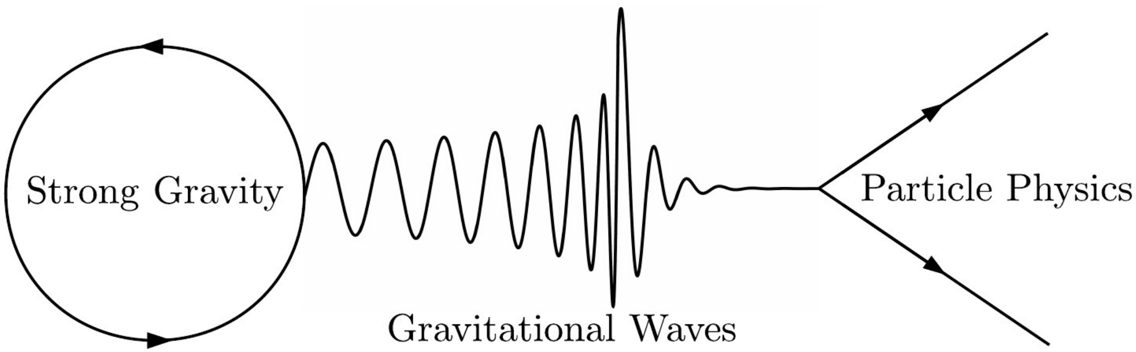
Fundamental Physics with ET



Paolo Pani

Sapienza University of Rome & INFN Roma1

https://web.uniroma1.it/gmunu

On behalf of the ET OSB Div1 (Fundamental Physics)

Coordinators: Chris Van den Broeck, Paolo Pani, Rafael Porto

Outline

1. GW science: much more than astrophysics!

2. Testing Fundamental Physics with GWs: an overview

3. Some highlights and challenges ahead

4. Focused talks:

   - 14:30-14:45: Christoph Dlapa, *"Advances in GW predictions through quantum field theory methods"*
   - 14:45-15:00: Swetha Bhagwat, *"Prospects of ringdown-based tests of gravity with ET"*
   - 15:00-15:15: Elisa Maggio, *"Searches for near-horizon structures and echoes"*
   - 15:15-15:30: Richard Brito, *"Searching for ultralight bosons with ET"*

Fundamental Physics & Gravity

Some of the deepest open questions in fundamental physics involve gravity:

- **The nature of gravity.** *How does General Relativity (GR) break down? What building blocks can be tested? Can we probe quantum gravity with observations?*
- **The nature of black holes (BHs).** *How well classical BHs in GR describe observations? What is the fate of black hole evaporation? Remnants? Singularities?*
- **The nature of compact objects.** *How does matter behave in the extreme conditions inside compact stars and in the early universe?* (synergies with Nuclear and Cosmo Divs)
- **The nature of dark matter.** *Is dark matter composed of new particles, dark objects, or modified gravity? New testable paradigms for the dark matter problem?*

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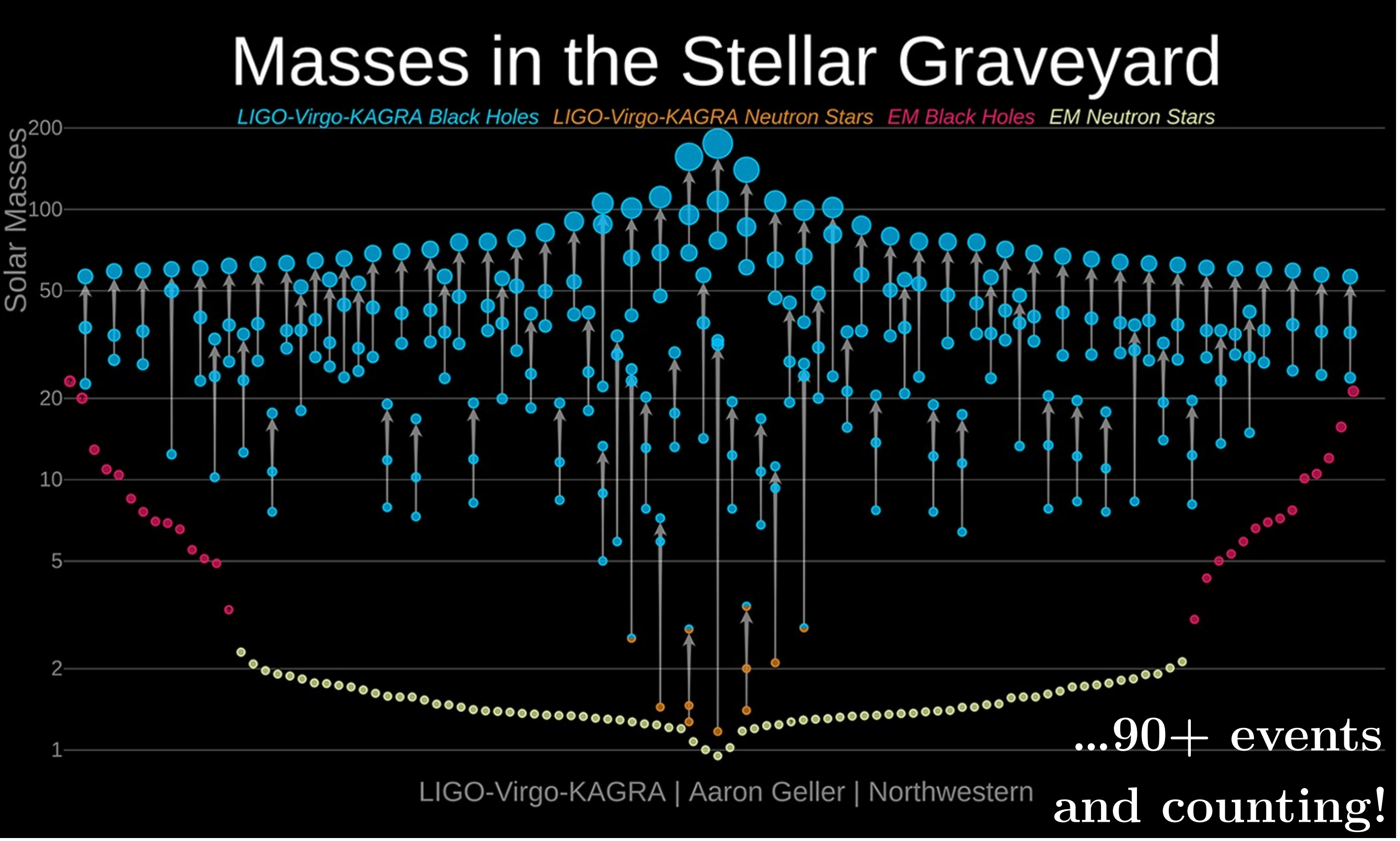
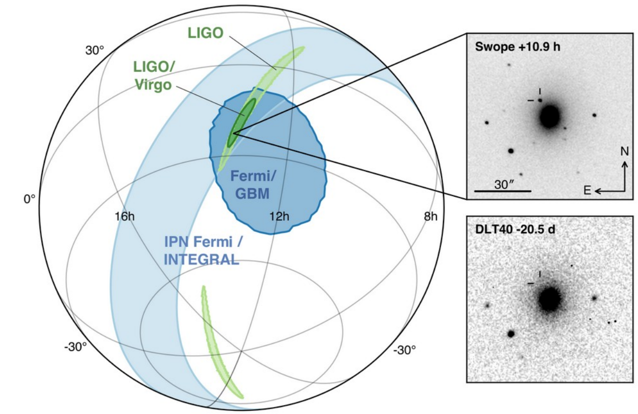
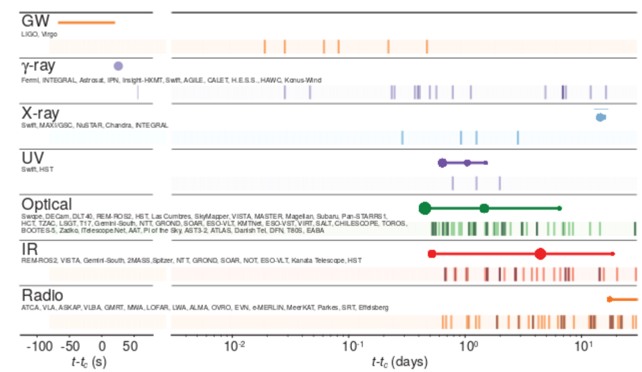
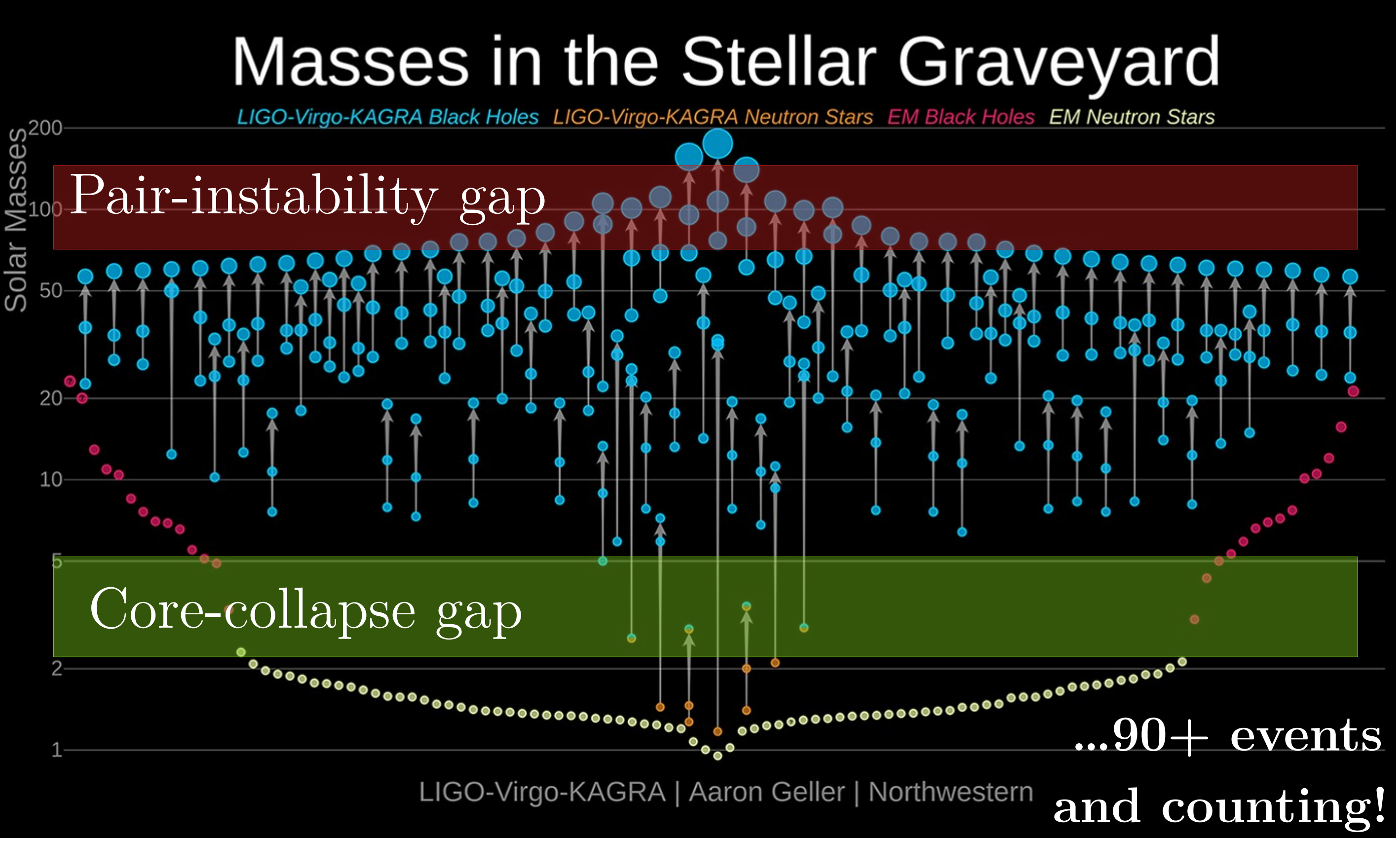
Can we address these questions with GWs?

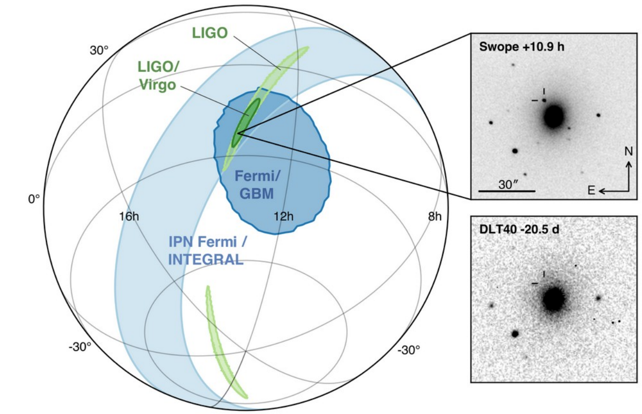


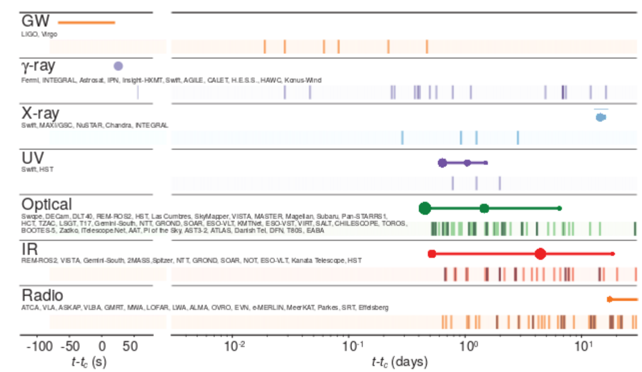




- **GW150914:** first black-hole binary → BH physics & tests of gravity
- **GW170817:** first neutron-star binary → birth of multi-messenger astronomy, constraints on equation of state, GW speed, tests of gravity
- **GWTC-3:** GW polarizations & tests of gravity
- **GW190814:** heaviest neutron star or lightest BH to date (~2.6 M_{sun})
- **GW190521:** first intermediate mass BH remnant (>100 M_{sun}), mass gap
- **GW200105/GW200115:** first evidence of mixed BH-NS binaries







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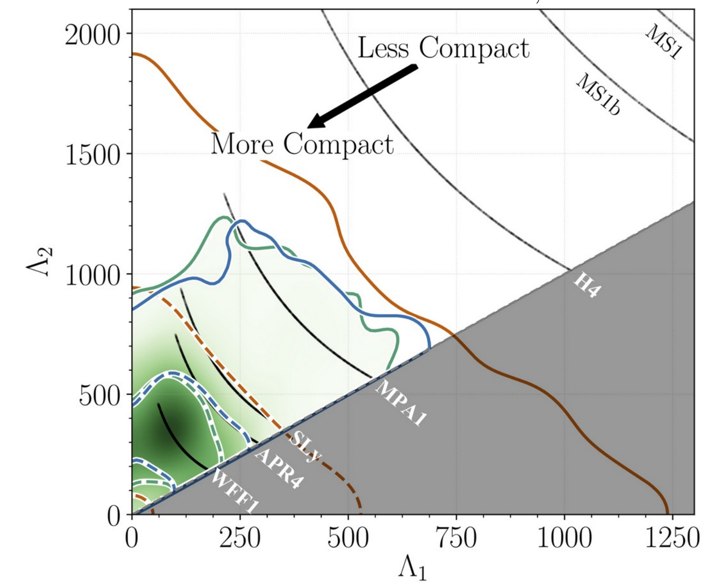
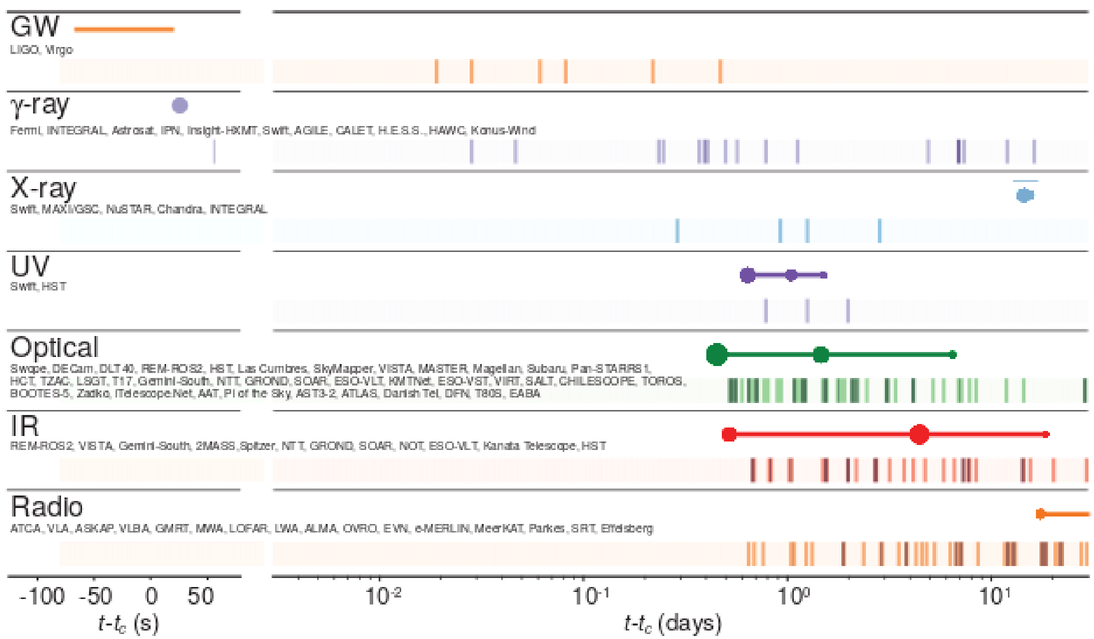
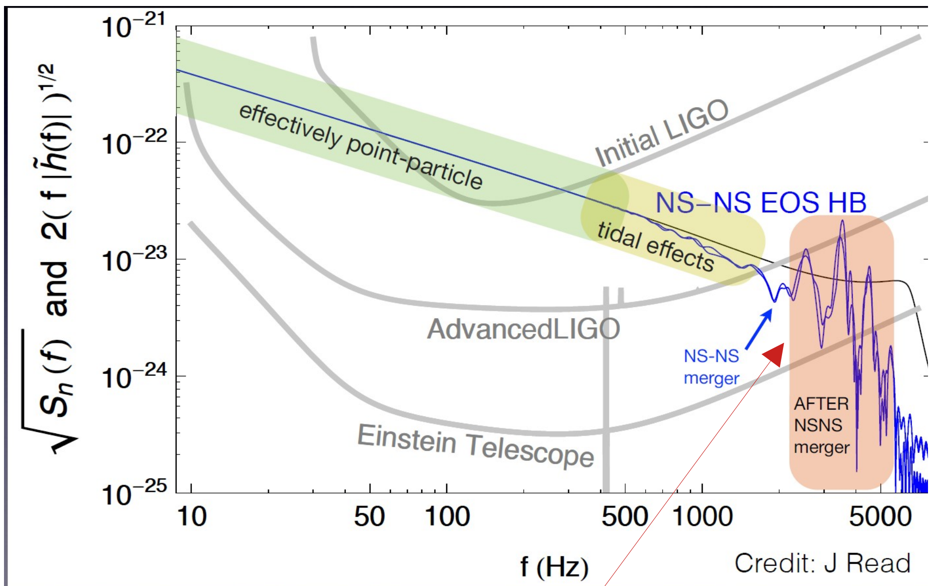
Case study A: GW170817

LVC PRL 2017, PRL 2018



- Constrains on the EoS (stiffer EoS disfavored)
- GW speed & constrain on dark energy
  [Baker+; Creminelli-Vernizzi; Ezquiaga-Zumalacárregui; Sakstein-Jain; PRL 2017]
- EM counterpart crucial to characterize the source

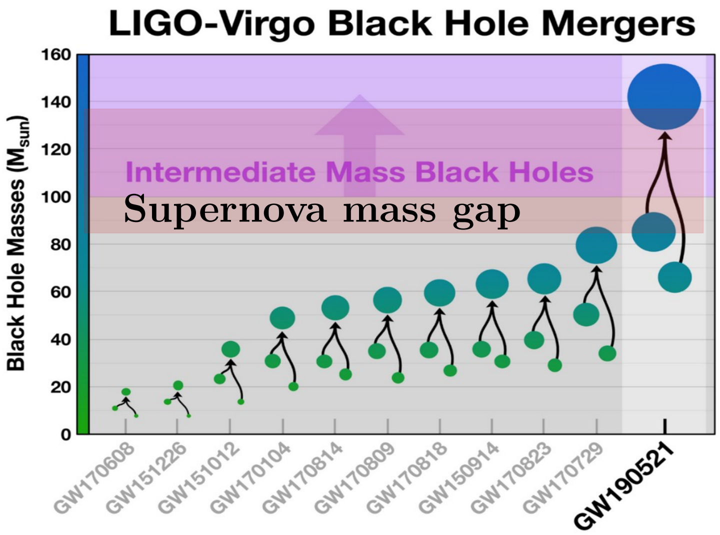


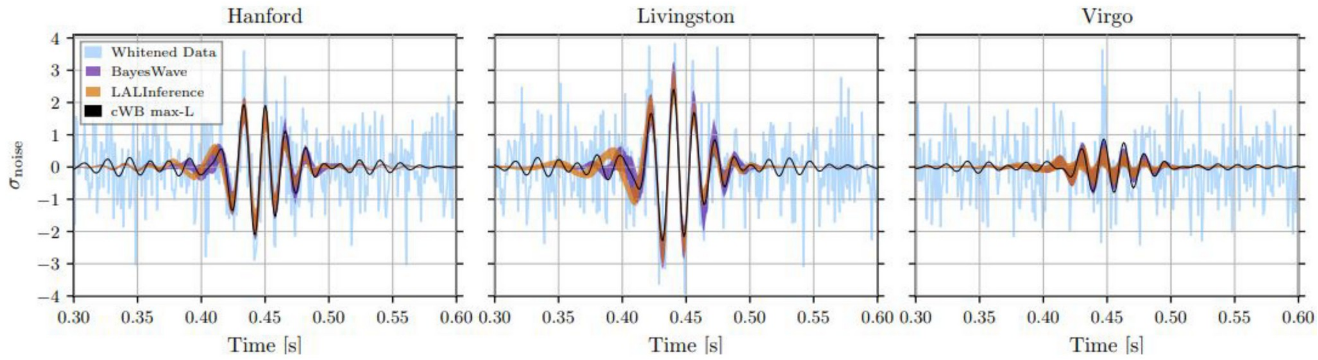


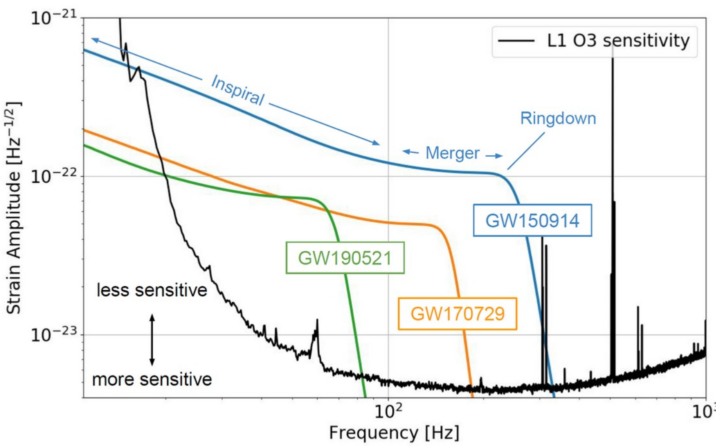
Merger and post-merger not detected by LIGO/Virgo

Case study B: GW190521

- M_1 challenges astro formation channels
  - 2^{nd} generation BH? [Farrell+ MNRAS 2021] AGN?
  - Primordial BH? [De Luca+ PRL 2021, **see G. Franciolini's Div3 talk**]
  - Exotic compact object? [Calderón Bustillo+ PRL 2021]
  - Beyond Standard Model? [Sakstein+ PRL 2021]
- $M_{remnant} \rightarrow$ Intermediate-mass BH (seeds?)
- Secondary ringdown mode? [Capano+ 2021]
- Eccentric? [Romero-Shaw+ ApJL 2020, Gayathri+ Nat. Astro. 2022]



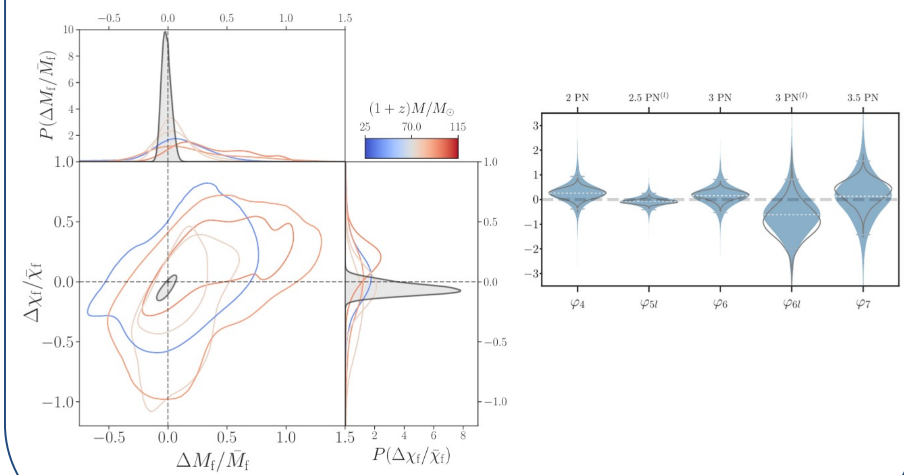




Better low-freq sensitivity needed for inspiral, higher SNR for ringdown

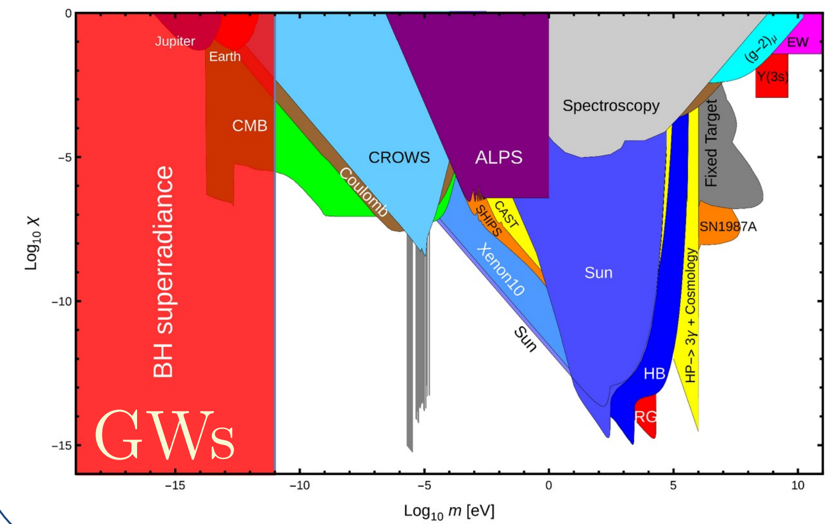
What's next?

"Precision Gravity" frontier

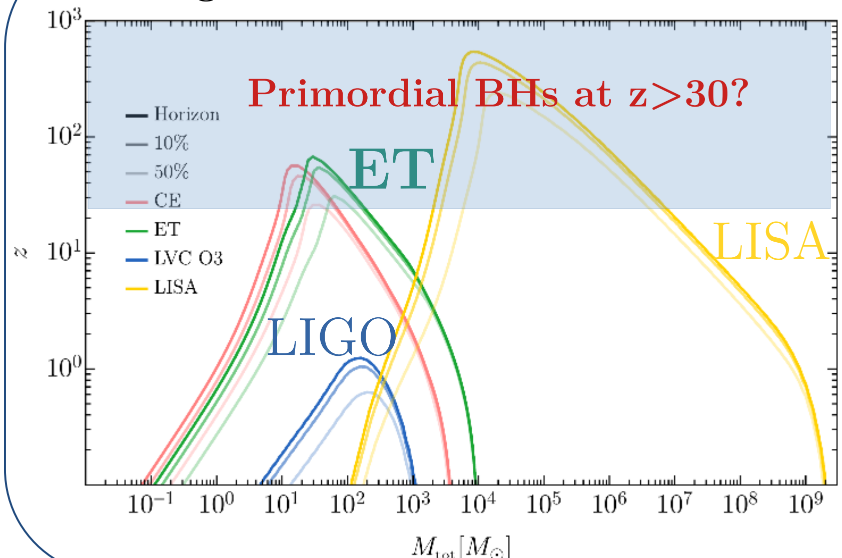


[LVK tests with GWTC-3, 2022]

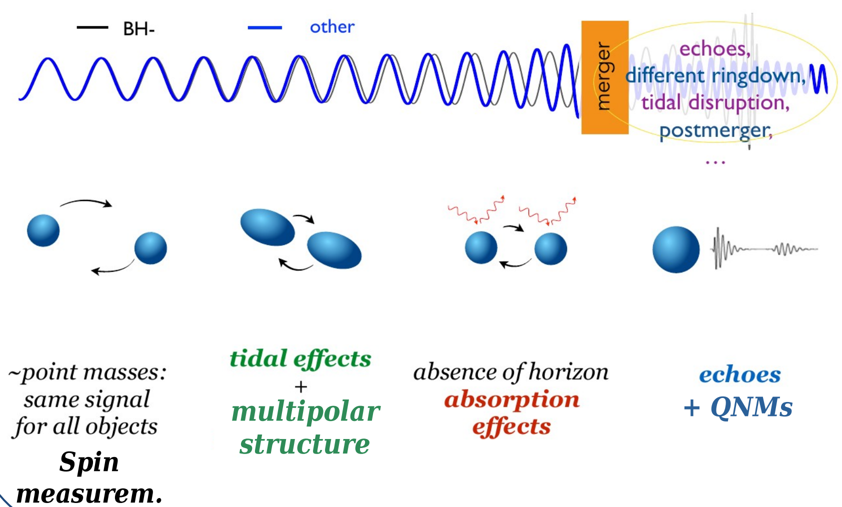
GW searches for ultralight dark matter



Origin and families of BH binaries



Near-horizon physics & tests of compact objects



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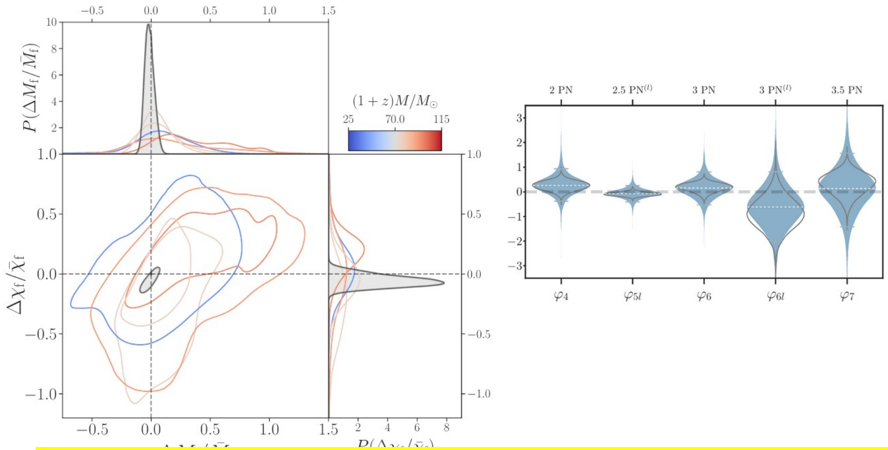

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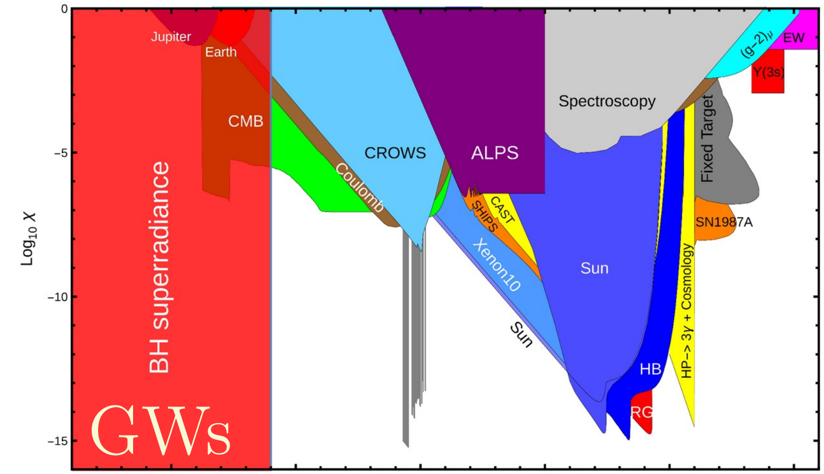
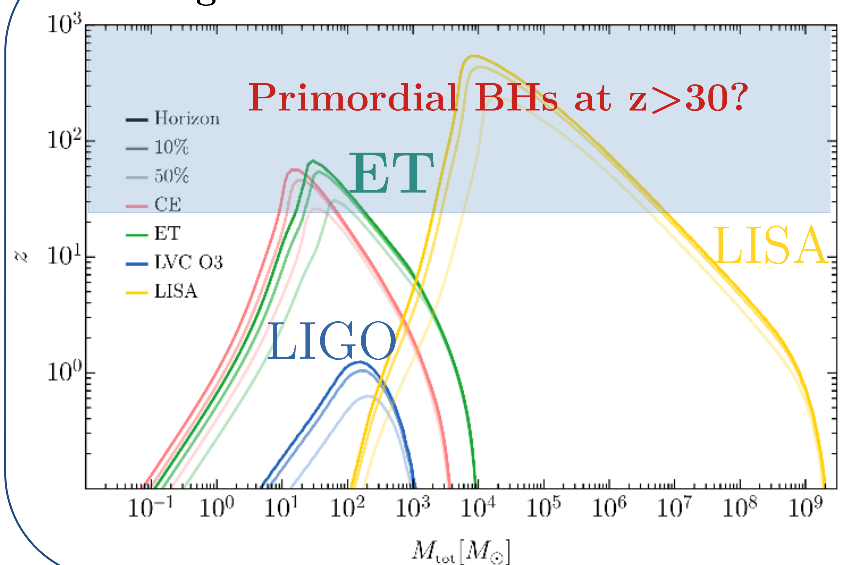
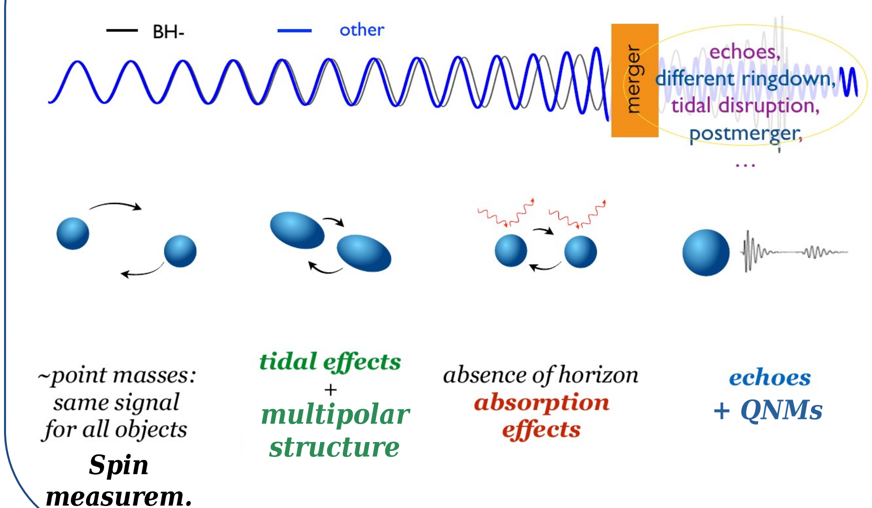


Require *both* better sensitivity and wider frequency range!

Origin and families of BH binaries



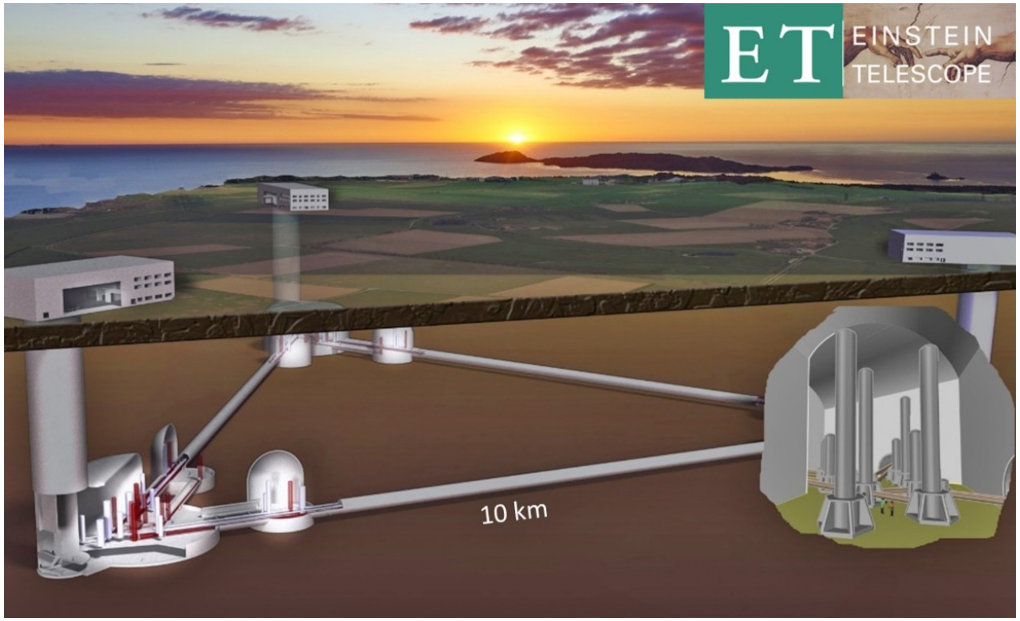
Near-horizon physics & tests of compact objects



Einstein Telescope (ET)

ET pioneered the idea of a 3rd generation GW observatory:

- New infrastructure capable to host future upgrades for **decades** without limiting the observation capabilities (~50yr time scale)
- Sensitivity **at least 10 times better** than (nominal) adv. detectors on a large fraction of the (detection) frequency band
- Dramatic improvement in sensitivity at **low frequency (few Hz – 10Hz) range** → intermediate-mass BHs
- **High reliability** and improved observation capability
- **Standalone localization** & polarization disentanglement



See **Branchesi, Maggiore et al., 2303.15923** for a discussion of the science case with different designs

Both precision physics and discovery machine!

ET science in a nutshell

Astrophysics:

- **Black hole properties**
  - Origin (stellar vs primordial)
  - Evolution, demography
- **Neutron star properties**
  - Interior structure (QCD at ultra-high densities, exotic states of matter)
  - Demography
- **Multi-band and -messanger astronomy**
  - Joint GW/EM observations (GRBs, kilonova)
  - Multiband GW detection (LISA)
  - Neutrinos
- **Detection of new astrophysical sources**
  - Core-collapse supernovae
  - Isolated neutron stars
  - Stochastic background of astrophysical origin

Fund. physics & cosmology:

- **The nature of compact objects**
  - Near-horizon physics
  - Tests of no-hair theorem
  - Exotic compact objects
- **Tests of General Relativity**
  - Inspiral tests, Strong-field regime
  - Extra polarizations
- **Dark matter**
  - Primordial black holes
  - Axion clouds, environment
- **Dark energy & modified gravity**
  - Dark energy equation of state
  - Modified GW propagation
- **Stochastic background of cosmological origin**
  - Inflation, phase transitions, cosmic strings, remnants

Testing the nature of gravity with GWs

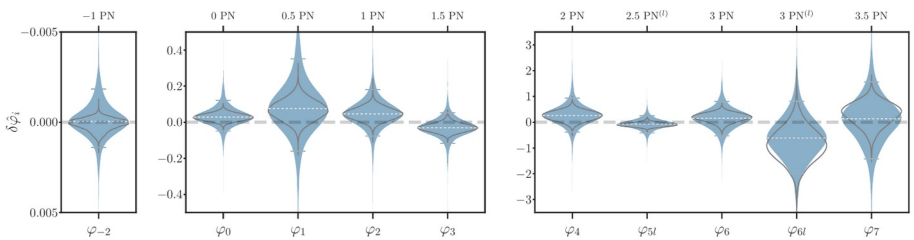
GR extensions predict different BHs/NSs, new fields, richer binary dynamics and GW signal:

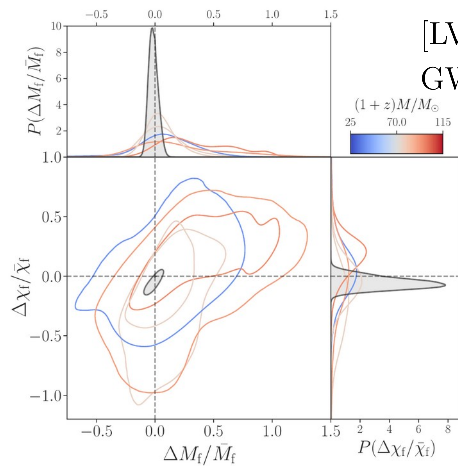
- Parametrized post-Newtonian/Einsteinian tests
- Extra polarizations
- No-hair theorem tests / BH spectroscopy
- Inspiral-merger-ringdown tests
- GW propagation tests (synergy with Cosmo Div)

Need to develop:

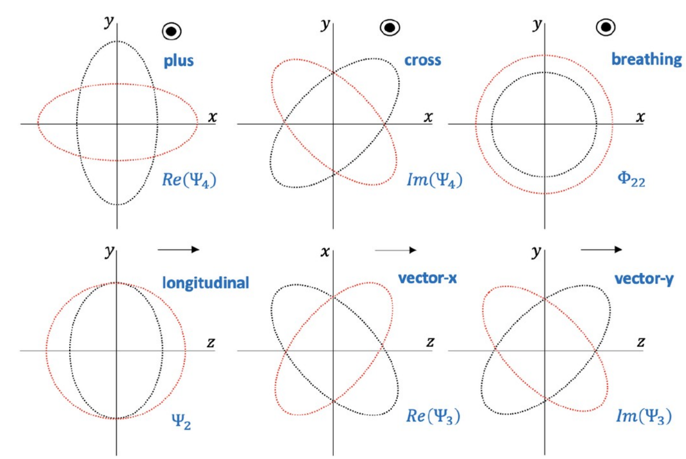
- Parametrized tests
- Agnostic searches
- Full waveforms & templates in specific models

$$h(t) = A_{\rm GR}(t)(1+\delta A)e^{\Psi_{\rm GR}(t)+\delta\Psi(t)}$$





[LVC, tests with GWTC3, 2022]



[Evstafyeva+ 2023]

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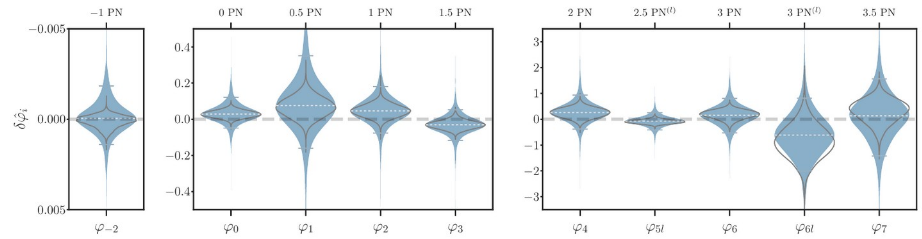

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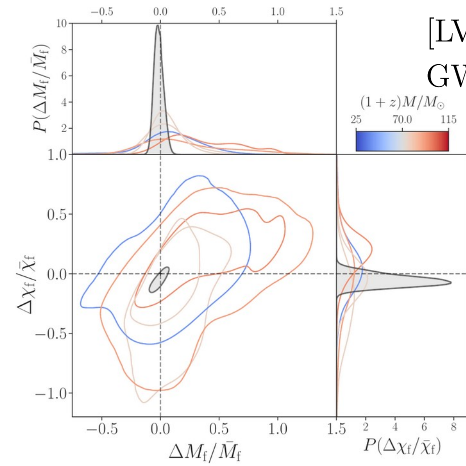

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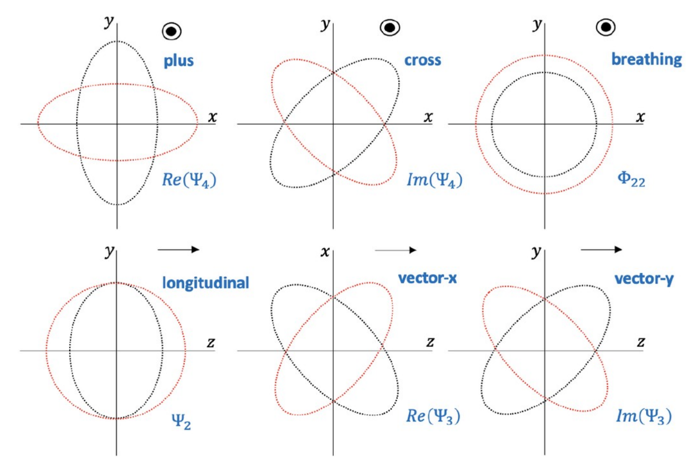


[Evstafyeva+ 2023]

Testing compact objects w/ ET: QNMs & echoes

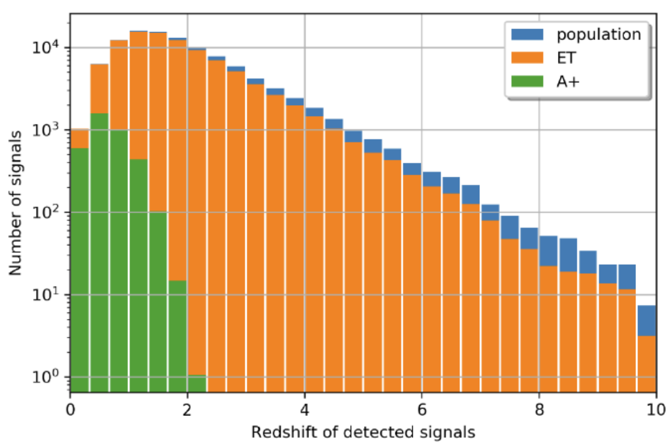
- BH spectroscopy: ~1 merger every 5 minutes!

$$h_+ + ih_\times \sim \sum_{i=(\ell mn)} A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i}$$

- Shift of QNMs (bkg geometry + dynamics + boundary conditions):

$$\omega_{lmn} = \omega_{lmn}^{\rm Kerr}(M,\chi) + \delta\omega_{lmn}(M,\chi,\ell_{\rm new})$$

BH mergers (events/yr)



Credits: M. Branchesi

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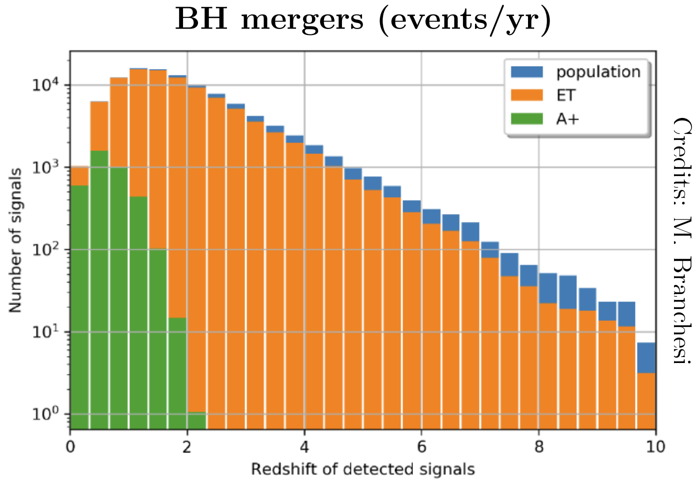
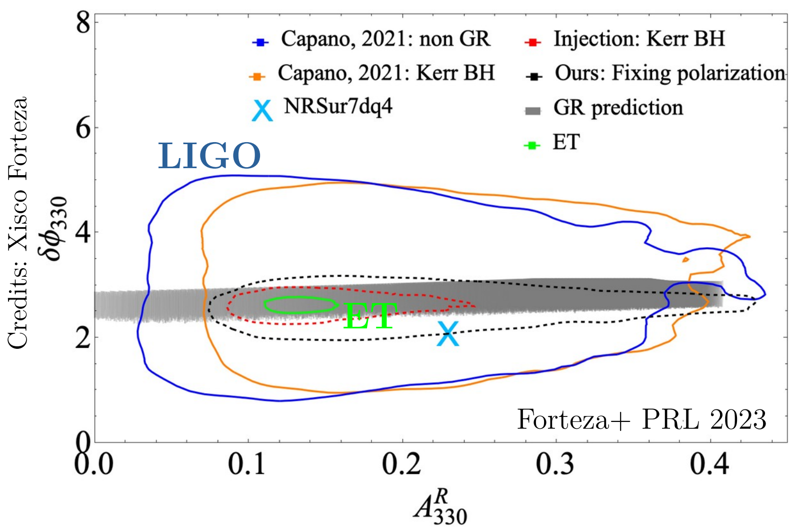


- ET will detect 2 QNMs events at percent level and allow for novel ringdown tests

[Forteza+ PRL 2023; Bhagwat, Pacilio+, 2023]

more in S. Bhagwat's talk later



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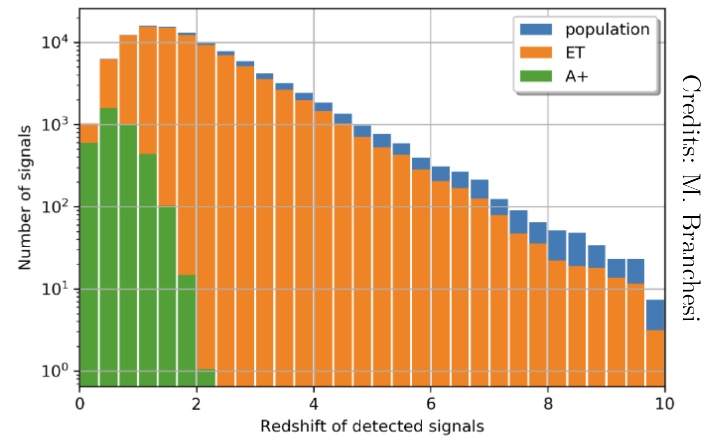

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[Forteza+ PRL 2023; Bhagwat, Pacilio+, 2023]

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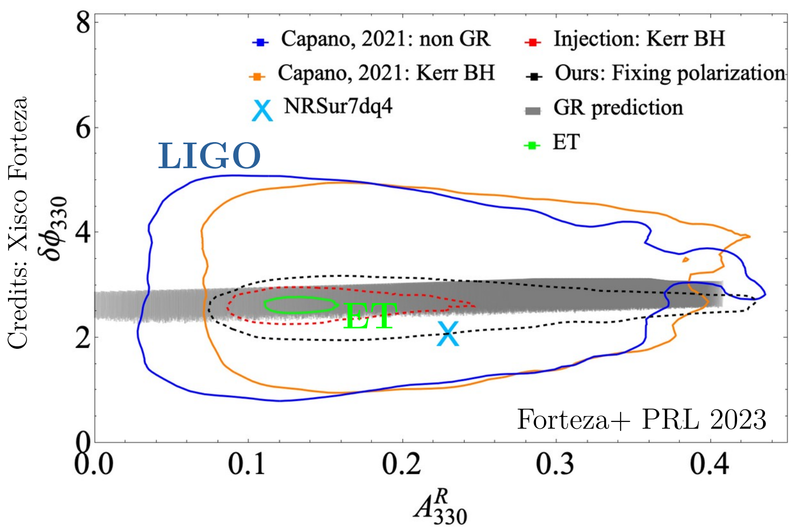
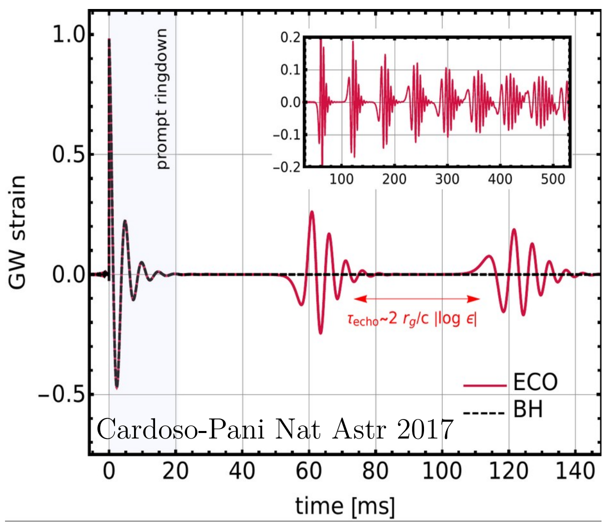
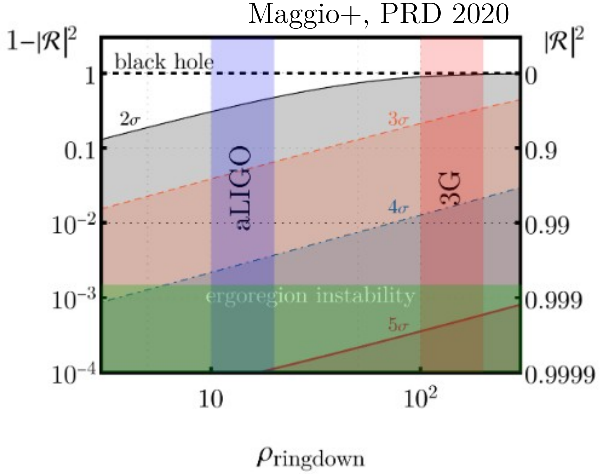
- GW echoes: smoking gun for near-horizon structure







more in E. Maggio's talk later

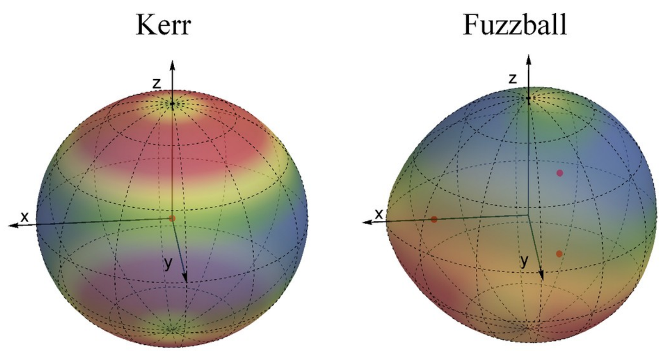
Testing compact objects with ET: inspiral

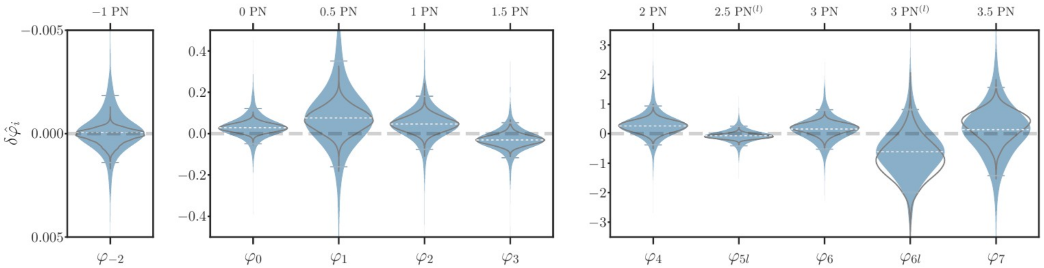
Multipolar structure (2PN)

$$\underset{\text{mass moments}}{M_\ell^{\rm Kerr}} + i\underset{\text{current moments}}{S_\ell^{\rm Kerr}} = \underset{\text{mass}}{M^{\ell+1}} \underset{\text{spin}}{(i\chi)^\ell}$$

- BHs in GR: multipoles depend on mass and spin
- Kerr BH: axially and equatorially symmetric
- ET can constrain mass quadrupole (M_2) and spin octupole (S_3) [Krishnendu+ PRL 2018]
- BH microstates, boson stars, etc have richer multipolar structure [Bena+; Bianchi+ PRL 2020]

Credits: G. Raposo





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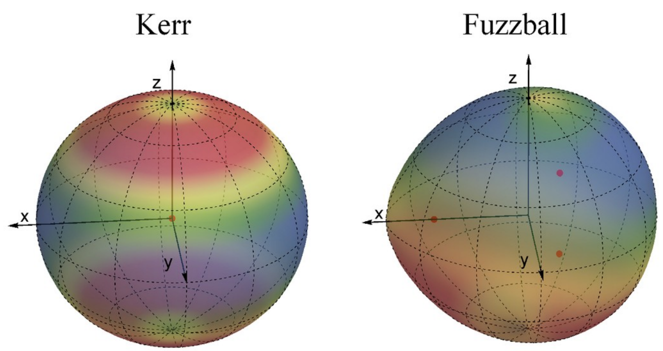

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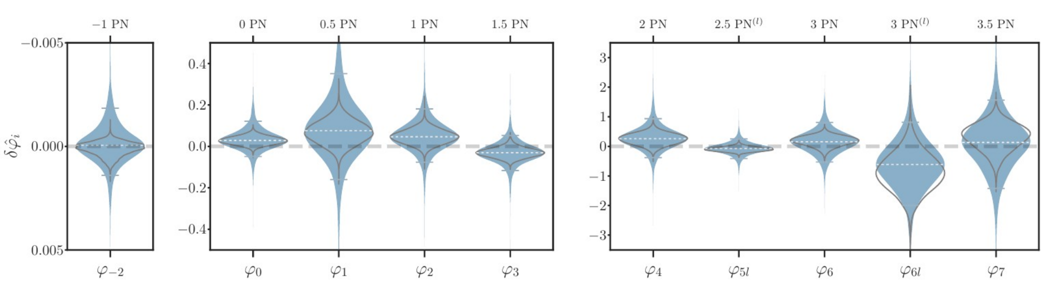
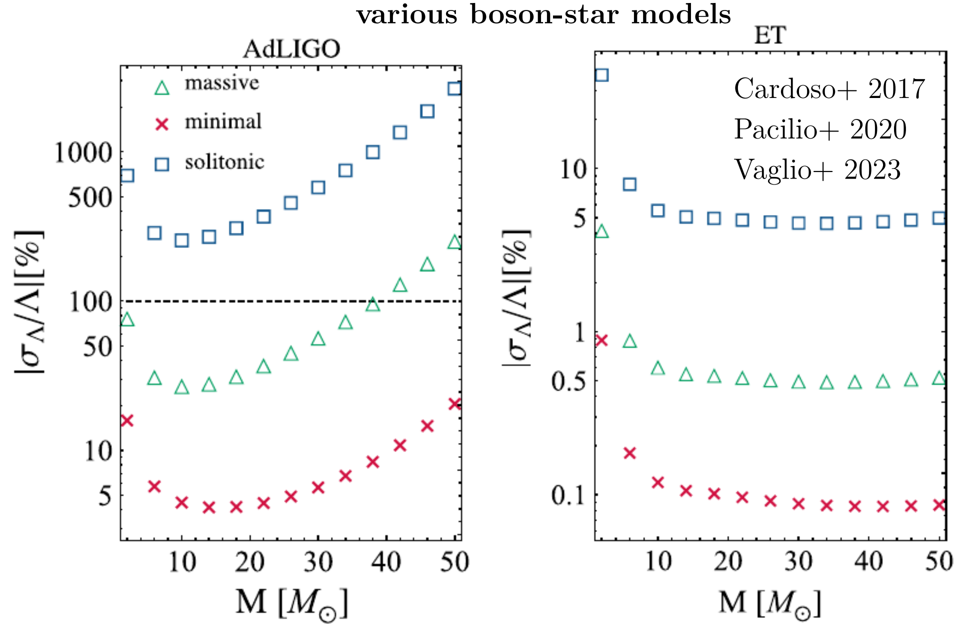


Tidal deformability (5PN)

$$\phi_{\text{tidal}} \sim \Lambda\, v^{10}$$

- Λ=0 for BHs in GR
- $\Lambda\neq$0 for anything else (nonBH or nonGR)
- Anomalous Λ → smoking gun for new physics!

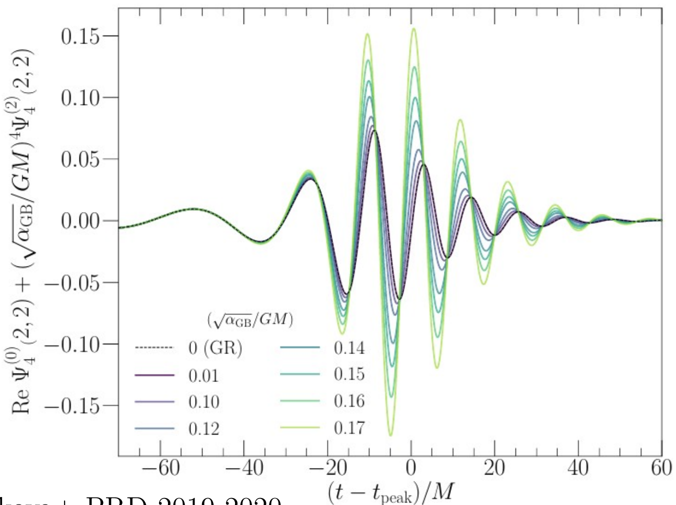
Large improvement on measurability of Λ in various boson-star models



Mergers beyond GR and beyond SM

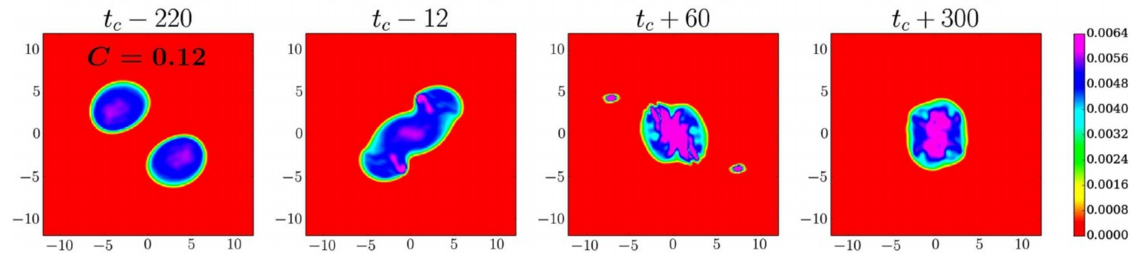
- Full inspiral-merger-ringdown waveforms crucial → require Numerical Relativity simulations!
- Huge progress on developing consistent theories of gravity and models of compact objects

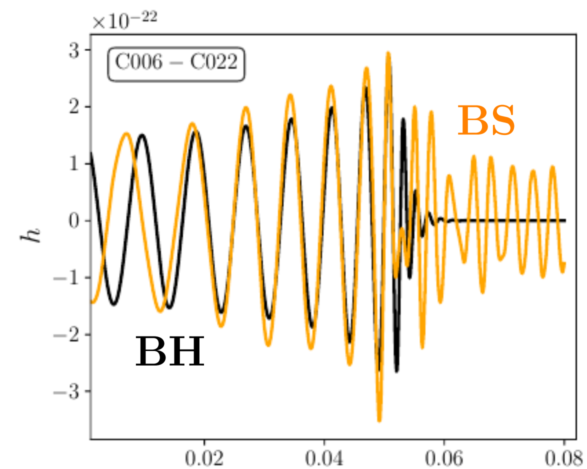
BH mergers in Quadratic Gravity



Okounkova+ PRD 2019-2020,
East-Ripley PRL 2021, Corman+ PRD 2023

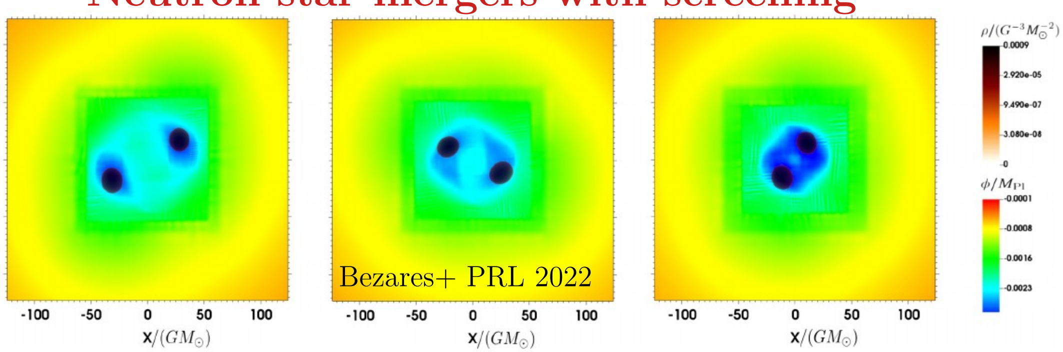
Boson star mergers





Palenzuela+ PRD 2008-2019
Salchis-Gual PRL 2019
Bezares+ PRD 2020-2022
Siemonsen-East PRD 2023

Neutron star mergers with screening



Synergy with Waveform Division
to produce accurate waveform templates

Searching for dark matter with GWs

Various dark-matter candidates and beyond-standard-model scenarios can be probed with GWs:

- **Ultralight bosons** (mass <1e-11 eV) would produce macroscopic clouds around BHs due to superradiance
- **Ordinary particle dark-matter** can induce environmental effects in binary waveforms
- **ECOs** in various mass ranges might be dark matter
- **Primordial BHs** might account for a subpopulation of GW mergers (synergy with Div3)
- **Stochastic GW bkg associated with primordial dark-matter relics** (synergy with Div2 and Div3)

Bertone+, 2019

Searches for ultralight dark matter with ET

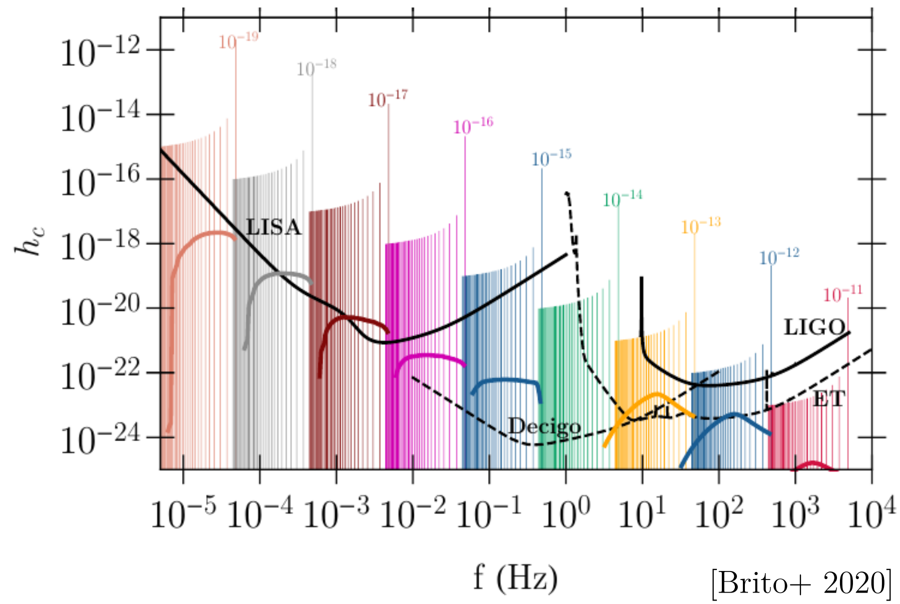
more in R. Brito's talk later

- Light bosonic fields & BH superradiance:

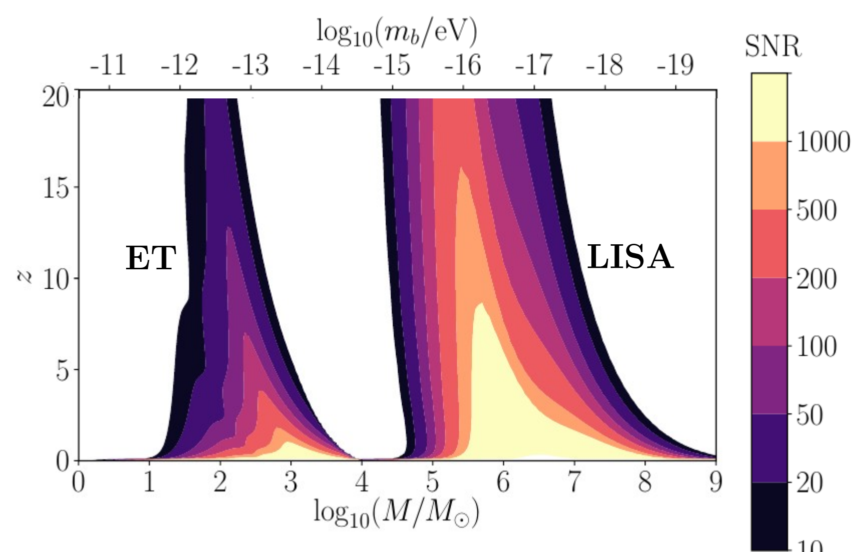
$$\frac{G}{\hbar c} M \mu \sim \left(\frac{M}{10 M_\odot}\right)\left(\frac{\mu c^2}{10^{-11}\,\mathrm{eV}}\right) \sim \mathcal{O}(1)$$

Coupling parameter

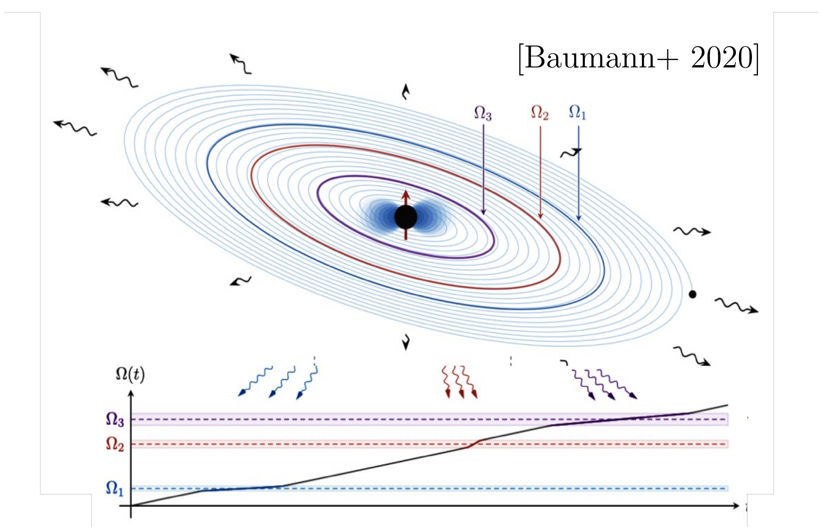
- Indirect constraints from BH mass-spin measurements
- IMBH detections could fill gap between stellar and supermassive BHs
- Several effects in binaries (dephasing, floating orbits, disruption, tidal effects)



[Brito+ 2020]



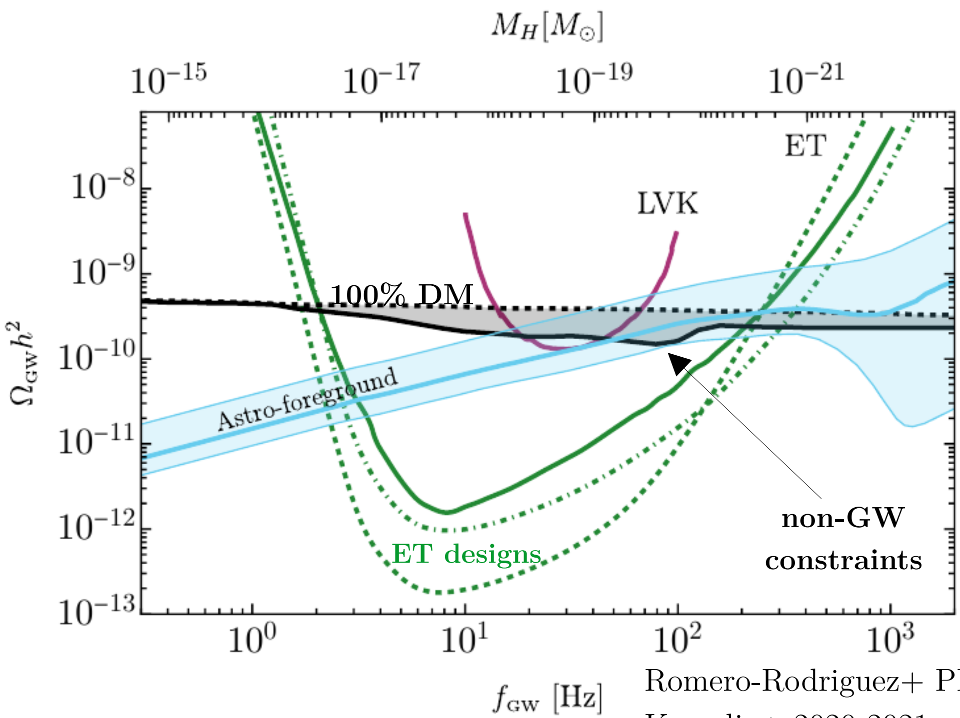
- ET-LISA ranges are complementary
- Potentially detectable up to z~20



[Baumann+ 2020]

An example of FP-Cosmo-Astro synergy...

- Primordial microscopic relics could evade Hawking-evaporation bounds and be 100% of the dark matter
- Stochastic GW background associated with their formation is almost undetectable by LVK
- Unique target for ET!



Romero-Rodriguez+ PRL 2022
Kapadia+ 2020-2021
Franciolini-PP, 2023

- Requires Num Rel in early universe, understanding astro foreground, models of Hawking relics, stochastic GW signal...

... where ET will be a game changer

Discovery potential = Accuracy

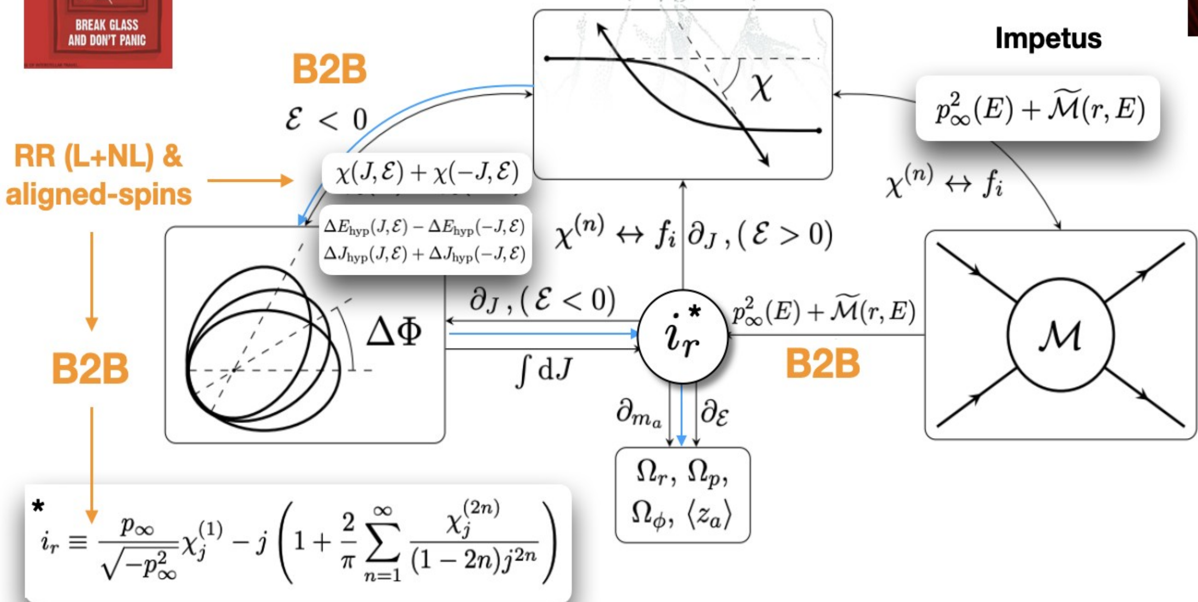
- Goal: borrow/extend sophisticated hep techniques to compute waveforms

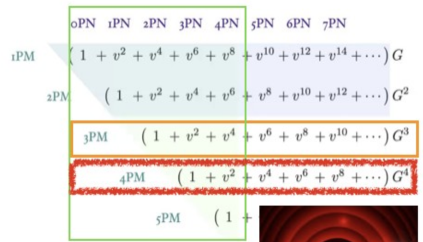
(EFT, scattering amplitudes, double copy, high-order post-Newtonian, self-force)

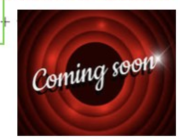
[synergy with Waveform Division]

- Instrumental to search for "new physics" at colliders through precision data

Credits: R. Porto







$1\text{PN} = \frac{v^2}{c^2}$

$1\text{PM} = G$

Bern+ PRL 2019

Kälin+ PRL 2021

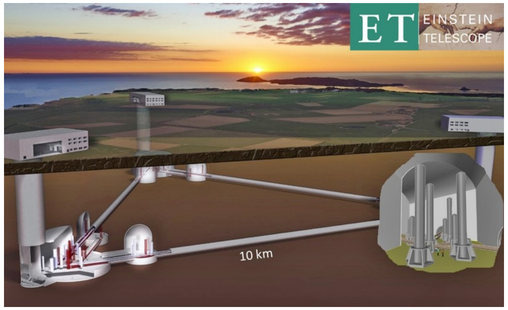
Dlapa+ PRL 2022, PRL 2023

Mougiakakos+ PRL 2023

more in C. Dlapa's talk later

"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 the ET OSB Div Fundamental Physics:
  - 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, …)
- *Many challenges ahead: we need an* ***active*** *and* ***enthusiastic*** *group of people!*

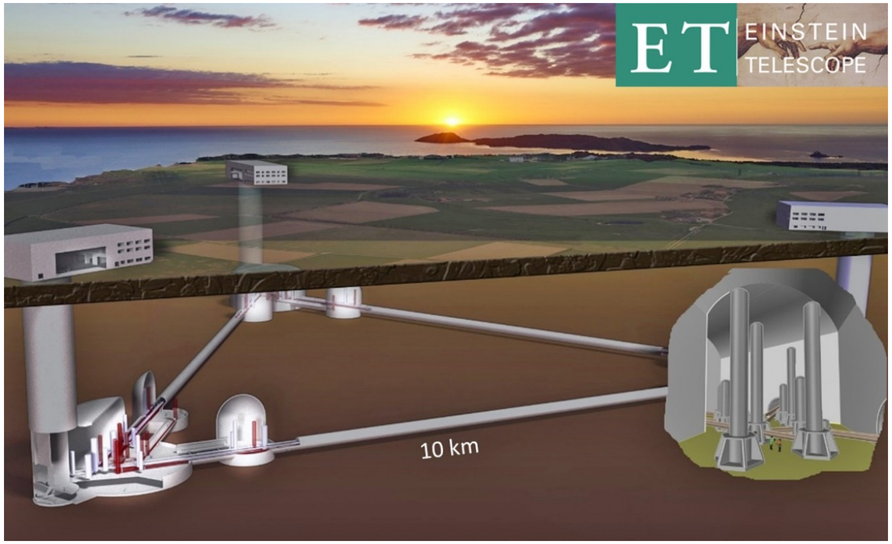
"Recording a GW […] has never been a big motivation for LIGO, the motivation has always been to open a new window to the Universe"

– Kip Thorne (BBC interview, 2016)

Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]

Thanks for the attention!



"Recording a GW [...] has never been a big motivation for LIGO, the motivation has always been to open a new window to the Universe"

– Kip Thorne (BBC interview, 2016)

Science goals of the ET OSB FP Division

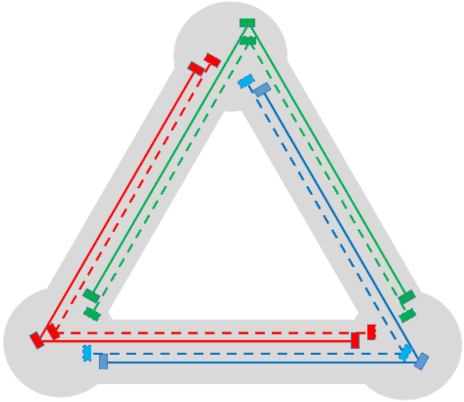
- Fundamental Physics objectives of ET: *tests of GR, the nature of compact objects, and of matter and particle physics at the most extreme conditions*
- High-gain/high-risk & cross-cutting: Potentially groundbreaking goals with profound implications for cosmology, nuclear and particle physics, dark-matter searches, as well as for certain quantum-gravity programs
- Borrow & extend sophisticated hep methods 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

ET key elements

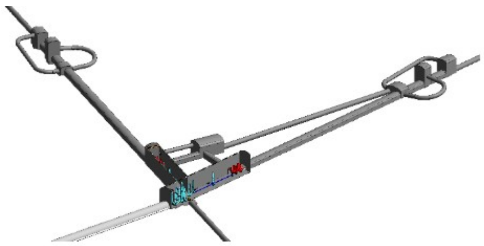


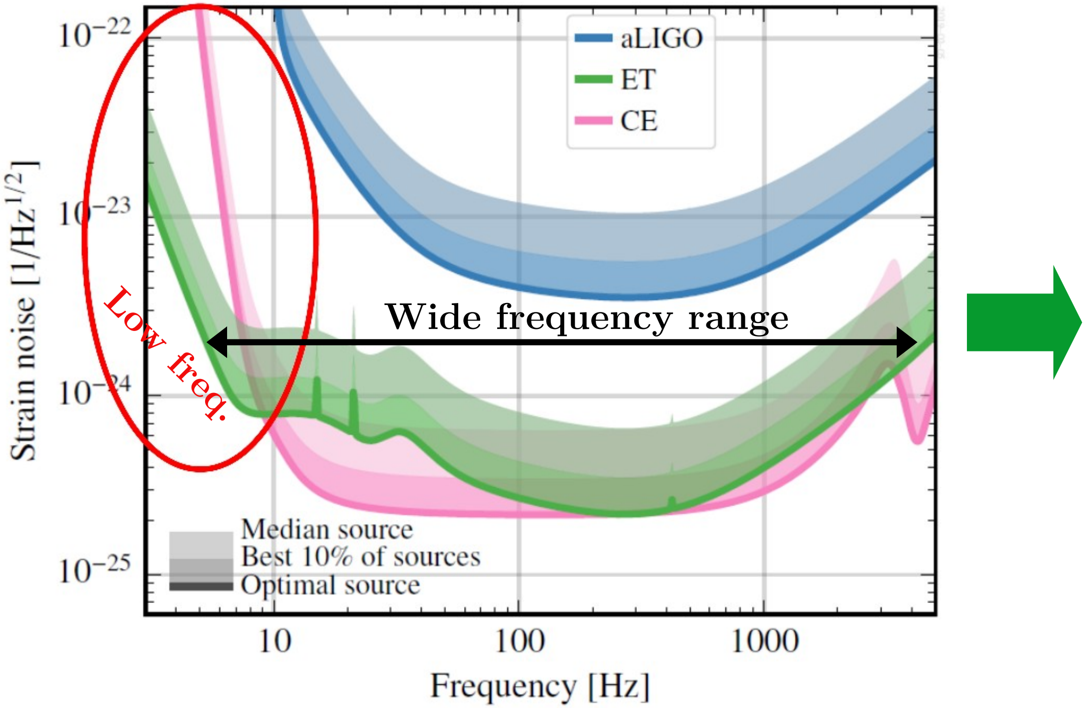
Requirements

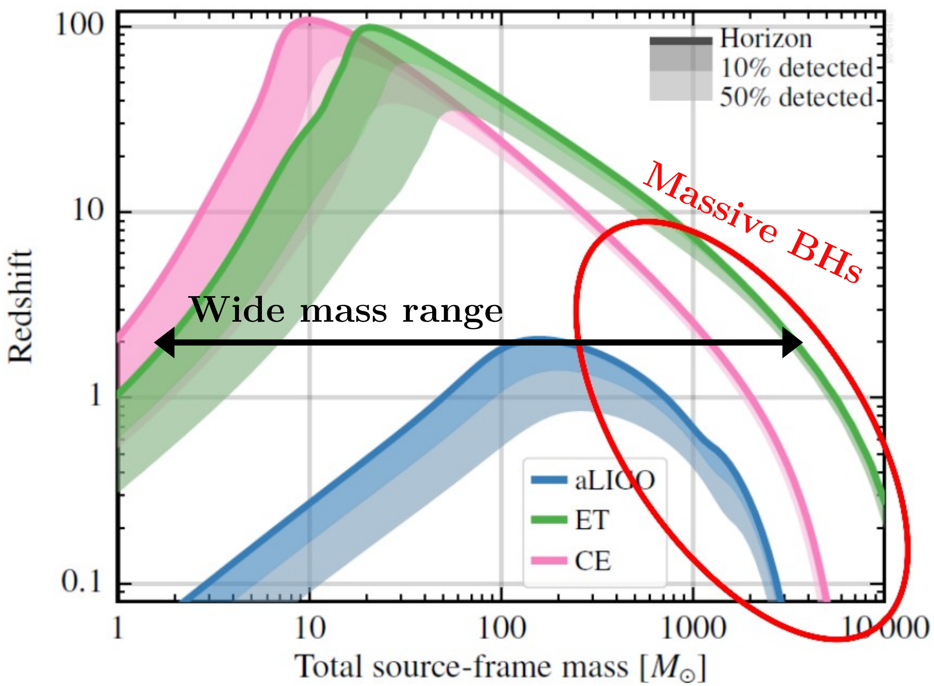
- Wide frequency range
- Low-frequency sensitivity
- Localization capability
- (more) Uniform sky coverage
- Polarization disentanglement
- High reliability (high duty cycle)
- High SNR

Design specifications

- Xylophone (multi-interferometer) design
- Underground
- Cryogenic
- Triangular shape
- Longer arms (>10km)

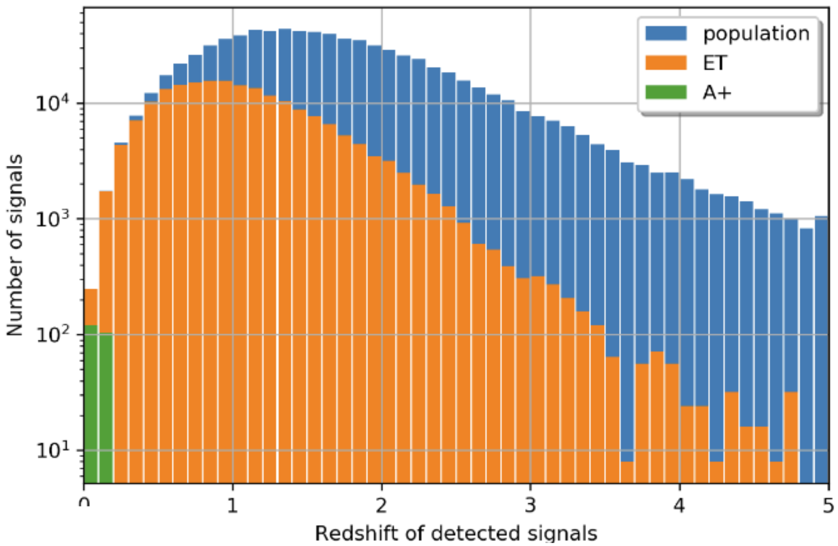




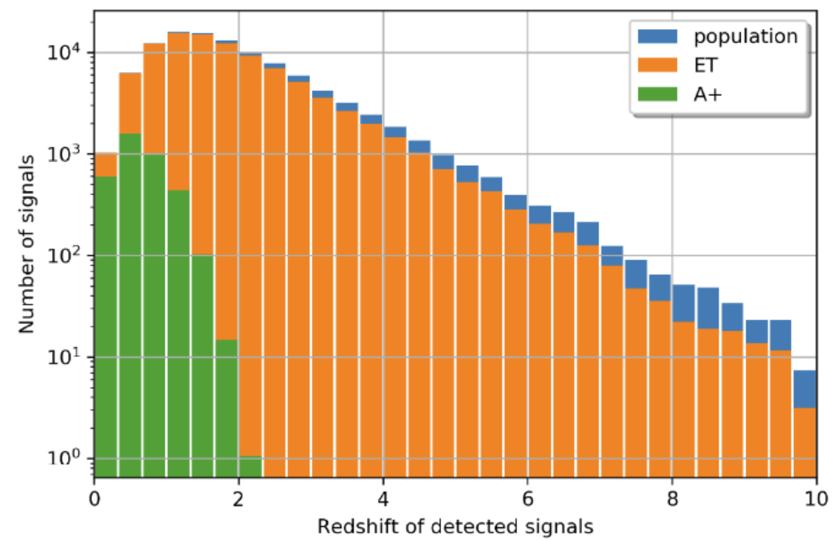


BH & NS demography: 10^5 events/yr (1 event every 5min)

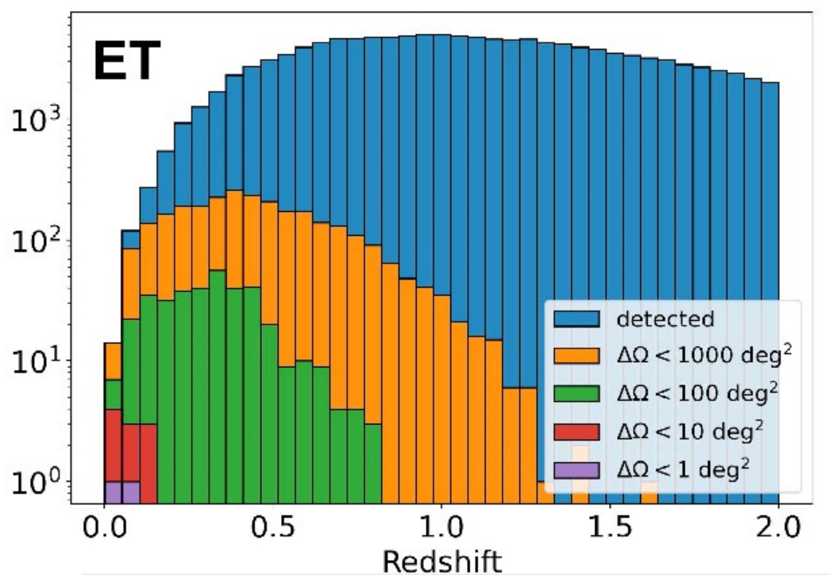
BNS mergers



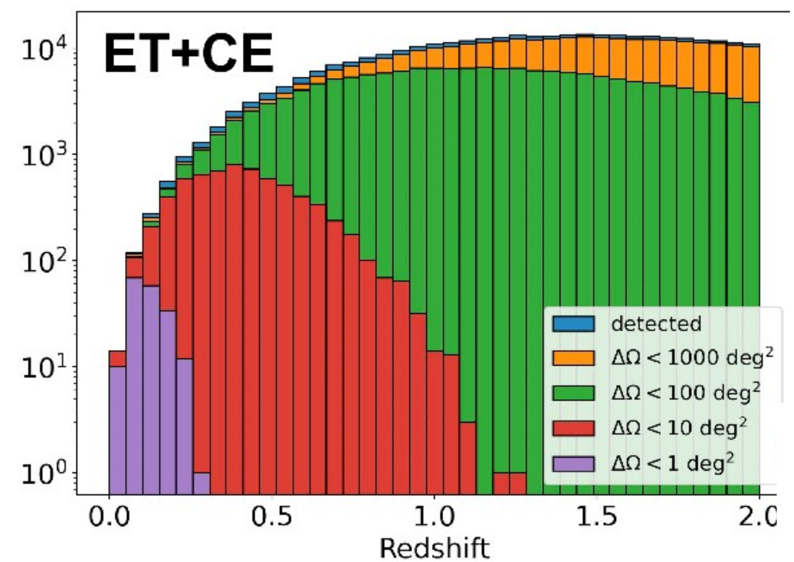
BBH mergers



Low-freq. sensitivity → localization & early alerts



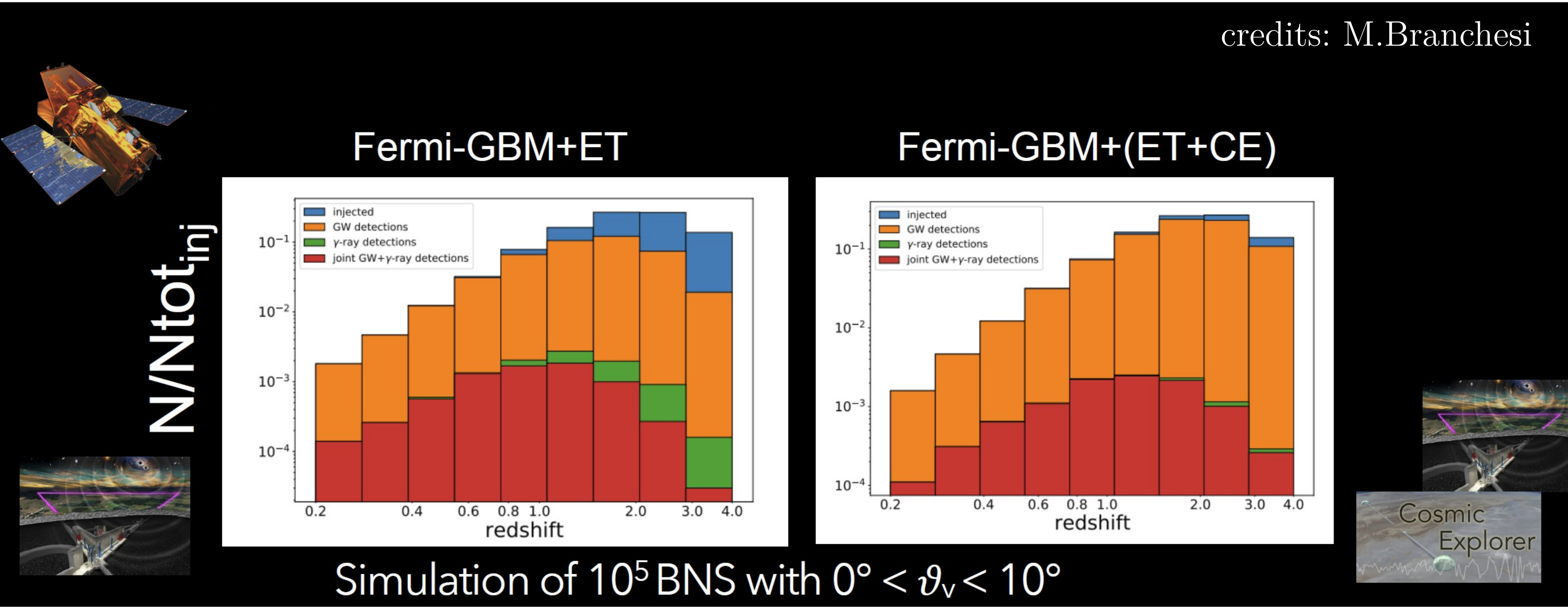
O(100) events/yr with sky-localization <100 deg^2



O(1000) events/yr with sky-localization <10 deg^2

credits: M.Branchesi

Multimessenger Astronomy



A large fraction of detected short GRBs will have a GW counterpart!

GW science: much more than Astro

feature article

Fundamental Physics in the Gravitational-Wave Era

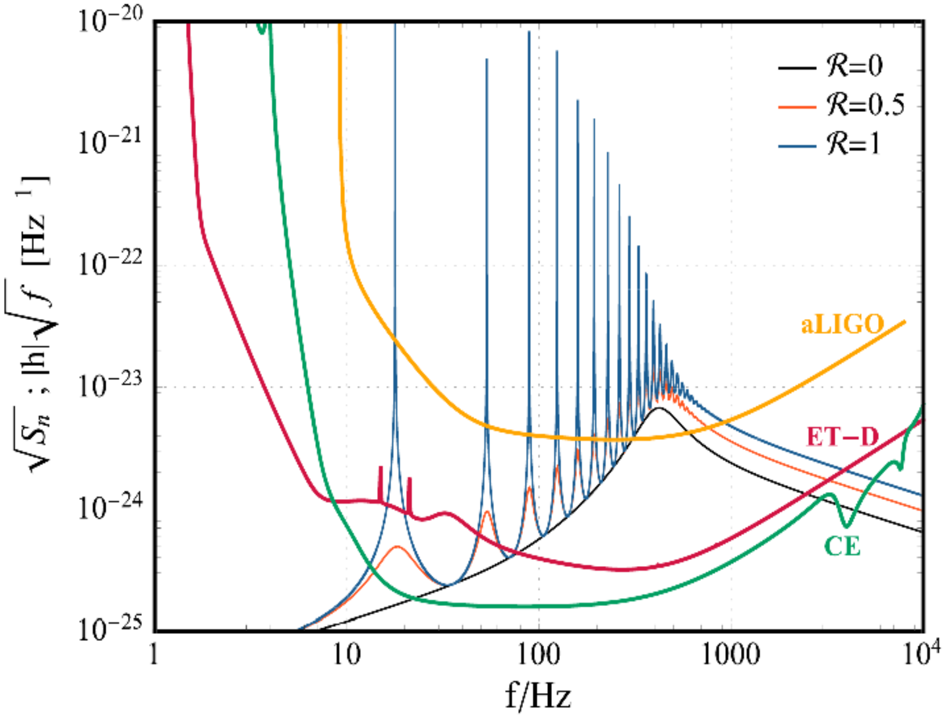
Sonja Bernitt[1], Gianfranco Bertone[2], Vitor Cardoso[3], Roberto Emparan[4], Tetyana Galatyuk[5], Aleksi Kurkela[6], Ann-Cecilie Larsen[7], Marlene Nahrgang[8], Samaya Nissanke[2], Paolo Pani[9], Rafael Porto[10], Antonio Riotto[11], and Stephan Rosswog[12]

April 2022

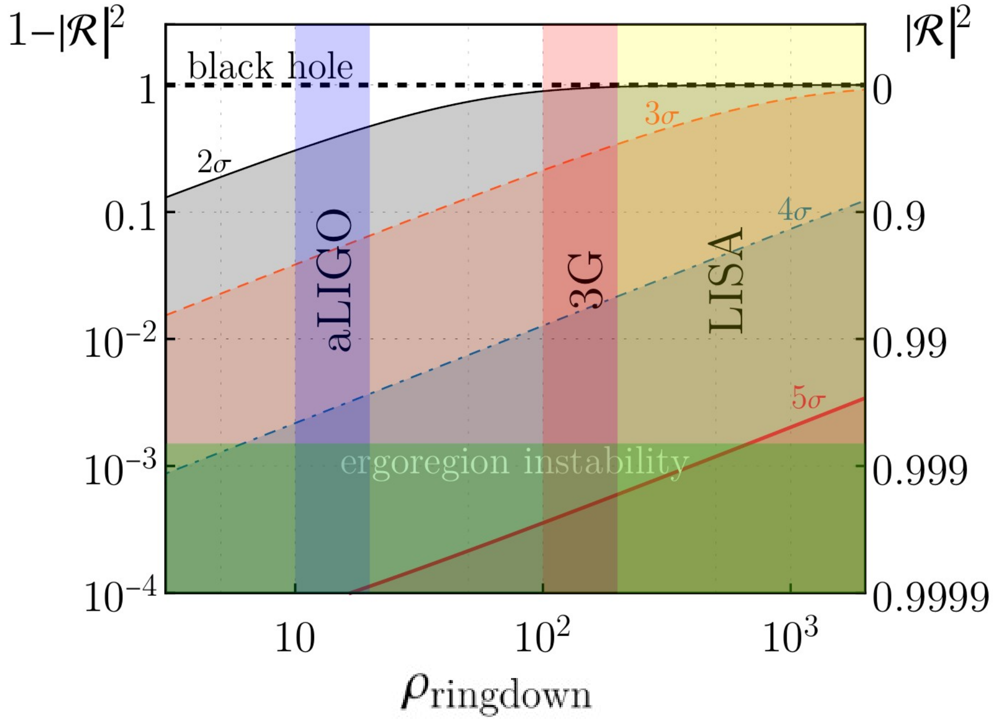
- GW revolution opened new avenues for fundamental physics:
  - Matter under extreme conditions
  - Multimessenger astronomy: role of nuclear and atomic physics
  - GWs & Cosmology
  - Fundamental problems in hep and grav physics
- Multidisciplinary, cross-cutting effort at the interface between different communities $\rightarrow$ synergies, complementarities, community building

Echo detectability

• d=100 M, M=30 Msun, D=400 Mpc



[Testa & PP PRD 2018, Maggio+ PRD 2019]



- Contrasting results with LIGO data [Abedi+, 2017/18, Conklin+ 2018/19, Ashton+ 2017, Westerweck+ 2018] but no statistical evidence in O1-O2 [Uchikata+ 2019, Tsang+ 2019] and in O3a [GWTC-2, 2020]
- Near-horizon corrections are within reach! Echo search pipelines now routine
  - Large reflectivity crucial for detection with LIGO/Virgo
  - Much better prospects with ET and LISA