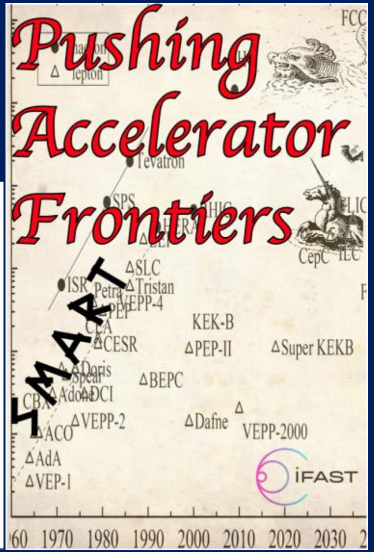
Summary of the ARIES WP6 workshop – SRGW2021 –Storage Rings and Gravitational Waves

https://indico.cern.ch/event/1008814

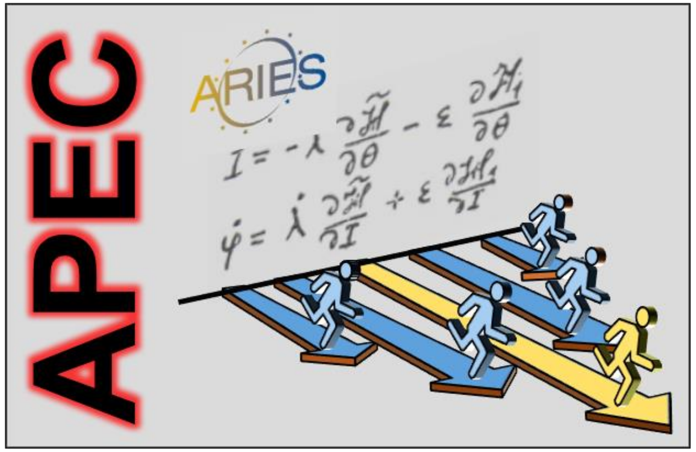
Frank Zimmermann, SRGWmb2025

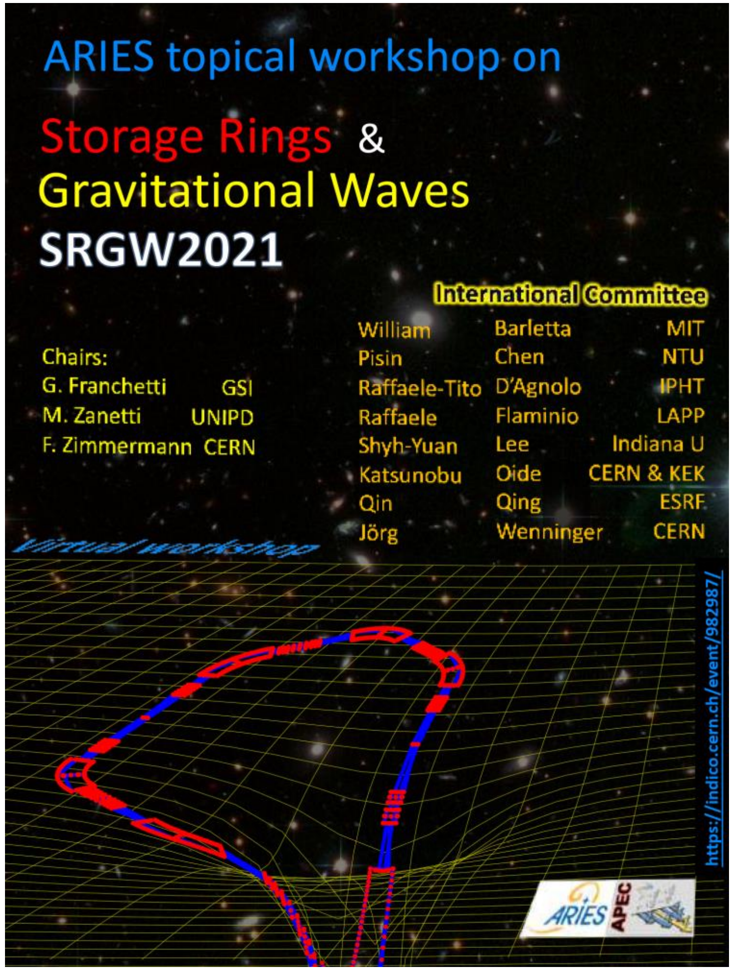
10 February 2025

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.



Storage Rings & Gravitational Waves

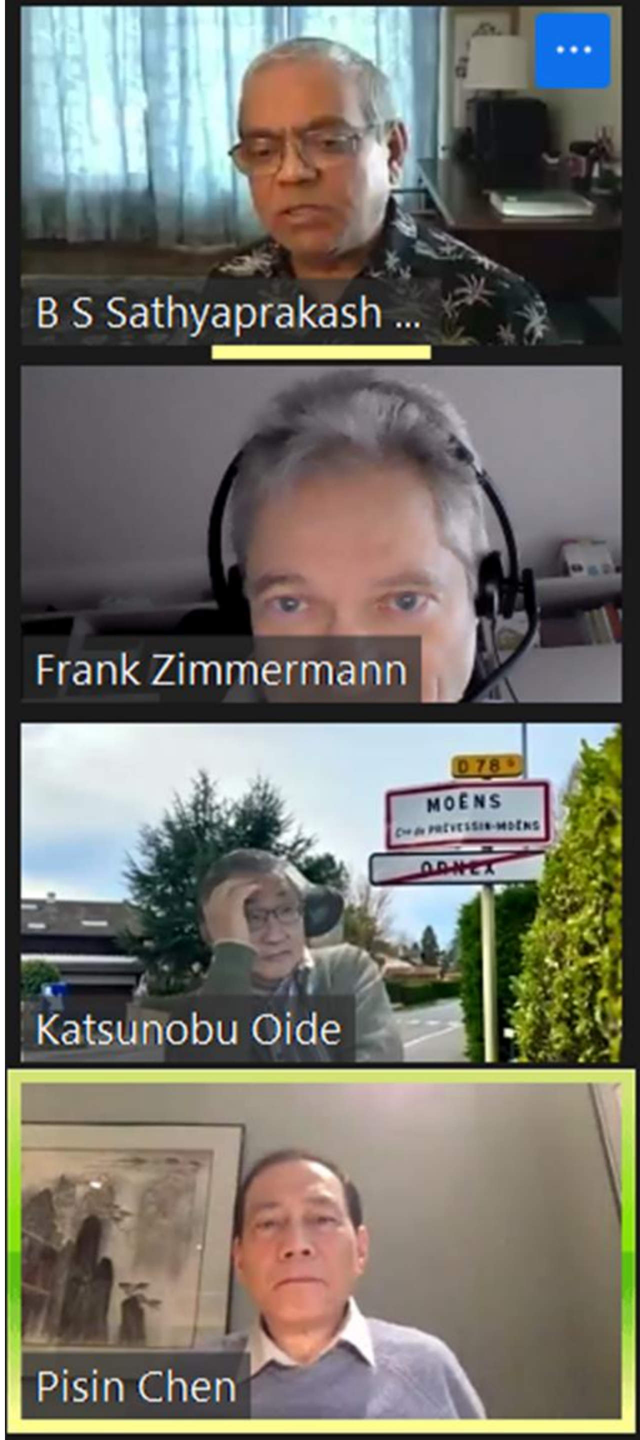




Earlier event, R.T. D'Agnolo: Storage rings as gravitational wave antennas, EuCARD-2 XBEAM, **Valencia, February 2017**

https://indico.cern.ch/event/982987/

Virtual Space, **2 & 18, 4 & 11 & 18 March 2021**



Giuliano Franchetti, Marco Zanetti, Frank Zimmermann

GOETHE UNIVERSITÄT FRANKFURT AM MAIN
1222·2022 800 ANNI UNIVERSITÀ DEGLI STUDI DI PADOVA
INFN PADOVA Istituto Nazionale di Fisica Nucleare Sezione di Padova
GSI
CERN

topic which has inspired physicists for past 50 years

ON GRAVITATIONAL RADIATION EMITTED BY CIRCULATING PARTICLES IN HIGH ENERGY ACCELERATORS

G. DIAMBRINI PALAZZI and D. FARGION
University of Rome "La Sapienza", I-00185 Rome, Italy
and INFN, Section of Rome, I-00185 Rome, Italy

Received 29 July 1987

PHYSICAL REVIEW D VOLUME 15, NUMBER 8 15 APRIL 1977

Laboratory experiments to test relativistic gravity*

Vladimir B. Braginsky
Physics Faculty, Moscow State University, Moscow, U.S.S.R
Carlton M. Caves† and Kip S. Thorne
California Institute of Technology, Pasadena, California 91125
(Received 3 January 1977)

NIKHEF/99-019

Cyclotron motion in a gravitational-wave background

J.W. van Holten

SLAC–PUB–6666
September, 1994
(T/E/A)

RESONANT PHOTON-GRAVITON CONVERSION IN EM FIELDS: FROM EARTH TO HEAVEN*

Pisin Chen
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

Gravitational Radiation Produced by High Energy Accelerators and High Power Lasers.

GIORDANO DIAMBRINI PALAZZI
University of Rome 'La Sapienza' and INFN (Sezione di Roma), Italy.

Storage rings as detectors for relic gravitational–wave background ?

A. N. Ivanov*† and A. P. Kobushkin‡§
August 27, 2018

CERN-EP/98-63
March 25, 1998

Detection of gravitational waves in circular particle accelerators

Suvrat Rao,* Marcus Brüggen, and Jochen Liske
Hamburger Sternwarte, University of Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany
(Dated: December 2, 2020)

Here we calculate the effects of astrophysical gravitational waves (GWs) on the travel times of proton bunch test masses in circular particle accelerators. We show that a high-precision proton bunch time-tagging detector could turn a circular particle accelerator facility into a GW observatory sensitive to millihertz (mHz) GWs. We comment on sources of noise and the technological feasibility of ultrafast single photon detectors by conducting a case study of the Large Hadron Collider (LHC) at CERN.

On the Detection of Gravitational Waves through their Interaction with Particles in Storage Rings

Daniel Zer-Zion
CERN, CH-1211 Geneve 23
Switzerland

Numerous questions, e.g.

- Is there a realistic possibility for detecting and/or generating gravitational waves with storage rings?
- How does sensitivity/effect scale w ring size, beam energy, particle type?
- Could there be another use of the LHC, or 2nd motivation for the FCC?
- Need we build a dedicated smaller ring?
- Or should we just use accelerator technologies ? SRF, atomic beam interferometry etc.
- Could one perhaps envision a network of storage rings around the globe for this type of application? (Bill Barletta)

SRGW2021 Scientific Programme

Session 1, Tuesday 2 February 2021, chaired by Pisin Chen, NTU

15:00 Welcome, Frank Zimmermann

15:05 A Brief History of Gravitational Waves, Jorge Cervantes Cota ;

15:45 Expected sources of gravitational waves, Bangalore Sathyaprakash ;

16:25 Response of a storage-ring beam to a gravitational wave – a few considerations, Katsunobu Oide ;

16:45 Discussion

Session 2, Thursday 18 February 2021, chaired by SY Lee, Indiana U

14:30 Measurement approach and sensitivities of detectors like LIGO and VIRGO, Raffaele Flaminio ;

15:15 Storage ring sensitivity to tides & large-scale perturbations, earthquakes, noise – examples from LEP and LHC, Jorg Wenninger ;

15:55 Discussion

Session 3, Thursday 4 March 2021, chaired by Jörg Wenninger, CERN

14:30 Detection of gravitational waves in circular particle accelerators - a proposal for the LHC, Suvrat Rao ;

15:15 Storage rings as detectors for relic gravitational-wave background?, Andrei Ivanov ;

16:00 Update on Theoretical Effects of Gravitational Waves on Storage Rings, Raffaele Tito D'Agnolo ;

16:40 Discussion

Session 4, Thursday 11 March 2021, chaired by Frank Zimmermann, CERN

14:30 Radiofrequency cavities and gravitational wave signals?, Sebastian Ellis ;

15:00 Using storage rings as a GW source, Pisin Chen ;

15:45 Gravitational synchrotron radiation, some history revisited, and FCC-hh, John Jowett;

16:00 Use of atom-interferometry for possible GW detection and other gravity experiments, Oliver Buchmüller, John Ellis;

16:45 Discussion

Session 5, Thursday 18 March 2021, chaired by Giuliano Franchetti, GSI and John Ellis, CERN

14:30 Ground Vibration at SSRF Site, Rongbing Deng;

15:00 What Governs the Flow of Energy? Questions on Gravitational Impedance Matching, Peter Cameron ;

15:15 Discussion

"Since past colliders turned into photon sources, it would be logical if future ones became graviton sources …"

John Jowett

gravitational synchrotron radiation

$$W_{GSR} = \frac{5\pi}{16} \frac{m^2}{M_P^2} \frac{\hbar c^2 \gamma^4}{\rho^2} n_b^2 N_b^2$$

assuming coherence over all n_b bunches

P. Chen, SLAC-PUB-6666 (1994)

$$W_{SR} = \frac{2}{3} \alpha \frac{\hbar c^2 \gamma^4}{\rho^2} n_b \, N_b$$

$$\frac{W_{GSR}}{W_{SR}} = \frac{15\pi}{32} \frac{m^2}{\alpha M_P^2} n_b \, N_b \;\sim 3.5 \times 10^{-21}$$

for LHC

gravitational beamstrahlung

$$W_{GB} = \frac{\pi}{4}\frac{1}{\alpha}\frac{m^2}{M_P^2}\left(\frac{\sigma_z}{\lambda_c}\frac{B}{B_c}\right)^2 N_b n_b W_{EM}$$

P. Chen, SLAC-PUB-6666 (1994)
P. Chen, Modern Phys. Lett. 6 (1991) 1069

with a cut off at $\omega \geq c/\sigma_z$

for FCC-ee-Z:

$\sigma_z \approx 12$ mm
$M_P \approx 1.2 \times 10^{19} \frac{\mathrm{GeV}}{c^2}$ (Planck mass)
$B_c \approx 4.4 \times 10^9$ T (Schwinger critical field)
$\lambda_c \approx 2.4 \times 10^{-12}$ m (electron Compton wavelength
$\langle B \rangle \approx (2^{3/2}/\pi) N_b\, r_e/(\gamma \sigma_x^* \sigma_z)\, p/e \approx 10$ T

$$\frac{\pi}{4}\frac{1}{\alpha}\frac{m^2}{M_P^2}\left(\frac{\sigma_z}{\lambda_c}\frac{B}{B_c}\right)^2 N_b n_b^2 \approx 10^{-21}$$

$W_{EM} \sim 0.5$ MW
$\rightarrow W_{GB} \sim 0.5$ fW (tbc)

assuming coherence over all n_b bunches

Detection by SRF cavity

2.9 Revisiting Gravitational Wave Detection in an SRF Cavity

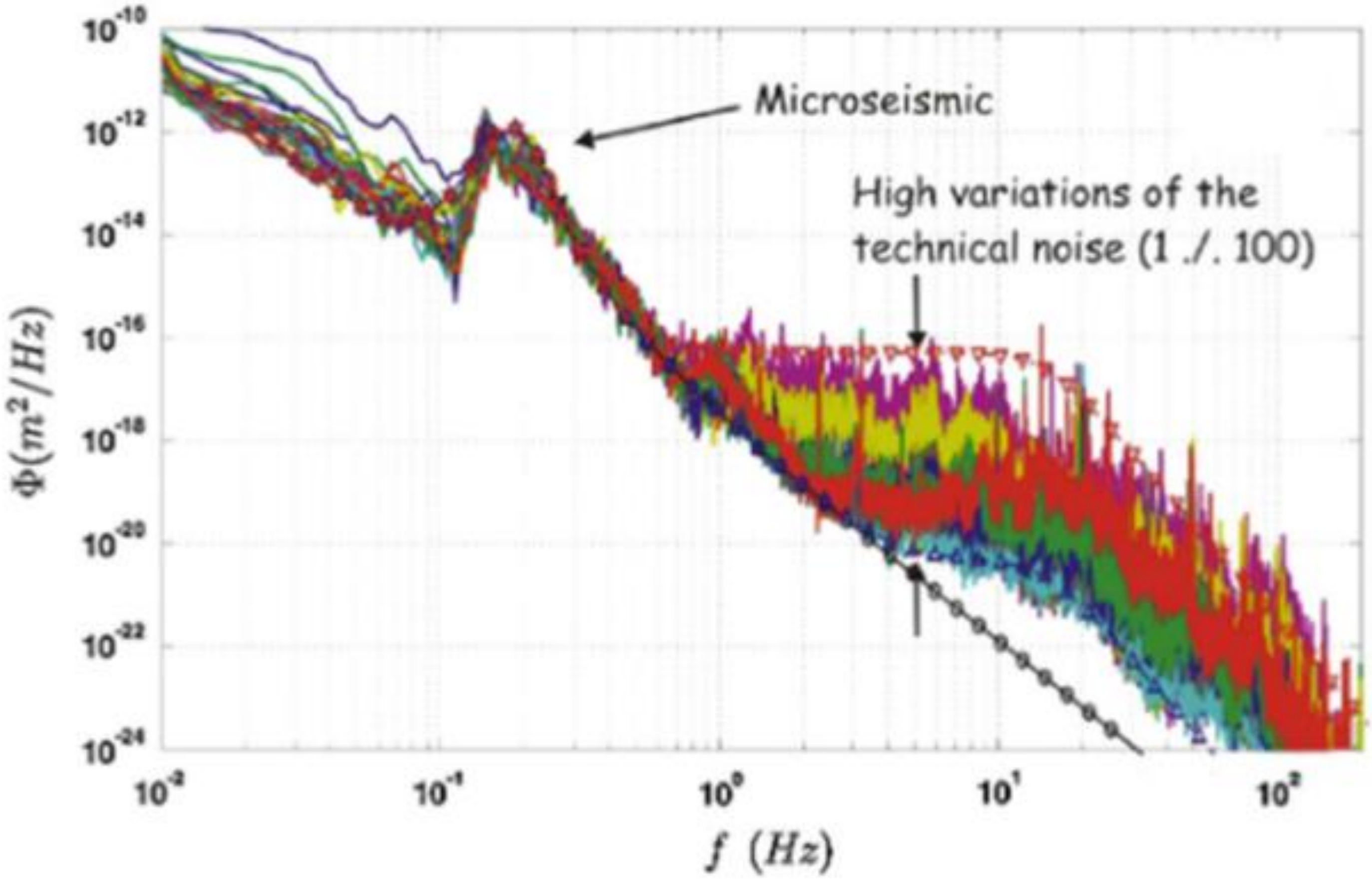
A. Berlin, R. T. D'Agnolo, S. A. R. Ellis

In the late 1970s, proposals to search for GWs using superconducting radio-frequency (SRF) cavities were made by Pegoraro, Picasso and Radicati (PPR) and by Caves.

Prototypes were constructed in the 1980s and early 2000s, culminating in the MAGO collaboration. The approach was abandoned, however, due to political decisions prioritizing other GW searches where known astrophysical sources exist.

Due to the renewed theoretical and experimental interest in high-frequency GWs, and advances in SRF technology, we have revisited the use of carefully-controlled SRF cavities to detect gravitational waves.

Storage ring sensitivity to tides, perturbations, earthquakes, noise

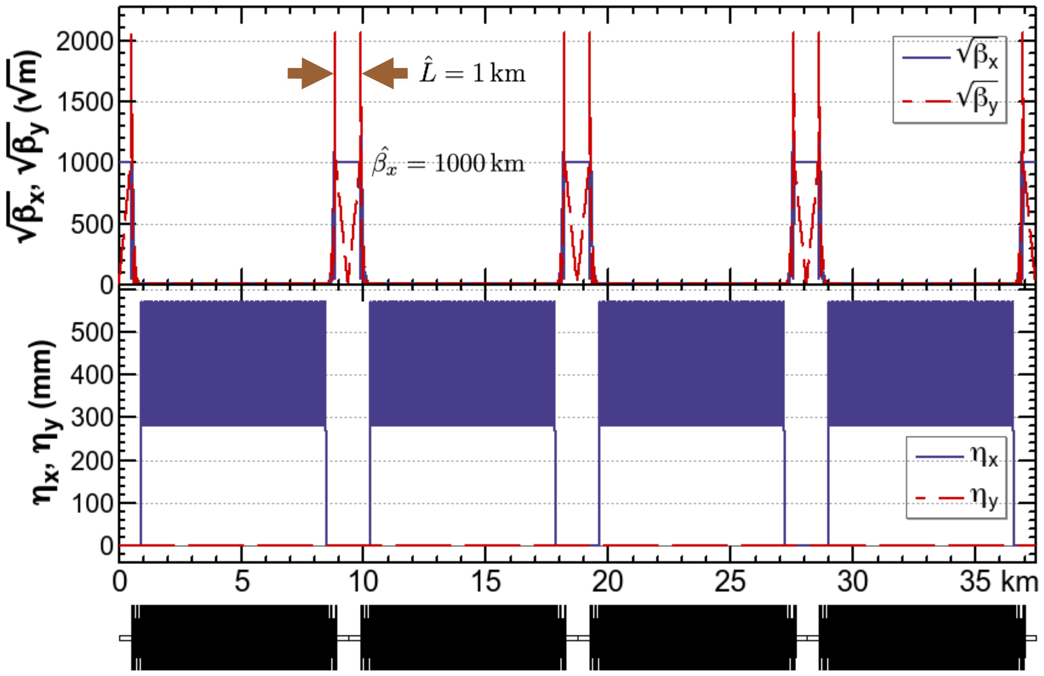


Measurements of the seismic noise power spectrum in the LHC tunnel (J. Wenninger)

GW detection by resonant betatron oscillations

Response of a storage-ring beam to a gravitational wave
(K. Oide)

ring optics for a GR antenna



In the case of such an "antenna", the response to GR in the arc is small compared to the $\hat{\beta}_x$ sections, to we ignore below. Thus Eq. 7 is reduced to

$$\Delta\hat{x} = -\frac{k^2 R\hat{L}}{2} h \sum_{m=0}^{n} \hat{\beta}_x \sin\left(2(n-m)\pi\Delta\nu_x\right) \cos\left(\frac{m\pi}{2} kR\right) \cos m\pi\,, \quad (11)$$

where $\Delta\mu_x$ is the phase advance between two $\hat{L}$ sections, and we have used $\theta = m\pi/2$ at the m-th $\hat{L}$ section.

Equation 11 has resonances at

$$2\Delta\nu_x = \pm kR + N\,, \quad (12)$$

where N is an integer. At the resonance, the horizontal amplitude accumulates by

$$\Delta\hat{x} \approx -\frac{k^2 R\hat{L}}{2}\hat{\beta}_x h \quad (13)$$

per turn.

If we set $\omega_{\mathrm{GR}} = 2\pi \times 1\,\mathrm{kHz}$ and with parameters above, Eq. 13 gives $\Delta\hat{x} \approx 1000h\,\mathrm{m}$, which seems still too small to detect. As the amplitude is proportional to ω_{GR}^2, there may exist a possibility to detect a GR in $\omega_{\mathrm{GR}} = 2\pi \times 1\,\mathrm{MHz}$ range, giving $\Delta\hat{x} \approx 10^9 h$ m (0.1 pm for $h = 10^{-22}$), if there are sources.

sensitivity of resonant betatron oscillations

$$\Delta x \approx \frac{\omega^2 R\hat{L}\hat{\beta}}{2c^2} h$$

signal over 1 turn (K. Oide)

signal could be accumulated over $1/\Delta Q \sim 10^4$ turns

$$h_{sens} \approx \frac{2c^2 \Delta Q}{\omega^2 R\hat{L}\hat{\beta}} \Delta x \longrightarrow \frac{h_{sens}}{\sqrt{\Delta f}} \approx \frac{c^2 \Delta Q}{2\pi^2 f^2 \sqrt{\Delta f} R\hat{L}\hat{\beta}} \Delta x$$

$$\Delta Q \approx \frac{\Delta f\ C}{2c} \longrightarrow \frac{h_{sens}}{\sqrt{\Delta f}} \approx \frac{c\sqrt{\Delta f / f}}{2\pi f^{3/2} \hat{L}\hat{\beta}} \Delta x$$

other GW responses of storage rings: longitudinal & very slow

2.4 Detection of millihertz gravitational waves using storage rings

S. Rao, M. Brüggen and J. Liske

2.5 Storage rings as detectors for relic gravitational-wave background?

A. N. Ivanov, A. P. Kobushkin, M. Wellenzohn

2.6 Gravitational Waves at Particle Storage Rings

R. T. D'Agnolo

At the LHC we have $\frac{\Delta T}{T} \simeq 10^{-7}$ from the phase measurement in the RF system [15] and $\omega_l \simeq 60$ Hz. We thus get a sensitivity (without backgrounds)

$$h \gtrsim 10^{-13} \left(\frac{2\pi \times 10 \text{ Hz}}{\omega_l}\right) \left(\frac{10 \text{ hours}}{\tau_l}\right) \left(\frac{\Delta T/T}{10^{-7}}\right) . \quad (14)$$

This is about 7 orders of magnitude larger than what we expect from realistic GW sources [17]. However, there is in principle a path towards vastly increasing the sensitivity of a storage ring:

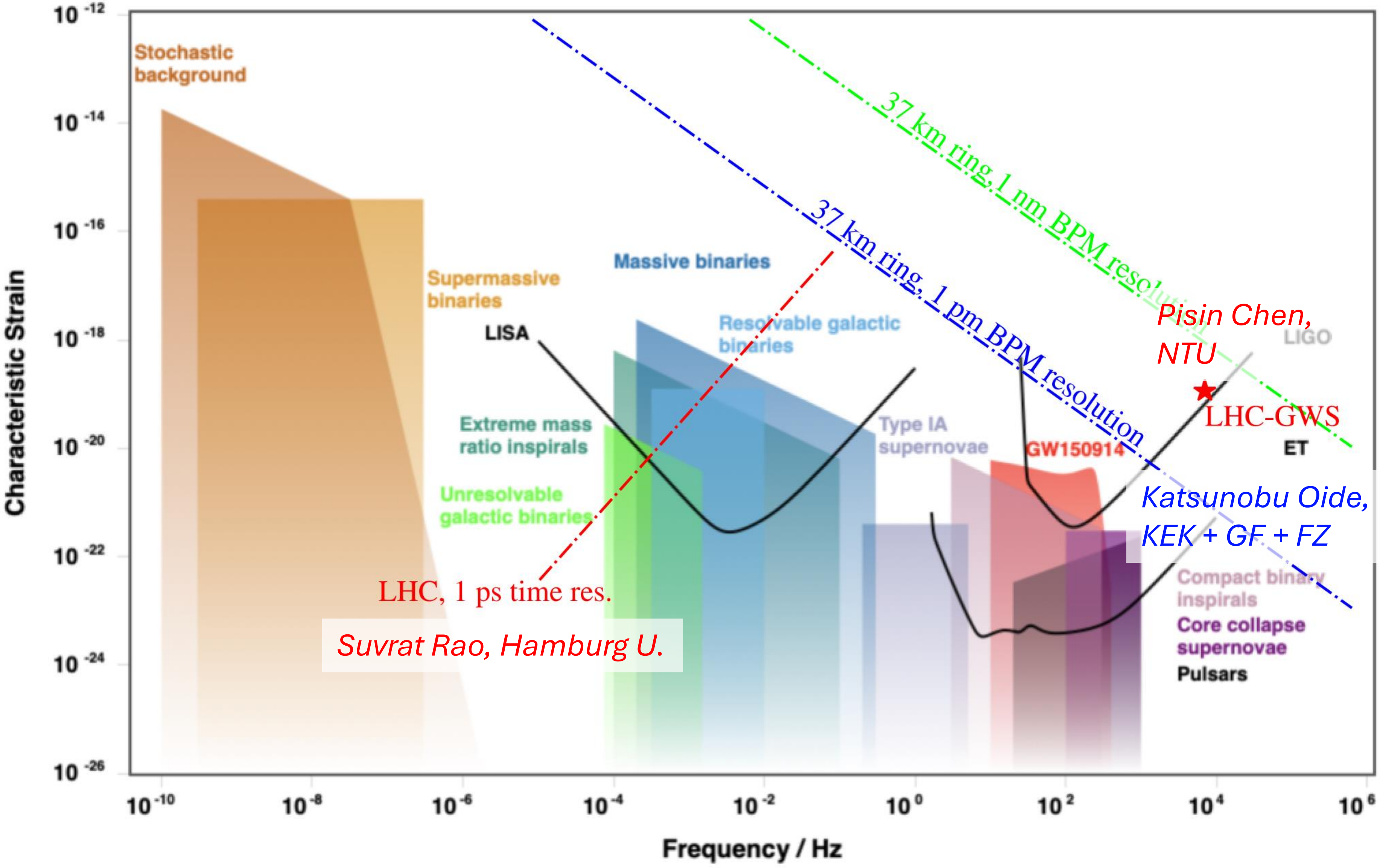
1. The effect saturates when $T \simeq \omega_g^{-1}$. So we can either increase ω_l or increase T by about three orders of magnitude compared to the LHC, where $T \simeq 1/(11 \text{ kHz})$, increasing the sensitivity on h by the same amount. Increasing ω_l reduces the amplitude of expected astrophysical signals, so it is better to consider rings with either non-relativistic protons or sizes even larger than the LHC.

2. One can improve the time resolution of the measurement. Using electro-optical sampling as in other storage rings [18] could improve $\Delta T/T$ by one order of magnitude.

3. Decreasing the energy of the protons also goes in the direction of increasing τ_l. Maybe one can envision operating a storage ring in stable conditions for days or even weeks.

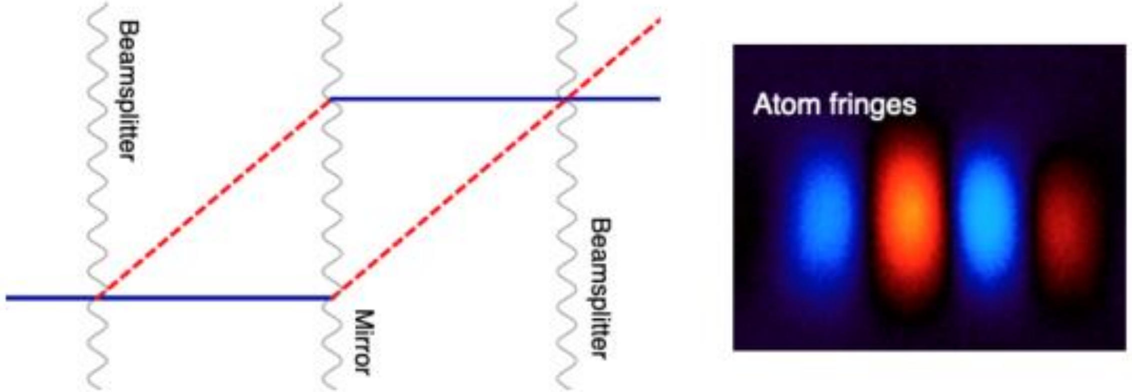
The three above points indicate future avenues of investigation that might lead to the detection of GWs at storage rings. Another interesting option is to make the protons as freely-falling as possible, i.e., $\omega_l \to 0$.

Detection (& Generation) by Storage Rings

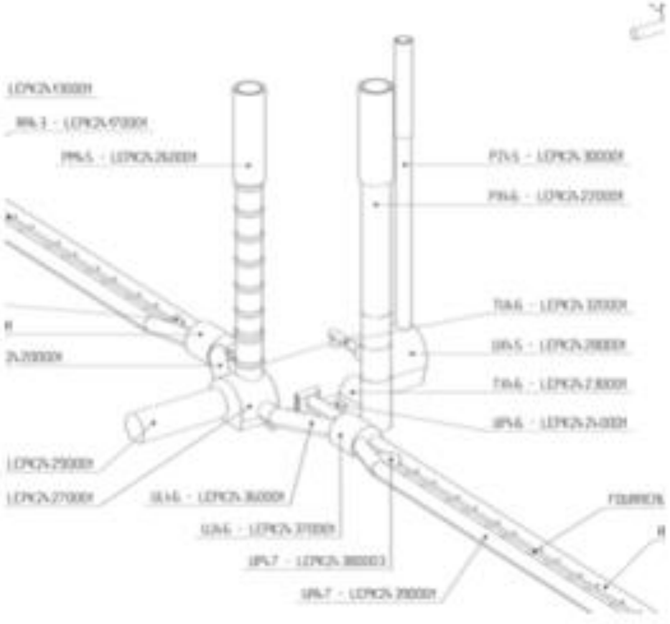


G. Franchetti et al.

Detection by Atom Interferometer



The principle of atom interferometry: blue lines are atoms in the ground state, red dashed lines are atoms in the excited state and the wavy lines are laser pulses; and a typical interference pattern



One possible location of the 100m Stage 2 of AION at CERN is in the PX46 access shaft to the LHC

SRGW2021 summary paper

Workshop summary ,
arXiv:2105.00992
https://arxiv.org/pdf/2105.00992

Storage Rings and Gravitational Waves: Summary and Outlook

A. Berlin[1], M. Brüggen[2], O. Buchmueller[3], P. Chen[4], R. T. D'Agnolo[5], R. Deng[6], J. R. Ellis[7,×,*], S. Ellis[5], G. Franchetti[8], A. Ivanov[9], J. M. Jowett[8], A. P. Kobushkin[10], S. Y. Lee[11], J. Liske[2], K. Oide[12], S. Rao[2], J. Wenninger[13], M. Wellenzohn[9], M. Zanetti[14], F. Zimmermann[13,×,†]

[×] *Editors*

[1]New York U., USA; [2]U. Hamburg, Germany; [3]Imperial College London, UK; [4]National Taiwan University, Taiwan; [5]IPhT Paris, France; [6]SARI Shanghai, China; [7]King's College London, UK; [8]GSI, Germany; [9]Vienna U., Austria; [10]BITP, Ukraine; [11]Indiana U., USA; [12]KEK, Japan; [13]CERN, Switzerland; [14]U.& INFN Padua, Italy

May 4, 2021

Abstract

We report some highlights from the ARIES APEC workshop on "Storage Rings and Gravitational Waves" (SRGW2021), held in virtual space from 2 February to 18 March 2021, and sketch a tentative landscape for using accelerators and associated technologies for the detection or generation of gravitational waves.

KCL-PH-TH/2021-28, CERN-TH-2021-068

final SRGW2021 discussion

3 Final Workshop Discussion

Moderated by J. R. Ellis

The final discussion centred on the following five main topics:

1. The proposal by K. Oide (Section 2.3) of GW detection by resonant betatron oscillations in a storage ring, sensitive in the 10 kHz range;

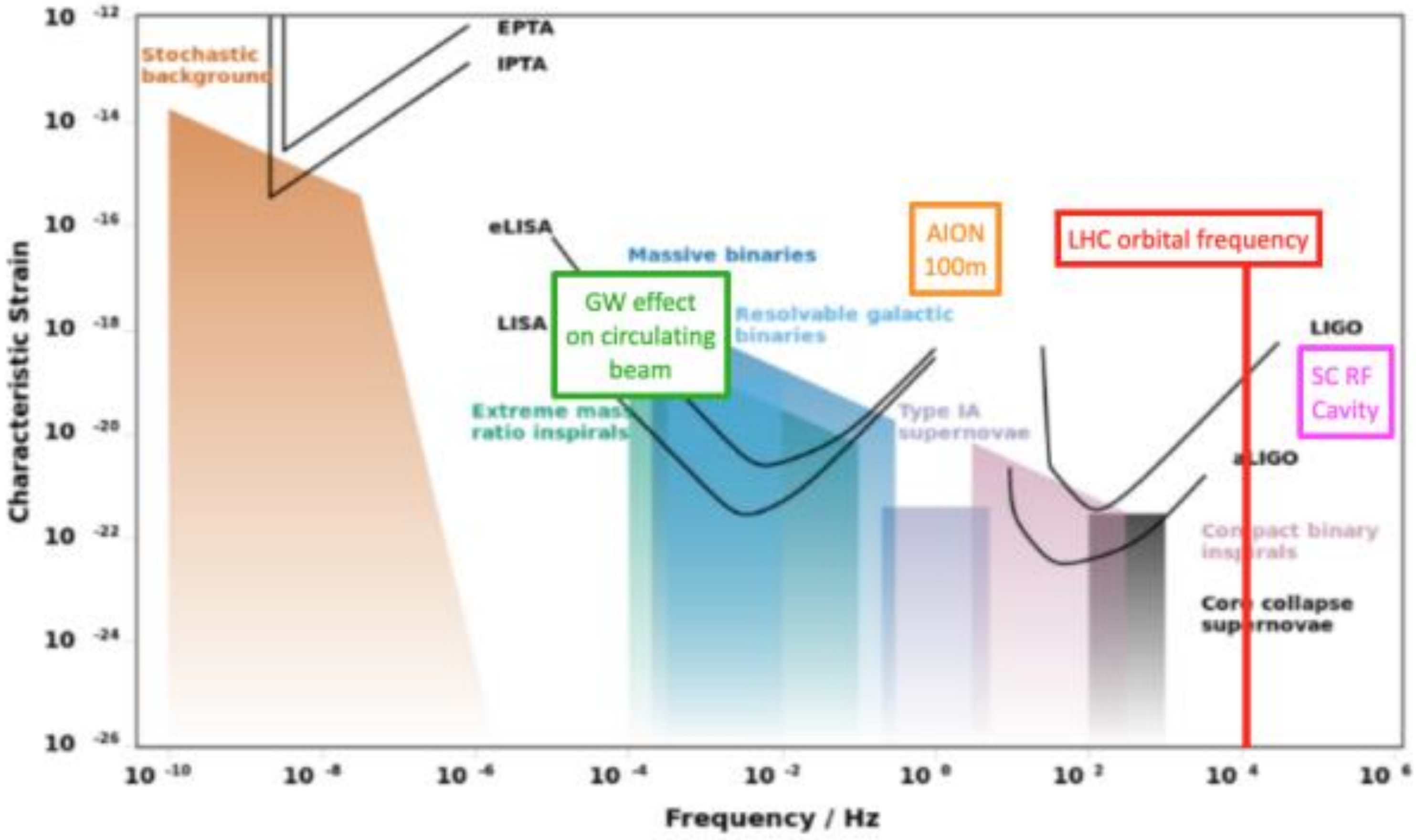
2. A variant of the proposal by S. Rao (Section 2.4) and R. T. D'Agnolo (Section 2.6) of GW detection through the change in revolution period, but using a "low-energy" coasting ion beam without RF, aiming at sensitivity down to 10^{-5} Hz;

3. The proposal by P. Chen (Section 2.7) (discussed also by J. Jowett (Section 2.8) of gravitational synchrotron radiation generated by the beam at frequencies close to the orbital frequency, $\sim 10^4$ Hz for LHC. Section 2.7 also discussed the Gertsenshtein effect, whereby electromagnetic synchrotron radiation is converted to GWs of much higher frequency;

4. The suggestion by S. Ellis and collaborators (Section 2.9) of heterodyne GW detection using SRF, which could be sensitive up to $\sim 10^7$ Hz;

5. The possibility suggested by O. Buchmueller and J. Ellis (Section 2.10) of using an LHC access shaft to house a 100m atom interferometer targeting the 1 to 10^{-2} Hz range.

landscape of the GW frequency spectrum with some workshop proposals



The landscape of the GW frequency spectrum, illustrating the ranges in which various astrophysical and cosmological sources are expected, and the sensitivities of some present and planned experiments. Also shown are the frequency ranges targeted by some of the proposals discussed during this Workshop.

gravitational wave as a force on the beam ?!

S. Rao

P.R. Saulson / C. R. Physique 14 (2013) 288–305 289

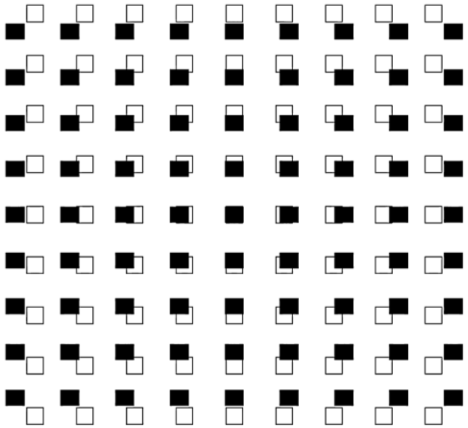
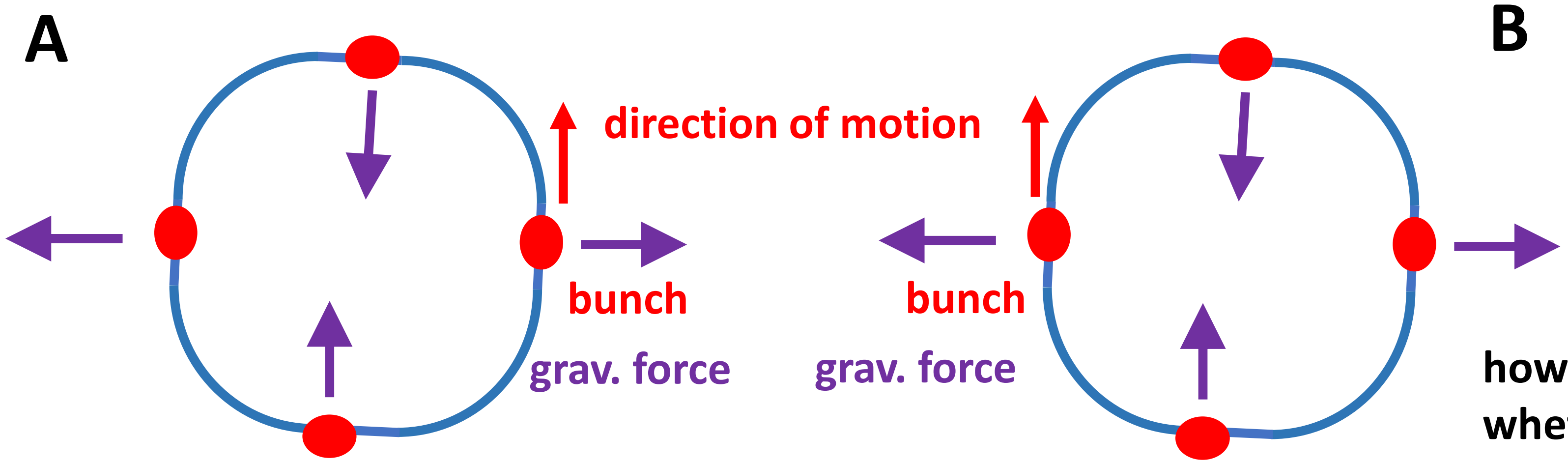


Fig. 1. A gravitational wave causes a set of free masses to change their separations from one another in a pattern like the one shown here. Open squares represent the original positions of the masses, while the filled squares represent their instantaneous relative positions while a gravitational wave of polarization h_+ is present.



how does the bunch "know" whether it is in ring A or B?

perhaps force occurs inside dipoles?

objective(s) for this workshop

derive and agree on (frequency-dependent?) “**equations of motion” for a beam in a storage ring subject to gravitational waves**, in a format useful for accelerator physicists

- design optimization (big or small?), synergies with other precisions storage rings (EDM, quantum computing)
- limitations

use of accelerator technology (SRF cavities) for gravitational wave detection

- pushing the state of the art?

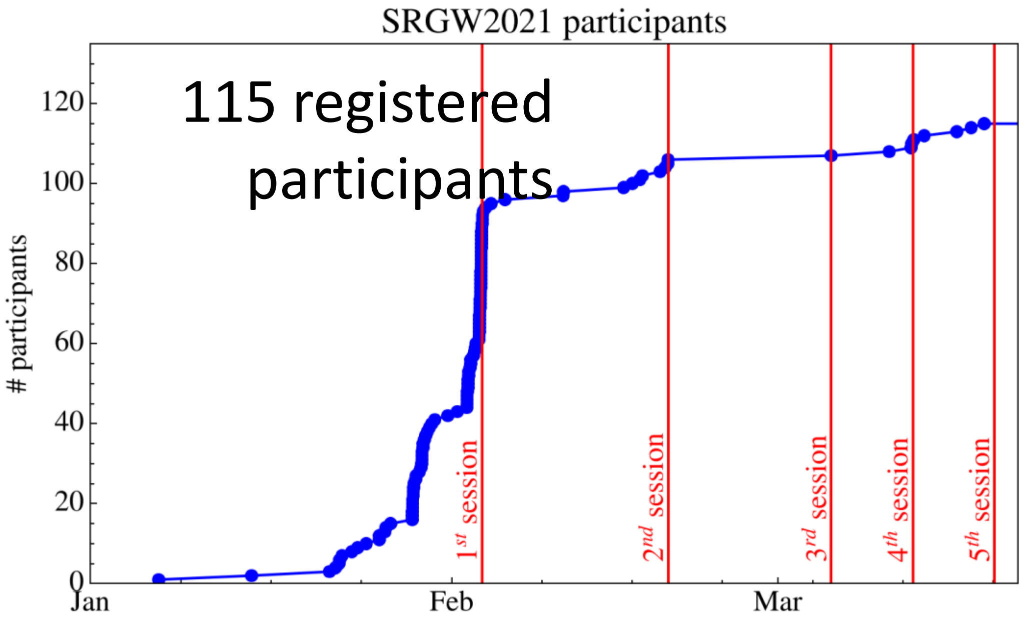
steps for atomic interferometry

- status of experiments in UK and around the world
- updated timeline and steps for installation at CERN

spare slides

ARIES Workshop on Storage Rings and Gravitational Waves (SRGW2021), virtual space, 2 February -18 March 2021 ; chaired by G. Franchetti, Marco Zanetti, and F. Zimmermann

Scientific Programme Committee	
William A. Barletta	MIT
Pisin Chen	NTU
Raffaele-Tito D'Agnolo	IPHT
Raffaele Flaminio	LAPP
Giuliano Franchetti (co-chair)	GSI
Shyh-Yuan Lee	Indiana U
Katsunobu Oide	CERN & KEK
Qing Qin	ESRF & U. Peking
Jorg Wenninger	CERN
Marco Zanetti (co-chair)	U. Padova
Frank Zimmermann (co-chair)	CERN



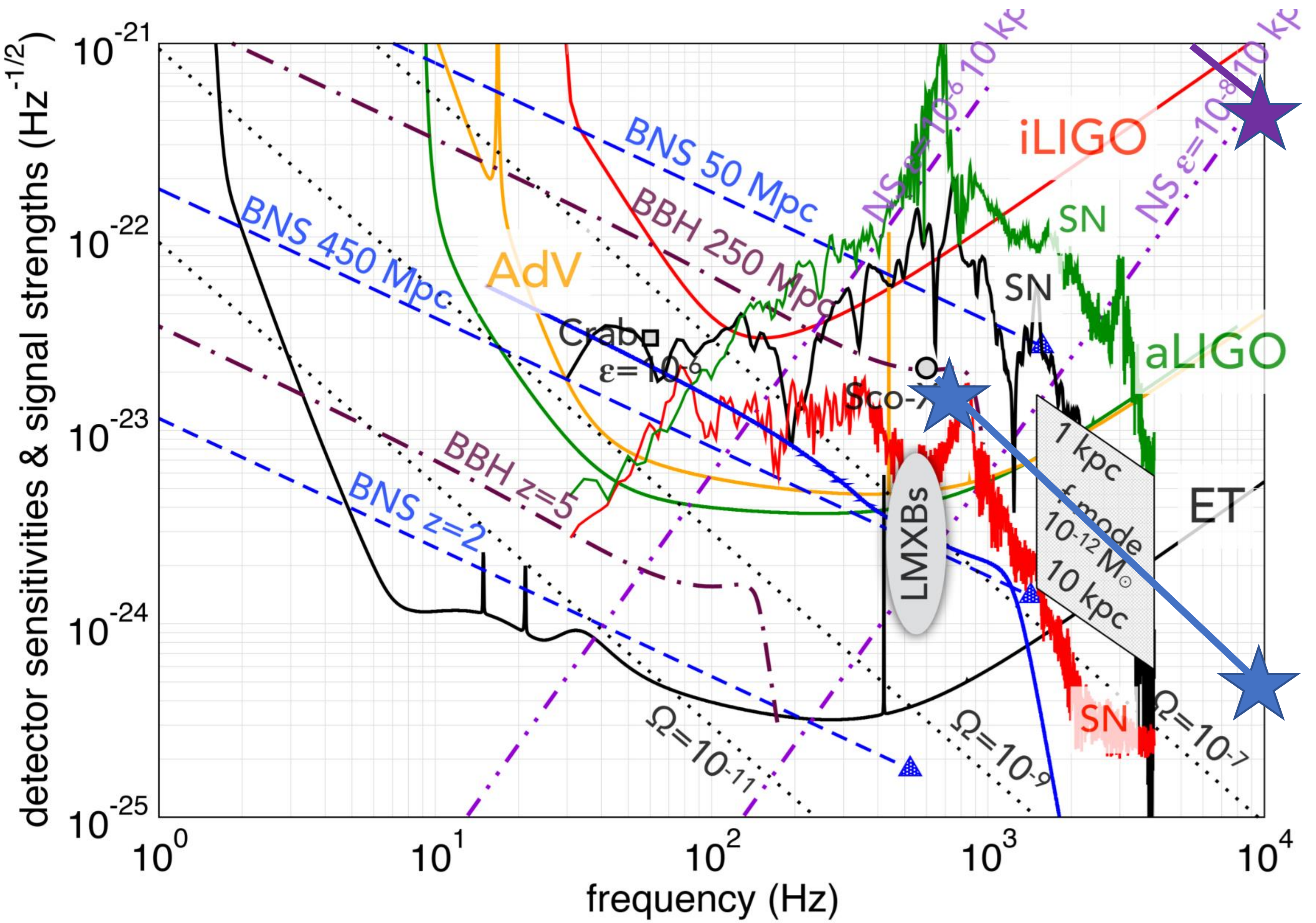
main focus: detection and/or generation of gravitational waves or other gravity effects using storage rings & accelerator technologies

Sessions:

2/2/2021, **Introduction to Gravitational Waves and their effects,** chair: *Pisin Chen / NTU Taiwan*
18/2/2021, **Measurements and sensitivity,** chair: *Shyh-Yuan Lee / Indiana U*
4/3/2021, **Proposals and Schemes**, chair*: Jörg Wenninger / CERN*
11/3/2021, **Gravitational wave generation and detection,** chair: *Frank Zimmermann / CERN*
18/3/2021, **Ground motion and final discussion,** chairs: *Giuliano Franchetti/GSI; John Ellis/CERN*

source summary & ground-based detectors

noise sources to be assessed



β=1000 km

L = 1 km

$\sqrt{\Delta f / f} \approx 0.01$

B.S. Sathyaprakash

“Accelerator Research and Innovation for European Science and Society” (ARIES) is an Integrating Activity project which aims to develop European particle accelerator infrastructures, co-funded under the European Commission's Horizon 2020 Research and Innovation programme, coordinated by M. Vretenar (CERN)

ARIES WP6 “Accelerator Performance and Concepts” (APEC), coordinated by G. Franchetti (GSI) and F. Zimmermann (CERN) covers Beam Quality Control in Hadron Storage Rings and Synchrotrons, Reliability and Availability of Particle Accelerators, Improved Beam Stabilization, Beam Quality Control in Linacs and Energy Recovery Linacs, and

Task 6.6 “Far Future Concepts & Feasibility”, coordinated by Marco Zanetti (INFN & U. Padova), Frank Zimmermann (CERN)

“Accelerator Research and Innovation for European Science and Society” (ARIES) is an Integrating Activity project which aims to develop European particle accelerator infrastructures, co-funded under the European Commission's Horizon 2020 Research and Innovation programme, coordinated by M. Vretenar (CERN), May 2017-April 2022

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