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Radiation Spectra from Magnetic Reconnection using PIC Simulations

Interlinking experiment and theory

Sergey Ermakov; Klaus Steiniger; Richard Pausch

06.06.2024

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1. PIConGPU radiation Calculation
2. Pritchett Setup
3. Previous Work
4. Radiation Analysis - Frequency Spectra
5. Radiation Analysis - Polarization

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Preliminaries:
Radiation Calculation in PIConGPU

Single Particle Radiation Calculation

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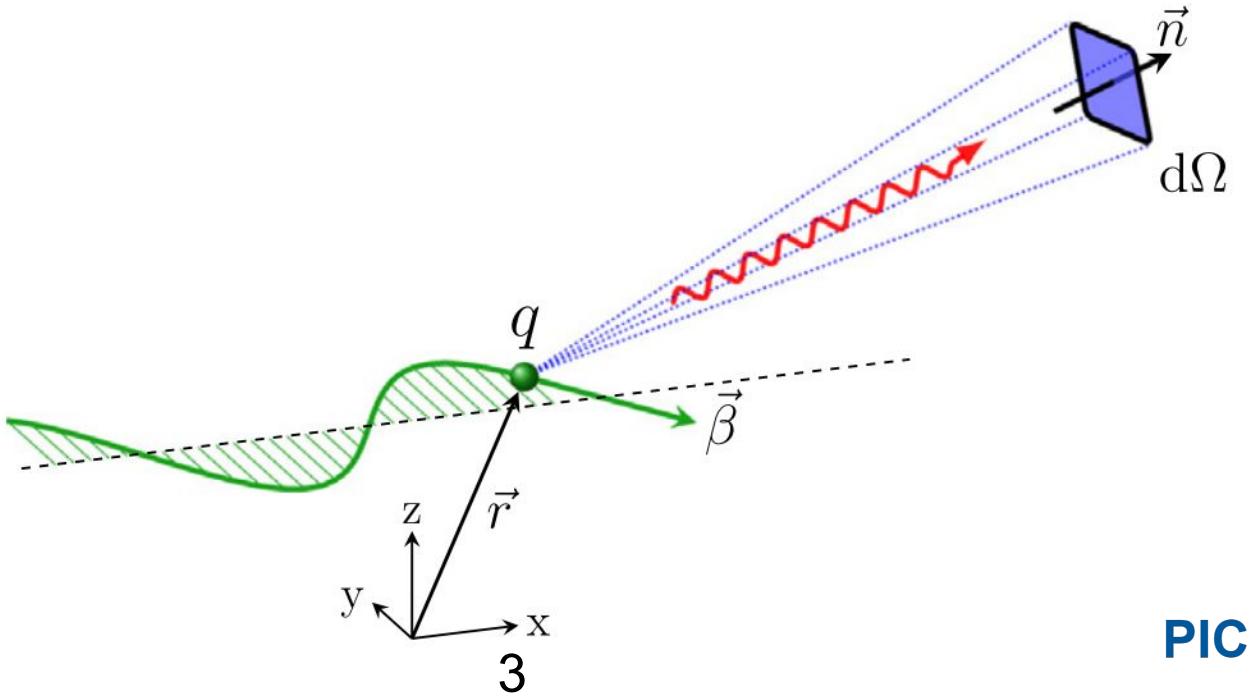
$$\vec{E}(\vec{r},t) = \vec{E}^{\text{vel}}(\vec{r},t) + \vec{E}^{\text{acc}}(\vec{r},t)$$



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Single Particle Radiation Calculation

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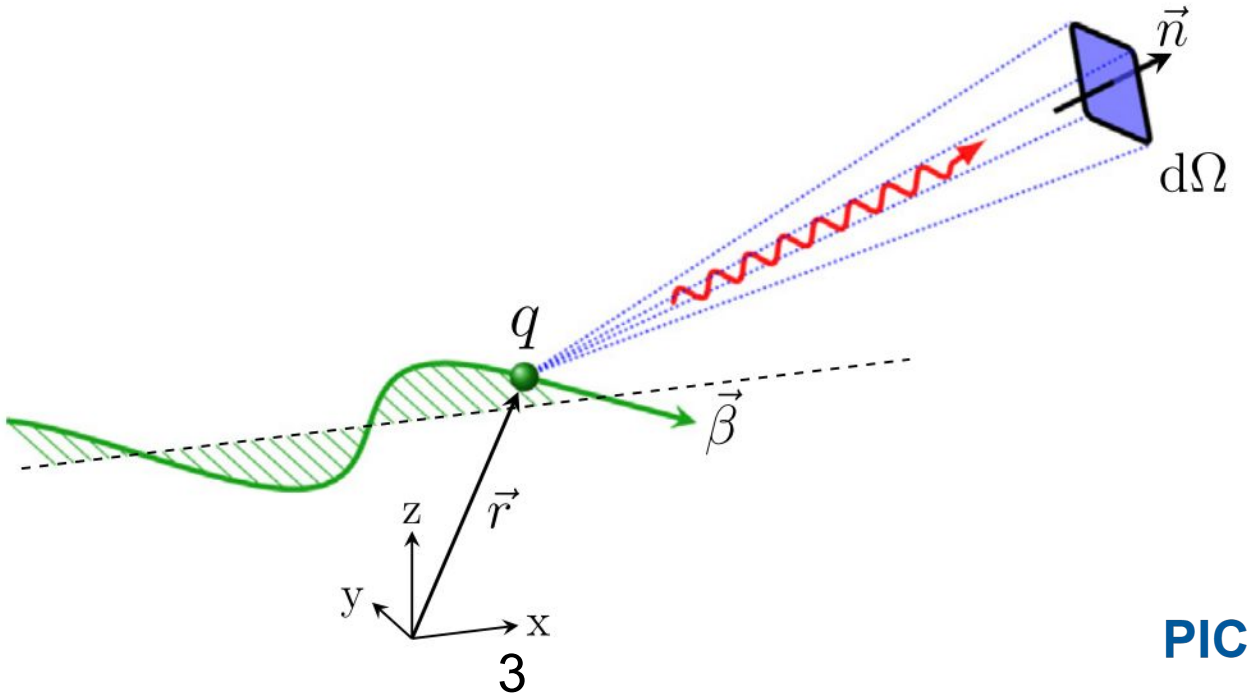
$$\vec{E}(\vec{r},t) = \vec{E}^{\text{vel}}(\vec{r},t) + \vec{E}^{\text{acc}}(\vec{r},t) \longrightarrow$$



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Single Particle Radiation Calculation

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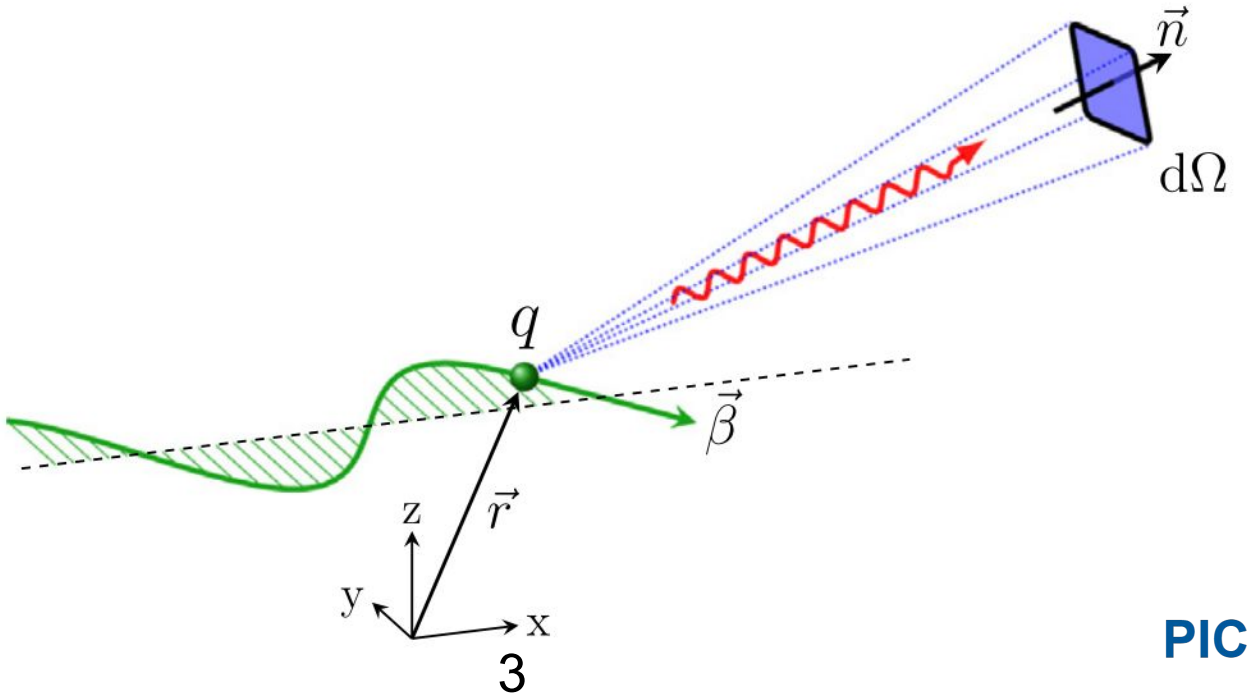
$$\vec{E}(\vec{r},t) = \vec{E}^{\mathrm{vel}}(\vec{r},t) + \vec{E}^{\mathrm{acc}}(\vec{r},t) \longrightarrow \frac{\mathrm{d}^2 W}{\mathrm{d}\,\Omega\,\mathrm{d}\,\omega} = \frac{1}{16\pi^3\varepsilon_0 c}\left|\sum_{k=1}^{N_p}\int_{-\infty}^{+\infty} q_k \cdot \frac{\vec{n}\times\left[\left(\vec{n}-\vec{\beta}_k\right)\times\dot{\vec{\beta}}_k\right]}{\left(1-\vec{\beta}_k\cdot\vec{n}\right)^2}\cdot \mathrm{e}^{\mathrm{i}\omega(t-\vec{n}\cdot\vec{r}_k(t)/c)}\,\mathrm{d}\,t\right|^2$$



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Multiple Particles Radiation Calculation

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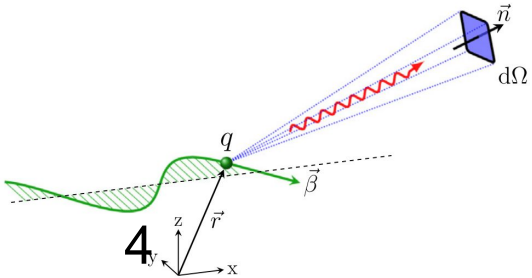

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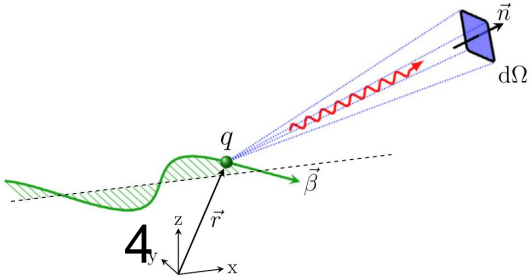
Lienard Wiechert



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Multiple Particles Radiation Calculation

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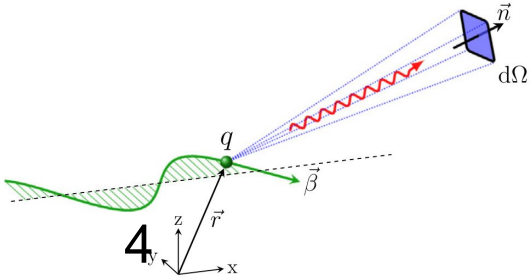
Lienard Wiechert

Fourier Transform



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Multiple Particles Radiation Calculation

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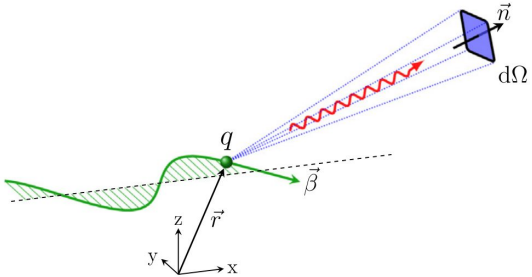
Contribution from selected Particles

Lienard Wiechert

Fourier Transform



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Multiple Particles Radiation Calculation

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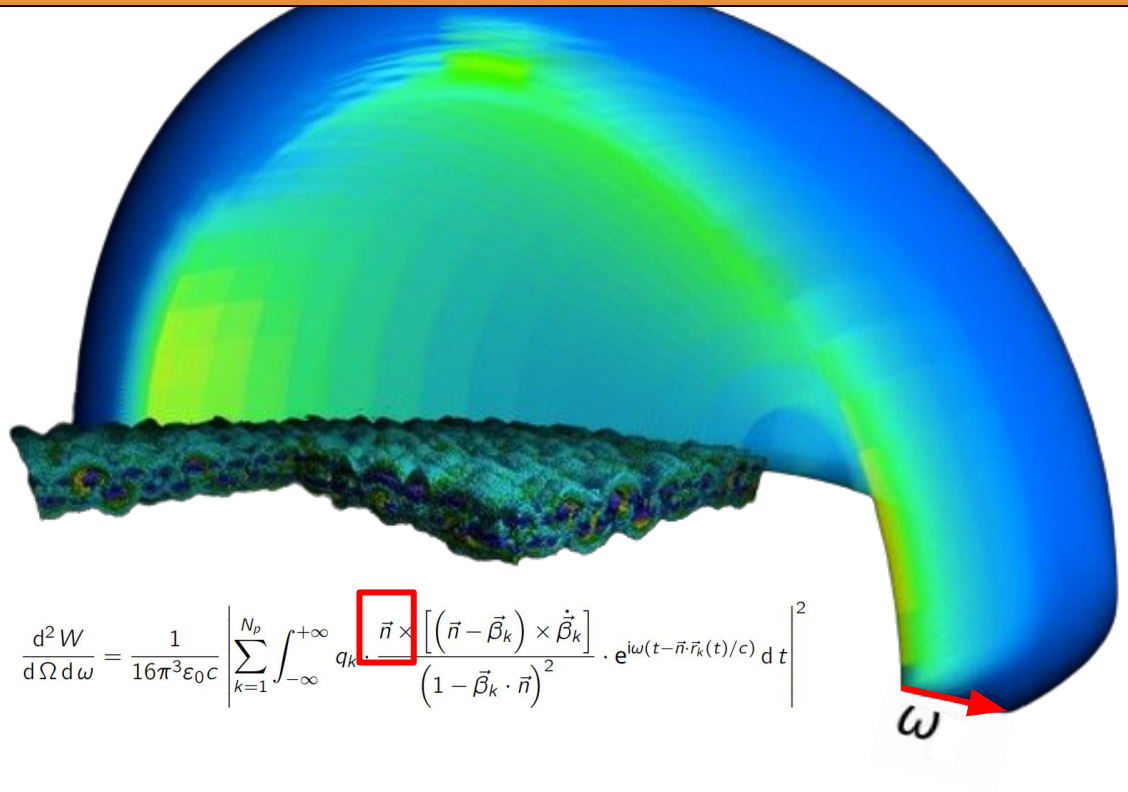

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- Probing radiation from various directions
- Especially important for astrophysical contexts!

  → Understand every possible angle

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Radiation Calculation - In Total

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- “Very accurate” radiation calculation
- Angular resolution
- Selectively choosing radiative particles

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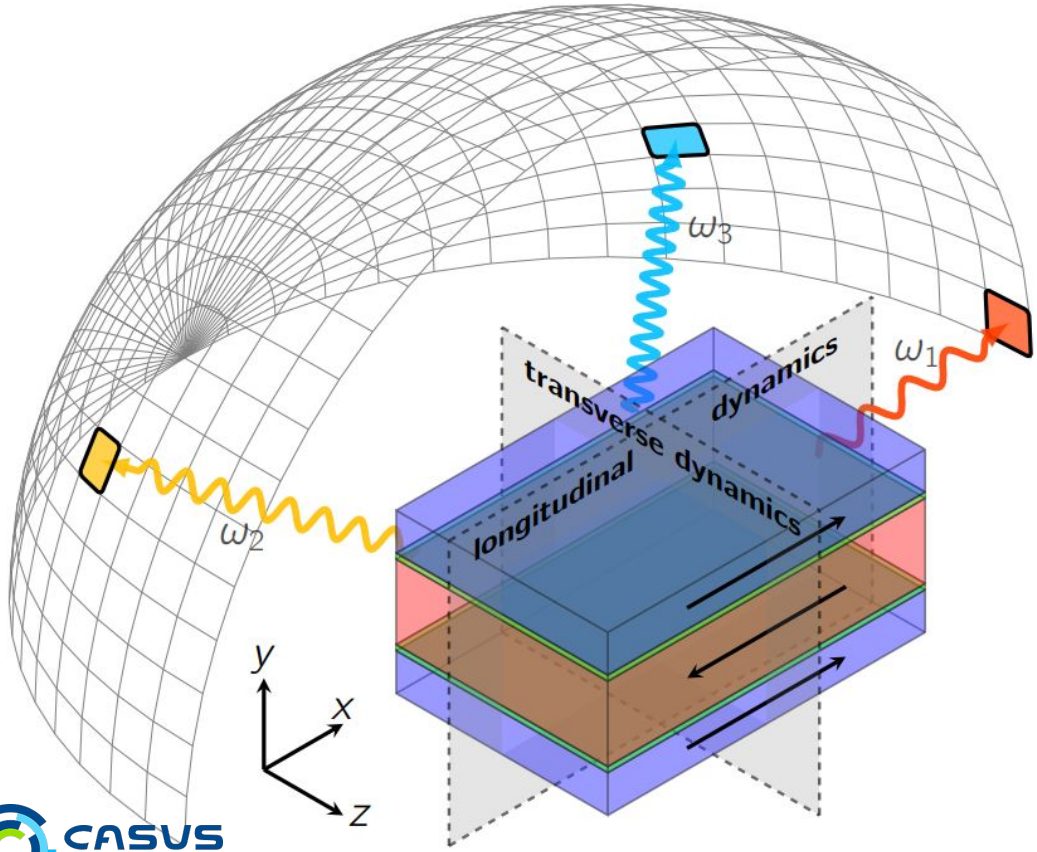
Preliminaries:
Pritchett Setup and Relevant Dynamics

Pritchett Like Setup - General Idea



Pritchett Like Setup - General Idea

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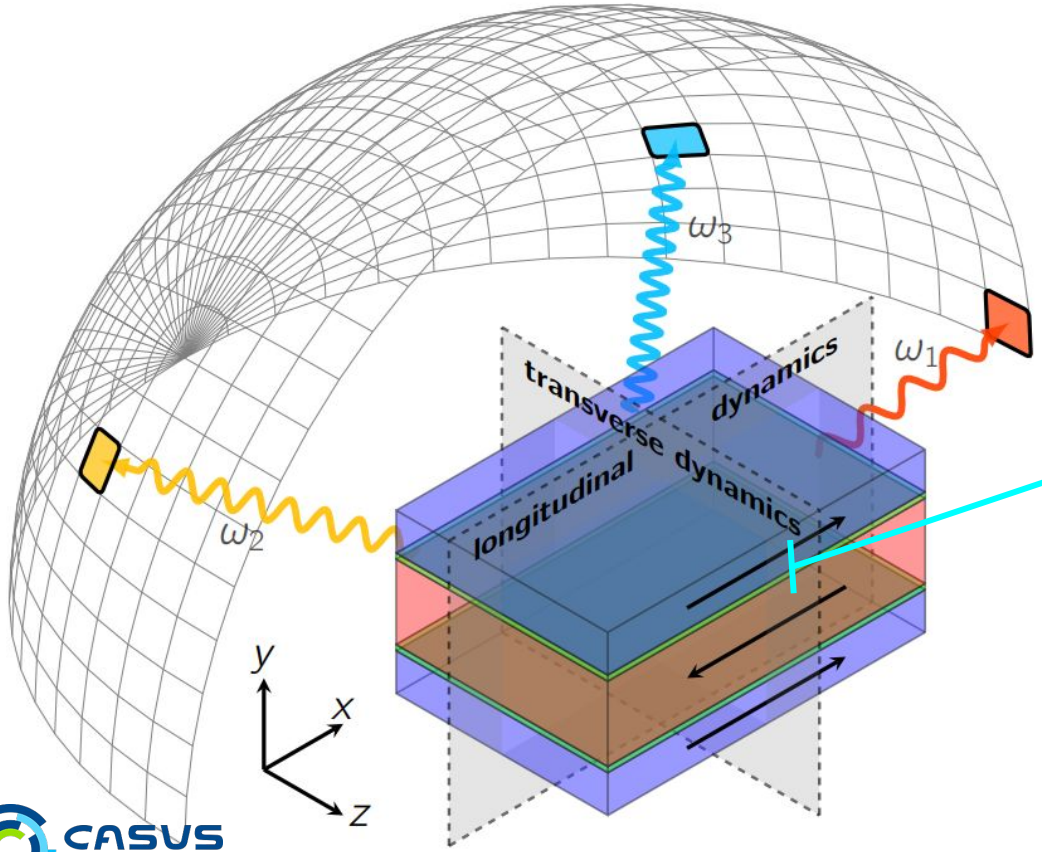

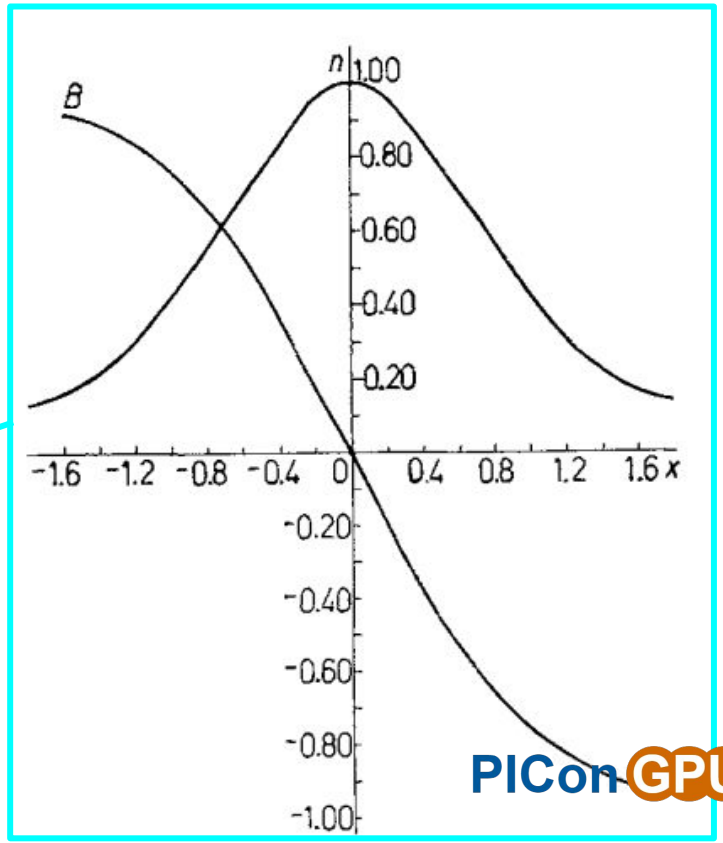

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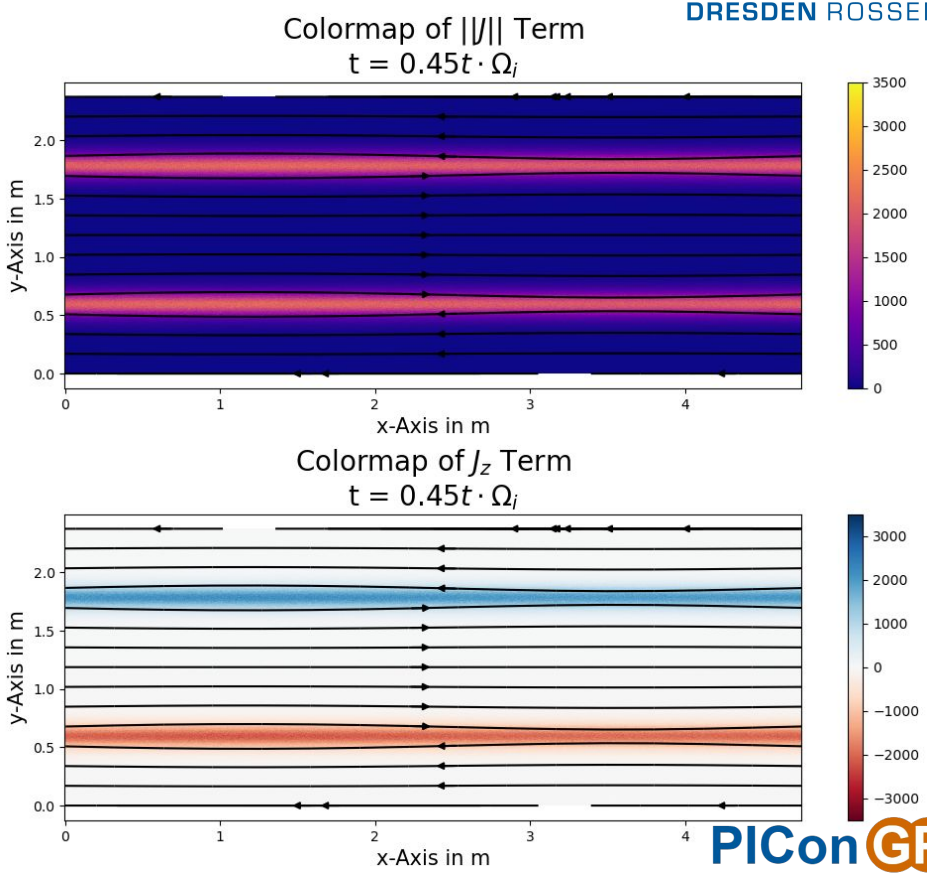
Pritchett Like Setup - Parameters

- $\frac{m_i}{m_e} = 25$
- $\frac{T_i}{T_e} = 5$
- $T_i = 1\text{keV}$
- $\frac{n_B}{n_0} = 0.1$
- $\gamma = 1.00048$
- $B_0 = 0.001T$



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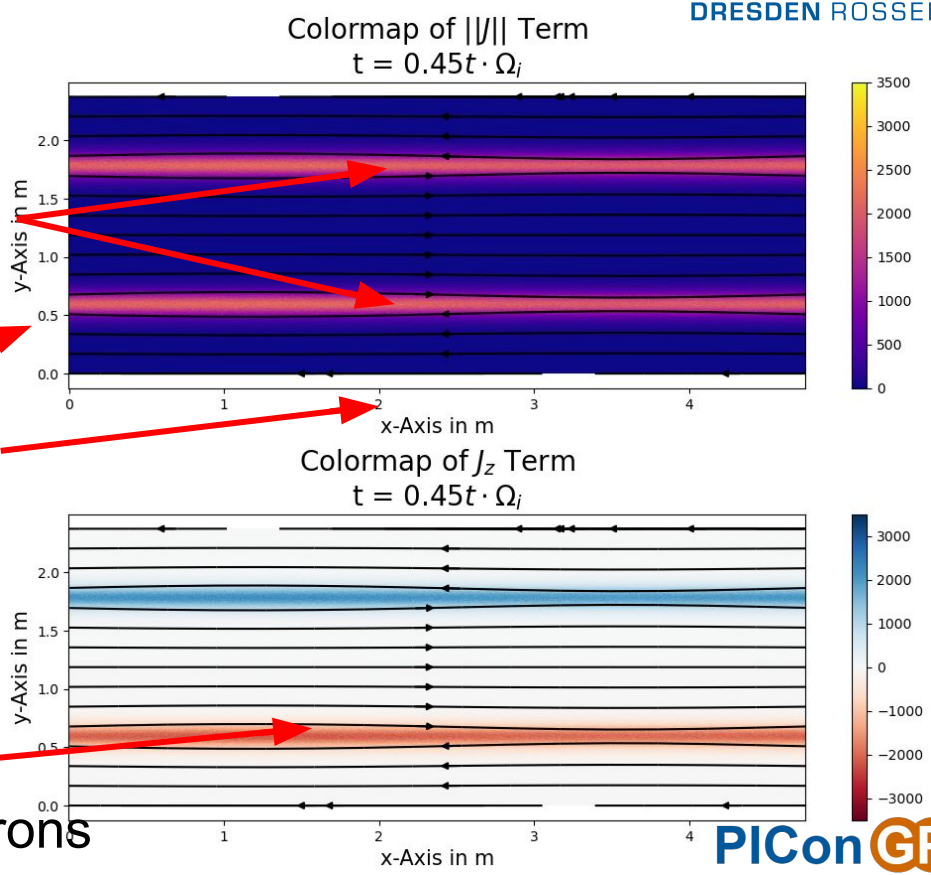
Double Current Sheet

Periodic Boundaries

Radiation Electrons Sampled Here



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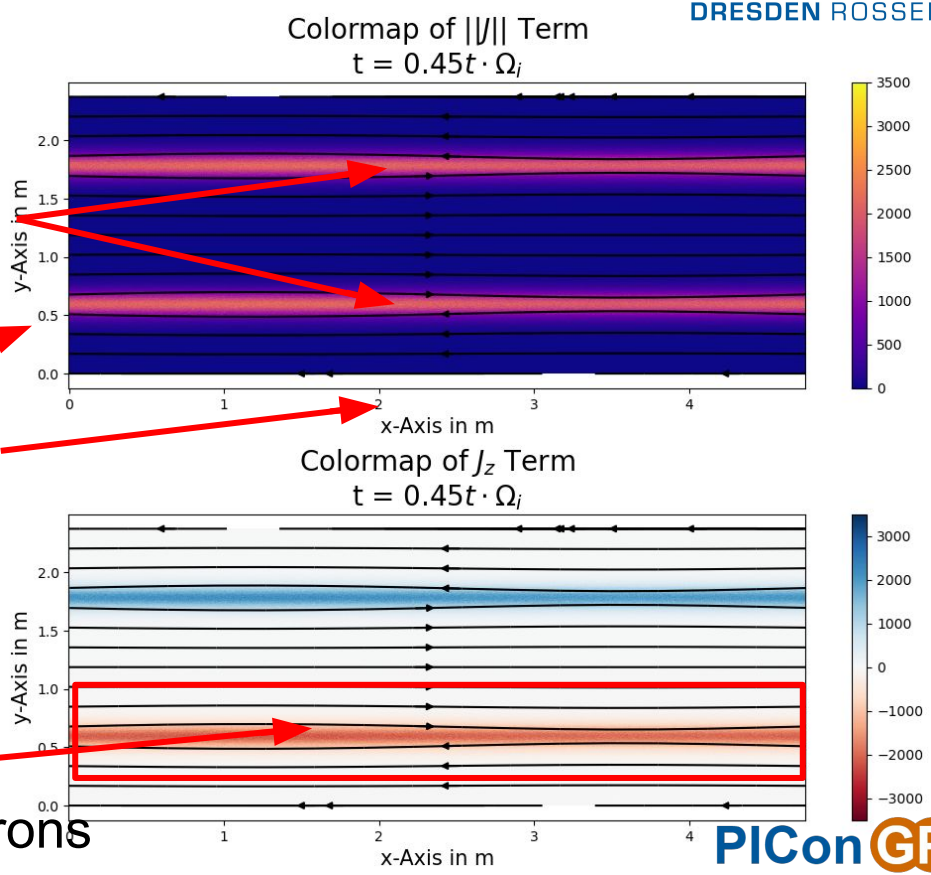
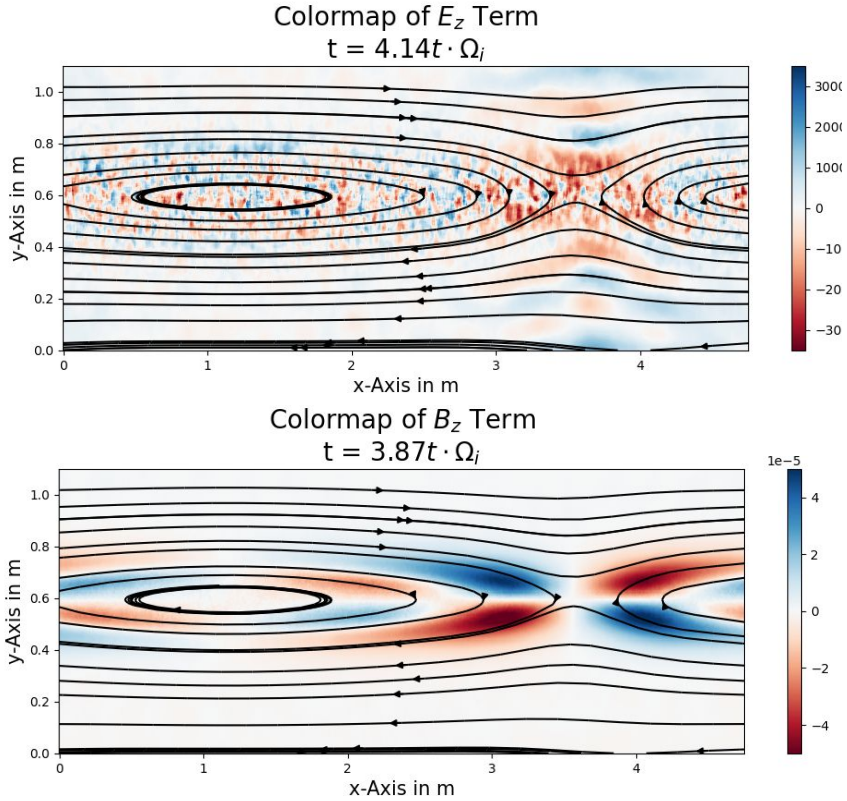
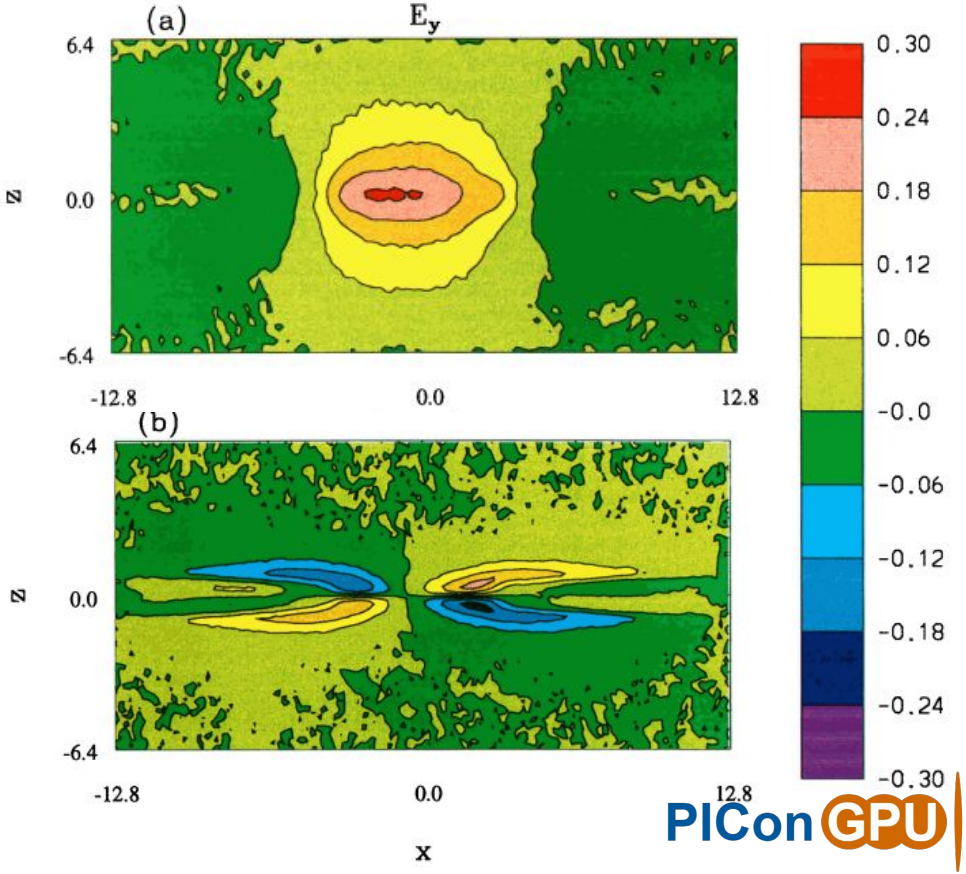


Pritchett Like Setup - Comparison





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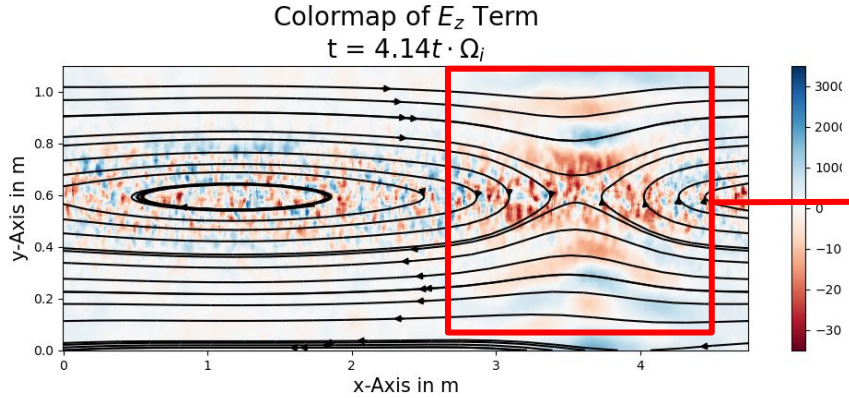

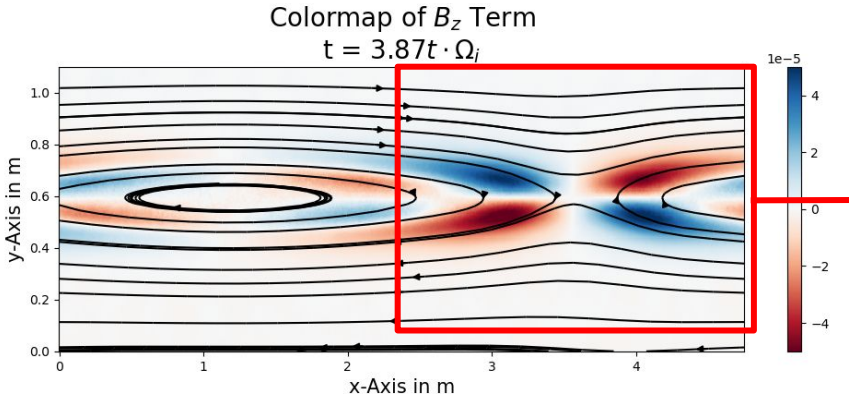

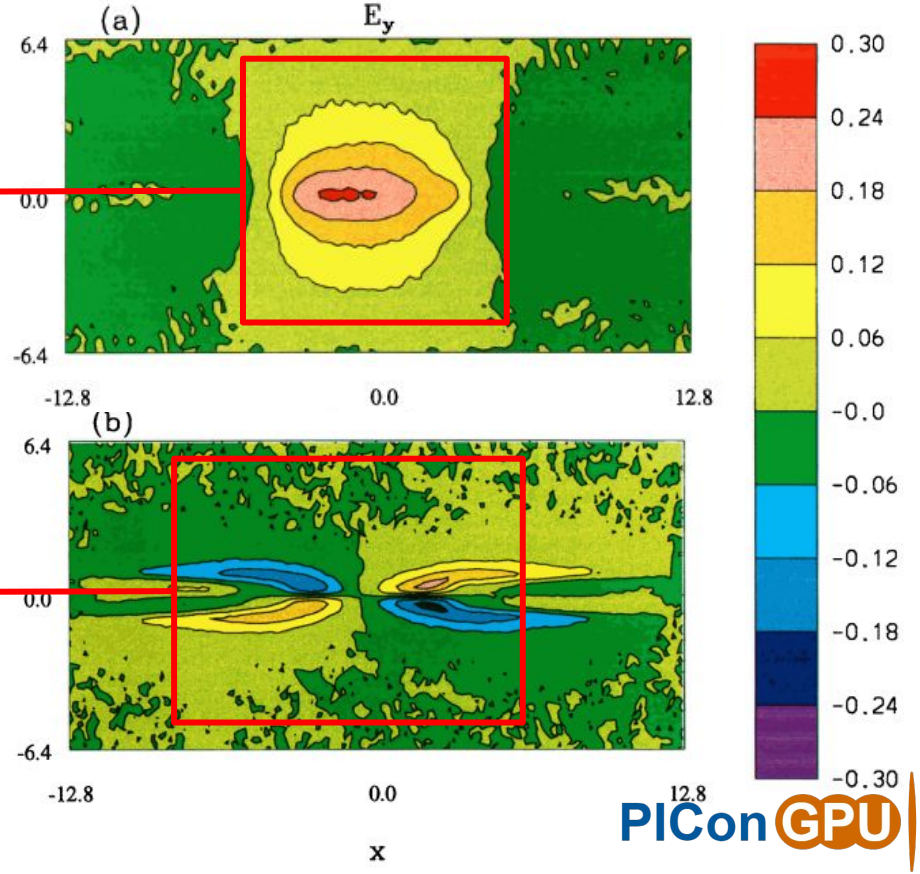

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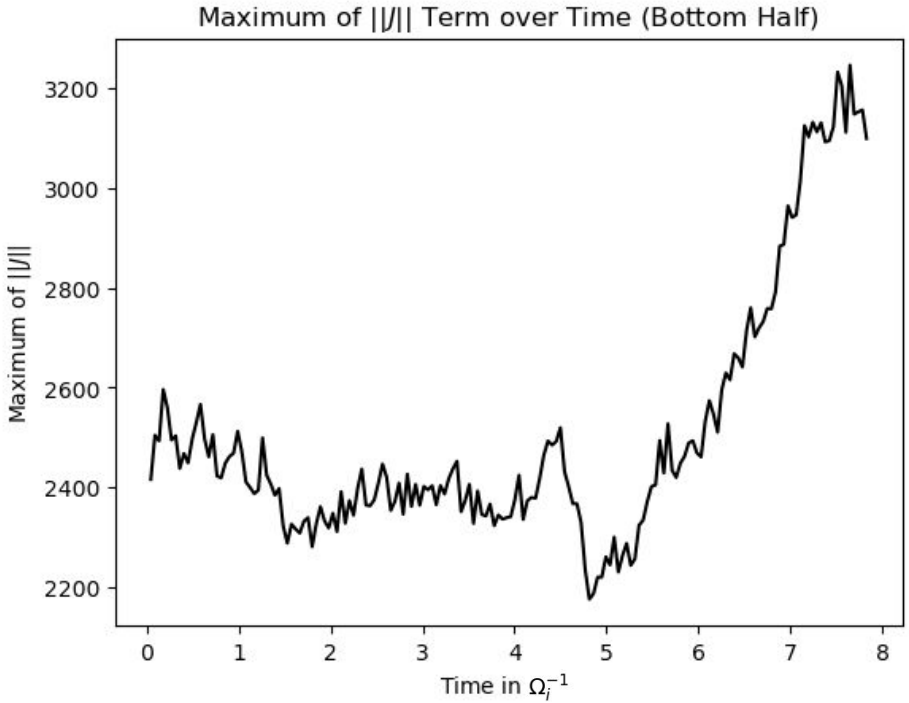
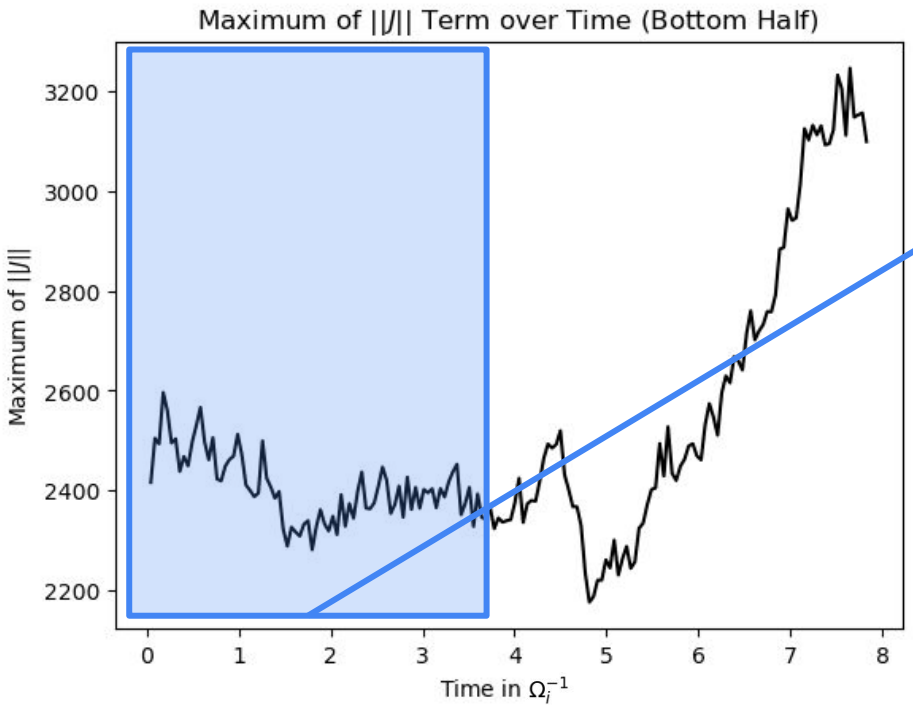
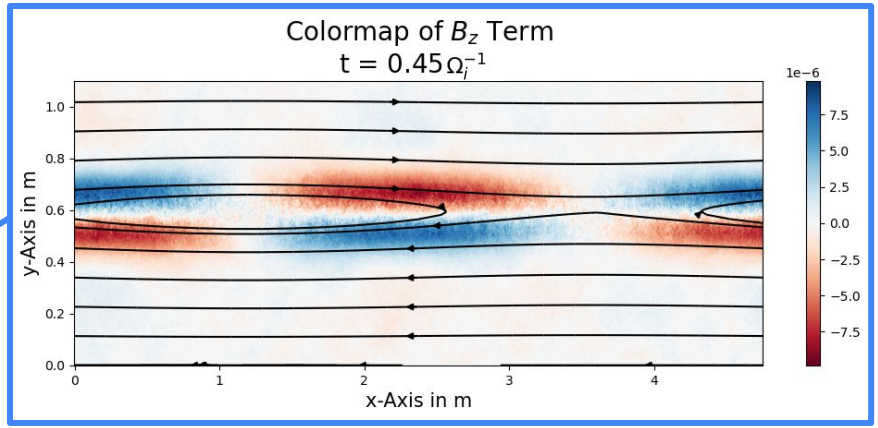
Dividing Dynamics into Time Periods



Dividing Dynamics into Time Periods





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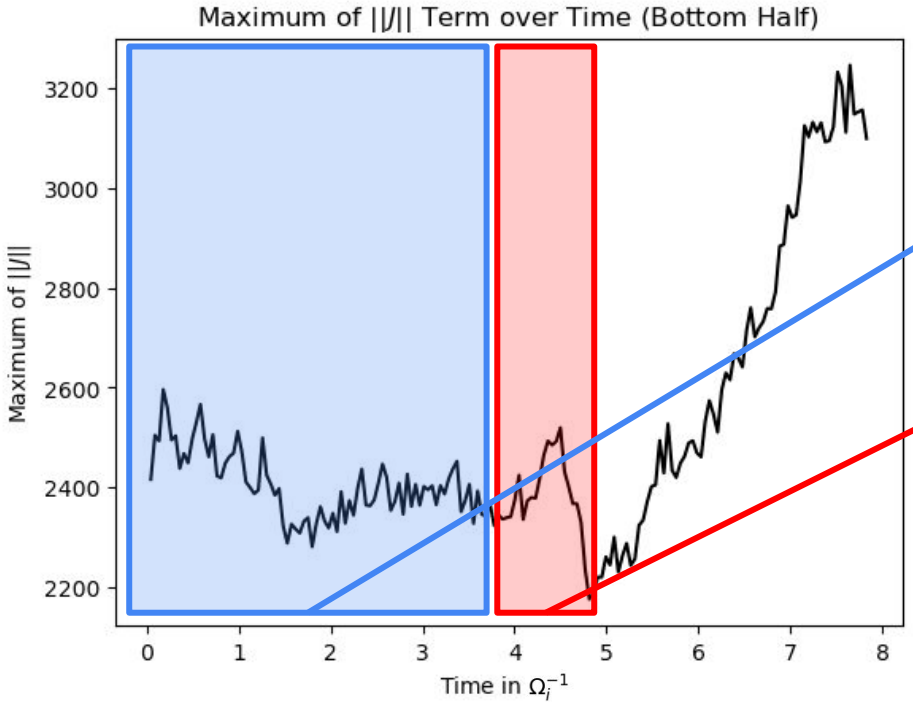

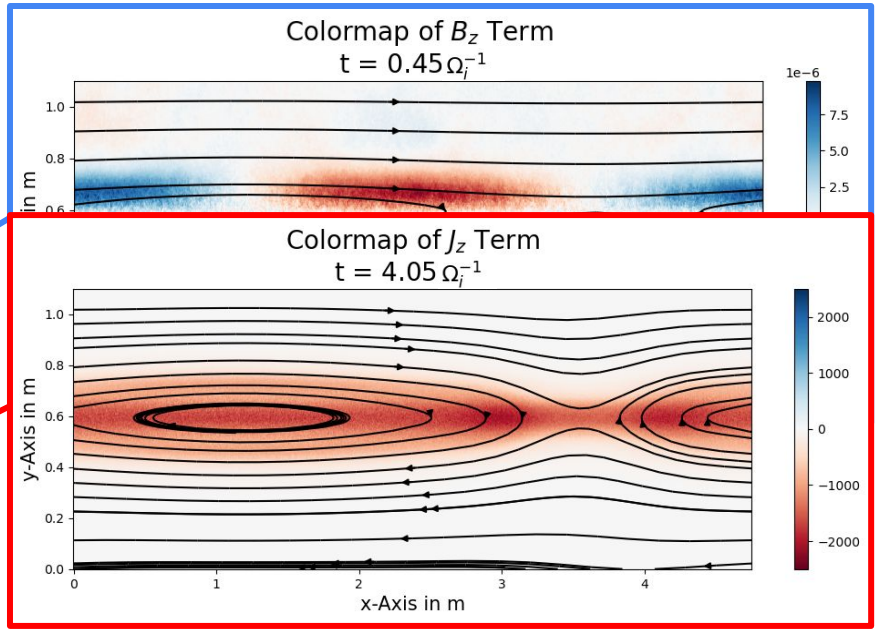

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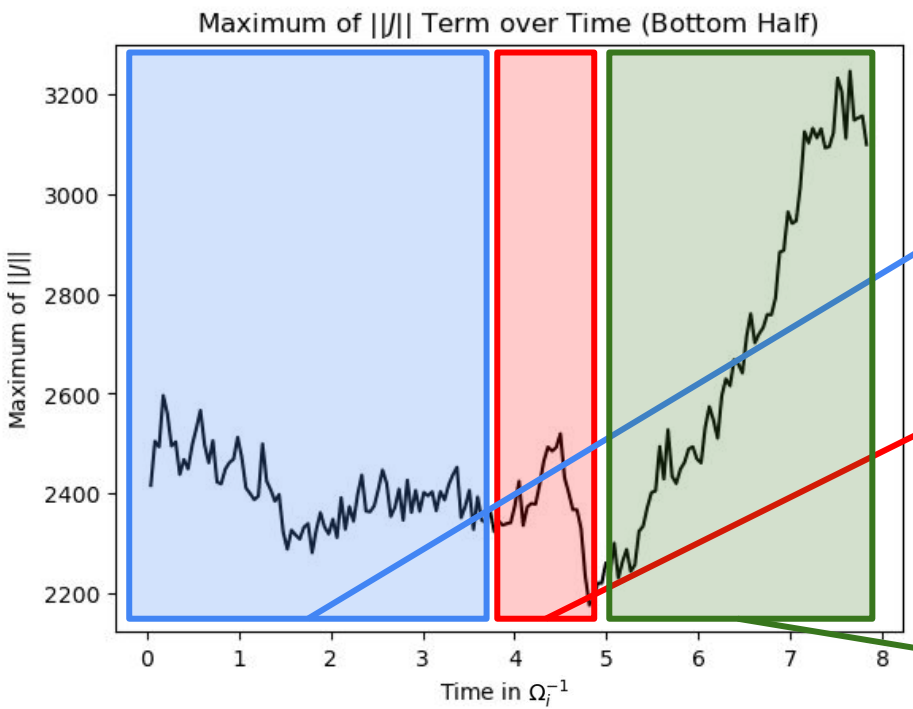

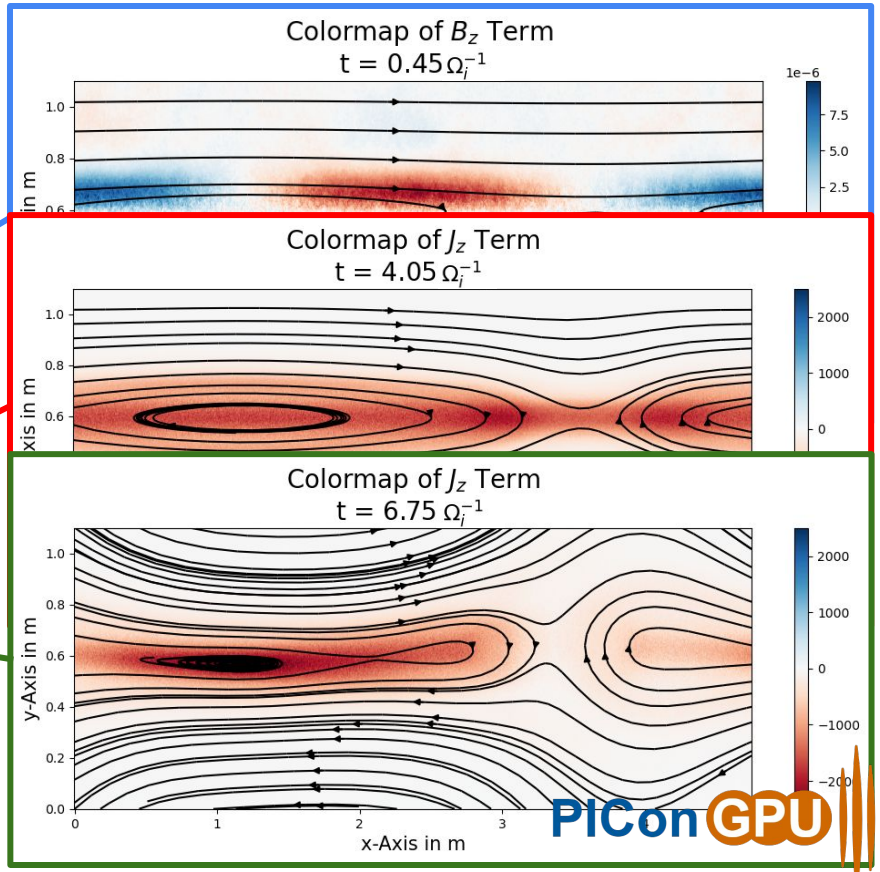

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Pritchett Like Setup - Summary

- Setup consists of Pritchett parameters, used for double current sheet
- Still dynamics identical
- Subdivision into three parts

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Preliminaries:
Previous Work on Radiation of MR

Why Work on Radiation Spectra?

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- Allow for experimentally testable simulations
- Magnetic reconnection serves as a theory for many astrophysical phenomena
- Previous works on Blazars, we search for near earth environment

Zhang's Model for MR Radiation

- Examines relativistic reconnection of Blazars
- Uses Synchrotron Model
  → divides simulation box into parts
  → each part uses average magnetic field and energy distribution to calculate radiation power
- Considers only out of plane direction

Zhang's Result for Radiation Signatures

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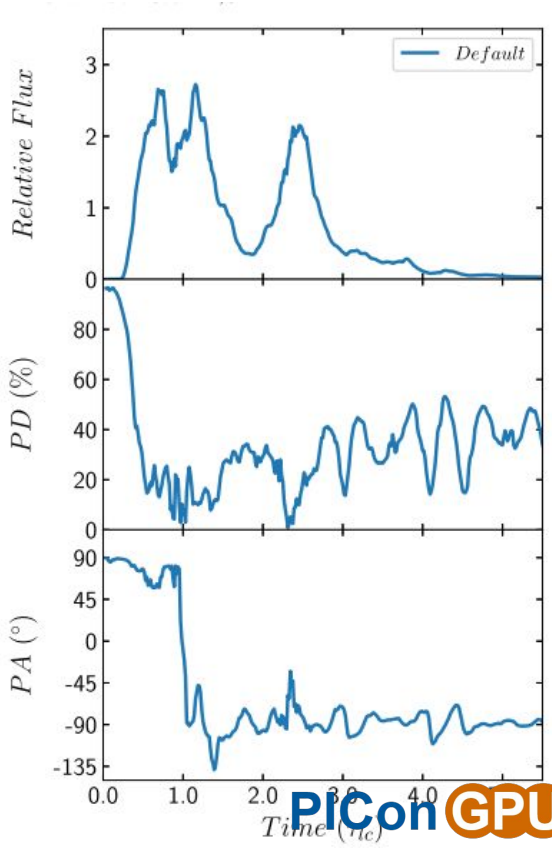
- Radiation flux peak at reconnection and plasmoid merging
- Further Examinations on Polarization Degree
- Unique reconnection signature: Merging of plasmoids causes PA-Swing, direction of swing depends on dominant MF-direction



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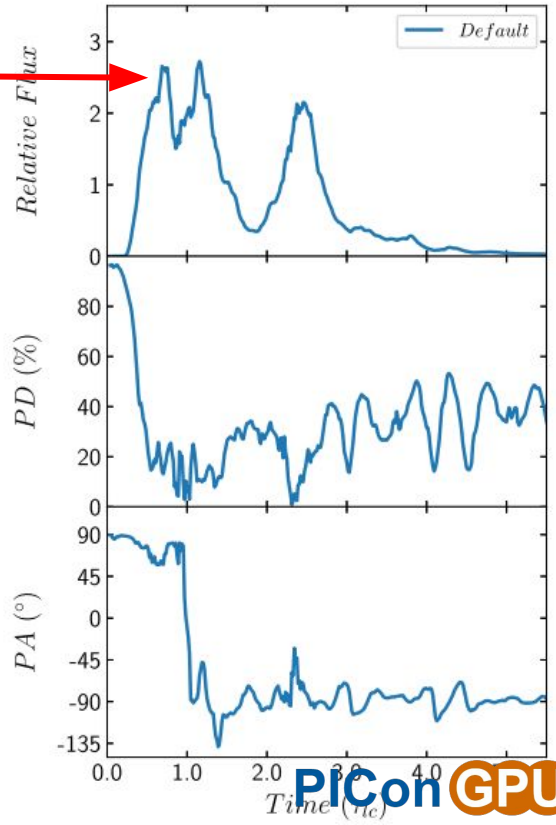

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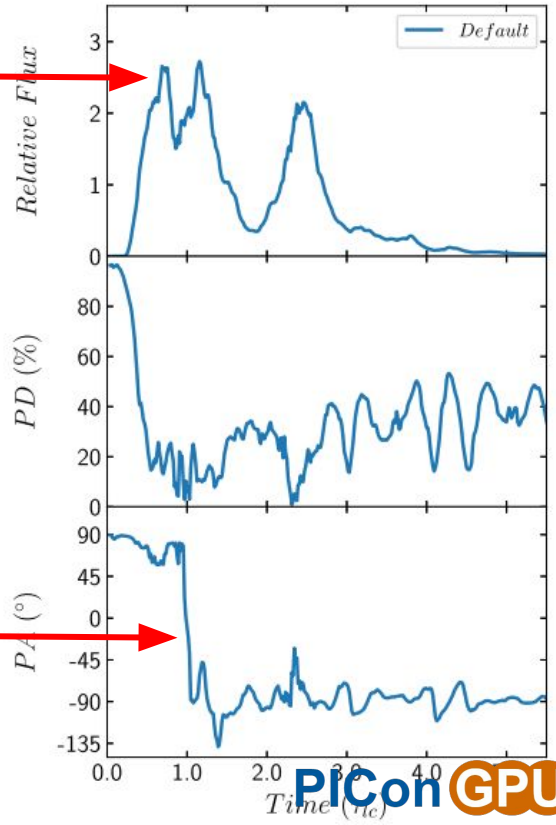

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Radiation Calculation - In Total

- Relativistic magnetic reconnection- focuses on Blazars
- Radiation model is limiting
- Results show characteristic PA swing

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Radiation Analysis of MR:
Time Evolution of Radiation Spectra

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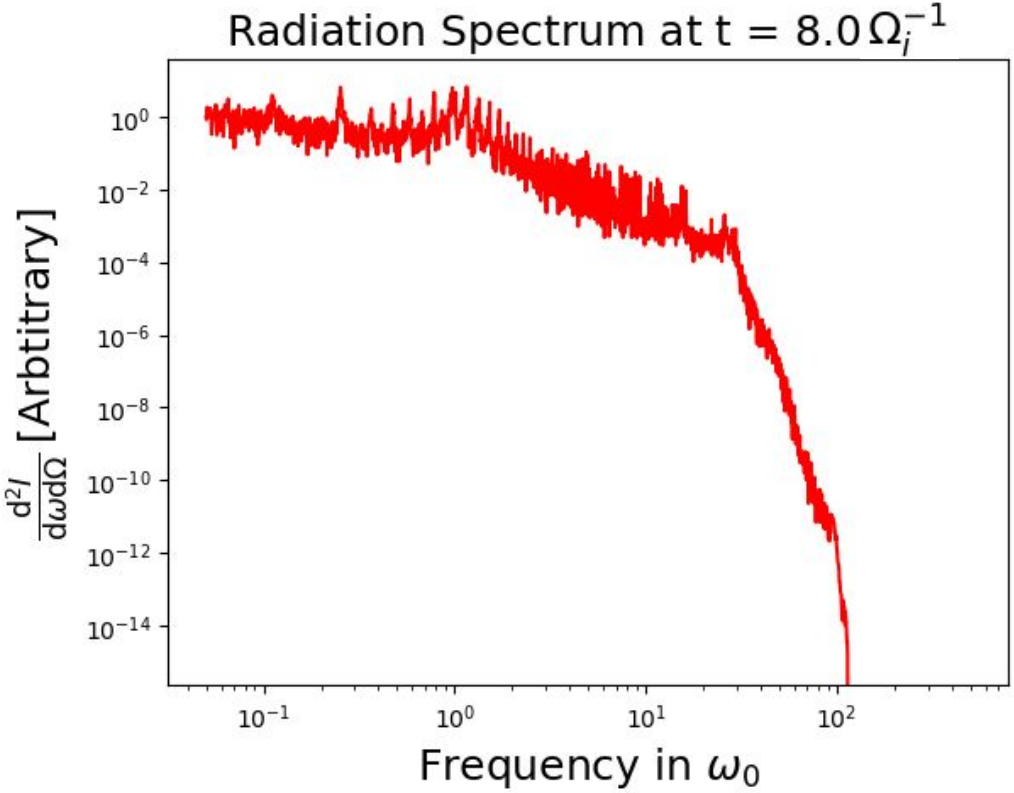
Radiation Spectra Inspected over Time



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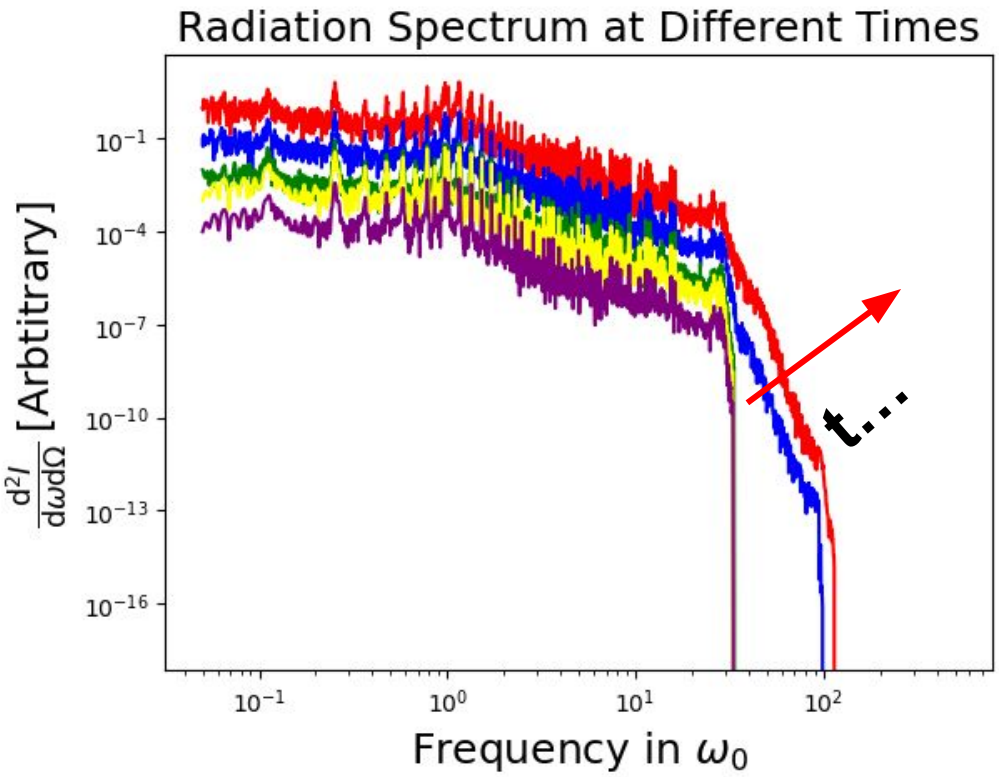
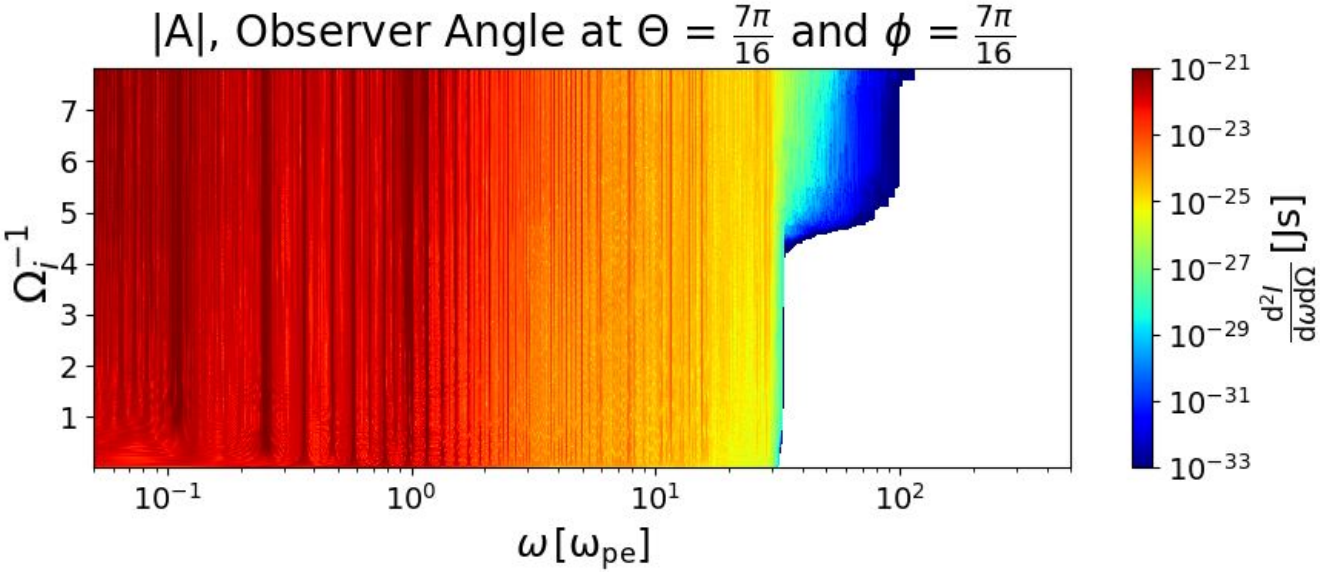


Radiation Features and Peaks in Time



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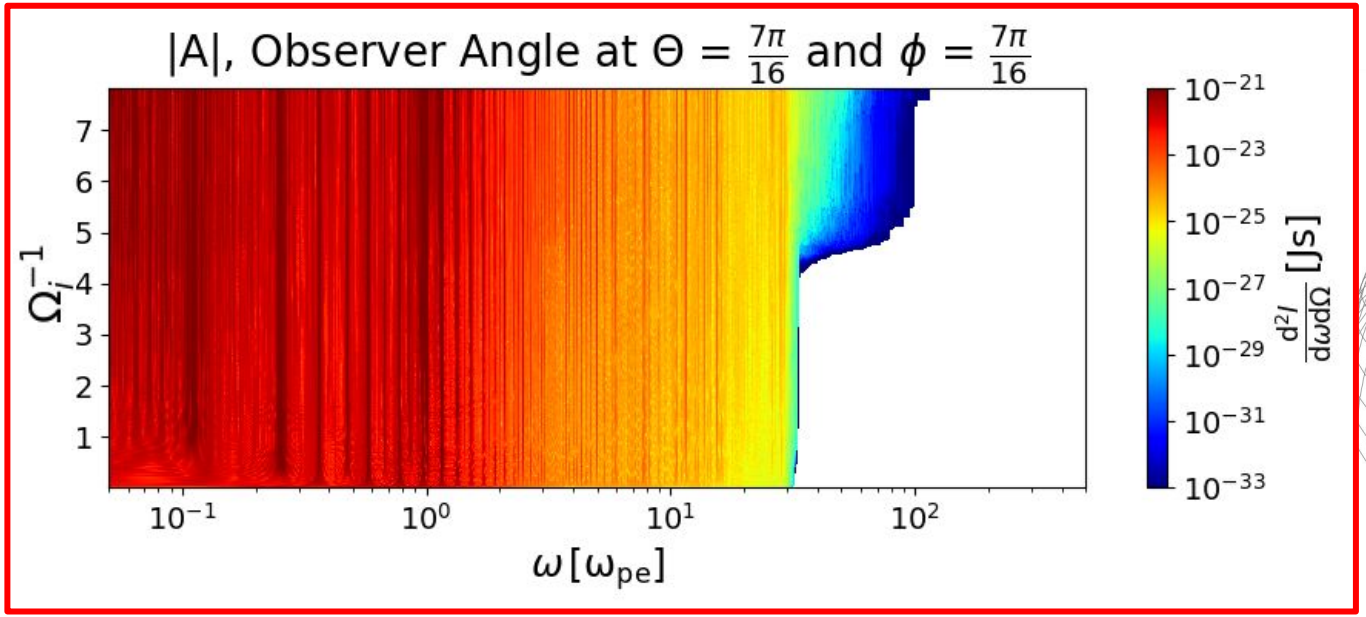

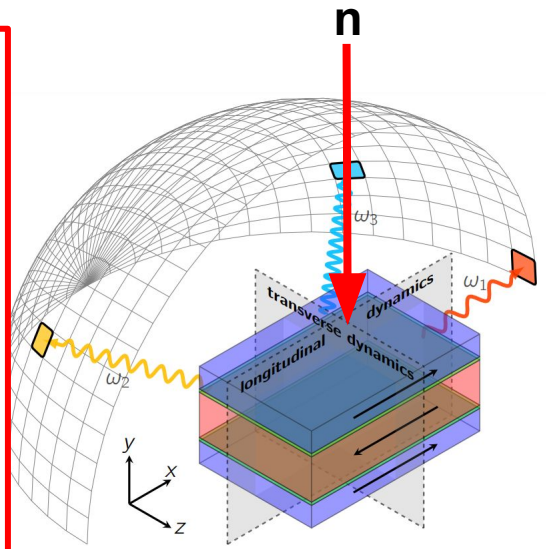

Radiation Features and Peaks in Time

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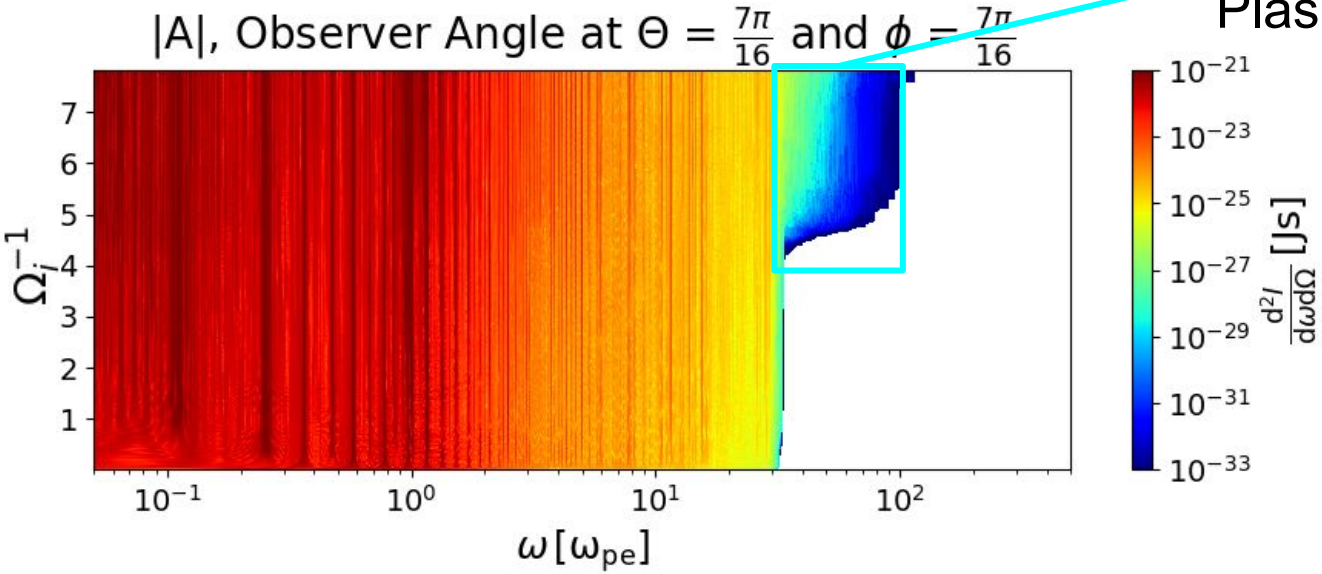
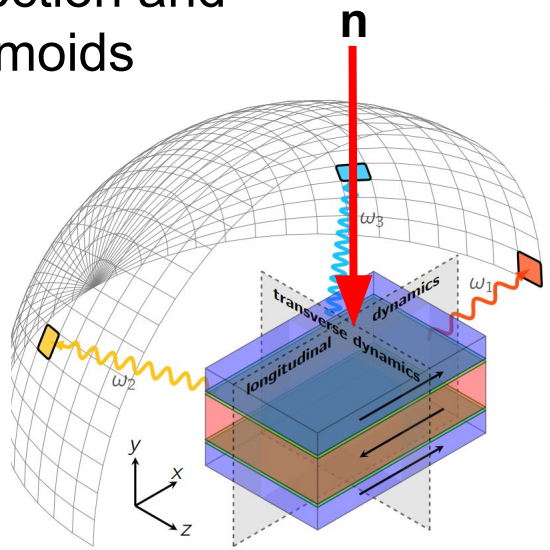
Reconnection and Plasmoids





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Radiation Features and Peaks in Time

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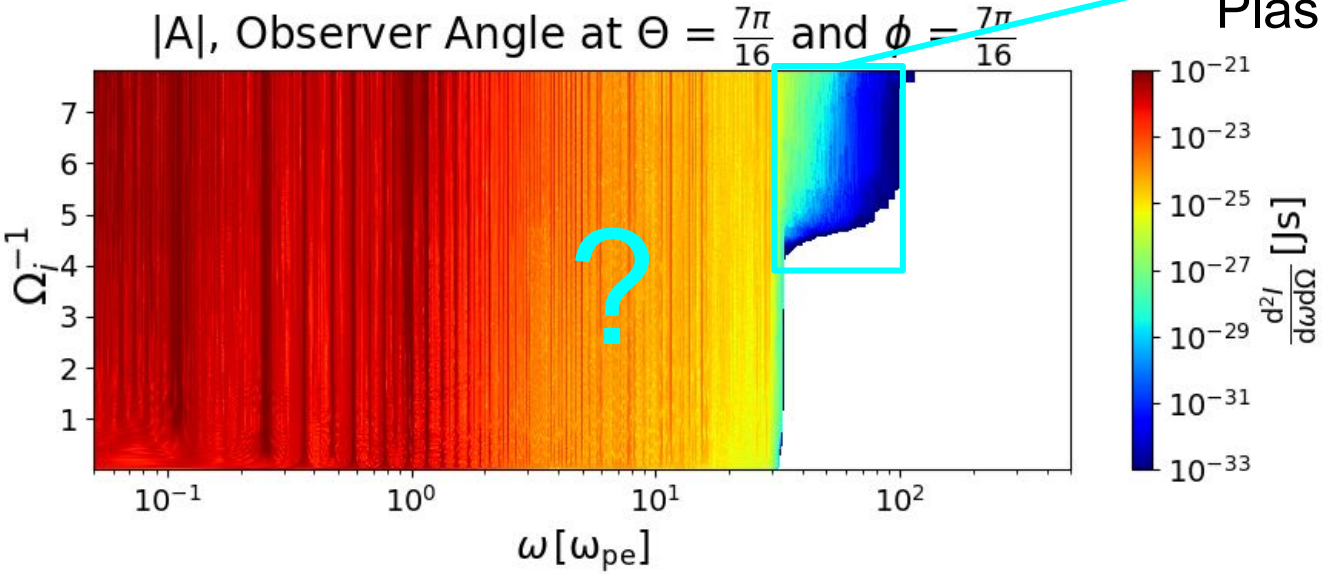
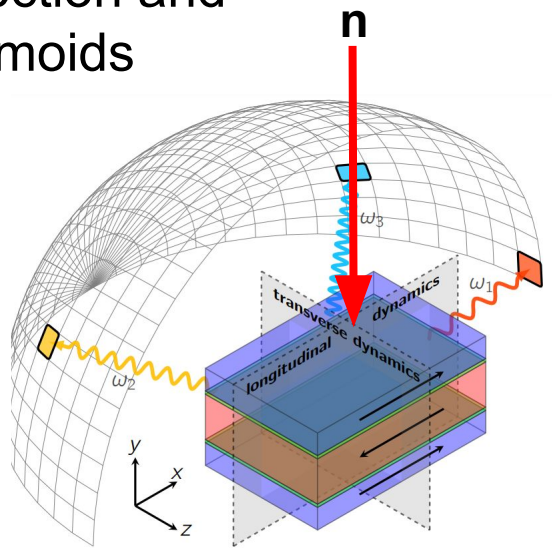
Reconnection and Plasmoids





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Radiation Features and Peaks in Time

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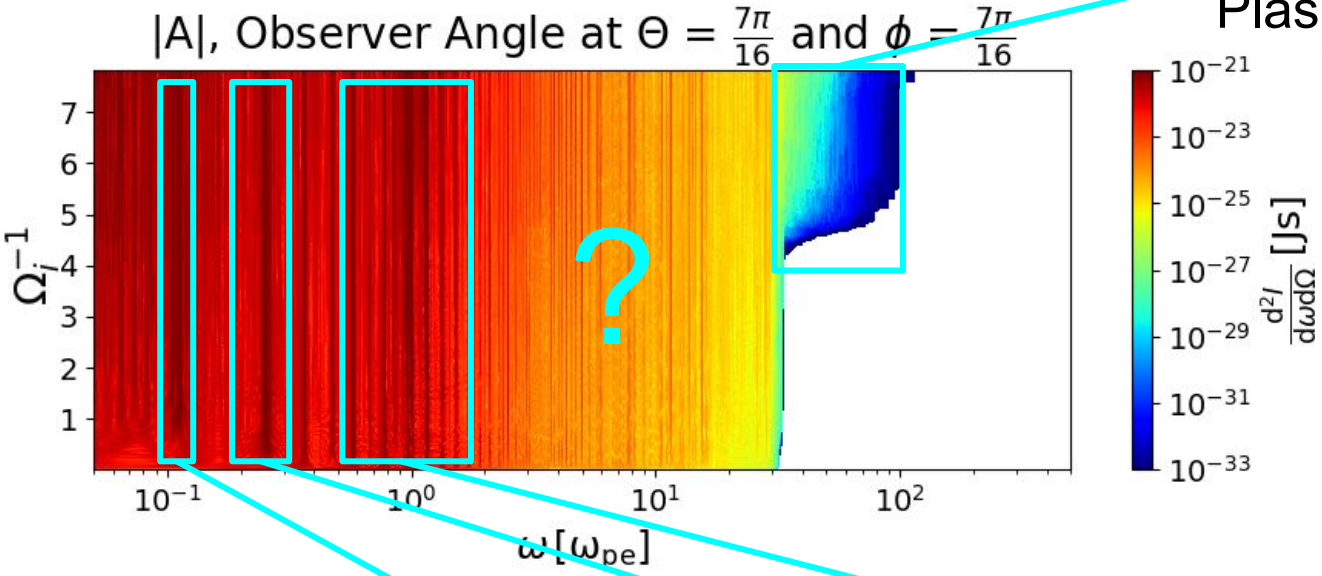
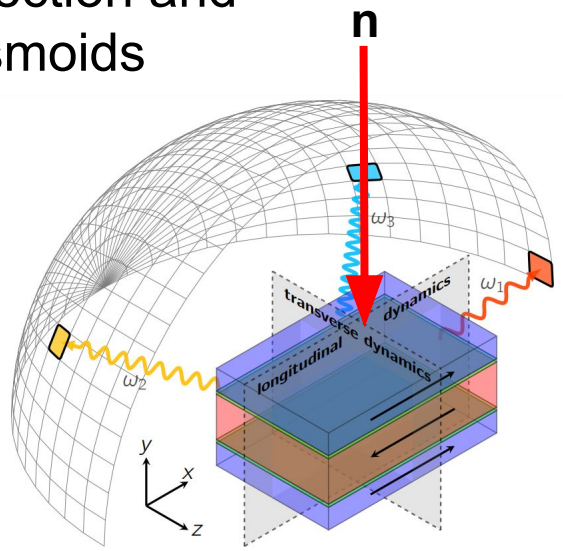
Reconnection and Plasmoids





Electron gyro frequency

Perturbation

Sinc structure!

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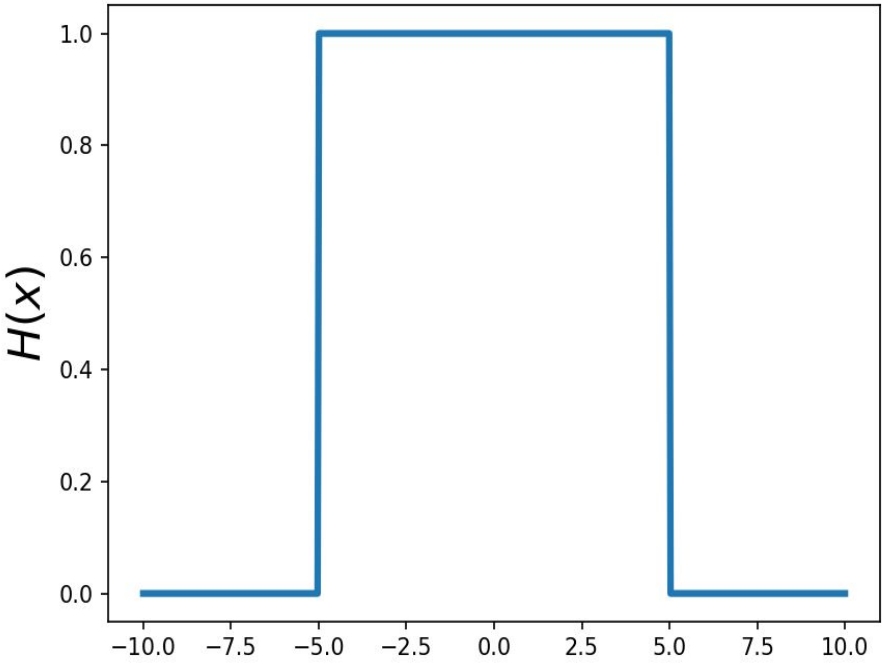
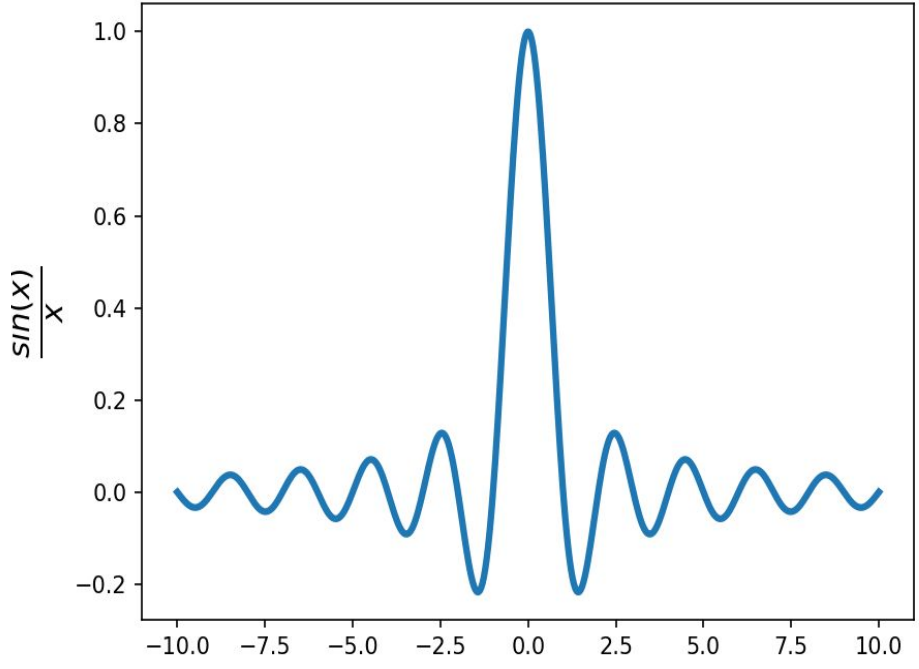
Why is a Sinc Exciting in Radiation?





Fourier Transform

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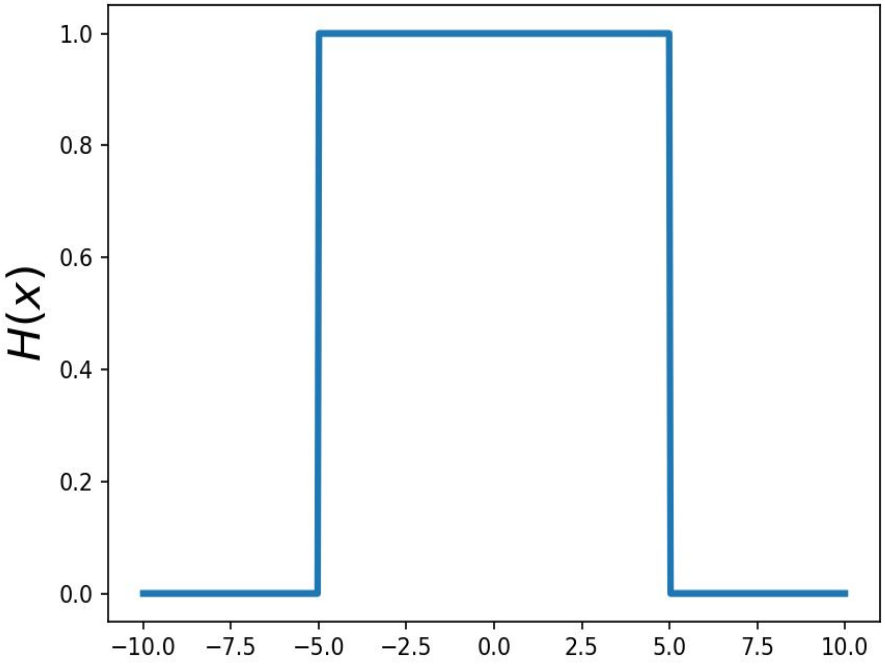
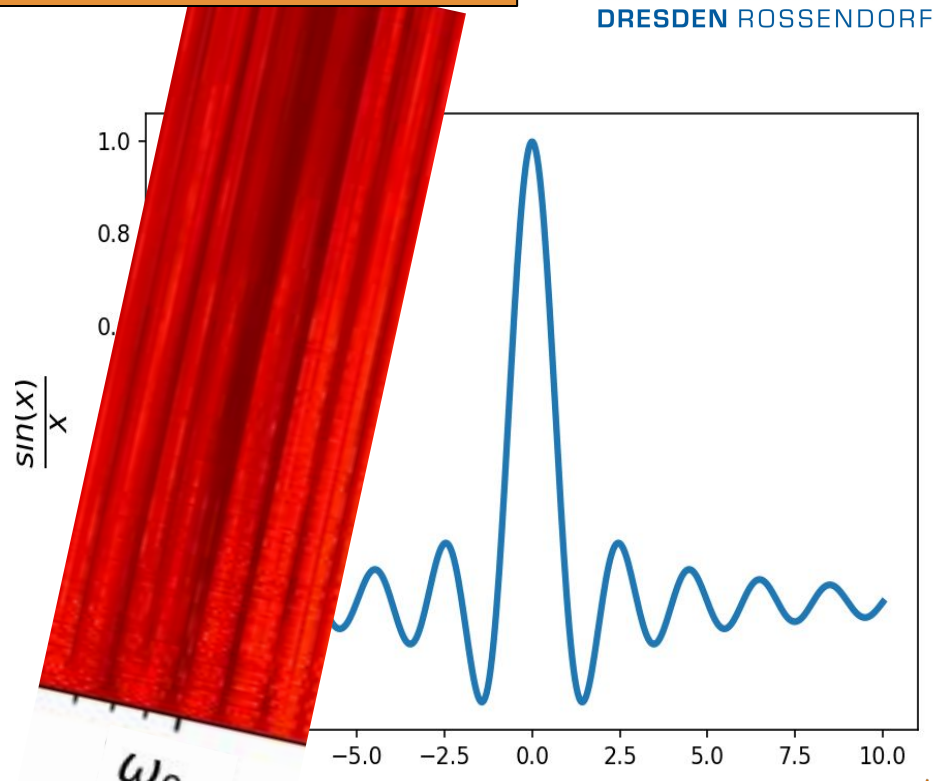
Why is a Sinc Exciting in Radiation?





Fourier Transform

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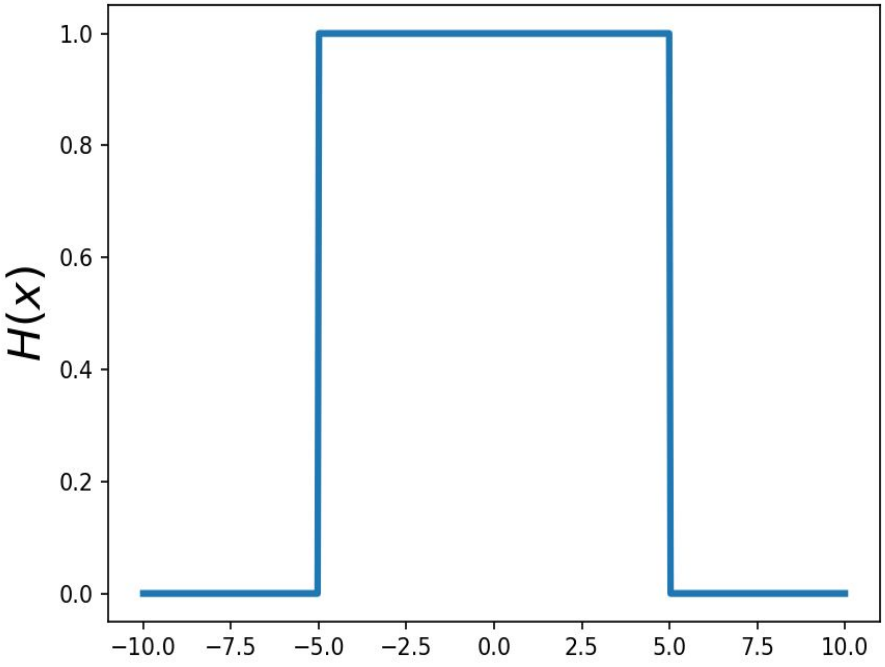
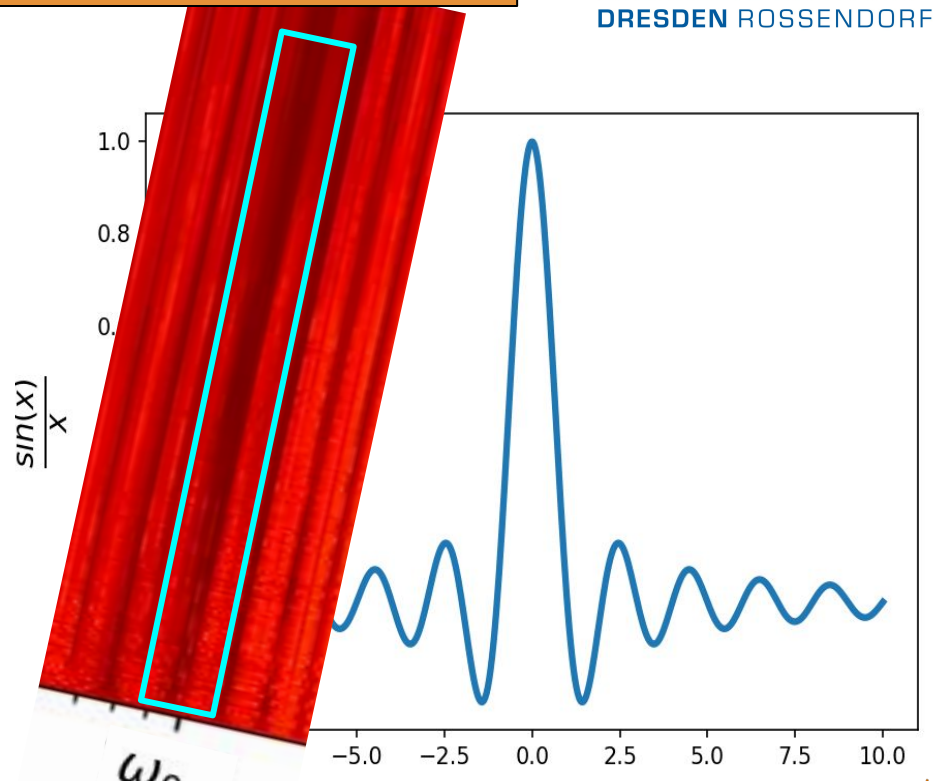
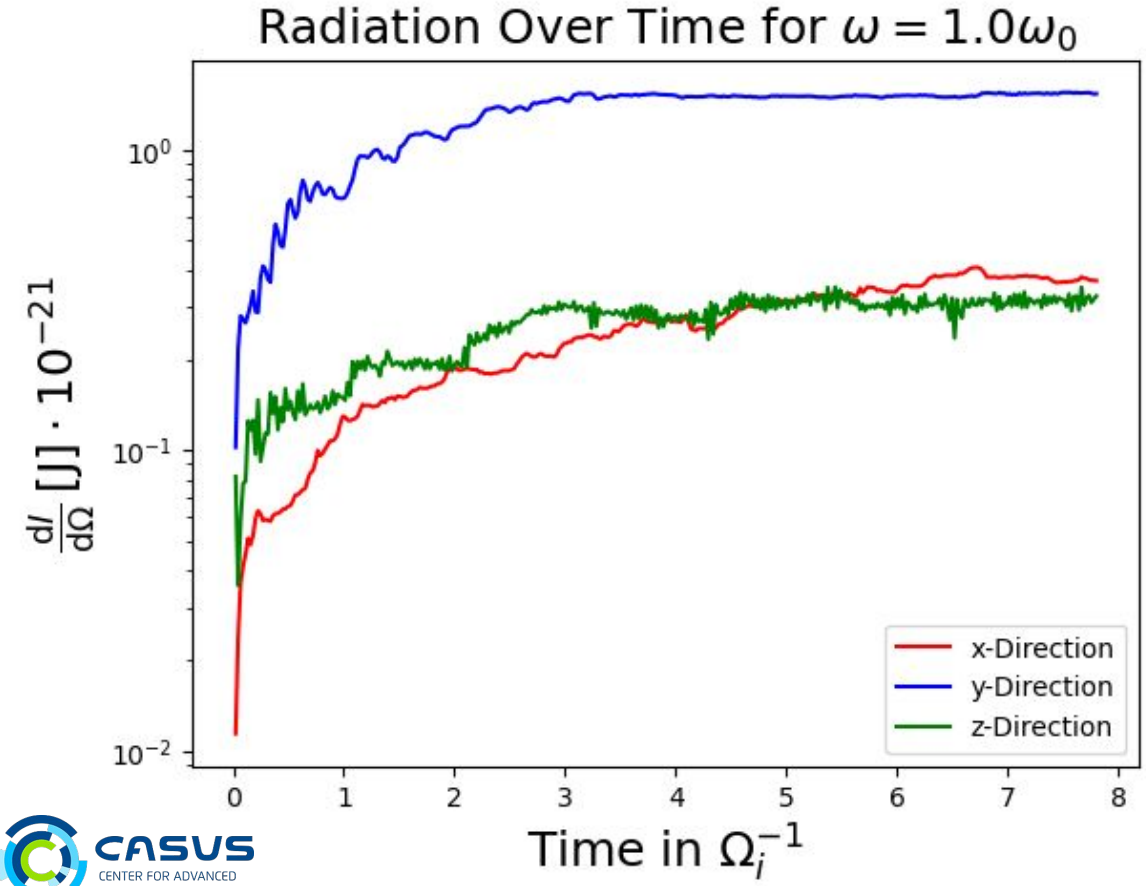




Fourier Transform

Signal of Plasma Frequency over Time



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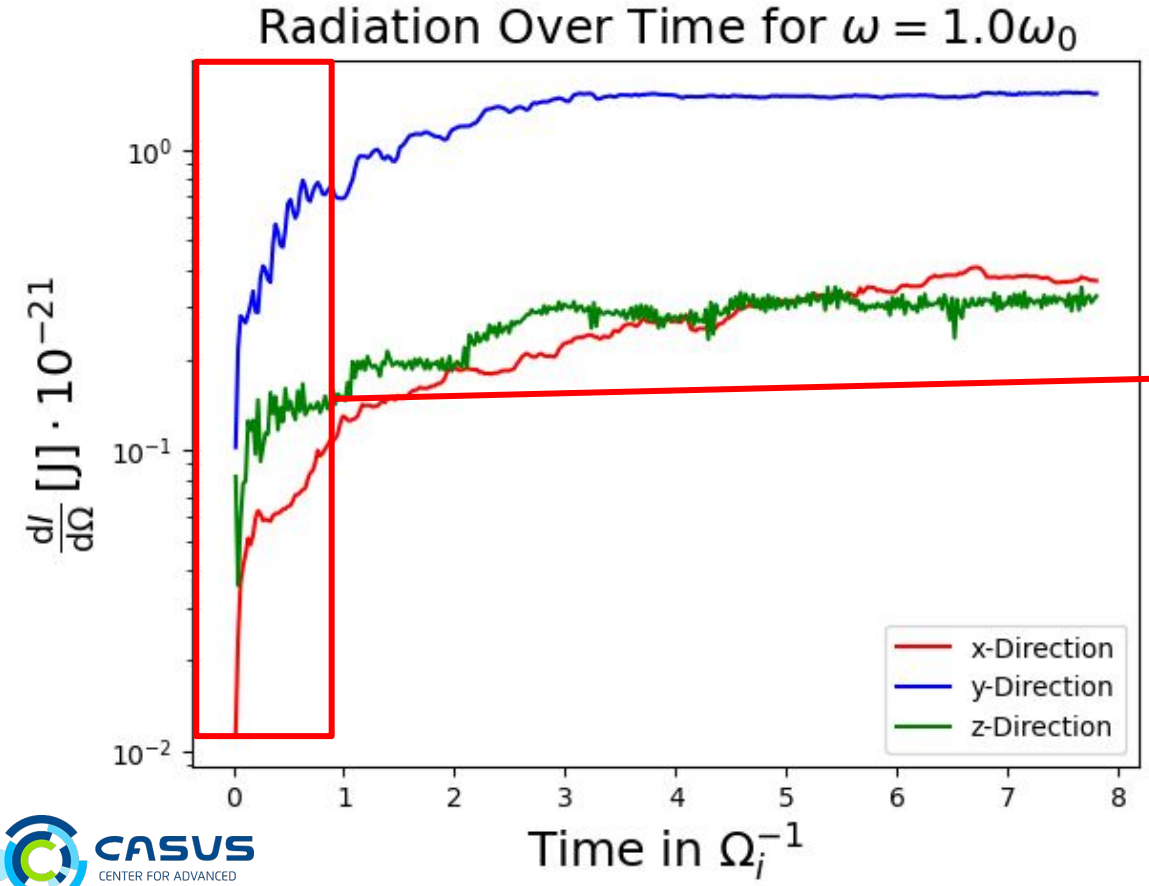
Signal of Plasma Frequency over Time



Large initial contribution
(Integrated!)

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What did we learn from these spectra?

- Not just initial flare, but sinc!
  (holds more generally!)

- Spectra peaks give insight about physical processes/quantities

- Opportunities for further search, enabled through improved radiation model!

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Radiation Analysis of MR:
Polarization of Radiation

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Polarization using Stokes Parameters

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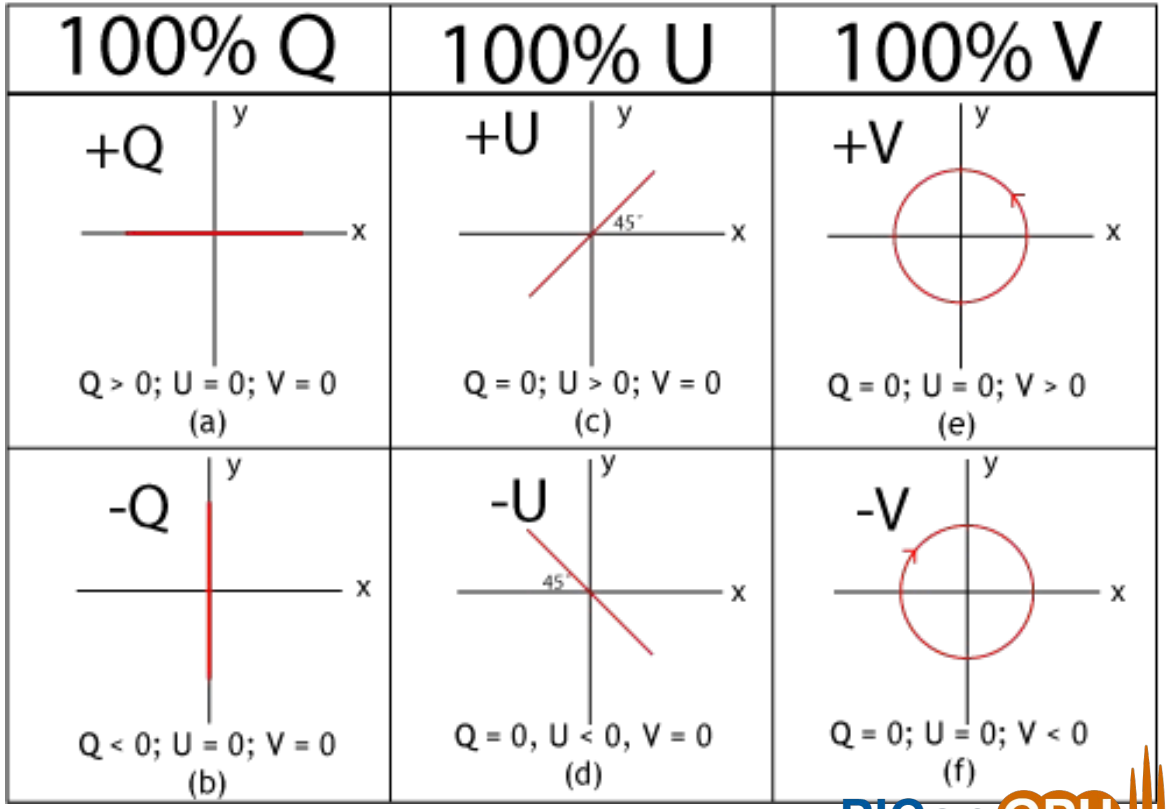
- Parameters need to be adapted for each direction

  (Light not polarized in direction of movement)

- Parameters present time average!



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Polarization Features over Time!

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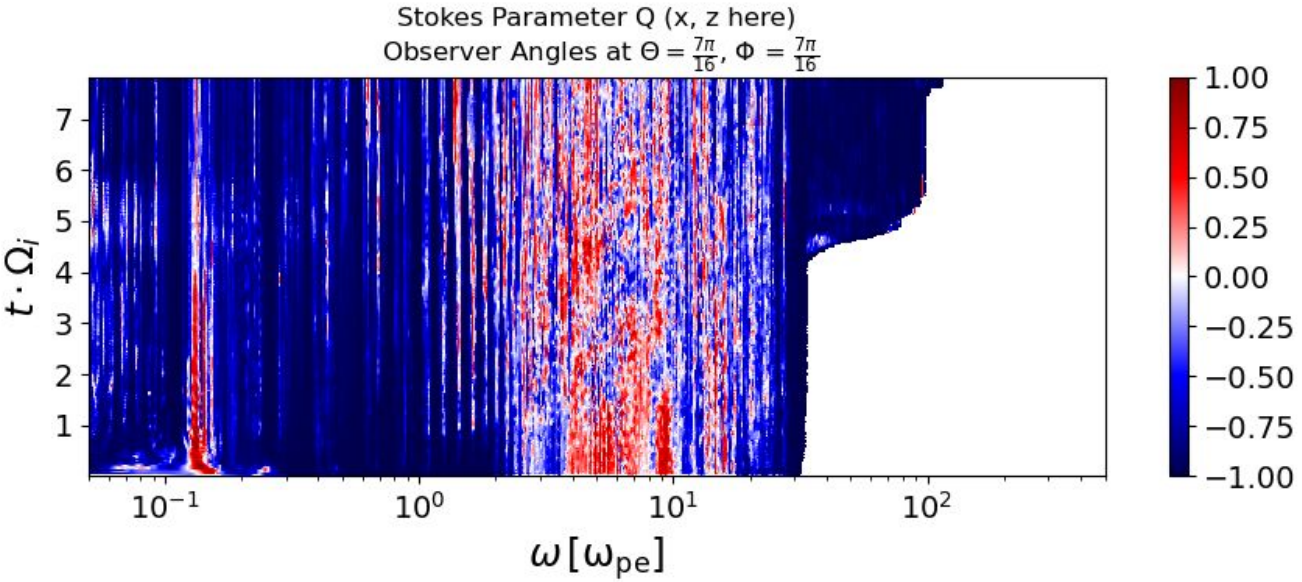

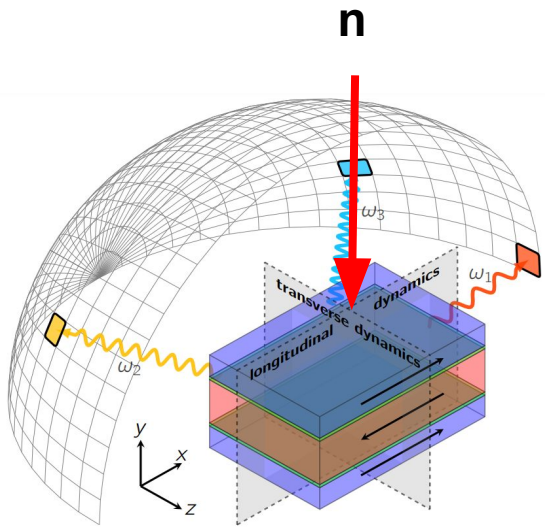

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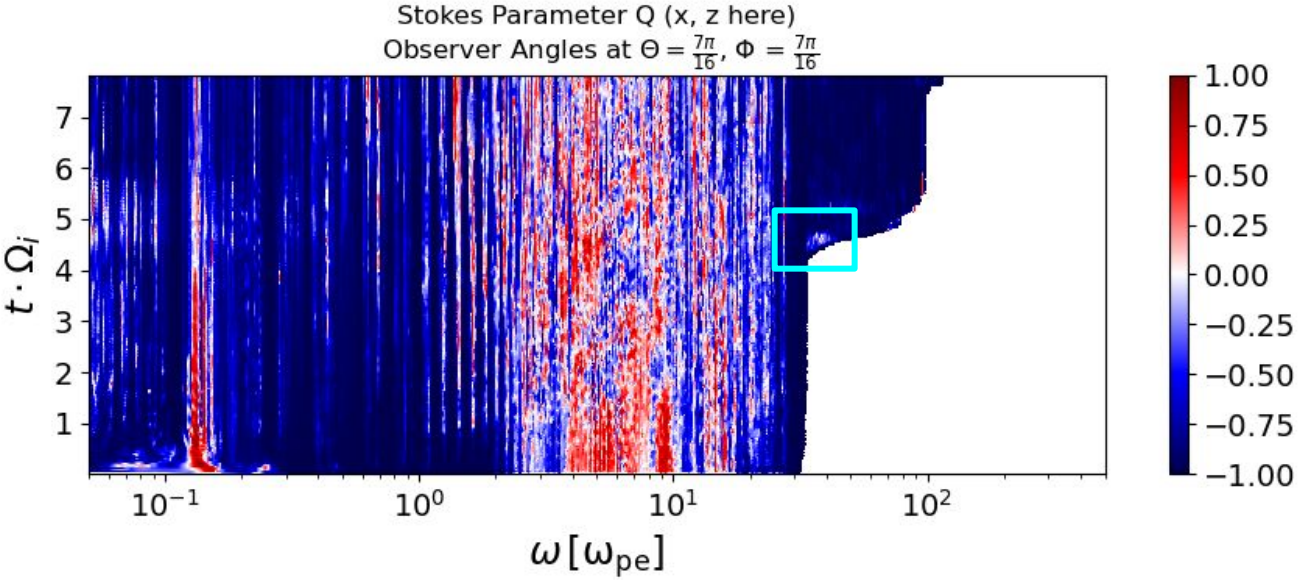

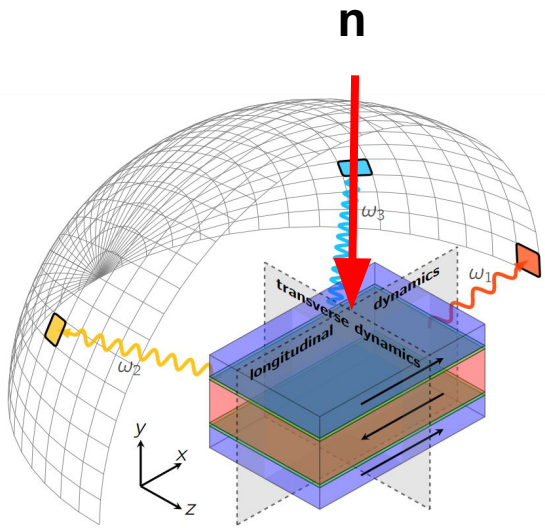

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Polarization Features over Time!

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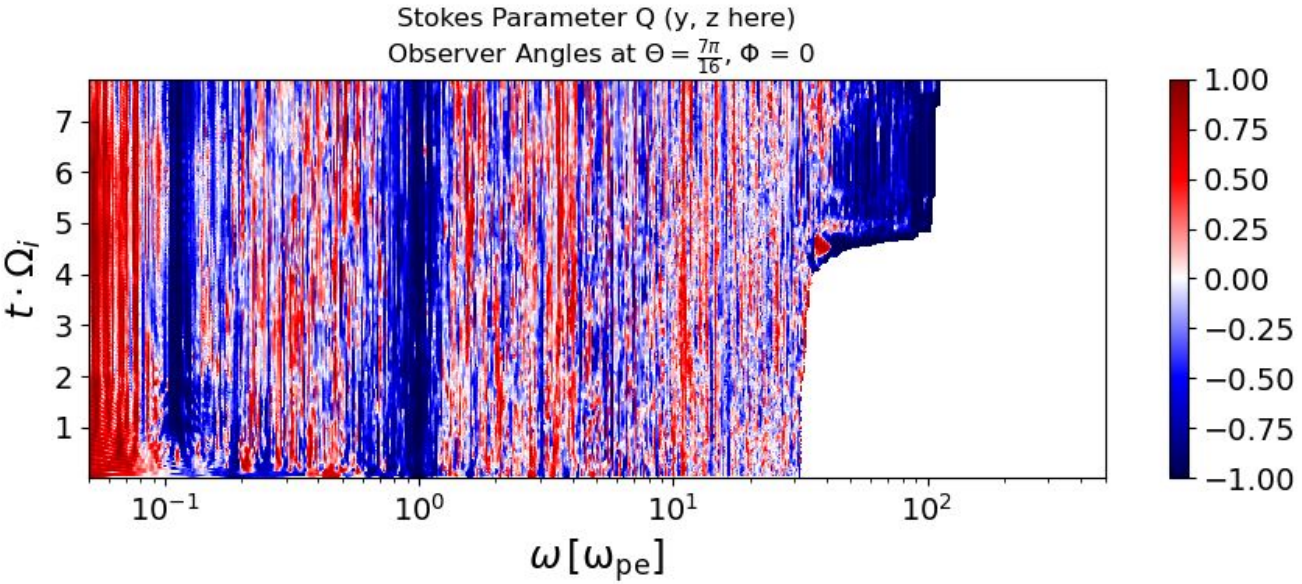

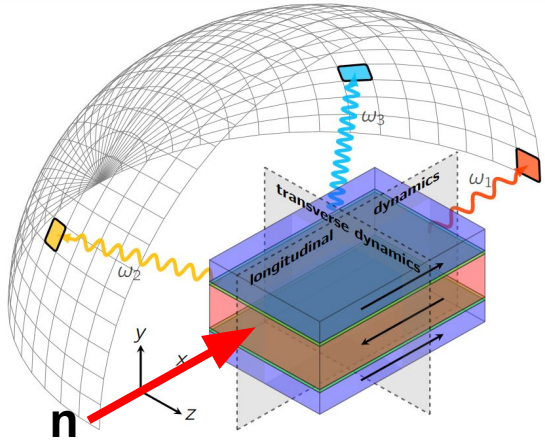

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Polarization Features over Time!

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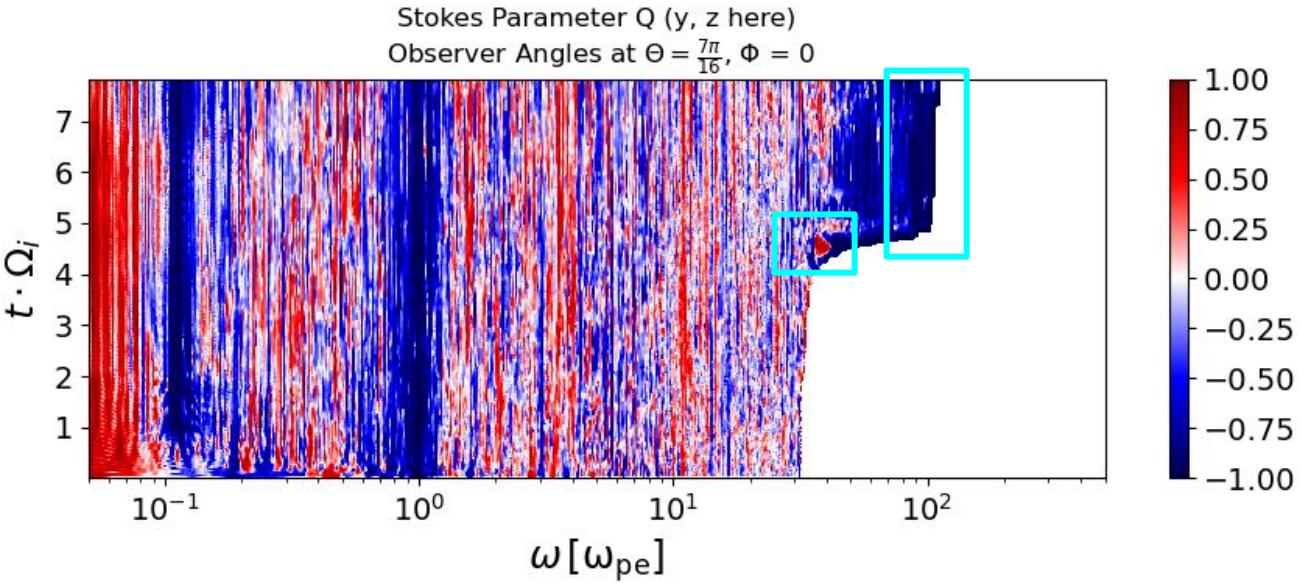

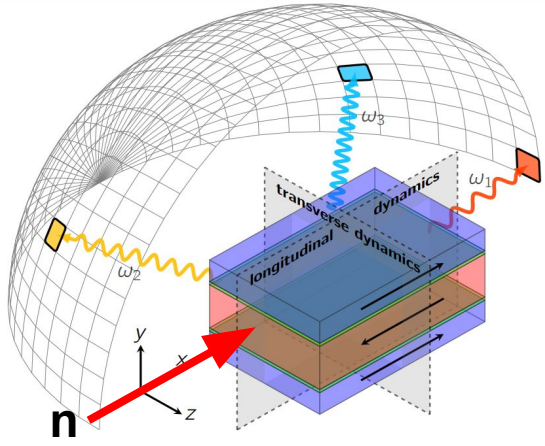

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Polarization Features over Time!

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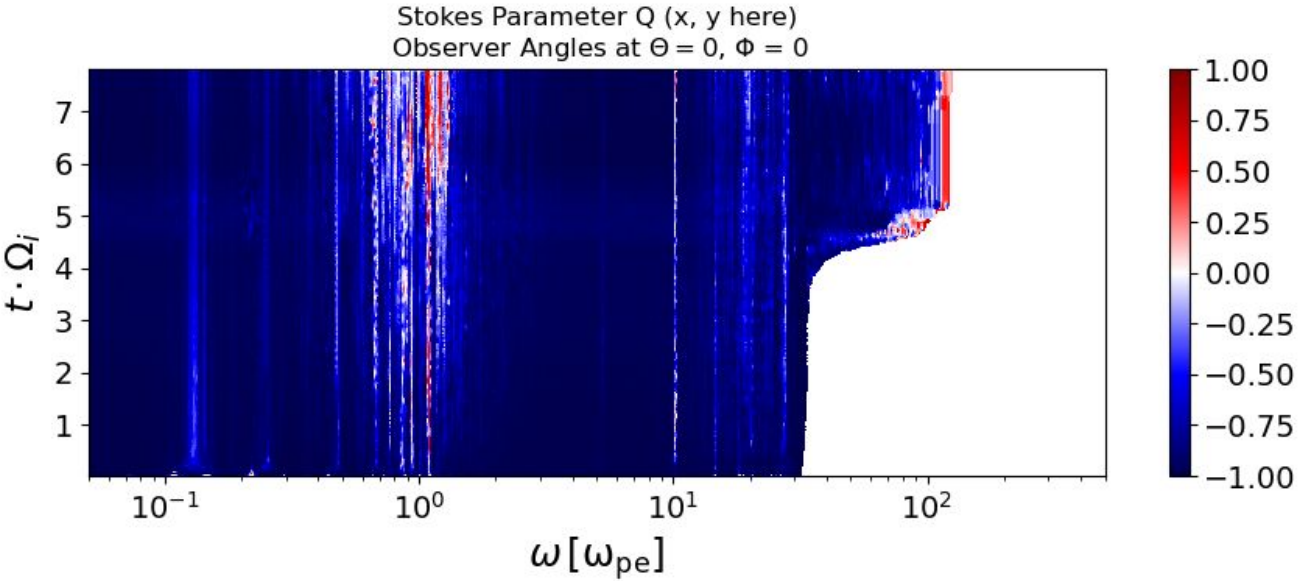

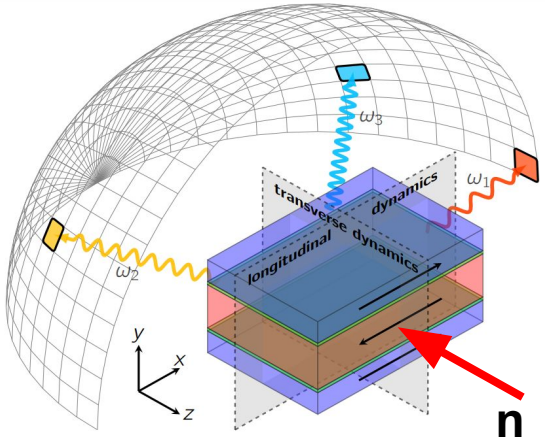

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Polarization Features over Time!

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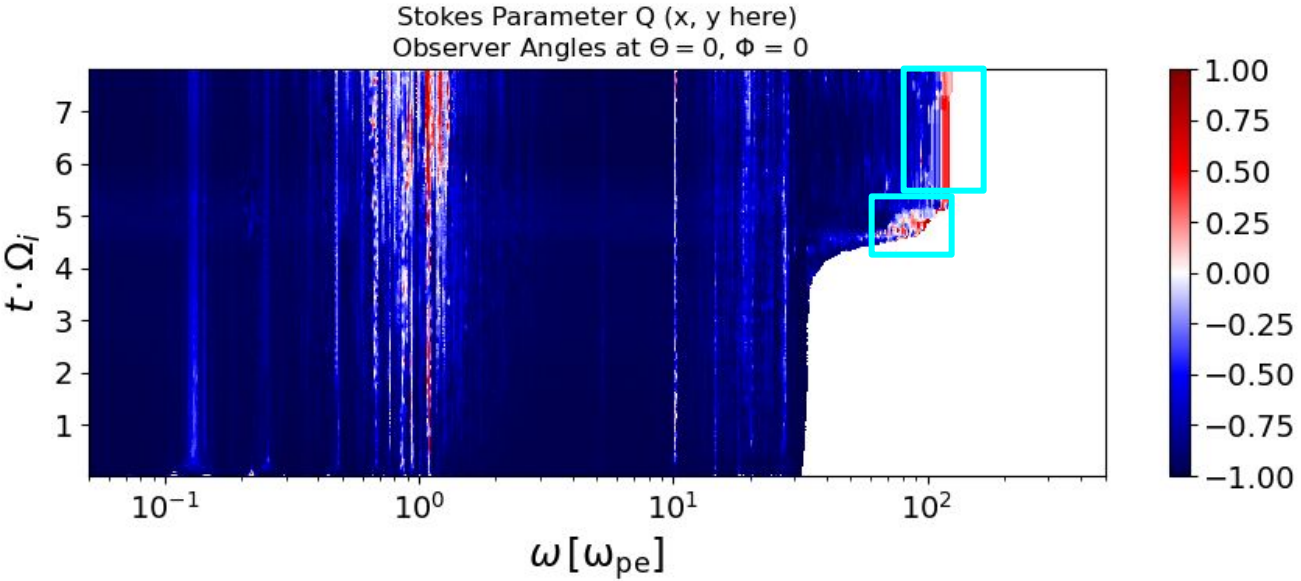

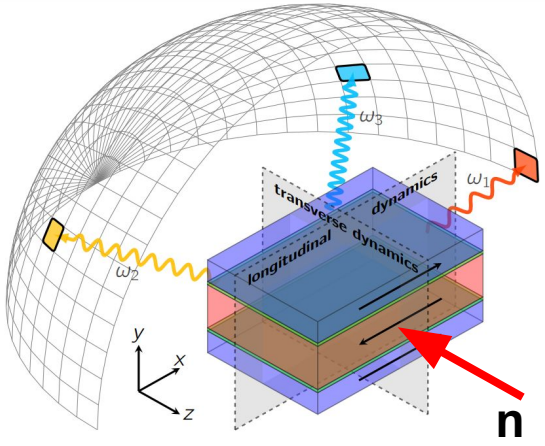

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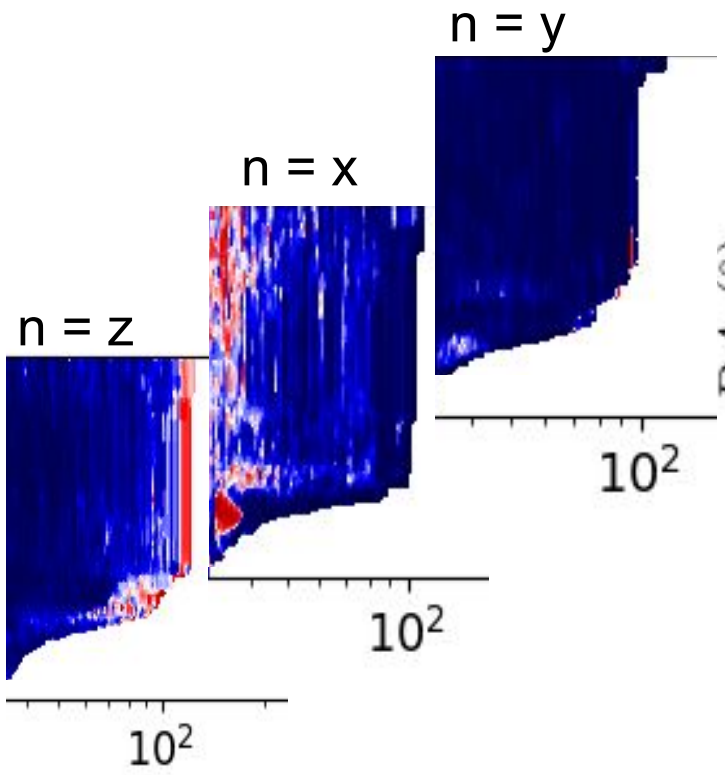
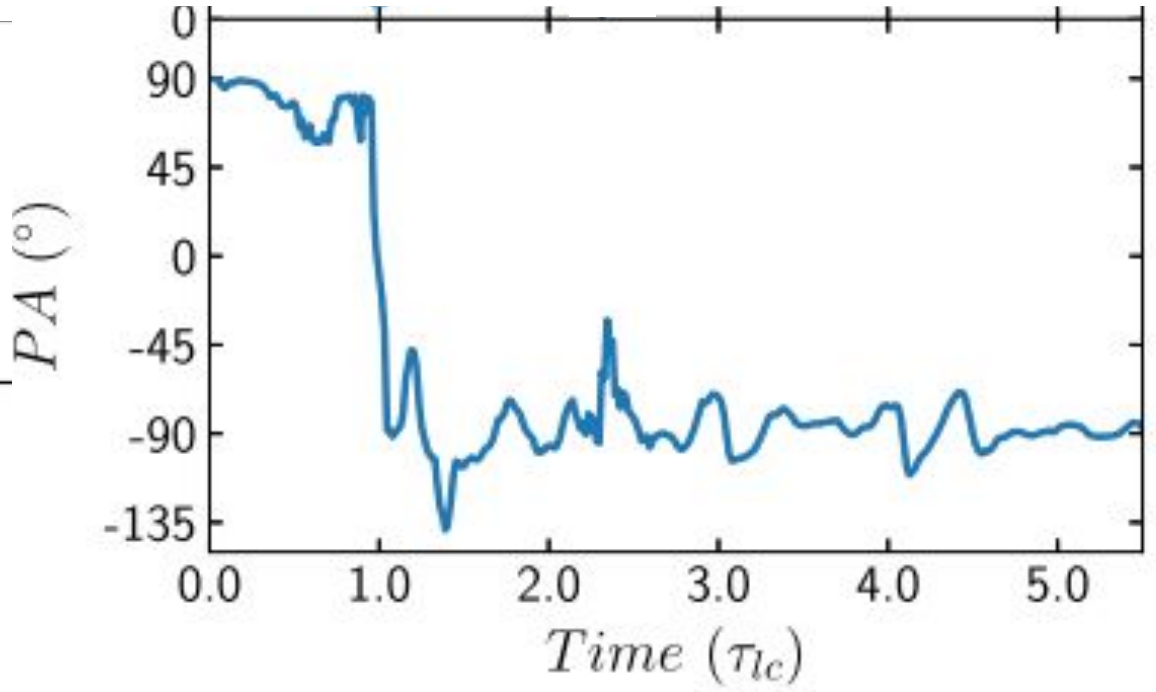
Zhang's Polarization Swing and More!





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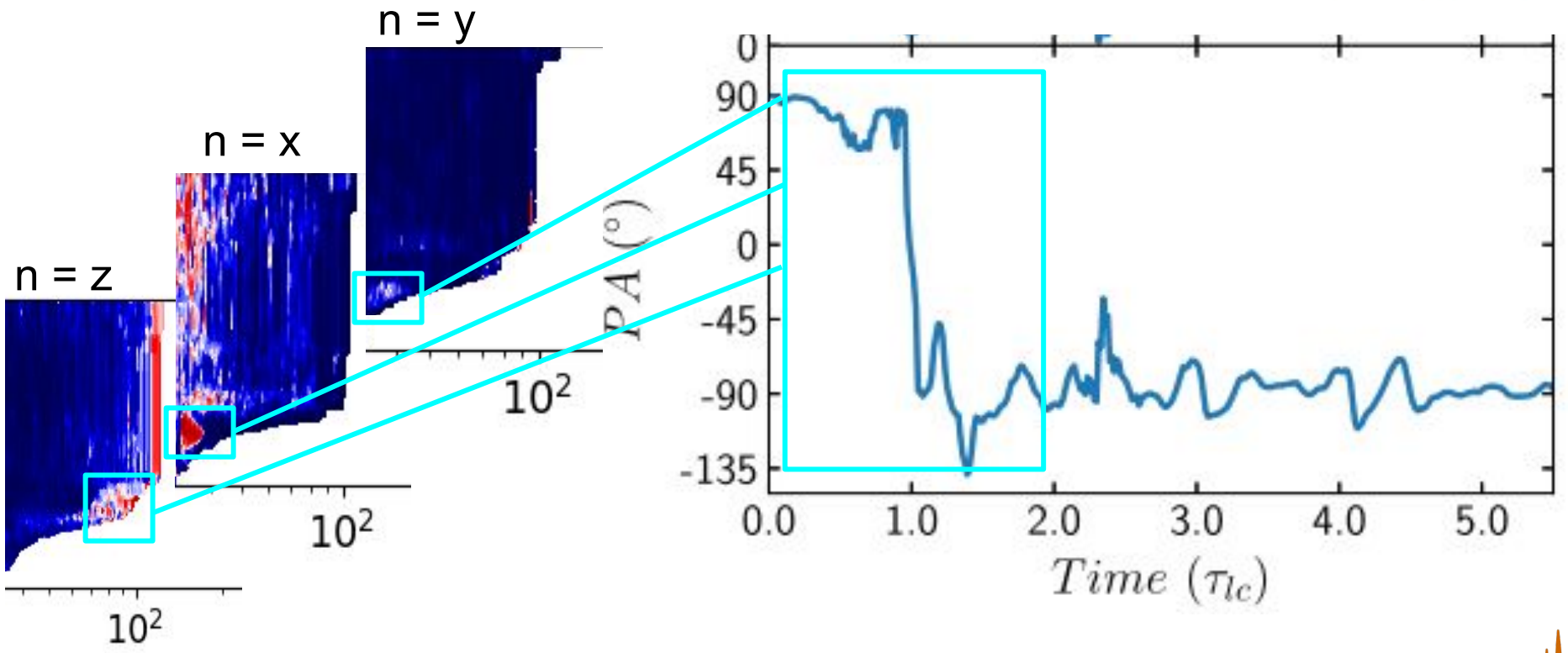

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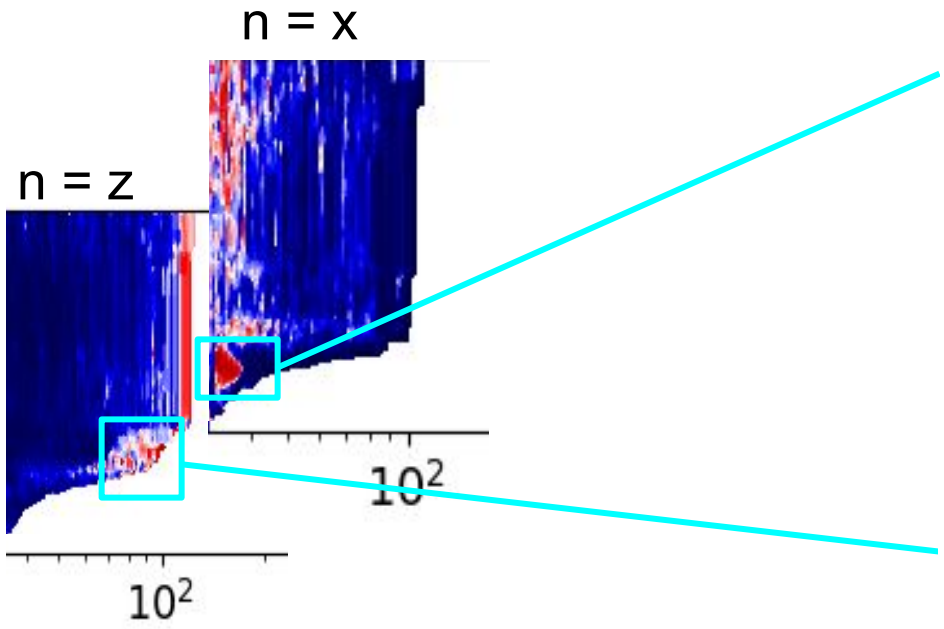

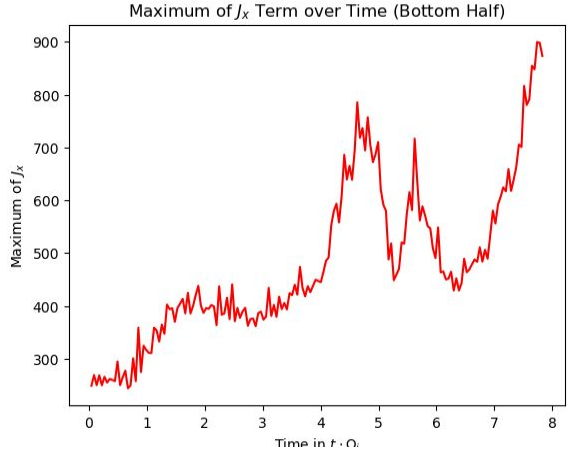

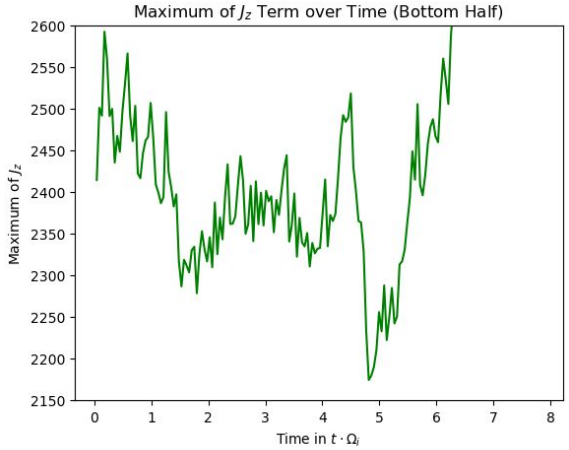

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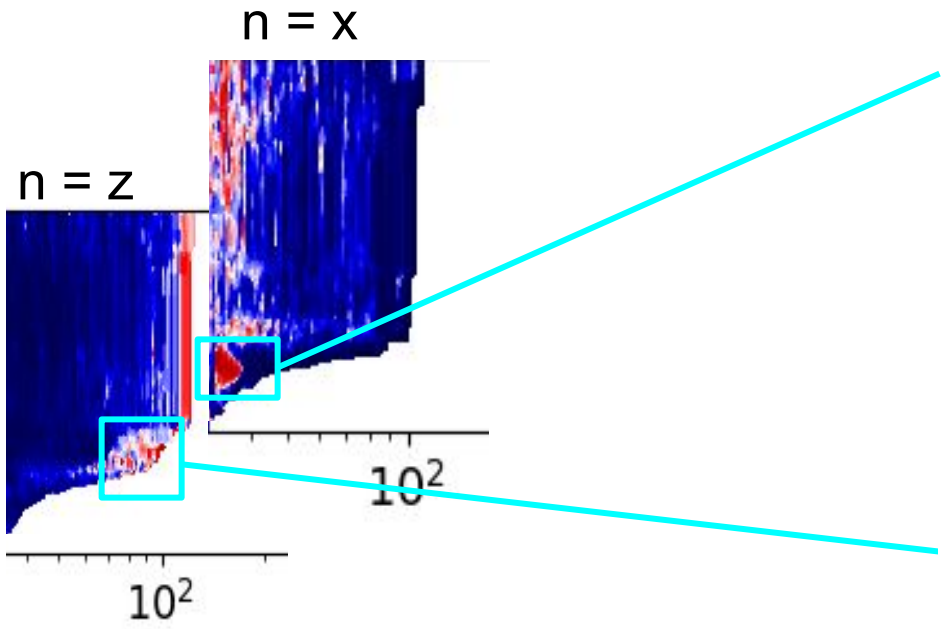
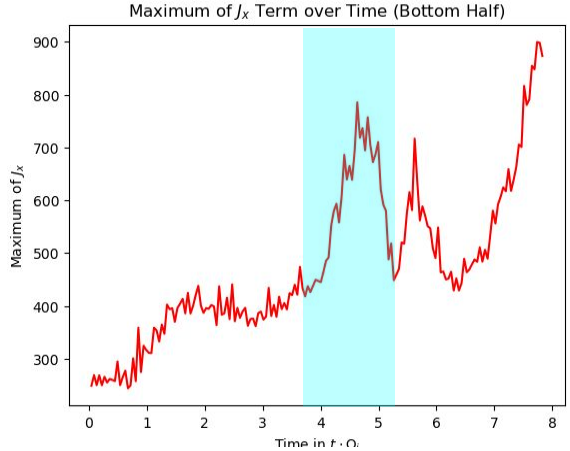
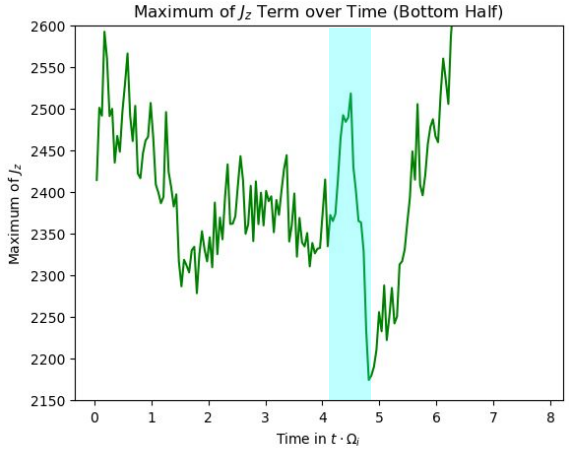
Zhang's Polarization Swing and More!







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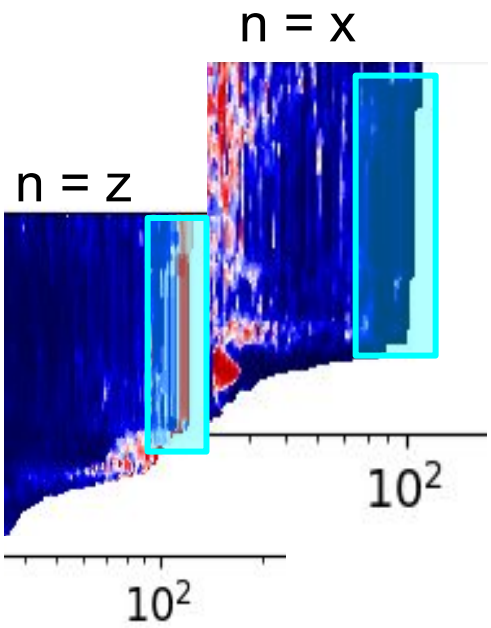
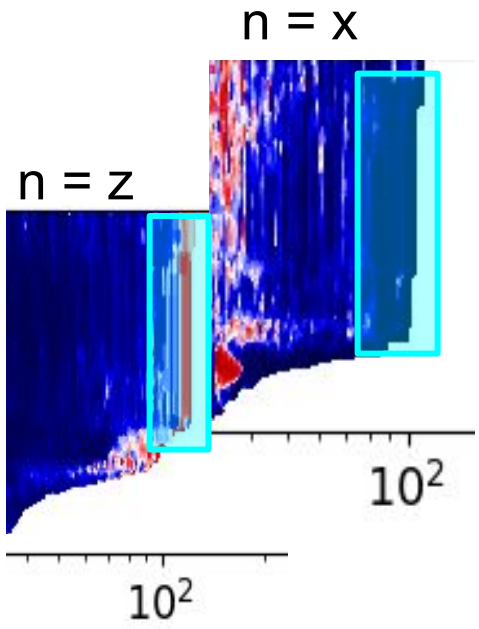
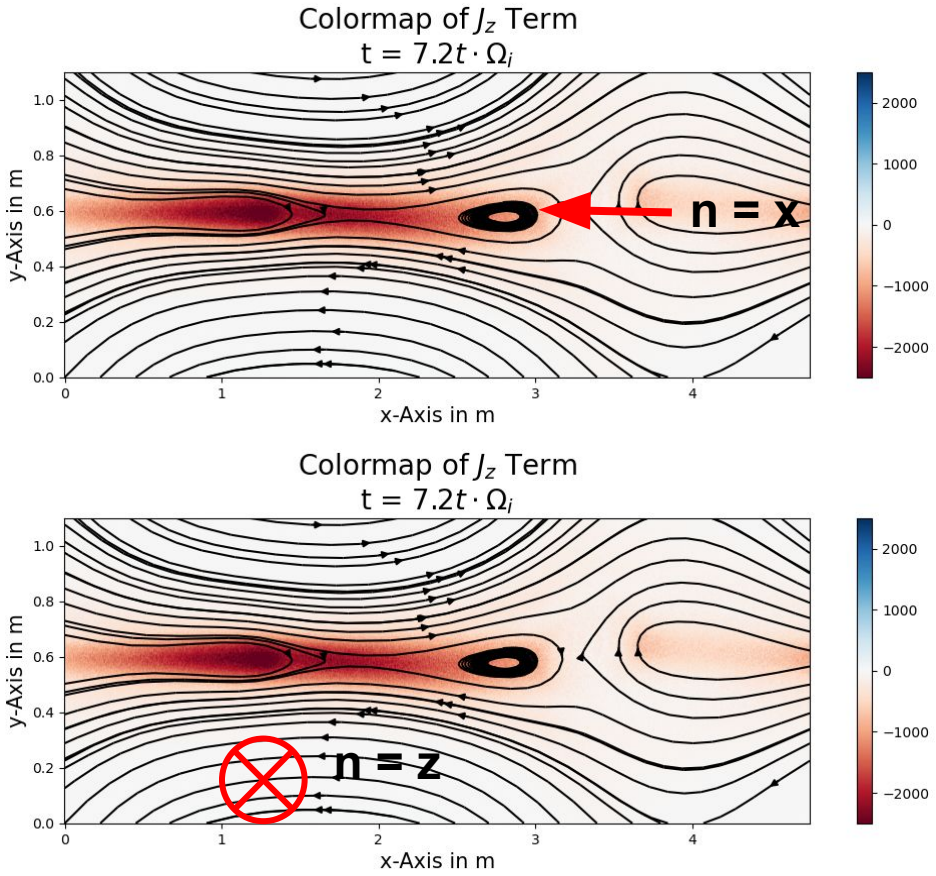
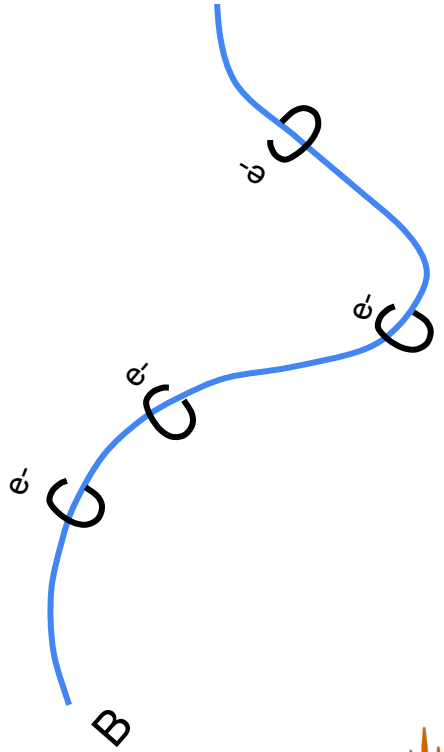
Reducing Dimension - Time Average



Reducing Dimension - Time Average







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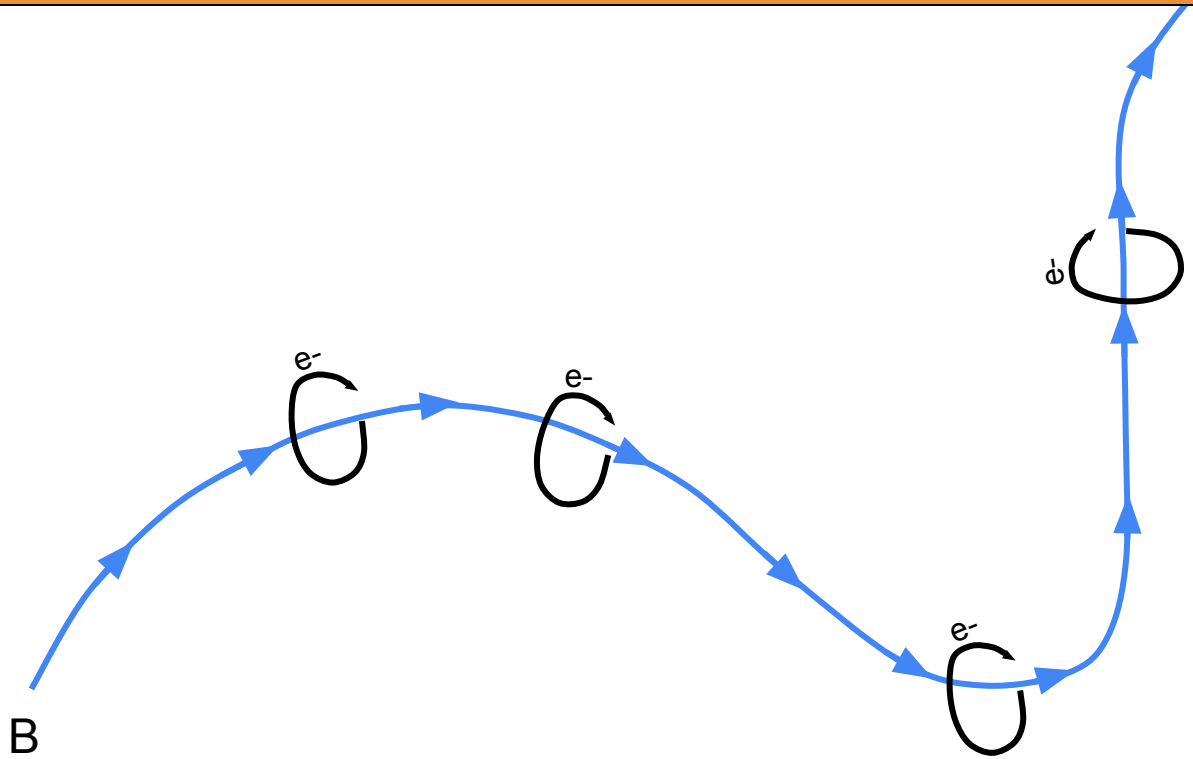
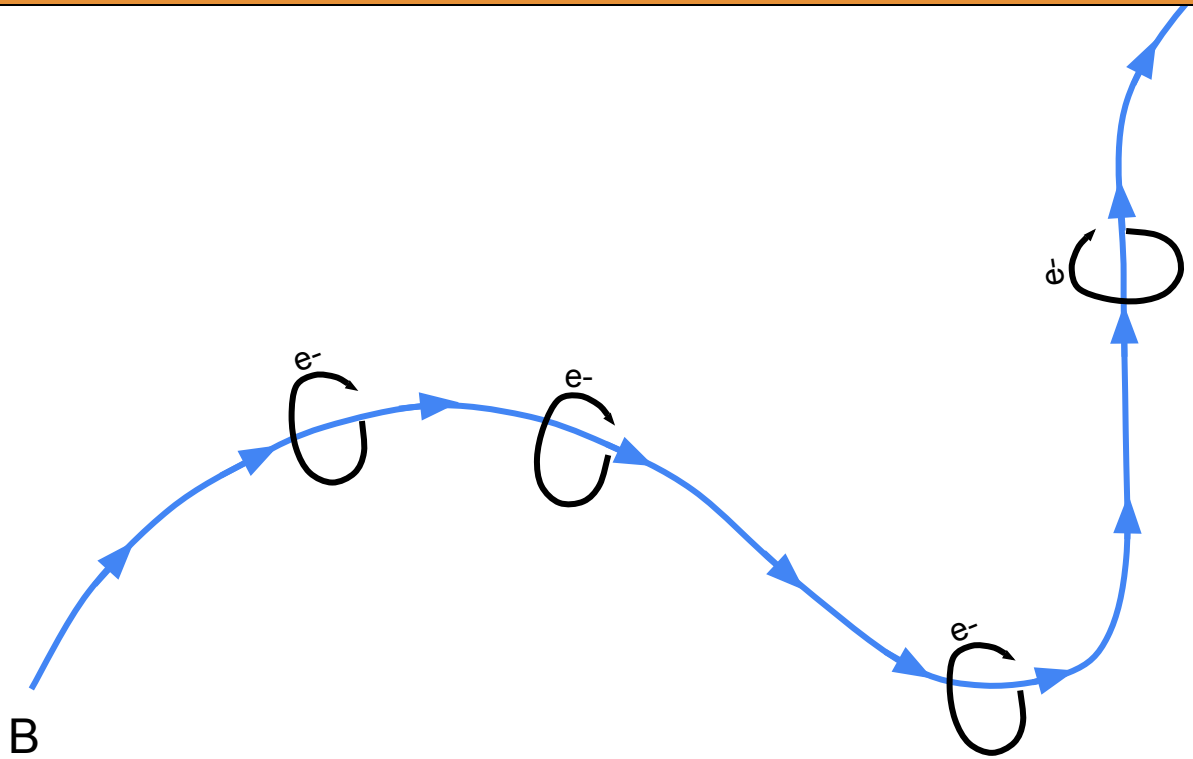
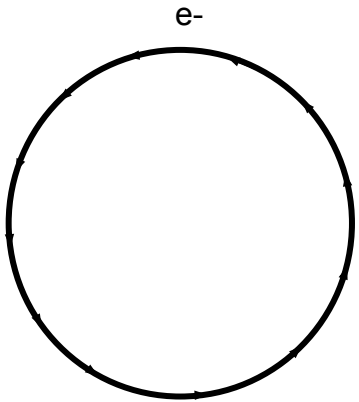
Why Angular Resolution Matters here



Why Angular Resolution Matters here





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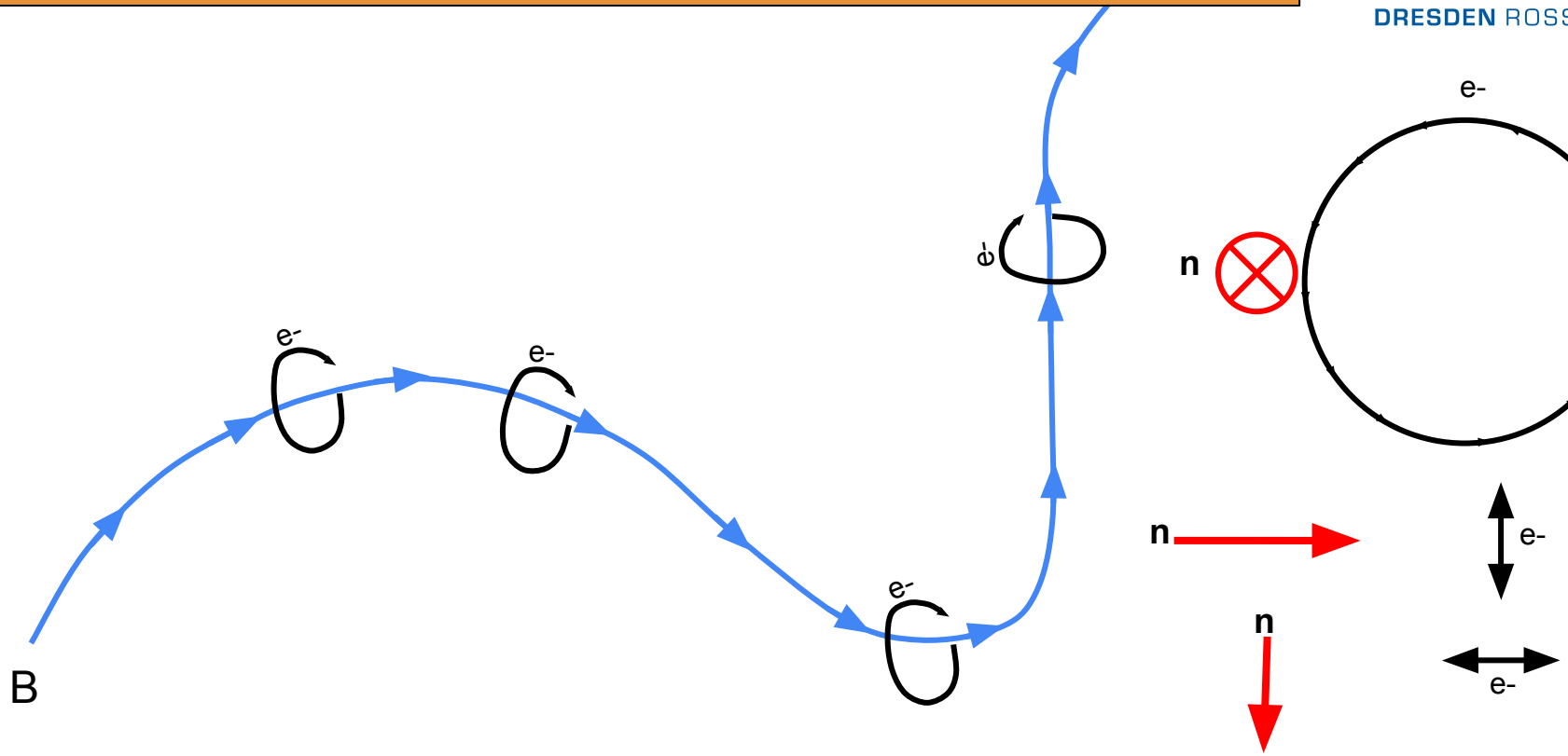
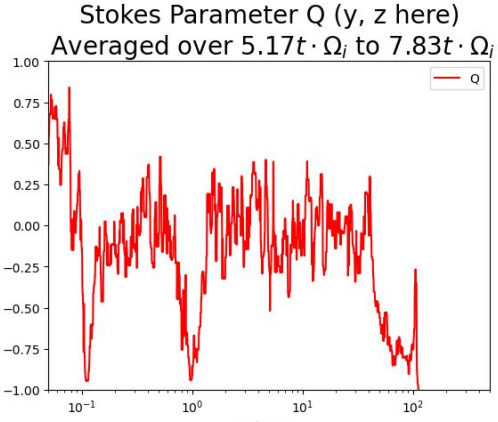
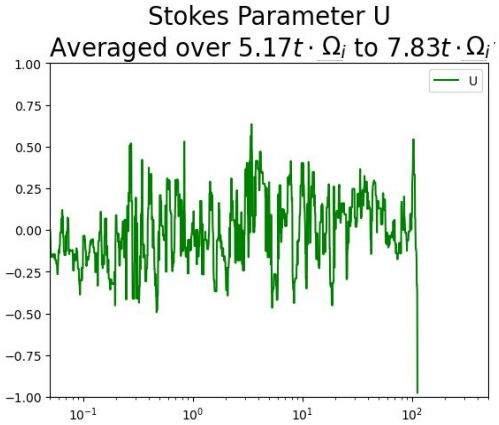
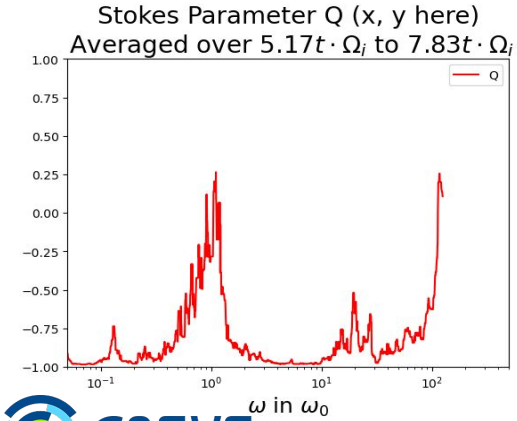
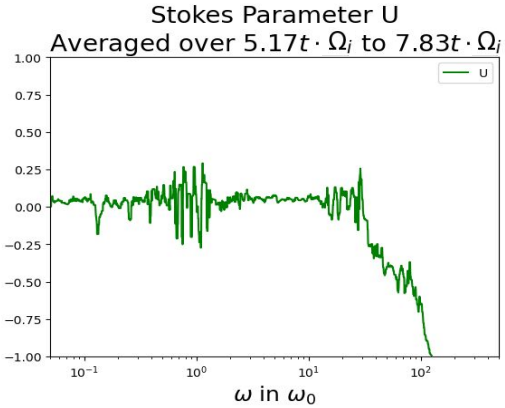


Time Average for Plasmoid Dynamics









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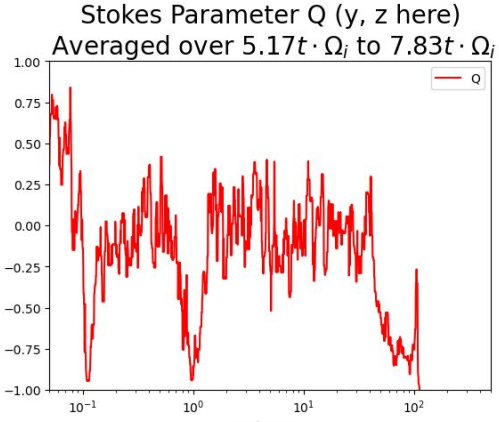
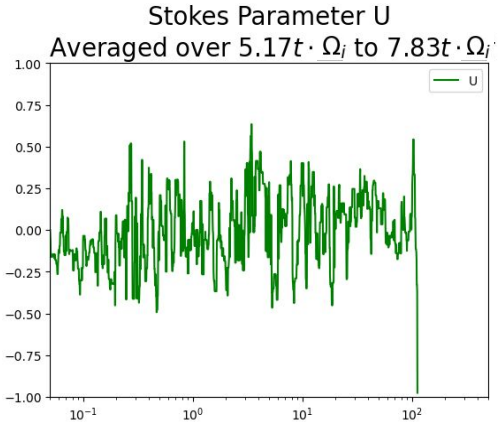
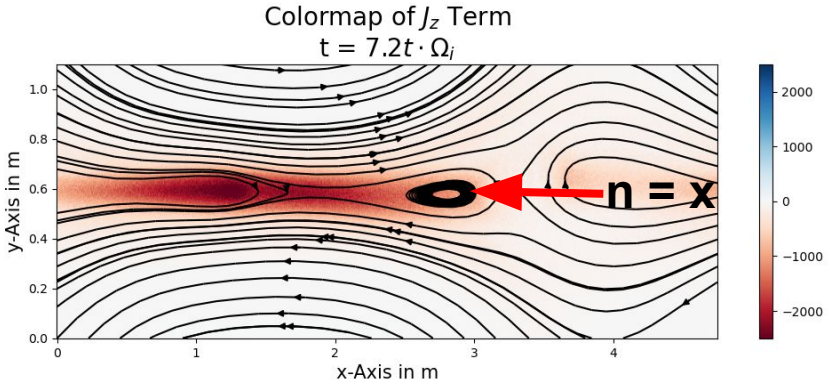
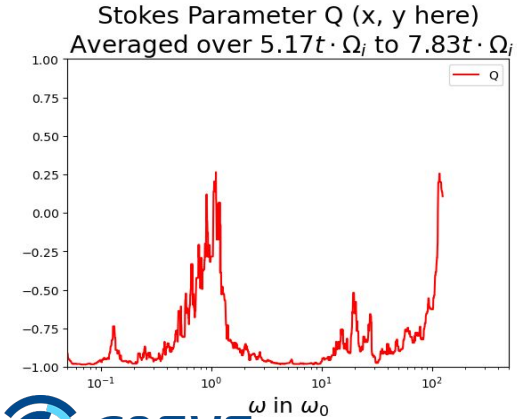
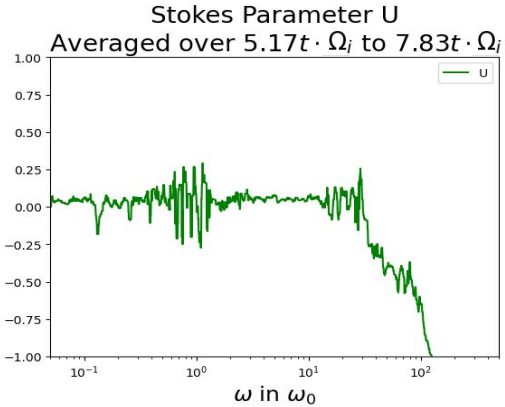
Time Average for Plasmoid Dynamics

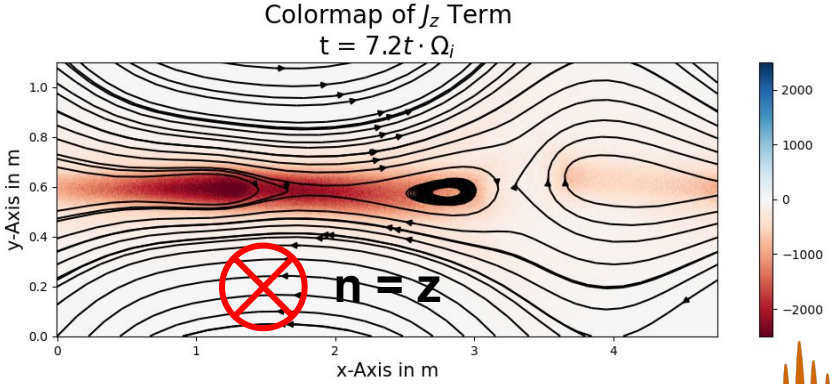












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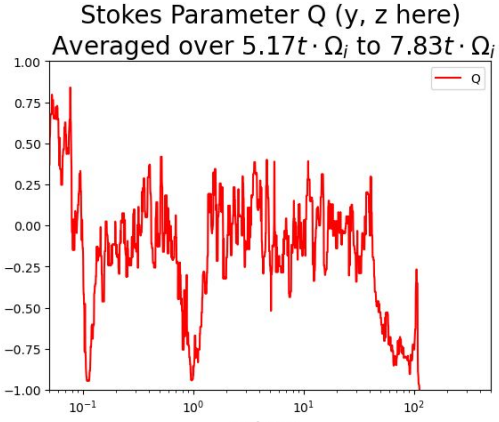

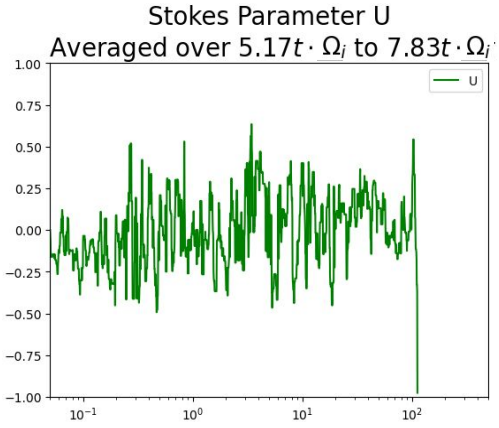

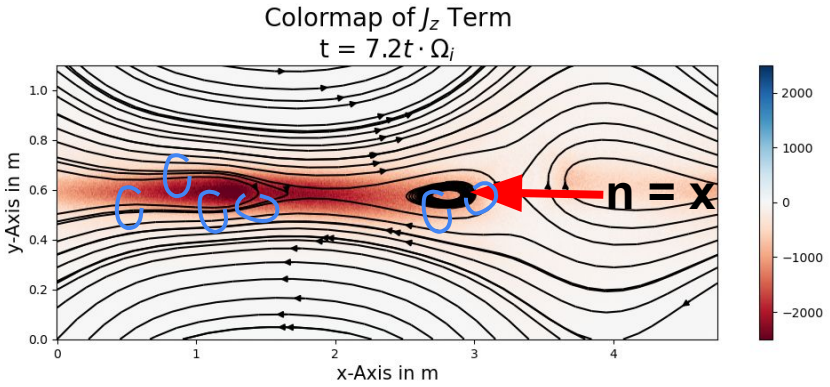

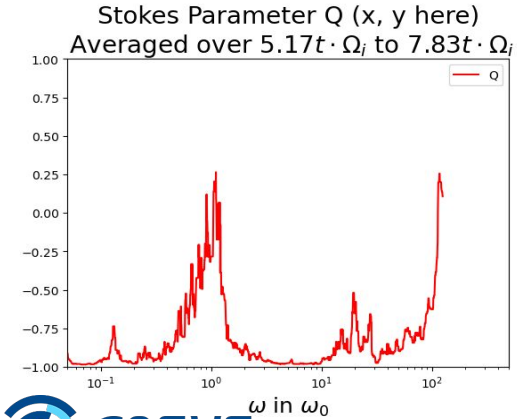

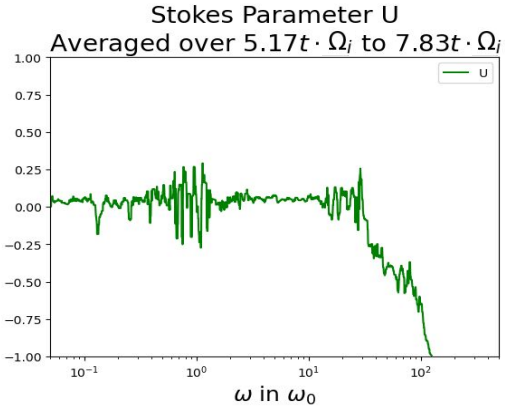

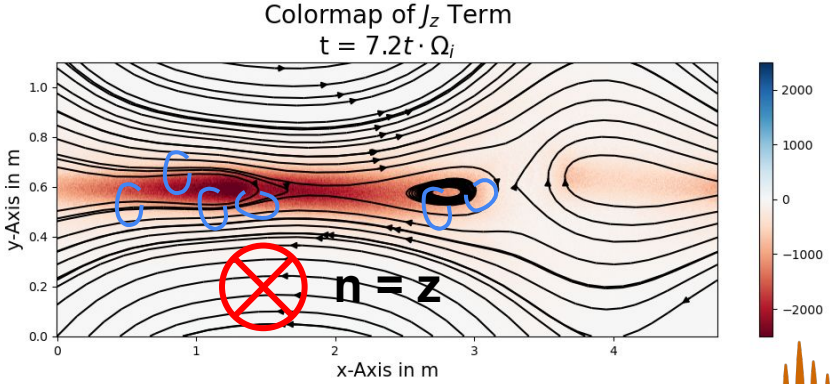

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First Master Equations for Quantities

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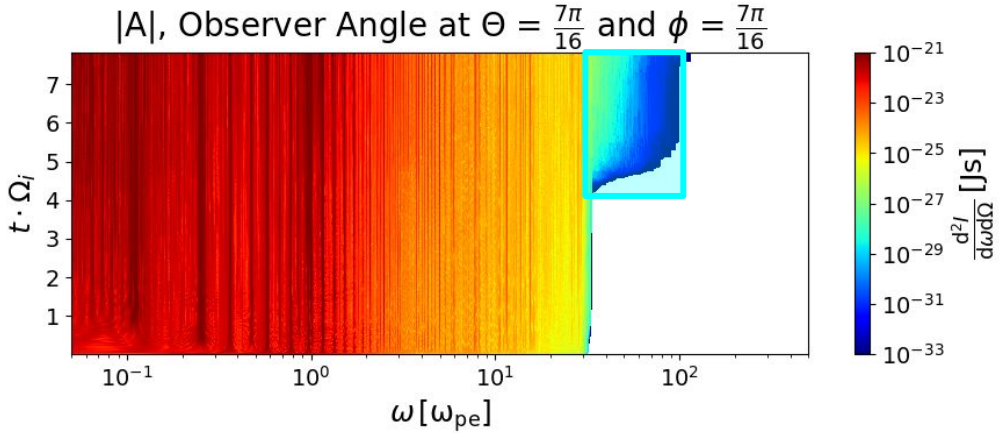

$$m_e c\dot{\beta} = \epsilon q t \longrightarrow \epsilon^2 N$$

First Master Equations for Quantities

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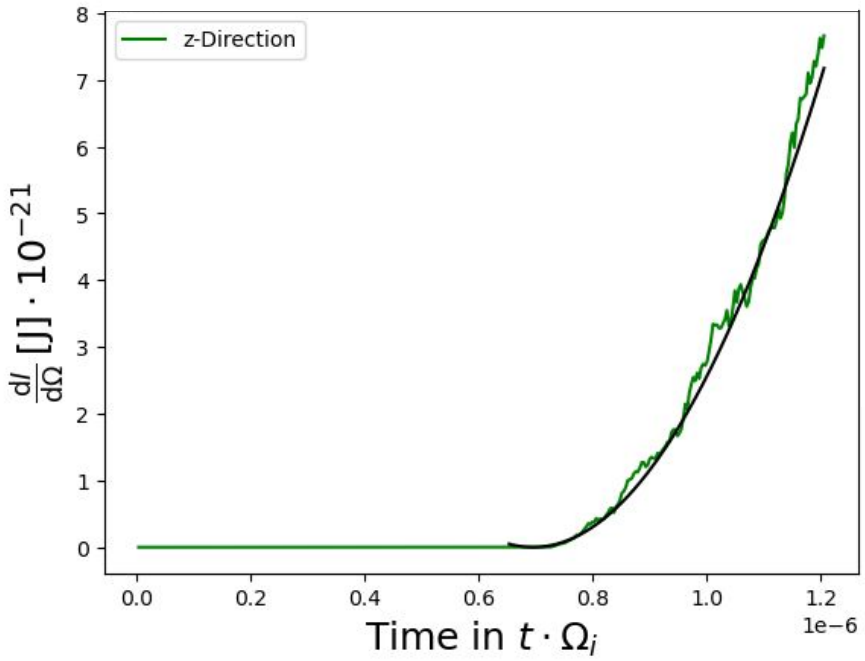
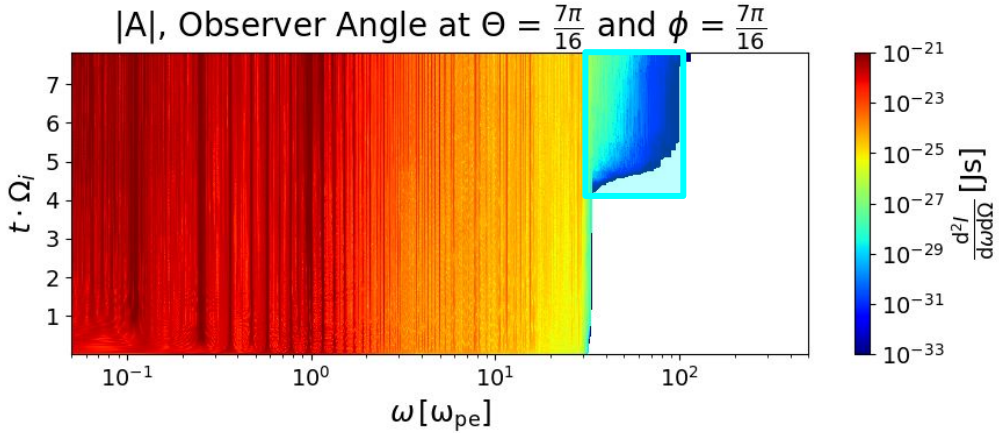
Frequency integrated Radiation





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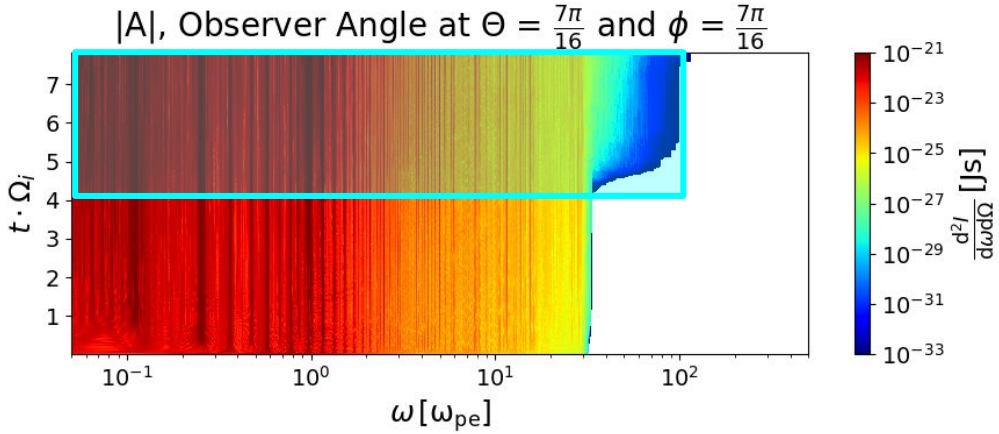
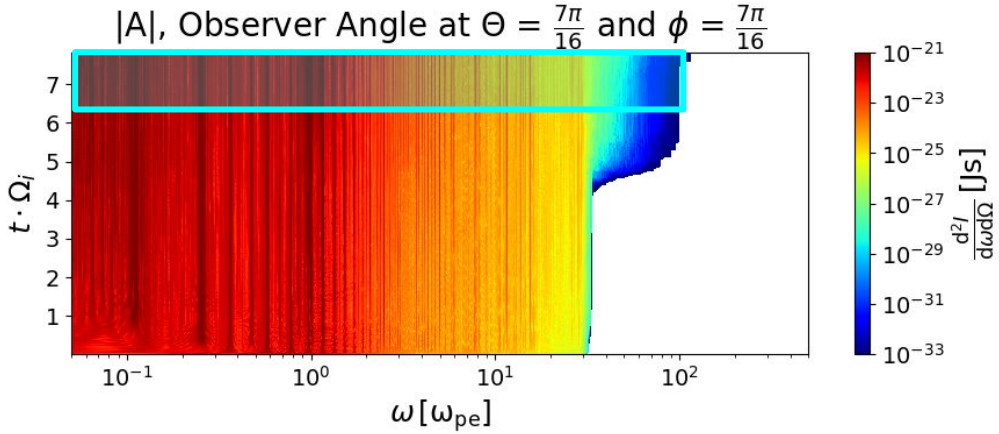


Post Acceleration…

First Master Equations for Quantities



Post Acceleration…

$$P(\gamma) = P_0 \gamma^{-\alpha} \longrightarrow B^2 N \cdot f(\alpha)$$

What did we learn from polarization?

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- Reconstruct origin magnetic field from skymap resolution of polarization
- Zhang's polarization swing, now frequency resolved!
- Persistently polarized radiation from plasmoids!
- First Analytic Models!

Take Aways - What is New about This?

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

- PIConGPU offers detailed calculation of radiation spectra
- Allows to find new features:
  - 😐 Reproduces polarization swing

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PLASMA PEPSC

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Questions?

Sergey Ermakov; Klaus Steiniger; Richard Pausch
06.06.2024

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