Kick Off Workshop of the ET Observational Science Board

21-22 September 2021 -Online

ET OSB

Division 1: Fundamental Physics

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Fundamental Physics & Gravity

Several of the deepest questions in fundamental physics involve <u>gravity</u>:

- **The nature of gravity.** Is Einstein (still) right? What building-block principles and symmetries invoked by General Relativity (GR) can be challenged? Extra degrees of freedom in the gravitational interaction?
- **The nature of neutron stars.** How does nuclear matter behave in the extreme conditions present in the inner core of neutron stars? Does exotic physics show up in these objects? [synergy with nuclear/atomic physics]
- **The nature of black holes.** How well classical BHs in GR describe observations? Do exotic species of compact objects exist? Signatures of quantum gravity near event horizons?
- **The nature of dark matter.** Is dark matter composed of particles, compact objects, or modified gravity? How to constrain the properties of dark matter using GWs? [synergy with particle physics and cosmology]

The science goals of our Division

- Fundamental Physics objectives of ET:
  tests of GR, the nature of compact objects, and of matter and particle physics at the most extreme conditions
- Potentially groundbreaking goals with profound implications for cosmology, nuclear and particle physics, dark-matter searches, as well as for certain quantum-gravity programs.
- The discovery potential in GW science has reinvigorated the ongoing efforts to construct *high-accuracy waveforms*, in particular using sophisticated computational methods from particle physics that have been instrumental to search for "new physics" at colliders through precision data.

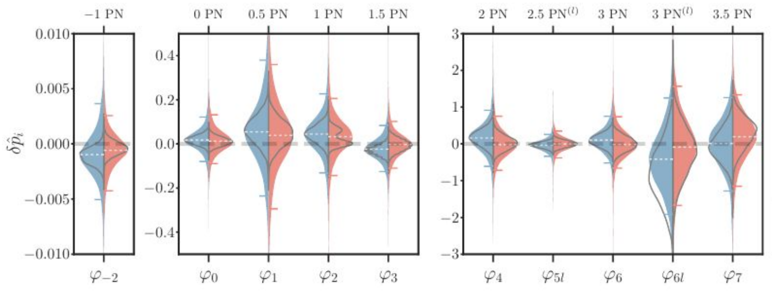
Key Science Questions:

- Testing the fundamental principles of the gravitational interaction
- Identifying the origin of merging binaries across cosmic history (synergy with Population Division)
- Testing the nature of compact objects
- Probing near-horizon physics
- Develop GW-based searches for dark-matter candidates
- Improve current waveforms to match ET requirements (synergy with Waveform Division)
- Identify science goals that are *unique* for ET

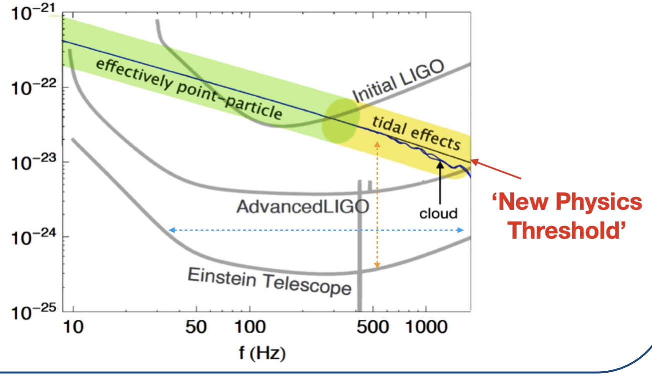
Groundbreaking discoveries rather than incremental improvement compared to LIGO/Virgo

Fundamental Physics with GWs

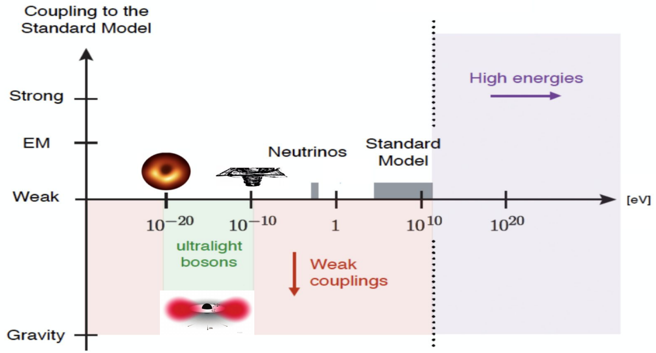
Tests of gravity



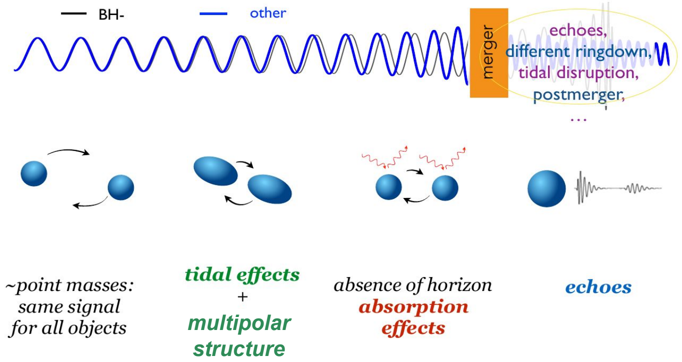
Precision Gravity Frontier



Dark-matter searches & new fields

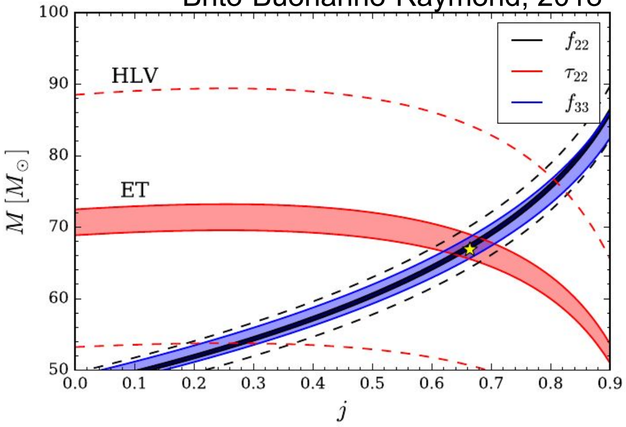


Tests of compact objects



Testing the nature of gravity with ET

Brito-Buonanno-Raymond, 2018



- **Parametrized post-Newtonian/Einsteinian tests**
- **GW propagation tests** (synergy with Cosmo Div)
- **Extra polarizations**
- **No-hair theorem tests**
  - ET: O(100) events/yr allows for BH spectroscopy
  - Deformed QNMs, new modes, different amplitudes
- **Inspiral-merger-ringdown tests:**
  - Numerical simulations beyond GR under development
  - Needed for model selection in case of anomalies

Challenges:

- Improve IMR waveforms to meet ET requirements (with Div8)
- Modelling modified gravity at the same level of GR

Testing compact objects with GWs

- **Near-horizon physics:** The *late-inspiral*, *merger*, and *ringdown* provide smoking guns for deviations from the classical BH picture.
- **Quantum gravity effects (?)** Various quantum gravity models predict O(1) corrections at the horizon of astrophysical BHs
- **Exotic compact objects (ECOs):**
  - *Are there compact sources other than BHs and NSs?*
  - Dark matter objects (e.g. *boson stars*)?
  - Puzzling events (e.g. *GW190521*, *GW190814*) might suggest exotic explanations
  - ...

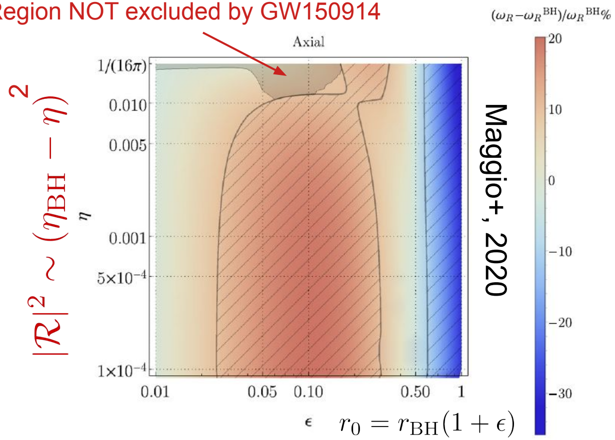
Challenges:

- Better theoretical understanding
- Consistent, first-principle ECO models
- Bring onboard new ideas from hep community

Current sensitivity not enough to rule out many models

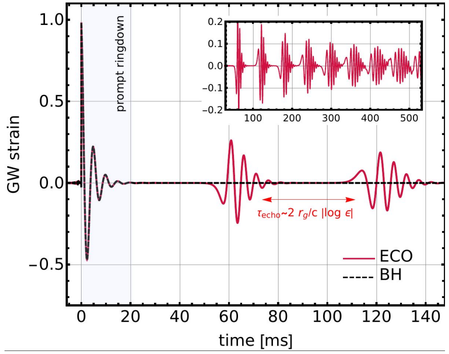
Testing compact objects with ET: QNMs & echoes

- QNM spectrum of an ECO vs BH:
  - Deformed
  - New modes
  - Different amplitudes (simulations?)

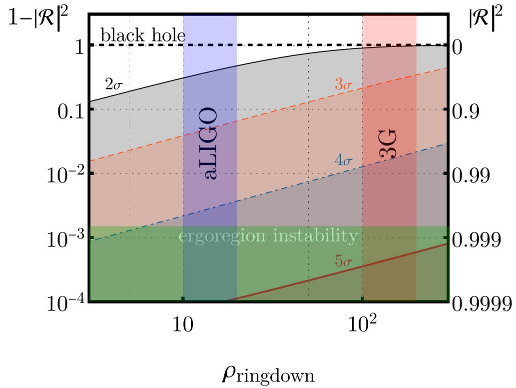


Maggio+, 2020

- GW echoes: a smoking gun of near-horizon “structure”



Cardoso-Pani 2017



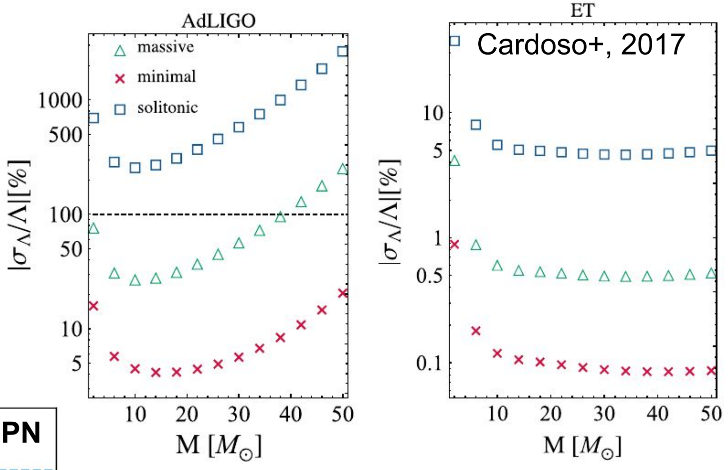
Challenges:

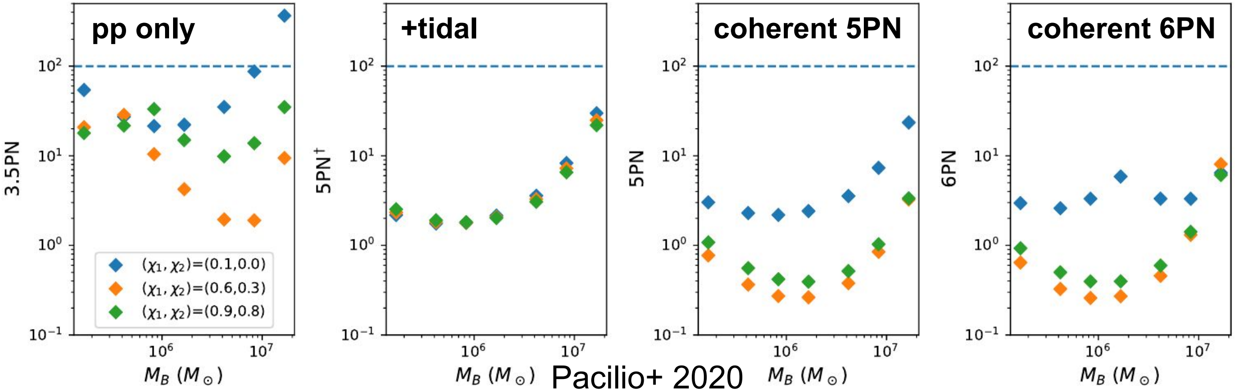
- QNMs for spinning objects beyond Kerr
- ECO coalescence simulations
- High-accuracy boson-star mergers
- Echo waveform modelling

Testing compact objects with ET: tidal Love numbers

- **BHs in GR:** zero tidal deformability in the GW signal
- **Anything else (nonBH or nonGR):** nonzero tidal Love number
- **"Anomalous" Love would exclude "ordinary" BHs**
- **Higher-order PN terms are crucial:**

Measurability of the Love numbers of various boson- models





Challenges:

- High-accuracy waveforms
- IMR-Phenom for ECOs?
- Tidal response of consistent models

Searching for dark matter with GWs

Various DM candidates and beyond-standard-model scenarios can be tests with GWs:

- **Ultralight bosons** (mass <1e-11 eV) would produce macroscopic clouds around spinning BHs due to superradiance
- **Ordinary particle dark-matter** can produce small environmental effects in binary waveforms
- **ECOs** in various mass ranges might be dark matter
- **Primordial BHs** might account for a subpopulation of GW mergers (collaboration with Div3)

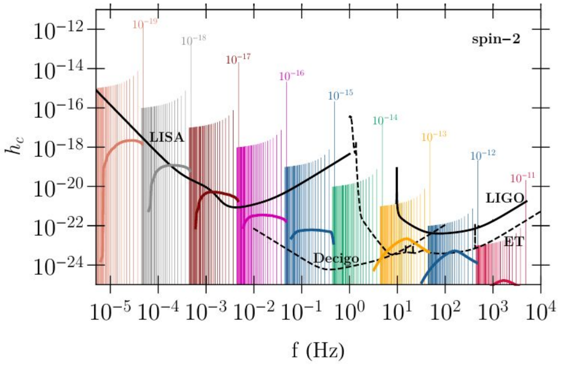
Bertone+, 2019

Searching for ultralight fields with ET

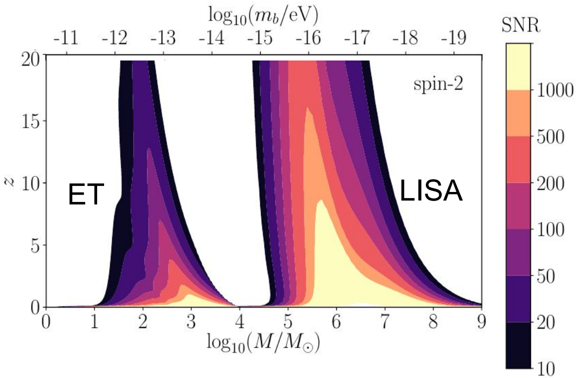
- Light bosonic fields & superradiance:

$$\frac{G}{\hbar c} M \mu \sim \left(\frac{M}{10 M_\odot}\right)\left(\frac{\mu c^2}{10^{-11}\,\mathrm{eV}}\right) \sim \mathcal{O}(1)$$

Coupling parameter



[Brito+ 2020]

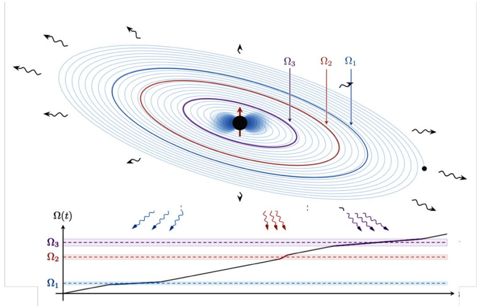


- Indirect constraints from BH mass-spin
- IMBH detections could fill gap between stellar and supermassive BHs
- ET-LISA ranges are complementary
- Potentially detectable to z>20
- Several effects in binaries (dephasing, floating orbits, disruption, tidal effects)

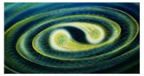
Challenges:

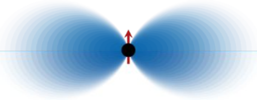
- Pipelines for generic (spin-0,1,2) massive bosons
- Improve waveforms for cloud effects in binaries (e.g. tides & dynamics)

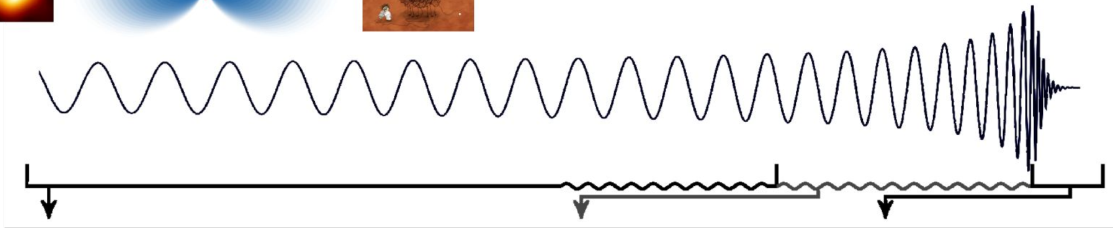
[Baumann+ 2020]

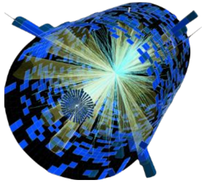


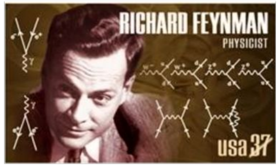
Discovery Potential = Accuracy











$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{\overbrace{1+\cdots+[\cdots]x^{7/2}}\right\}$$

"Waveforms will be far more complex and carry more information than expected. Improved modeling will be needed for extracting the GW's information"

Summary & Challenges

- Scientific goals of Div1:
  - In short: *testing Fundamental Physics with ET*
  - Speculative, ambitious, high-gain/high-risk, potentially groundbreaking goals
  - Get ready to meet ET precision standards also for FP tests
  - Explore complementary with other communities (e.g. particle/nuclear physics, cosmo, theory)
- Organizational goals:
  - *Organize a community*: facilitate communication and collaborations, … (esp. for early-career scientists)
  - *Serve the ET OSB*: preparatory studies related to FP, blue book, projected bounds, forecasts...
  - *Develop synergies* with most other Divisions (e.g. Cosmo, Populations, Multimessenger, Nuclear Physics, Data Analysis, Waveforms, ...)
- <u>*Many challenges ahead: we need an **active** and **enthusiastic** group of people!*</u>