Ideas from quantum optics based on coherence and interference have proven extremely successful for the study and manipulation of atoms and molecules, and this success heavily relies on the availability of suitable light sources. Naturally, upcoming novel coherent x-ray light sources prompt the question whether similar techniques could also be applied beyond atoms and molecules. This on the one hand would promote preparation, control, and detection, e.g., with nuclei, but on the other hand would open the door for coherent and non-classical effects in x-ray science.

Motivated by this, I will first discuss possibilities to directly drive nuclear transitions with free electron lasers [1]. Particularly interesting model systems are nuclear isomers which are long-lived excited nuclear states. Isomers have been suggested for fascinating applications such as nuclear batteries, but also play an important role in the formation of the universe [2].

I will then discuss prospects to advance to even shorter time scales and higher photon energies, which is of interest for high-precision spectroscopy and structural studies at the nuclear scale. First, I will show that high-energetic photon pulses down to the yoctosecond timescale can be produced in heavy ion collisions [3]. In particular, I will discuss the light emission from the initial phase of an expanding quark-gluon plasma (QGP), and show how the time evolution and properties of the plasma may influence the duration and shape of the photon pulse.

Finally, I will discuss methods to characterize and detect high-energy $\gamma$-ray pulses above the MeV energy and below the attosecond time scale, with a technique inspired by atto-second streaking, but building up on electron-positron pair creation from the vacuum [4]. This technique could be the first viable application for pair creation, exploiting it as a measurement tool.

FIG. 1: (a) Possible setup for the direct driving of nuclei with x-ray free electron laser sources. A suitable acceleration of the nuclei would help to bring higher transition frequencies in resonance with the laser. (b) Schematic setup for the generation of yoctosecond pulses in a heavy-ion collision. After the collision of the two nuclei, a quark-gluon plasma is formed, which emits a short burst of light. (c) Setup for the characterization of high-energy $\gamma$-ray pulses above the MeV energy and below the attosecond time scale based on electron-positron pair creation.