PhD Open Days

Multiscale modeling of pulsar magnetospheres

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Motivation

Modeling one of the most extreme environments in the Universe

Pulsars are compact astronomical objects ($M \sim M_\odot$ in $R \sim 10$ km) that gather a wealth of extreme physical conditions, making them **extraordinary physics laboratories** (for fields as diverse as general relativity, quantum mechanics, and plasma astrophysics). They are surrounded by **strong magnetic fields** ($B \sim 10^{12}$ G) and **support very active, exotic magnetospheres**.

The ultra-intense magnetic field existent in these regions is close to the **Schwinger field** for **vacuum breakdown**, and hence the dynamics of charged particles must take into account the **self-consistent interaction** with these fields, as well as **radiation reaction** and **Quantum Electrodynamics** (QED) mechanisms such as hard photon emission and their subsequent decay that results in electron-positron (e^-e^+) pairs.

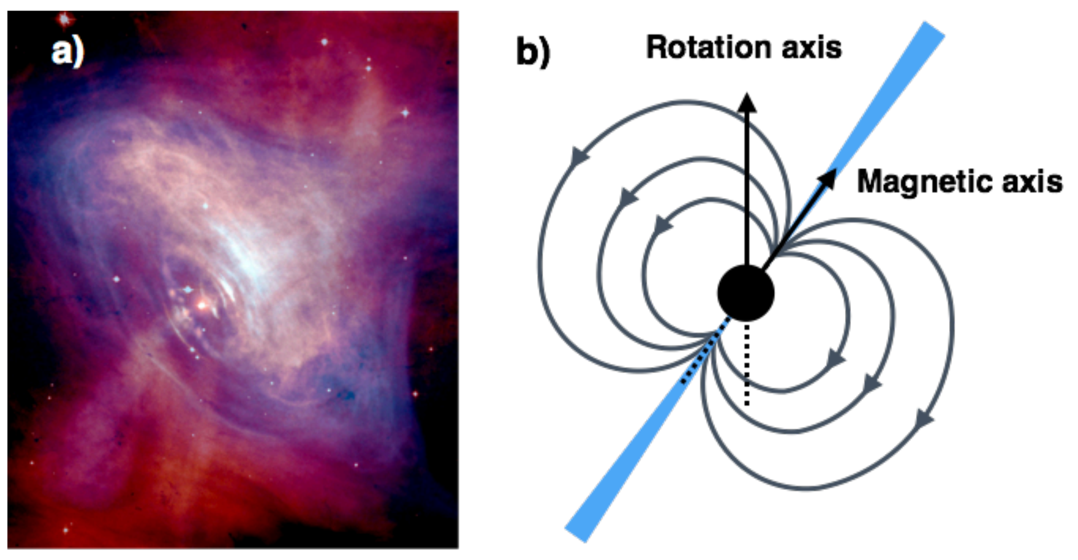


Figure 1: a) composite optical/X-ray image of the Crab Nebula pulsar, credits: NASA/HST/CXC/ASU/J. Hester *et al.*; b) schematic illustration of a pulsar as a rotating neutron star.

Unravelling the dynamics of **astrophysical plasmas** in these environments is a critical step towards a complete understanding of a multitude of pulsar phenomenology, including:

- their **radiation spectrum** and **spin down**;
- their **formation** and the **quasi-steady state** of their **magnetospheres**;
- the acceleration of the most energetic particles in the Universe.

Accurate, *ab initio* **numerical models** of these high energy density systems require **advanced simulation techniques** and remain to be explored.

State-of-the-Art

Main open scientific questions

Q1) How are pulsar magnetospheres formed?
The low altitude regions near the pulsar magnetic poles is thought to be the source of their magnetospheric **e^-e^+ plasma**. In these regions, the presence of strong fields leads to the development of a **cascade** of photons and e^-e^+ pairs.

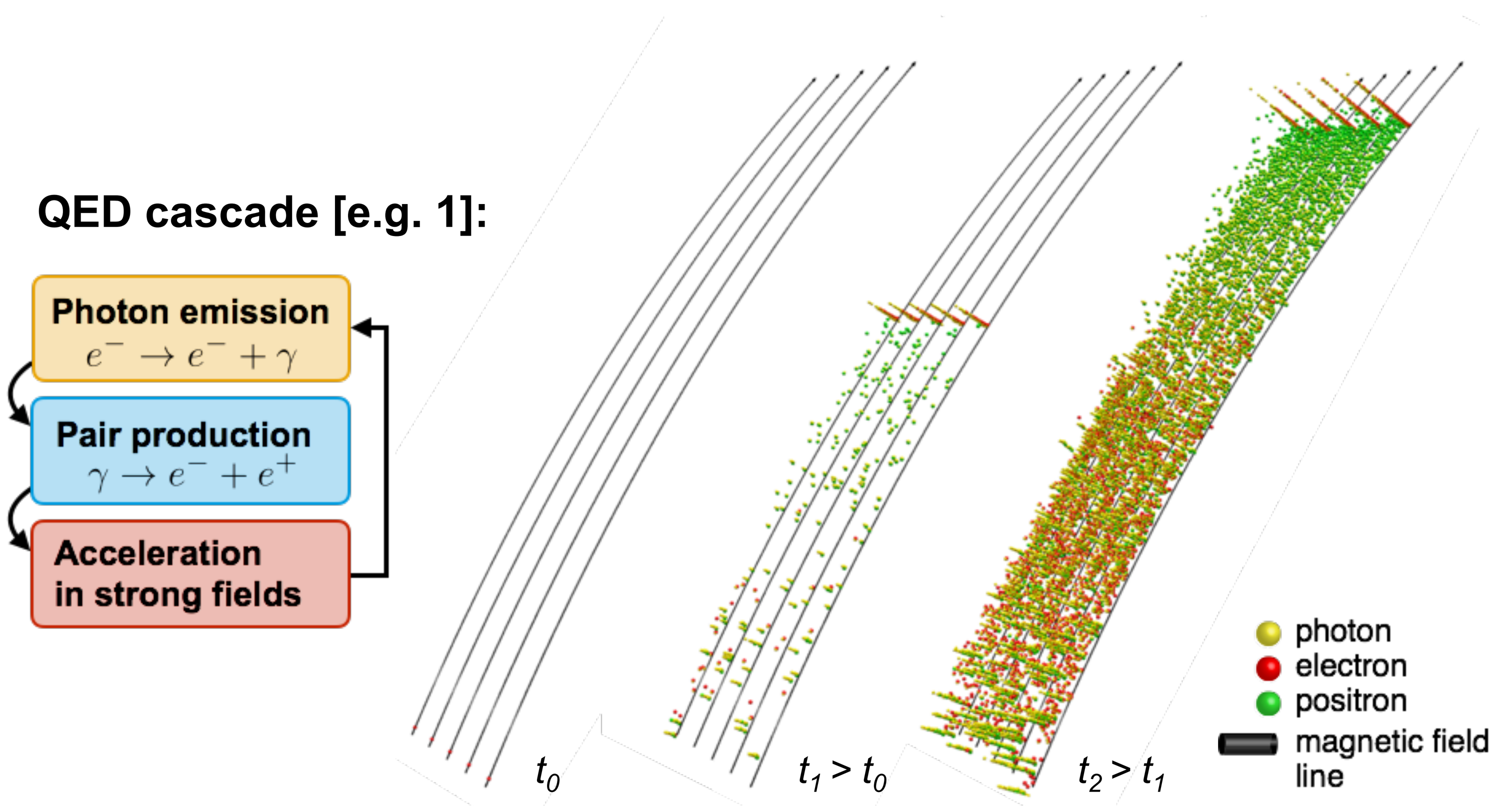


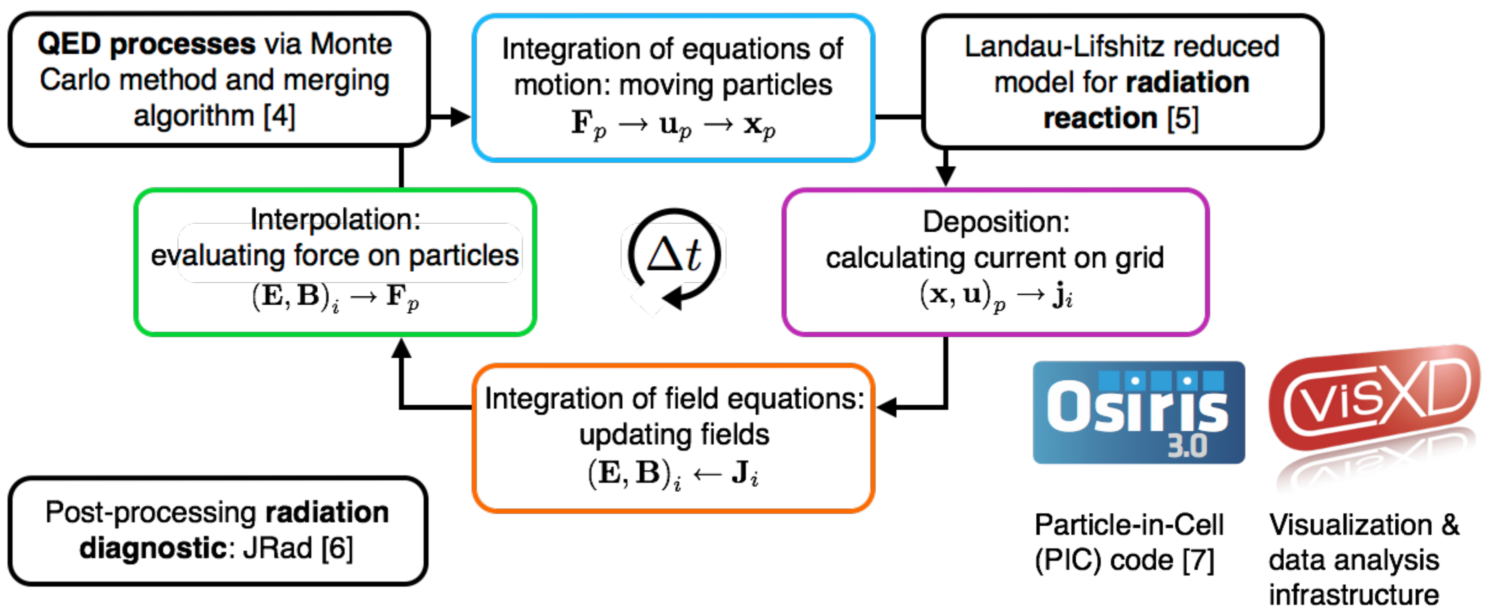
Figure 2: Preliminary *ab initio* simulation of the development of a QED cascade in an ultra-intense, curved magnetic field (comparable to pulsar gaps).

Q2) How to integrate kinetic-scale physics in global pulsar models?
Previous **global models** [e.g. 2] agree on the **general shape** of pulsar magnetospheres, however the intrinsic character of phenomena such as the **production and acceleration of the e^-e^+ plasma** necessary to produce the observed radiation spectrum **requires a kinetic approach** [e.g. 3].

Q3) What are the key radiation emission mechanisms in pulsars?
Can we combine the results from the previous **multiscale approach** and extract the **key radiation signatures** of pulsars from *ab initio* simulations?

Methodology and preliminary results

***Ab initio* QED and radiation modules coupled with PIC**



Current work includes the development of a modified spherical coordinate system in the OSIRIS framework. The different modules of the PIC loop are independently developed and benchmarked.

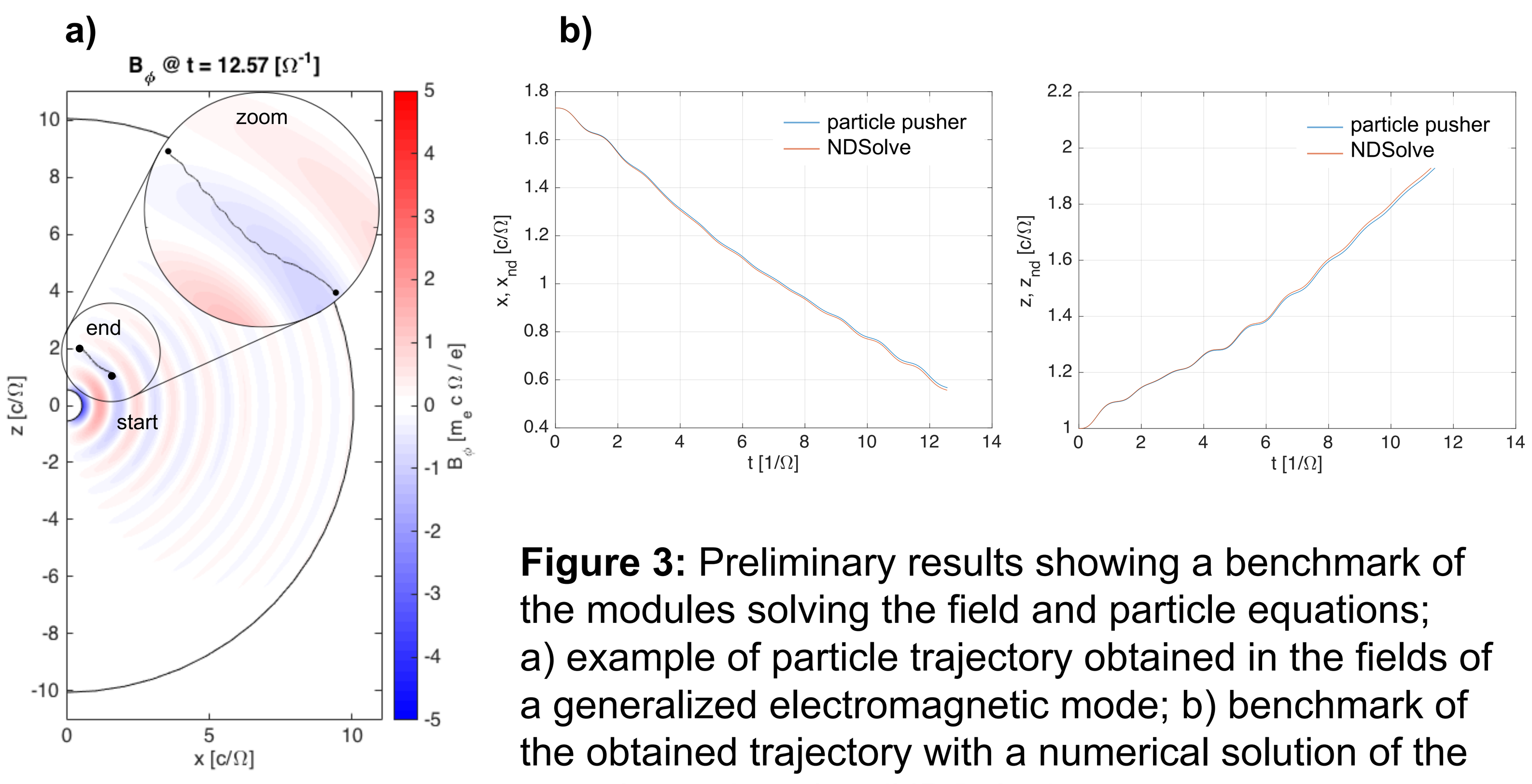


Figure 3: Preliminary results showing a benchmark of the modules solving the field and particle equations; a) example of particle trajectory obtained in the fields of a generalized electromagnetic mode; b) benchmark of the obtained trajectory with a numerical solution of the equations of motion (NDSolve).

Summary

Multiscale analysis is critical to understand particle and radiation spectra of pulsar magnetospheres

- It requires the development of *ab initio* theoretical and numerical models of QED cascades and their connection with global, macroscopic models
- It has the potential to make impact in the field, resorting to a suite of recent numerical tools integrated in the OSIRIS framework

References and Acknowledgements

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