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PARTICLE ACCELERATORS TO MEET GRAVITATIONAL WAVES

S. P. Petracca*, University of Sannio at Benevento and INFN
I. M. Pinto†, University of Naples Federico II and INFN

Abstract

The observation of the Higgs boson by the LHC (2012), and the direct detection of gravitational waves from a coalescing binary system by LIGO (2015) marked the end of long-standing efforts, and the dawn of a new era where both Particle Accelerator (PA) and Gravitational Wave (GW) Physics, may further advance capitalizing on ideas and technologies developed by the other party.

INTRODUCTION

The CERN SRGW2021 workshop [1], where storage-rings/colliders as GW sources/detectors were discussed, and the ICTP and CERN workshops [2, 3], focused on high frequency (HF) GWs, set the stage for future cooperations between PA and GW Physicists. Here is a minimal review of relevant ideas and references.

GW SPECTRAL COVERAGE

The two US LIGOs [4] the EU Virgo [5] and the (cryogenic, underground) japanese KAGRA [6] are the four legs of the LIGO-Virgo-Kagra (LVK) Observatory, featuring (albeit limited) direction-of-arrival and source-reconstruction capabilities. Addition of a LIGO-clone in India [7] is foreseen[1]. Seismic noise (at low frequencies) and laser shot noise (at high frequencies) limit the observational window of these instruments to (20 - 200 Hz) where the noise floor is dominated by thermal noise in the mirrors terminating the interferometer arms. Next-gen Earth-bound interferometric detectors, such as the Einstein Telescope (ET) [12], and the Cosmic Explorer [13], with lower noises and improved source-localization/reconstruction capabilities, will be similarly limited in terms of spectral coverage.

Observing lower frequency GWs will be possible with the advent of LISA [14], a large scale ($2.5 \cdot 10^6$ km armlength) space-borne interferometric detector, planned for launch in 2037, following the remarkable success of its pathfinder mission [15]. A comparable chinese project [16], and a smaller-scale (three drag-free satellites in Earth orbit) japanese project [17] are underway; and further developments are envisaged [18].

Pulsar-timing [19], eventually, will open a window on the extreme low-frequency segment of the GW spectrum; several international Teams are already gathering data [20–25], and early results may be expected in a few years.

Overall, the spectral coverage of running and planned GW detection experiment is shown in Fig. 1 [26].

* petracca@sa.infn.it
† LIGO-Virgo-KAGRA Collaboration, Optica (OSA) Fellow

[1] Smaller scale interferometers are currently used as technology testbeds, including GEO-600 [8], TAMA-300 [9], CLIO [10], and the Caltech-40m [11].

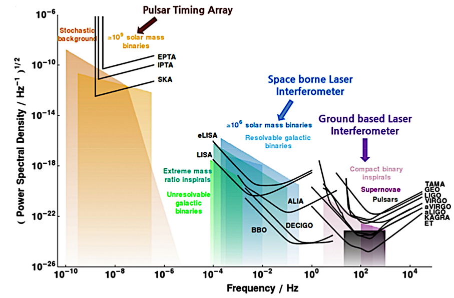

Figure 1: GW spectral coverage of mainstream GW detectors: expected source bands and strain spectral densities (credit L.H. Park).

PA AS GW SOURCES/DETECTORS

Old and new ideas on particle accelerators as GW sources or detectors have been reviewed in a recent Meeting at CERN [27]. Betatron motion response to an incoming GW [28], its enhancement by proper lattice design, and possible tuning to a specific steady GW source (e.g., PSR B0531 + 21) have been discussed [29]. A preliminary analysis of the noise budget of a MHz-GW detector based on accurate longitudinal orbit-timing in a coasting-beam SR has been proposed [30]. The claim that relic GW may produce a continued, ring-size independent shrinkage in SR circumference [31], perhaps already observed [32], has been reconsidered.

Revised estimates of gravitational synchrotron radiation [33], both direct (at ω_{circ}), and indirect (by Gershtensteyn conversion of EM synchrotron radiation, at $\gamma^3\omega_{circ}$), have been presented [34, 35]; detectability has been discussed.

Technology Cross-Breeding

GW detectors based on matter (e.g., ultracold Sr atom beams) rather than light interferometry may greatly benefit from PA technologies, and may target the 0.01 to 1 Hz range [36] . At least two such experiments are under active development [37, 38]. Housing of a prototype in an LHC access is being considered [39].

On the other hand, it has been suggested that GW detector technology achievements, notably in the fields of, extreme metrology [40] and noise control [41], may open new perspective in hadronic/nuclear cross-sections measurements [42].

HF GW SOURCES/DETECTORS

Potential HF GW sources[2] are being actively investigated (Fig. 2). See Ref. [44] for a recent review. The related estimates, however, are still very speculative.

[2] It would be good, to avoid misunderstandings, to use the *HF* shorthand in compliance with std. usage in Electromagnetics, where the *ELF, SLF, ULF, VLF, LF, MF, HF, VHF, UHF, SHF, EHF, THF* spectral bands span a frequency decade each, and the HF band starts at 3 MHz [43].

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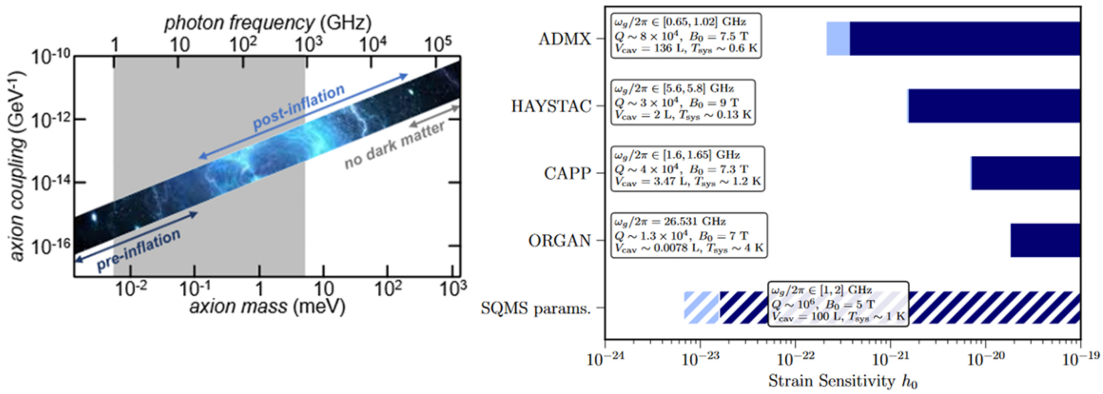

Figure 2: Left: Axion mass, coupling, and photon-frequency (Primakoff-conversion). The grey zone corresponds to active experiments; the diagonal band to possible QCD (Peccei-Quinn) generation mechanisms (credit: F. Paolucci & F. Giazotto). Right: extrapolated GW strain sensitivity of some axion experiments (credit: A. Berlin et al.).

Before the first bunch of coalescing-binary detections, we faced similar uncertainties about the relevant event rates and source parameter distributions. A pragmatic approach [45], aimed at operating/improving available HF GW detectors to set upper bounds on natural HF GW emission(s) seems advisable.

HF GW Detectors: Optical Interferometers

Laser interferometers designed to work at 10-100 MHz, with typical fractional bandwidth 10^{-3} were first proposed in [46], and built [47] around 2010.

Correlation between conceptually similar co-located instruments with 40 m arm-length, originally designed to probe quantum-geometrical fluctuations of spacetime [48], has been used to set an upper limit on the stochastic GW energy density in the 1-10 MHz band [49], and to rule out the existence of multi-harmonic sources (eccentric binaries and string loops) above a GW-strain level $\sim 10^{-21}\text{Hz}^{-1/2}$ in the same band [50]. An improved apparatus is under development at Cardiff University [51].

HF GW Detectors: RF Resonators

High frequency GW sources and detectors based on Gertshensteyn effect [52] (photon $\longleftrightarrow$ graviton conversion in a strong magnetic field) have been studied in depth by the Russian School [53, 54]. Different EM detectors of GWs have been proposed (see Ref. [55] for a recent review) exploiting the interaction of a GW with the cavity walls and/or the equivalent vacuum dielectric properties (depending on the GW frequency, different gauges may provide handier descriptions of these interactions [56]). In particular both HF-GW [57–59] and LF-GW detectors [60, 61] (Fig. 3) have been studied and prototyped [62–64], and are likely worth further work, in view of advances in key technologies.

HF GW Detectors: ALP Experiments

Remarkably, experiments aimed at exploring the spectrum of Axion-like particles (ALP) are also based on high-Q EM resonators [65], in view of the analogy between Gertshensteyn and Primakoff effect [66]. These experiments may be used to place limits on natural GW radiation in various bands of the HF-GW spectrum, almost at no added cost [67, 68]. Upper limits on (stochastic) GWs in the frequency bands $(2.7 \text{ to } 14) \cdot 10^{14}$ Hz and $(5 \text{ to } 12) \cdot 10^{18}$ Hz, have been already obtained from data gathered by axion experiments [69].

Figure 3: The 2005 MAGO detector cavities and coupling tuner (credit R. Ballantini et al.).

HF GW Detectors: Other

Two other promising (relatively) new ideas for HF-GW detectors, based respectively on optically levitated microspheres/disks, and on HF phonon trapping in bulk-acoustic resonators are being pursued. Such detectors are relatively narrowband, but can be tuned over wide frequency ranges, spanning respectively the LF [70] and HF to UHF band [71].

HF GW Hertz Experiment?

The feasibility of a GW-based Hertz experiment based on Gershtensteyn effect has been repeatedly discussed [72]. Back in 1991, in a mantic discussion about GW-based Communications, John D. Kraus (a father of Radioastronomy) suggested that a key to succeed in such a dream would be matching the extremely low GW vacuum impedance [73]. Twenty years later, Ray W. Chiao suggested that superconductors may act as GW mirrors, as an effect of WEP violation by Cooper-pairs [74]. Albeit still controversial – see Ref. [75] for a discussion and an alternative derivation – Chiao's claim, if experimentally confirmed, could be a game-changer [76].

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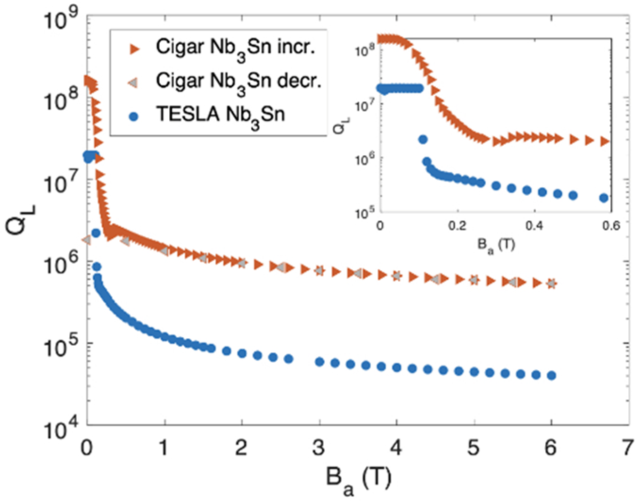

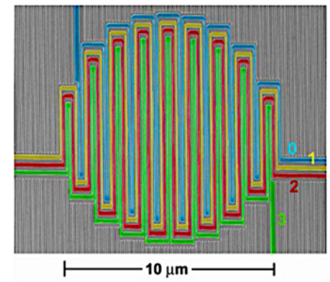

Figure 4: Left: Loaded Q of different SC RF cavities vs applied magnetic field w. increasing/decreasing amplitude (credit S. Posen et al.). Right: SEM image of superconducting-nanowire single-photon detector (credit K. Ilin).

CRITICAL TECHNOLOGIES

Advances in the following areas, at the intersection between the PA and GW realms, will be of special value :

- SC RF Technologies - These have been crucial for colliders [77], and will be also for for future GW/ALP detectors [65]. GHz-SC resonators with $Q > 10^{10}$ are currently manufactured [78]; Nb_3Sn or NbTi cavities (in a vortex state) may host large magnetic fields ($B \sim 10\,\mathrm{T}$) with $Q > 10^5$ (Fig. 4) [79].
- Single Photon Detectors (SPD) - They are developing along several directions (SNSPD, SPAD, TES). SPDs for THz [80] and GHz [81] operation are now available.
- Large Magnetic Fields – steady operation of hybrid (SC/resistive) DC magnets at $B \sim 45\,\mathrm{T}$ has been achieved [82]; pulsed (15 msec fields $\sim$ 100 T are now routinely generated [83]. Localized giant ($\sim 10^3 T$) pulsed fields (via magnetically-driven implosion) have been demonstrated [84].

CONCLUSIONS

We believe that enhanced interaction between PA and GW Scientists would trigger important developments for Astroparticle Physics, and should be actively pursued.

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