Testing fundamental physics with gravitational waves

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Future colliders for Early-Career Researchers Workshop

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Overview

1. Introduction

2. GW sources
   - Individual GW sources
   - Stochastic Gravitational Wave Backgrounds (SGWBs)

3. SGWB detection to constrain HEP

4. Conclusions and outlook
The dawn of GW astronomy

Gravitational Waves (GWs) are:
- Spacetime perturbations
- Almost free streaming
- The ultimate cosmological probe

Why GWs are interesting?
- Finally detected (GW150914)!
- Some detectors are active now
- More will join in the next years
- New window on high energy physics
- Unveil new details on gravity

Exploring the cosmic history with GWs

GWs decouple much earlier than photons and neutrinos!

Could bring info on scales we cannot access in any other way

* Figure from https://home.cern/news/series/lhc-physics-ten/recreating-big-bang-matter-earth
BICEP2 Collaboration/CERN/NASA
Present and future GW detectors

Different types of detectors will probe different frequency bands (and sources)

* Figure adapted from GWPlotter
Individual GW sources

**Individual (and possibly resolvable) sources**

Signals having a predictable morphology in time and frequency

Loud sources can be seen individually (like LVK detectors do)

Choose your favourite template (GR or something beyond) and reconstruct the parameters

Combine single events to constrain the population parameters (or your favourite cosmological model)

Some aspects we can probe with individual sources

- Nature of Black Holes
- Dispersion and Speed
- SEP and Symmetries
- Dark Energy and Screening
- Astrophysical Systematics
- Waveform Systematics
- Fundamental Physics

- Echoes from ECOs
- Horizon Structure
- EM coincident tests
- Propagation tests
- Ultra-light scalar fields
- TeVeS-like theories
- Dark Matter and Primordial BHs
- Other Model Independent Tests
- ppE
- Null Channels

- Lorentz violation
- Parity violation
- Bigravity and Massive Gravitons
- Standard sirens

- the unknown...
- inspiral, merger, ringdown models
- EMRI models
- Accretion Disks
- Third Bodies
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SGWBs are:
- Stochastic signals from the whole sky
- Either *cosmological* or *astrophysical* origin
- Invaluable source of information (*HEP!*)
- A *target for all future detectors*
Stochastic Gravitational Wave Backgrounds (SGWBs)

SGWBs detection and characterization

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Detection prospects?
● At least two SGWB components (SOBBHs and CGBs) are guaranteed signals for LISA!
● LIGO/Virgo/KAGRA + future Earth-based interferometers (LIGO-India, ET, CE, ...)
● Millisecond pulsars timing to detect GWs (hints for SGWB detection..)
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Few characteristics to classify SGWBs:

- Isotropy / Anisotropy
- Stationary / Non-stationary
- Polarized / Unpolarized
- Statistical properties
- Frequency shape
Sources for SGWBs of cosmological origin

The detection of any of these signals could unveil signatures from HEP:
- Inflaton’s coupling to other particles?
- Occurrence of first order phase transitions in the early Universe?
- Generation (and interactions within networks of) cosmic strings?

* Figure from LISA Cosmology Working Group WP, P. Auclair et al., *Living Rev.Rel.* 26 (2023) 1, 5, ArXiv: 2204.05434
Inflation

Minimal realization of inflation:

\[ S = \int d^4x \sqrt{-g} \left( \frac{R}{2\kappa^2} + \frac{\dot{\phi}^2}{2} - V(\phi) \right). \]

GWs from slow-roll inflation are too feeble to be detected!
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Things change dramatically in non-minimal scenarios:
(see, e.g., N. Bartolo et al., JCAP 12 (2016) 026, ArXiv: 1610.06481)

- Axion inflation: \[\mathcal{L} \supset \frac{\alpha}{4\Lambda} \phi F \tilde{F}\]
- Spectator fields: \[\mathcal{L} \supset P(\tilde{\sigma}, \sigma)\]
- Symmetry breaking: \[m_h \neq 0\]
- …

* Figures from Baumann, ArXiv: 0907.5424
Cosmic Strings

CS might form in the early Universe

Evolution turn long strings into loops

GWs from CS form a (loud?) SGWB (and also produce bursts)!
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First order phase transitions

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\[ V_{eff}(\phi) \]

**Second order**

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\[ \Rightarrow \]

**FOPT → Bubble nucleation**

Bubble collisions, sound waves in plasma, and MHD turbulence contribute to SGWB!
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**FOPT → Bubble nucleation**

Bubble collisions, sound waves in plasma, and MHD turbulence contribute to SGWB! In SM both EW and QCD PTs should be second order \[ \Rightarrow \] Detection implies BSM!

Conclusions and outlook

Some general conclusions:

- **GWs** have a great potential to probe **High Energy Physics** (HEP)
- Individual sources → direct way to test modifications of gravity
- **SGWBs** of cosmological origin → new window on BSM!
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New ideas and tools will be necessary:

- Cross-correlations with other probes (CMB, LSS, ...?)
- Identification of “smoking-gun” observables for the different mechanisms (chirality, anisotropy, time modulations, statistical properties, ...)
- Data analysis techniques to fully exploit the data
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More detectors to cover all frequencies:

- More Earth-based detectors (also new generation) will join the network
- First space-based detectors: LISA + (maybe ?) Taiji/TianQin
- Others?
High frequency GWs?

What about high frequency GWs??
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Several mechanisms predict signals at high frequency

“Ultra-high frequency gravitational waves: where to next?”

Workshop @ CERN, Dec 4 - 8, 2023

Other probes?

Some astro/cosmo DM probes:

- Detection of X-rays and $\gamma$-rays
- High-energy neutrinos searches
- Charged cosmic rays
- Axion Indirect Detection
- ...
The end

Thank you for your attention