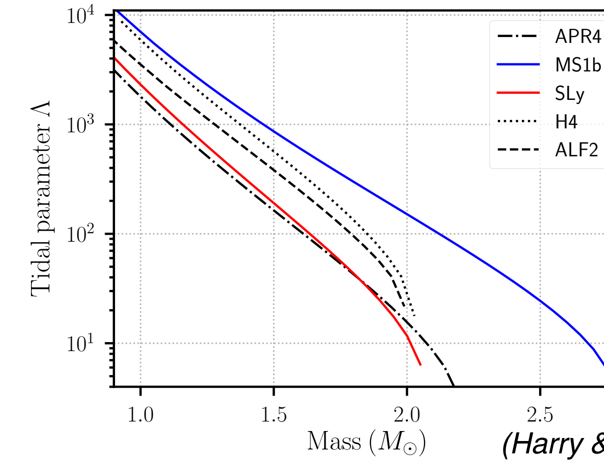

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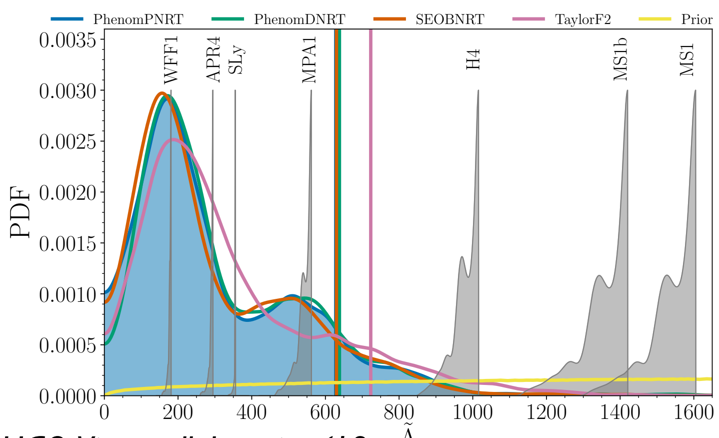

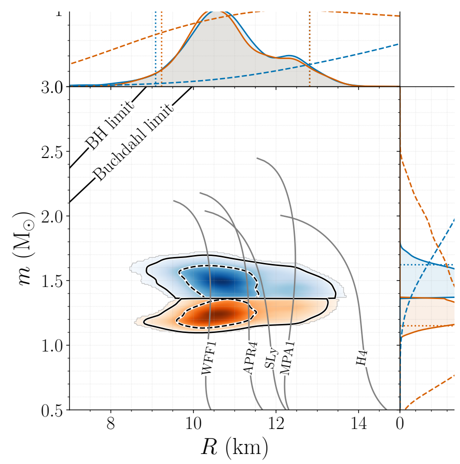

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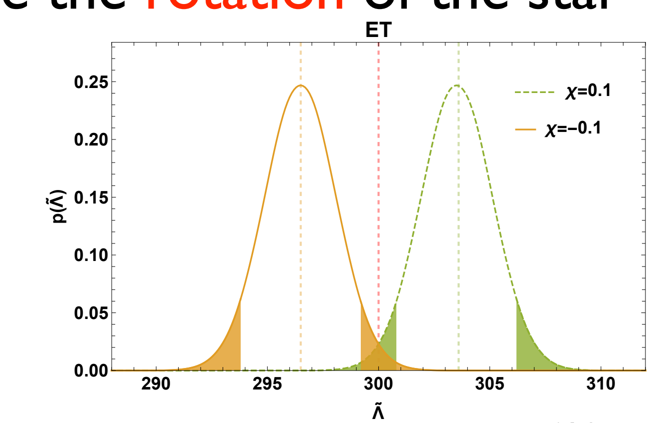

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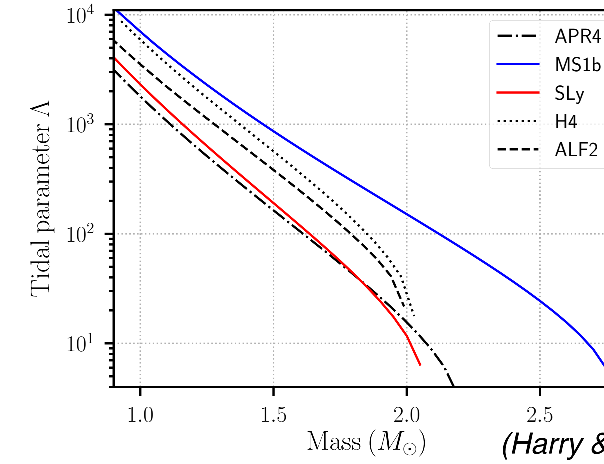

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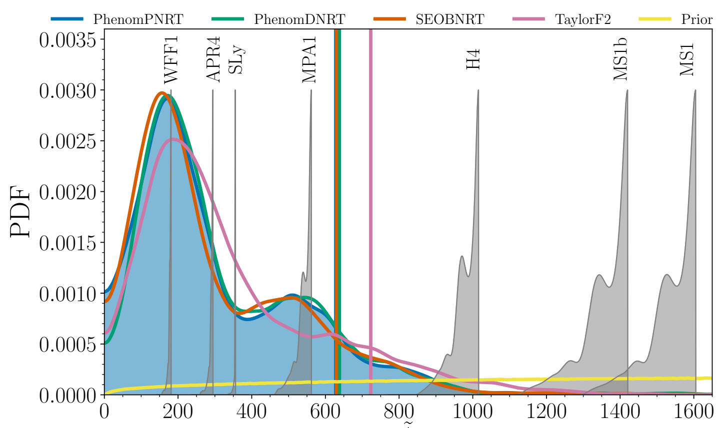

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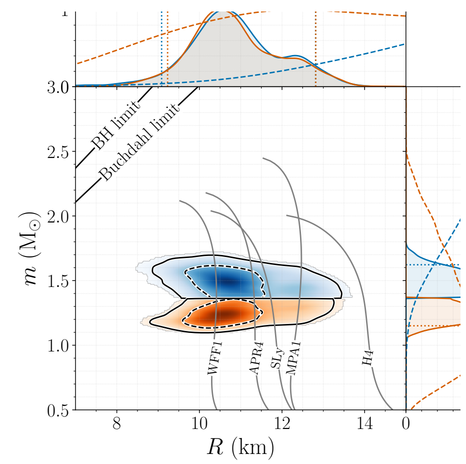

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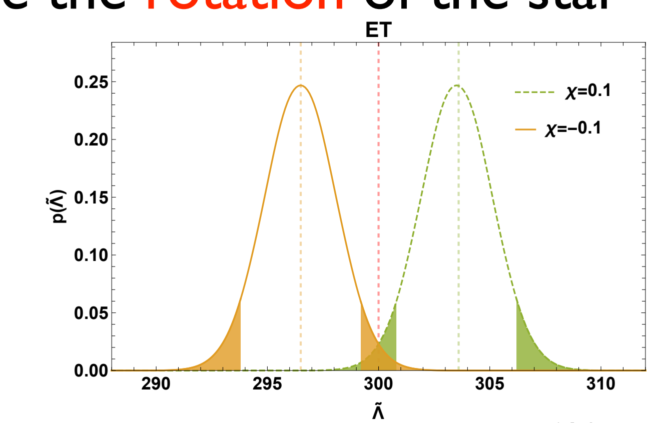

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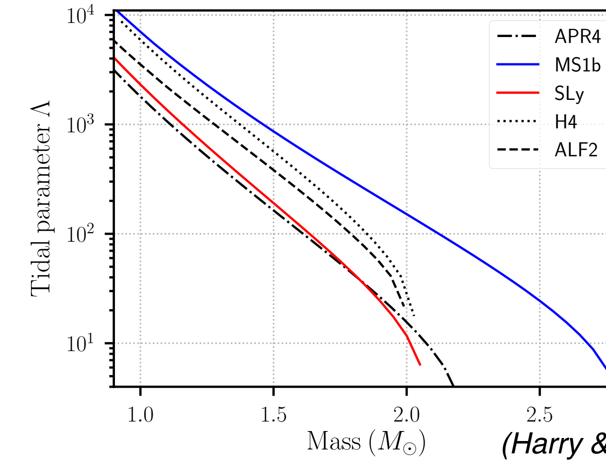

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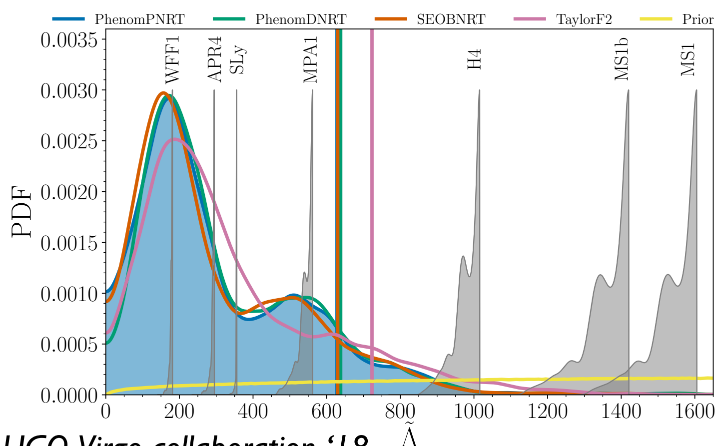

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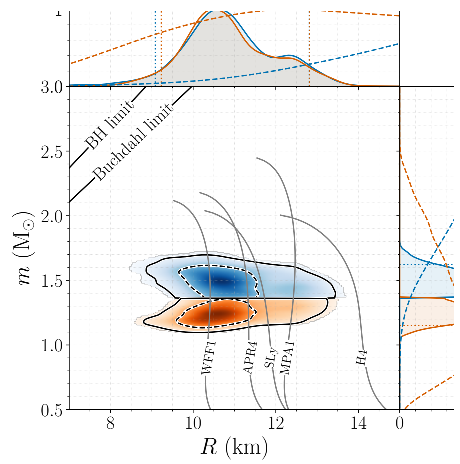

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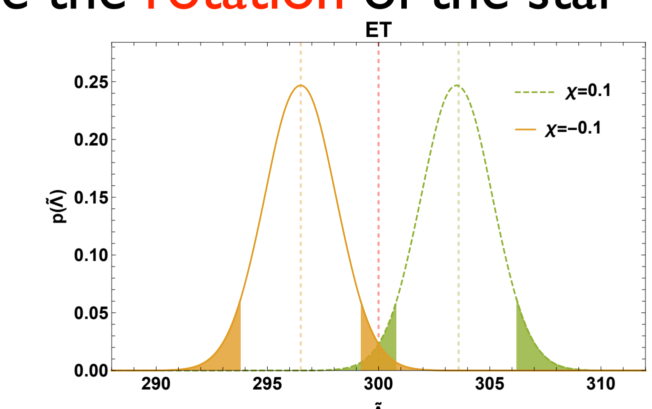

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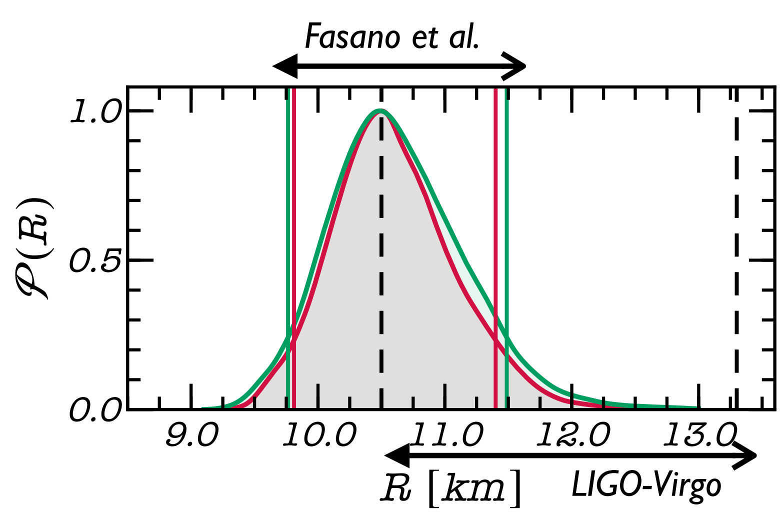

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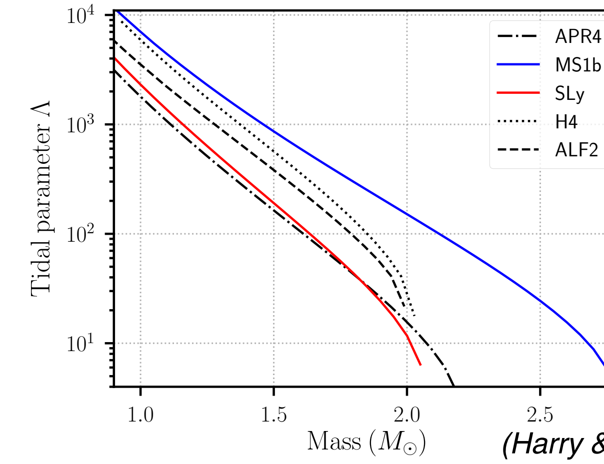

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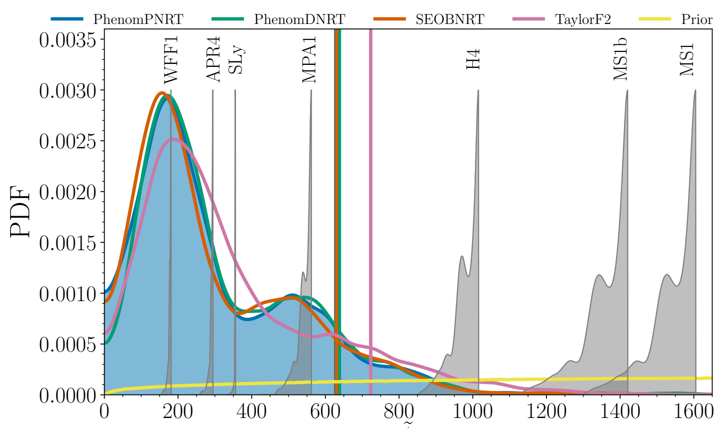

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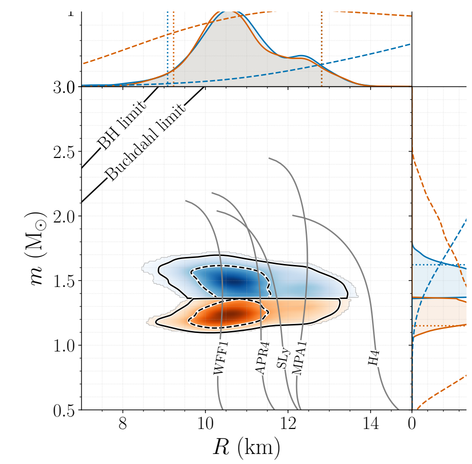

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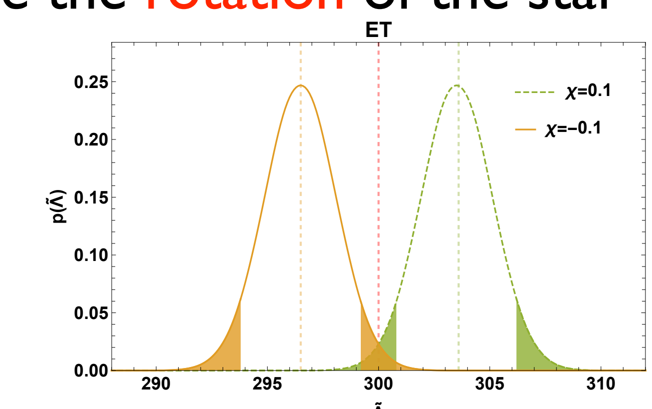

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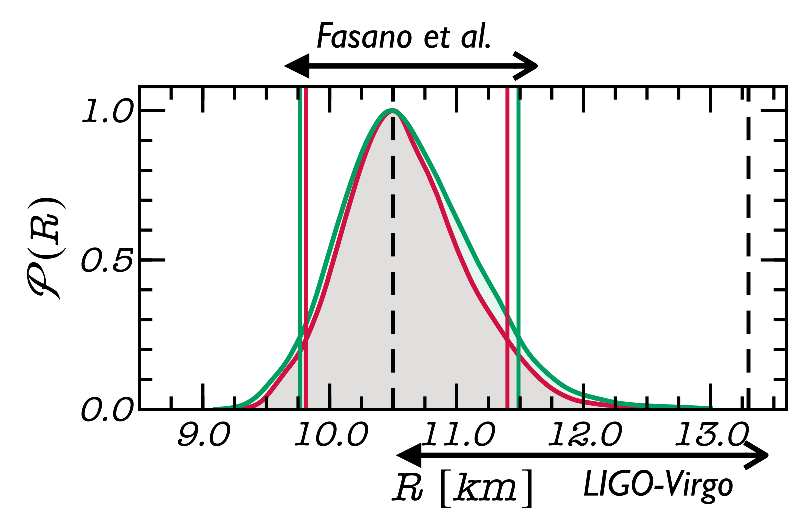

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- Work in progress: phenomenological parametrization of the neutron star EoS based on microphysics quantities (e.g. symmetry energy) to set up an "inverse problem" from GW observables

1. Modelling sources of Gravitational Waves

2. Test the gravitational interaction, looking for general relativity deviations in the strong-field regime

3. Determine the equation of state of nuclear matter in the inner core of neutron stars

4. **Test the nature of compact objects**

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- quantum gravity & string theory suggest the existence of Planck-scale deviations near the horizon (fuzzbals, firewalls, etc.), also [but not only] to solve information paradox

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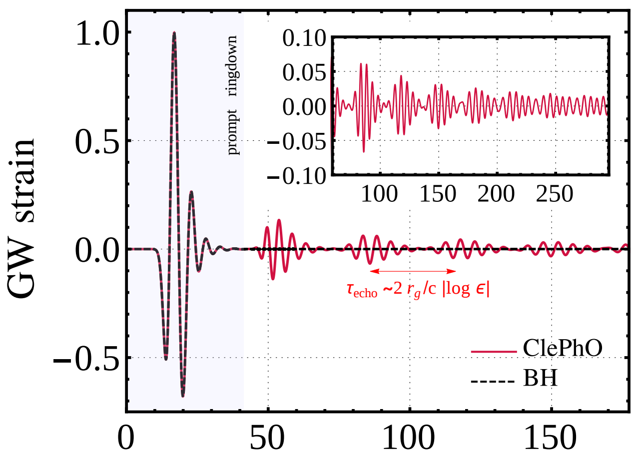

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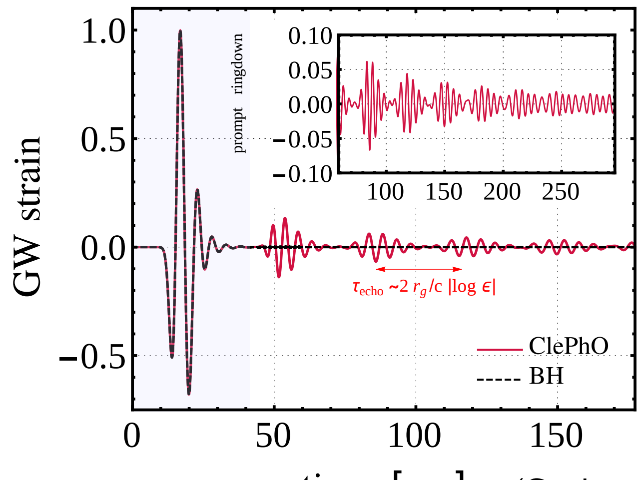

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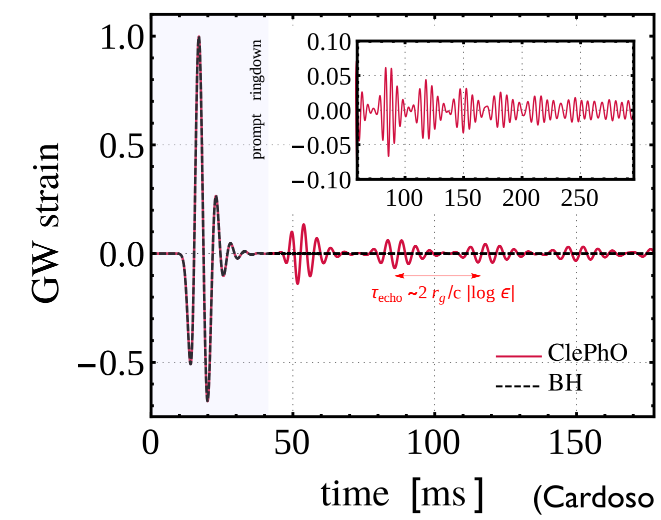

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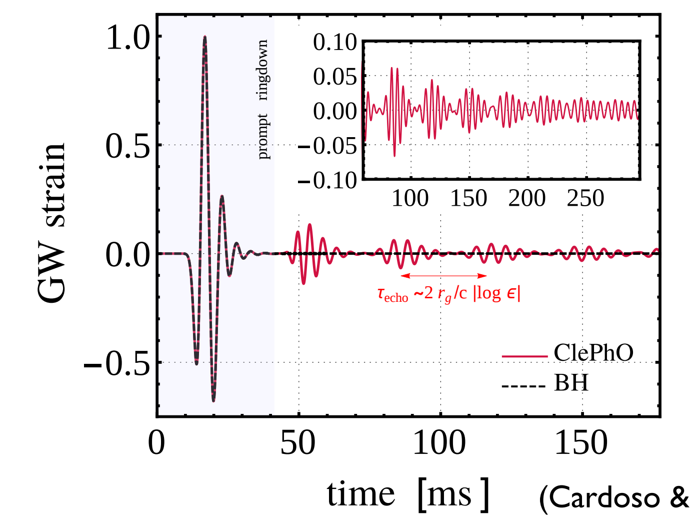

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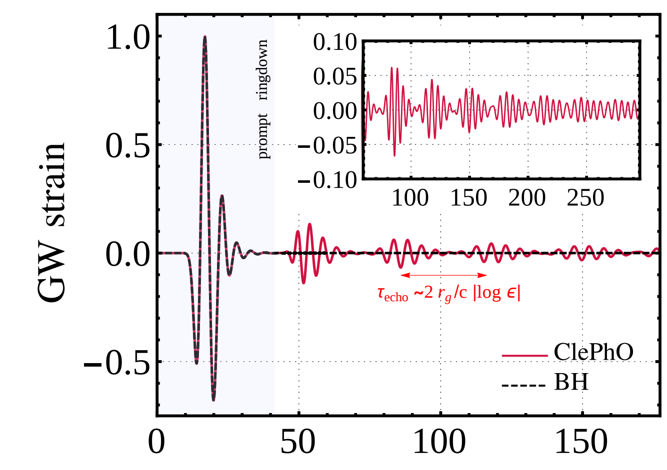

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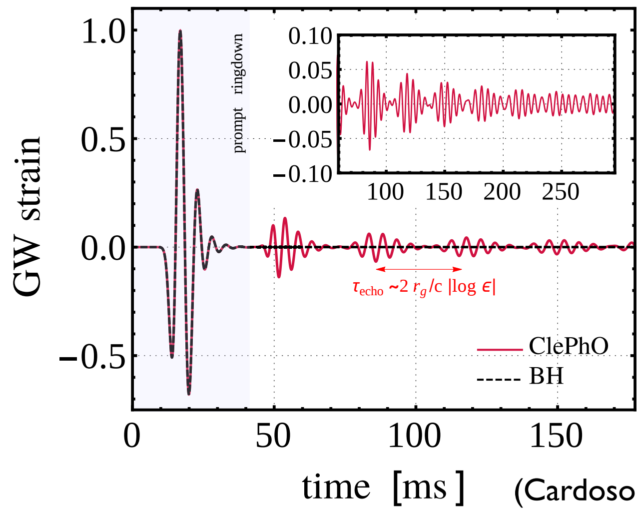

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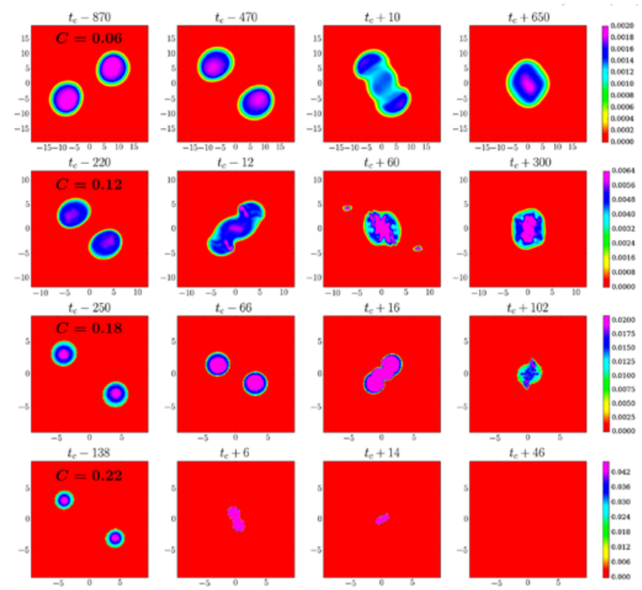
Example: boson stars i.e. self-gravitating scalar field configurations. If the supermassive objects at the center of galaxies are boson stars, they would have a scalar field halo which could be an alternative to Dark Matter.



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2. Test the gravitational interaction, looking for general relativity deviations in the strong-field regime

3. Determine the equation of state of nuclear matter in the inner core of neutron stars

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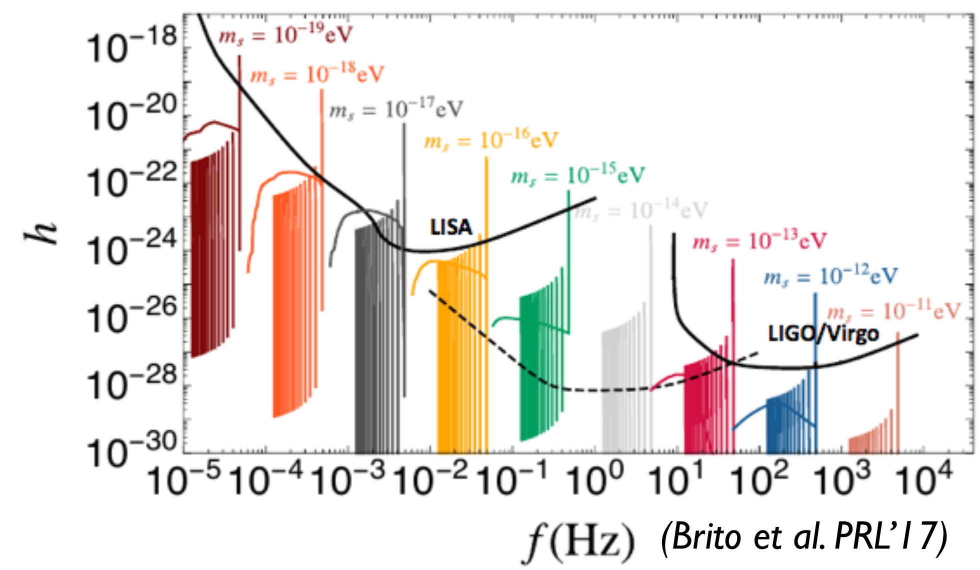

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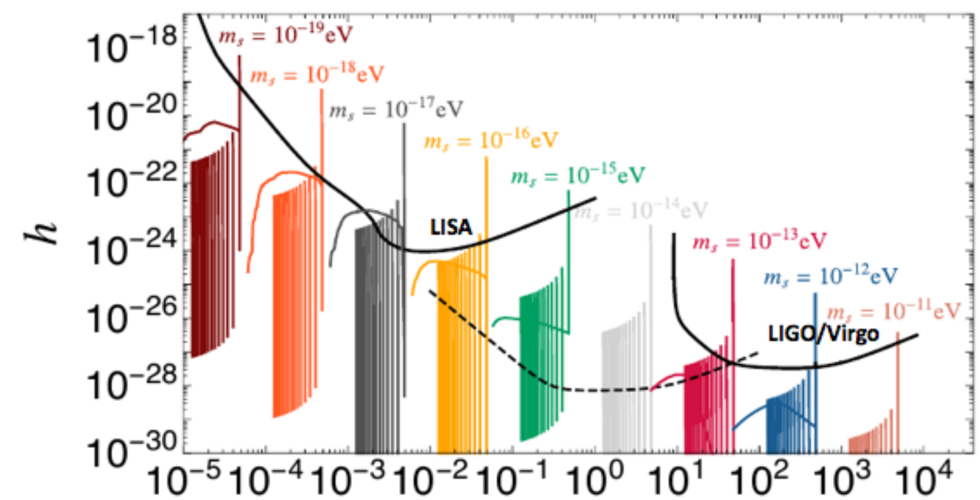

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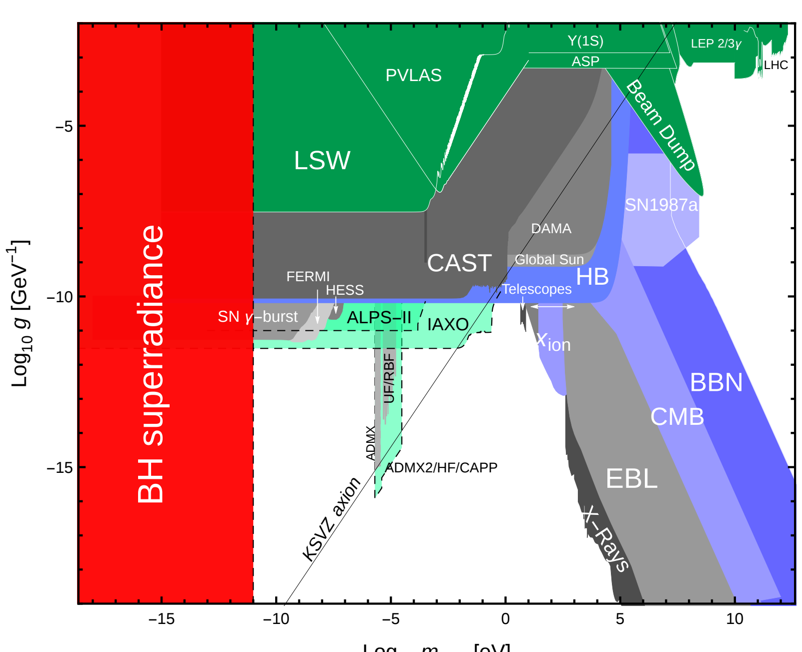

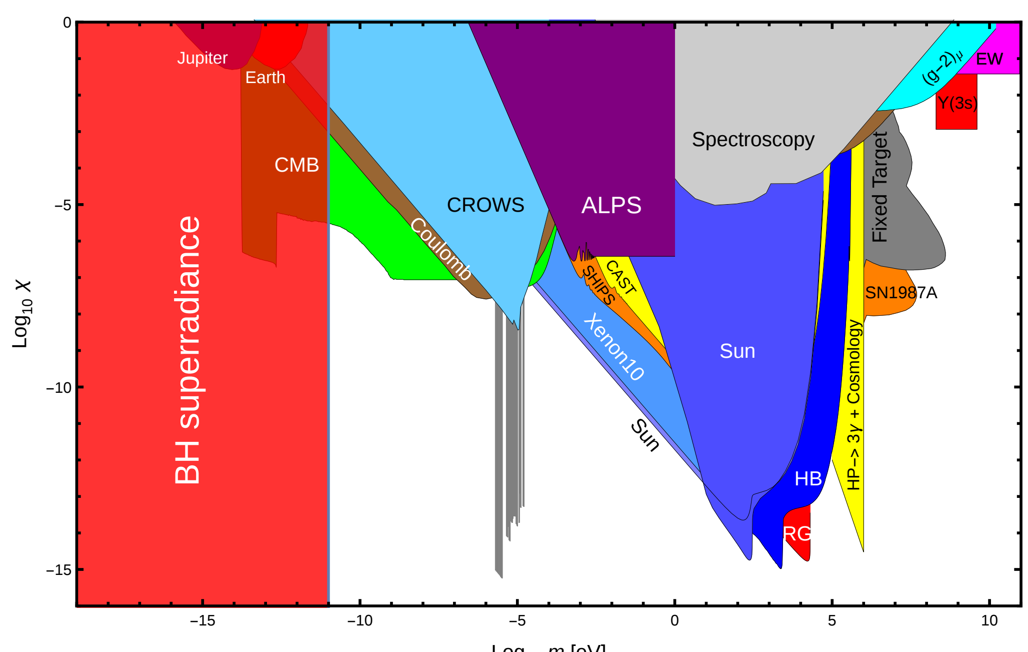

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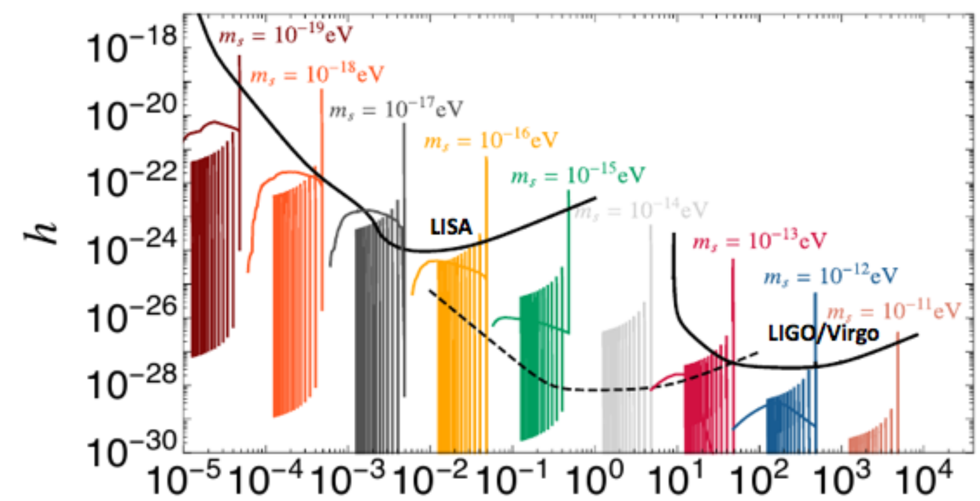

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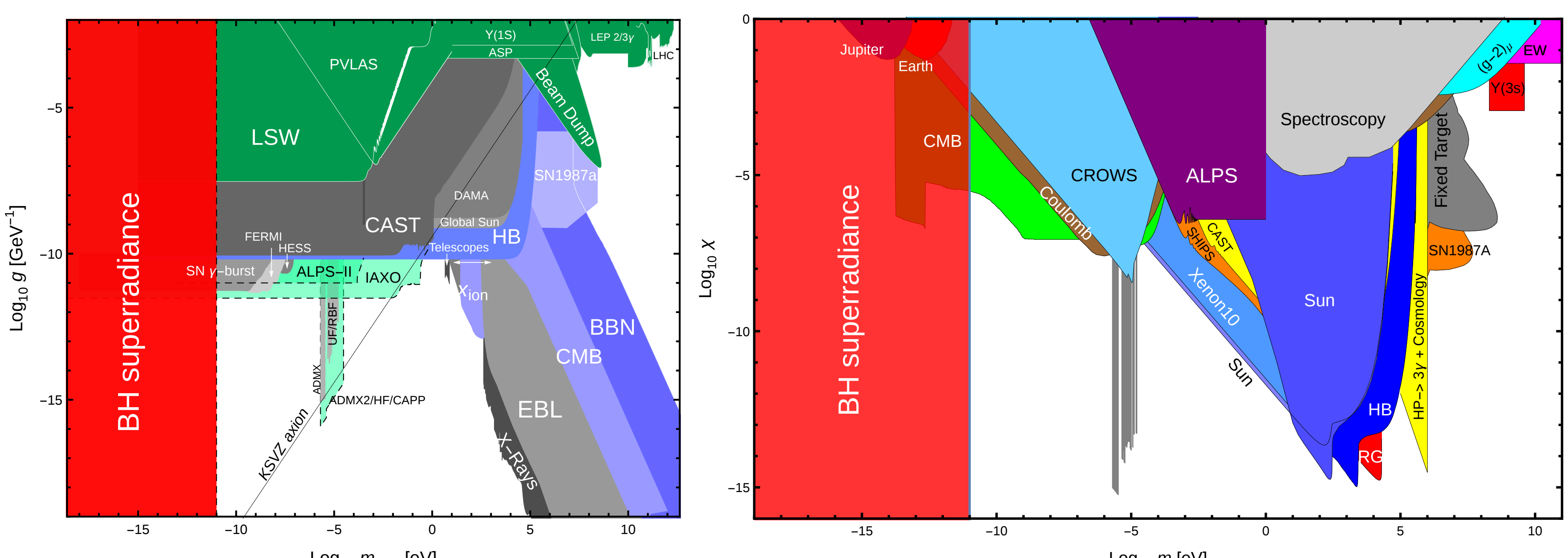

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These research line is also supported by ERC-2017-StG DarkGRA (P.Pani)
"Unveiling the dark universe with GWs"
https://www.darkgra.org/

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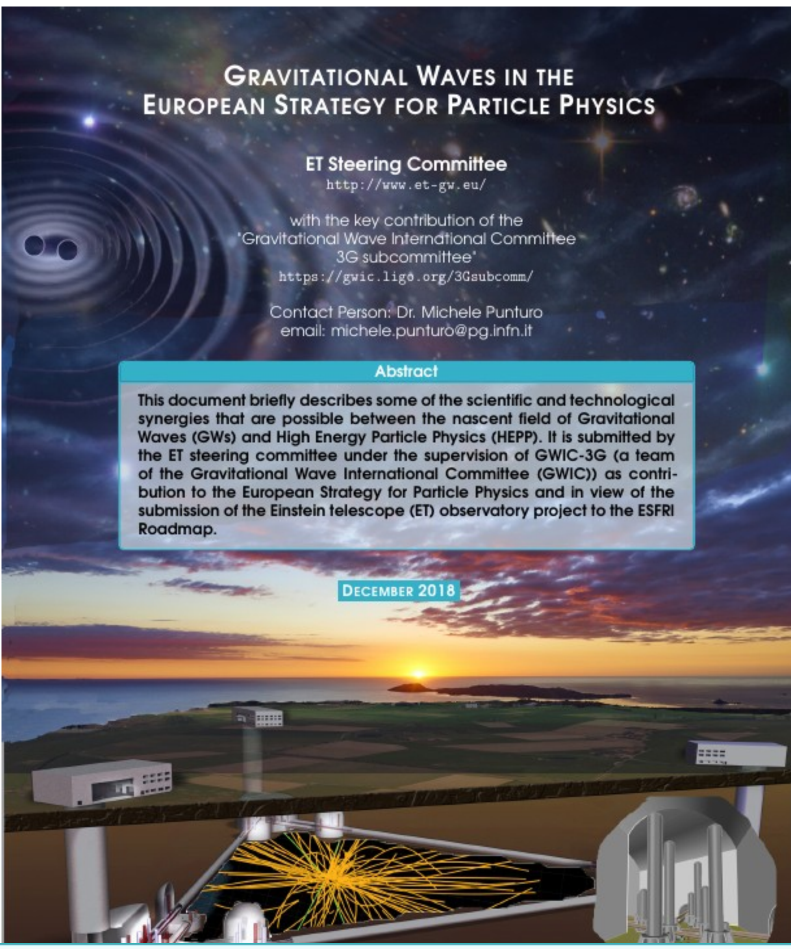

Future GW observations will enable unprecedented and unique science in extreme gravity and fundamental physics. They will allow us to explore and address an impressive set of questions in these topics, which will affect future science at profound levels. The next generation of GW observatories will address:

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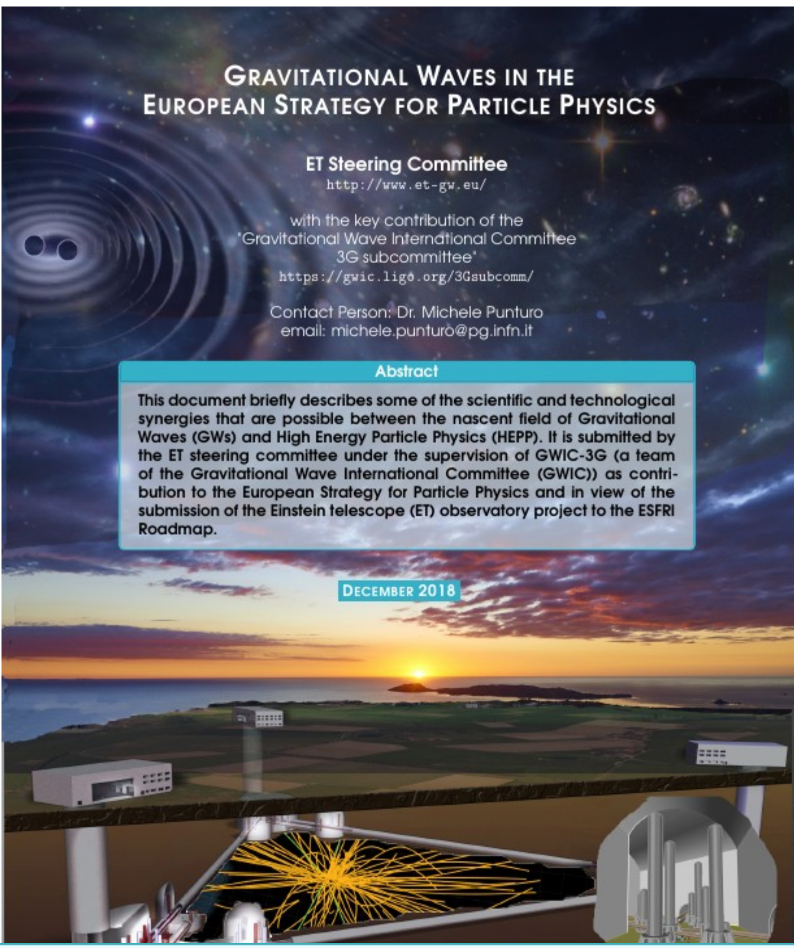
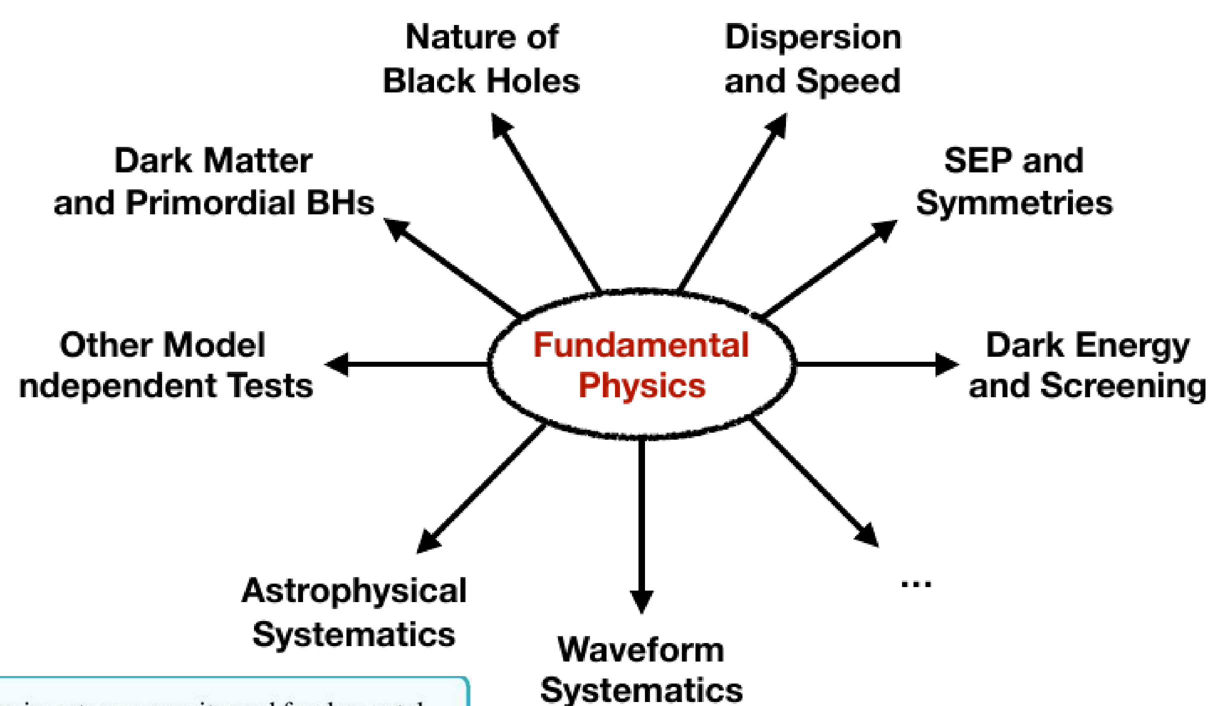
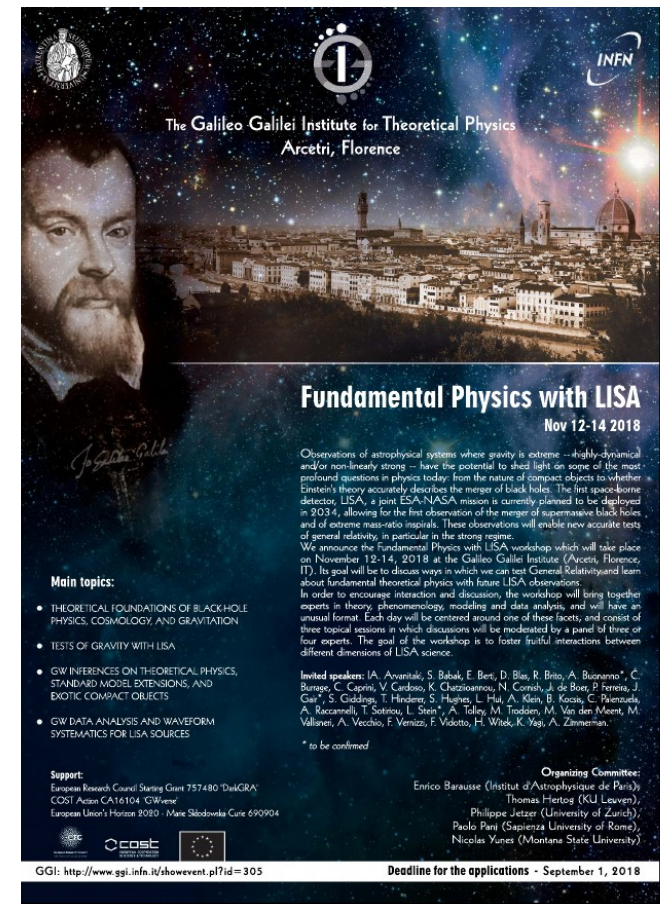


The LISA Fundamental Physics Working Group: A Manifesto





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- ⋆ **The nature of compact objects.** *Are black holes and neutron stars the only astrophysical extreme compact objects in the Universe? Are there subtle signatures of quantum gravity in the spacetime geometry of these compact objects?*
- ⋆ **Cosmology and the early unniverse** *What phase transitions took place in the early history of the Universe and what are their energy scales? How do cosmological parameters vary with redshift?*