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FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
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CONCEPT STUDY OF A STORAGE RING GRAVITATIONAL WAVE OBSERVATORY FOR EARTH-BASED DETECTION AND TERRESTRIAL GRAVITY NOISE MITIGATION

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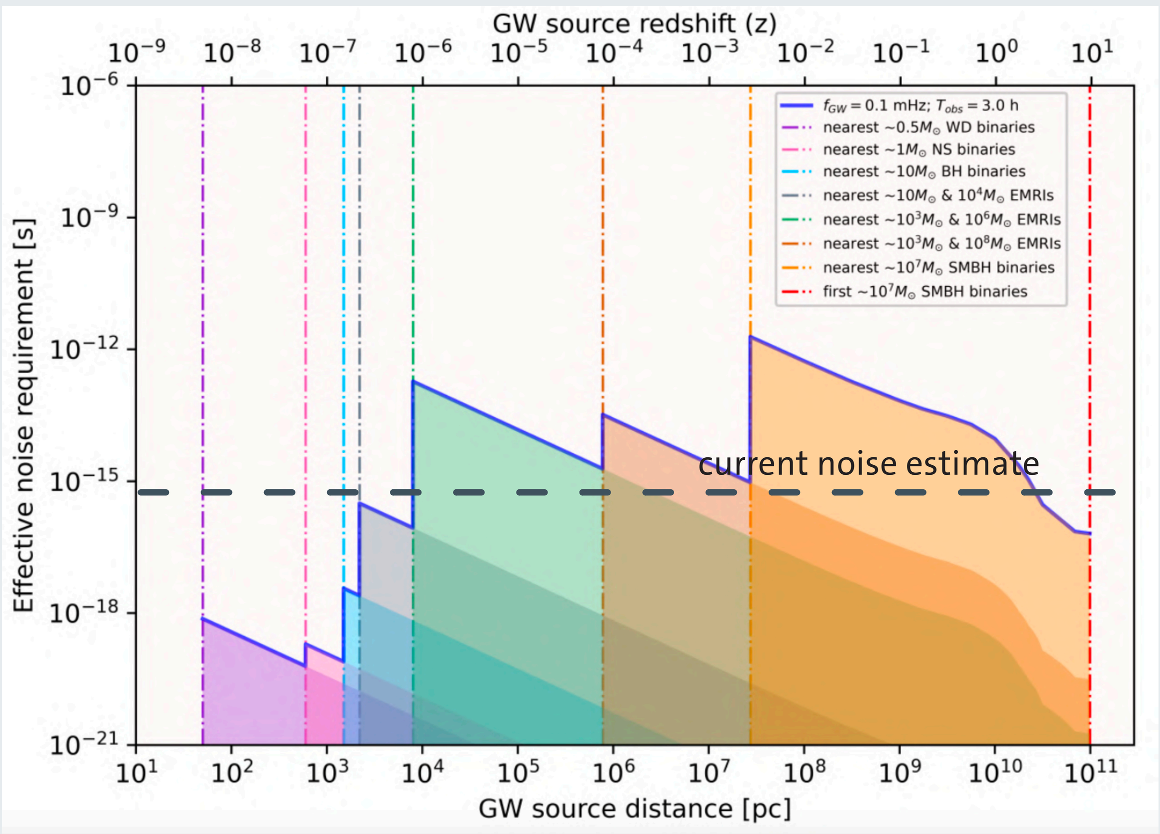
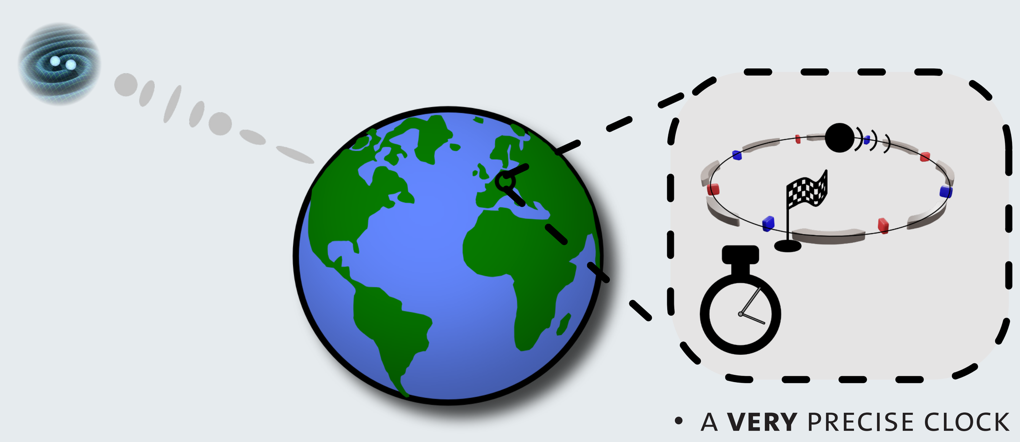
SCIENCE CASE-MILLIHERTZ GW



Temporal resolution required to measure astrophysical sources with signal-to-noise ratio of unity with a storage ring GW observatory [1].

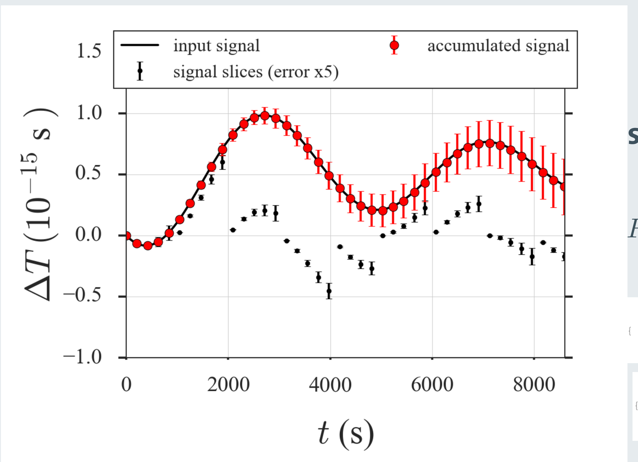
TIME-OF-FLIGHT OF HEAVY IONS



Experiment idea: Gravitational wave strain encoded in circulation time of heavy ions in a storage ring [2,3].

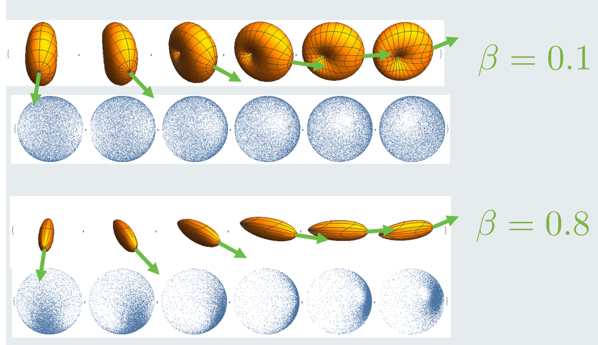
- **variation of circulation time** encodes GW signature
- need: particle on fixed circular trajectory in **longitudinal free fall**
- best candidate: particles in storage ring
- can circulate for minutes up to hours: **mHz GW**
- instead of bunches: **ion chains**
- heavier ions → less recoil from synchrotron radiation

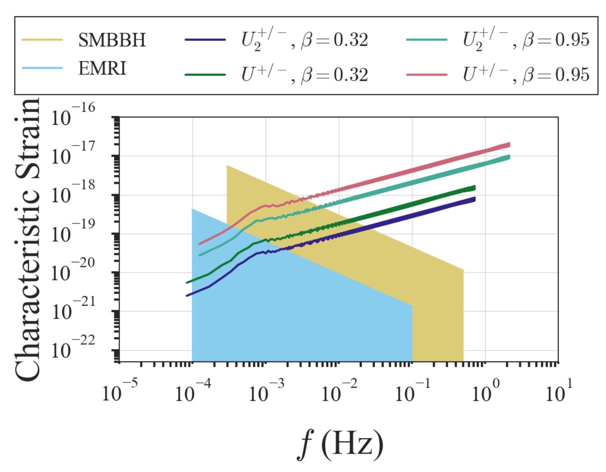
SYNCHROTRON RADIATION



sampling of synchrotron photons

$$F(\theta,\phi) = \frac{(1-\beta\cos\theta)^2 - (1-\beta^2)\sin^2\theta\cos^2\theta}{(1-\beta\cos\theta)^5}$$

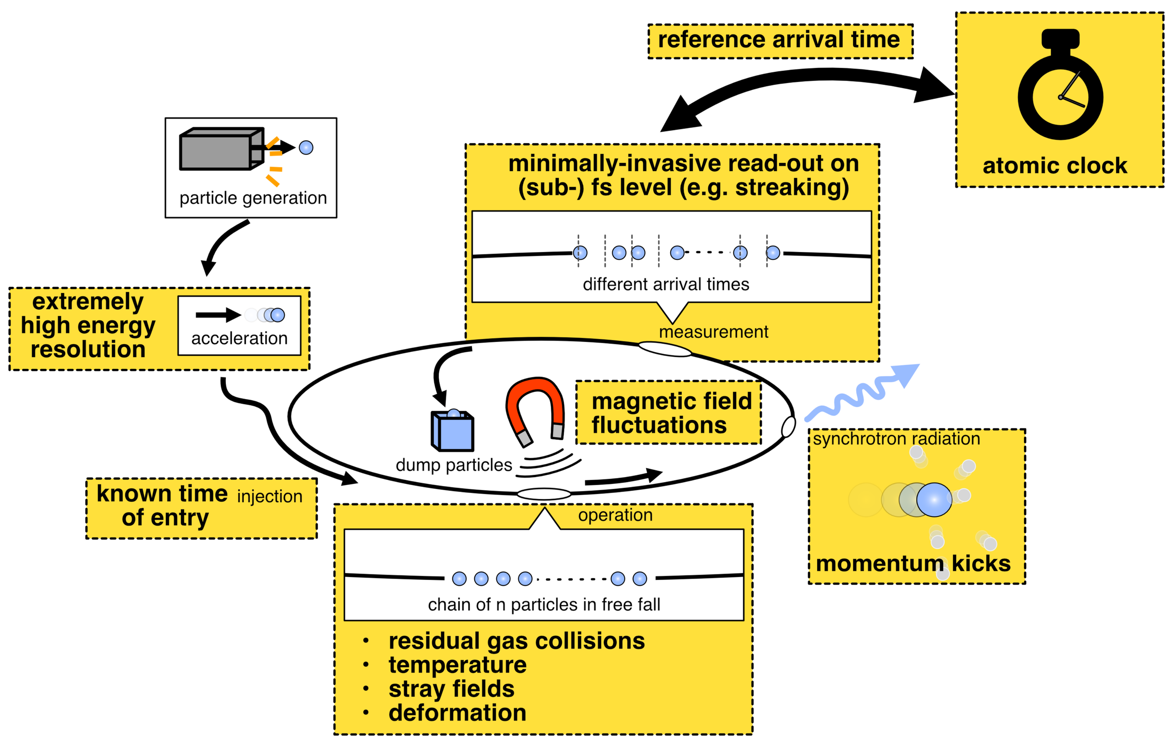




1) $\{\theta_i, \phi_i\} \in [0,\pi] \times [0, 2\pi]$
2) stratification
3) $f_i \in [0, F(0,0)]$ ("rejection sampling")

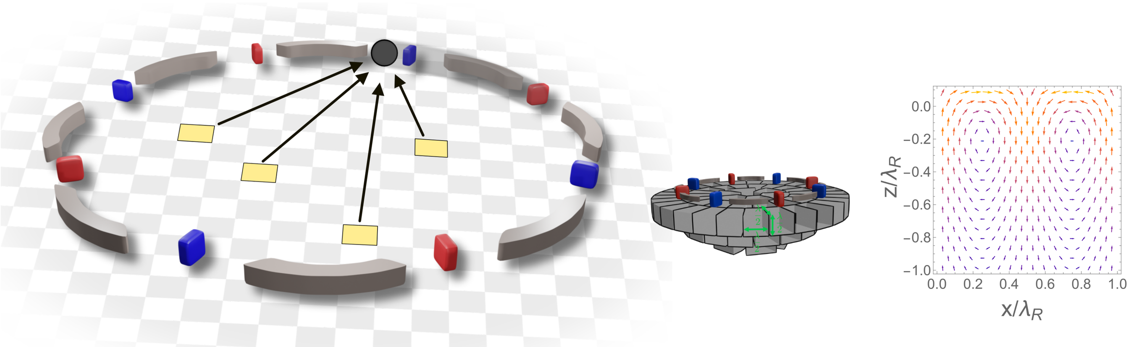
left top) accumulated time delay of GW signal + photon emission of $(2U^{238})^+$. bottom) Comparison of GW strain and photon shot noise strain for LHC with different particle velocities of 100 ion chain. right) 3D photon scatter distribution for different particle velocities [4].

EXPERIMENT DESIGN

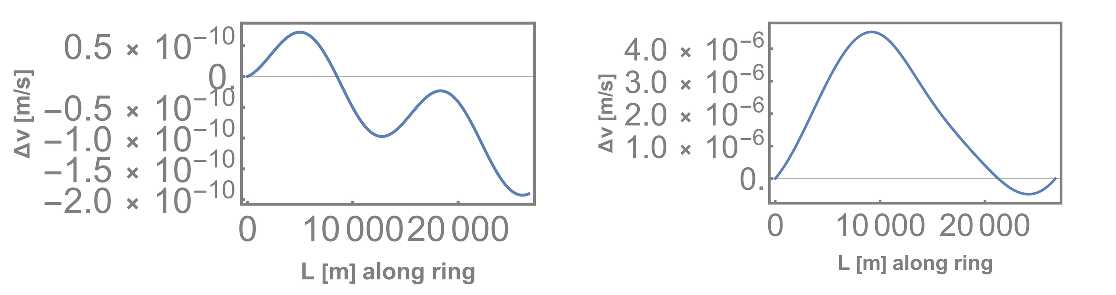


Experimental setup from particle generation to read-out with different noise sources for the time-of-flight experiment of a chain of singly-charged heavy ions in a storage ring.

TERRESTRIAL GRAVITY NOISE IN STORAGE RING OBSERVATORIES

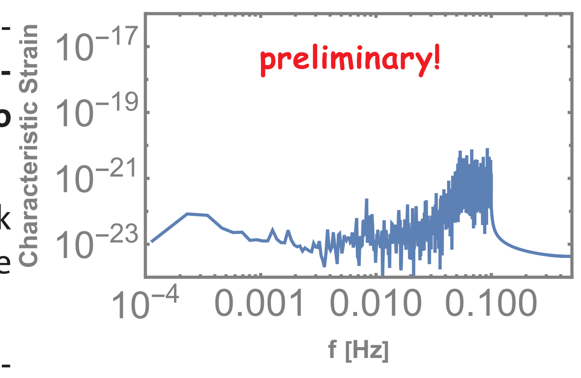


left) finite elements of the ground excert force on the particle in the ring. center) 3D Model of the division used in the calculation of Rayleigh wave terrestrial gravity noise. right) Rayleigh wave displacement direction as a function of depth.



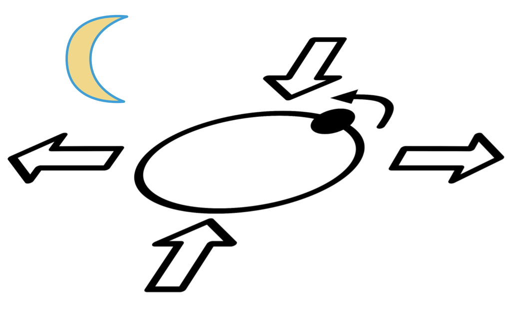
left) velocity change relative to nominal velocity due to a GW signal along the ring. right) velocity change due to Rayleigh wave field scaled with Peterson PSD.

- Terrestrial gravity noise from conservative forces (**Rayleigh Waves!**) is suppressed, because **no work is applied on the particles.**
- In comparison, **GWs** apply work and **consecutively slow down** the circulating particles each round.
- despite orders of magnitude larger force from **Rayleigh waves**, the **noise PSD is very low.**



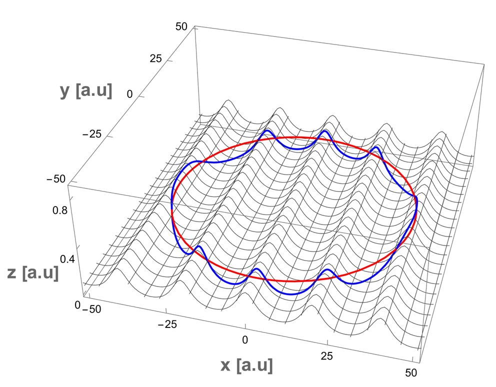
Characteristic noise strain of **Rayleigh wave field** scaled with Peterson PSD.

EFFECT OF SEISMIC NOISE



Tidal deformation of the ring.

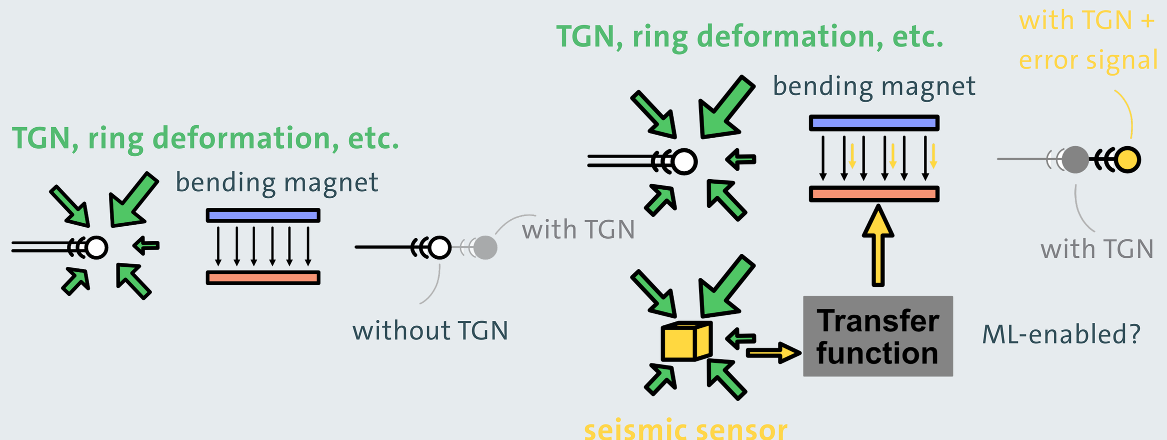
- Tidal deformation of Earth cause displacement of ring magnets, leading to **path length variation**
  → well-predictable
- seismic activity causes deviations from design path of the particle due to displacement of magnets
- *could* be mitigatable by active noise cancellation



variation of height (not to scale) of the storage ring plane with (blue) and without (red) passage of a seismic wave.

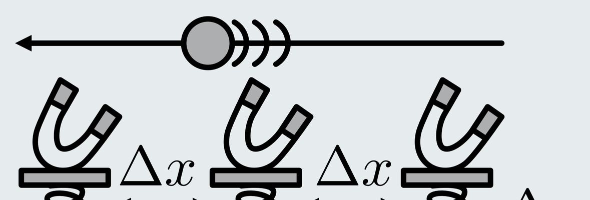
SEISMIC NOISE & TGN MITIGATION

Different sources for terrestrial gravity noise (TGN) and seismic noise in the typical environment of a storage ring. (credit: midjourney)



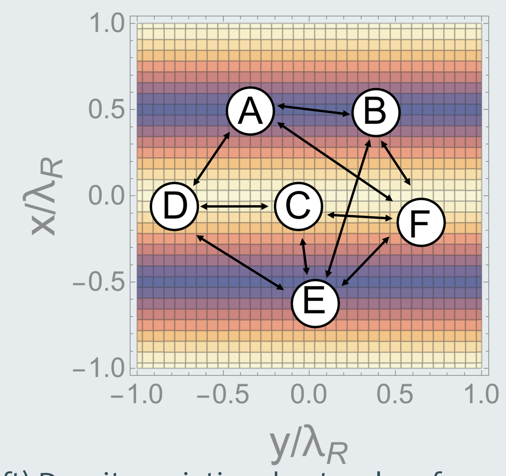
left) Forces from TGN and seismic noise coupled e.g. into the storage ring magnets lead to an error in the detector signal. right) Using seismic data, active noise cancellation could compensate for ring deformation, TGN etc.

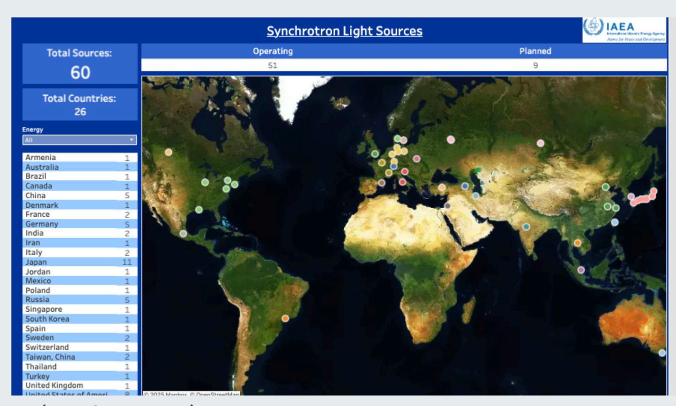
POSSIBLE COLLABORATION WITH ET



Relative displacement of magnets in storage ring due to deformation of the ground is a primary noise source, requiring seismic isolation..

- detector network.
- technology transfer (e.g. seismic noise isolation)
- multi-band observations
- seismic signal & TGN measurements





(credit: IAEA)

left) Density variation due to a low-frequency Rayleigh wave, which passes through a detector network. The detectors each measure a different signal, but due to the same noise source and hence could collaborate to better determine low-frequency seismic perturbations. right) Circular accelerators located around the world.

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[4] T. Schmirander, S. Rao, V. Miltchev, M. Brüggen, F. Grüner, W. Hillert and J. Liske, Phys. Rev. D 110, 082002 (2024)

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