Lepton-driven Non-Resonant Streaming Instability

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Based on arXiv:2106.07672

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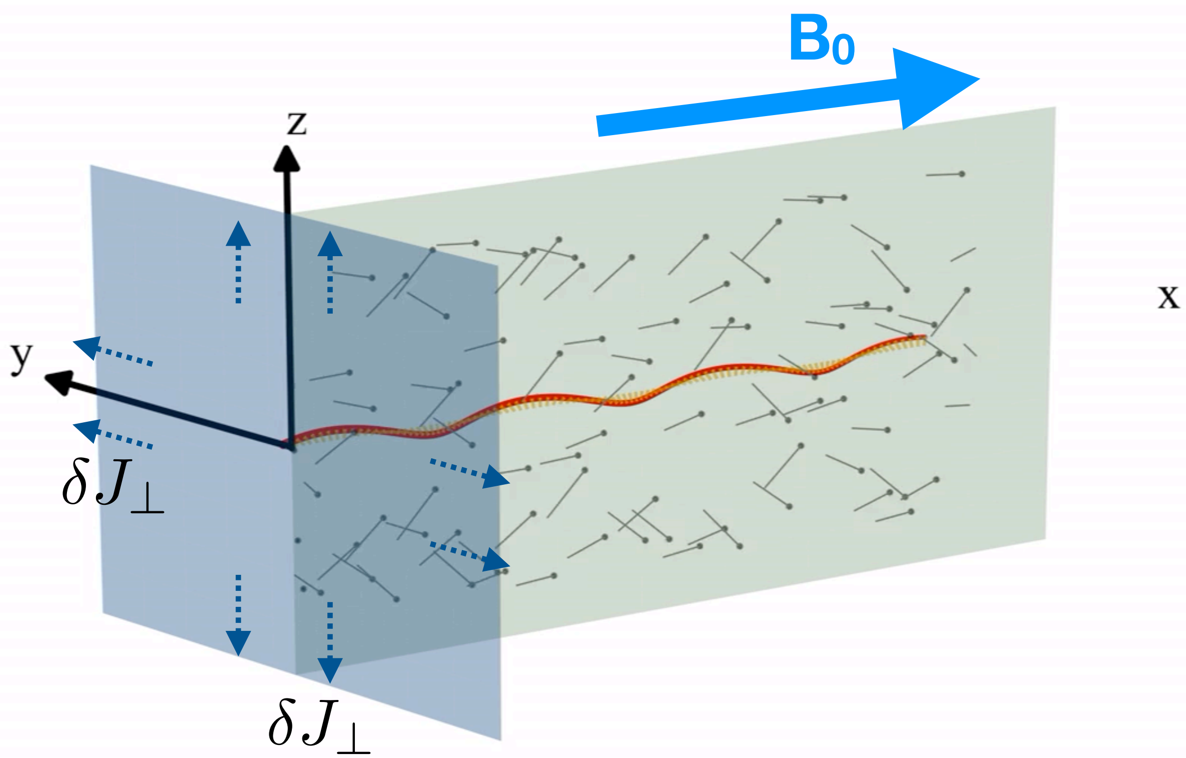
Observations demand LARGE magnetic field!

~$ cd Session:12 / ID1371 /

- Non-resonant streaming instability: $\delta B/B_0 \gg 1$ (Lucek & Bell 2000, Bell 2004,05)
- Particle acceleration up to knee (~ PeV) — self confinement and propagation
- Relevant for laboratory experiments (e.g., Jao+2019)

What is Non-Resonant Instability?

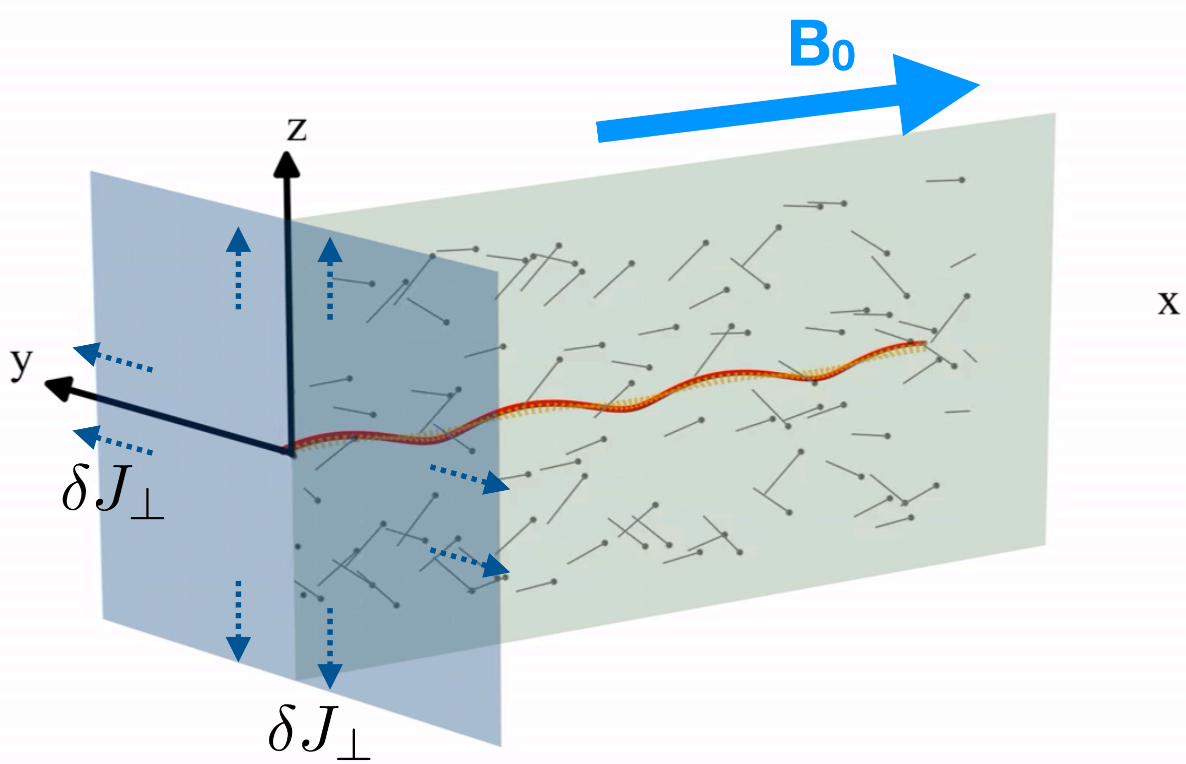


- **CRs stream through magnetized plasma.**
- **Transverse fields grow**
- $k_{\rm fast} = \frac{1}{2}\frac{n_{\rm cr}}{n_0}\frac{v_{\rm d}}{v_{\rm A0}}\, d_{\rm i}^{-1} \sim \left(n_{{\rm cr},-8}\, v_{{\rm d},4}\, v_{{\rm A0},1}^{-1}\right)\frac{1}{10^{-5}{\rm pc}}$
- $\gamma_{\rm fast} = \frac{1}{2}\frac{n_{\rm cr}}{n_0}\frac{v_{\rm d}}{d_{\rm i}} \sim \left(n_{{\rm cr},-8}\, v_{{\rm d},4}\right)\frac{1}{0.1\,{\rm yr}}$
- $(1) v_{\rm d} \gg v_{\rm A0}$, $(2)\ \gamma_{\rm fast} < \omega_{\rm ci}$, and $(3)\ \lambda_{\rm fast} \ll R_{\rm L}$

References: e.g.,

Achterberg 1983, Lucek & Bell 2000, Bell 2004,05, Niemiec+2008, Zirakashvili+2008, Reville+2008, Riquelme & Spitkovsky 2009, Ohira+2009, Zweibel & Everett 2010, Gargate+2010, Amato & Blasi 2009, Bret+2010, Schure+2012, Caprioli+2014, Blasi+2015, Matthews+2017, Weidl+2019, Haggerty+2019, Zacharegkas+2019, Marret+2020, …

What is Non-Resonant Instability?



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CRs relativistic protons	Background temperature	CR distribution function	What if ... continued

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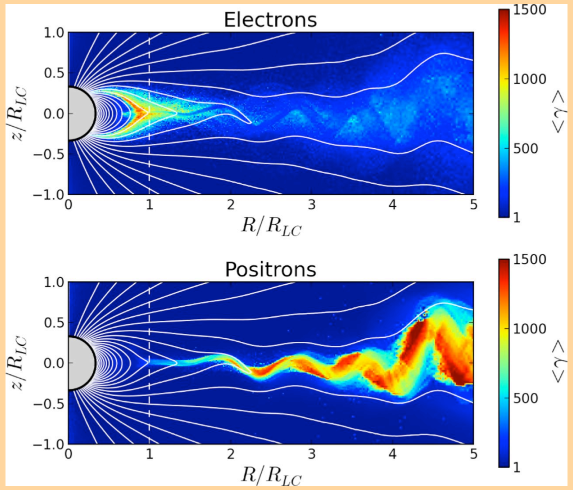
What if ...

- CR electrons
- Energetic electron-positron beam
- Pair (e+,e-) background

Perpendicular shocks — efficient in accelerating electrons (e.g., Guo+2014; Bohdan+2019; Xu+2020)

Laboratory experiments (e.g. Jao+2019)

Extended gamma rays around pulsar wind nebulae (e.g., PSR B0656+14)
e.g. Abeysekara+2017



Cerutti+2015

e.g., Philippov & Spitkovsky 2018, etc…

Do these produce the non-resonant (Bell) instability?

Does the final field, $\frac{\delta B_\perp}{B_0}$, scale similarly as the ion-driven case?

We have investigated these questions

from

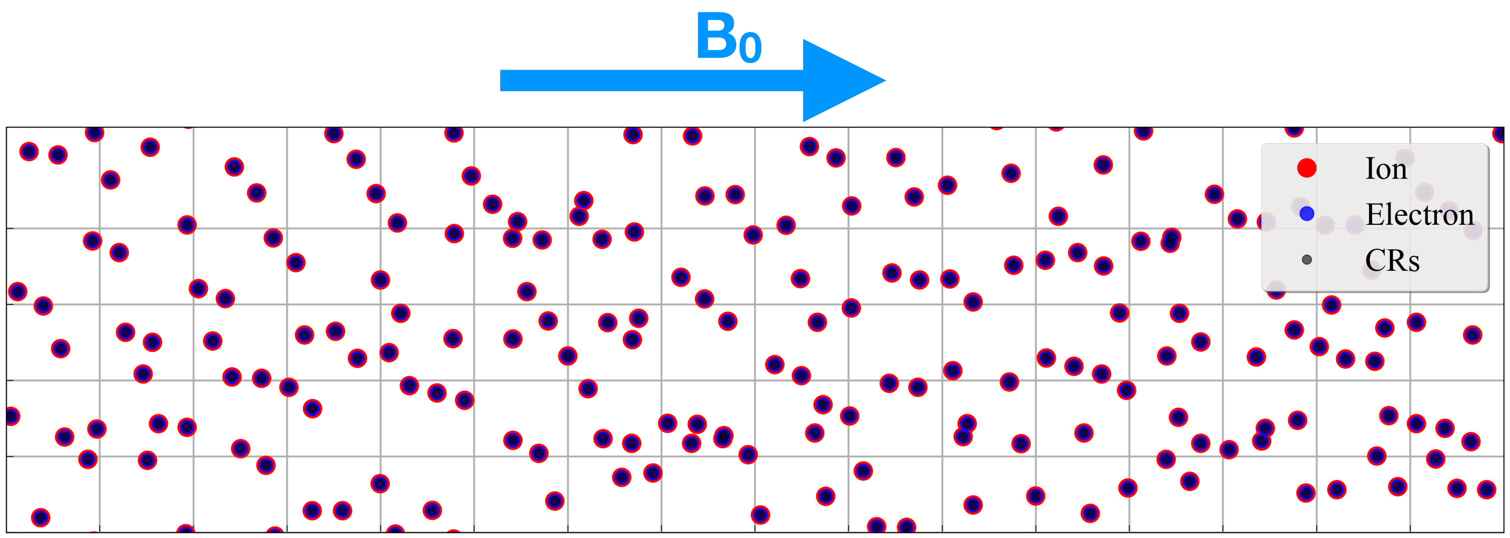
the first-principle

using

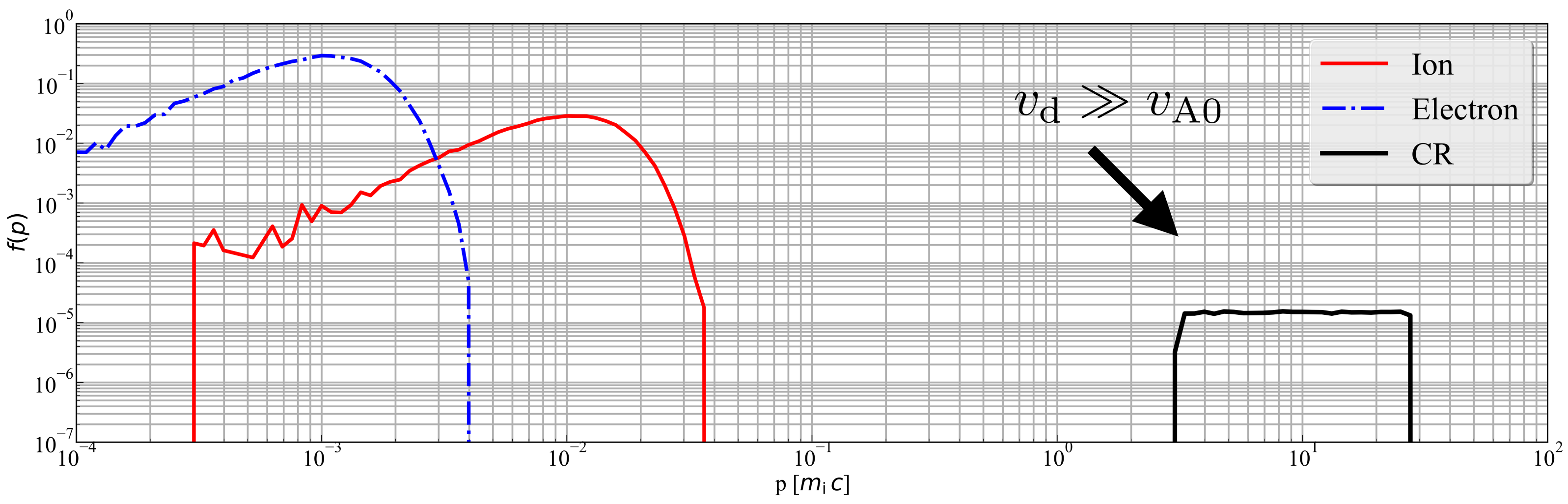
Particle-In-Cell (PIC) simulations

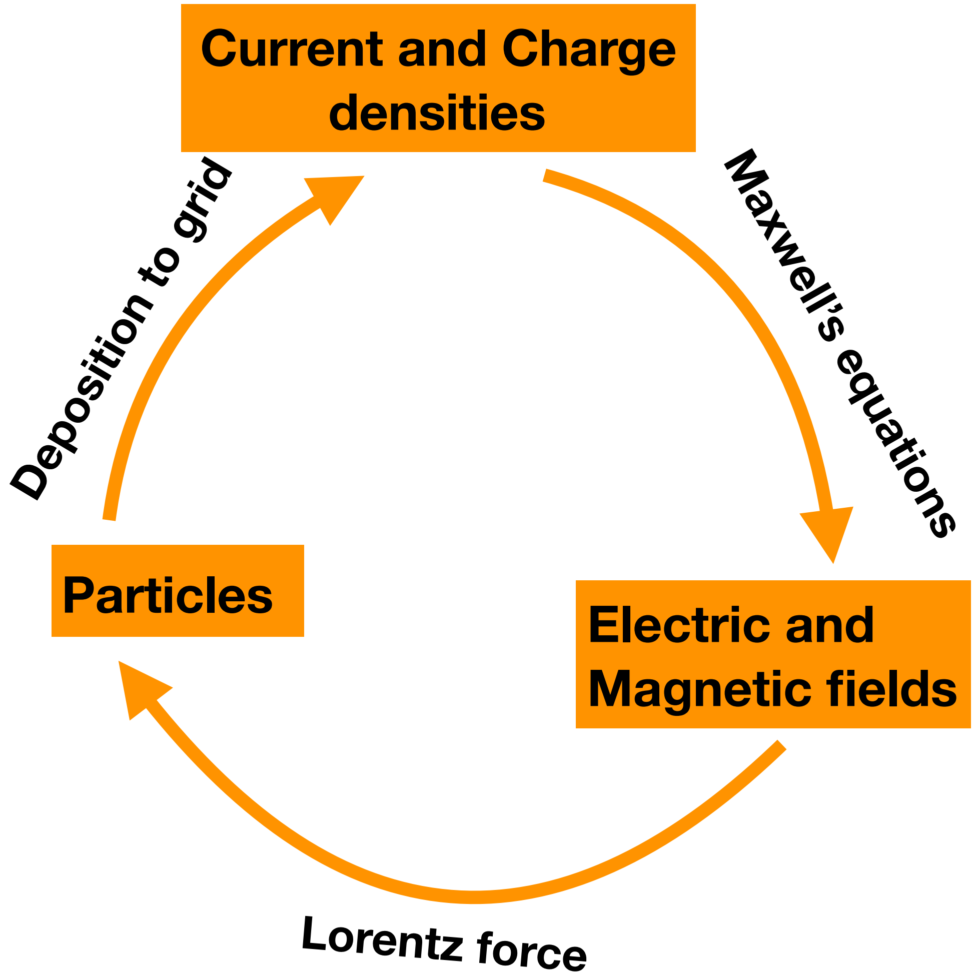
SG, Caprioli, Haggerty (arXiv:2106.07672)

PIC simulation setup



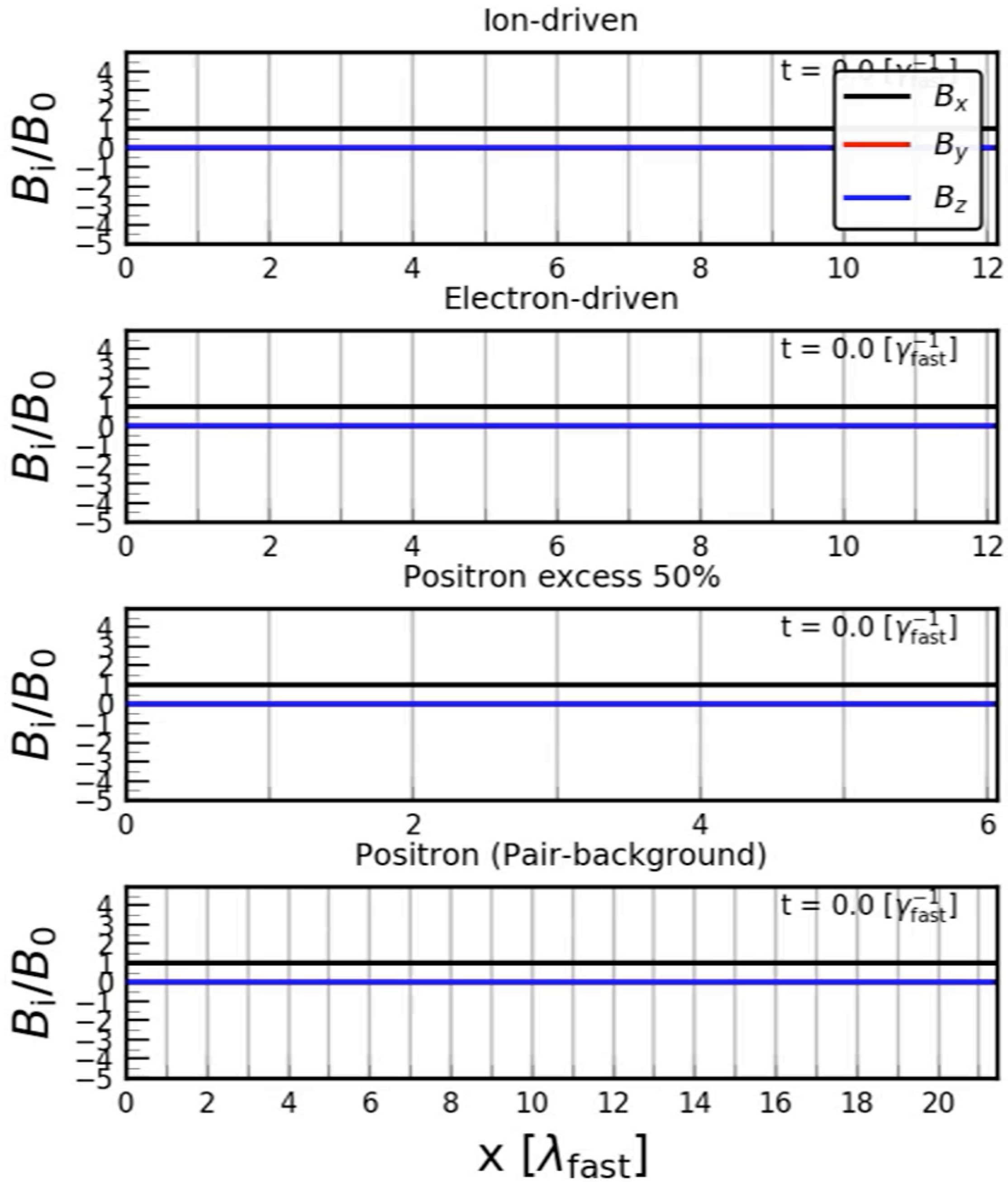
- $\beta = P_g / P_B \approx 1$
- $T_i = T_e$
- γ_{cr}
- **Charge and bulk current densities = 0**

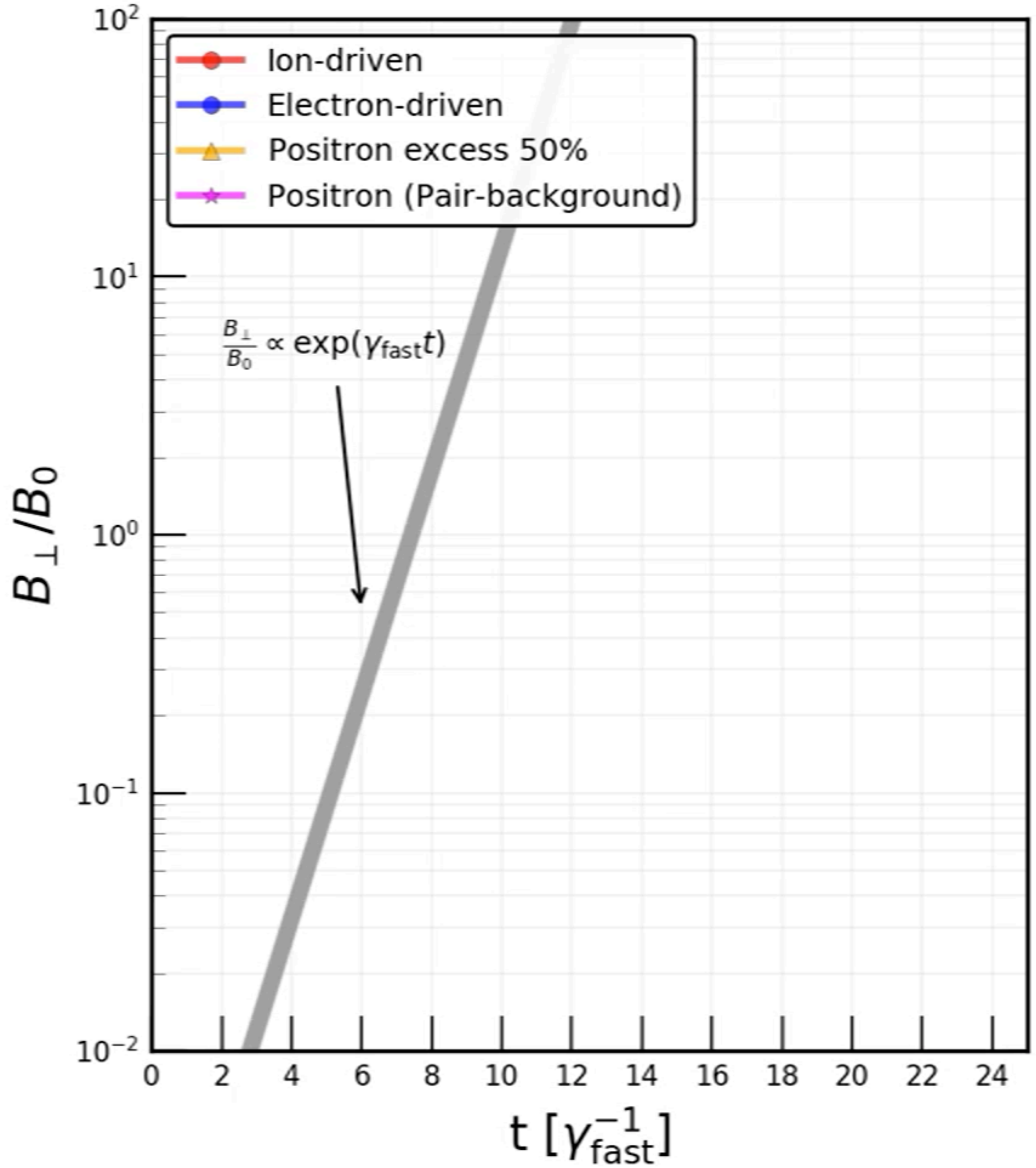




Tristan-MP (Spitkovsky 2005)

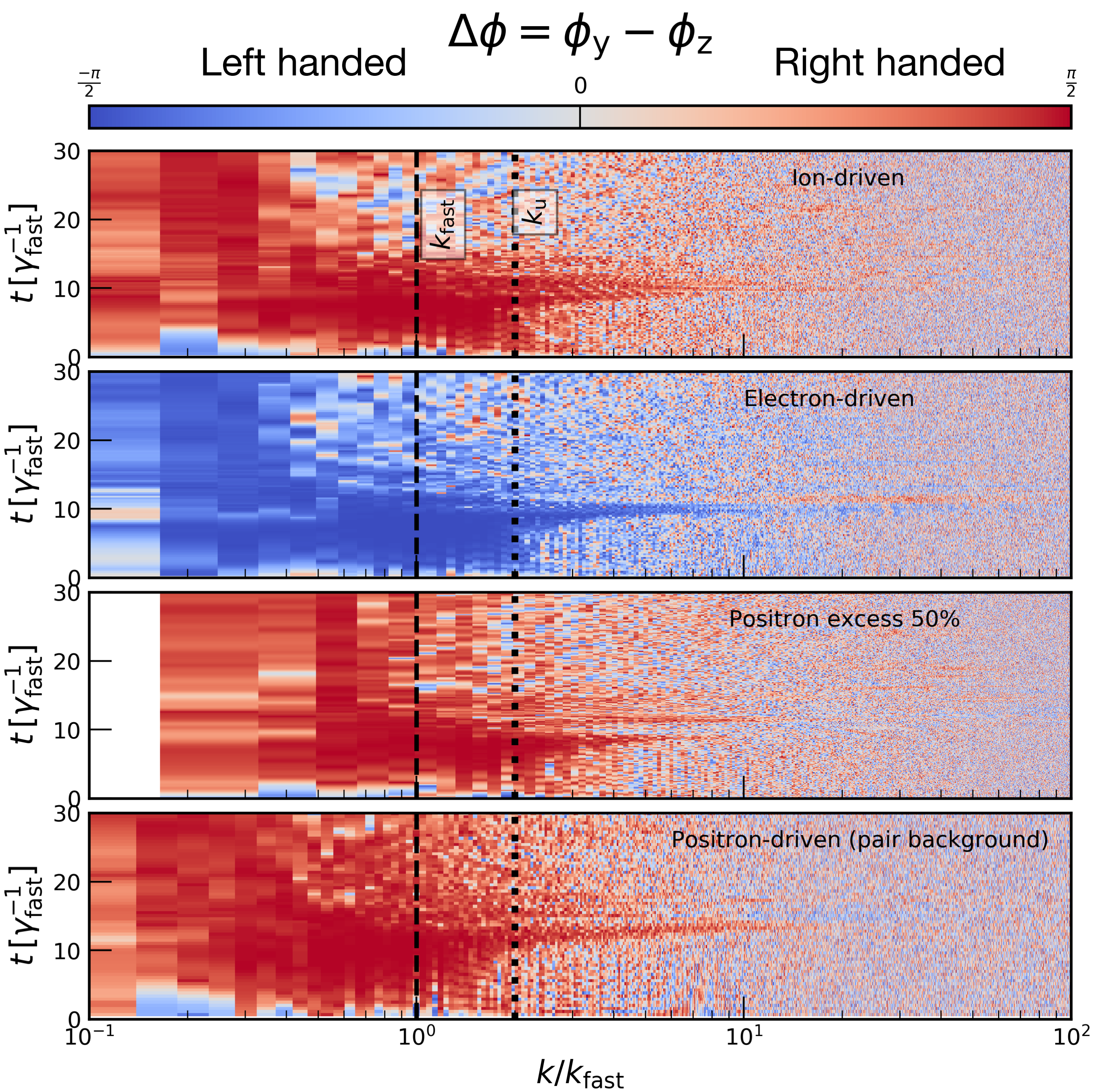
Results: Different composition and background





SG, Caprioli, Haggerty (arXiv:2106.07672)

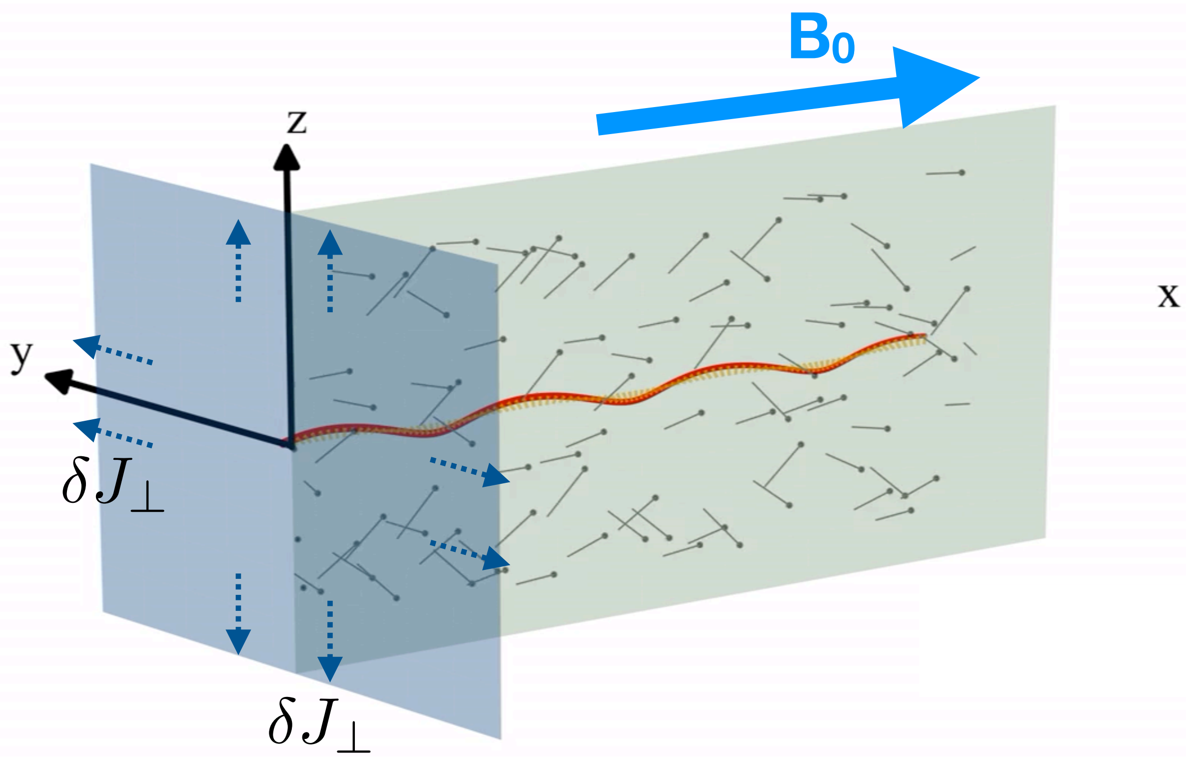
Results: Structure (helicity) of growing fields



- Dynamic mass of CRs
- Helicity depends on charge
- As long as non-zero current in the beam - instability works
- Linear growth until $\approx 10\gamma_{\rm fast}^{-1}$
- JxB becomes non-negligible

semi-classical theory → SG, Caprioli, Haggerty (arXiv:2106.07672)

Results: Saturation of lepton-driven Bell instability

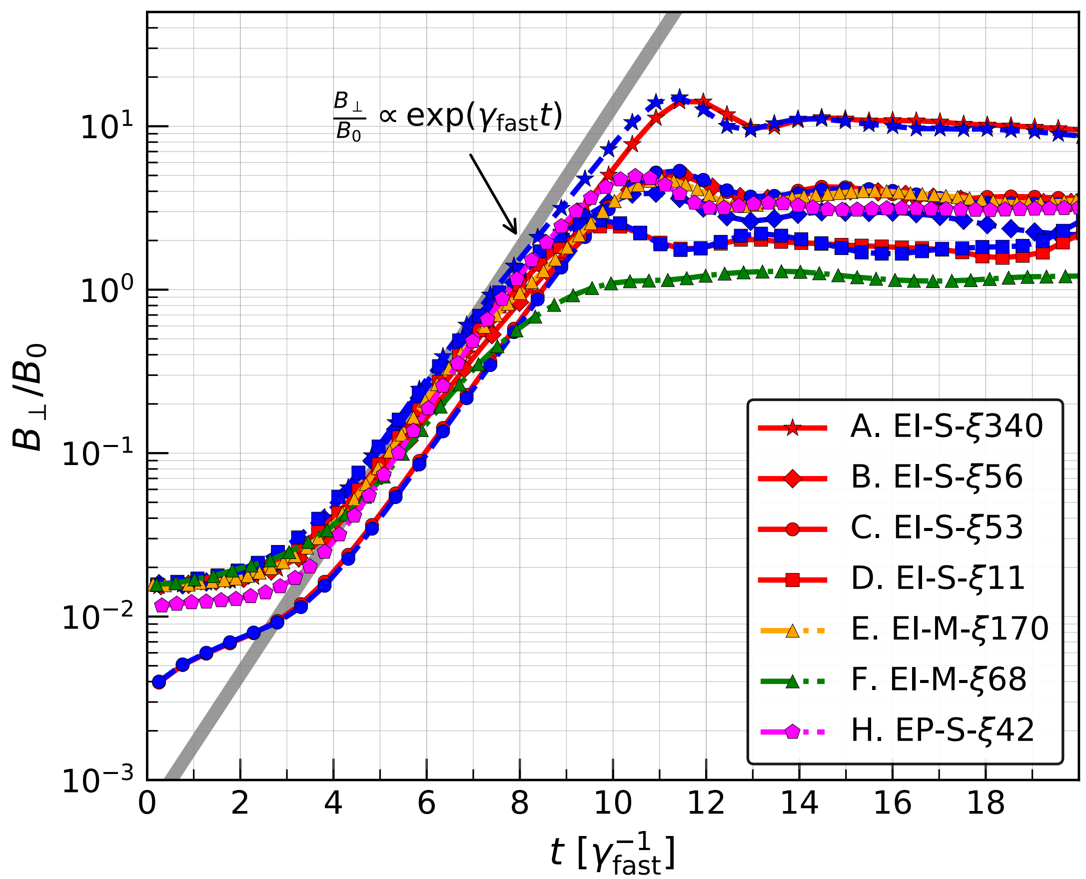


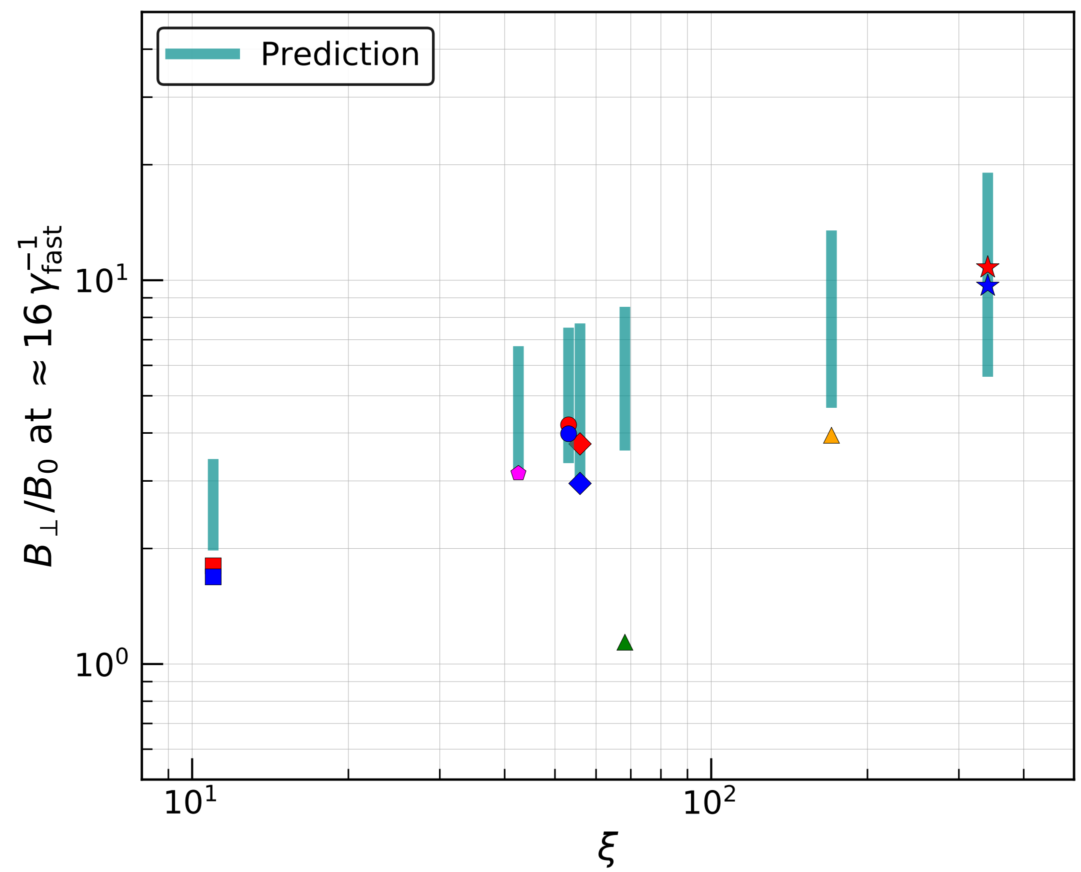
Back-reactions (~JxB force)

↓

Saturation

Results: Saturation of lepton-driven Bell instability





CR momentum flux in plasma frame

- Magnetic field at saturation $\delta B/B_0 \gtrsim 1$ **SG, Caprioli, Haggerty (arXiv:2106.07672)**

See also, Georgios Zacharegkas's poster

Computational resources: Thanks to University of Chicago Research Computing Center, and XSEDE TACC!

Take home messages

- We have explored the non-resonant streaming instability (NRSI) for
  - different charge and mass of cosmic rays
  - mixed compositions (small excess of one charge)
  - in different background plasma (electron-ion, pair plasma)

  } Linear growth depends on 'effective' current.

- Saturations of lepton-driven instability

  Different compositions can produce magnetic field larger than the seed field.

  1D simulations are good to comment on saturation.

Strengthens the applicability of the NRSI to different plasma backgrounds,
and to the mixed composition of CRs
—>> astrophysical environments (shocks, electron strahl in the solar wind, PWNe)
as well as in laboratory experiments

SG, Caprioli, Haggerty (arXiv:2106.07672)

What is next?

Local simulations are in good agreement with theory.

Need to address global questions