



Hybrid Simulations of the Resonant and Non-Resonant Cosmic Ray Streaming Instability

Colby Haggerty
Damiano Caprioli
Ellen Zweibel

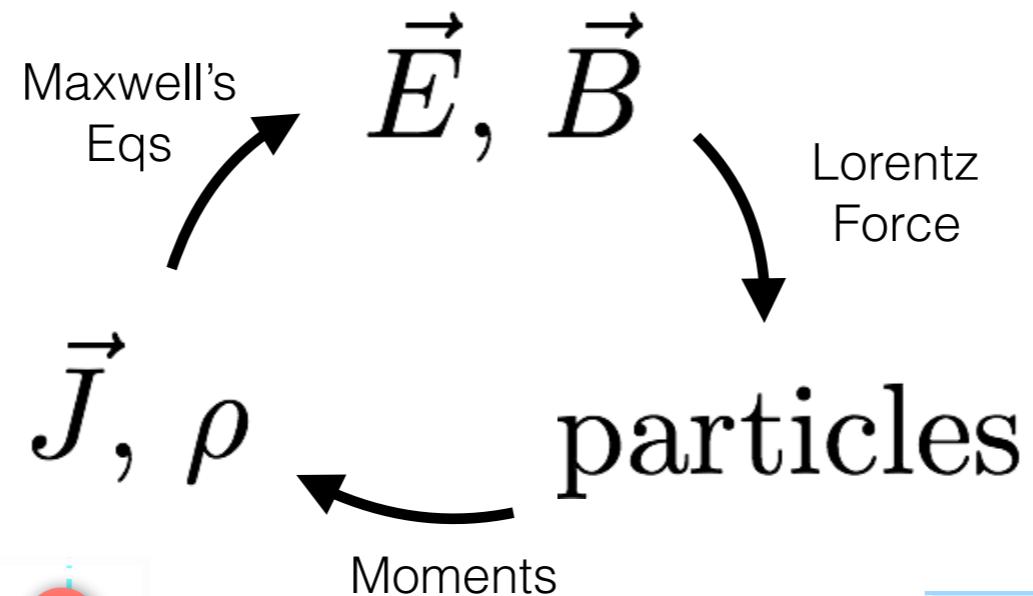


THE UNIVERSITY OF
CHICAGO

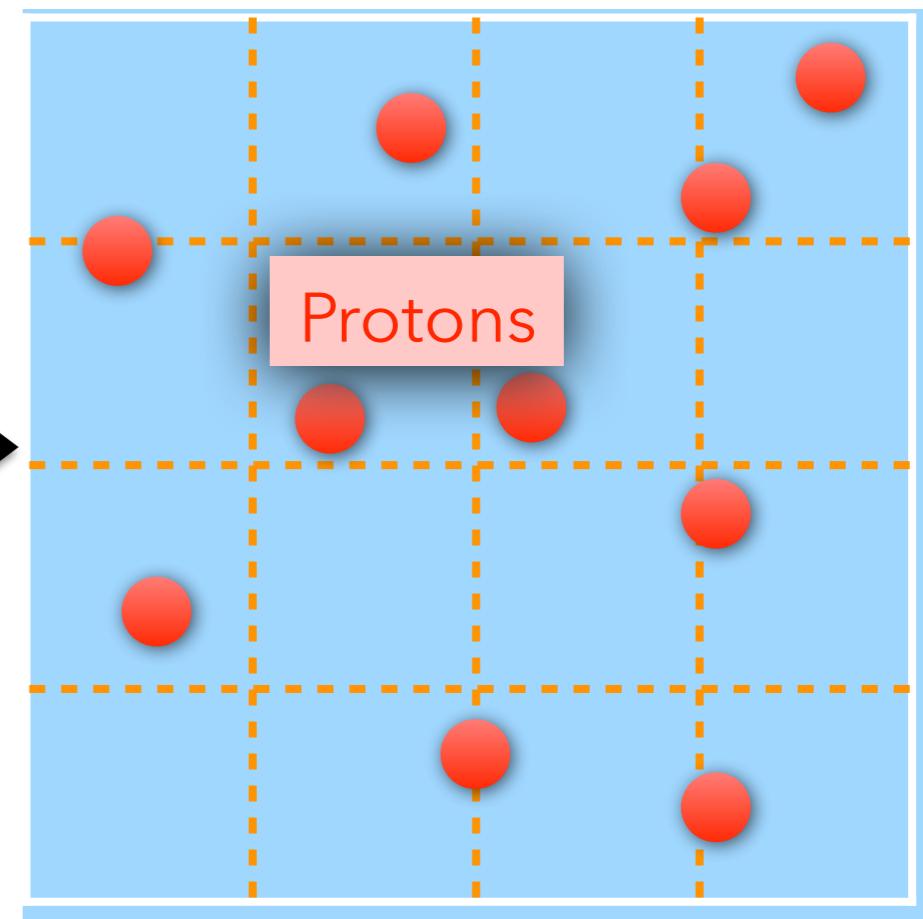
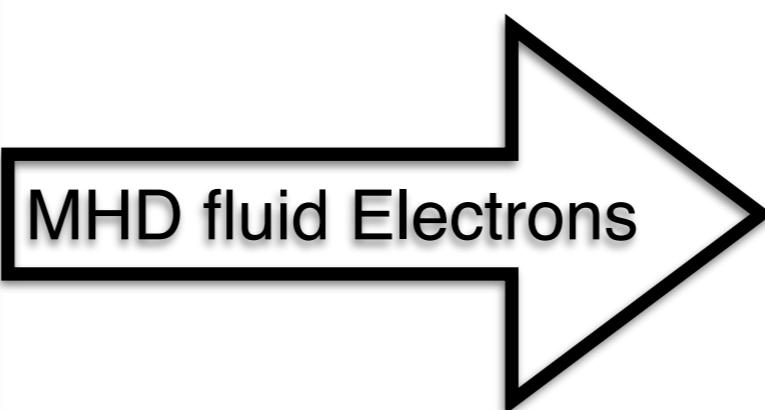
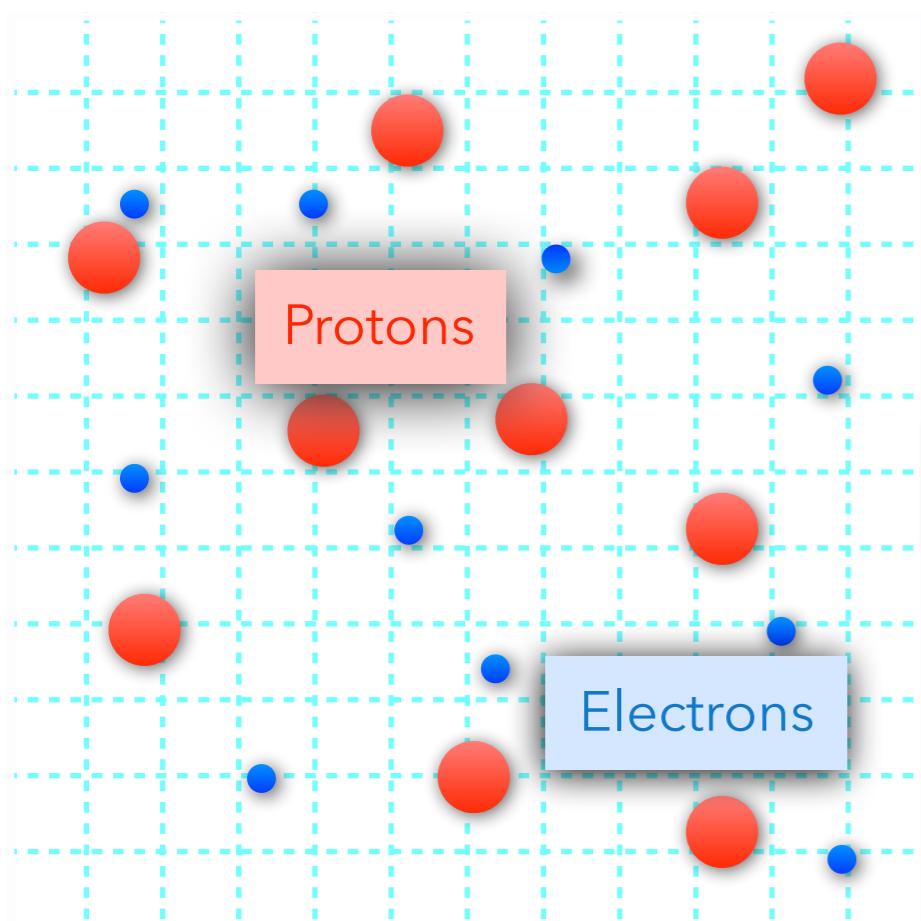


Kinetic Simulations

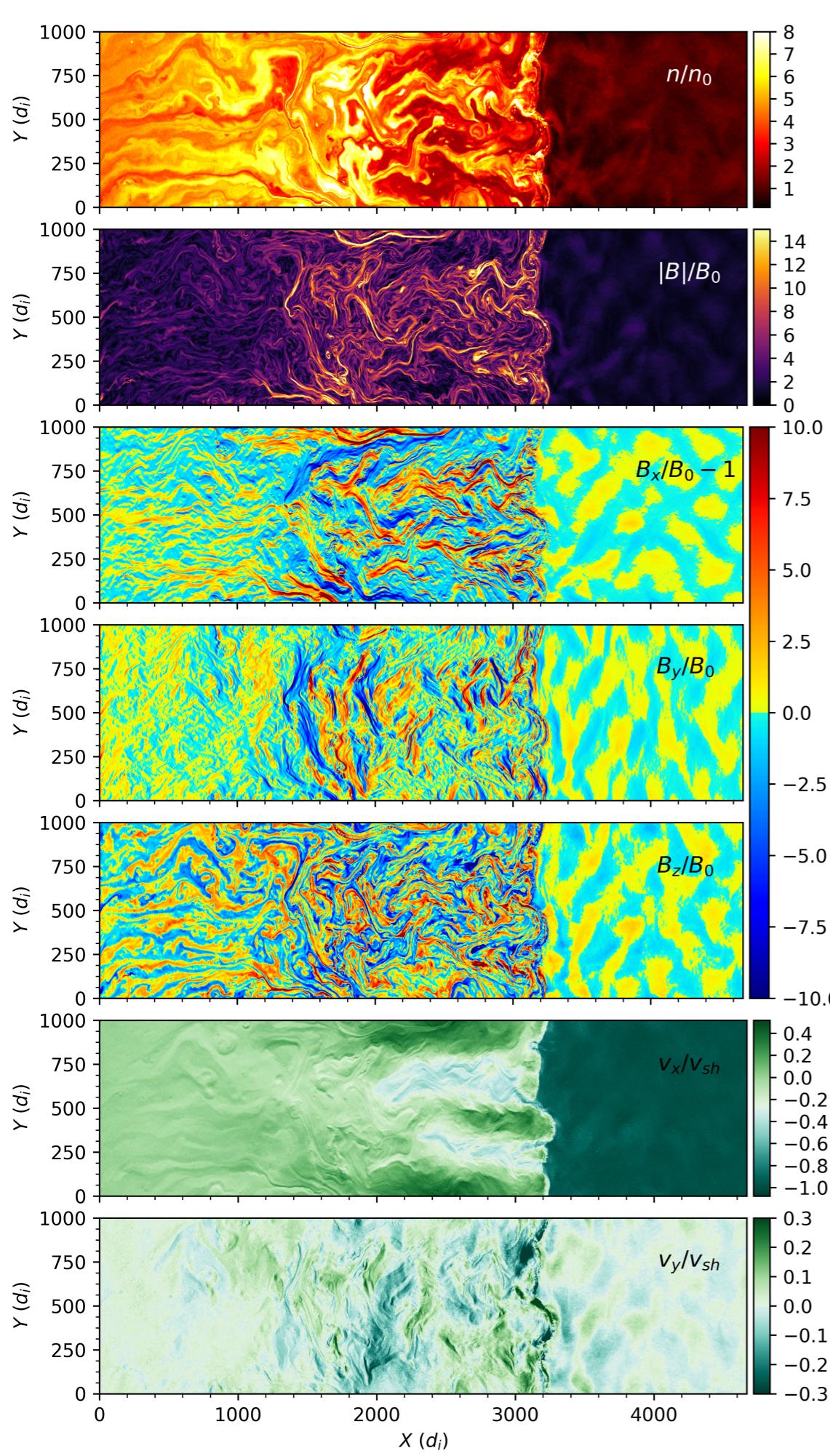
Particle in Cell
(PIC)



Hybrid with
Kinetic Ions



dHybridR



- Hybrid PIC code that retains relativistic ion dynamics

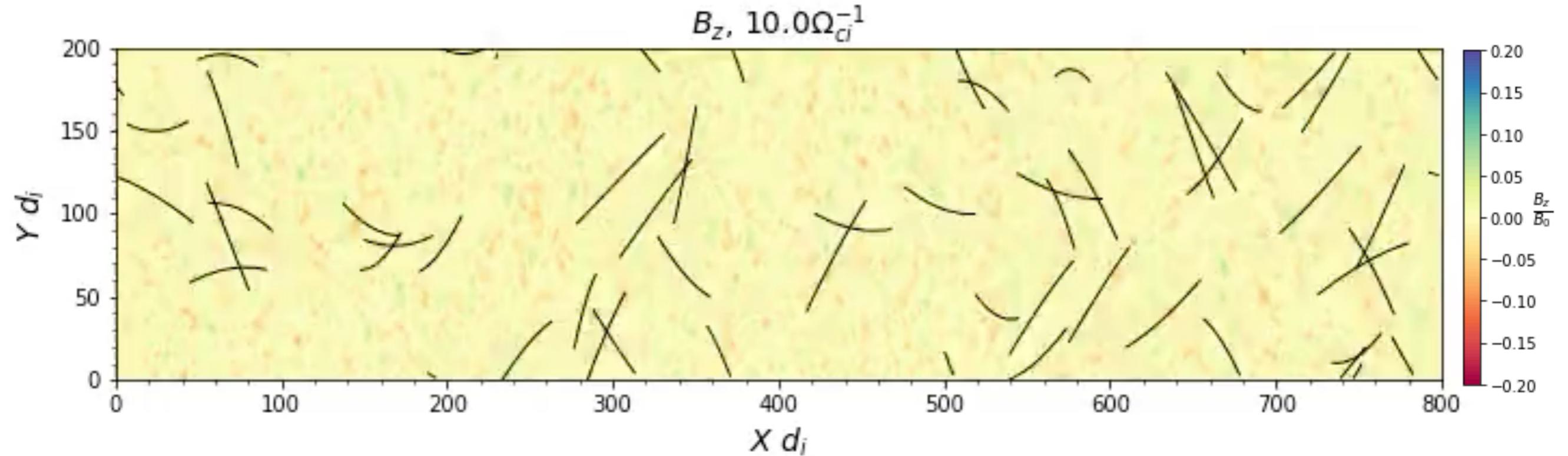
$$\vec{J} = \frac{c}{4\pi} \vec{\nabla} \times \vec{B} - \cancel{\frac{1}{4\pi} \frac{\partial E}{\partial t}} \rightarrow \left(\frac{u}{c}\right)^2$$

- Approximations are ok when the bulk flow is small:

$$\frac{d\gamma \vec{v}}{dt} = \frac{q}{m_i} \left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B} \right)$$

- We can treat CRs relativistically!
- Haggerty C.C. & Caprioli D. 2019

Streaming Instabilities



- CRs transfer energy to magnetic fields
- Required for CR acceleration for DSA in shocks
- Change the CR diffusion coefficients in the ISM
- couple CRs to thermal plasma, heat and push, lead to galactic winds

Resonant and Non-Resonant

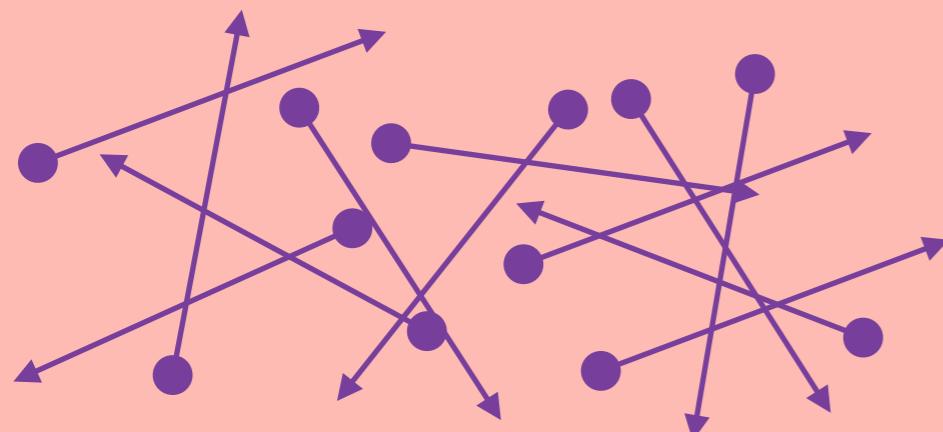
- Two different instability regimes

$$\bar{\sigma} \equiv \frac{4\pi}{c} \frac{J_{cr} r_L}{B} = \frac{n_{cr}}{n_0} \frac{p_{\min} v_D}{m_i v_A^2} \begin{cases} \ll 1, & \text{Resonant} \\ \gg 1, & \text{Non Resonant (Bell)} \end{cases}$$

- Two different CR distributions

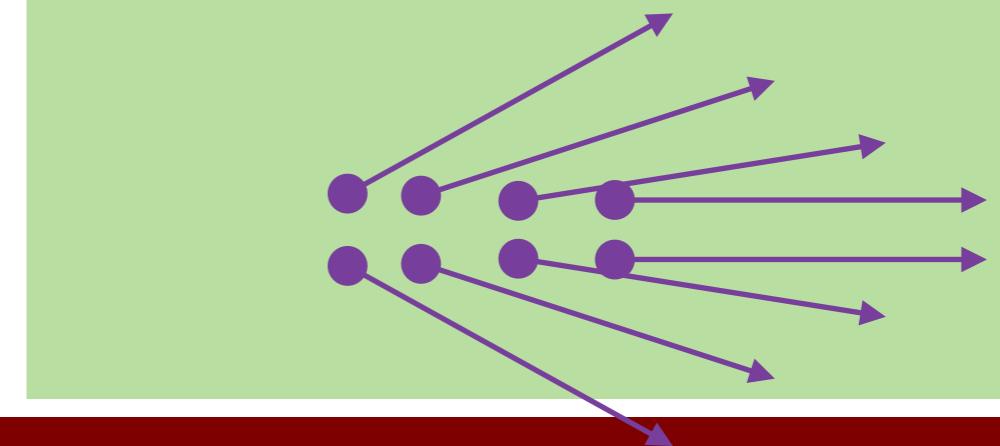
**“Hot” Drifting
Power-law**

$$f(p) \sim p^{-4.5}; v_D = 10v_A$$



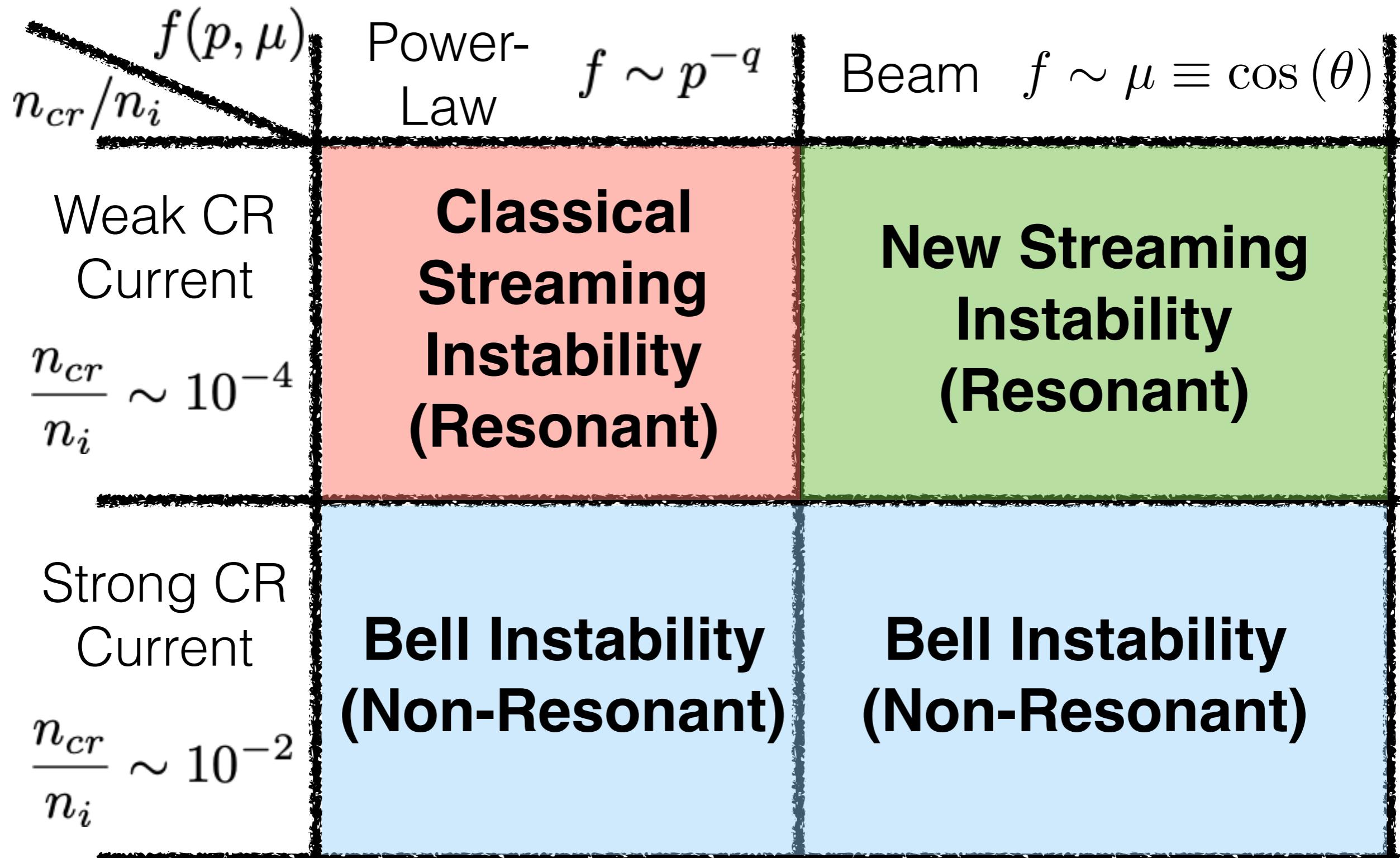
**“Beam” Like
distribution**

$$f(p) \sim \delta(p - p_b)(\mu + 1)$$

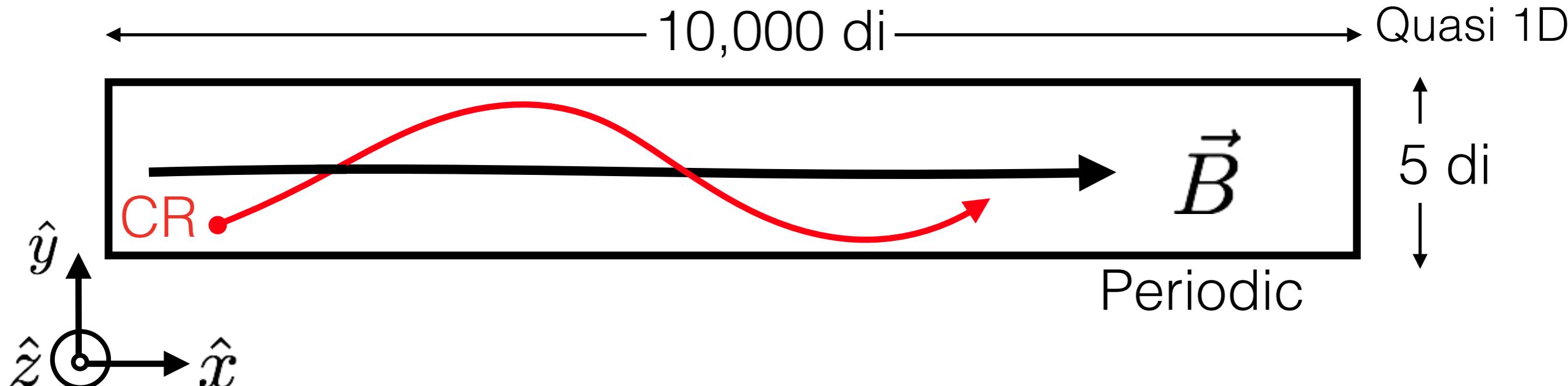




Parameter Space



Simulation Setup



Stationary background plasma

$$\beta_i = \frac{nT}{B^2/8\pi} = 2$$

$$c = 100v_A$$

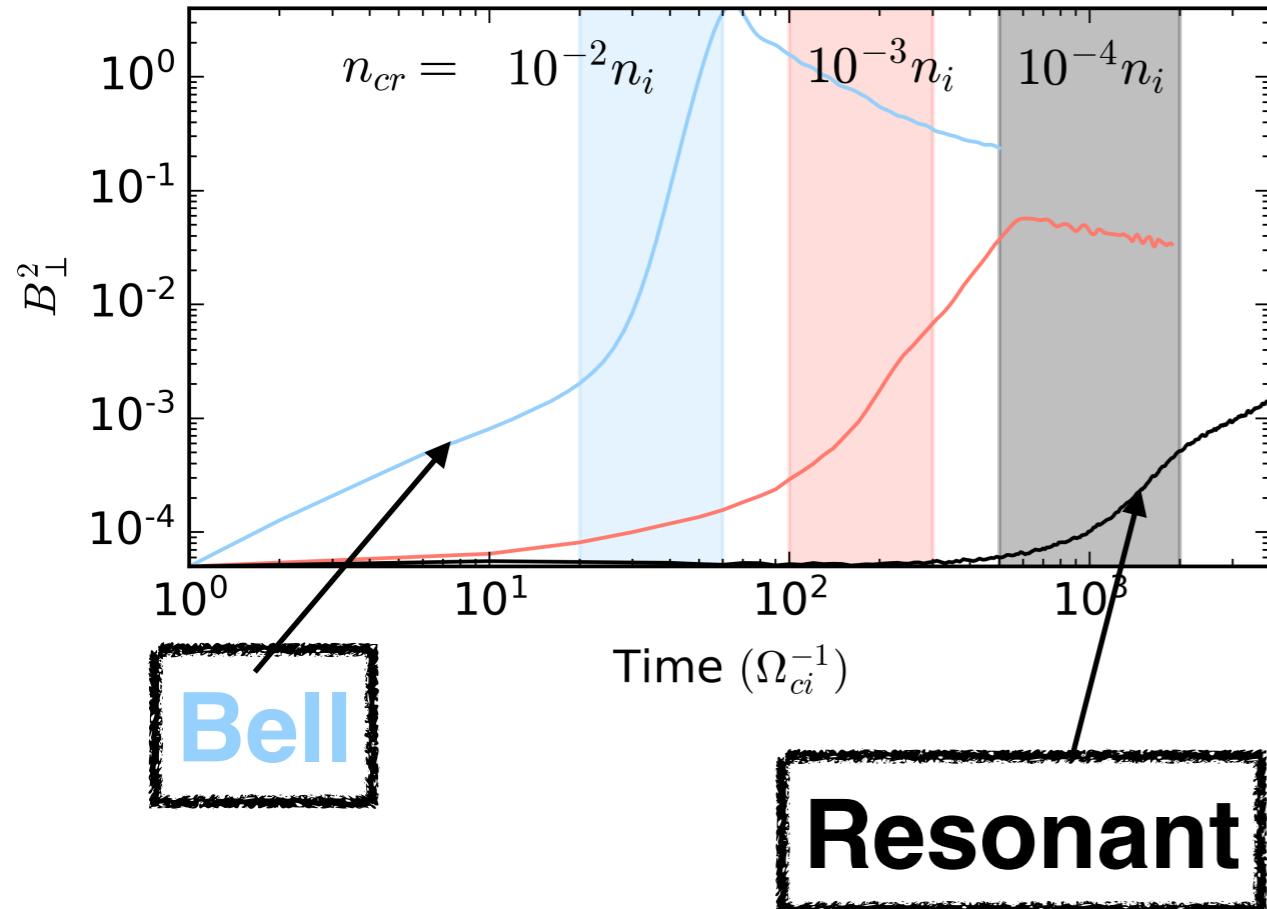
Superimposed low density high energy CR population

$$\frac{n_{cr}}{n_0} \rightarrow 10^{-2} - 10^{-4}$$

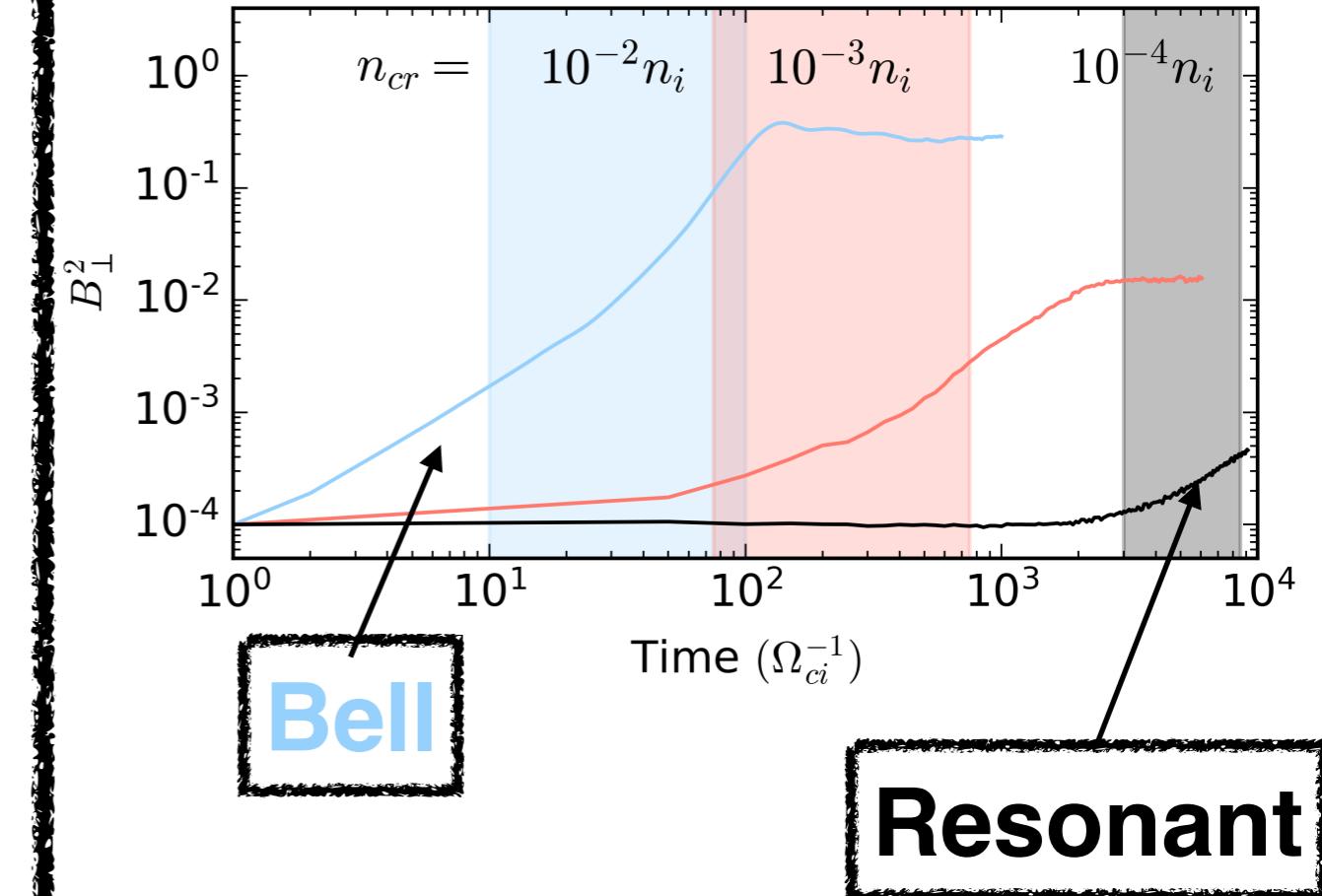
Streaming in +x direction

Magnetic Field Amplification

Power-Law Setup



Beam Setup

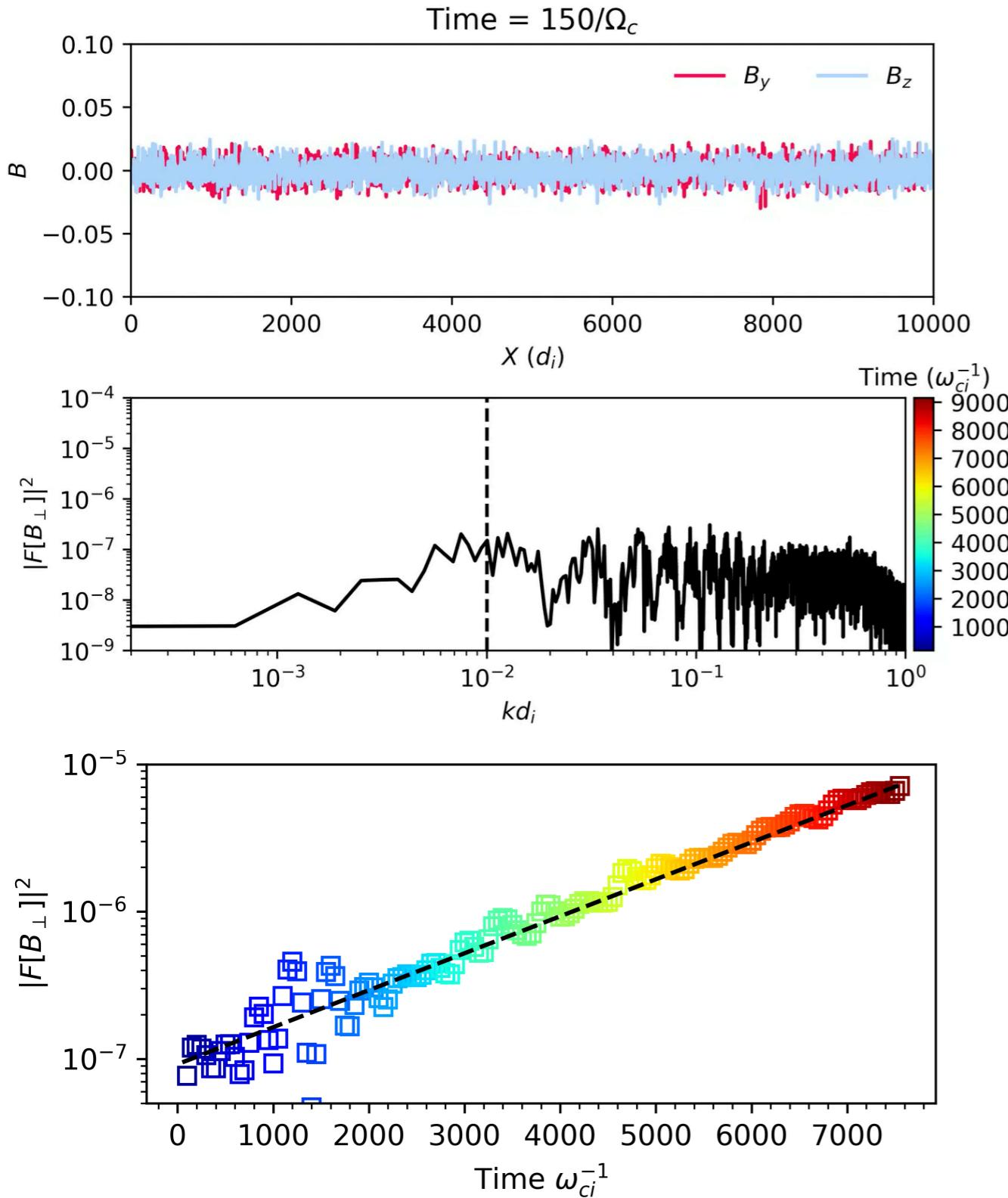


- All cases trigger instability, with different growth rates and different saturations. Shaded regions denote averaged area

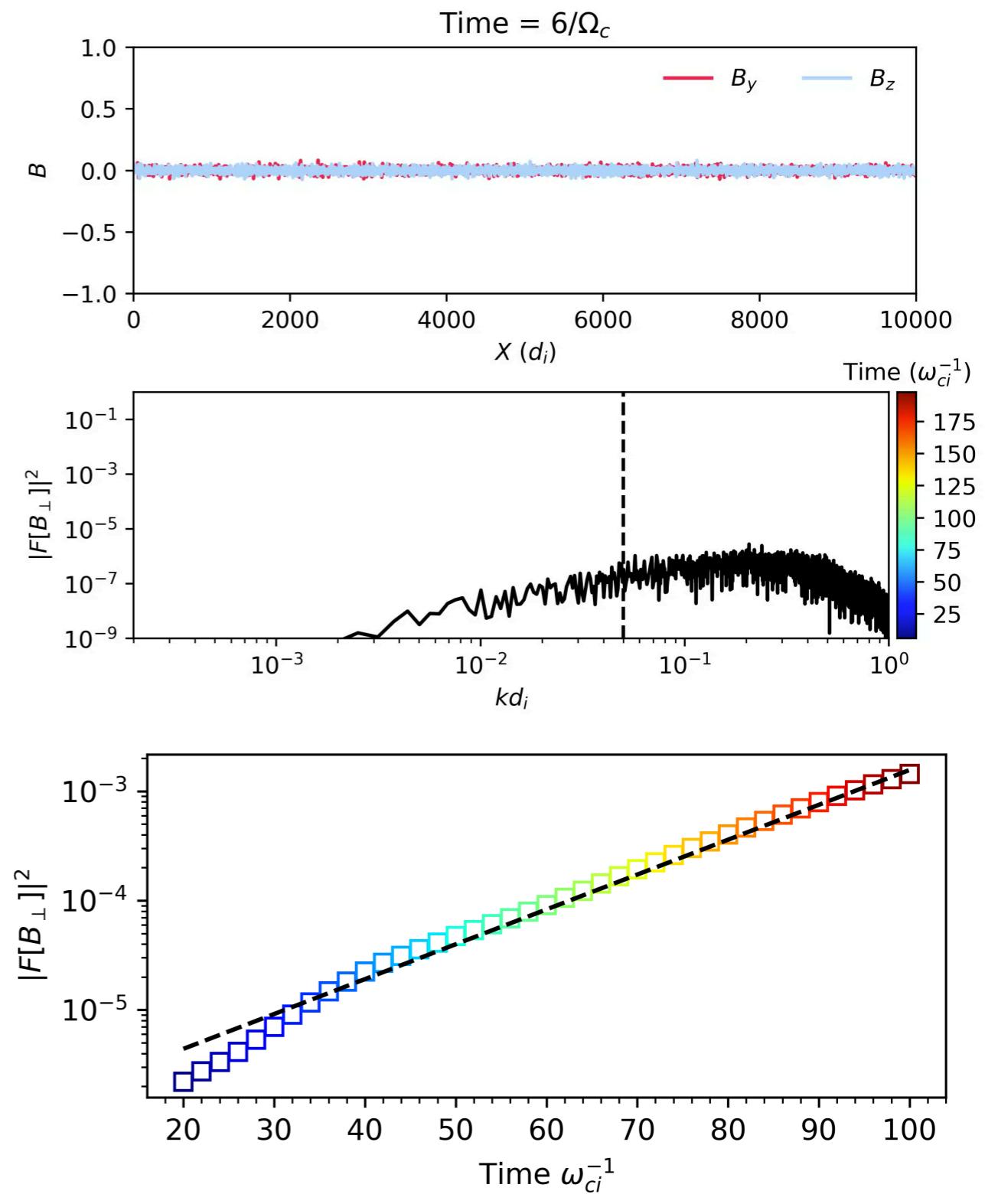


Instability Growth Rates for Power-Law

Resonant



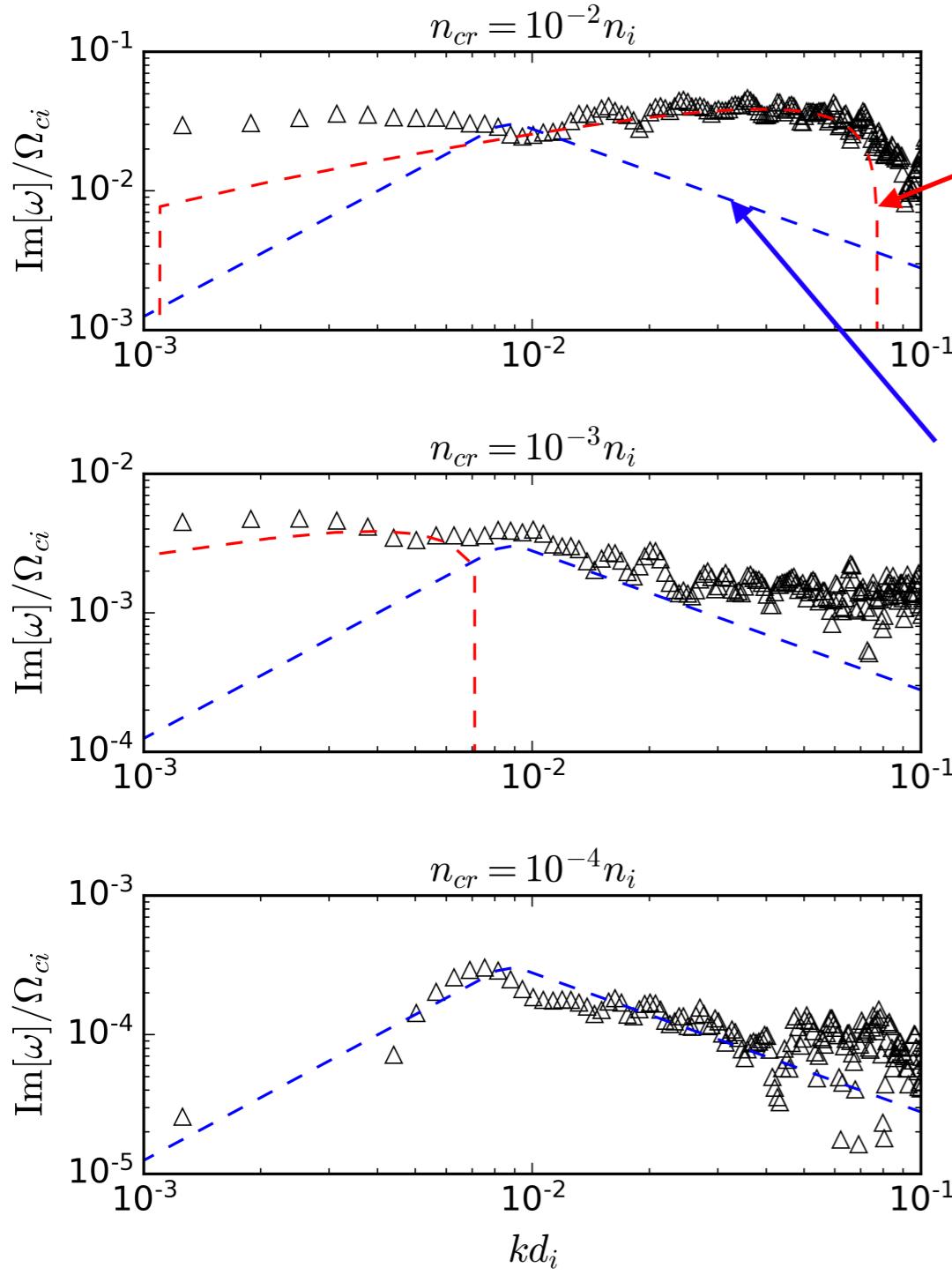
Non-Resonant



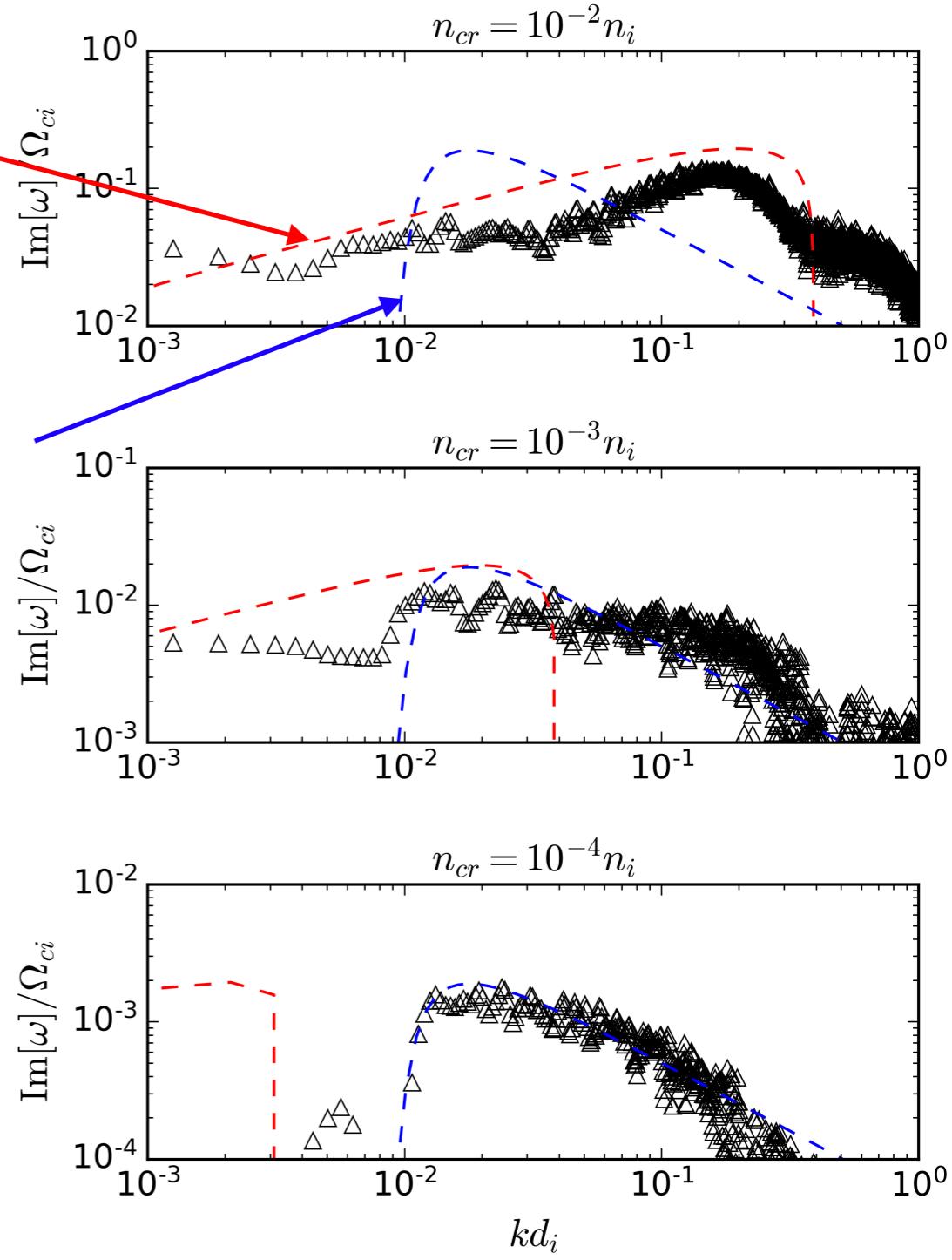
Instability Growth Rates



Power-Law Setup



Beam Setup

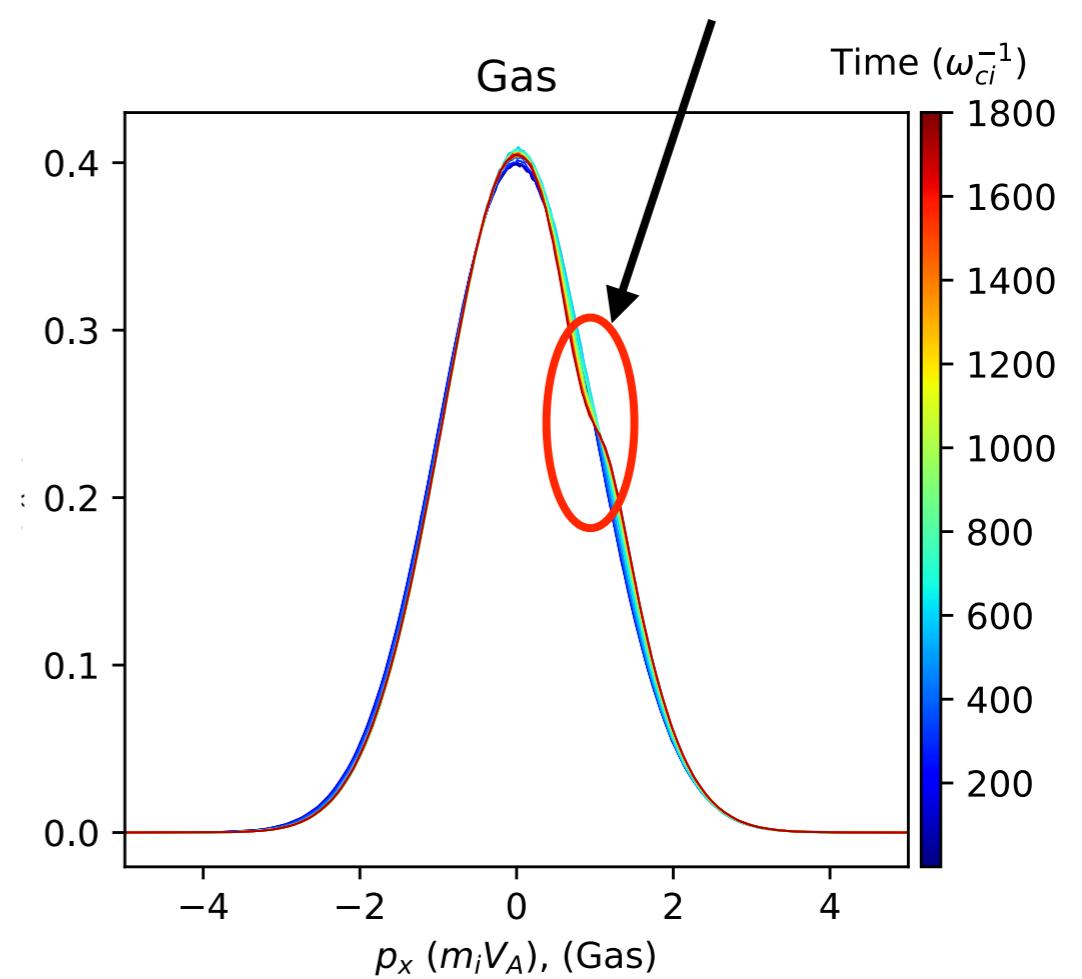
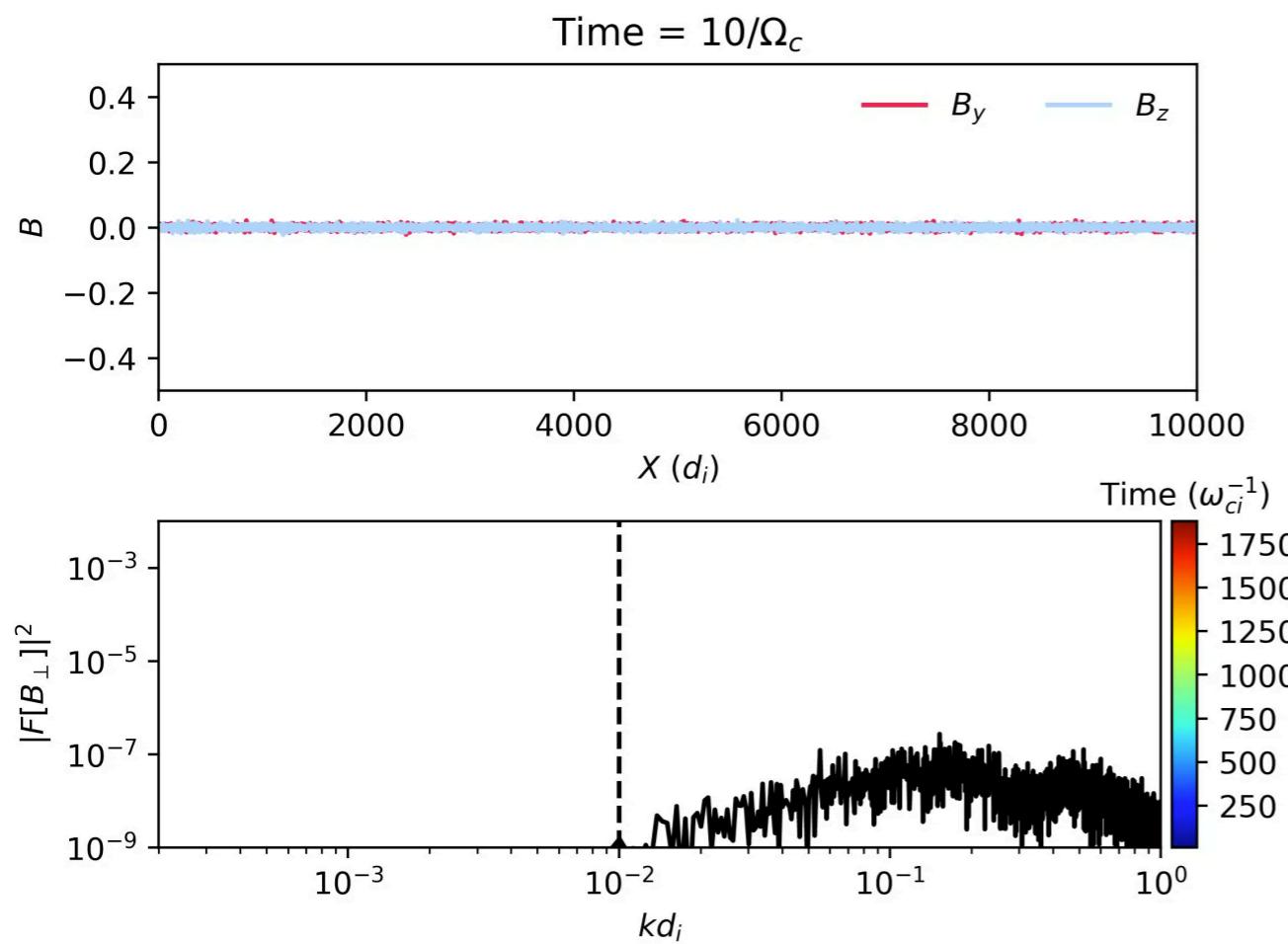


Non-
Resonant

Resonant

Non-Linear Saturation

- Linear theory well predicts the growth of the instability
- Future work to examine saturation **Heating by Landau Damping!**



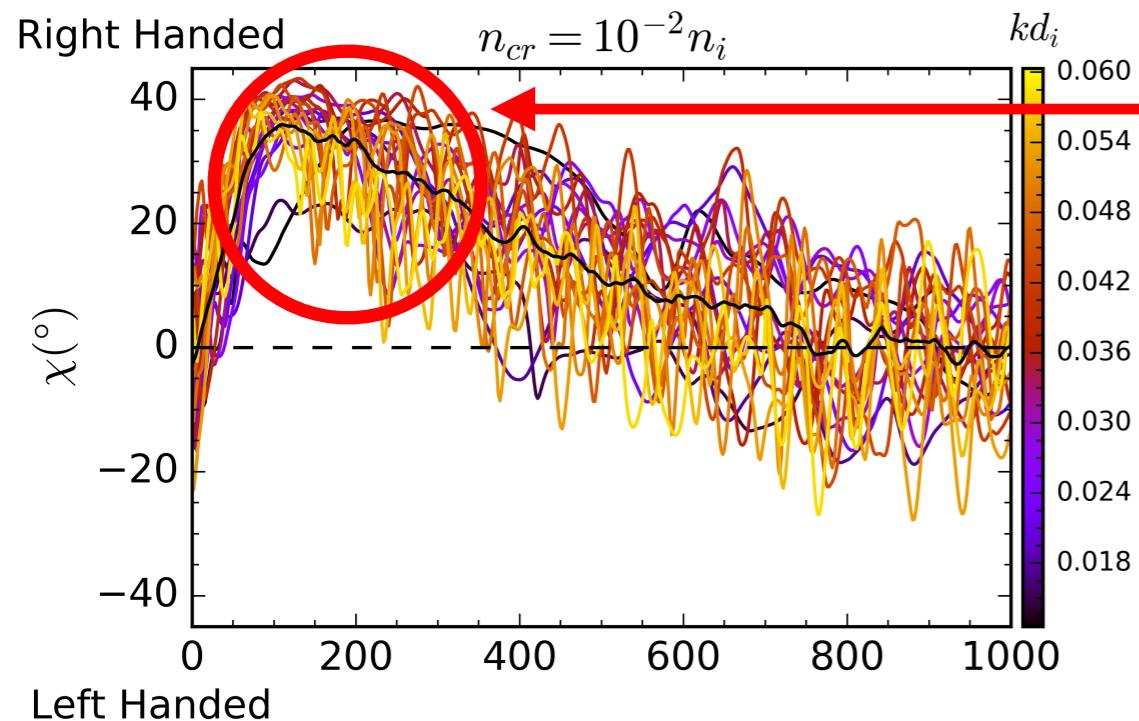


Conclusions

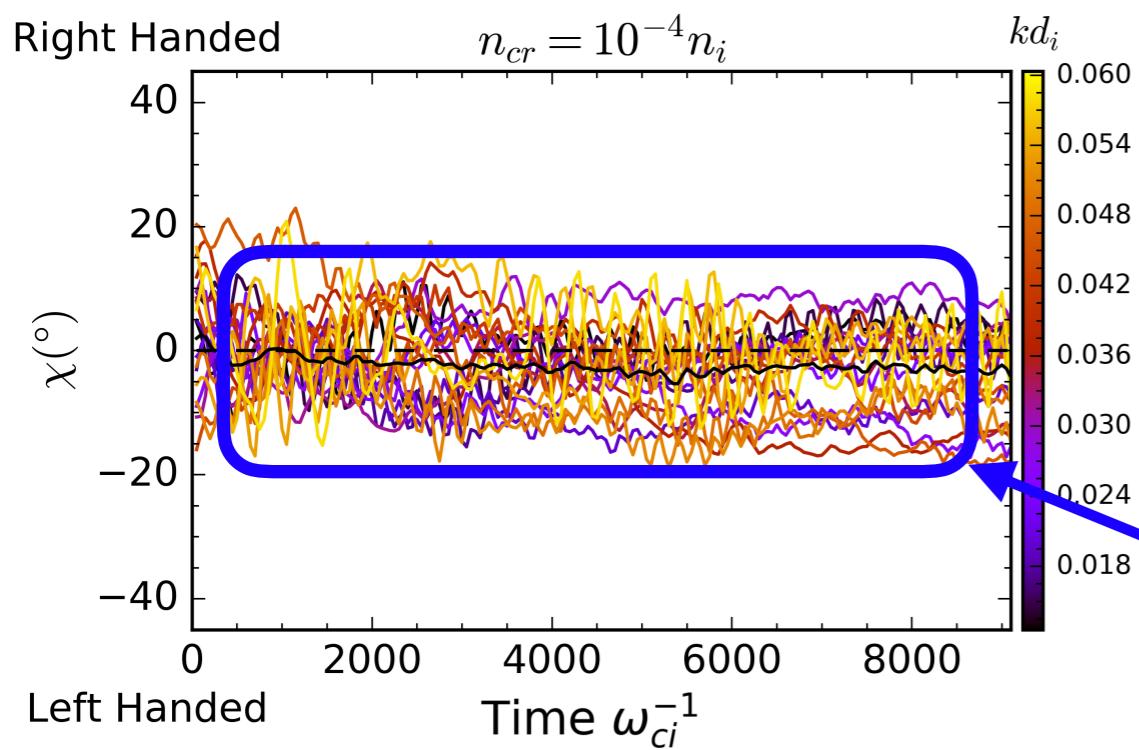
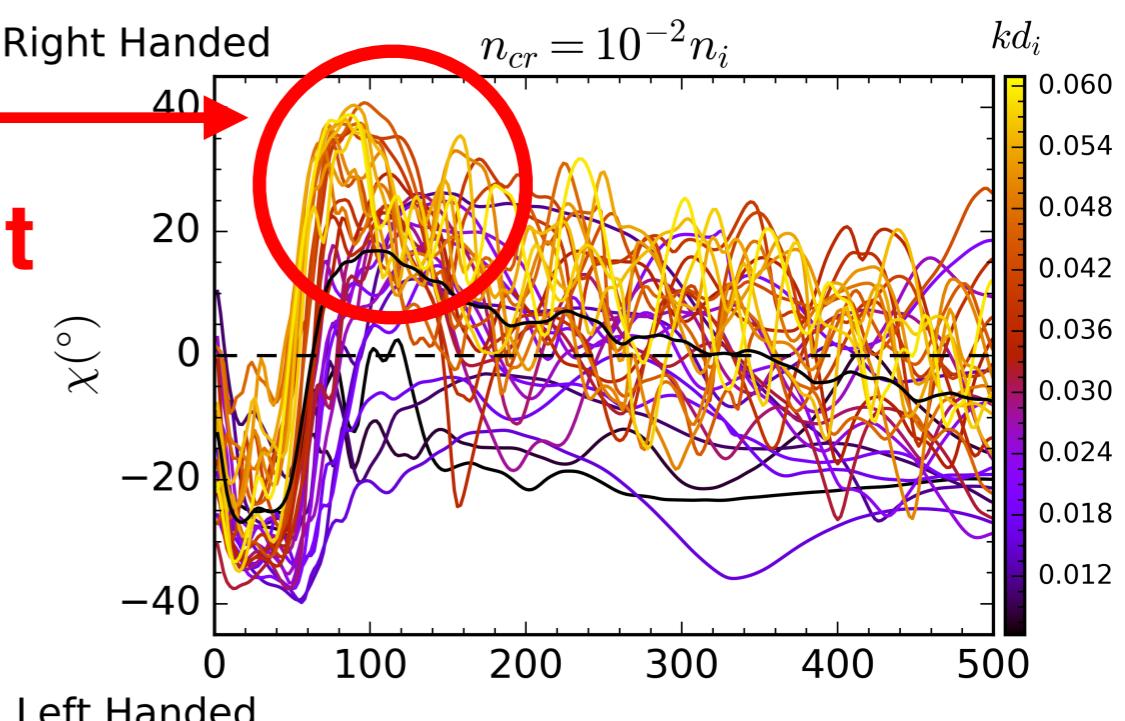
- New Hybrid simulation code *dHybridR*, which retains fully relativistic ion dynamics. Well suited for studying systems with CRs
- Simulations of non-resonant and resonant CR streaming instability agree well with linear theory. Helictites (Polarization) consistent with (non) resonant instability for different distributions
- Future works: study of saturation, including damping and non-linear effects; determination of diffusion coefficient

Helicity (Polarization)

Power-Law Setup



Non-
Resonant
(Bell)



Resonant

