Production, detection and search of ultra-high frequency gravitational waves with high-power pulsed lasers

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with thanks to:
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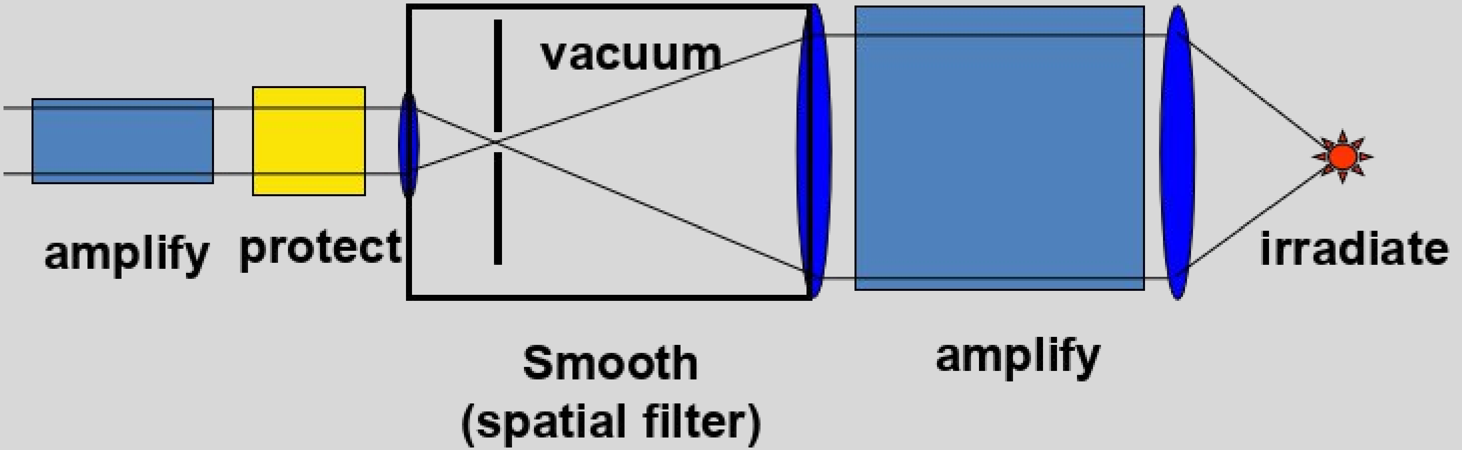
R Bingham (Rutherford Appleton Laboratory)
A Higuchi (University of York)

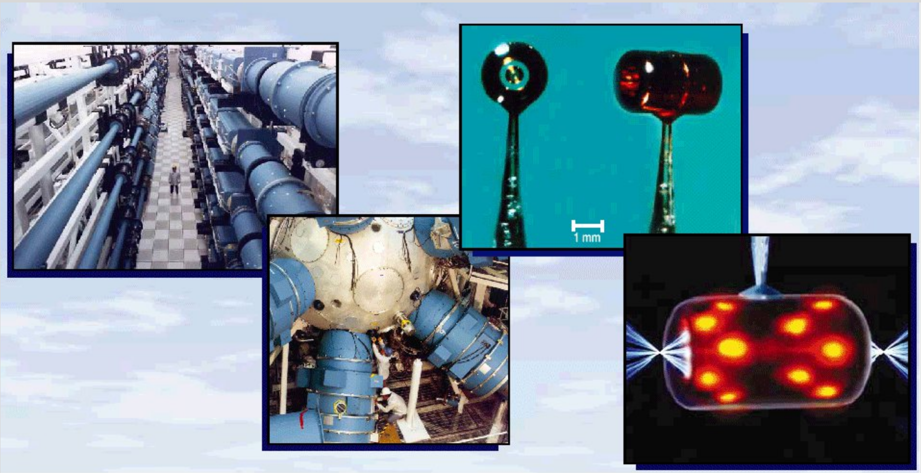
CERN, 6th Dec 2023

Overview of high power lasers

A big laser works in the same way as a small one



This results in lots of energy delivered in a short time and a small volume: high-energy means large laser facilities.

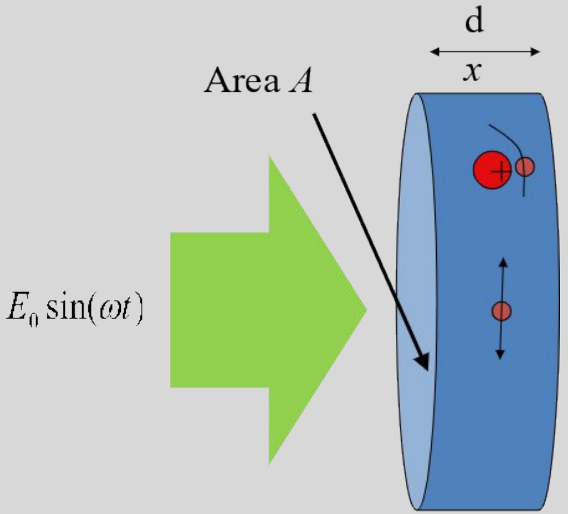


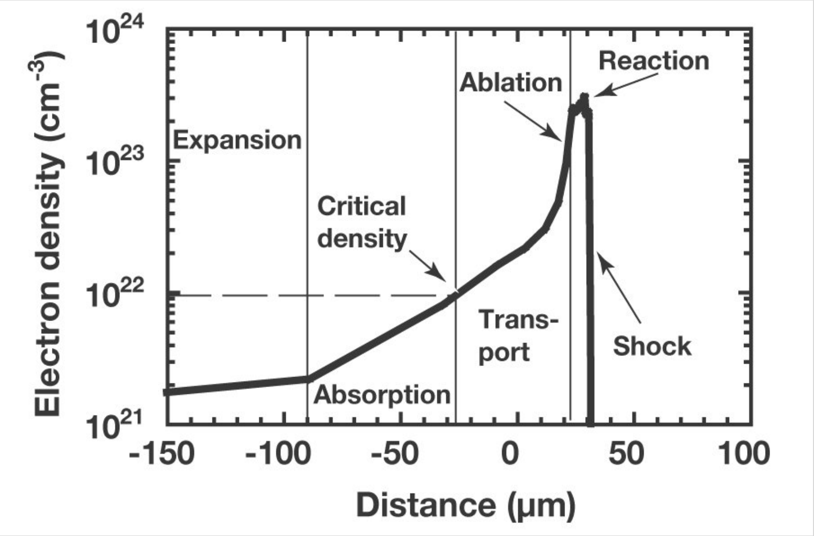
The US National Ignition Facility (NIF) laser

The NIF laser at the Lawrence Livermore National Laboratory is the largest laser in the world. It has 192 beams of *infrared* light (converted to *blue light*), producing a total of about 1-3 MJ of light energy in pulses of 10^{-8} seconds (100 TW).

That's an enormous power….
comparable to the power delivered by the US national grid

Basic concepts on laser-plasma interactions (I)





Drake, *High-Energy-Density Physics*, Springer (2006)

- Laser propagates only when:

$$\omega_L > \omega_{pe} \equiv \frac{\sqrt{k_B T / m_e}}{\lambda_D}$$

- This occurs at the critical density:

$$n_{crit} = \frac{m_e \omega_L^2}{4\pi e^2}$$

- Laser energy flows down the temperature gradient to the target. Material is ablated away at the ablation surface.
- As the plasma expands away from the target, the velocity increases (mass flow approximately constant).

Basic concepts on laser-plasma interactions (II)

- Assume the laser irradiance (I_L) is carried away with efficiency *f* by the flowing electrons in the plasma:

$$I_L = f\epsilon_{th}\sqrt{T/m_e}$$

- The thermal energy is evaluated at the critical surface:

$$\epsilon_{th} = \frac{3}{2}n_{crit}k_B T$$

- And solving for the temperature:

$$T \simeq 2\left(\frac{I_L}{10^{14}\ \mathrm{W/cm^2}}\right)^{2/3}\left(\frac{\lambda_L}{1\ \mu\mathrm{m}}\right)^{4/3}\ \mathrm{keV}$$

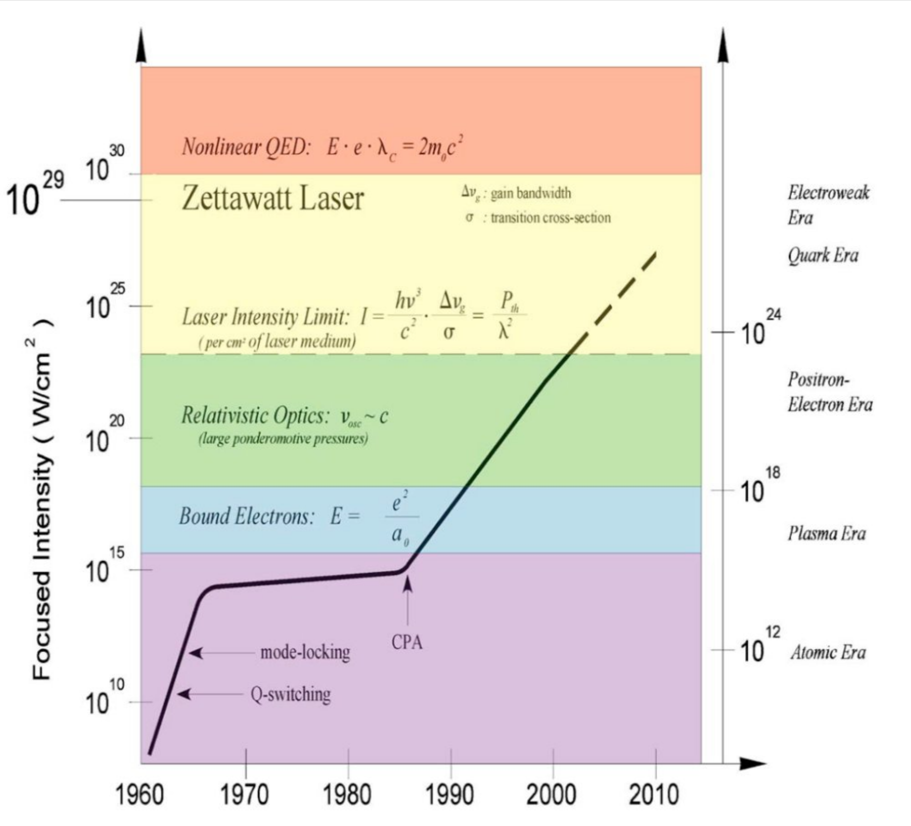
Basic concepts on laser-plasma interactions (III)

The ablation pressure is:

$$P_a = n_{crit} k_B T \simeq 3.5 \left(\frac{I_L}{10^{14} \ \mathrm{W/cm^2}} \right)^{2/3} \left(\frac{\lambda_L}{1 \ \mu\mathrm{m}} \right)^{-2/3} \ \mathrm{Mbar}$$

- This is a very large pressure! It can be used to compress matter and/or to propel the sample to very high accelerations.
- At higher laser intensities, other absorption mechanisms becomes important, but the concept is still the same: we can achieve very large pressures.

Progress on high-intensity lasers has been enormous in the past decades



- Progress enabled by CPA technique
- Normalized vector potential:

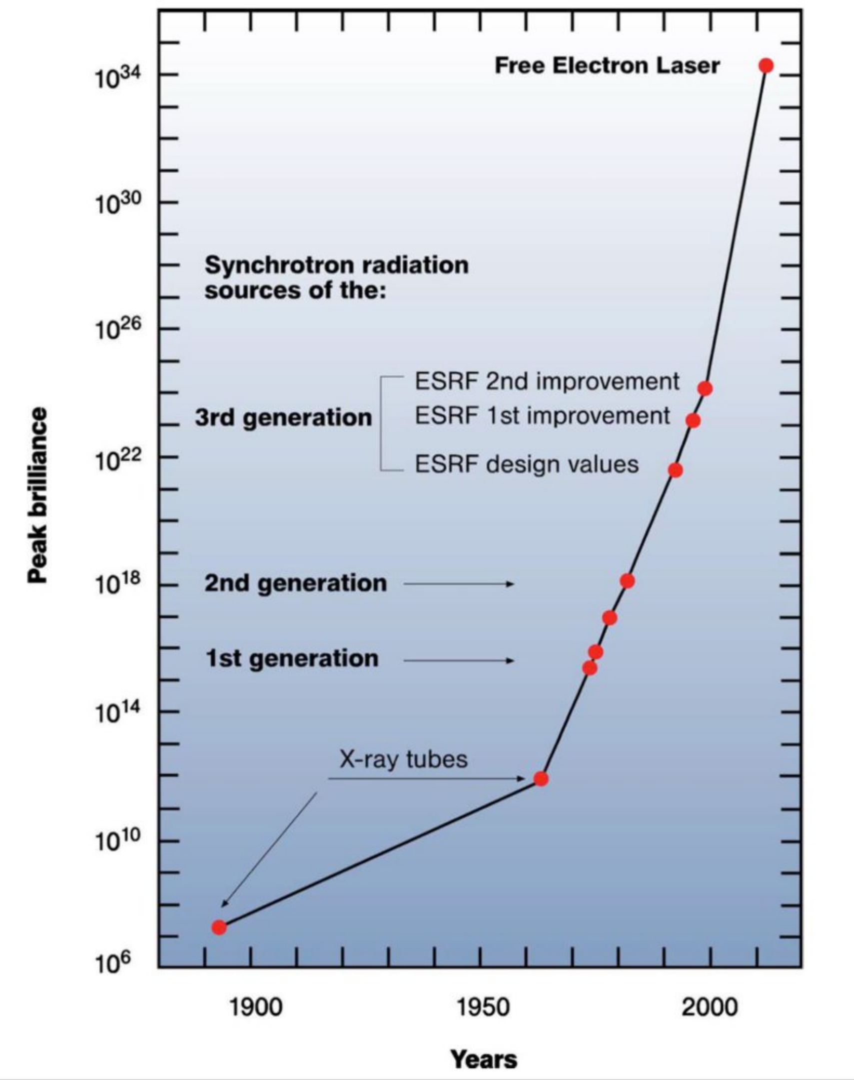
$$a_0 = \frac{eE}{mc\omega} = 0.6\left(\frac{I}{10^{18}W/cm^2}\right)^{1/2}\left(\frac{\lambda}{\mu m}\right)$$

- $a_0 > 1$ implies relativistic motion for the electron
- Quantum non-linearity parameter:

$$\eta = \frac{2\,a_0^2\hbar\omega}{mc^2} = 0.18\left(\frac{I}{10^{23}W/cm^2}\right)\left(\frac{\lambda}{\mu m}\right)$$

- $\eta > 1$ means that pair production is important

4th generation sources provide large brightness in X-ray and THz regimes



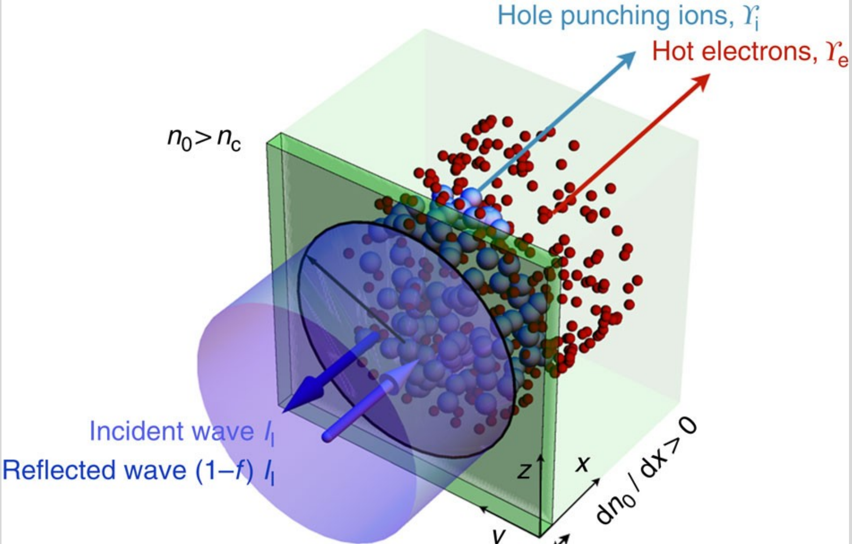
- FELs have a brightness which is 10^{10} times higher than conventional 3rd generation sources (e.g., Synchrotrons)
- In the X-ray regime, large number of photons, high photon energy, but a_0 and η are small
- In the THz regime, we can have larger values for the normalized vector potential ($a_0 \sim 1$)

Optical and Free Electron Lasers can be used for axion searches

- ➜ ELI laser will achieve intensities $>10^{23}$ W/cm^2, much higher than any current laser system.
- ➜ EU.XFEL has achieved highest brightness in X-rays than any other sources.
- ➜ **A combination of these facilities may be envisioned for fundamental physics research.**

Examples of gravitational waves generation with lasers

Piston-model for accelerating ions in a laser-driven slab (I)

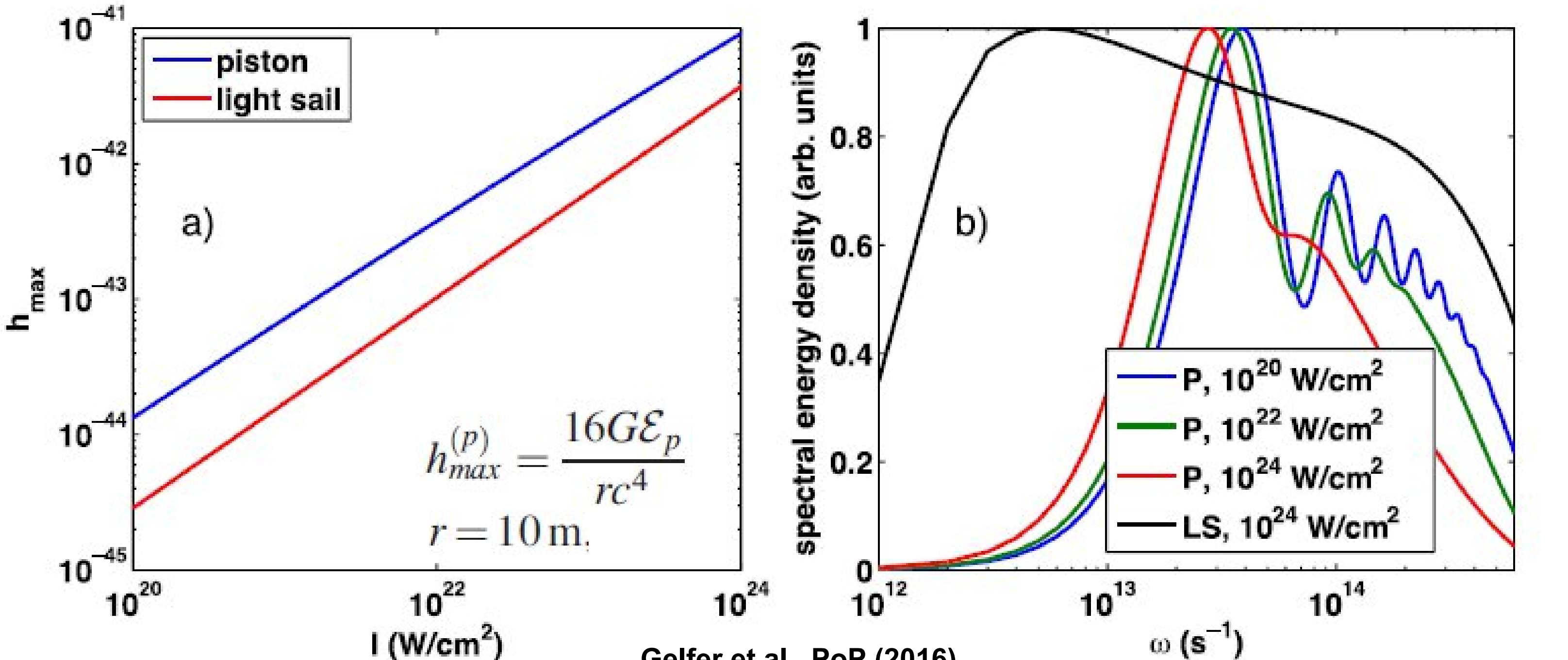


Levy et al., Nat. Comm. (2014)

- Electrons are push forward by the radiation pressure. This generates an electrostatic field (due to charge separation).
- Ions are accelerated by both the ablation pressure and the electric field.
- The non-vanishing component of the energy-stress tensor is:

$$T_{xx} = \rho \gamma^2 v^2$$

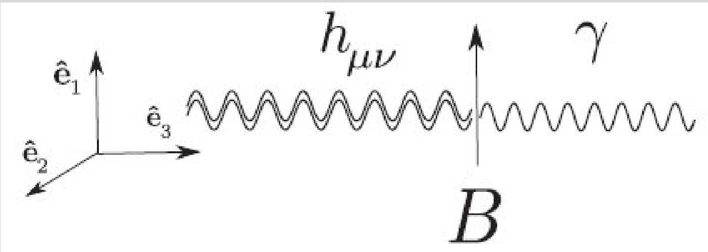
Piston-model for accelerating ions in a laser-driven slab (II)



Gelfer et al., PoP (2016)

- The strain depends on the total kinetic energy of the accelerated ions.
- The calculated strain is very small for currently available laser intensities.
- The spectrum of the emitted GWs falls into the radio-THz frequency domain.

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.

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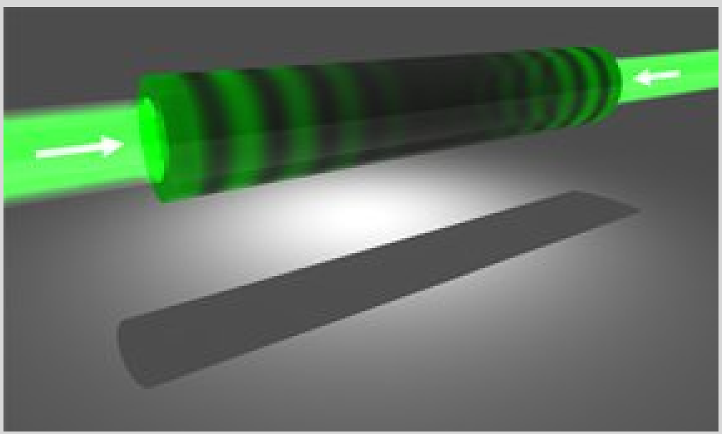
Counter-propagating laser beams



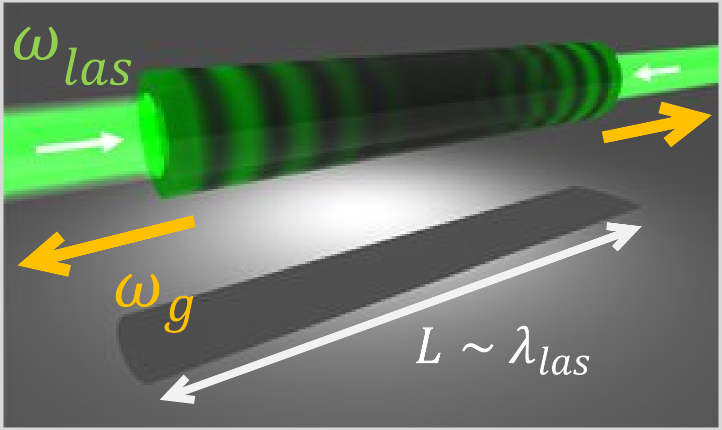
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$ Linearised gravity

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$$ 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)

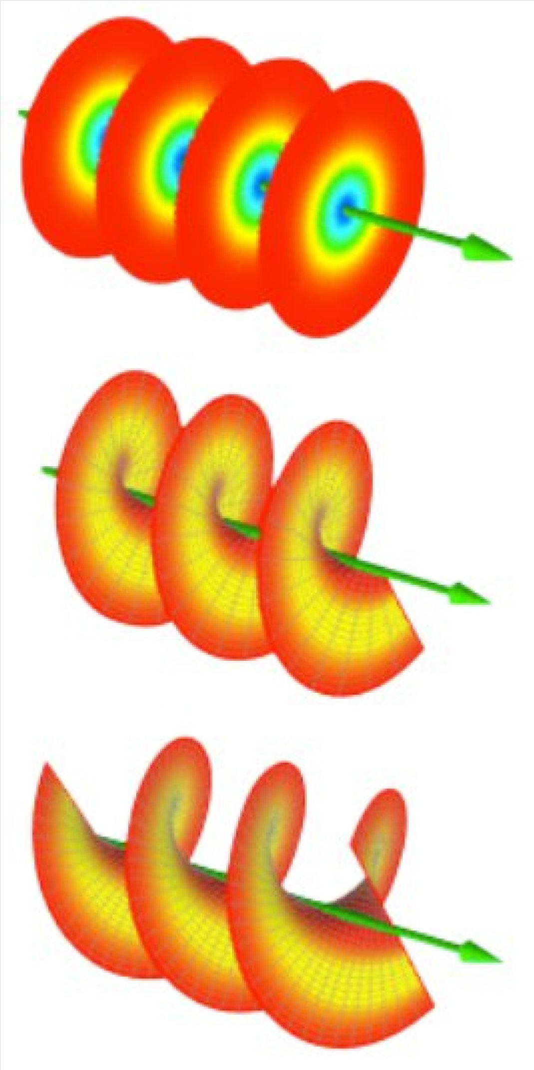


$$h \sim \frac{GIL^3}{c^4 R}, \quad \omega_g = 2\omega_{las}$$

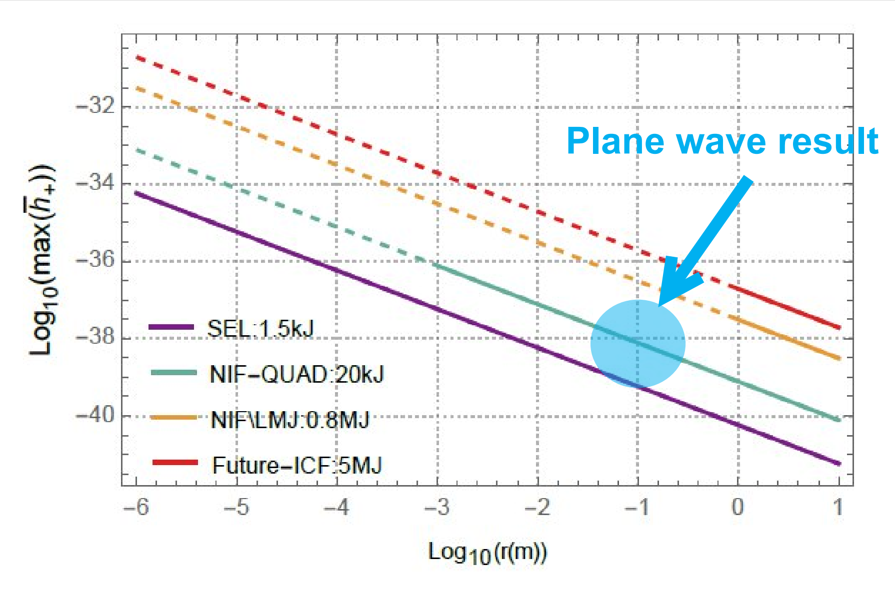
- We can calculate the induced strain by the EM field.
- The generated GW has maximum strain at twice the laser frequency.
- The values of the expected strain are still small, but significantly higher than those produced by the previous technique.

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

Further improvement can be obtained using twisted light

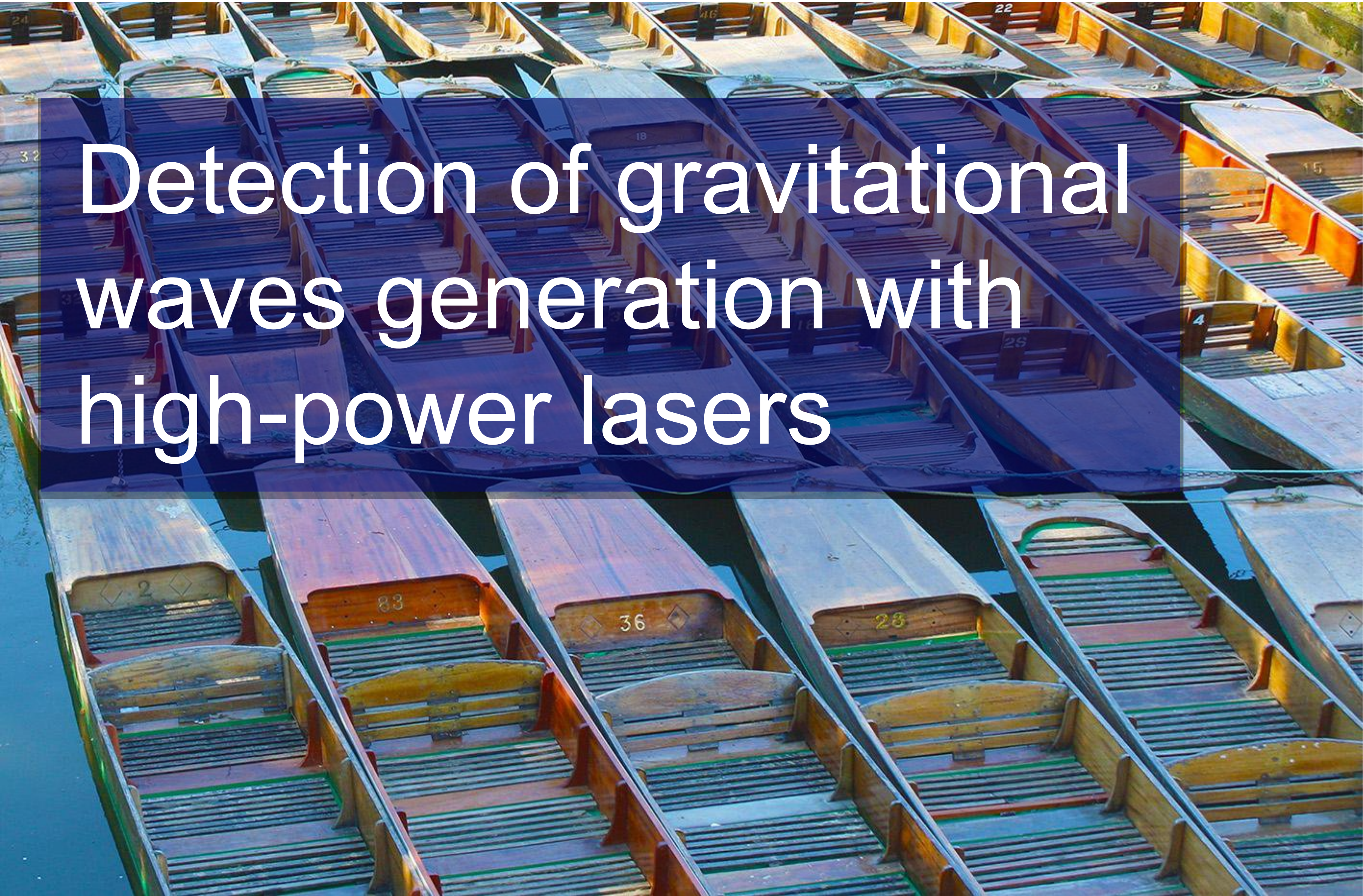


- Laser beams with orbital angular momentum (OAM) have a twisted phase front.
- While the total energy density is the same as for plane waves, OAM offers the advantage of possibly separating the GW signal from the background.



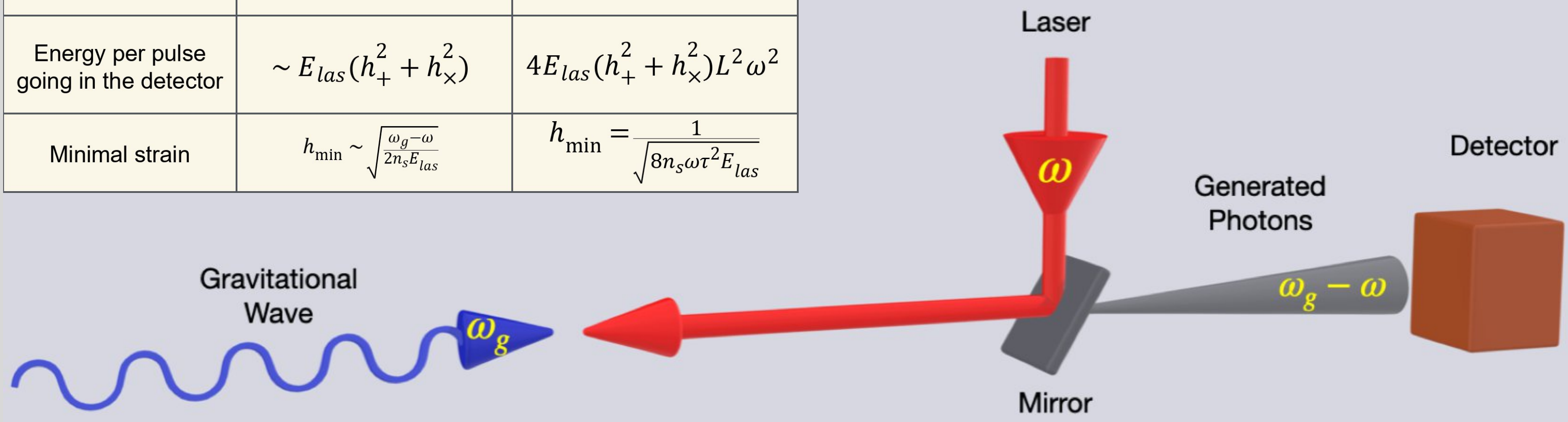
Atonga et al., arXiv (2023)

Detection of gravitational waves generation with high-power lasers



Detection of gravitational waves from the inverse Gertsenshtein effect

Frequency	$\omega_g \neq 2\omega$	$\omega_g = 2\omega$
Energy per pulse going in the detector	$\sim E_{las}(h_+^2 + h_\times^2)$	$4E_{las}(h_+^2 + h_\times^2)L^2\omega^2$
Minimal strain	$h_{\min} \sim \sqrt{\frac{\omega_g - \omega}{2n_s E_{las}}}$	$h_{\min} = \frac{1}{\sqrt{8n_s\omega\tau^2 E_{las}}}$

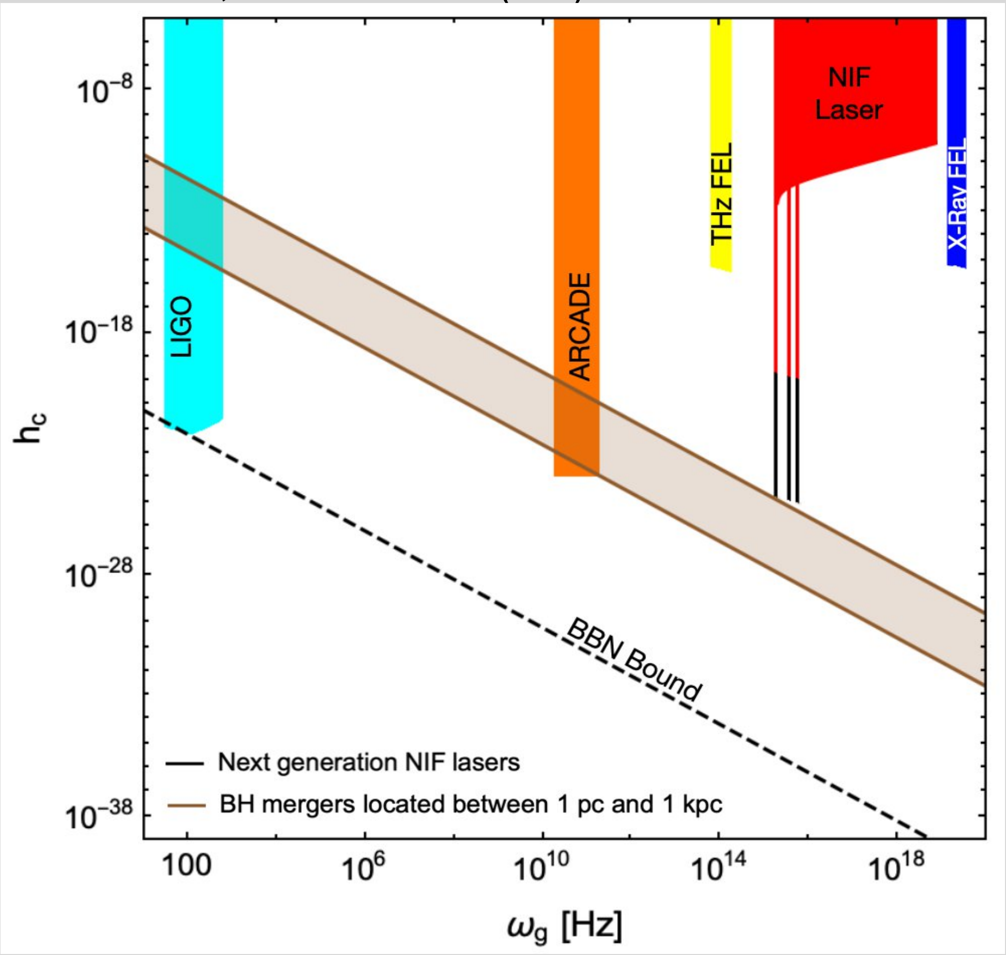


Vacalis et al., Clas. Quant. Grav. (2023)

- Gravitational waves that are counter-propagating a high-power laser beam scatter photons back towards the laser.
- The process is maximized when the gravitational wave frequency is double of that of the probe laser.

Detection uses currently available laser technology in THz, Optical and X-ray

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



- **THz FEL**: Rep. rate of 200 kHz, $\tau = 1\,ps, E_{las} = 100\ \mu\text{J}$, $1\text{THz} \leq \omega/2\pi \leq 30\text{THz}$
- **NIF laser**: Rep. rate of 4 shots per day, $\tau = 20$ ns, $E_{las} = 9.4$ kJ, $\lambda = 1051, 527, 351$ nm
- **Next gen NIF**: Rep. rate of 10 kHz, $\tau = 20$ ns, $E_{las} = 1.8$ MJ, $\lambda = 1051, 527, 351$nm
- **EuXFEL**: Rep. rate of 10 Hz, $5.8\text{ keV} \leq \omega/2\pi \leq 24\text{ keV}$, $\tau = 0.1$ ps, $E_{las} = 2, 1, 0.5$ mJ,

- **Unlikely this technique will be able to detect GW due to classical sources, but possibly BSM process may generate GW in these frequency range.**

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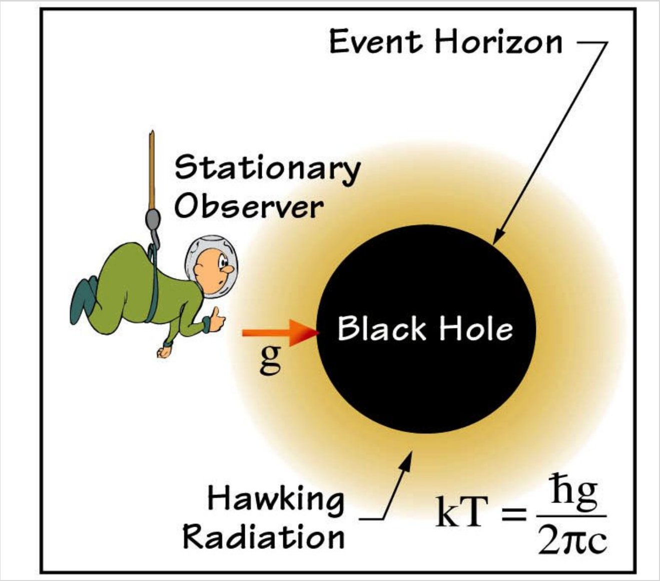
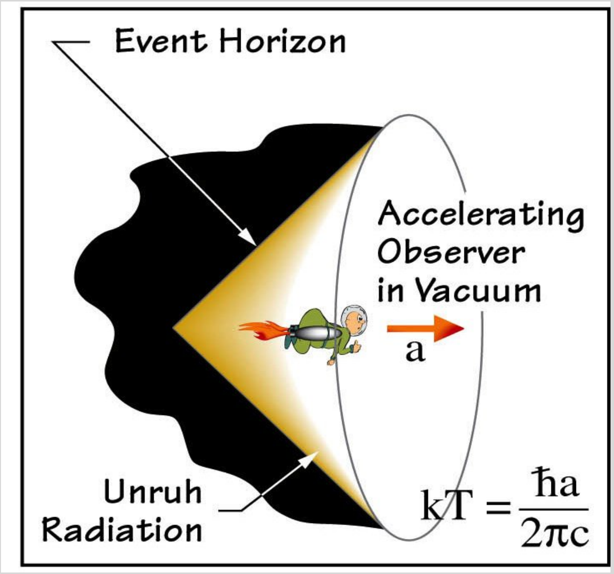
New ideas for the generation of high-frequency GWs

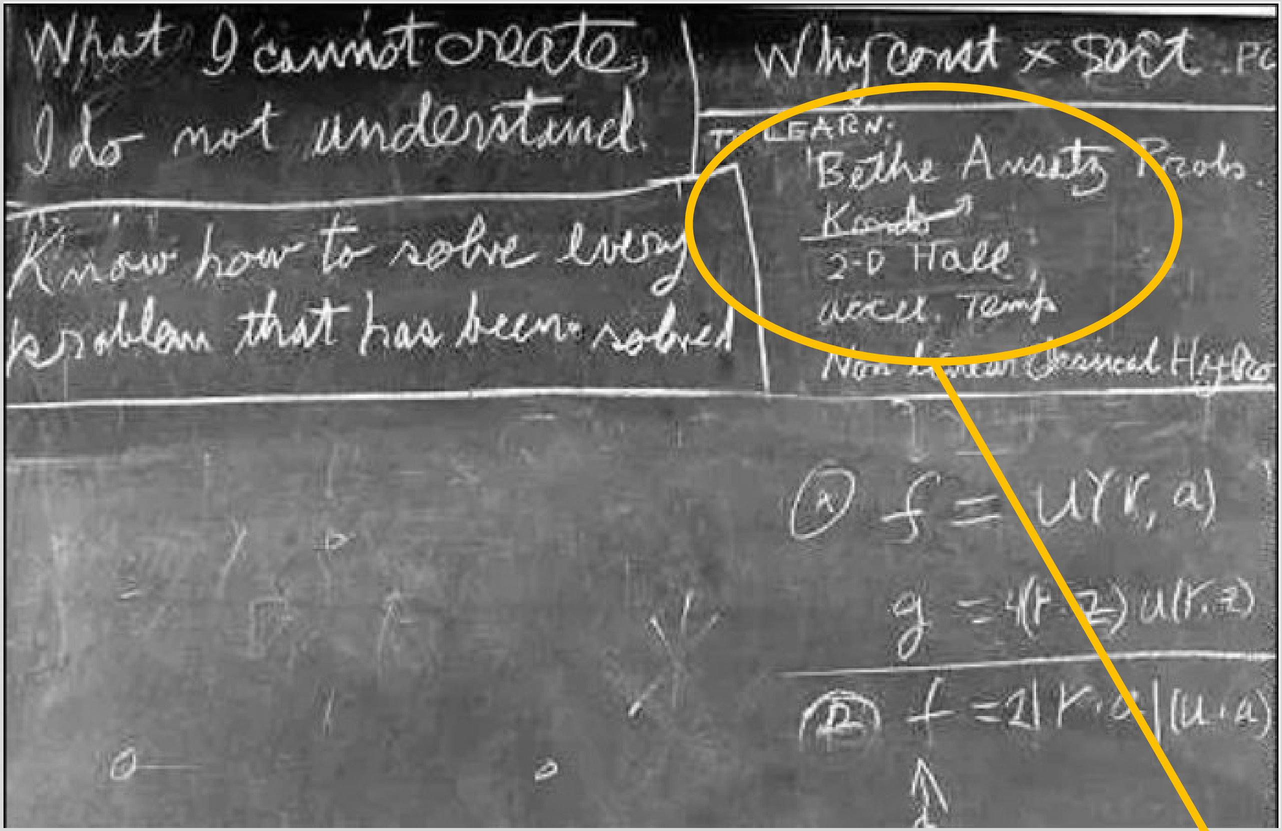
High intensity lasers can reach extreme accelerations

- Electrons at the focus of a high intensity laser experience very high accelerations, $a = 4.8 \times 10^{16} I^{1/2}$ 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 the optical frequency.





Acceleration temperatures has been a difficult problem to tackle for decades

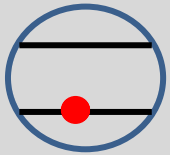


Feynman's last blackboard:

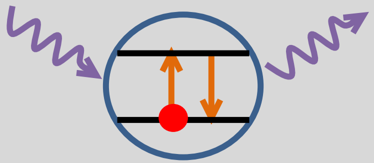
"To Learn: accel temp."

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.



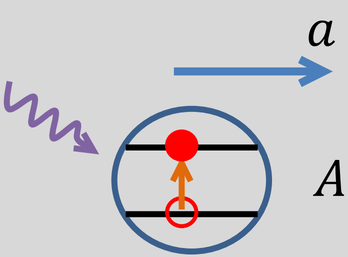
atom at rest



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.



$$A_{21} = a/2\pi c$$

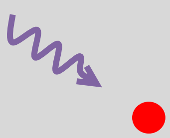
accelerated atom sees itself surrounded by a thermal bath

real photon is emitted to observer

$$F_{\upsilon} = \frac{2\pi h \upsilon^3}{c^2} \frac{1}{e^{\frac{h\upsilon+\mu}{k_B T_U}}-1}$$

A simple picture of the Unruh effect (III)

- Unruh effect is not limited to atoms. Any accelerated “detector” that can change its state will experience this process.
- Moreover, this is not limited to emission of photons. Any particle that can interact with the detector is allowed (**gravitons**, axions, millicharged particles, etc.)
- For detectors without an internal structure, we can consider scattering instead of a two-level transition.



$$A_{21} = \left(\frac{g^2}{4\pi}\right)\left(\frac{a}{2\pi c}\right)$$

accelerated electron sees itself surrounded by a thermal bath

real photon is emitted to observer

$$P_v = \frac{hg^2a^2}{12\pi c^2}$$ Larmor radiation formula

Vacalis et al., arXiv:2310.06127 (2023)
Gregori et al., arXiv:2301.06772 (2023)

Gravitational Bremsstrahlung

- We can use the same formalism 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 **could** corresponds to a strain:

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

- 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)

Summary & conclusions

- Laser technology has evolved rapidly in the past 50 years (Nobel prizes awarded in 2018 and 2023).
- Current high-power laser systems can achieve sufficient energy densities to enable the generation of GWs.
- While the strains are still very small, there are new ideas that use QFT in curved space time that should be explored.
- We are working on expanding our work on the Hawking/Unruh effect to generate a measurable graviton flux.