Multiple ion temperatures in collisionless plasmas: a review on the effects on magnetic reconnection in the dayside magnetosphere

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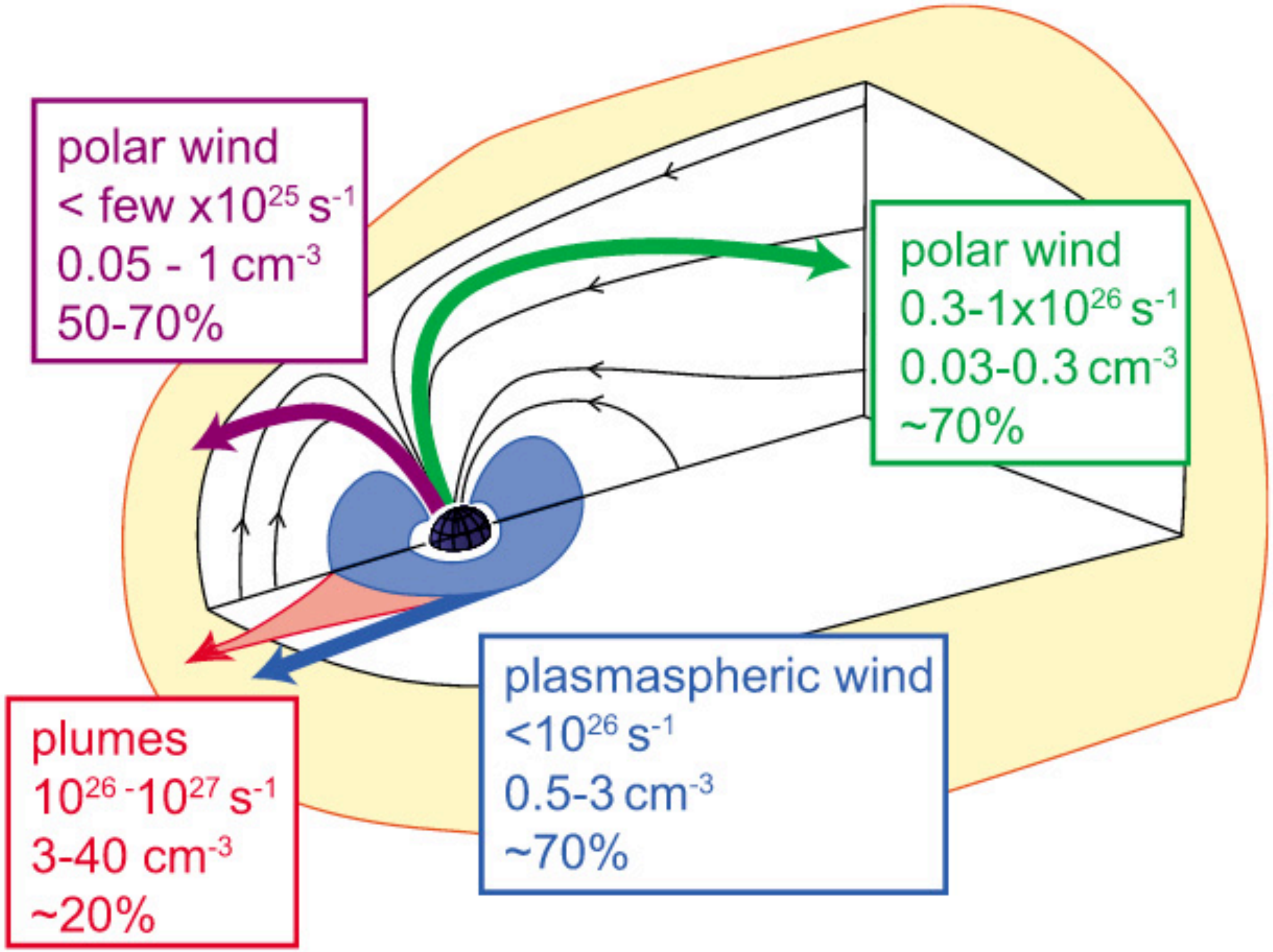
Statistics of cold ions in the magnetosphere



Andre+, GRL (2012)

- Ionospheric cold ions found throughout the magnetosphere, including reconnection regions
- Composed mainly by H+, He+, O+
- Can be very dense compared to other magnetospheric populations
- Difficult to observe

Olsen *JGR* 1982, Hirahara+ *JGR* 1996, Chandler+ *JGR* 1999, Su+ *JGR* 2000, Chen & Moore, JGR (2006), Engwall+ Nat. Geos. 2009, McFadden+ *GRL* 2008, Lee & Angelopoulos, JGR, 2014, Maggiolo & Kistler JGR 2014, Lee+ *JGR* 2015, Fuselier+ *GRL* 2016 etc.

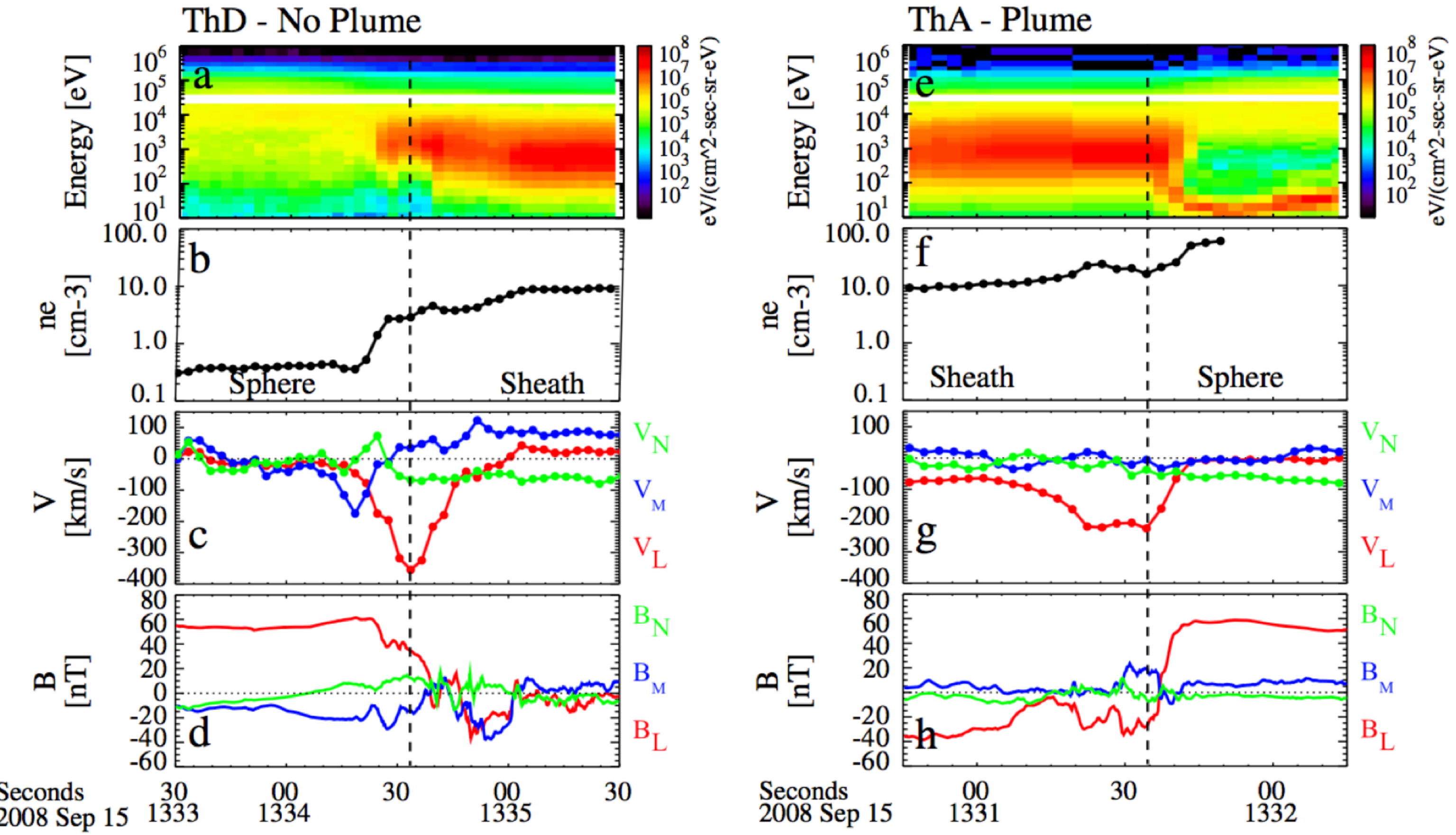
Reconnection mass-loading

$$E \sim \left(\frac{B_1 B_2}{B_1 + B_2}\right)\frac{v_{out}}{c}\frac{2\delta}{L}.$$

Cassak & Shay, PoP, [2007]

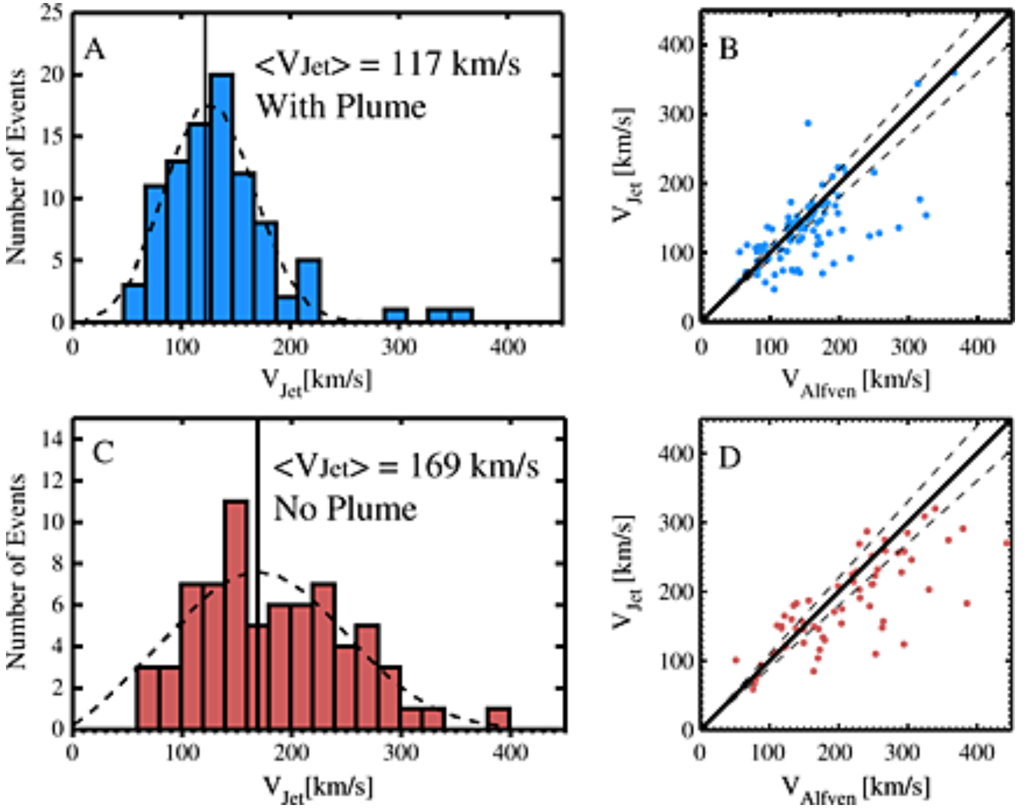
Cold ions of ionospheric origin **mass load** the magnetospheric plasma and **slow down the reconnection rate.**

$$v_{out}^2 \sim \frac{B_1 B_2}{4\pi}\frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$



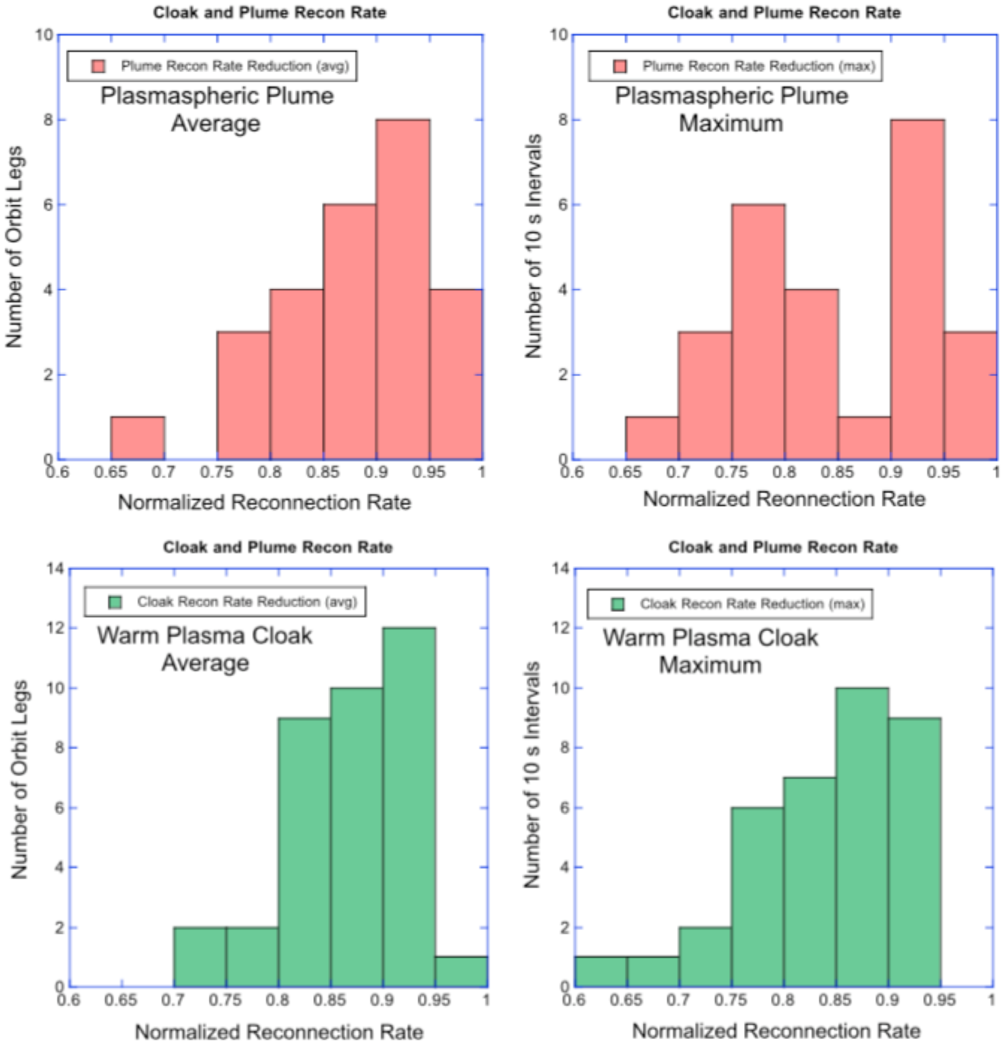
Walsh+, GRL (2014)

12% of analyzed orbits affected by dense plumes



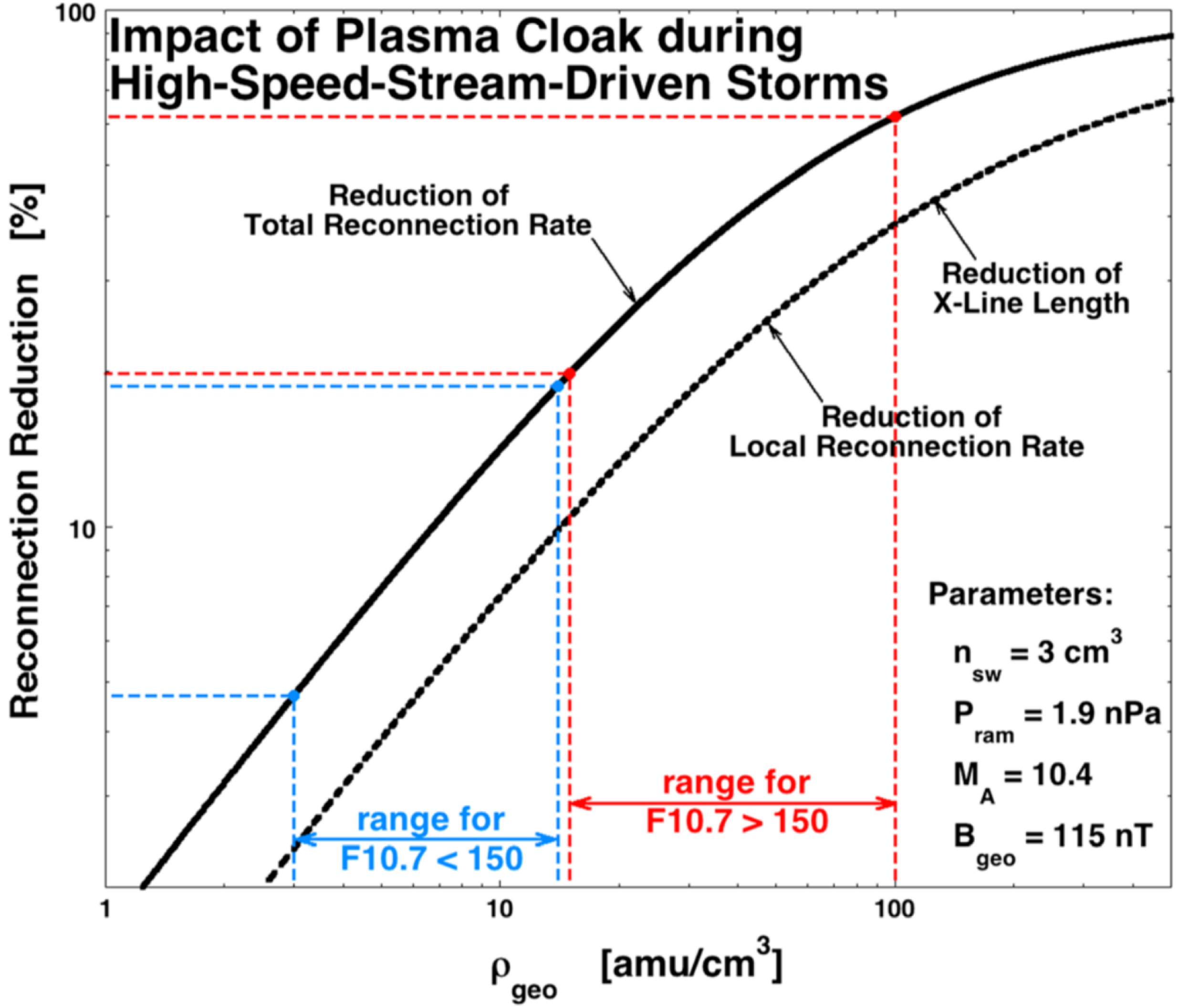
Walsh+, JGR (2013)

Reconnection mass-loading



HPCA statistics on Phase 1a: 6% of orbit legs modify Reconnection rate by more than 20% (following CS2007 prediction)

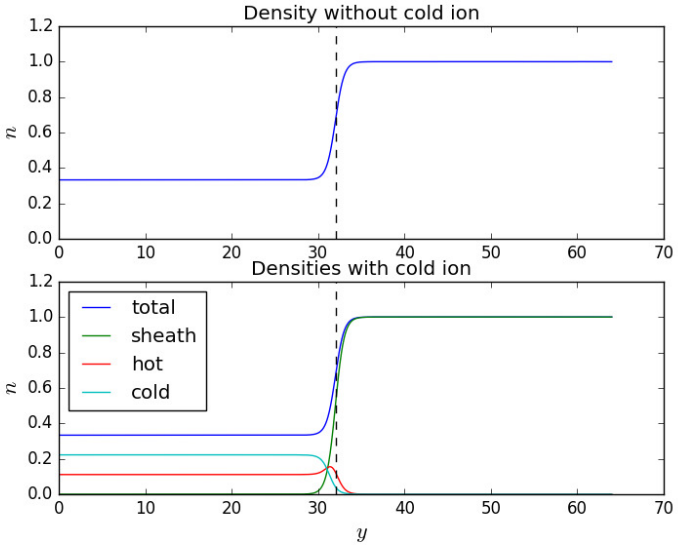
Fuselier+, JGR (2017)



Estimation of R. rate reduction at MP during HSSD storms, based on LANL measurements of plumes and plasma cloak. Measurements are taken at geosync. orbit but extrapolated to MP

Borovsky+, JGR (2013)

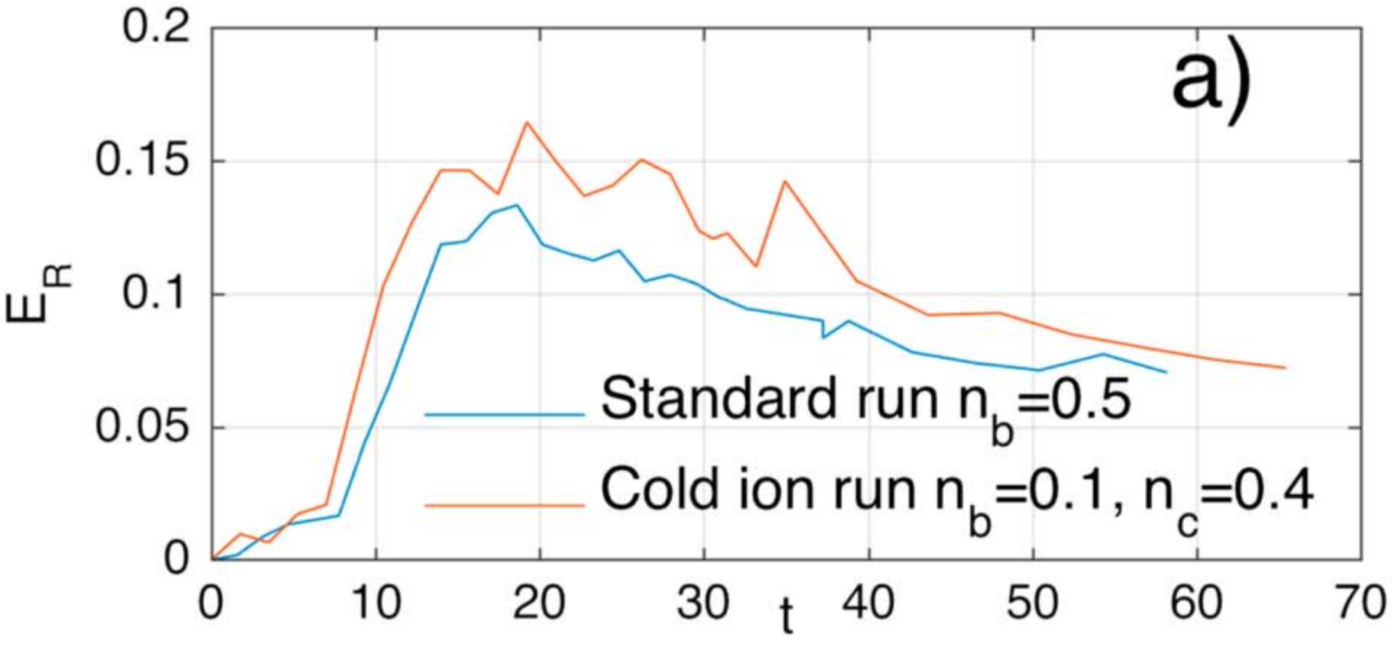
PIC simulations including cold ions



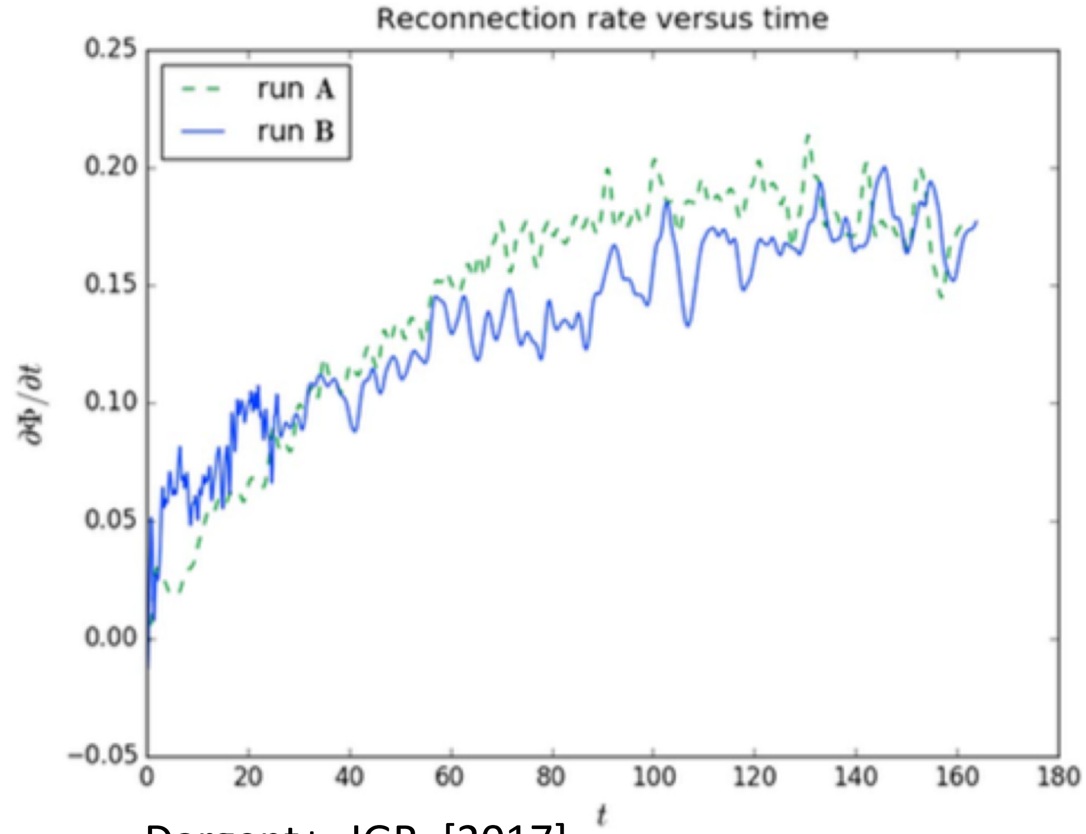
$$E \sim \left(\frac{B_1 B_2}{B_1 + B_2}\right)\frac{v_{\rm out}}{c}\frac{2\delta}{L}. \qquad v_{\rm out}^2 \sim \frac{B_1 B_2}{4\pi}\frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$

Cassak & Shay, PoP, [2007]

Including cold ions does not significantly change the normalized reconnection rate (aspect ratio) of the diffusion region.

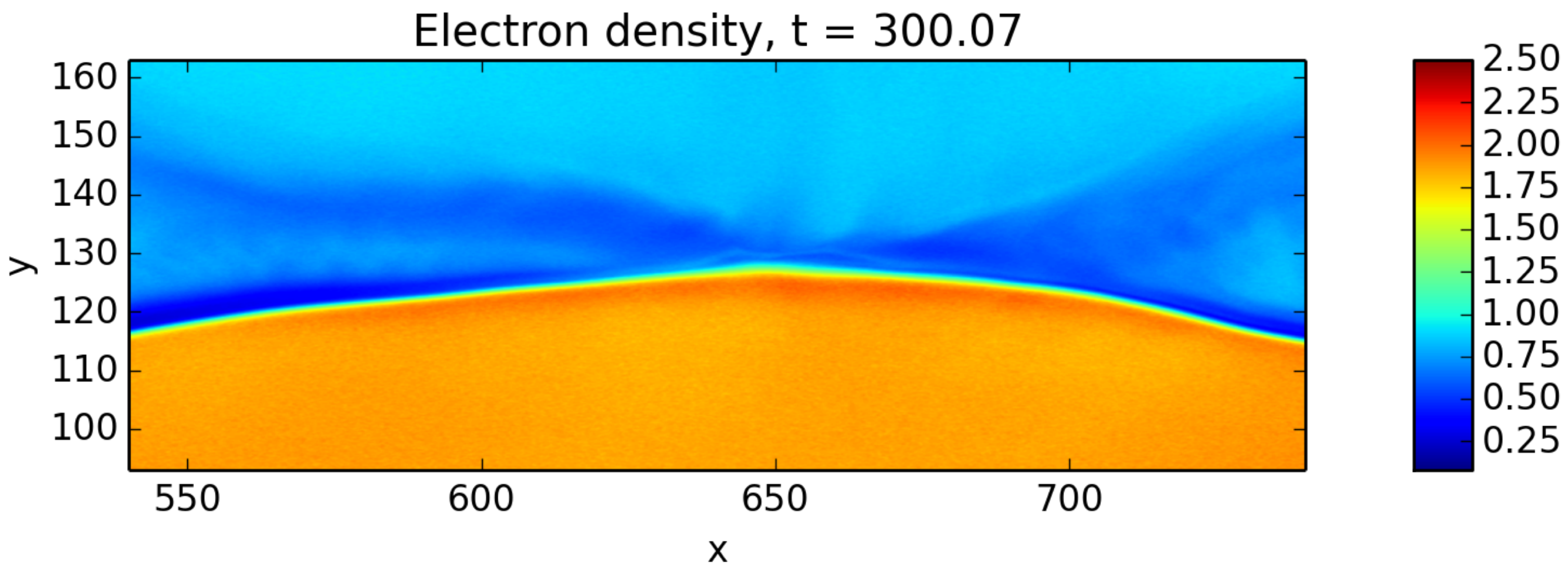


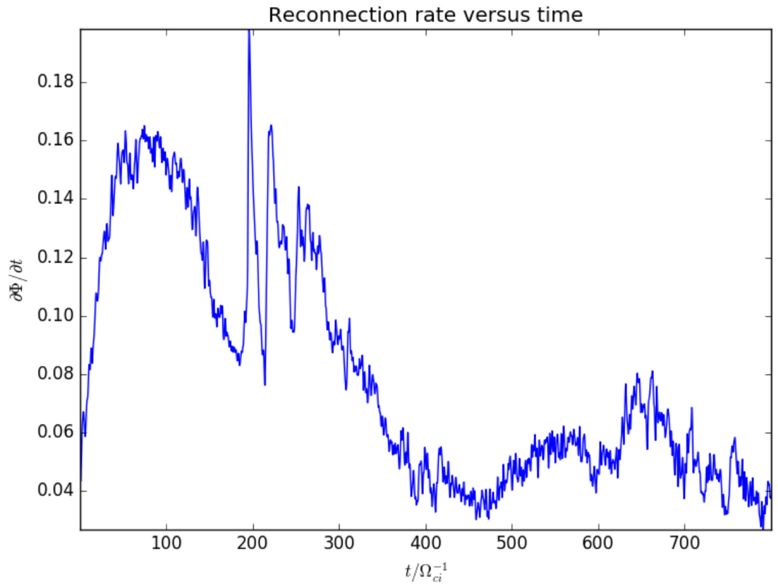
Divin+, JGR, [2016]



Dargent+, JGR, [2017]

Simulation with a cold ion plume





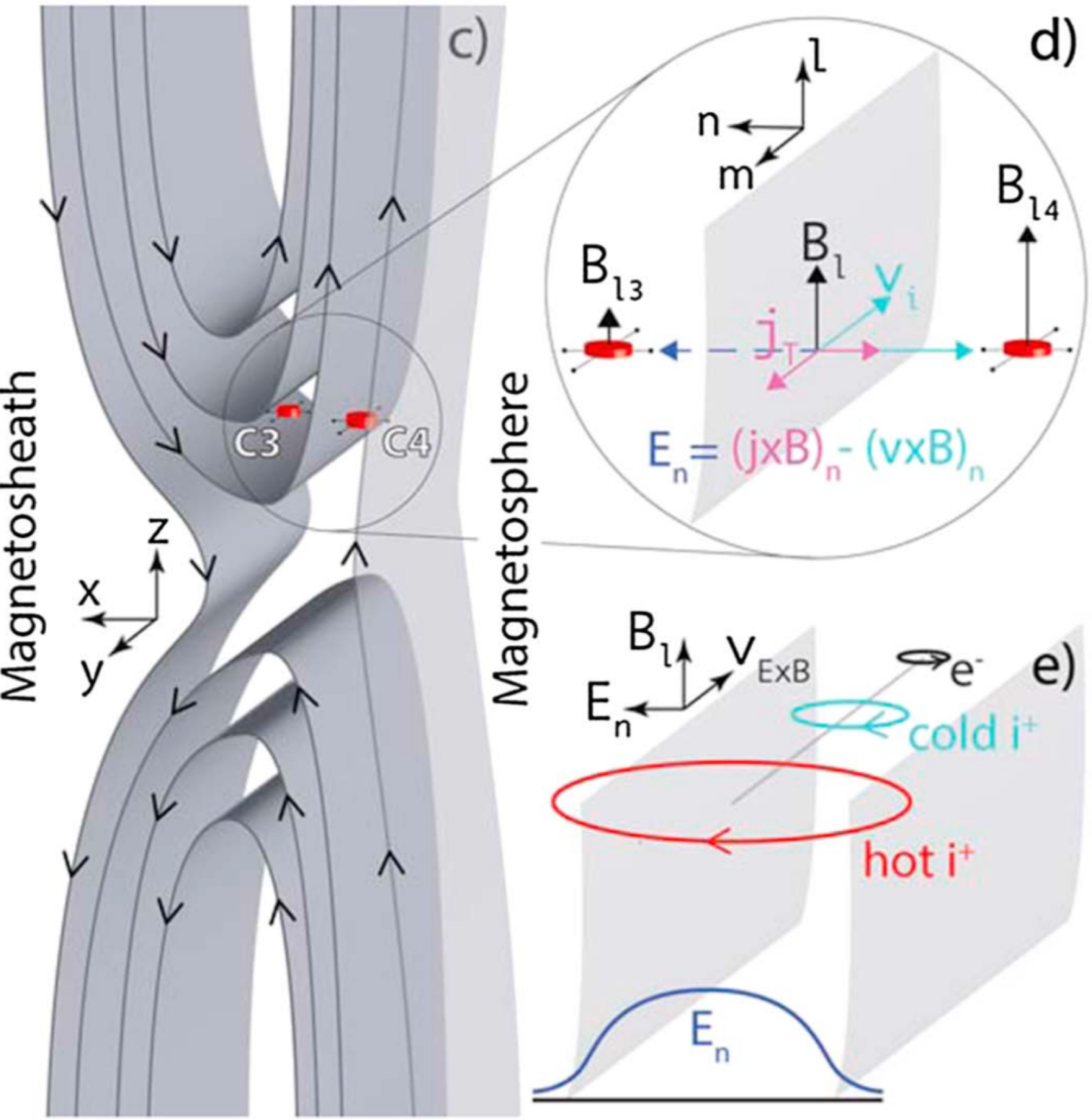
- R. rate roughly follows CS2007 prediction, although steady state is not clear for this run
- Reduction of outflow velocity allows formation of large islands

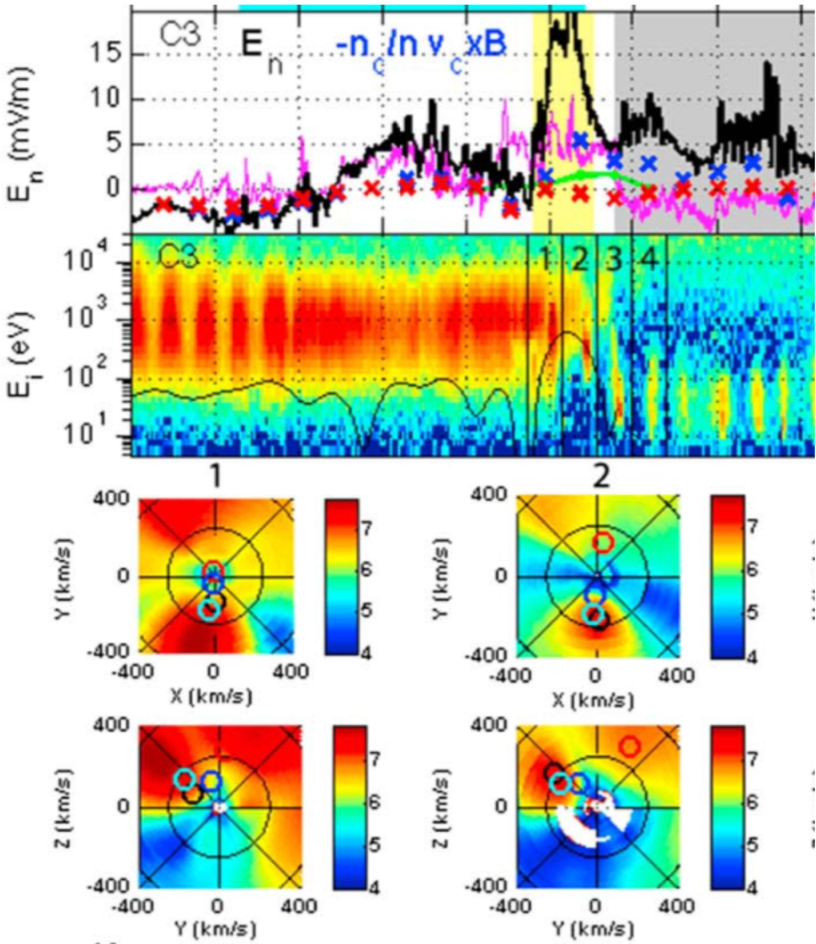
Full PIC, size of the simulation: 1280x256 di
simulation time T = 800 w_ci
mi/me=25

Cold ions introduce a new length-scale

$$\vec{E} = -\vec{v}\times\vec{B} + \frac{1}{ne}\vec{J}\times\vec{B} - \frac{1}{ne}\nabla\vec{P}_e$$

$$\vec{E} = -\frac{n_h}{n}\vec{v}_h\times\vec{B} - \frac{n_c}{n}\vec{v}_c\times\vec{B} + \frac{1}{ne}\vec{J}\times\vec{B} - \frac{1}{ne}\nabla\vec{P}_e$$

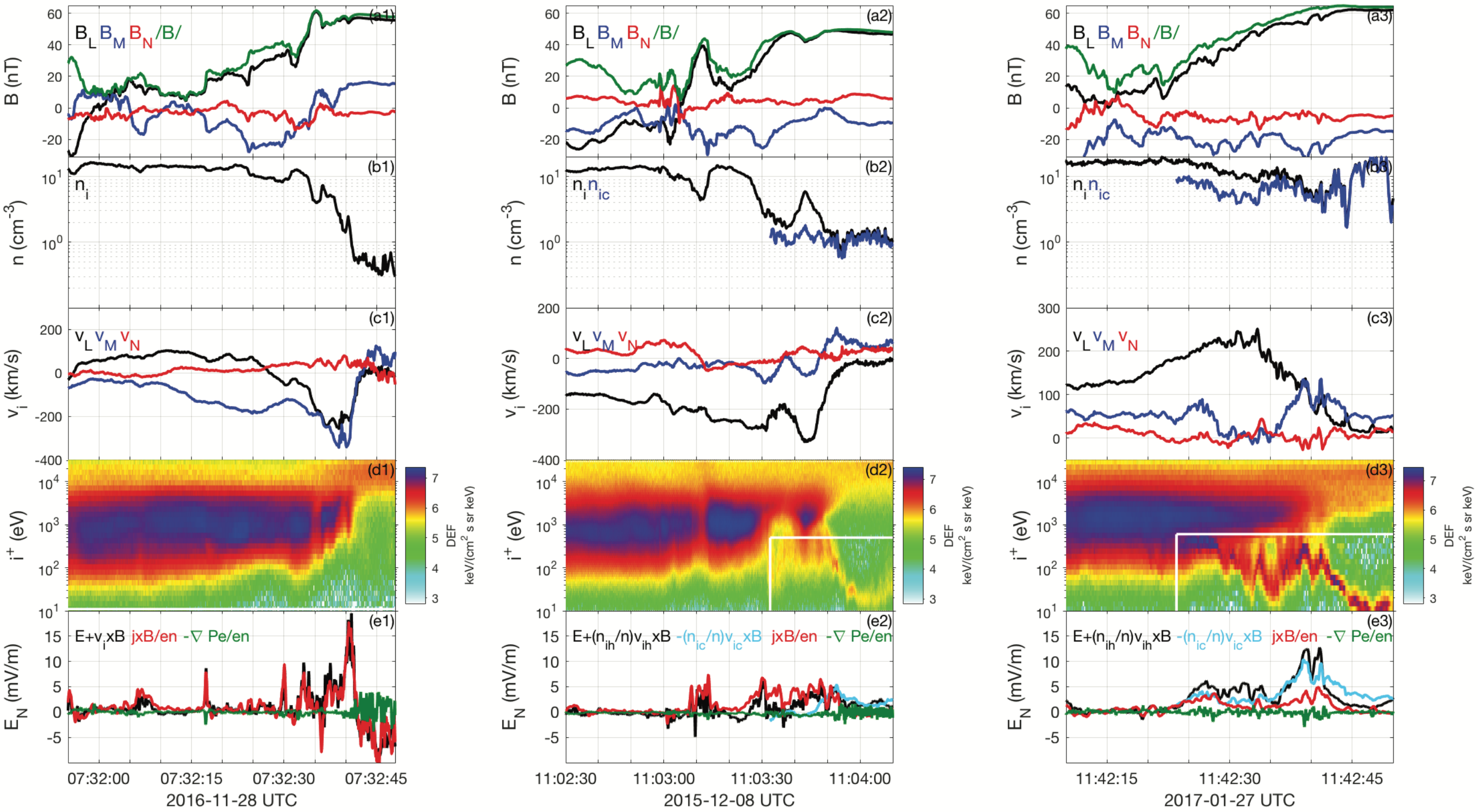




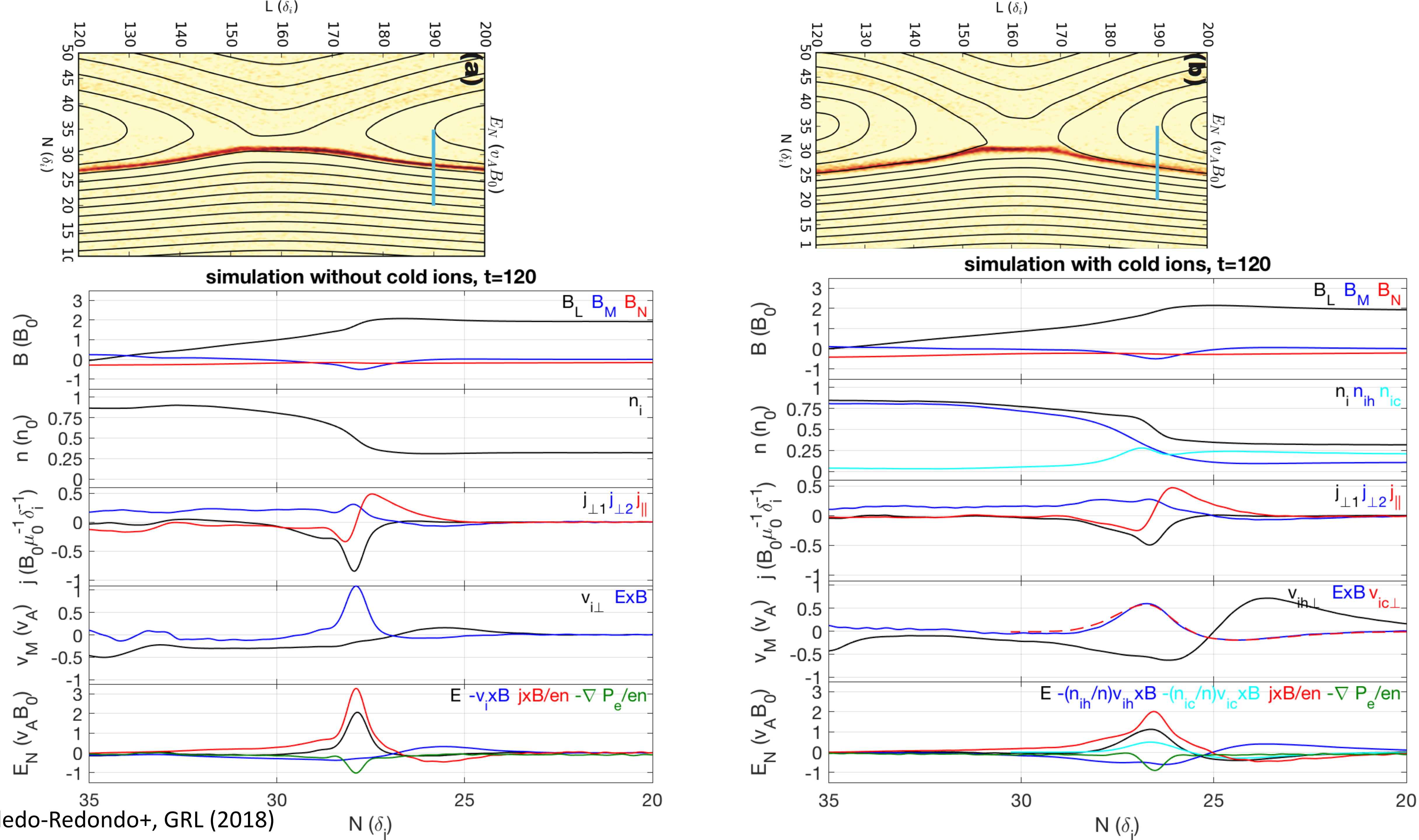
"Cold ions introduce a new length-scale owing to their smaller gyroradius. They can reduce the perpendicular currents at these scales."

Toledo-Redondo+, GRL (2015)

No cold ions   few cold ions (1cc)   many cold ions (10 cc)

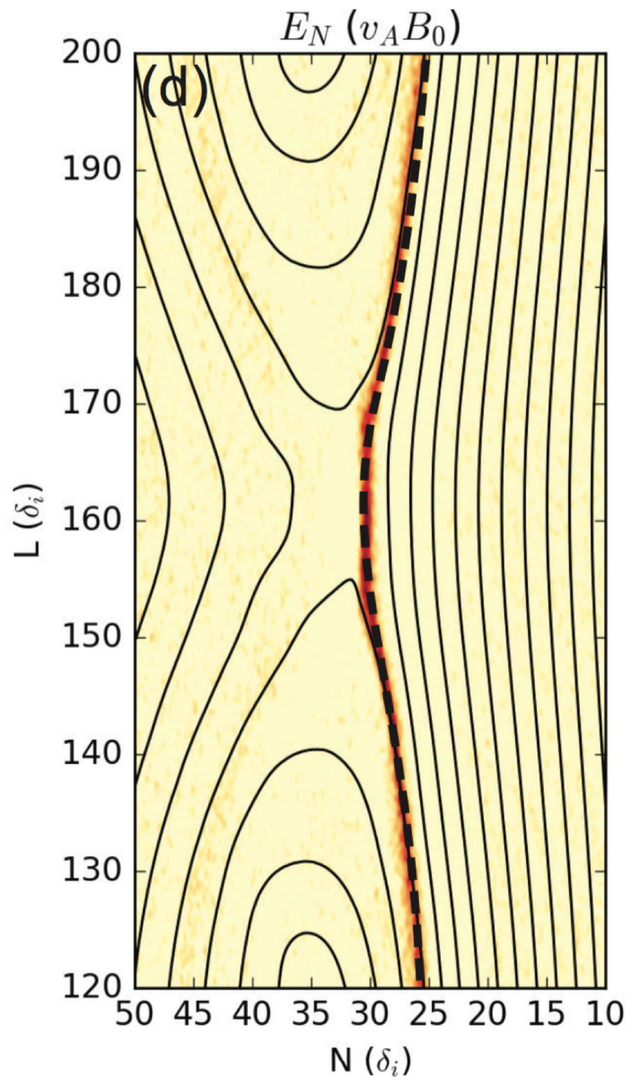


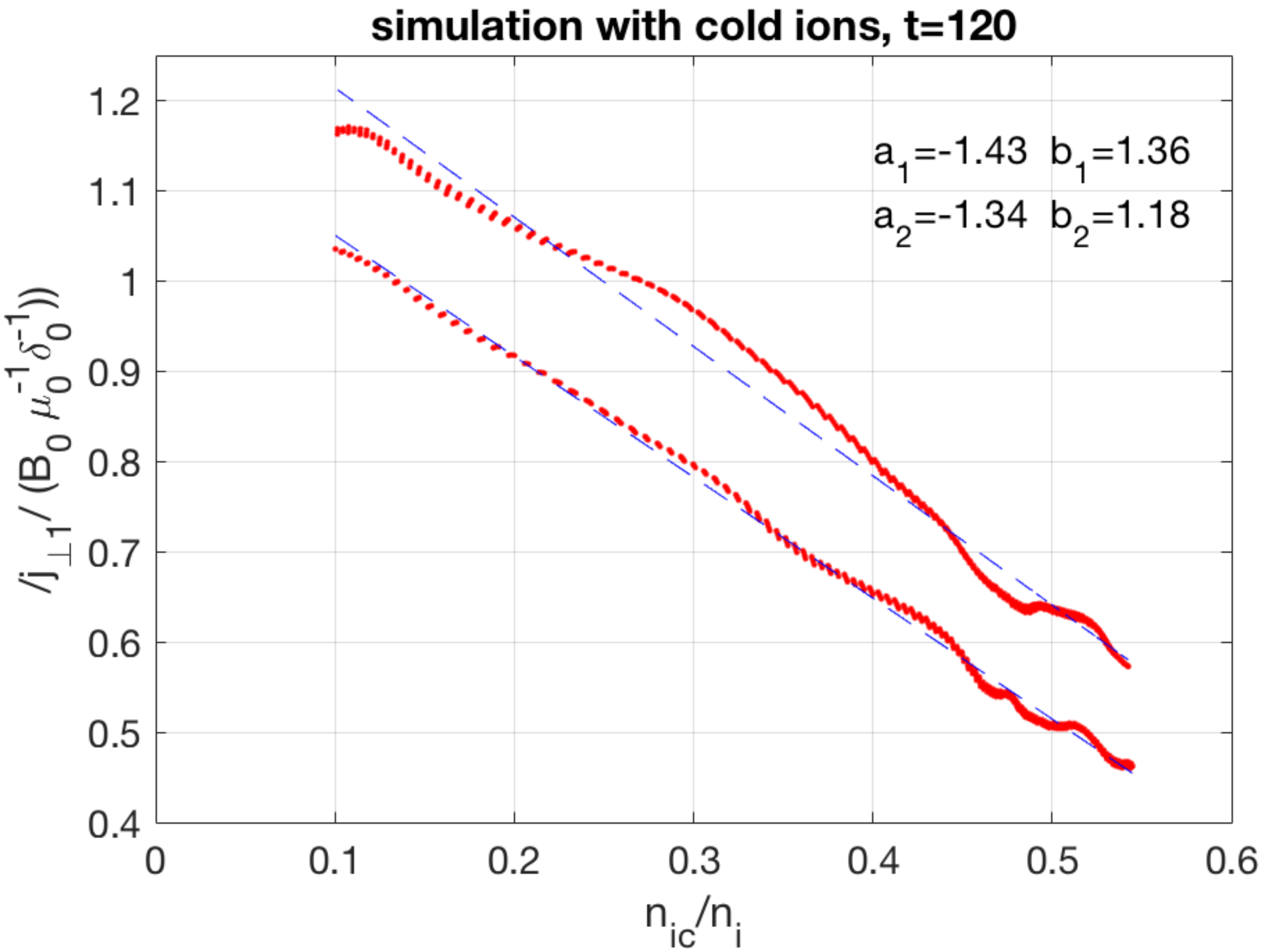
André+, GRL, [2016], Toledo-Redondo+, GRL (2018), Alm+, GRL (2018)



Toledo-Redondo+, GRL (2018)

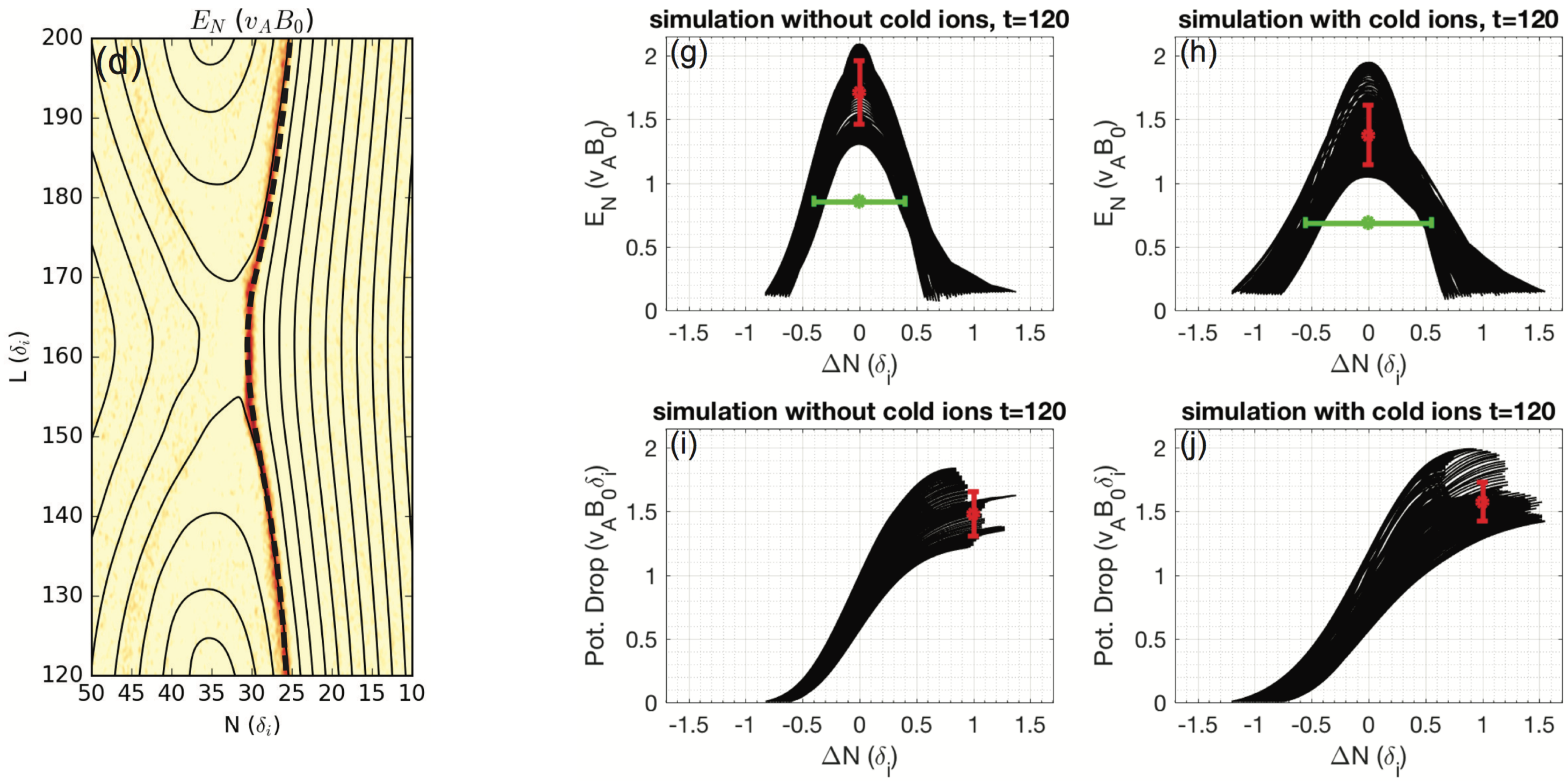
J_{perp} reduction as a function of n_{ic}/n





Toledo-Redondo+, GRL (2018)

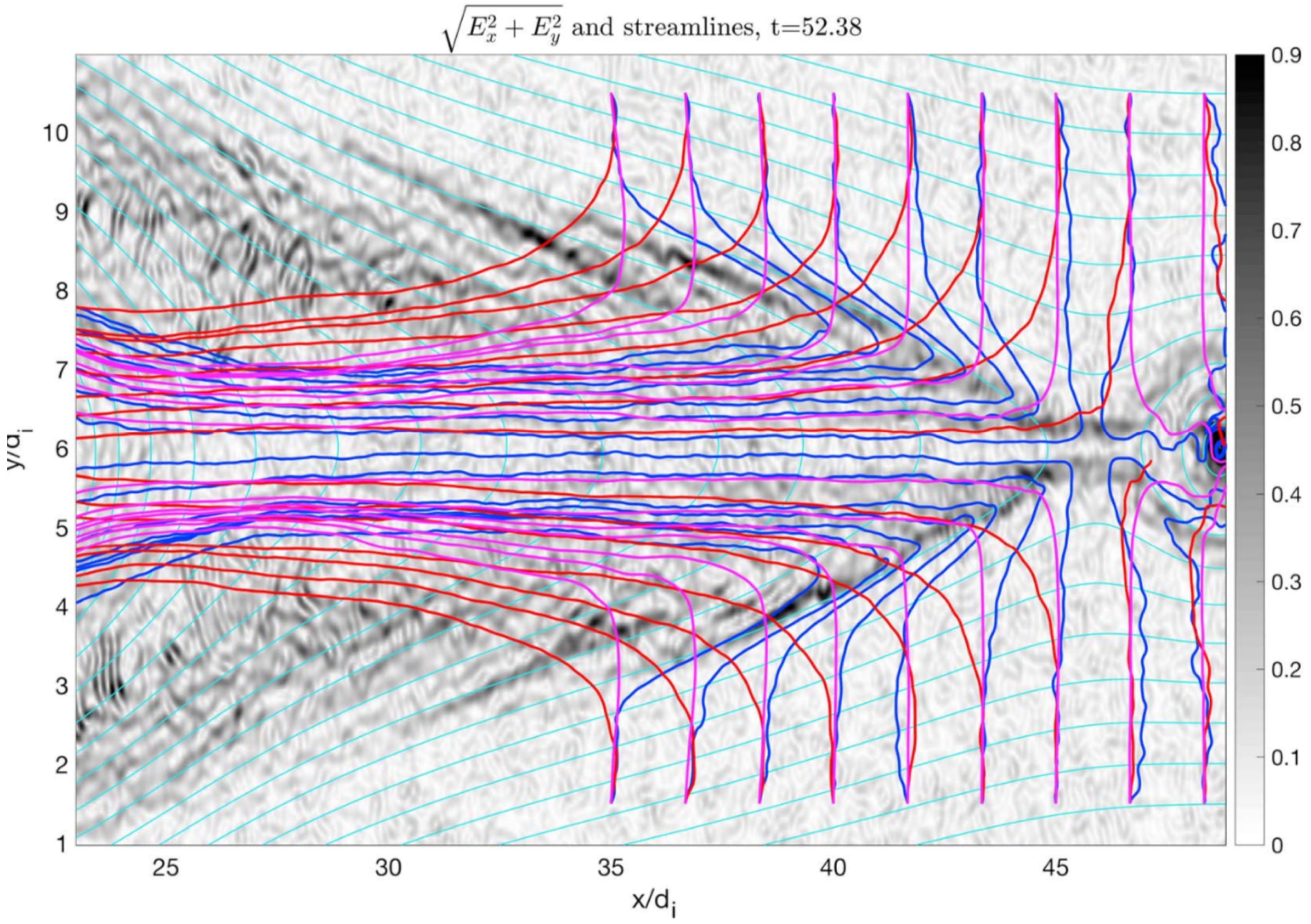
Hall electric field and potential drop



Toledo-Redondo+, GRL (2018)

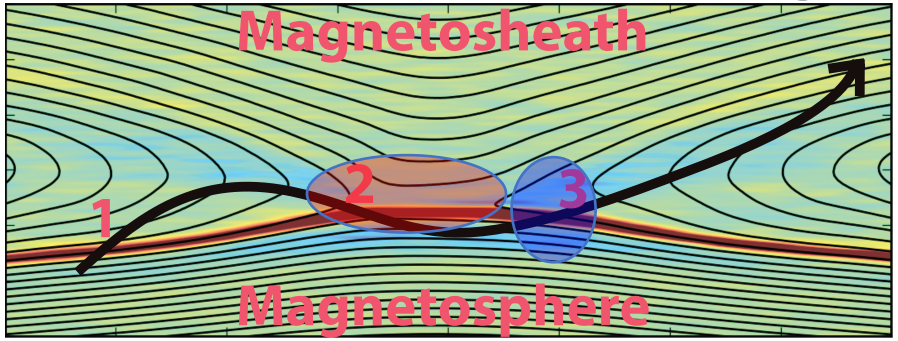
Cold ion diffusion region

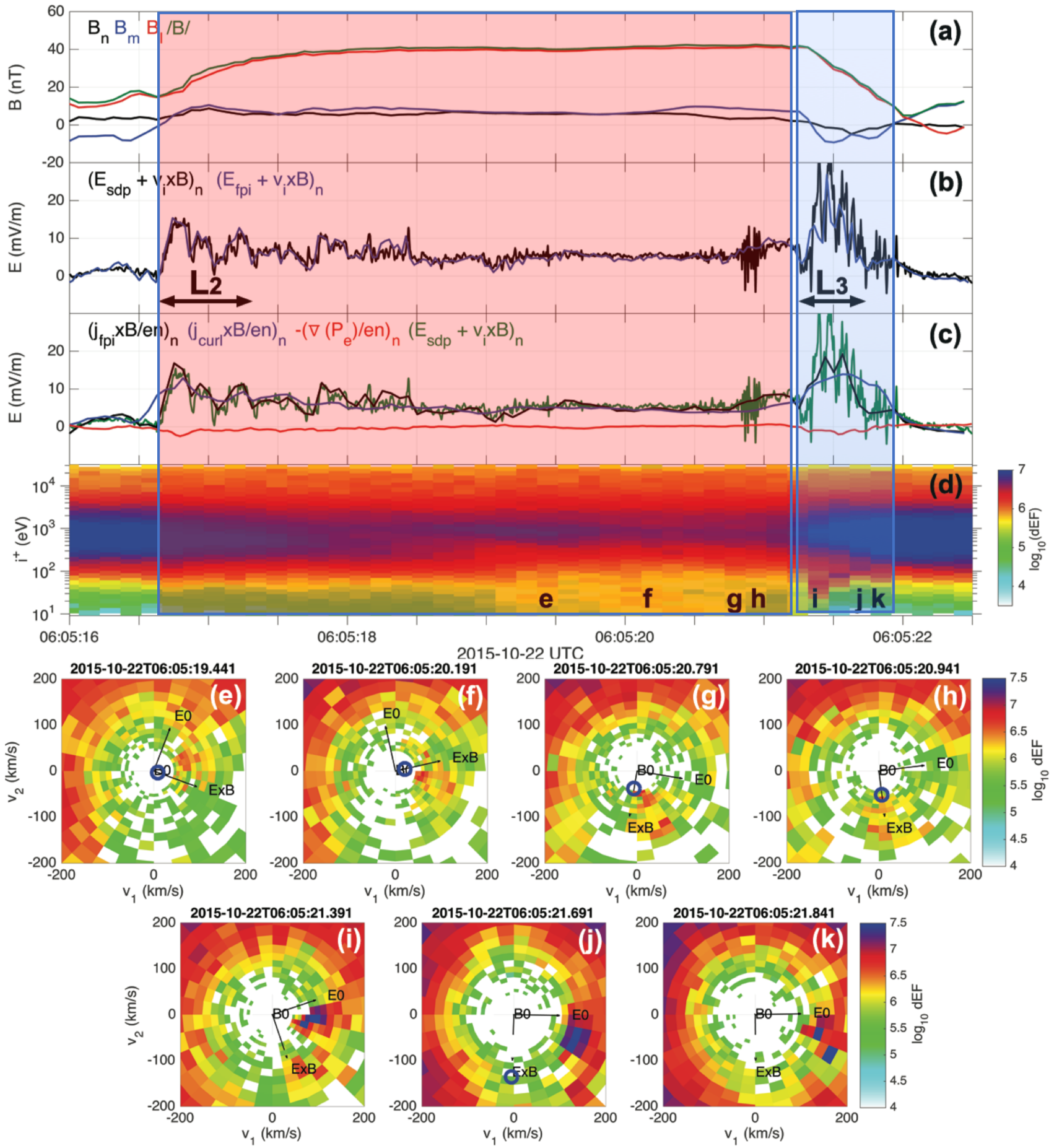
hot ions
cold ions
electrons

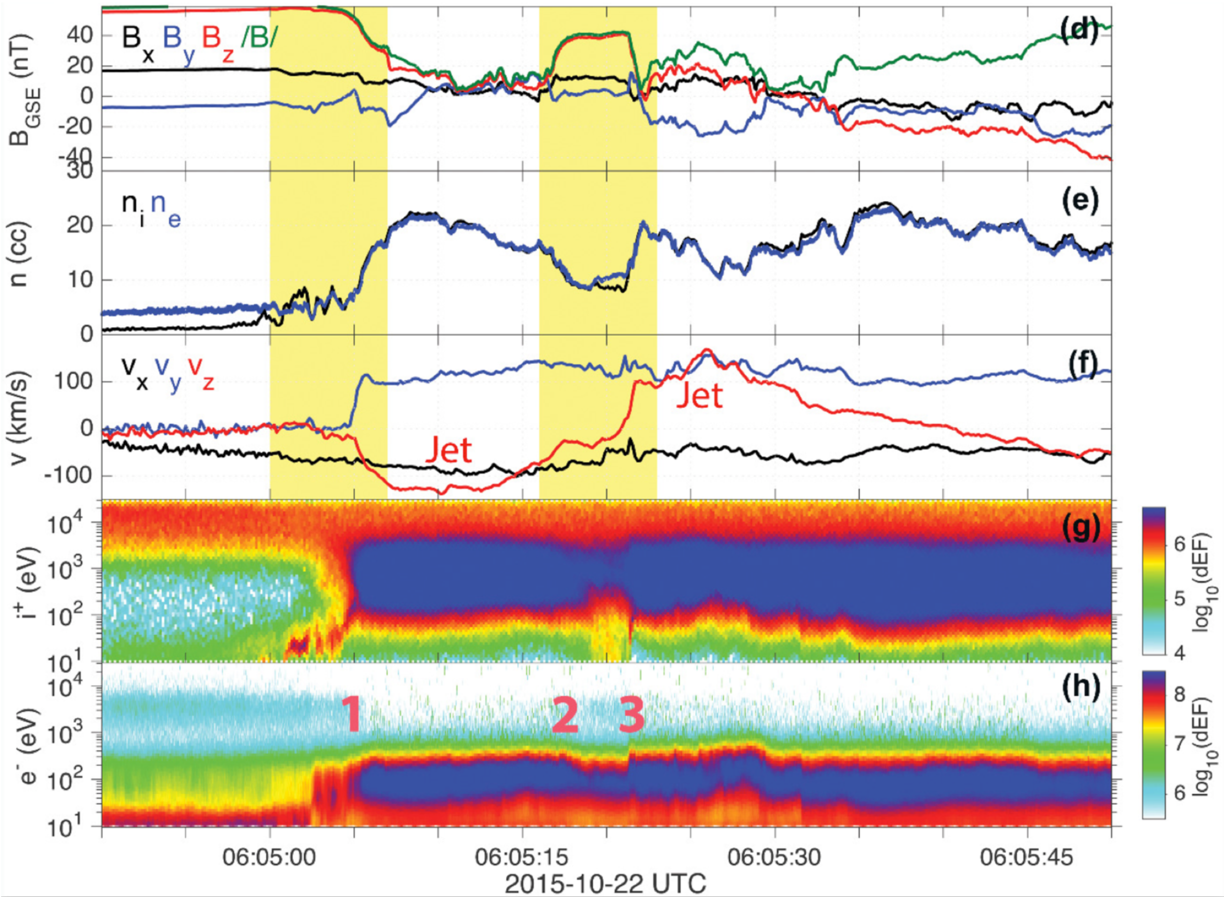


Divin+, JGR (2016)

Cold ion diffusion region

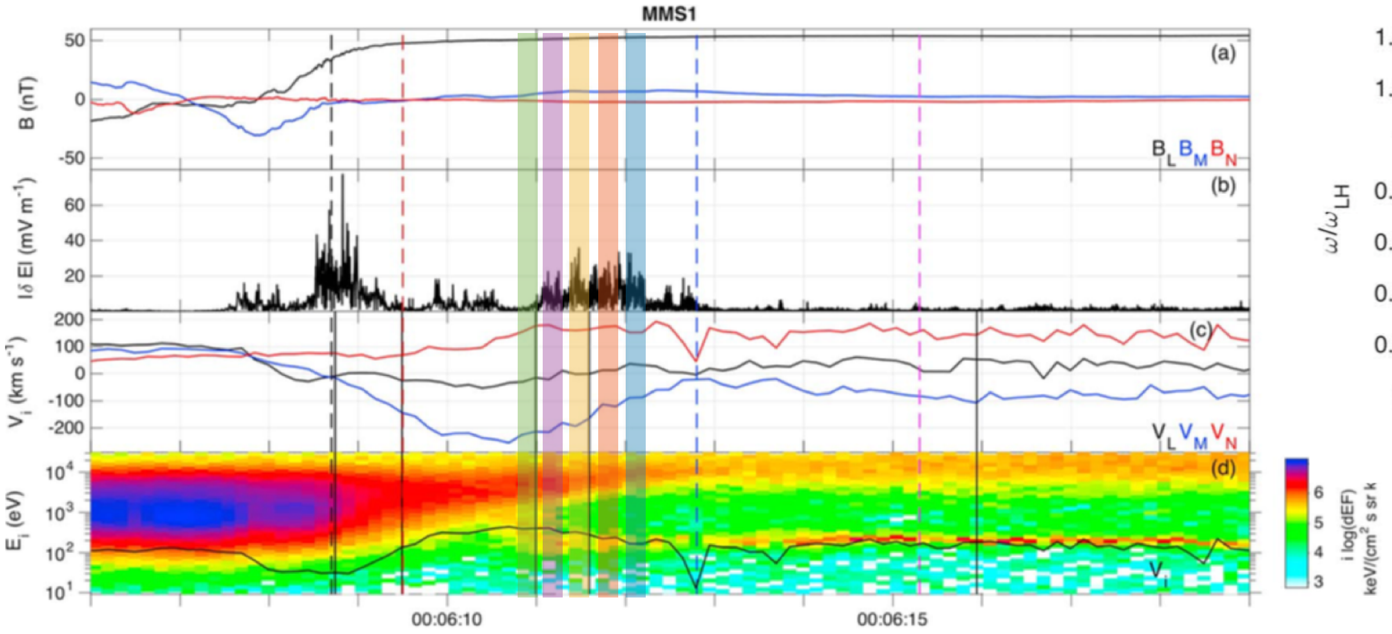


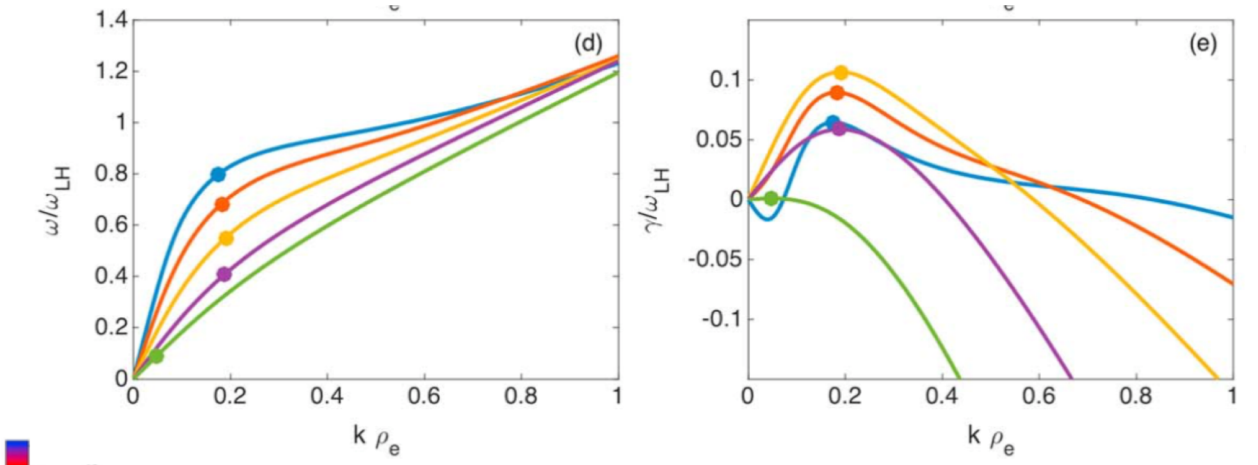




Toledo-Redondo+, GRL (2016)

Lower Hybrid waves at the separatrix owing to cold ions (ion-ion drift instability)





$$0 = 1 - \frac{\omega_{pic}^2}{k^2 v_{ic}} Z'\left(\frac{\omega - kV_{ic}}{kv_{ic}}\right) - \frac{\omega_{pih}^2}{k^2 v_{ih}^2} Z'\left(\frac{\omega - kV_{ih}}{kv_{ih}}\right) + \frac{\omega_{pe}^2}{\Omega_{ce}^2}\frac{1 - I_0(b)\exp(-b)}{b}$$

$$b = k^2 v_e^2 / 2\Omega_{ce}^2$$

1. $T_{ic} = 20$ eV, $n_{ih} = 0.05$ cm^{-3}, $T_{ih} = 3000$ eV, $V_{ih} = 900$ km s^{-1}.
2. $T_{ic} = 30$ eV, $n_{ih} = 0.1$ cm^{-3}, $T_{ih} = 2500$ eV, $V_{ih} = 800$ km s^{-1}.
3. $T_{ic} = 40$ eV, $n_{ih} = 0.2$ cm^{-3}, $T_{ih} = 2000$ eV, $V_{ih} = 700$ km s^{-1}.
4. $T_{ic} = 60$ eV, $n_{ih} = 0.4$ cm^{-3}, $T_{ih} = 1700$ eV, $V_{ih} = 500$ km s^{-1}.
5. $T_{ic} = 80$ eV, $n_{ih} = 0.8$ cm^{-3}, $T_{ih} = 1500$ eV, $V_{ih} = 350$ km s^{-1}.

The relative motion between the magnetized cold ions and the magnetosheath ions favours **an ion – ion drift instability** at the separatrix that generates **lower hybrid drift waves**. These waves can **heat the cold ions** and demagnetize them.

Graham+, JGR (2017), Toledo-Redondo+, JGR (2018)

Summary - Conclusions

- Ionospheric ions **mass load** the magnetosphere and **reduce the reconnection rate.** Cold temperature does not have an impact on the reconnection rate. Reduction of outflow speed may favour **growth of secondary islands**.

- Cold ions **remain magnetized inside narrow structures** such as the Hall E field region. They reduce the maximum Jperp associated to the Hall term.

- Inside the IDR, cold ions remain magnetized. They get demagnetized at smaller scales that hot ions --> **cold IDR**.

- In the separatrix region, **LHW** are formed owing to an **ion-ion drift instability** between cold ions and magnetosheath ions, that in turn **heat the cold ions**. The cold ion heating at the separatrix takes a **non-negligible part of the reconnection energy budget**.