Storage Rings and Gravitational Waves

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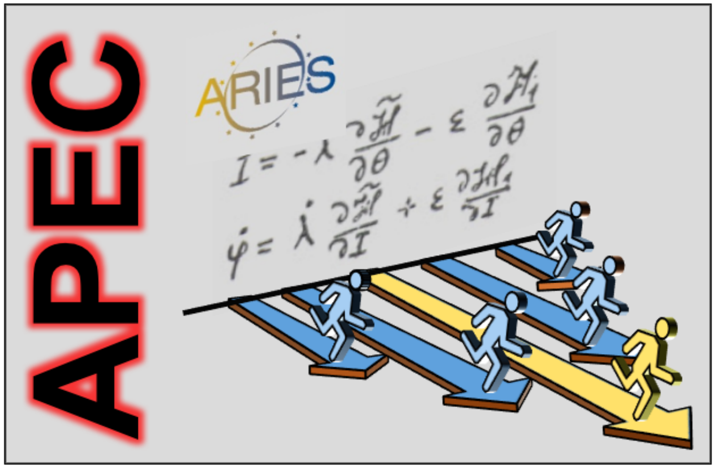
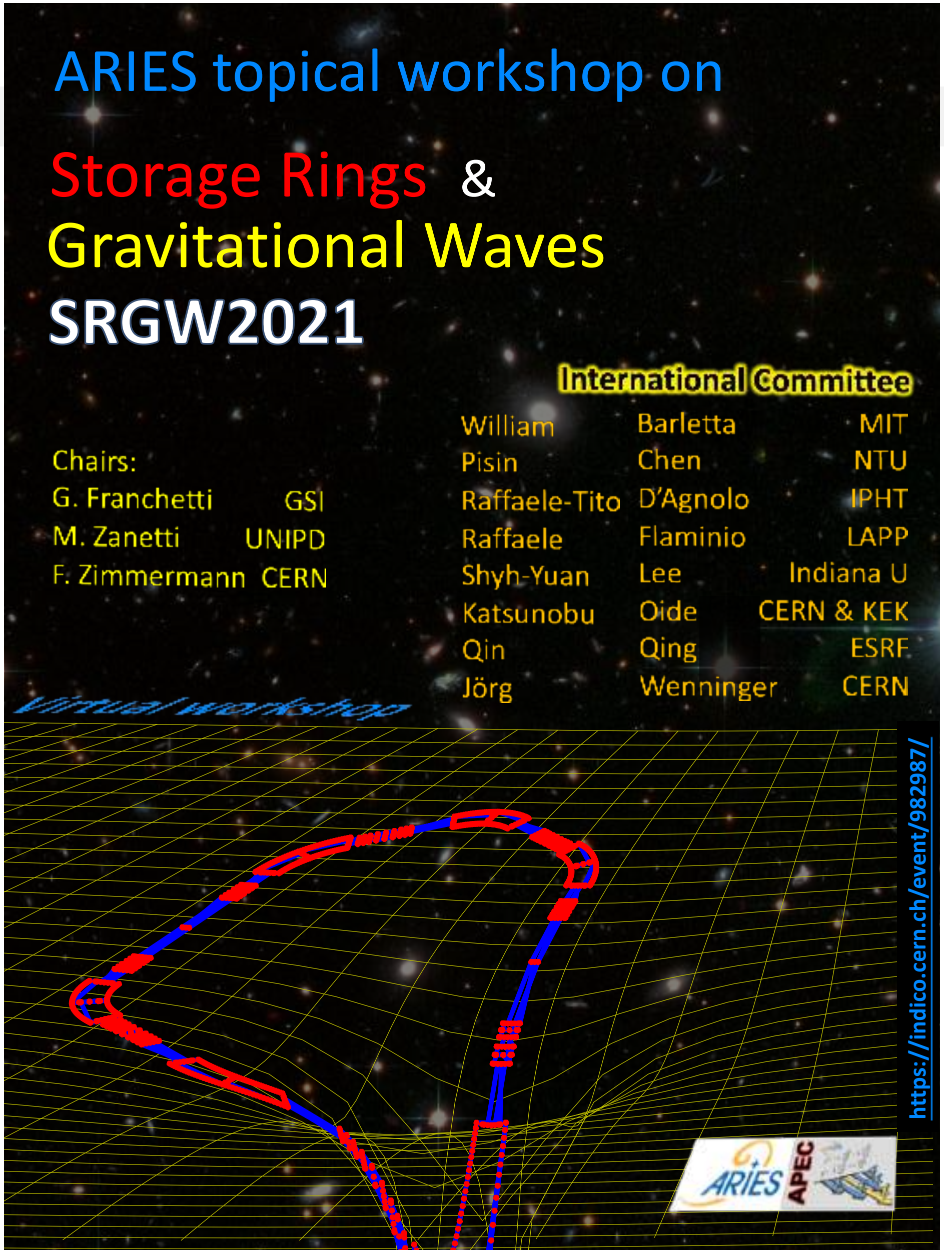
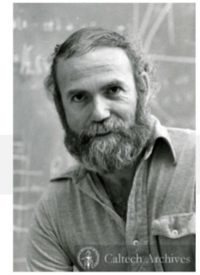
Workshop by: F. Zimmermann, M. Zanetti, G. Franchetti





Material from Jorge Cervantes



1919 Equation of graviatational waves

1936 Einstein denies GW

1949 Babson

1957 Chapel Hill Meeting “Sticky bead” argument by Feynmann

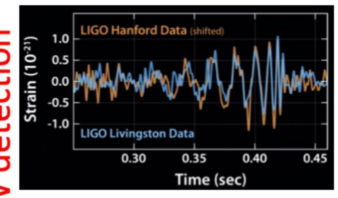
1960 → Interferometers. →

1967 Reiner Weiss

1975 kip Thorne

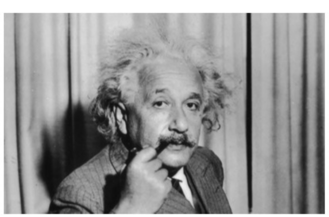
1994 LIGO Barry Barish

2015 GW detection



LIGO
VIRGO
KAGRA
LIGO-India

1915 General theory of relativity



1922 Eddington

1939-1945 WWII

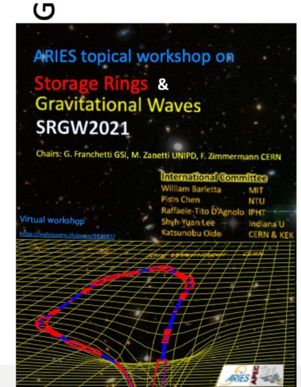
1956 Pirani Felix

1958 Weber GW antenna

1974-1979 Pulsar Binary pulsar Evidence of Existence of GW

1995 VIRGO construction

2021 Gravitational wave & Storage rings



Einstein Telescope

Cosmic Explorer

LISA

Space-time geometry

event $(t, \vec{x})$

Distance between two events

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Metrics (dimensionless)

$g_{\mu\nu}$ Defines the geometric properties of space-time

Einstein field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Stress-energy tensor

Einstein tensor: This is a nonlinear differential function of $g_{\mu\nu}$

In absence of gravity

$$g_{\mu\nu} = \eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

For weak gravity

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

perturbation

Einstein equation for weak field

$$\Box \overline{h}^{\mu\nu} = -16\pi \frac{G}{c^4} T^{\mu\nu}$$

Waves in $g_{\mu\nu}$

$$\left(-\frac{\partial^2}{\partial^2}+\nabla^2\right)\overline{h}^{\mu\nu}=-16\pi\frac{G}{c^4}T^{\mu\nu}$$ ← Source

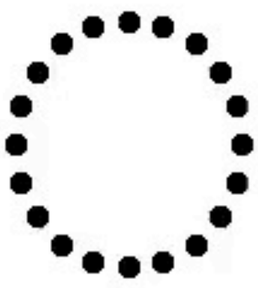
Far field solution: amplitude

Quadrupolar momentum

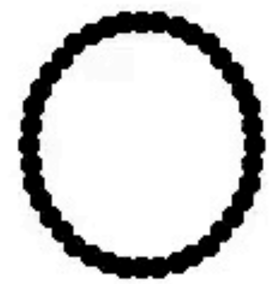
$$h_{jk}=\frac{G}{c^4}\frac{2}{r}\frac{d^2Q_{jk}}{dt^2}$$

$$Q_{jk}=\int_{source}\rho x_j x_k dx^3$$

GW polarization



plus +



cross ×

Amplitude estimates of h

$$Q_{jk} = \int_{source} \rho x_j x_k dx^3 \quad \Rightarrow \quad \frac{d^2}{dt^2} Q_{jk} \sim M v^2$$

Non-spherical

Maximum amplitude @ distance r

$$h \lesssim \frac{G}{c^4} \frac{2}{r} M v^2$$

Effect of the metric perturbation

$$\frac{\Delta l}{l} \simeq h$$

Example of GW source

Extreme Amusement Park Attraction

$$
\begin{array}{lll}
R & \sim & 10\,\mathrm{m} \\
N_{persons} & \sim & 28 \\
weight & \sim & 100\,\mathrm{Kg} \\
Structureweight & \sim & 6000\,\mathrm{Kg} \\
v_{max} & \sim & \underline{20\,\mathrm{m/s}}
\end{array}
$$

$$f = 0.3\,\mathrm{Hz}$$

At distance of one wavelength

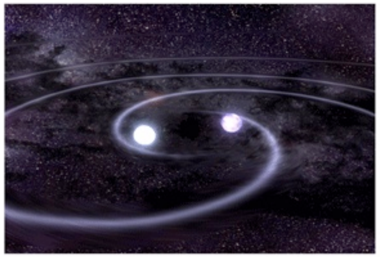
$$r = \lambda = 9.4 \times 10^{8}\,\mathrm{m}$$

$$h \sim 6 \times 10^{-47}$$

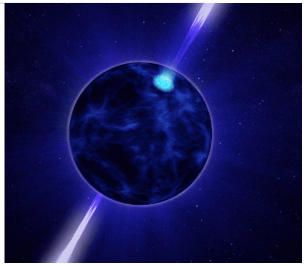
GW Sources

Characteristics of GW sources → f, h

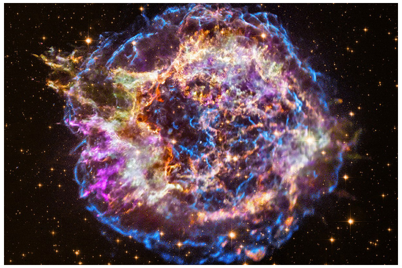
•**Binaries**
have a large and varying quadrupole moment



•**Continuous sources**
A spinning source can emit gravitational waves at a single frequency for a long time. → Neutron stars

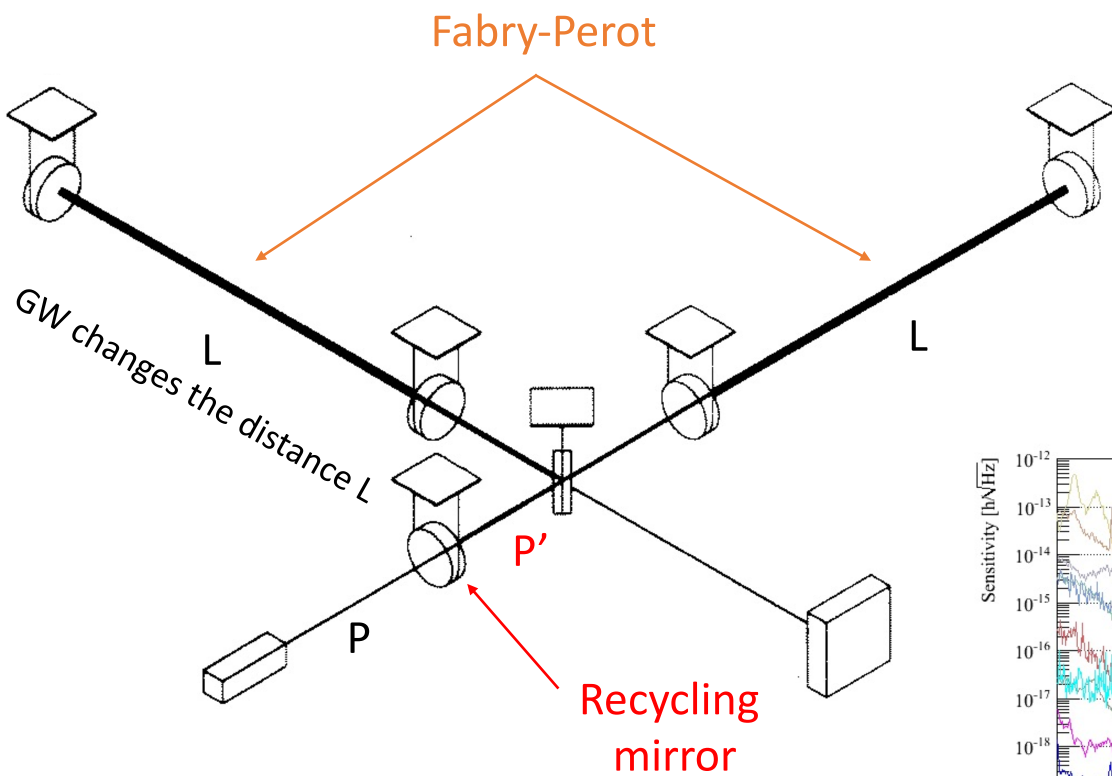


•**Bursts**
Events of very limited duration without any special periodicity.
An example → core-collapse supernova.

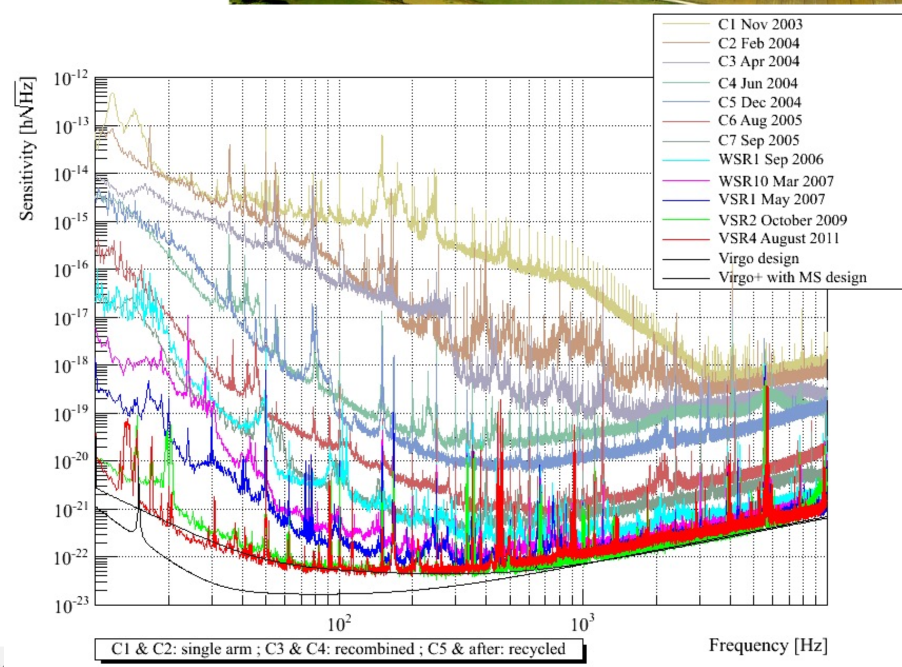


•**Stochastic sources**
Broad bands of frequency with many sources. Examples: huge foreground of double white dwarf binaries in our Galaxy, or possibly a background from the very early universe.

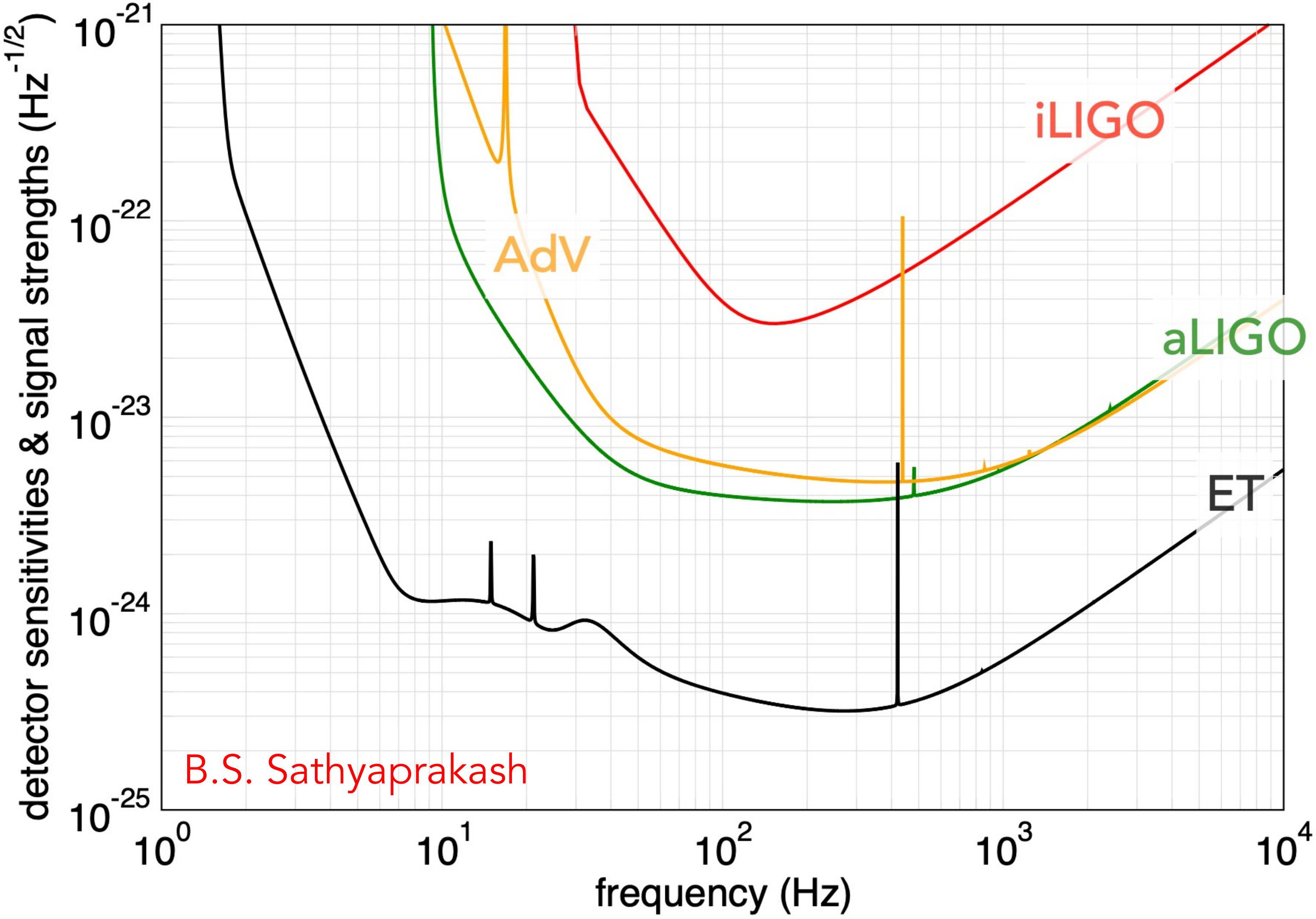
Ground-based LASER interferometry



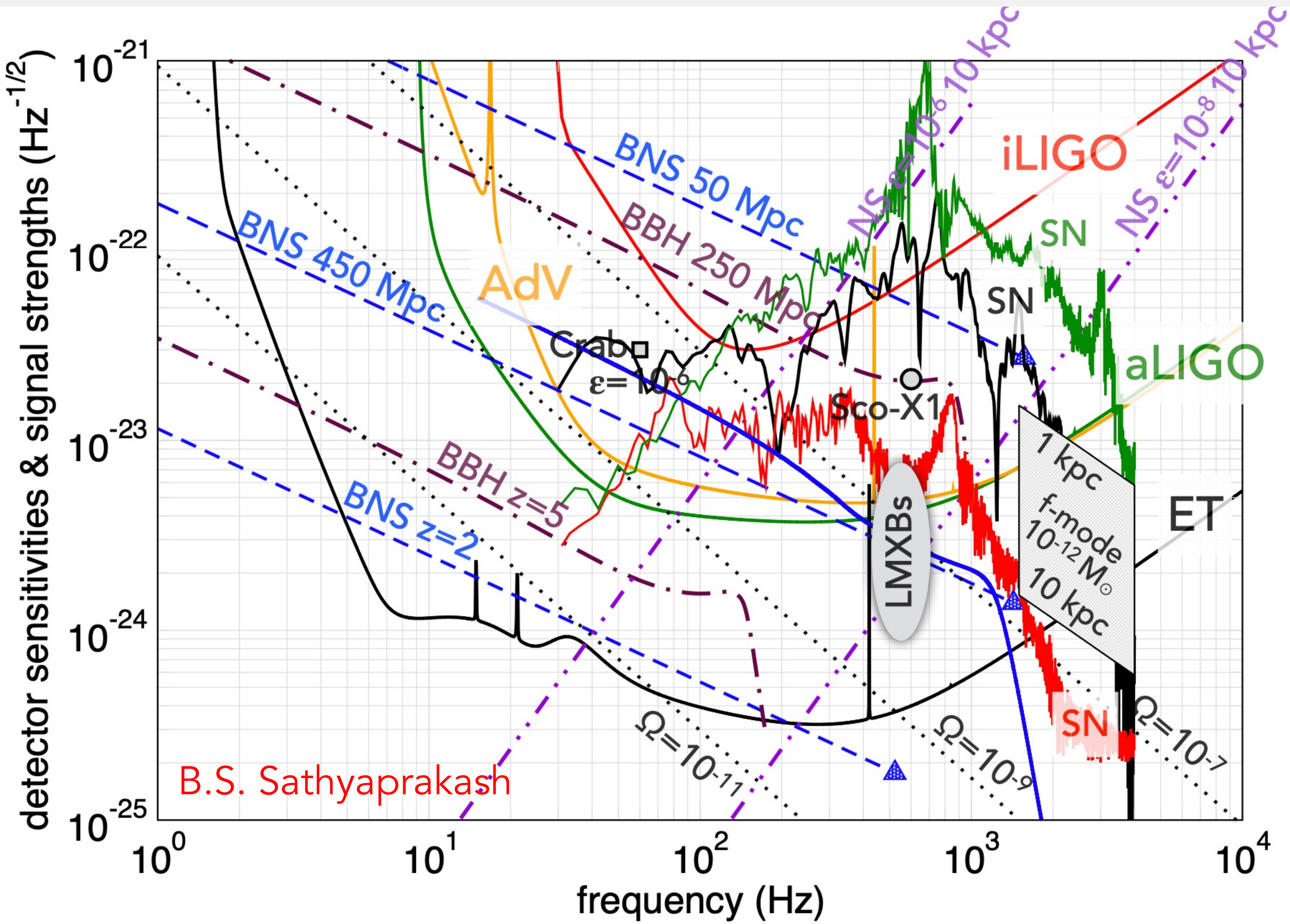
Raffaele Flaminio



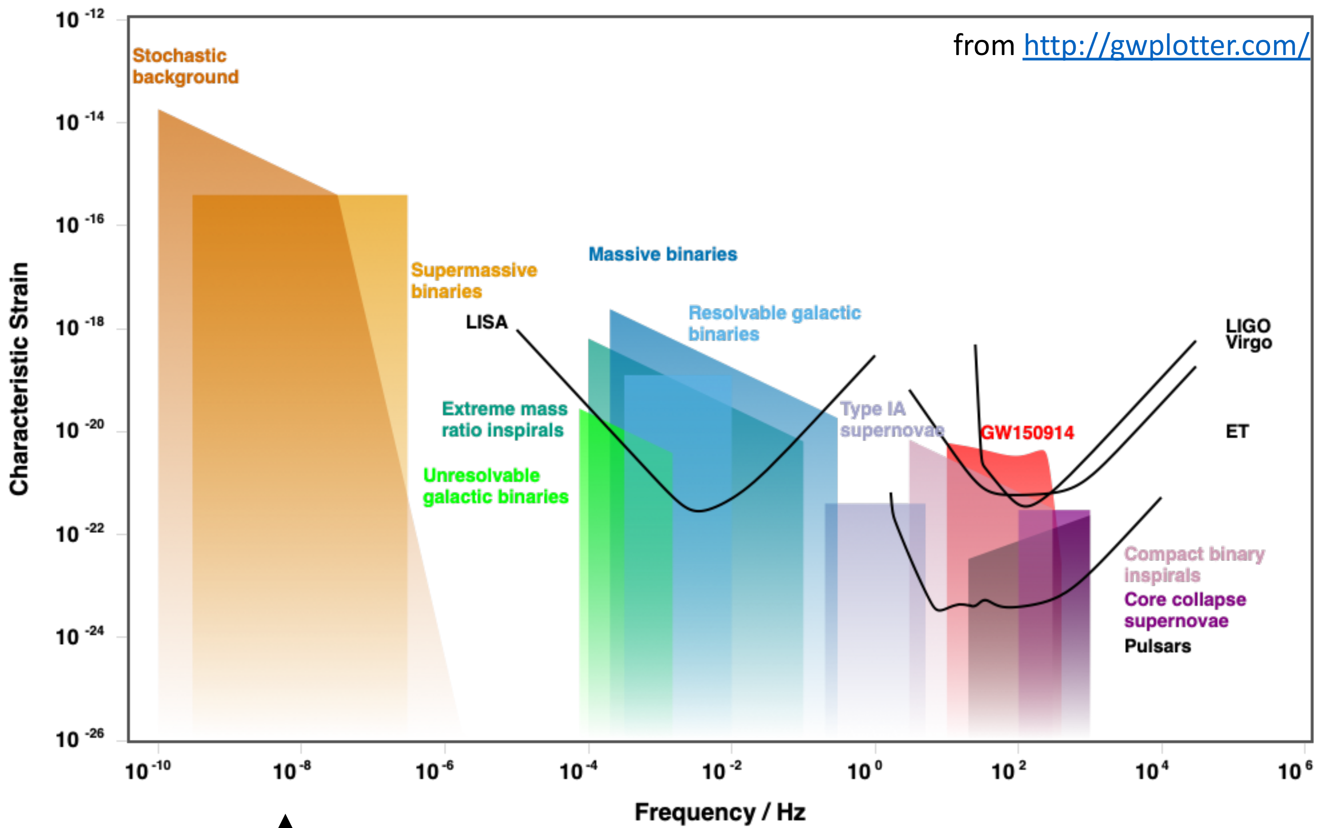
LASER interferometers sensitivity



Detector sensitivity and GW sources



GW sources and antenna sensitivity



Periodicity of GW 3 yrs

GW detection

$$h \sim 10^{-21}$$
$$\Delta x \sim 3 \times 10^{-18}\mathrm{m}$$

Power variation: 2 10^{-8} W

Fight against

1. Readout noises
2. Displacement noises

20 years of improvement

Reiner Weiss 1967

kip Thorne 1975

Interferometers. →

1960 →

Barry Barish

LIGO

1994

GW detection

2015

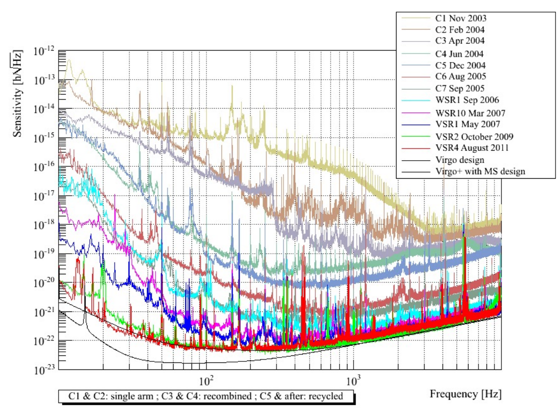
2021

1974-1979

Pulsar
Binary pulsar
Evidence of
Existence of GW

1995

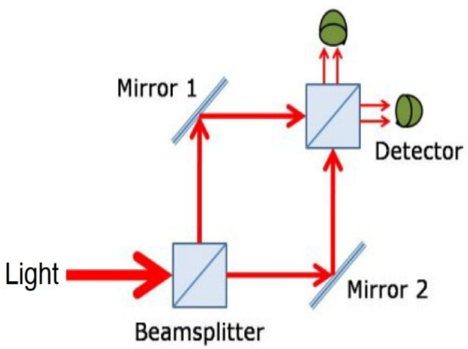
VIRGO construction

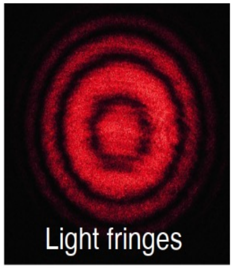


New ideas for GW detection

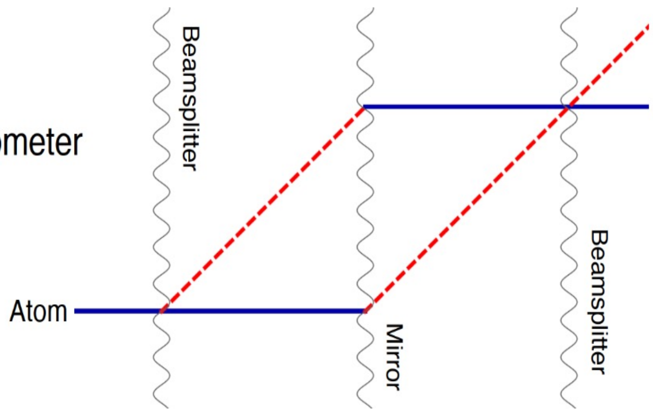
New concepts and R&D: GW detection with Atomic interferometry

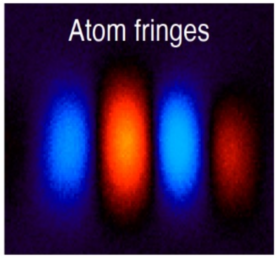
Light interferometer



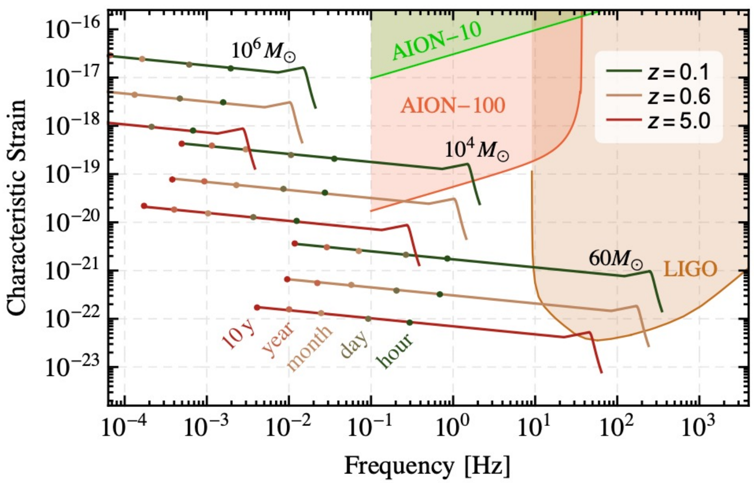


Atom interferometer

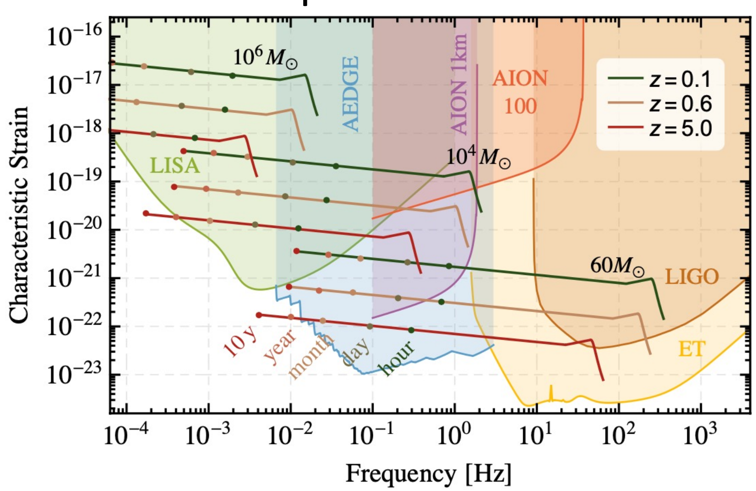




AION



AEDGE=Space version of AION



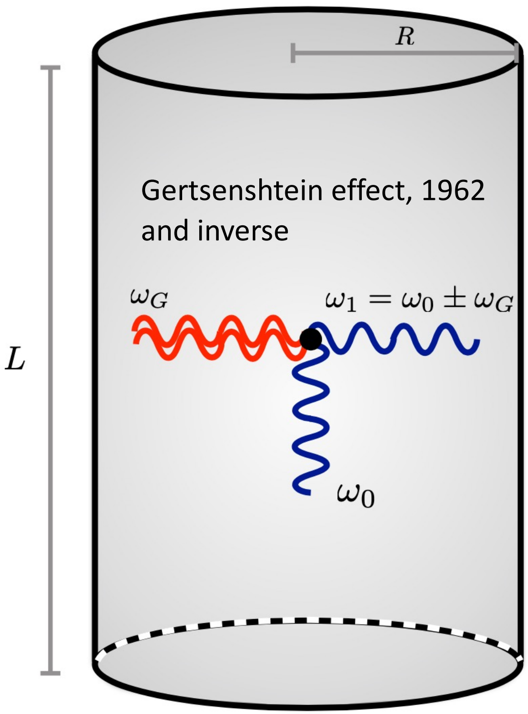
Oliver Buchmueller
J. E. Ellis

AION, AEDGE projects

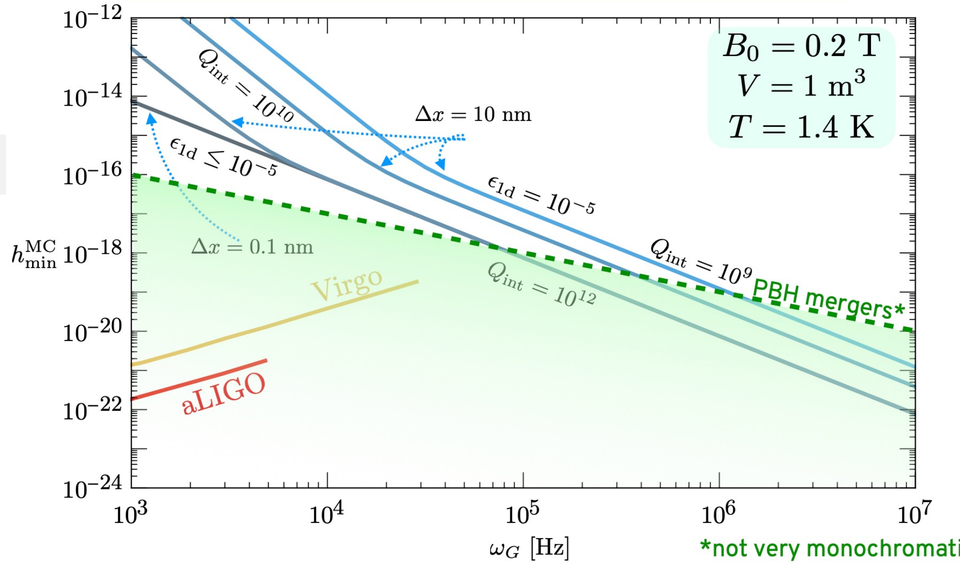
size 100 m 4.4 10^7 m

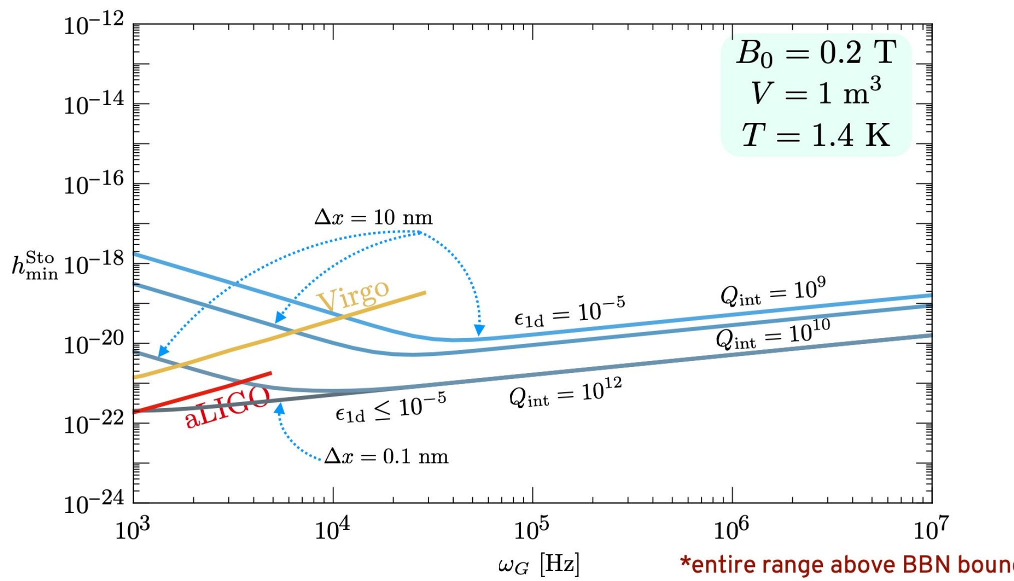
Detection in an SRF Cavity

Sebastian A. R. Ellis



Cylinder for illustrative purposes only!





pioneered in the 1970s by
Vladimir Braginskii & Mikhail Menskii,
Francesco Pegoraro, Emilio Picasso & Luigi Radicati

Storage rings and GW

Observables

- Storage ring circumference changes
- Revolution time around the storage ring changes
- Enhanced beam oscillation by GW

Topics

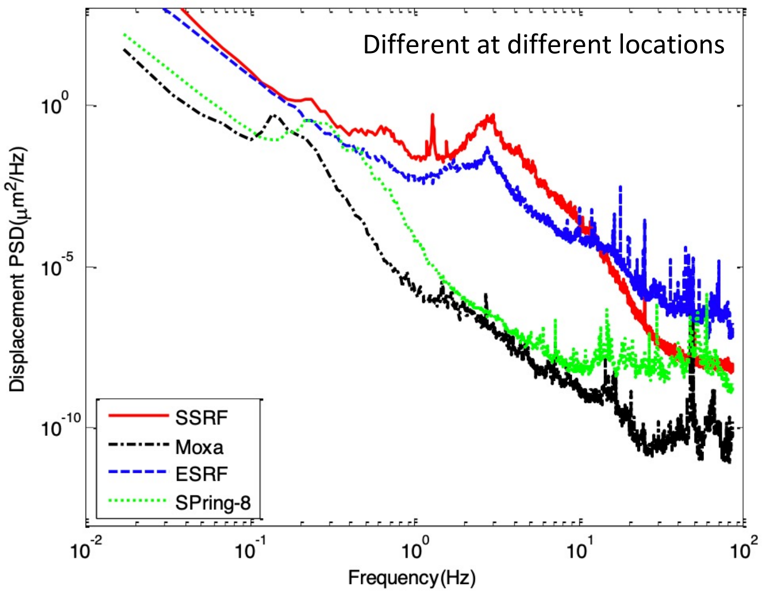
- Level of vibrations in storage rings, and beam response to vibrations, earthquakes, tides
- Can a GW be a driving term for a ring **resonance**?
- Disturbances

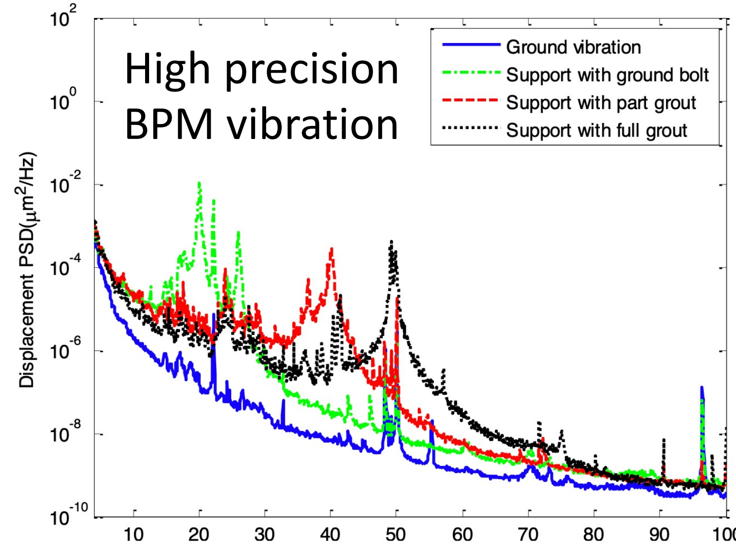
Vibrations in storage rings

Rongbing Deng

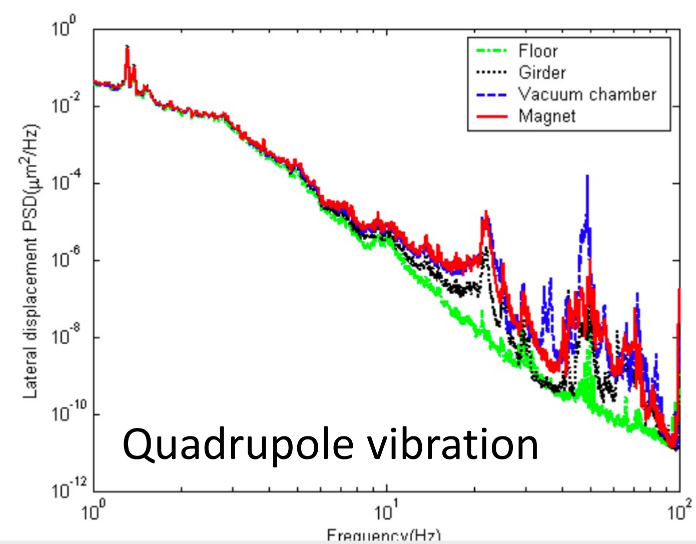
Shanghai Synchrotron Radiation Facility (SSRF, CHINA)

Ground vibrations





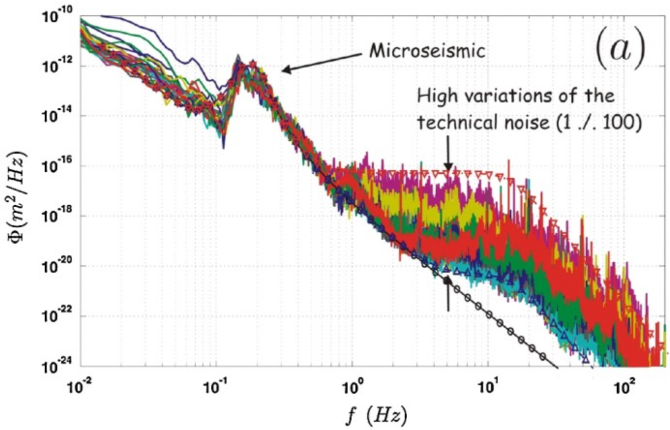
PSD in lateral direction



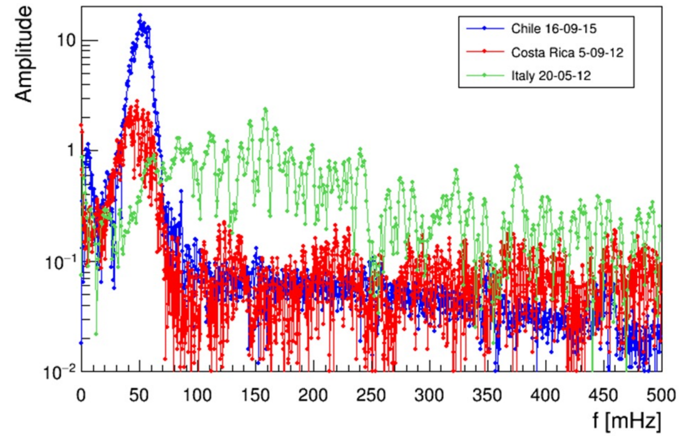
Vibrations and noise in the LHC

J. Wenninger

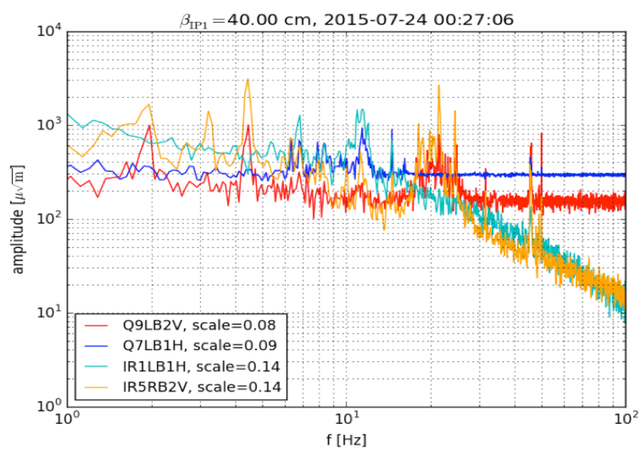
Noise on the tunnel



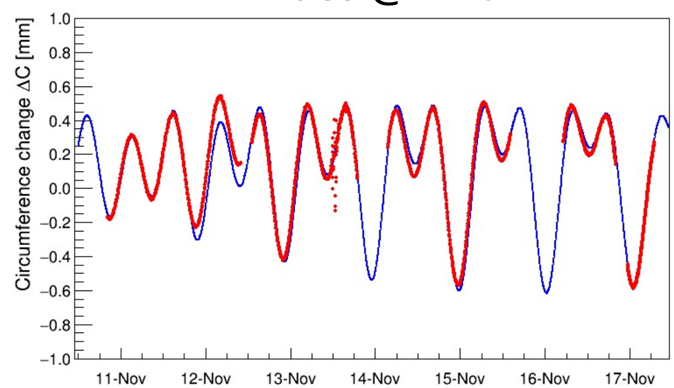
Earthquakes observation at LHC



Beam oscillations



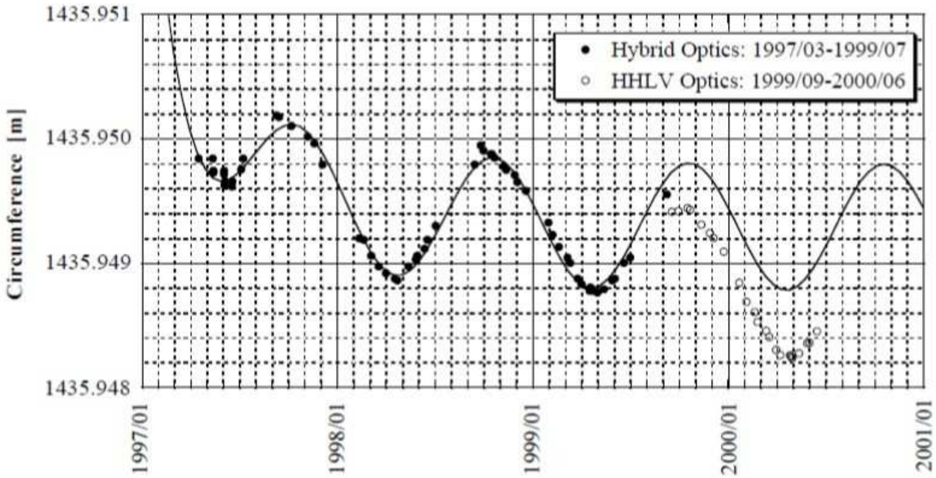
Tides @ LHC



frequency range ≈ 0.1-1 Hz provides the
highest sensitivity at the level of ≈10^{-12} for relative circumference changes.

Maybe already detected in SPring-8

Spring-8 seasonal variations of machine Circumference and damping



Gravitational strain on Earth

$$\frac{\Delta C}{\Delta t} = \left(\frac{\Delta C}{\Delta t}\right)_{\text{tid.}} + \left(\frac{\Delta C}{\Delta t}\right)_{\text{seas.}} + \left(\frac{\Delta C}{\Delta t}\right)_{\text{gw}}$$

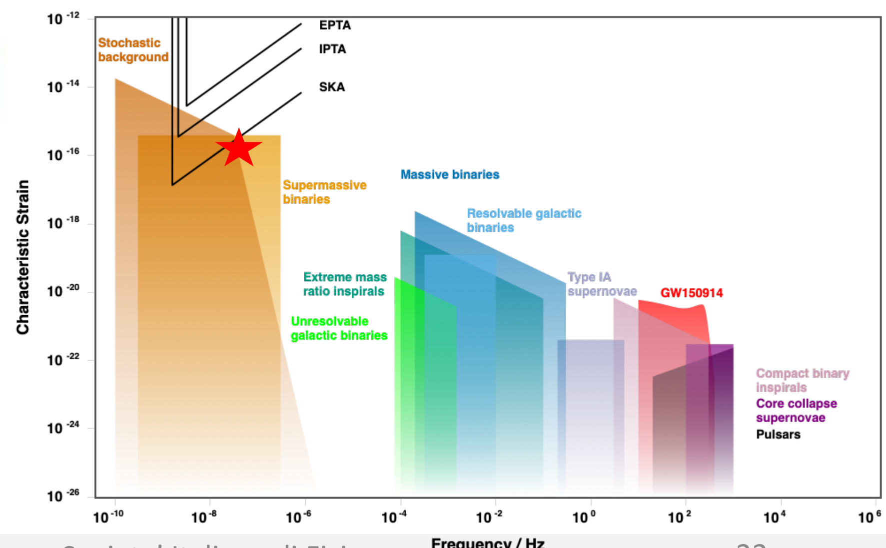
Andrey Ivanov

relic gravitational-wave background

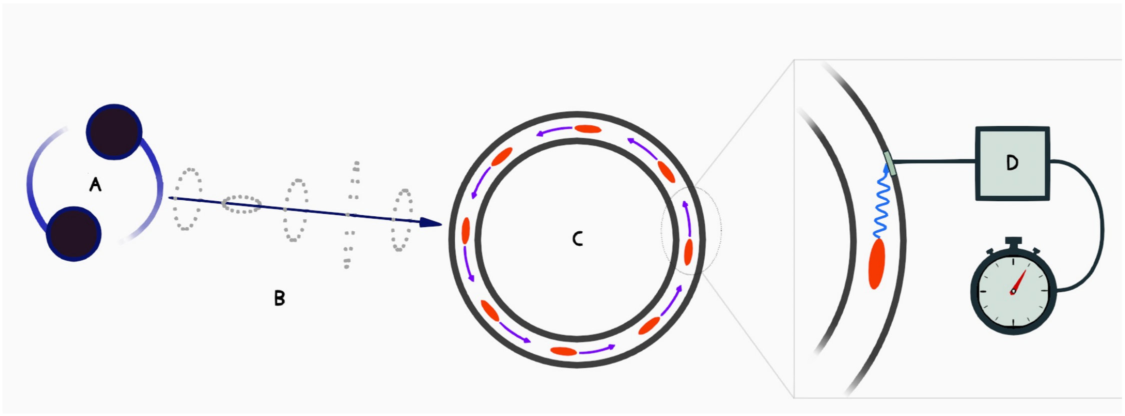
$$f \sim 10^{-7}\,\text{Hz} \quad h \sim 10^{-16}$$

$$\frac{\Delta C_{\text{gw}}(t)}{\Delta t} = -2 \times 10^{-4}\,\text{m/yr}$$

consistent with Spring-8 data



Travel time on LHC



$$\Delta T_{GW} = \frac{1}{2}\left(1 - \frac{v_0^2}{2c^2}\right)\int_0^T h_+(t).F_+(t)dt$$

$$F_+ = \sin^2\theta\cos 2\psi$$

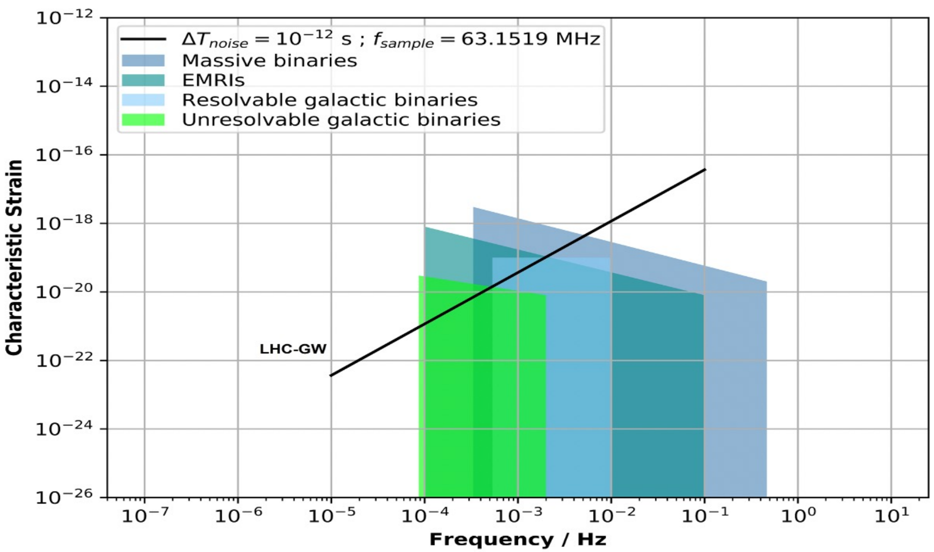
$$\Delta T_{\rm GW} \sim a\frac{h_0}{f_{\rm GW}},$$

Change in travel time due to change in test mass velocities, not orbit distortion!

Travel time orbit distortion → h^2

Travel time velocity change → h

Suvrat Rao



Travel time → noise budget

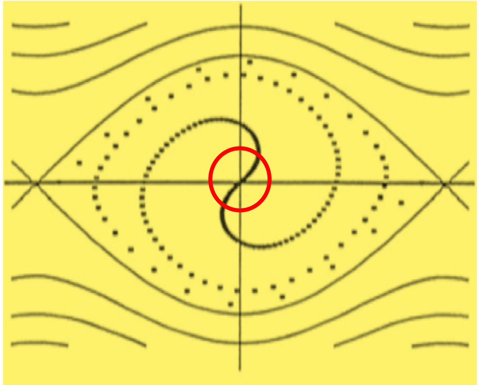
Order of magnitude over the observation period of 24 hours:-

1. Quantum noise (quantum uncertainty in time-tagging proton bunches): **$\Delta T_{quantum}$~10^{-20} s.**
2. Gravity gradient noise (due to Sun, Moon, Alps mountains etc.): **ΔT_{GG}~10^{-16} s**
3. Seismic noise (due to orbit distortion): **$\Delta T_{seismic}$~10^{-17} s.**
4. Radiofrequency phase noise (due to rf system): **ΔT_{rf}~10^{-12} s.**
5. Detector noise (due to detector timing jitter): **$\Delta T_{detector}$~10^{-12} s.**
6. Photon shot noise(due to photon statistics): **ΔT_{photon}~10^{-17} s.**

Suvrat Rao

Oscillations on the longitudinal plane

R. Tito d'Agnolo



$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

$$f(\omega_g, t) \simeq h \times L \times \cos(\omega_g t + \phi)$$

On the resonance

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

From phase measurement in an RF cavity the experimental → $\Delta T/T = 10^{-7}$

$$\omega_l \sim 10 \;\; H_z \qquad \tau_l = 1 \;\; hour$$

$h > 10^{-11}$

Slower proton →
3 orders of magnitude better

Exploiting transverse ring resonances

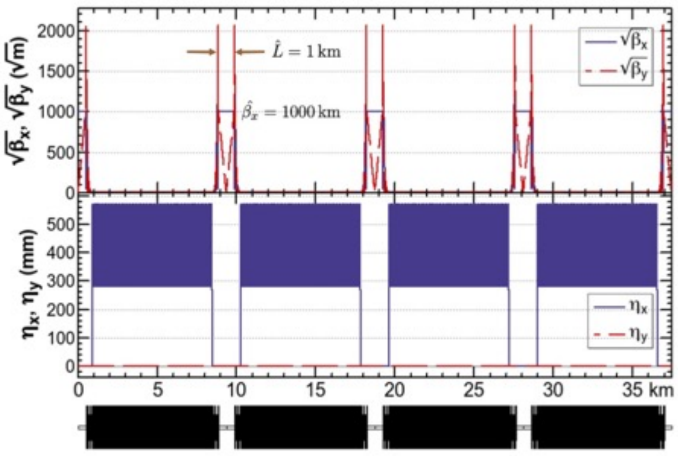
K. Oide

$$\frac{\mathrm{d}^2 X_\mu}{\mathrm{d}t^2} = \frac{1}{2}\ddot{h}_{\mu\nu} X^\nu \ ,$$

$$\frac{\mathrm{d}p_x}{\mathrm{d}s} = -\frac{k^2}{2} h R \cos 2\theta \cos(\omega_{\mathrm{GR}} t)$$

$$x(s) = \int_0^s ds' R_{12}(s,s') \frac{\mathrm{d}p_x}{\mathrm{d}s}(s')$$
$$= \int_0^s ds' \sqrt{\beta_x(s)\beta_x(s')} \sin\left(\psi_x(s) - \psi_x(s')\right) \frac{\mathrm{d}p_x}{\mathrm{d}s}(s') \, ,$$

Amplification of the resonance via a design that makes sector with large beta functions



Parameters		
Particles		p
Beam energy	TeV	1.0
Circumference	km	37.4
Length of an IR, $\hat{L}$	km	1.0
Number if IRs		4
β_x at the IR, $\hat{\beta}_x$	km	1000
β_x ave. in the arc	m	50
Betatron tunes, ν_x/ν_y		130.8/131.3
SR damping time in x	s	73600
SR equiv. emittance	fm	0.198

Accumulation per turn

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

$$\omega_{GR} \sim 1\,\mathrm{MHz}$$
$$h \sim 10^{-22}$$
$$\Delta x \sim 10^{-13}\, m$$

Sensitivity / Noise sources

Estimate sensitivity scaling $fh \sim 10^{-14} \times (\mathrm{BPM\,resol.\,in\,nm})$

* Noise due to the thermal vibration of quadrupoles

$$x_Q \sim 6\,\mathrm{pm}$$
$$x_n \sim 3 \times 10^4 \Delta x_Q = 0.17\,\mu\mathrm{m}$$

Center of mass fluctuation due to finite number of particle

$$\Delta \hat{x}_s = \sqrt{\frac{\hat{\beta}_x \epsilon_x}{N_p}} = 0.19,\ \mu m$$

K. Oide

after the damping time in LHC → emittance ~ 0.2 fm → Δx_s = 40 pm

* Beam fluctuation due to synchrotron radiation, acceleration

Summary of topics discussed

(1) gravitational wave (GW) detection by resonant betatron oscillations, for the 10 kHz range;

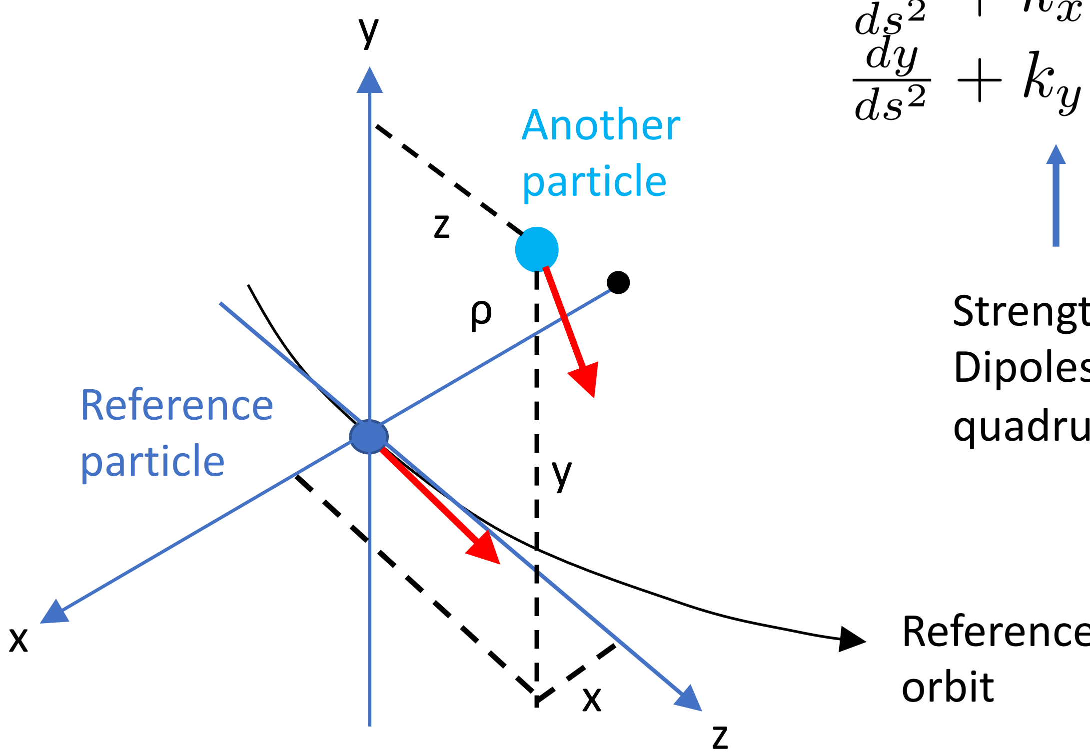
(2) GW detection through the change in revolution period, but using a ``low-energy'' coasting ion beam without a longitudinally focusing radiofrequency system – Can the sensitivity be down to 0.01 mHz?

(3) Heterodyne detection using superconducting radiofrequency cavities, with a sensitivity possibly up to 10 MHz.

(4) GW generated by the beam, and the orbital frequency ~10 kHz for LHC, at the LHC and FCC-hh bunch frequency of 40 MHz, or, with a Gertsenshtein signal in the 10 THz range – combined with a high-frequency detector concept. By **Pisin Chen (NTU Taiwan)**

(5) Possibility of using an LHC access shaft to house a 100 m atom interferometer targeting the 1 to 0.01 Hz range.

Dynamics in accelerator physics



$$\begin{aligned} \frac{dx}{ds^2} + k_x(s)x(s) &= F_x(x,y) \\ \frac{dy}{ds^2} + k_y(s)x(s) &= F_y(x,y) \end{aligned}$$

Strength from
Dipoles and
quadrupoles

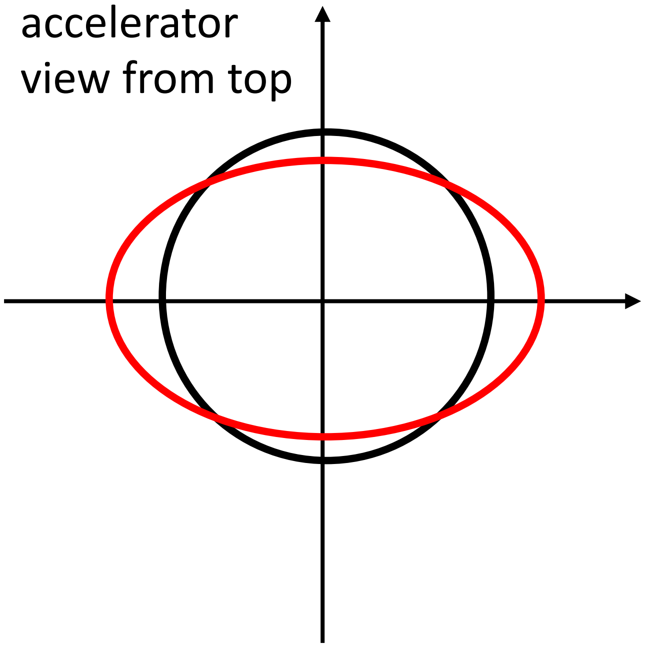
Nonlinear fields,
Collective effects
Space charge
IBS

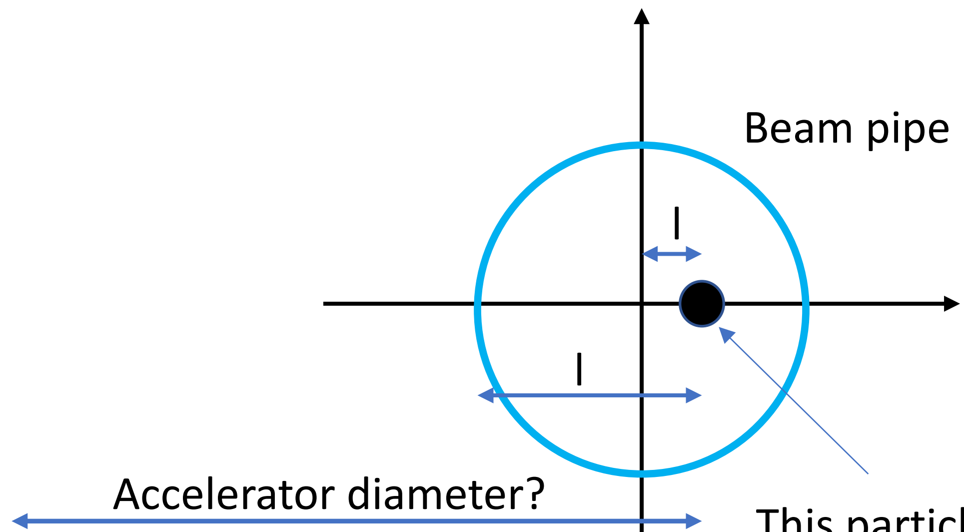
Confusions

$$\frac{\Delta l}{l} \simeq h$$

What is it the effect of GW on a beam particle?

accelerator
view from top



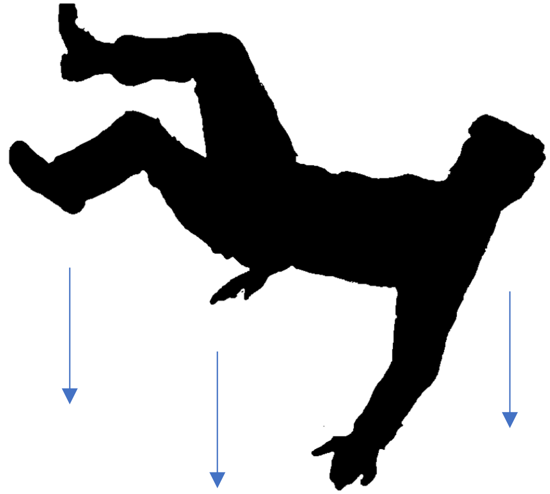


This particle
is shifted by GW
as Δl/l, but from
where?

Subtleties

General Relativity community

$$\ddot{x}^{\mu} + \Gamma^{\mu}_{\lambda\nu}\dot{x}^{\lambda}\dot{x}^{\nu} = \frac{q}{m}F^{\mu}{}_{\nu}\dot{x}^{\nu}$$



Accelerator community

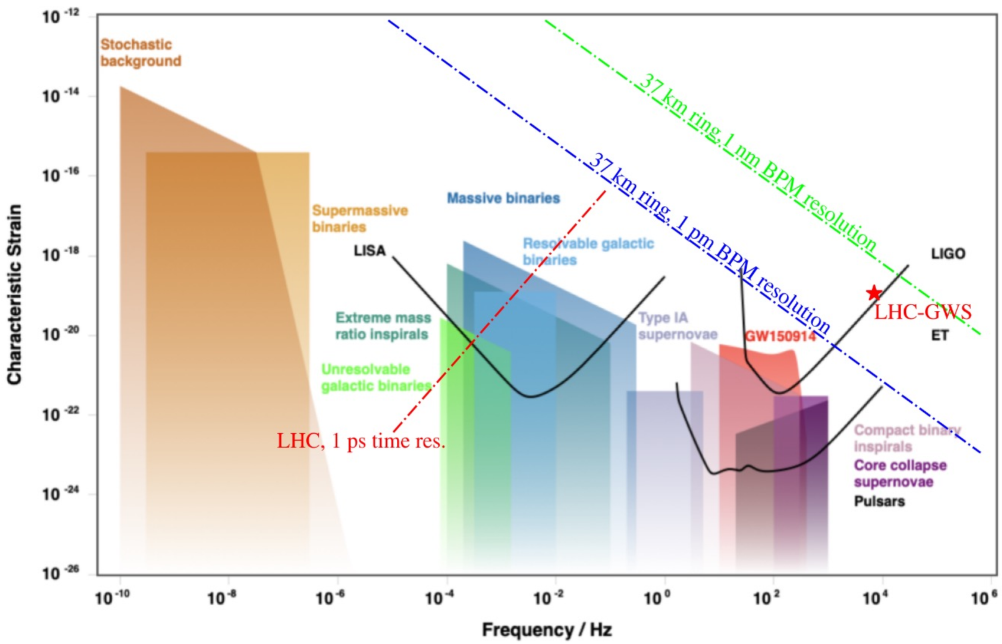
$$\begin{aligned} \frac{dx}{ds^2} + k_x(s)x(s) &= F_x(x,y) \\ \frac{dy}{ds^2} + k_y(s)y(s) &= F_y(x,y) \end{aligned}$$

Force

Force by GW on a beam particle?

Summary/Outlook

- Detection of gravitational waves has a strong interest for testing GR and understanding cosmo
- New approaches: atomic interferometry. Existing ideas are revived → SRF cavity
- Noise influence on the beam is presently large with respect to amplitudes to be measured
- Proposed methods: use detection of
  1. Travel time
  2. Frequency shifts
  3. GW resonate with beam oscillation
- Sensitivity of the methods discussed
- There are still difficulties to formulate the particle accelerator beam dynamics under the influence of GW



- Renaissance of exploring the use of storage rings for detecting GW

Renaissance: exploring storage rings for detecting GW

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Laboratory experiments to test relativistic gravity*

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

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March 25, 1998

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

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Storage rings as detectors for relic gravitational–wave background ?

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August 27, 2018

ON GRAVITATIONAL RADIATION EMITTED BY CIRCULATING PARTICLES IN HIGH ENERGY ACCELERATORS

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(T/E/A)

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

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NIKHEF/99-019

Cyclotron motion in a gravitational-wave background

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Detection of gravitational waves in circular particle accelerators

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(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.

Thank you for the attention