Acceleration Radiation and Beyond Standard Model Physics with High-Power Lasers and XFELs

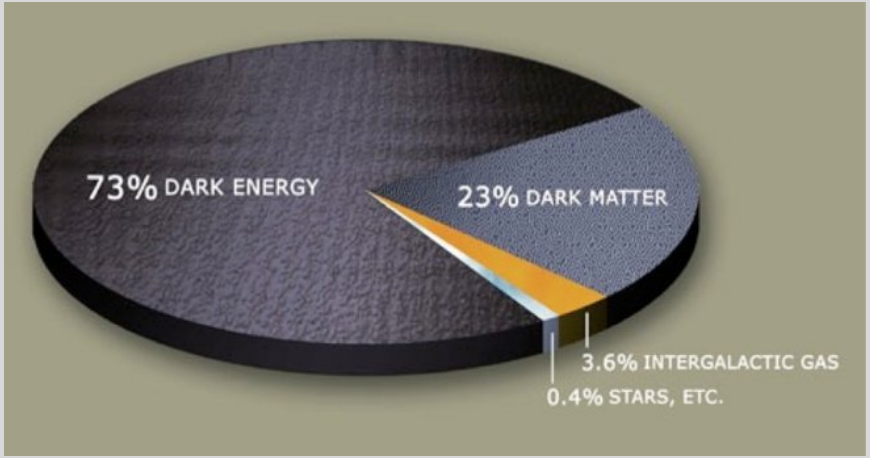
Gianluca Gregori, *University of Oxford*

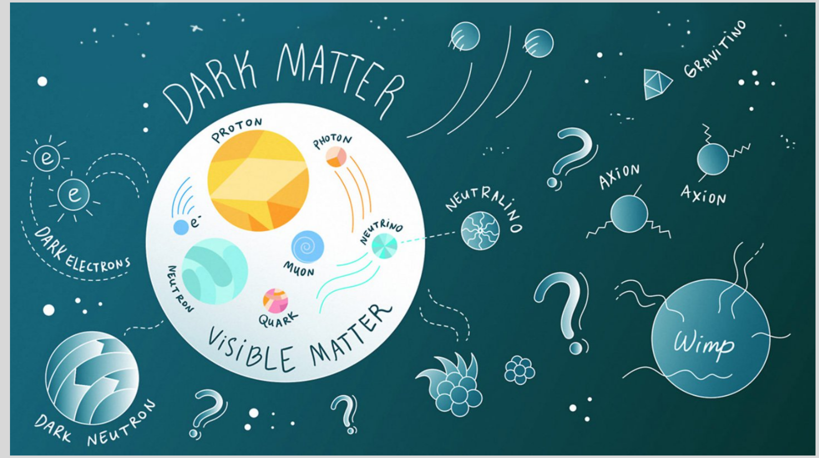
with thanks to:
G Vacalis, S Sarkar, J Halliday (University of Oxford)
R Bingham (Rutherford Appleton Laboratory)
A Higuchi (University of York)
G Marocco (Lawrence Berkeley Laboratory)

Plymouth, 18th Jan 2024

Overview lasers and their applications to fundamental physics

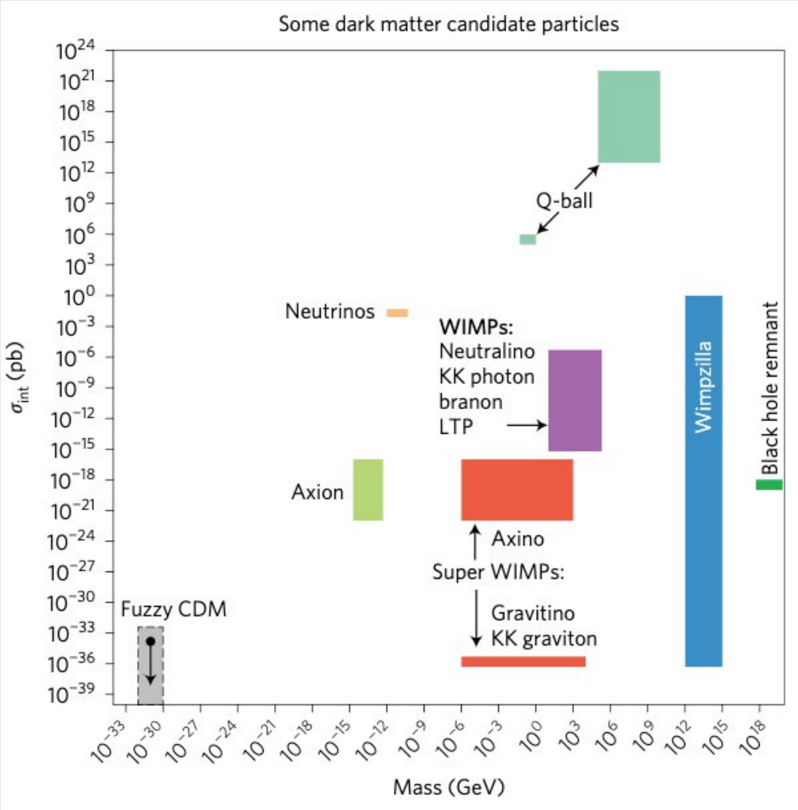
Our understanding of the Universe is limited to only the luminous matter





- The existence of dark matter is inferred from:
  - Rotation curves of galaxies (but evidence is debatable as distance galaxies are dim background light from Milky Way needs to be subtracted)
  - Micro-lensing
- Dark energy is believed to explain the acceleration of the Universe
- *So far there is no direct experimental evidence of neither dark matter or dark energy*
- *Experimental laboratory searches are important*

Many possibilities for dark matter candidates

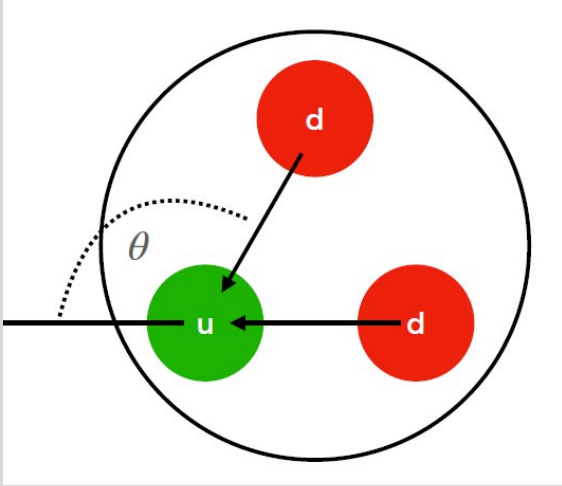


Conrad & Reimer, Nature Phys. 2017

- ➜ Many possibilities spanning an enormous range of energies/masses.
- ➜ Some theories are more developed than others.
- ➜ Searches with particle accelerators have mostly concentrated on the higher mass regions (WIMPs) but no positive detection has been made.
- ➜ Astrophysical observations provide some indirect bounds.

Axions are required to fix the Standard Model

- Axions are pseudo-scalar particles postulated to exist to explain the absence of CP violation by the strong interaction $\mathcal{L}_{QCD} = \ldots + \theta_{QCD}\mathbf{G}\tilde{\mathbf{G}}$



> A naive classical calculations shows that the electron EDM is ~10^{-13} (1-cos(θ_{QCD})$^{1/2}$) e.cm, but experiments shows that the neutron EDM is <10^{-26} e.cm.
> This implies an unnaturally small QCD vacuum angles
>
> $$\theta_{QCD} \ll 10^{-10}$$

- Promote θ_{QCD} to dynamical variable which can relax to zero (Peccei & Quinn 1977). The axion is Nambu-Goldstone boson of the high energy breaking of $U(1)_{PQ}$ symmetry.

- String theory compactification leads to (pseudo)scalar particles that do not necessarily couple to the QCD fields. These are axion-like particles (ALPs) are less prescribed by theory.

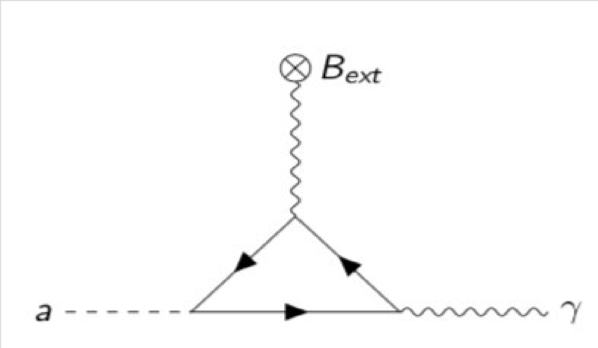
QCD axions and ALPs

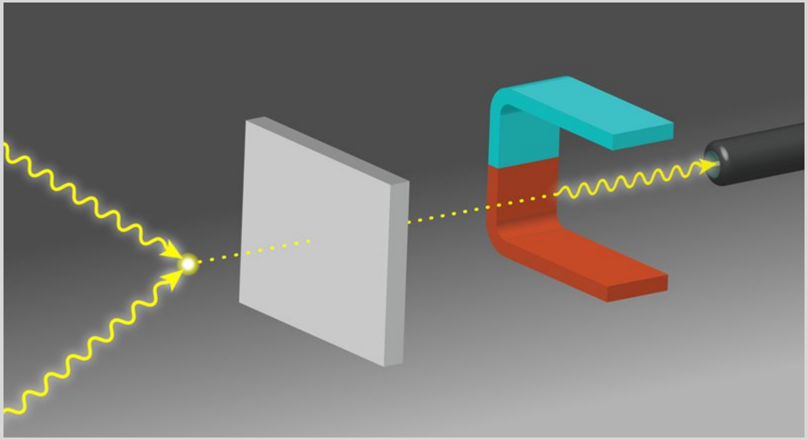
- QCD axions and pions share the same quantum numbers. Mixing with the pion gives it a small mass

$$m_a = m_\pi (f_\pi / f_a)$$

- Hence, axions couple to QED via a loop-induced two-photons diagram
- In presence of an external field, this is an effective mass mixing between axions and photons

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4}\mathbf{F}\tilde{\mathbf{F}}a = -g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}a$$





$$g_{a\gamma\gamma} \approx 2\times 10^{-22}(m_a/\mathrm{meV})^{-1}\ \mathrm{eV}^{-1}$$

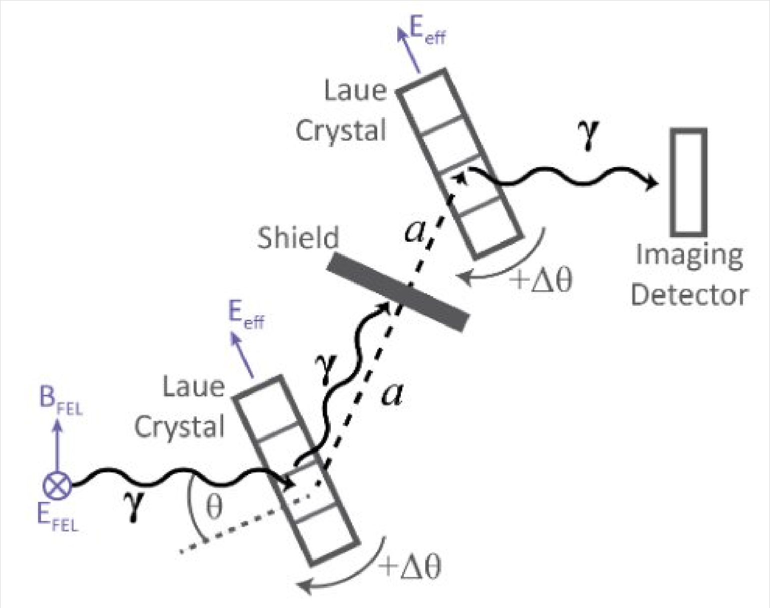
Axion searches at XFELs

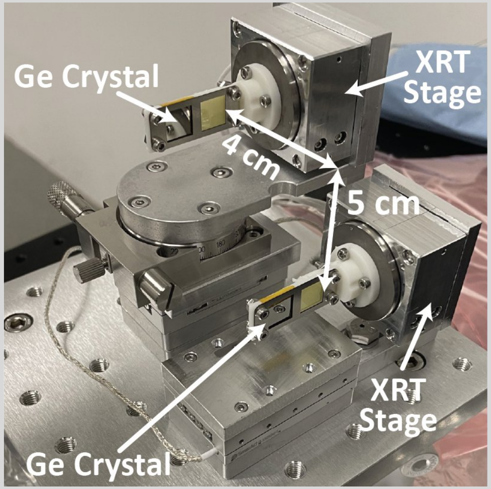
- The external field is provided by the crystal lattice.
- Detection sensitivity:

$$g_{a\gamma\gamma} < \frac{1}{E_{eff} L_{eff} \cos\theta_B} \left(\frac{N_o}{\eta N_{in}} \right)^{1/4}$$

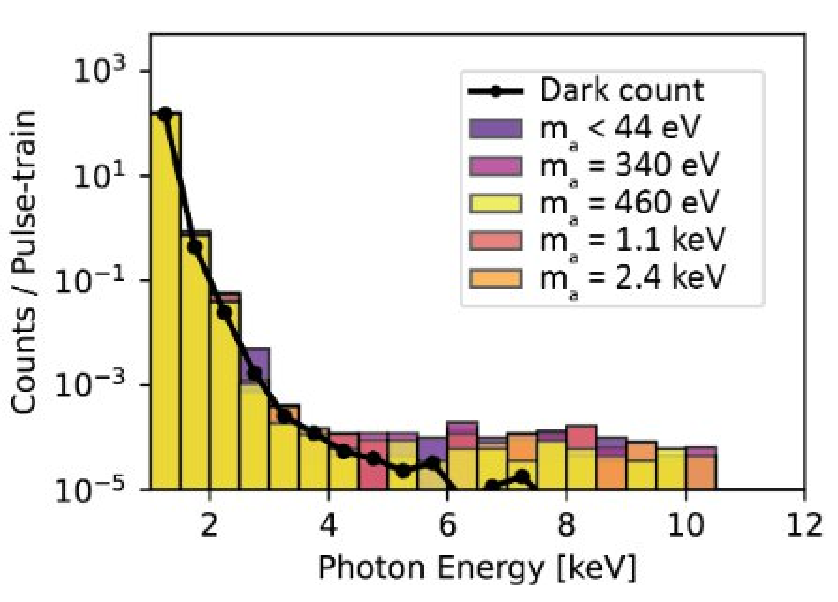
- Setup proposed by *Buchmüller et al. (1990)* and explored on Spring8 by *Yamaji et al. (2018)*.
- Mass sensitivity is provided by changing the detuning angle (away from Bragg):

$$\left| m_a^2 - m_\gamma^2 \right| < \frac{4k_\gamma}{L}$$





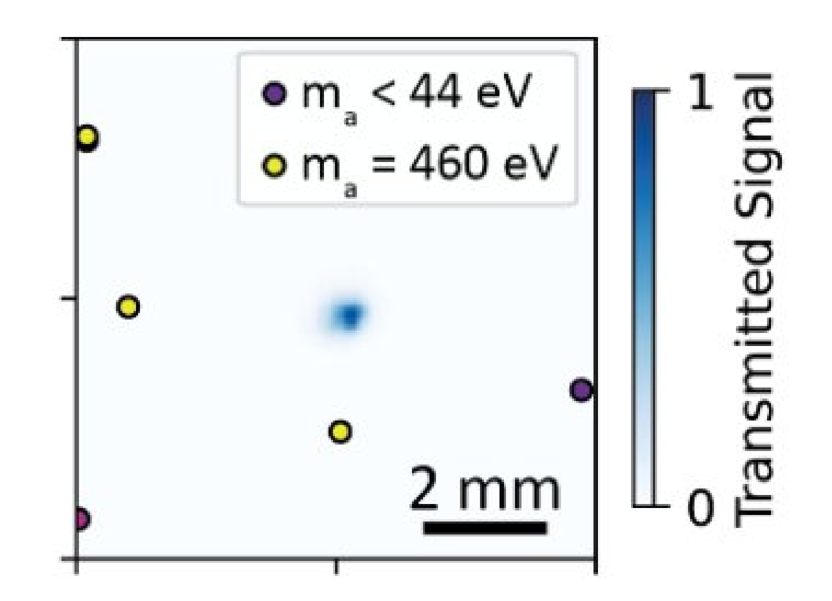
We have performed a proof-of-principle experiment at HED (EuXFEL)

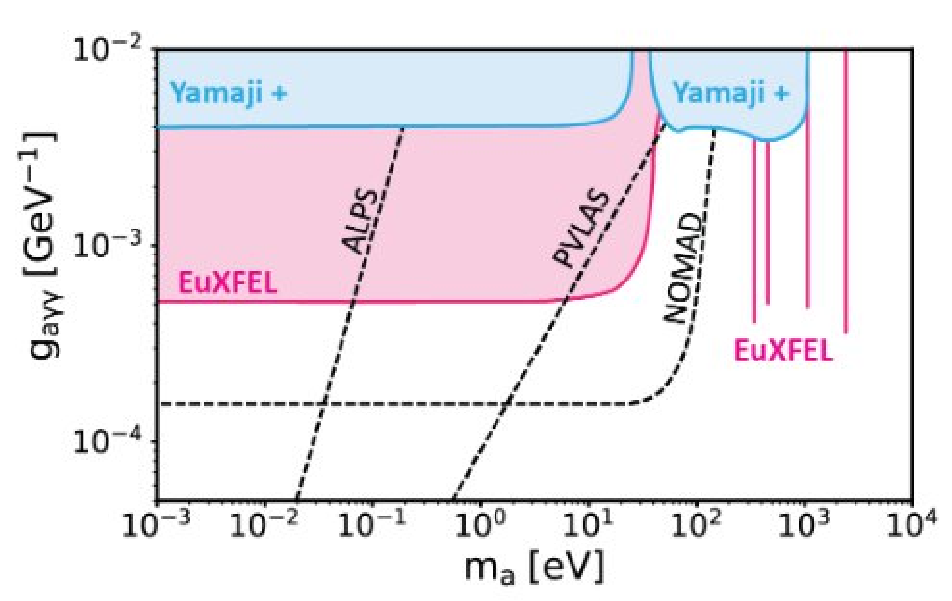


- JUNGFRAU hybrid silicon pixel instrument used as primary x-ray detector (noise level is very low).

We have performed a proof-of-principle experiment at HED (EuXFEL)

Halliday et al., in preparation (2024)





- JUNGFRAU hybrid silicon pixel instrument used as primary x-ray detector (noise level is very low).
- No 10 keV hits in same location as transmitted x-ray.
- Heavy axions ($\mathrm{m_a} \gg 10\ \mathrm{meV}$) avoid a domain wall catastrophe (Beyer & Sarkar 2023).

Oxford Physics

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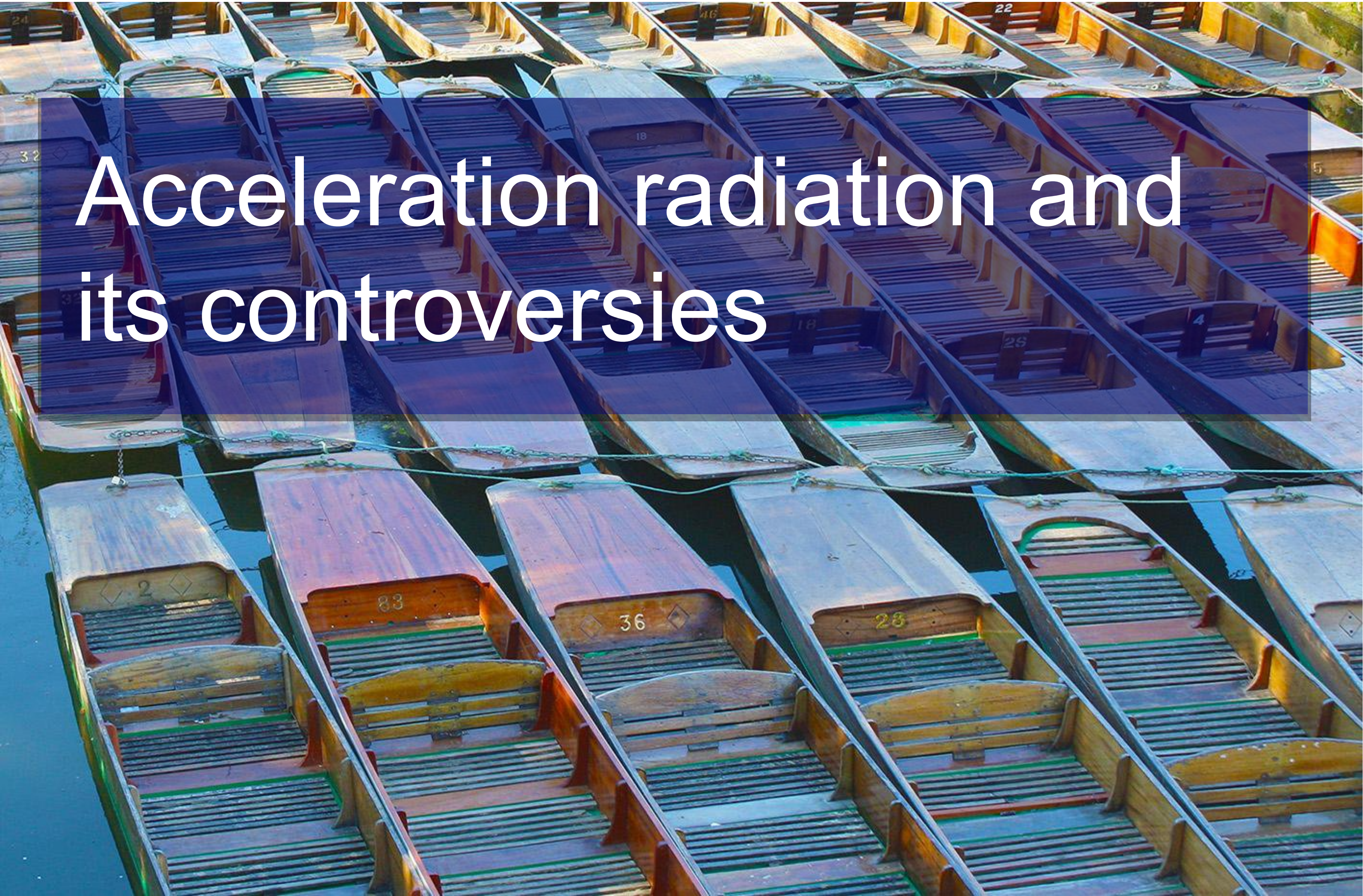
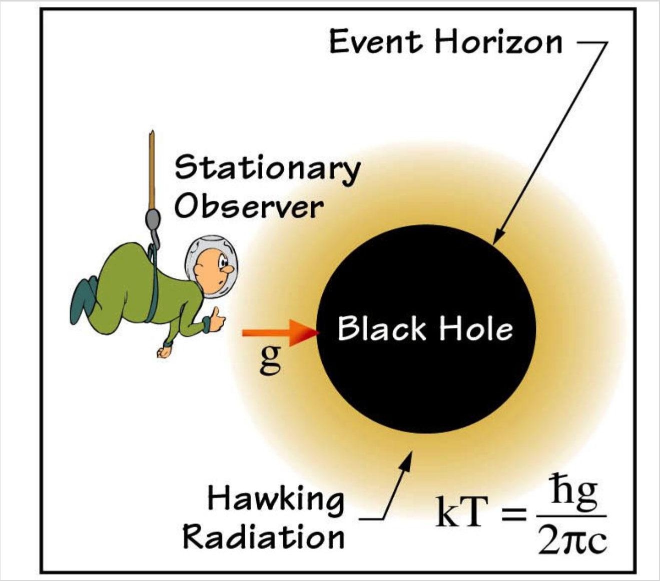
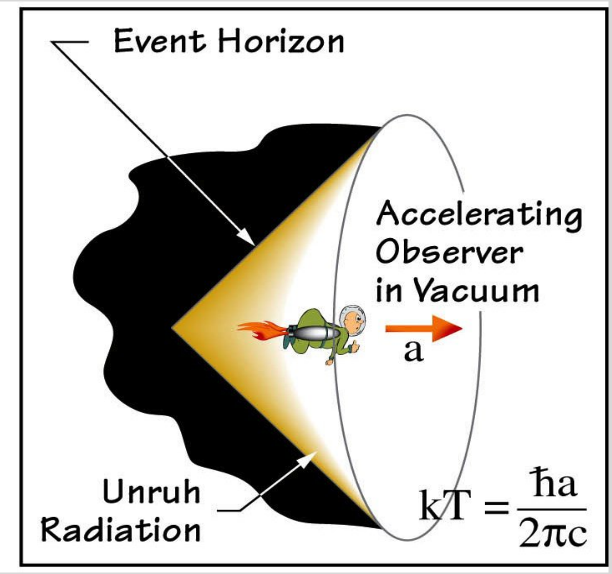
Acceleration radiation and its controversies



High intensity lasers can reach extreme accelerations

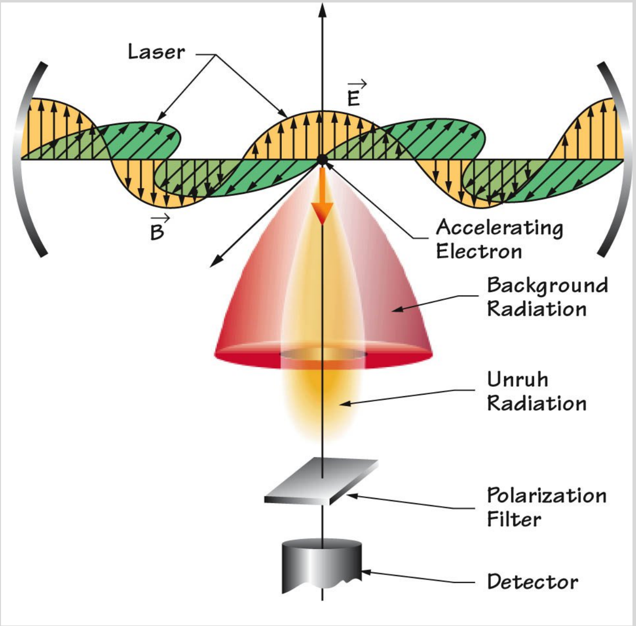
- Electrons at the focus of a high intensity laser experience very high accelerations, $g = 4.8 \times 10^{16} I^{1/2}$ cm/s^2
- An accelerated electron would then see itself surrounded by thermal radiation at the Unruh temperature
- Already at $I \sim 10^{19}$ W/cm^2 this corresponds to $T_U \sim 1$ eV, which is, in principle, measurable





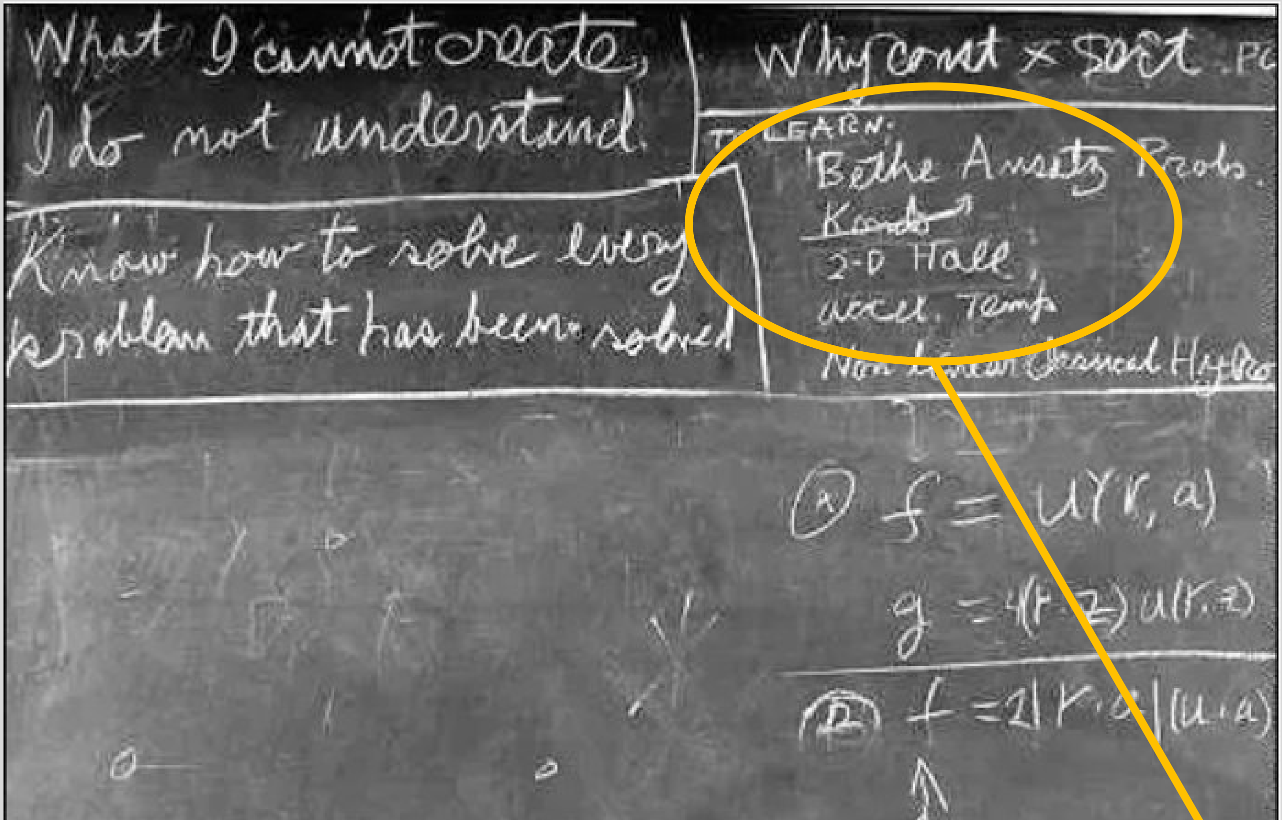
Measuring the acceleration temperature with high power lasers

- *Chen & Tajima (1999)* were the first ones to propose an experiment with high power lasers to look for the Unruh effect. They suggested looking in the direction where the Larmor radiation approaches to zero, in a small angle parallel to the acceleration vector.
- Accelerated electrons are considered as the observers, which feel the heat bath.
- The combined EM-field of two Petwatt lasers give a standing wave that produces a constant acceleration of electrons for sufficiently long times ($at \gg c$).
- The radiation emitted in response to the heat bath should be detected.



Chen & Tajima, PRL (1999)

Acceleration temperatures has been a difficult problem to tackle for decades



Feynman’s last blackboard:

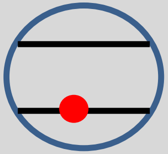
“To Learn: accel temp.”

There are also plenty of controversies when discussing Unruh effect

- While nobody disputes the Unruh effect as seen by the accelerated observer, the concept of Unruh radiation remains controversial to some extent when referred to the observer in the laboratory frame (where the experiment is performed). Some views from literature:
    - The Unruh effect depends on the existence of an event horizon, which in principle exists for an accelerated observer, but only if the acceleration continues an infinite time – NOT the case for laser experiments.
    - The accelerated electron is surrounded by this Unruh heat bath, but it does not respond to it by emitting radiation in turn.
    - In the laboratory frame, the Unruh effect is just the manifestation of ordinary QED, and the radiation emitted by the electron is nothing more than that.
    - While the scientific community generally believes that the derivation of Hawking radiation is sound, this is nevertheless made possible by several approximations that have not been tested.

Interaction between an accelerated detector and the thermal vacuum

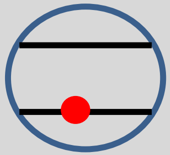
- Consider an accelerated detector. Compared to a detector at rest, it sees a vacuum filled with photons:
  - **Inertial frame:** an excitation of the vacuum corresponds to an emission of a photon.
  - **Accelerated frame**: an excitation of the vacuum corresponds to an emission or absorption of a photon (*Unruh & Wald, 1984*).



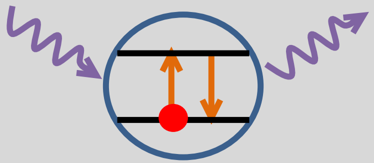
atom at rest

A simple picture of the Unruh effect (I)

- Consider an atom at rest. There is no emission or absorption of photons.
- In a higher order process the atom jumps from the ground state to an excited state by emitting a virtual photon, which is then immediately reabsorbed.
- This higher order process is energetically allowed.



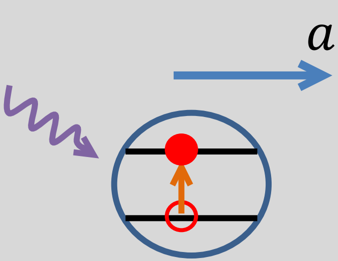
atom at rest



atom at rest with emission and absorption of virtual photons

A simple picture of the Unruh effect (II)

- If the atom is accelerated away from the original point of virtual emission, there is a small probability that the virtual photon will “get away” before it is re-absorbed.
- Acceleration breaks the entanglement between emission and absorption of virtual photons.
- The accelerated atom is left in an excited state and a real photon is emitted.



accelerated atom sees itself surrounded by a thermal bath

real photon is emitted to observer

QFT calculation of the power radiated by an accelerated electron

Assume we have an accelerated electron, with classical coupling $j^\mu = q \frac{dx^\mu(\tau)}{dt} \delta^{(3)}(\mathbf{x} - \mathbf{x}(\tau))$

Inertial Frame

- This is a well known problem: classically, the result is Larmor's formula.
- The calculation can also be done using Unruh's interpretation (see previous slides).
- If we only take a tree-level diagram, the result is again Larmor's formula.

Landulfo et al., PRD (2019)
Lynch et al., PRD (2021)

Accelerated Frame

- The emission probability in Rindler's space include both absorption and emission:

$$P_{tot} = \int d^2\mathbf{k}_\perp \int_0^{+\infty} d\omega \left[\frac{|\mathcal{A}^e_{\omega,\mathbf{k}_\perp}|^2}{1 - e^{-2\pi\omega/a}} + \frac{|\mathcal{A}^a_{\omega,-\mathbf{k}_\perp}|^2}{e^{2\pi\omega/a} - 1} \right]$$

- From this, the power emitted in the instantaneous rest frame of the accelerated electron is:

$$S_{\text{acc},\,inst} = \frac{q^2 a^2}{6\pi}$$

Vacalis et al., PRD (2024 – in press)

Does this put a rest to the controversies on Unruh radiation?

- At tree-level, the Unruh effect reduces to Larmor's formula for radiation: *absorption+emission in accelerated frame equals emission in the inertial frame.*

- This is not limited to emission of photons. Any particle that can interact with the detector is allowed (gravitons, axions, millicharged particles, etc.)

- Higher order corrections (beyond tree-level):
  - Backreaction (*Lin & Hu, 2005; Lynch et al., 2021*)
  - Thomson scattering (*Schützhold et al. 2006*)

The quantum Unruh effect

- If, however, in the accelerated frame we consider additional effects associated to the recoil of the electron (*Lynch et al. 2021*):

$$S = \frac{q^2 a^2}{6\pi}\left(1 - \frac{12\, k_B T_U}{m}\right)$$

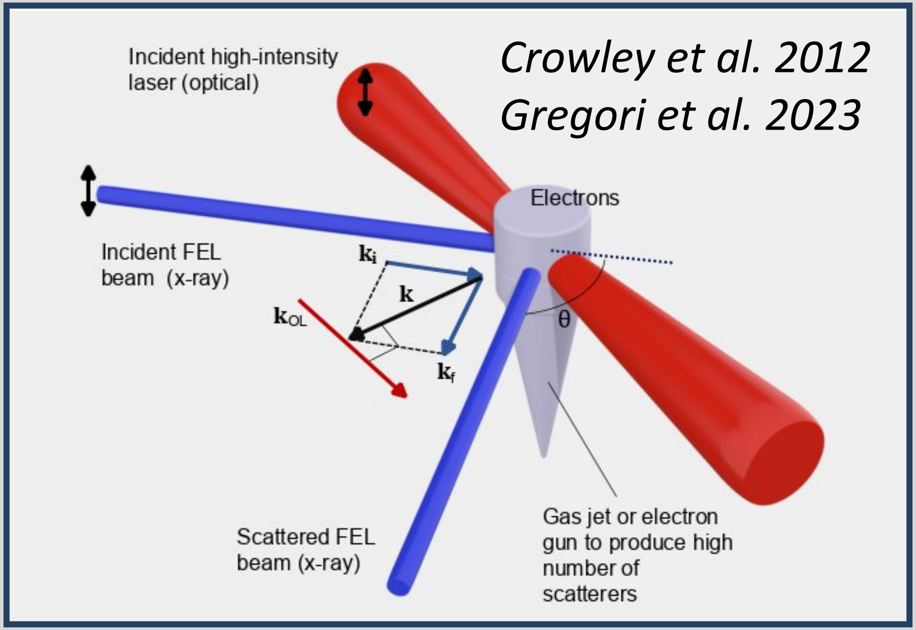
- The Unruh effect from an accelerated electron is thus measuring a (quantum) correction term in the classical Larmor formula (*Lin & Hu 2005*):

- There are many analogies between this interpretation and radiation reaction theories.

$$\delta P_v \sim a^3$$

Measuring the Unruh effect using a scattering probe laser

- The accelerated electron sees a bath of photons. These photons exchange momentum with the electron, and thus the accelerated electrons appear to have a higher temperature.
- We can set up an experiment to look for this increase in temperature as the electron is accelerated.
- The large frequency separation between optical laser (to accelerate the electron) and x-ray probe allows for the acceleration to be considered nearly uniform.



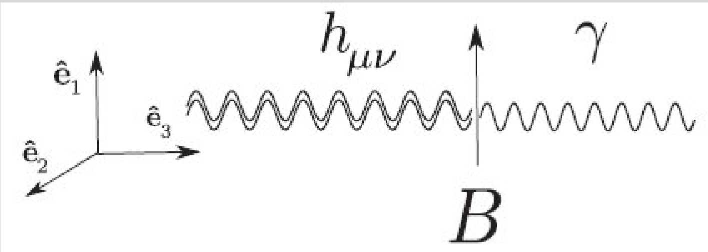
$$\frac{\Delta T}{T} = \left(\frac{20\pi^2 k_B}{hkc}\right)^2 T_U^3$$

$$\approx 0.1 \left(\frac{I_L}{10^{20}\ W/cm^2}\right)^{2/3} \left(\frac{\lambda_p}{0.1\ nm}\right)^2$$

These experiments are feasible within current laser/FEL facilities

Unruh radiation Beyond the Standard Model

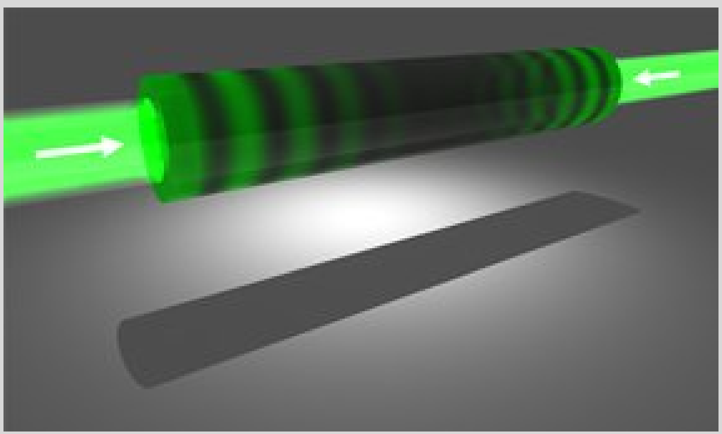
Generation of gravitational waves from the Gertsenshtein effect (I)



Domcke and Garcia-Cely, PRL (2021)

- In presence of a magnetic field, gravitons can convert into photons and vice-versa.
- Very similar to the process of axion generation and conversion

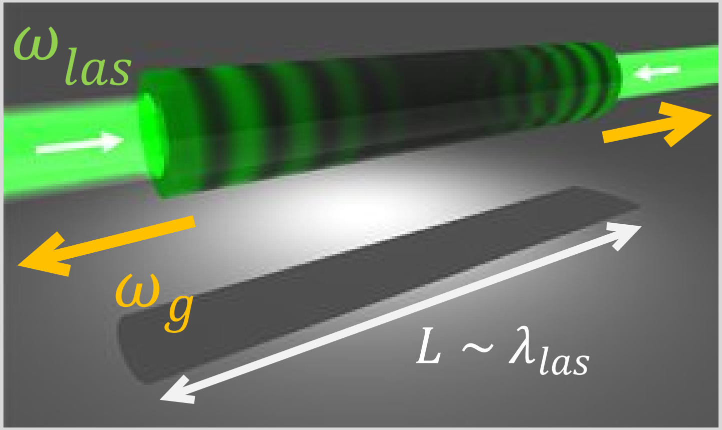
Counter-propagating laser beams



$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$	Linearised gravity
$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$	Traceless transverse frame
$\Box^2 \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$	$T_{\mu\nu}$ contains the EM field

$$\bar{h}_{\mu\nu}(t,\boldsymbol{x}) \approx \frac{4G}{c^4 R}\int d^3y\, T_{\mu\nu}(t - R + \boldsymbol{n}\cdot\boldsymbol{y}, \boldsymbol{y}), \quad R \gg y$$

Generation of gravitational waves from the Gertsenshtein effect (II)

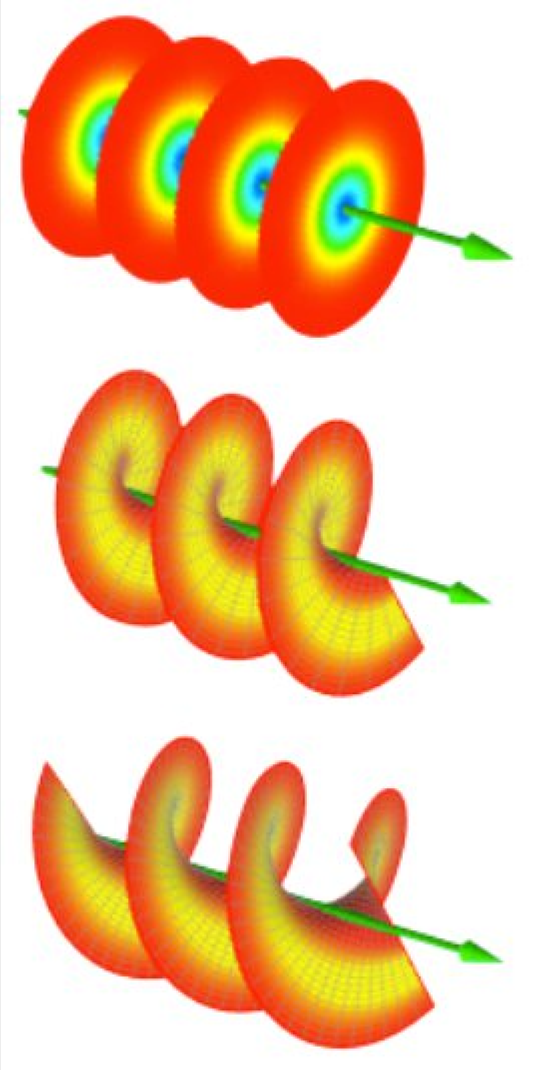


- We can calculate the induced strain by the EM field.
- The generated GW has maximum strain at twice the laser frequency.
- The values of the expected strain are still small, but significantly higher than those produced by the previous technique.

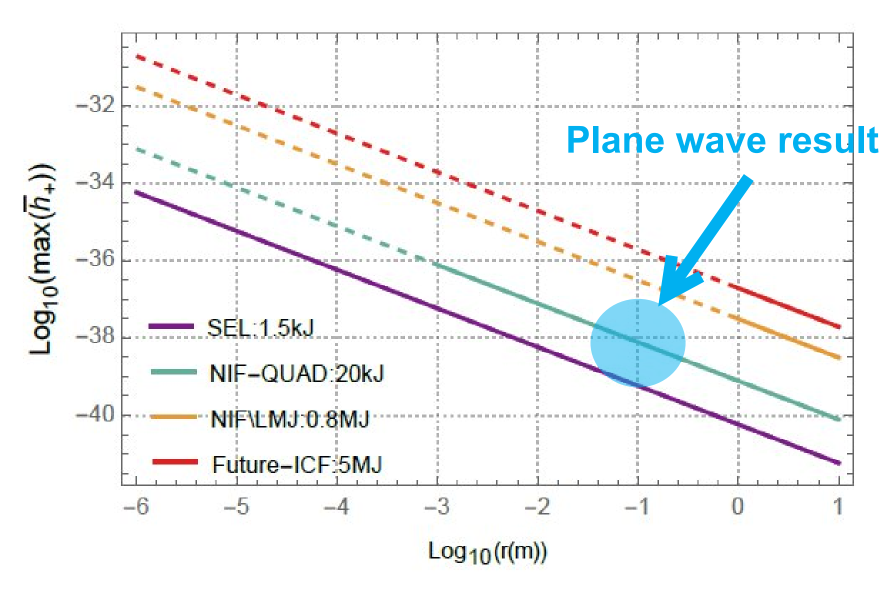
$$h \sim \frac{GIL^3}{c^4 R}, \quad \omega_g = 2\omega_{las}$$

$$h_{max} \sim 5.2 \times 10^{-38} \left(\frac{\lambda_{las}}{10\ \mu\mathrm{m}}\right)^2 \left(\frac{\tau}{10^{-12}\mathrm{s}}\right) \left(\frac{I}{10^{23}\ \mathrm{W\ cm^{-2}}}\right) \left(\frac{10\ \mathrm{cm}}{R}\right)$$

Further improvement can be obtained using twisted light



- Laser beams with orbital angular momentum (OAM) have a twisted phase front.
- While the total energy density is the same as for plane waves, OAM offers the advantage of possibly separating the GW signal from the background.



Atonga et al., arXiv (2023)

Gravitational Bremsstrahlung

- We can use the same approach used for Unruh radiation and calculate the emission of gravitons from an accelerated detector (*Lynch, PRD 2023*):

$$n_g = \frac{32\,\pi}{5}\frac{G\,m_e^2}{c^5\,\hbar}(\tau_{las}a)^4$$

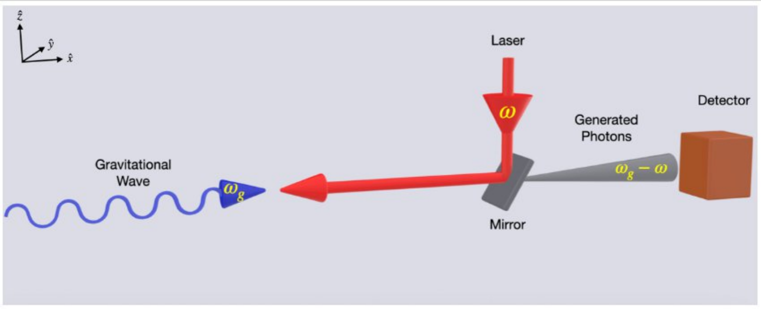
- This corresponds to a strain:

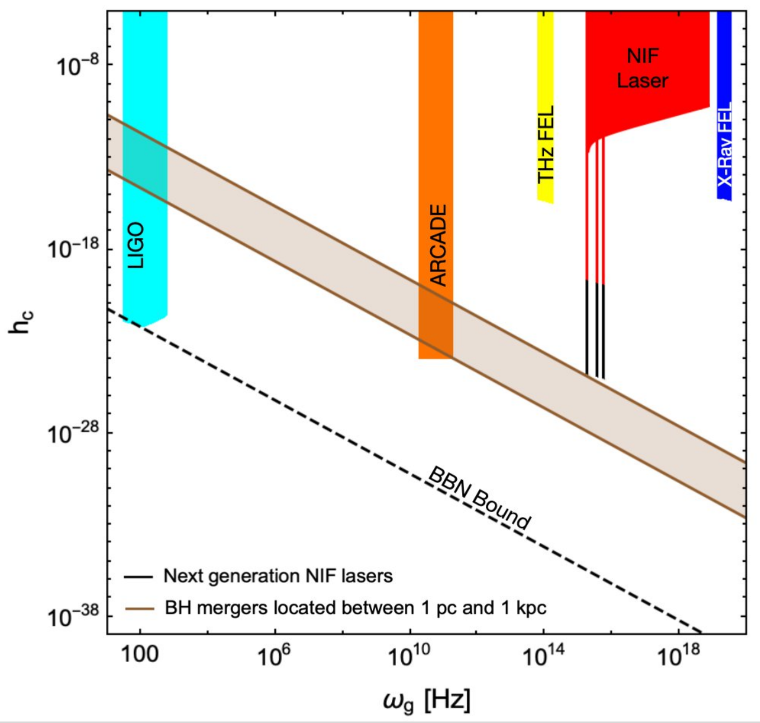
$$h = \frac{c}{\hbar}\frac{n_g k_B T_U}{L} \sim 5\times 10^{-16}\left(\frac{I_{las}}{10^{19}\mathrm{W\,cm^{-2}}}\right)^2\left(\frac{\tau_{las}}{1\ \mathrm{fs}}\right)^4\left(\frac{T_U}{1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{m}}{L}\right)$$

- This is a much larger strain than that obtained from other methods:
  - It requires further investigations (using proper QFT techniques).
  - If confirmed, it may provide a much more fruitful avenue for the generation of high-frequency GWs.

Brito et al., arXiv:2311.09025 (2023)
Portales-Oliva and Landulfo, arXiv:2311.06032 (2023)

High-frequency GW detection techniques





Vacalis et al., Clas. Quant. Grav. (2023)

- High-power laser or XFEL collides with GW and produces a photon (inverse Gertsenshtein effect).
- At these frequencies, the only possible sources of GW comes from black-hole mergers in the solar system (unlikely).
- But lab sources (as discussed earlier) may be strong enough.
- Strain from accelerated charges may be within reach of optical-laser GW detectors.
- New way to test gravity.

We are looking for three Postdocs in laboratory astro(particle)physics

Job Details

Postdoctoral Research Assistant in Warm Dense Matter (Theory/Computation/Experiments)

Department of Physics, Clarendon Laboratory, Parks ROad, Oxford

Applications are invited for two Postdoctoral Research Assistant positions in Warm Dense Matter (Theory/Computation/Experiments).

The post is available initially for a fixed-term duration of 2.5 years.

Exotic and high-pressure warm dense matter (WDM) states exists in gas giants, brown and white dwarf stars, the crust of neutron stars, and it can be created during Inertial Confinement Fusion (ICF) experiments. Warm dense matter is a strongly coupled quantum plasma, with ions moving in a partially degenerate electron fluid, and having kinetic energy comparable to the ion-ion interaction energy. Consequently, WDM inherits properties from both condensed matter systems and classical plasmas. Measuring a modelling the equation of state as well as other thermodynamic and transport properties of WDM is crucial not only for our understanding of astrophysical objects but also for the success of ICF.

We are looking for two postdocs in WDM studies. One vacancy is for an experimental scientist, to measure heat transport and viscosity in WDM systems under different drive conditions. For the other vacancy we are looking for a theory/computational scientist to perform large scale simulations of WDM plasmas using quantum simulation techniques based on Molecular Dynamics and/or Density Functional Theory.

For the experimental position, we expect the successful candidate to be involved in the planning, execution and analysis of experiments at high power laser facilities and fourth generation light sources. For the theory/computational position, we intend the ideal candidate to perform high-performance computing modelling of transport in WDM and compare predictions against experimental data. For both positions, we expect Machine Learning techniques to be used/deployed in the data analysis and in the creation of surrogate models.

The post-holder will have the opportunity to teach. This may include lecturing, small group teaching, and tutoring of undergraduates and graduate students.

Applicants should hold a PhD, or be close to obtaining in physics or a related field and have a strong background in plasma physics.

Previous experience (theory/experiments) in planetary physics and/or ICF research is welcome.

Candidates are expected to be able to work in a multidisciplinary environment.

Please direct enquiries about the role to Prof Gianluca Gregori and Prof Sam Vinko. (gianluca.gregori@physics.ox.ac.uk - sam.vinko@physics.ox.ac.uk)

Only applications received before midday (UK time) 9 February 2024 can be considered. You will be required to upload a statement of research interests, CV and details of two referees as part of your online application.

Contact Person :	HR Team	**Vacancy ID :**	170453
Contact Phone :		**Closing Date & Time :**	09-Feb-2024 09:00
Pay Scale :	STANDARD GRADE 7	**Contact Email :**	recruitment@physics.ox.ac.uk
Salary (£) :	Grade 7: £36,024 -£44,263 per annum		

Click on the link(s) below to view documents	Filesize
170453 JD and Person Spec Physics PDRArev.pdf	988.2

Job Details

Postdoctoral Research Assistant in Extreme Laboratory Astrophysics

Department of Physics, Clarendon Laboratory

Applications are invited for a Postdoctoral Research Assistant (PDRA) position in Extreme Laboratory Astrophysics.

The post is available initially for a fixed-term duration of 2.5 years.

The PDRA will lead a new approach to the understanding of extreme astrophysics (Blazars' Jets and Gamma Ray Bursts) using laboratory experiments performed at large accelerators' facilities such as CERN, SLAC and Laboratory Nazionali di Frascati (INFN, Italy). The basic idea is that of generating ultra-relativistic beams of electrons and positrons and then observe their propagation through an ambient plasma. We are interested at the formation of instabilities as well as the self-generation of magnetic fields and the corresponding synchrotron and inverse Compton scattering processes. The PDRA will lead a team of scientists in experiments aimed at studying the detailed micro-physics of these astrophysical objects – providing data that cannot be obtained from satellite observations, or too difficult to calculate given the limitations in spatial and temporal and resolution scales that computer simulation can nowadays achieve. In addition, the PDRA will also explore the interaction of high-intensity laser beams with particle beams to study the most extreme astrophysical environment in the laboratory.

We expect the successful candidate to be involved in the planning, execution and analysis of experiments at accelerator facilities and high power laser facilities. They will also perform data analysis (with appropriate computational methods) and interact with the theory team for the understanding of the results. We also expect Machine Learning techniques to be used/deployed in the data analysis.
The post-holder will have the opportunity to teach. This may include lecturing, small group teaching, and tutoring of undergraduates and graduate students.

Applicants should hold a PhD, or be close to completion in physics or a related field and have a strong background in plasma physics.

Candidates are expected to be able to work in a multidisciplinary environment.

Please direct enquiries about the role to Prof Gianluca.Gregori@physics.ox.ac.uk and Prof Subir.Sarkar@physics.ox.ac.uk

Only applications received before midday (UK time) 15th February 2024 can be considered.

You will be required to upload a statement of research interests, CV and details of two referees as part of your online application.

Contact Person :	Recruitment	**Vacancy ID :**	169982
Contact Phone :		**Closing Date & Time :**	15-Feb-2024 12:00
Pay Scale :	STANDARD GRADE 7	**Contact Email :**	recruit@physics.ox.ac.uk
Salary (£) :	£36,024-£44,263 per annum		

Click on the link(s) below to view documents	Filesize
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Any interested candidate, please contact me!

Summary & conclusions

- Laser technology has evolved rapidly in the past 50 years (Nobel prizes awarded in 2018 and 2023).
- Lasers can be used to accelerated charges and test the Hawking/Unruh effect.
- Current high-power optical laser and XFEL systems can achieve sufficient energy densities to enable the generation of axions and GWs.