Strong-field quantum electrodynamics in magnetar magnetospheres

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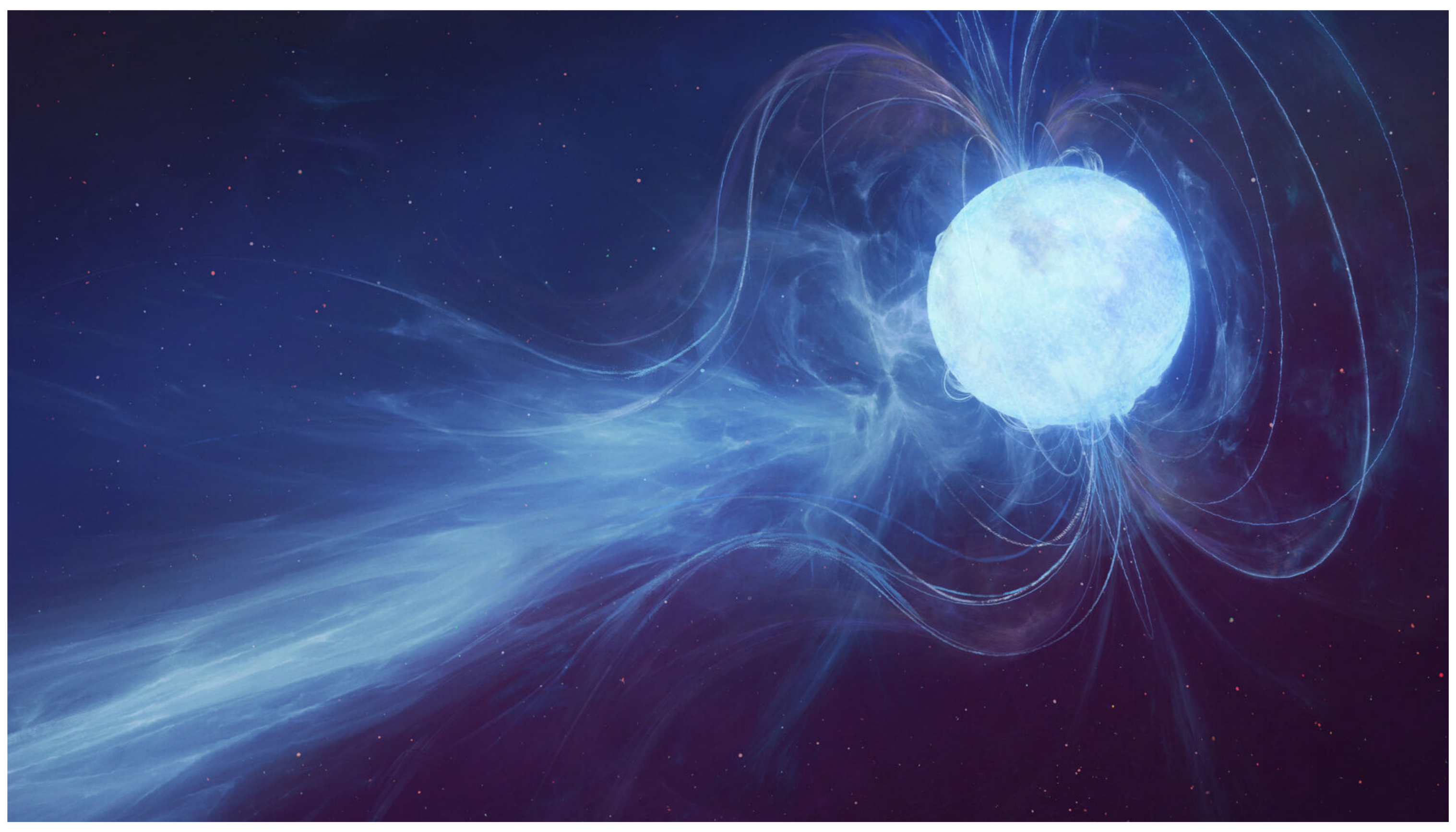
Motivation

Neutron stars are some of the most extreme environments known today. This makes them great objects for testing the limits of our theories of nature. In this work, I have studied how an ultra-strong magnetic field affects quantum electrodynamic (QED) scattering processes in the vicinity of neutron stars.



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Magnetic field of a neutron star.

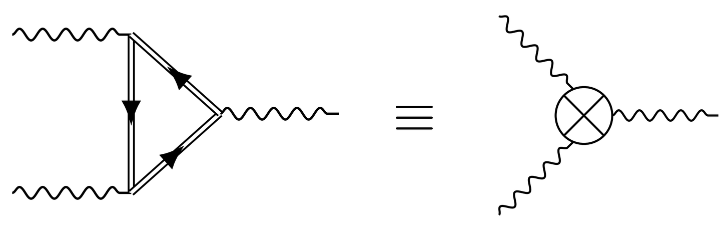
- QED scattering processes are vital for the plasma dynamics of magnetar magnetospheres.
- The origin of the double-peaked structure of magnetar emission spectra is poorly understood.
- A novel computational formalism is required to perform QED calculations in a strong magnetic field.

Magnetars

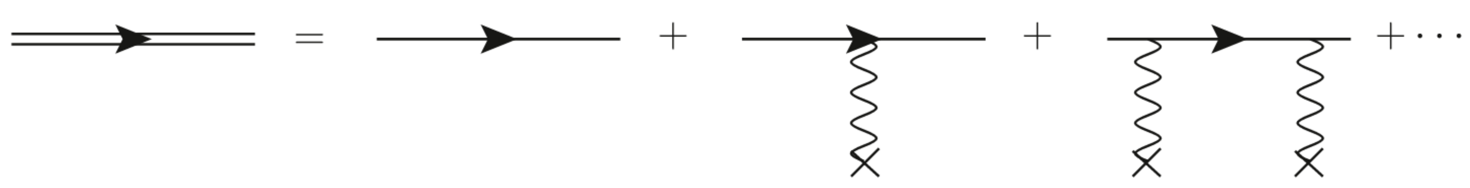
- Neutron stars that host the strongest known long-lived magnetic fields in the universe, $B \sim 10^{15}$ G.
- Born from rapidly rotating progenitor stars, where the magnetic field is amplified by a dynamo effect.
- Sources of many extreme transient phenomena like magnetar bursts and giant flares.

Strong-field QED

- QED becomes nonlinear at magnetic fields $B \gtrsim B_Q \approx 4.41 \cdot 10^{13}$ G.

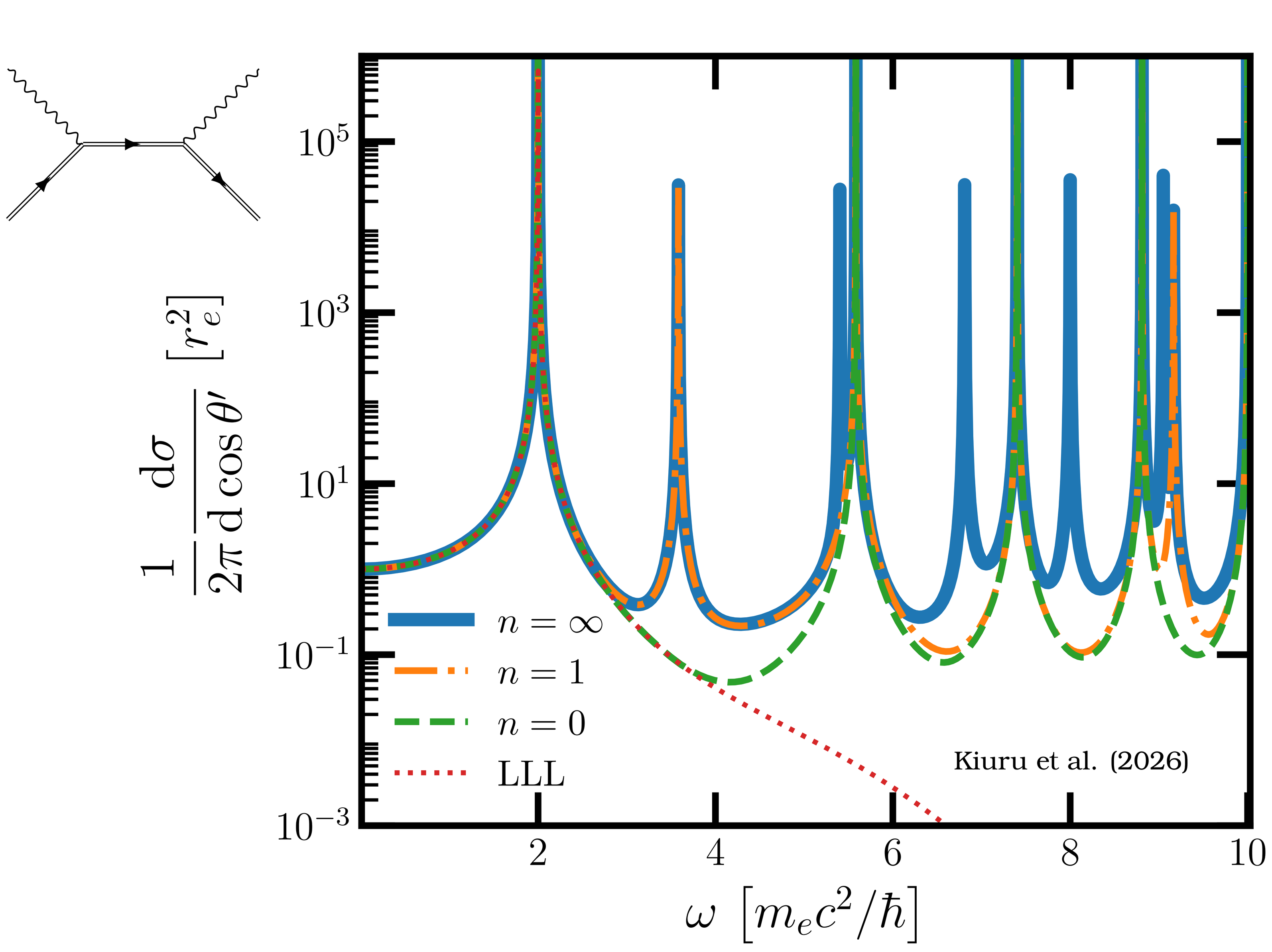


- The Furry expansion allows for a nonperturbative treatment of the magnetic field.

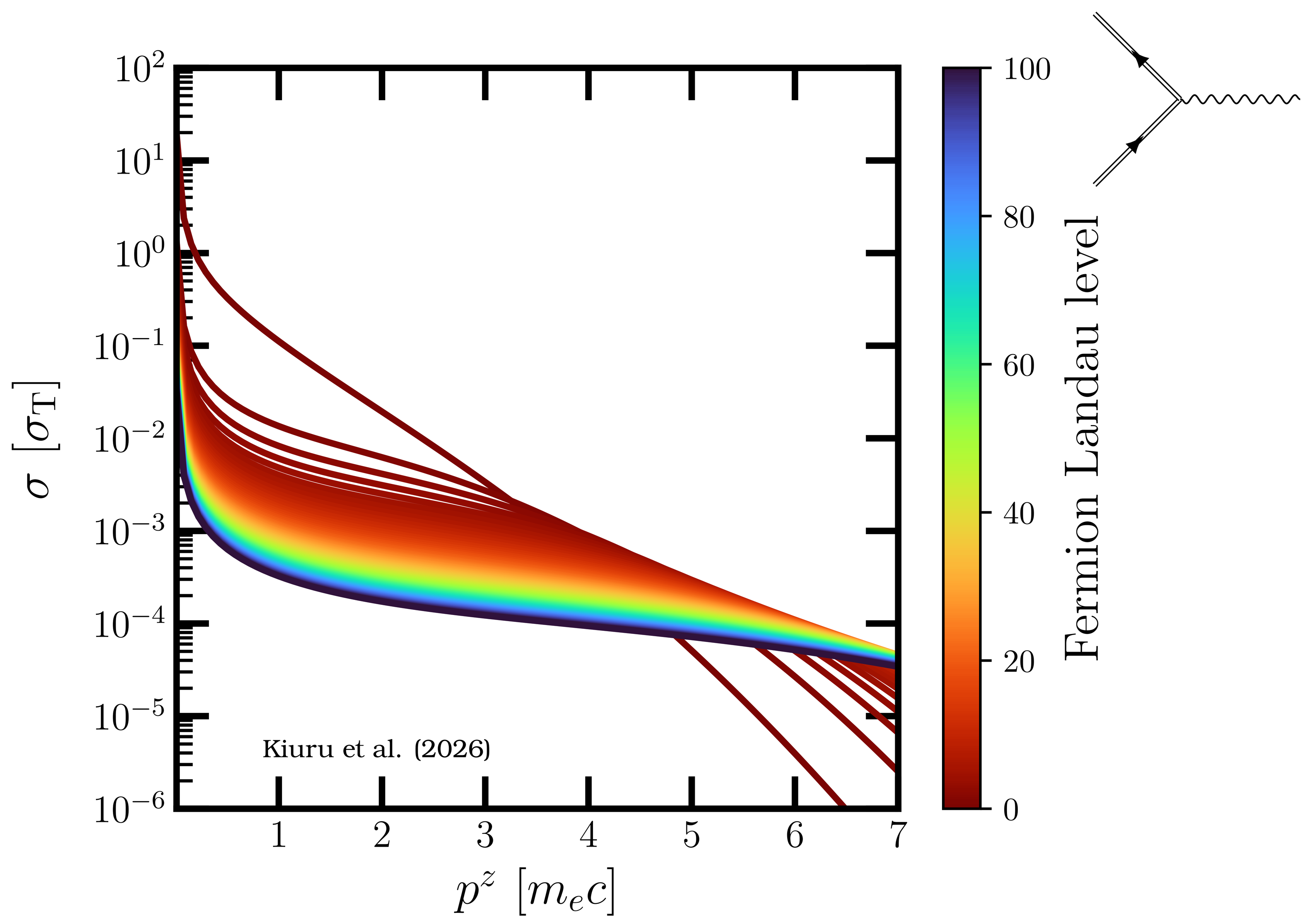


- Electron energies are quantized into *Landau levels* in a magnetic field.
- Resonances appear in the scattering cross section.
- The lowest Landau level (LLL) dominates scattering cross sections for transverse collision momenta $p_\perp \lesssim m\sqrt{\frac{B}{B_Q}}$.

Results



Differential cross section for Compton scattering as a function of the angular frequency of the incoming photon at $B = 10\ B_Q$. The solid blue line stands for the full result, dash-dotted orange and dashed green ones for approximations where the propagator includes the LLL and first excited state or just the LLL, and the red dotted line for the full LLL approximation.



Cross section of one-photon pair annihilation as a function of electron longitudinal momentum p^z at $B = 10\ B_Q$, averaged over incoming spin states and summed over outgoing polarization states. The color coding refers to the shared Landau levels of the electron and positron.

Conclusions

- Our formalism can be used to calculate any SFQED scattering cross section.
- All the results are implemented in an open-source Python package https://github.com/hel-astro-lab/SFQED.
- The Python package gives the user full freedom over all free parameters of the theory: magnetic field strength, particle spin and polarization states, momenta, energies, and Landau levels. $\Rightarrow$ Plasma dynamics of magnetar magnetospheres can be simulated more accurately than ever before.

References

Kiuru O., Nättilä J., Paatelainen R., and Vuorinen A., QED cross sections in strong magnetic fields (2026), arXiv:2603.25491 [hep-ph]
Kiuru O., Evaluation of QED cross sections in strong magnetic fields (2026), arXiv:2603.26545 [hep-ph]