Solar wind - magnetosphere coupling via magnetic reconnection and the effects of cold plasma of ionospheric origin

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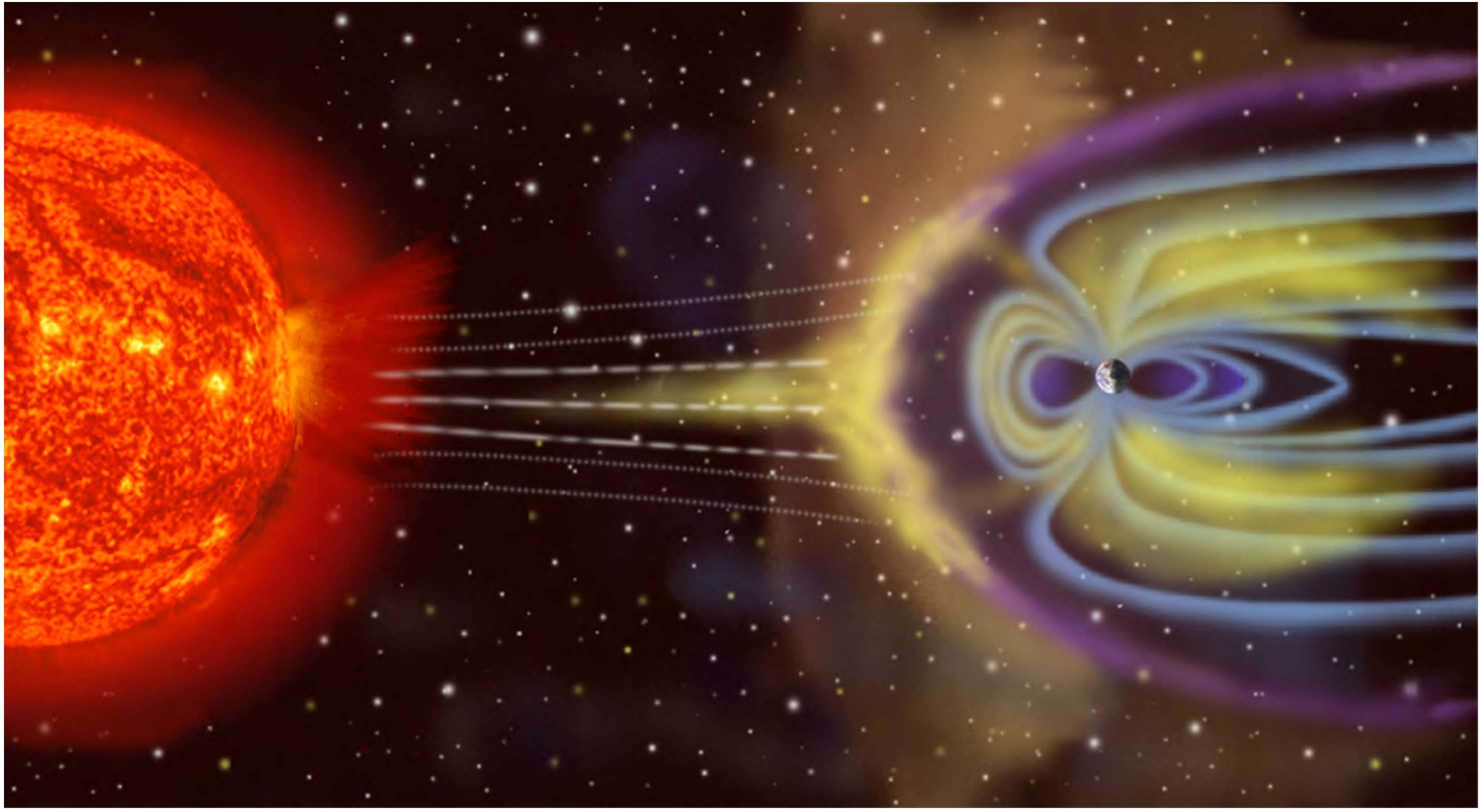
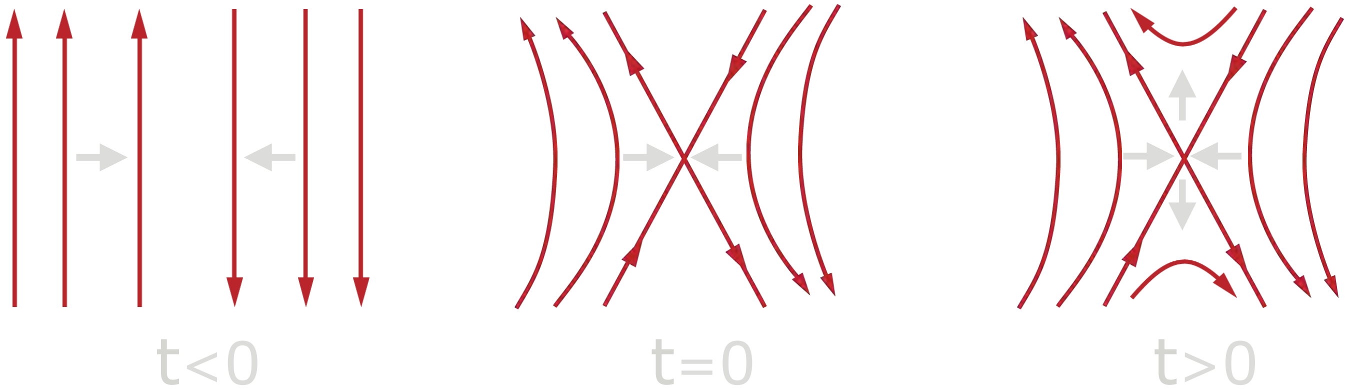
ESAC science seminar, 18 October 2018

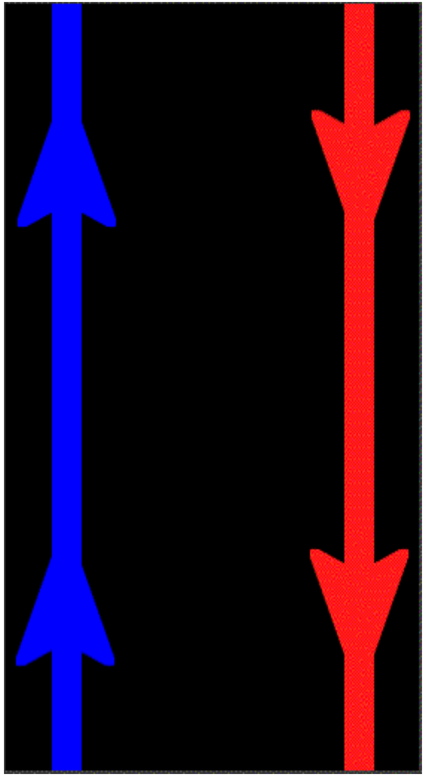
The Earth’s magnetosphere



Artist's rendition of Earth's magnetosphere. Image credit: NASA

Introduction: magnetic reconnection in plasmas

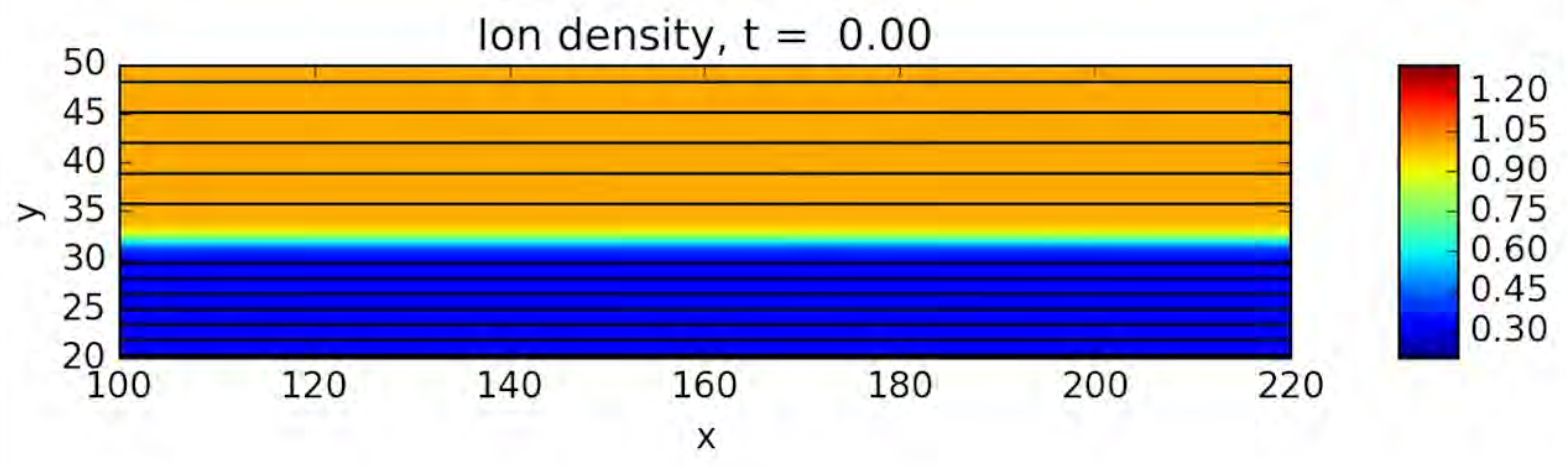




Magnetic reconnection in plasmas changes the **topology** of the magnetic fields, relaxing them and **transferring the energy** resulting into the particles (acceleration and heating).

Interconnects different plasma regions, allowing the **exchange of mass and energy** between them.

Magnetic reconnection simulation



Full Particle-In-Cell simulation, Dargent+, JGR (2016)
Simulation details: 220 hours x 512 core (64 MPI x 8 OpenMP)
Output size = 5.4 TB

Reconnection onset: the diffusion region

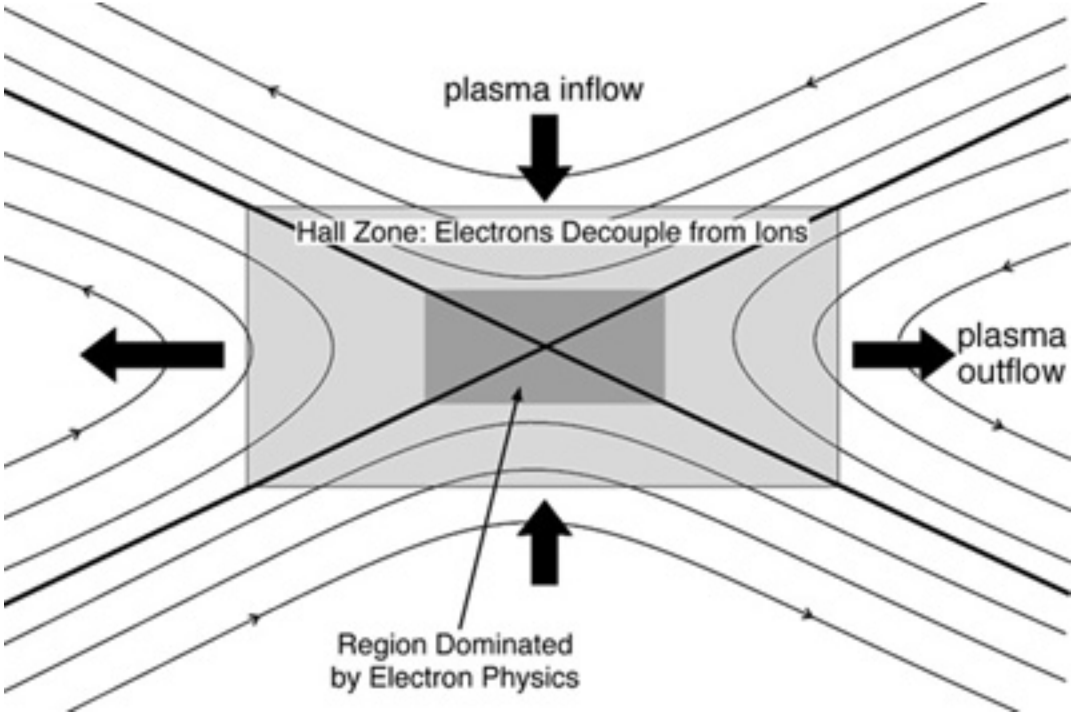
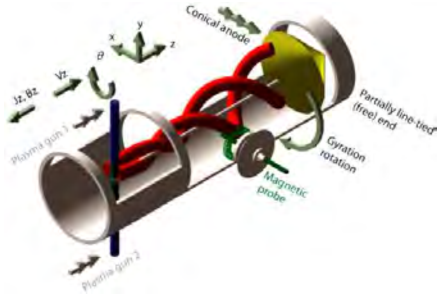


Figure credit: Southwest Research Institute

Ubiquity of magnetic reconnection

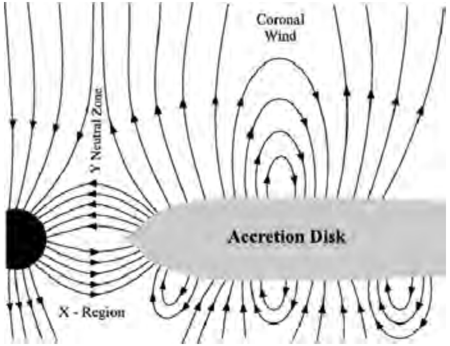


Intrator+, Nature Physics (2009)

Fusion reactors: totamaks

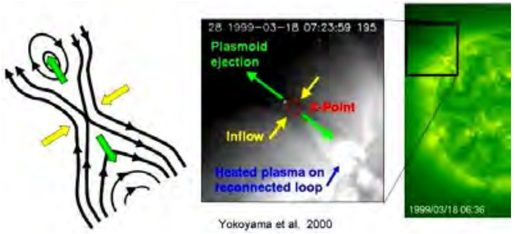
Uzdensky+, ApJ (2011)

Crab nebula observed by Chandra



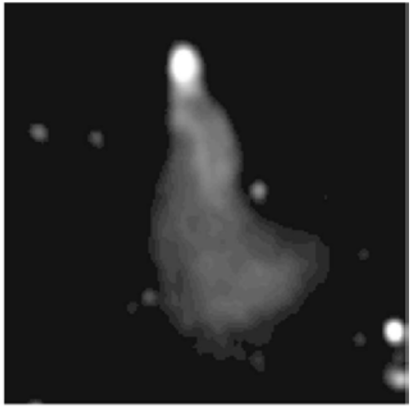
De Gouveia+, A&A (2010)

Accretion disks



Yokoyama+,ApJL (2001)

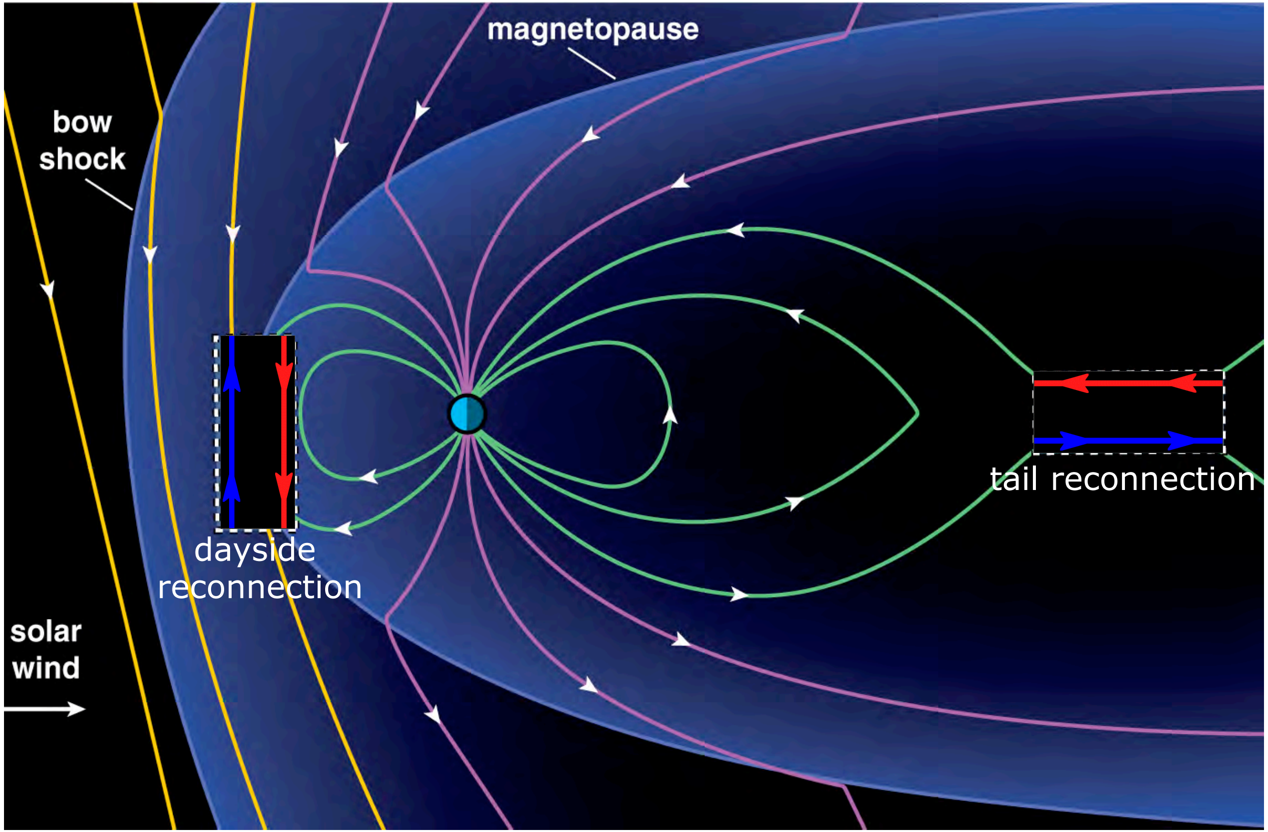
Solar corona, CMEs



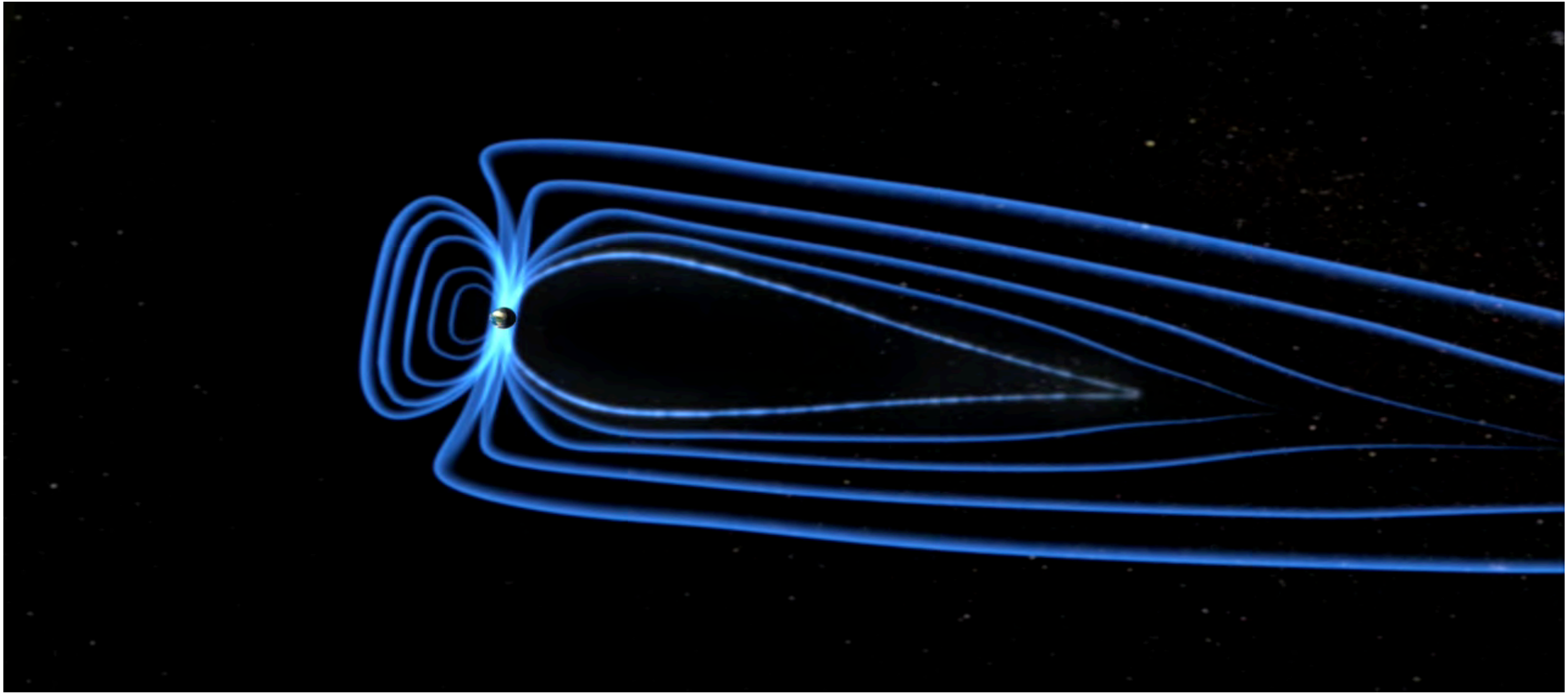
Kronberg+, ApJ (2004)

Radio jet in Galaxy lobe

Magnetic reconnection at Earth’s magnetosphere

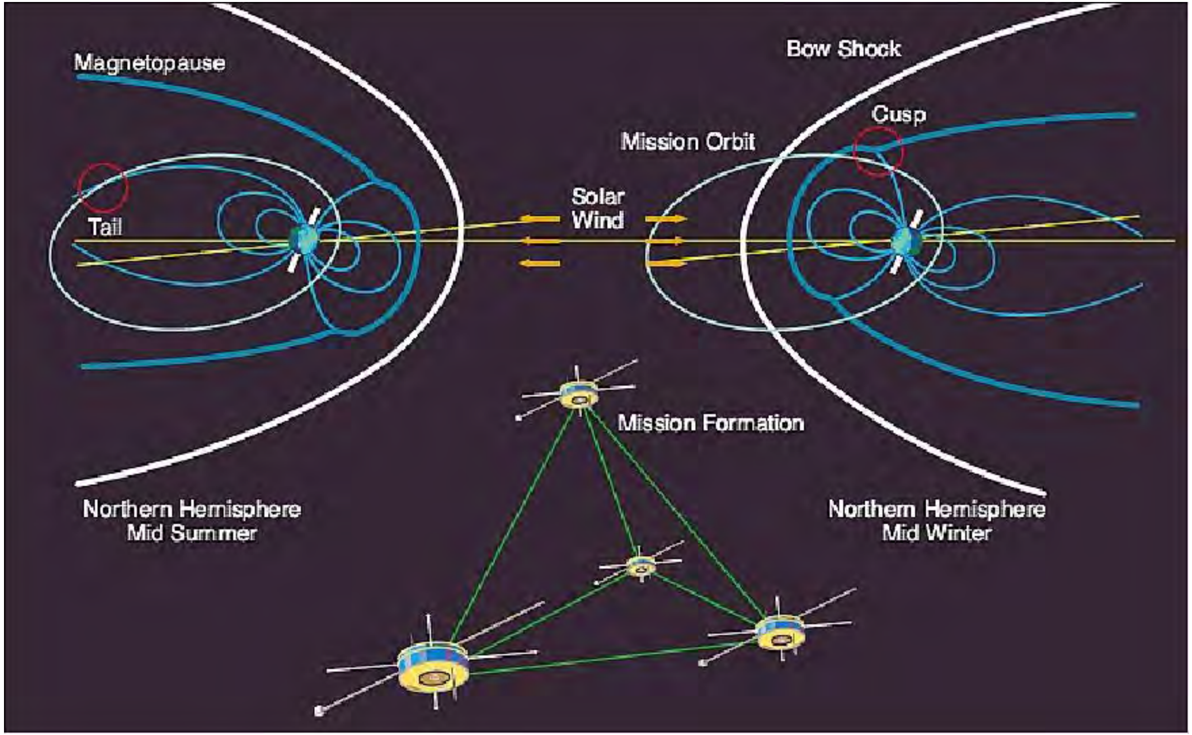


Magnetic reconnection and auroras



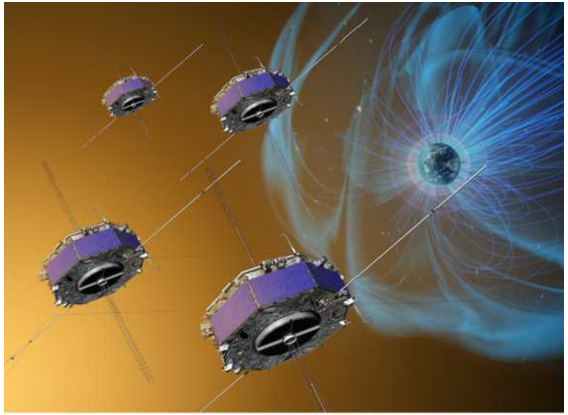
credit: NASA

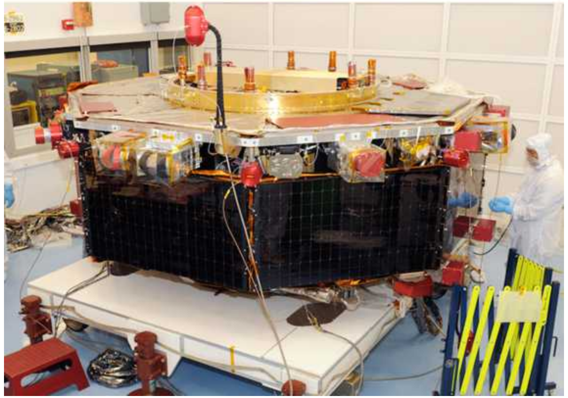
The Cluster mission

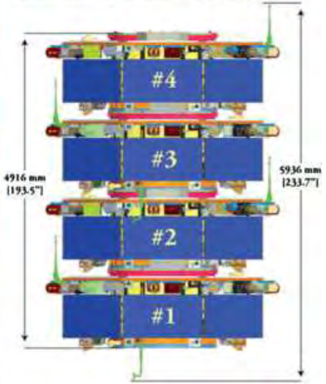


- Launched in 2000
- Polar orbit
- Tetrahedron at multiple scales
- Multiple regions
- Particle resolution
 (4s ions and electrons)

The Magnetospheric MultiScale (MMS-NASA) mission

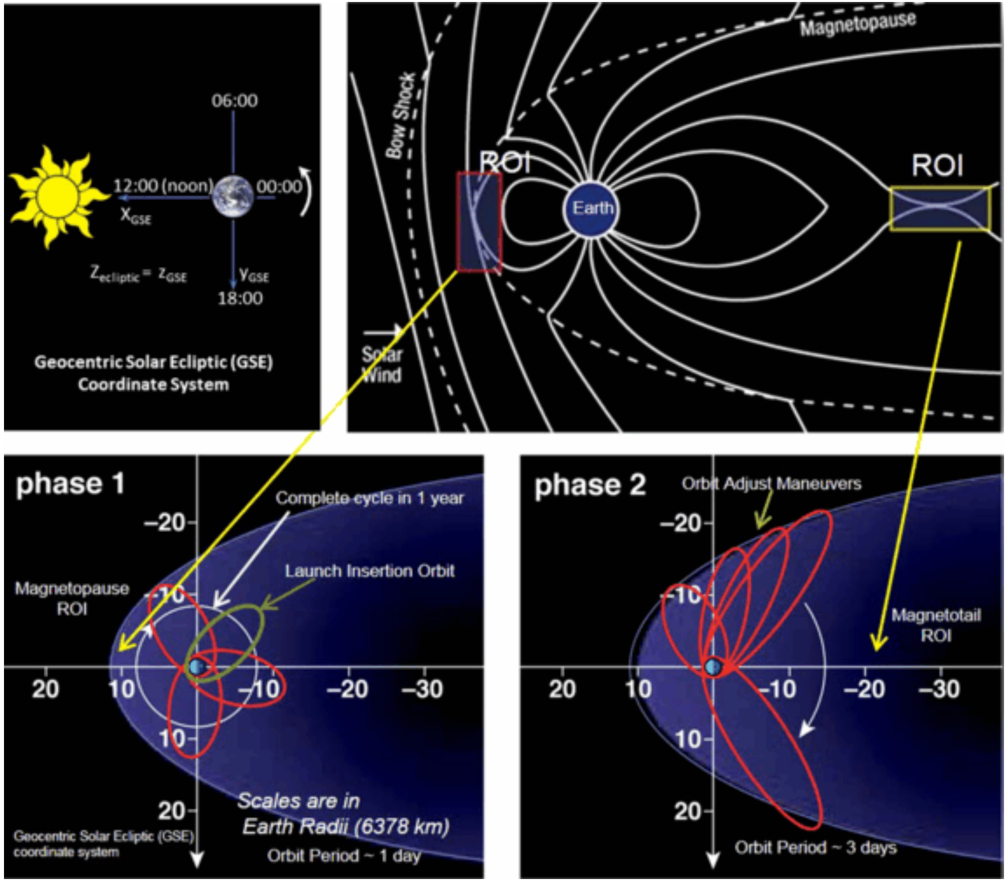




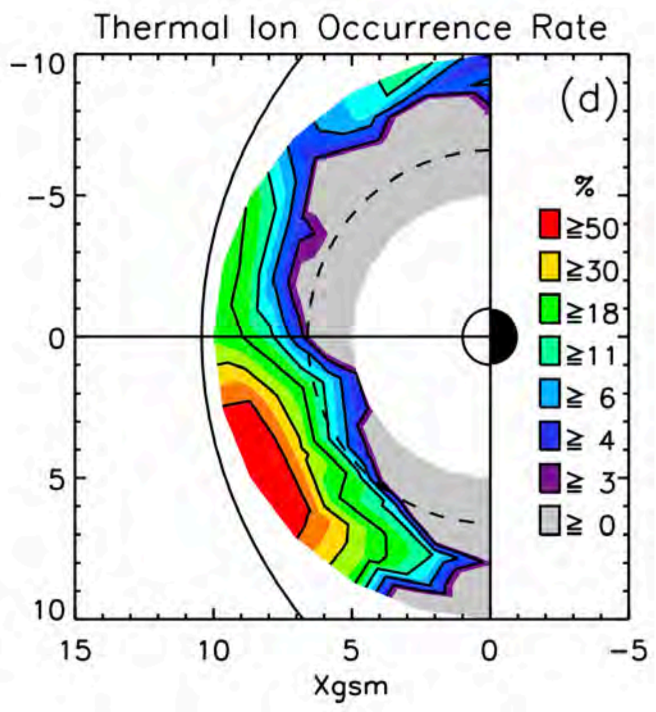


- Launched in 2015
- Equatorial orbit, focus on reconnection
- Tetrahedron at electron scales
- Magnetopause and magnetotail
- Particle resolution (150 ms ions, 30 ms electrons)

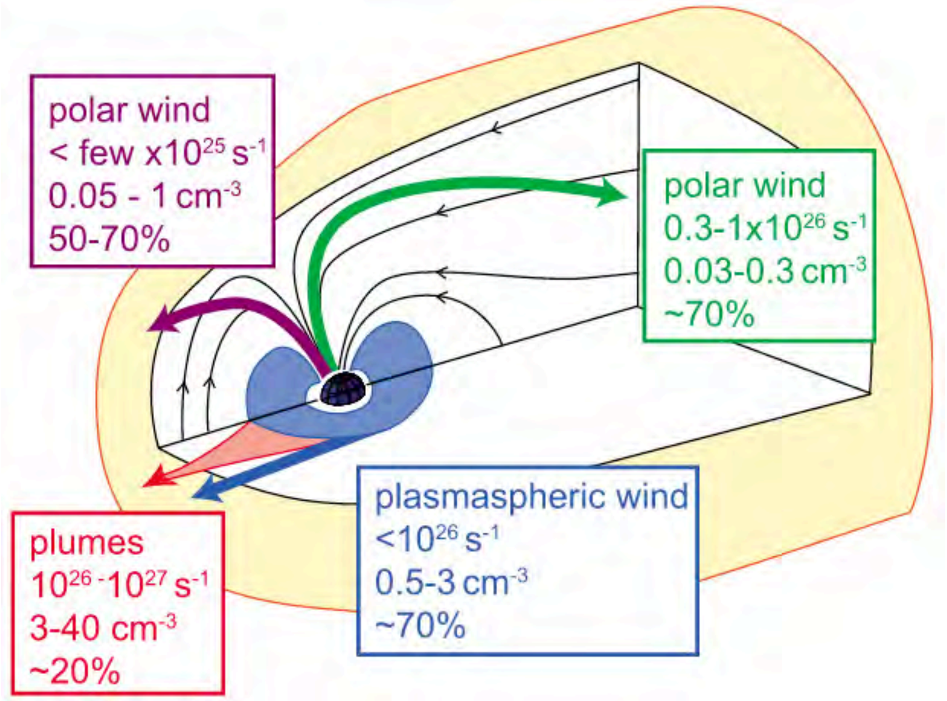
MMS mission: orbits and regions of interest



Statistics of cold ions in the magnetosphere

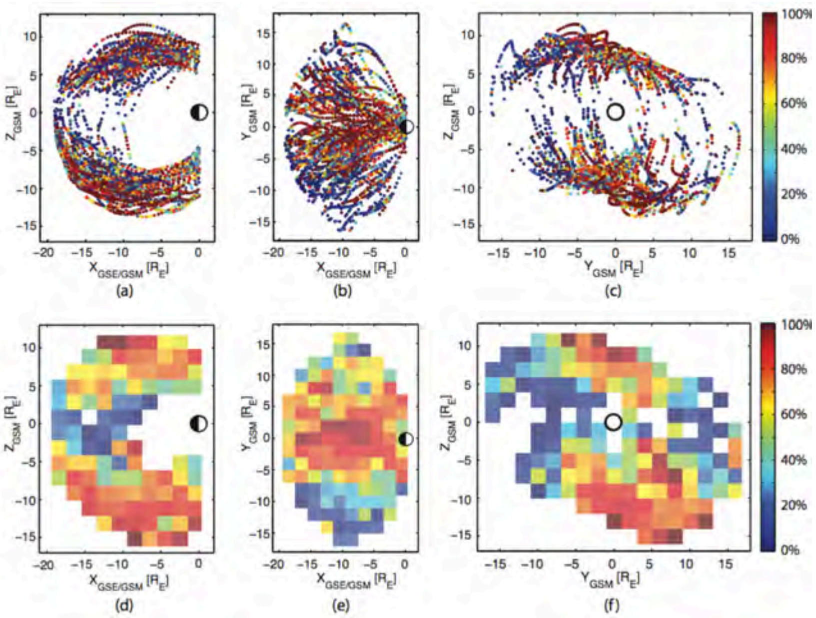


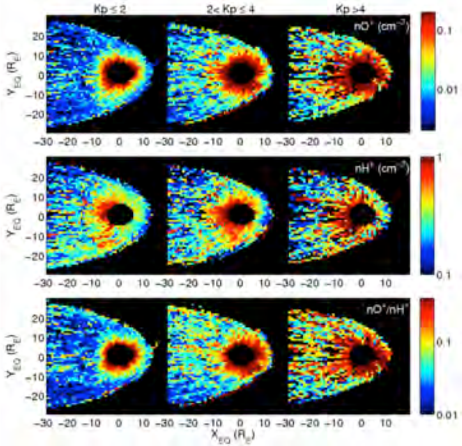
Chen & Moore, JGR (2006)

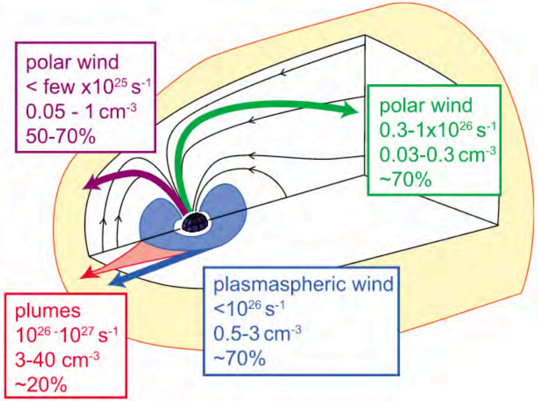


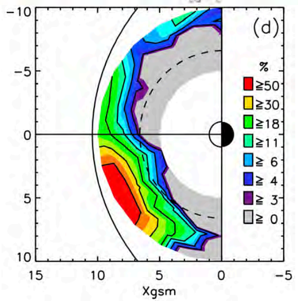
Andre+, GRL (2012)

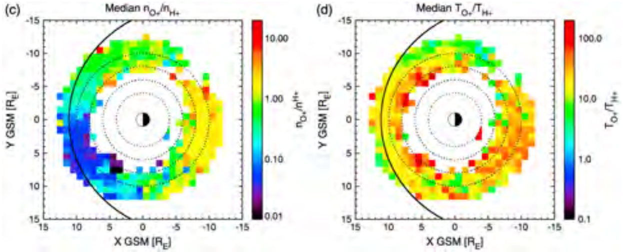
Statistics of cold ions in the magnetosphere





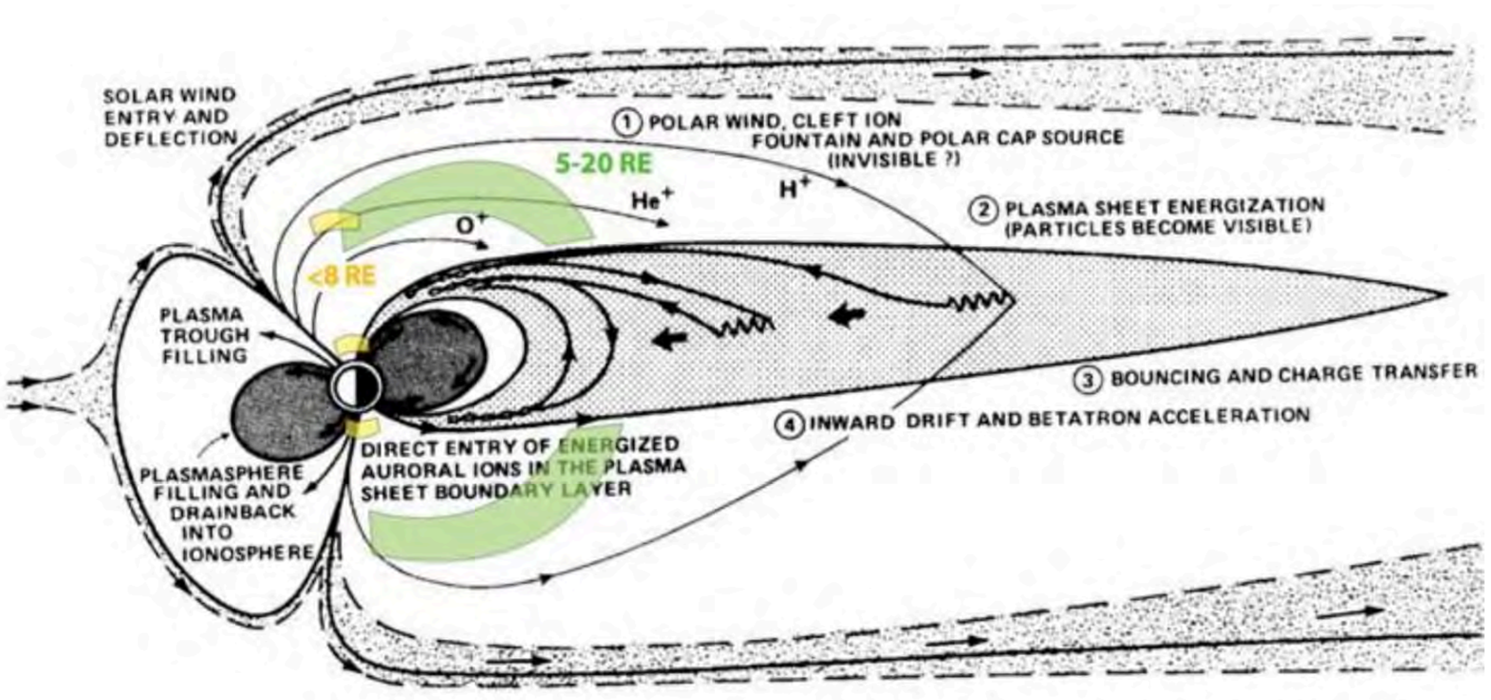






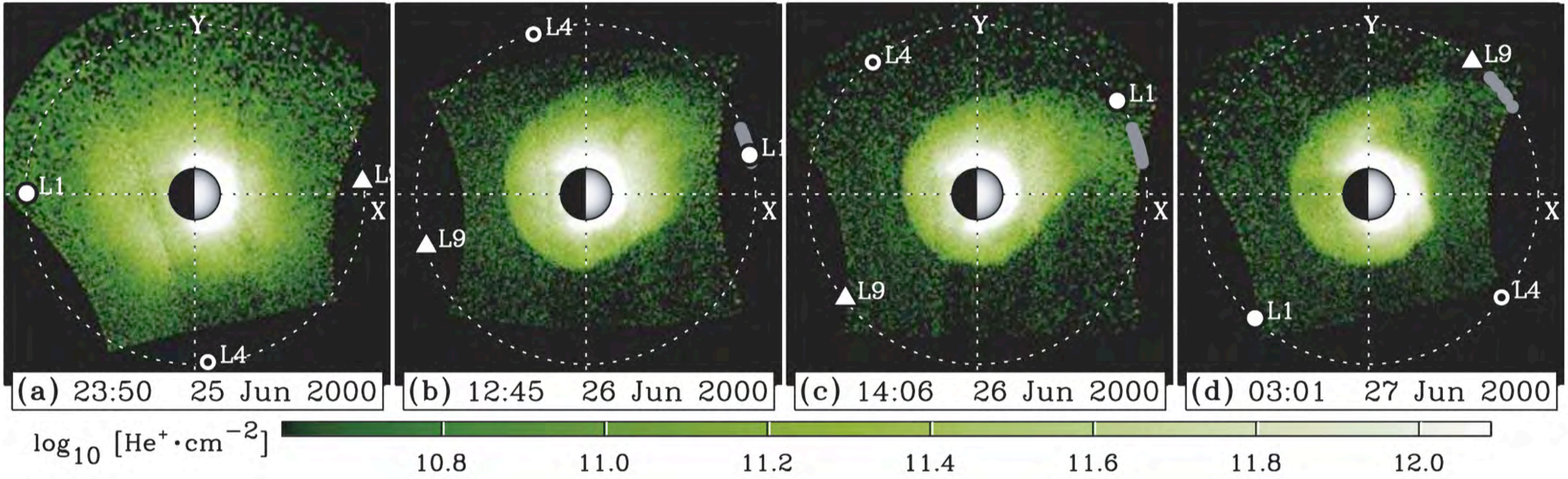
Olsen *JGR* 1982, Hirahara+ *JGR* 1996, Chandler+ *JGR* 1999, Su+ *JGR* 2000, Chen & Moore, JGR (2006), Engwall+ Nat. Geos. 2009, McFadden+ *GRL* 2008, Lee & Angelopoulos, JGR, 2014, Maggiolo & Kistler JGR 2014, Lee+ *JGR* 2015, Fuselier+ *GRL* 2016 etc.

Cold plasma: Ionospheric outflows



Chappell et al. [1987,2000]

Cold plasma: plasmaspheric plumes and wind



Goldstein+, JGR, 2004

Lemaire & Schunk, JATP, 1992
Dandouras+, Ann. Geoph., 2013

Mass loading

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

$$v_A^2 = \frac{B^2 / \mu_0}{\rho_m} = \frac{\text{Magnetic tension}}{\text{Mass density}}$$

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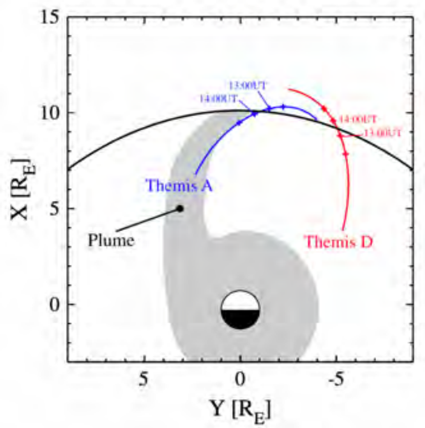

Walsh+, GRL (2014)

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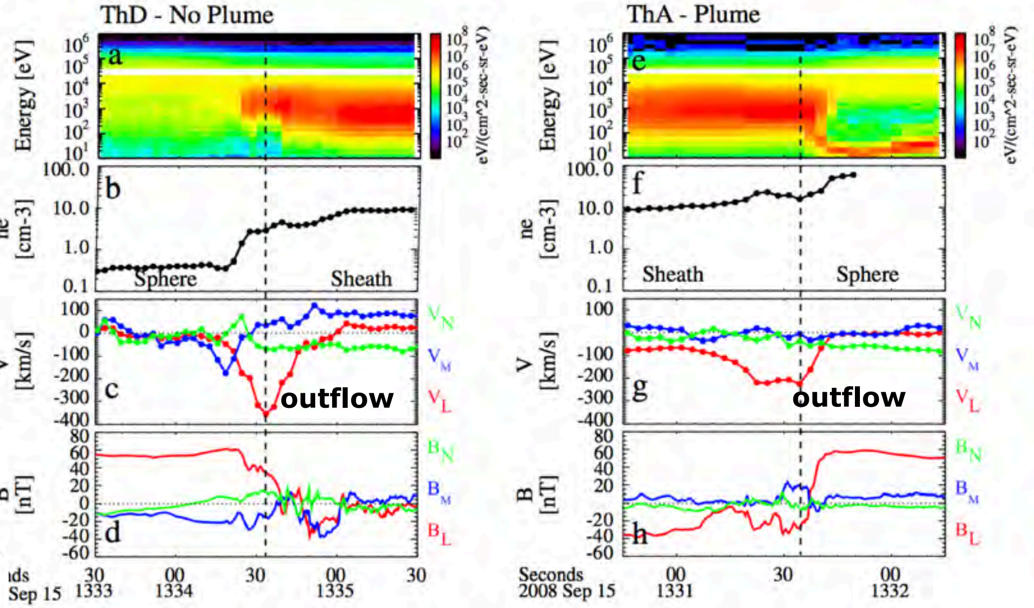

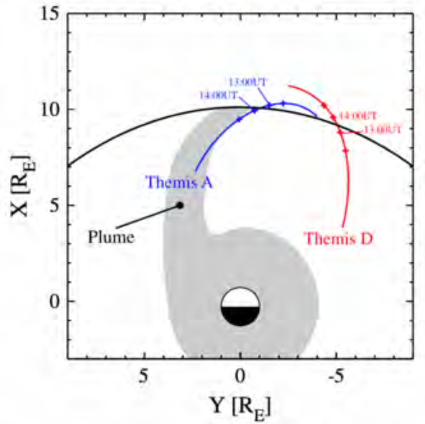

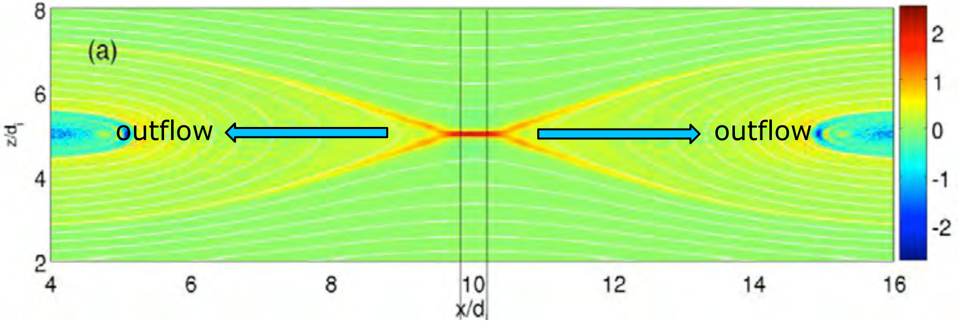

Walsh+, GRL (2014)

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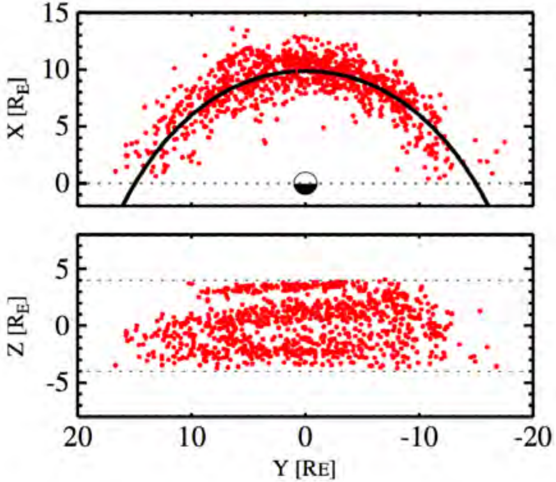
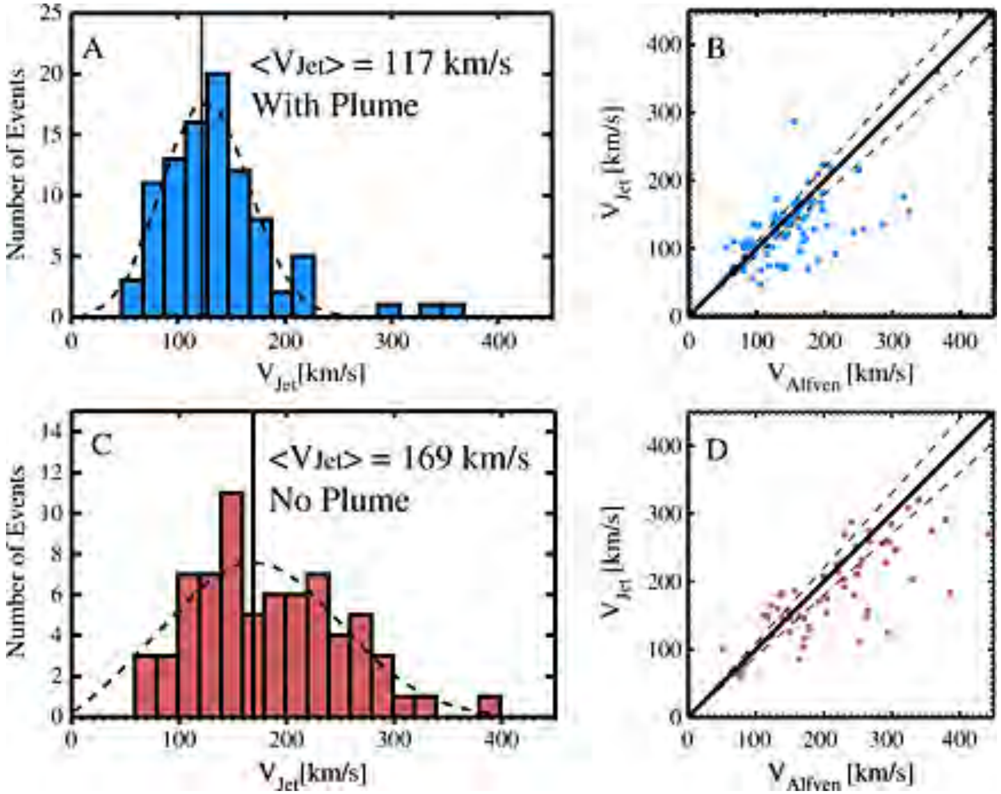


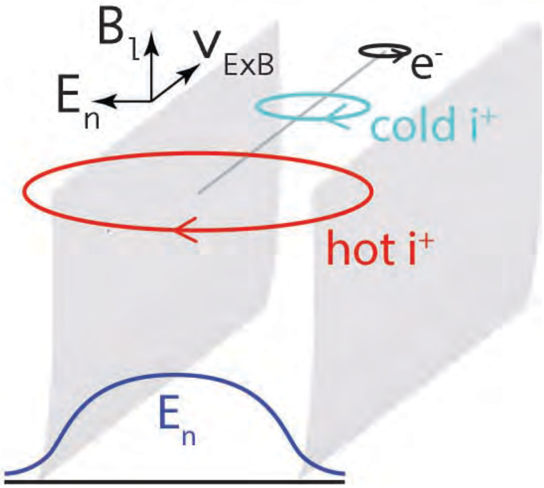


Simulation with a cold ion plume

Full Particle-In-Cell simulation, 816 hours x 16,384 core

Output data size = 380 TB

Cold ions introduce a new length-scale

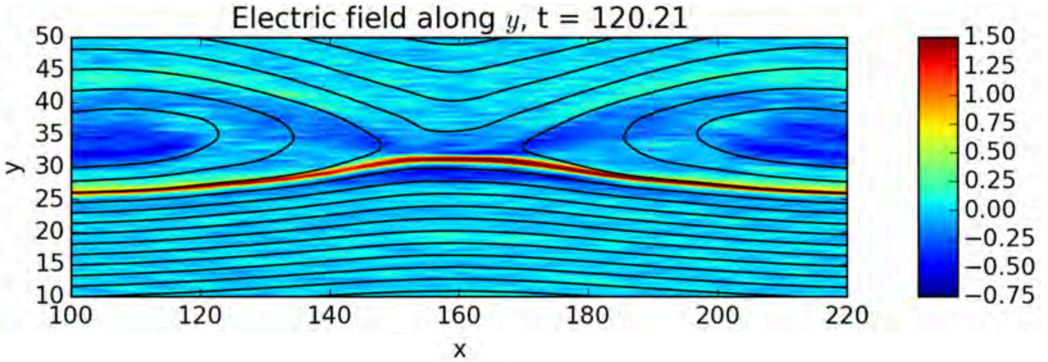


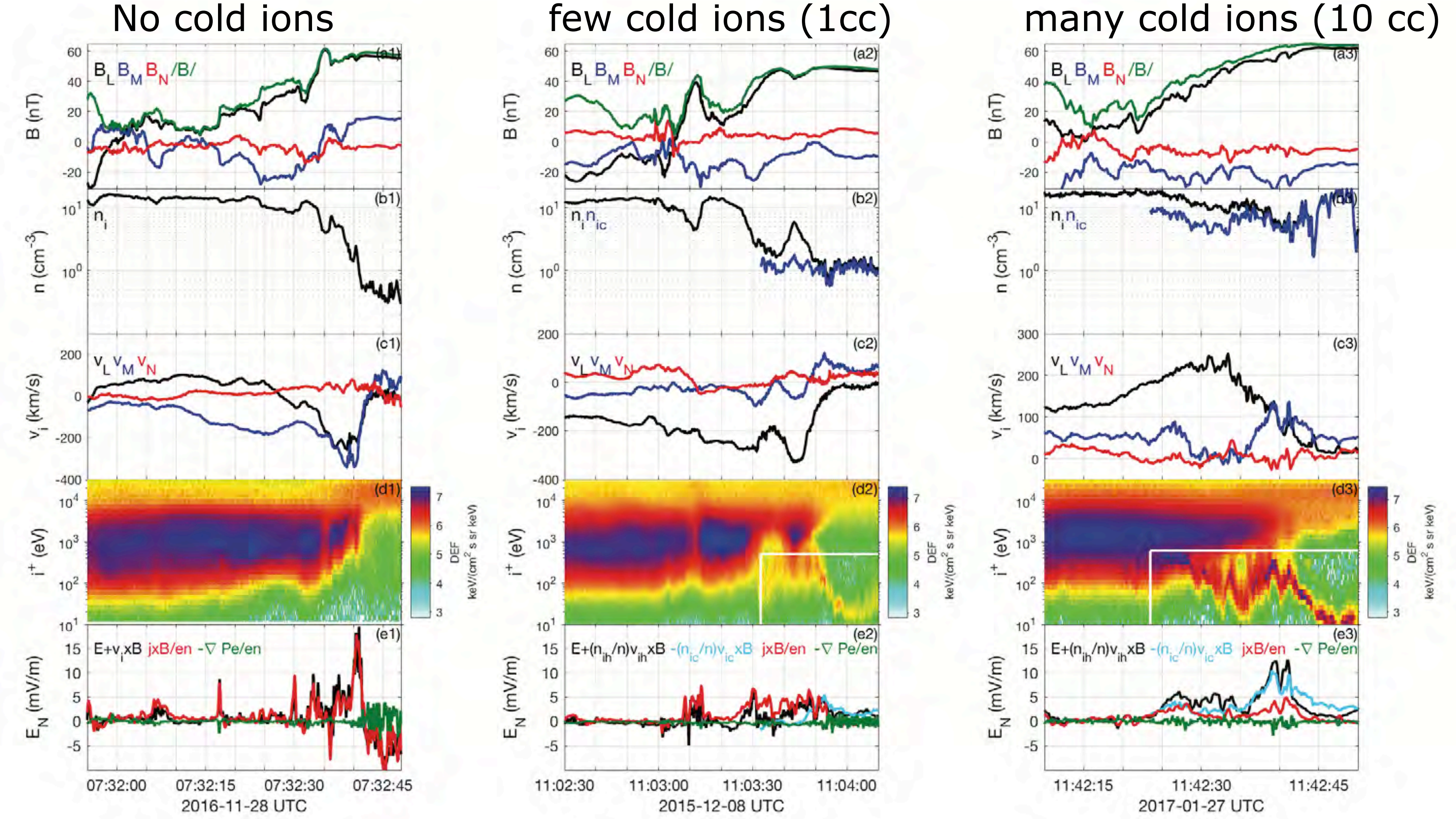
Toledo-Redondo+, GRL (2015)

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

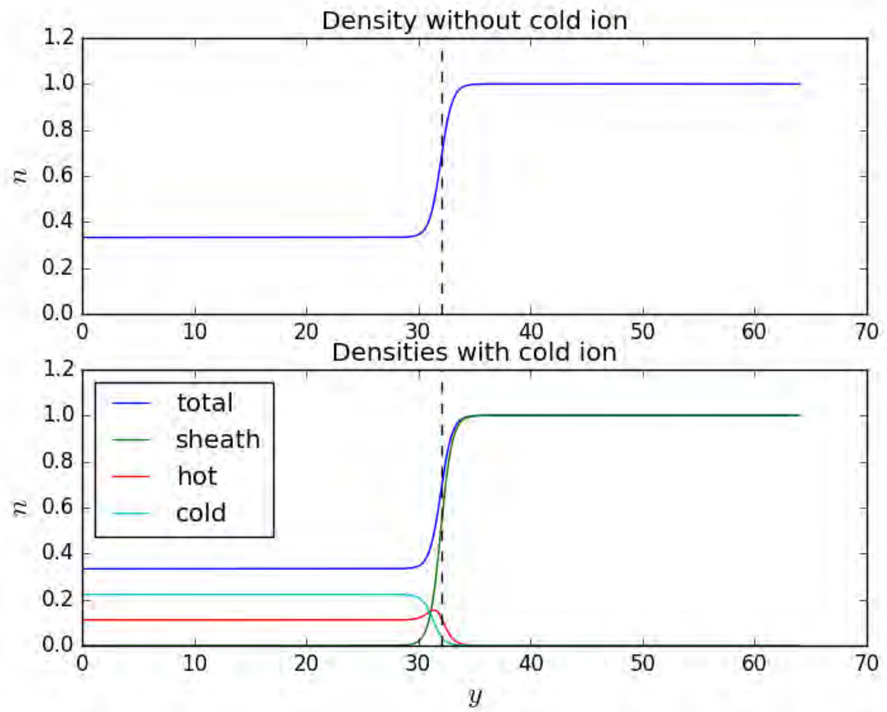
$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \overleftrightarrow{P}_e$$

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

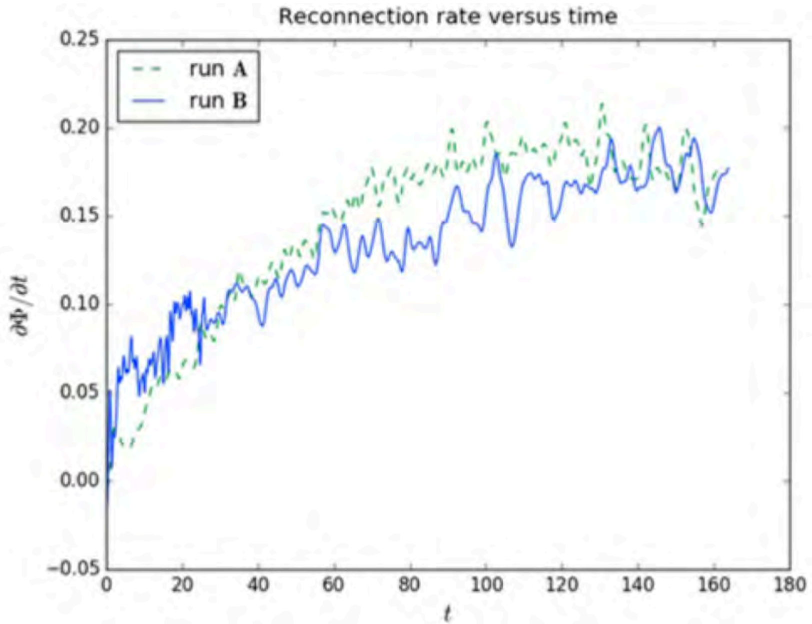



No cold ions
few cold ions (1cc)
many cold ions (10 cc)
(a1) (a2) (a3)
B_L B_M B_N /B/
B (nT)
(b1) (b2) (b3)
n_i
n_i n_{ic}
n (cm^{-3})
(c1) (c2) (c3)
v_L v_M v_N
v_i (km/s)
(d1) (d2) (d3)
i^+ (eV)
DEF keV/(cm^2 s sr keV)
(e1) (e2) (e3)
$E+v_i xB$ jxB/en $-\nabla$ Pe/en
$E+(n_{ih}/n)v_{ih}xB$ $-(n_{ic}/n)v_{ic}xB$ jxB/en $-\nabla$ Pe/en
E_N (mV/m)
07:32:00 07:32:15 07:32:30 07:32:45
2016-11-28 UTC
11:02:30 11:03:00 11:03:30 11:04:00
2015-12-08 UTC
11:42:15 11:42:30 11:42:45
2017-01-27 UTC

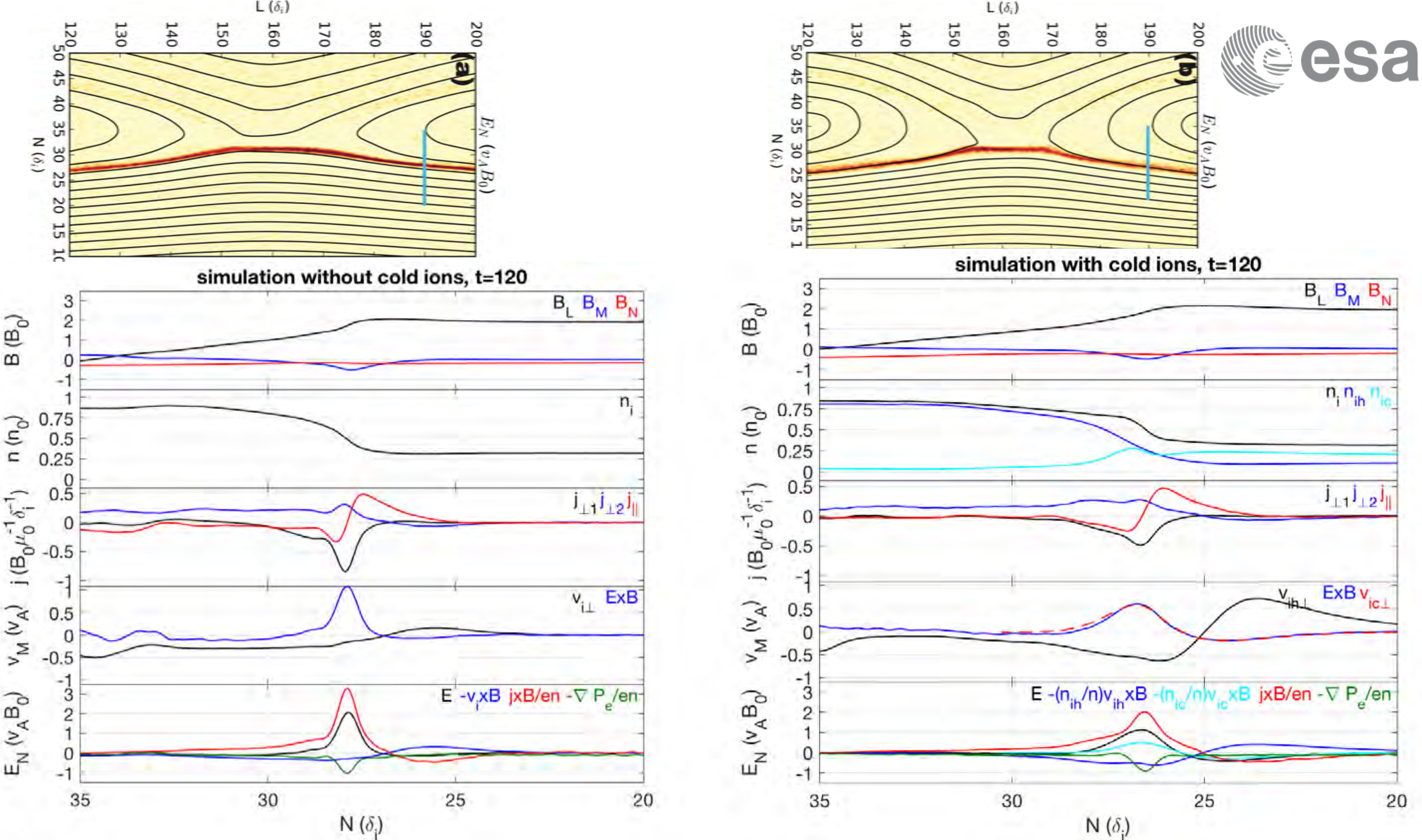
PIC simulation with and without cold ions



Dargent+, JGR, [2017]

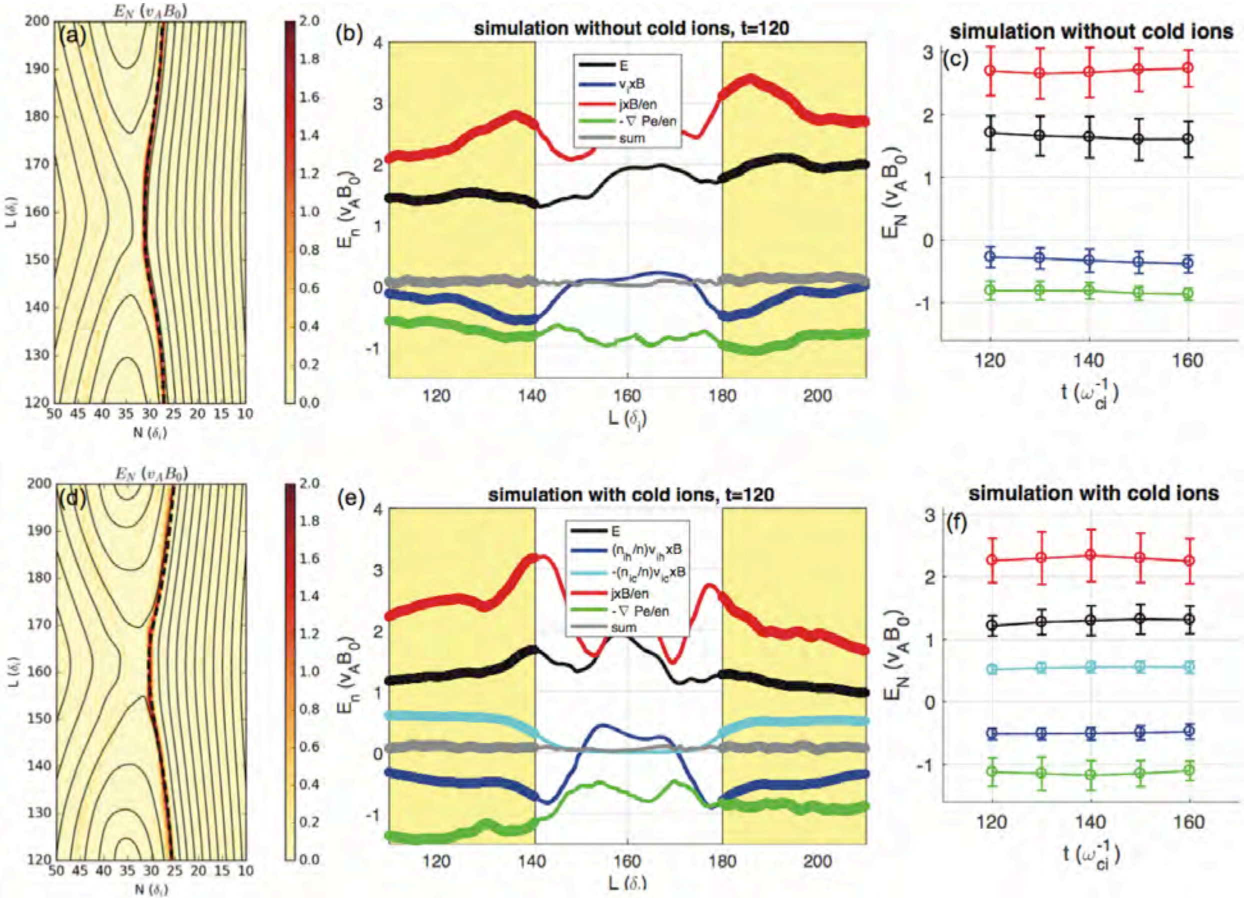


Full PIC simulations with and without cold ions on the magnetospheric side.
Harris current sheet as initial configuration.
$m_i/m_e=25$
$T_{ih}/T_{ic} = 500$

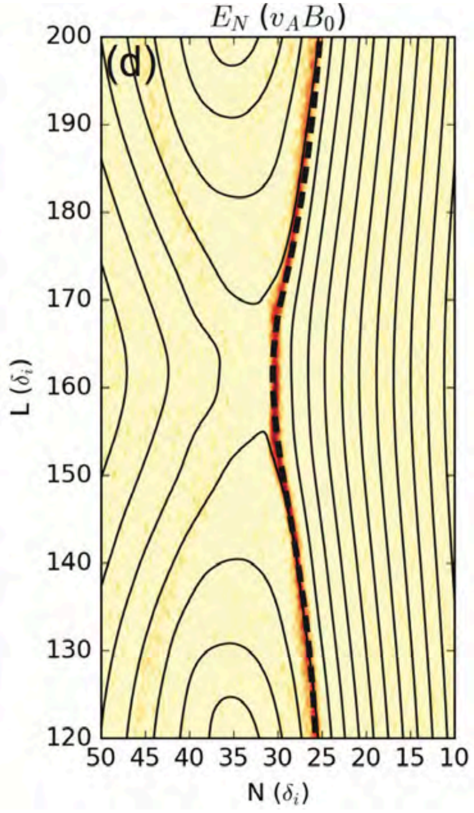


(a)
(b)
L (δ_i)
N (δ_i)
E_N ($v_A B_0$)
simulation without cold ions, t=120
simulation with cold ions, t=120
B (B_0)
B_L B_M B_N
n (n_0)
n_i
n_i n_{ih} n_{ic}
j ($B_0 \mu_0^{-1} \delta_i^{-1}$)
$j_{\perp 1}$ $j_{\perp 2}$ $j_{||}$
v_M (v_A)
$v_{i\perp}$ ExB
$v_{ih\perp}$ ExB $v_{ic\perp}$
E_N ($v_A B_0$)
E $-v_i$xB jxB/en $-\nabla P_e$/en
E $-(n_{ih}/n)v_{ih}$xB $-(n_{ic}/n)v_{ic}$xB jxB/en $-\nabla P_e$/en
N (δ_i)

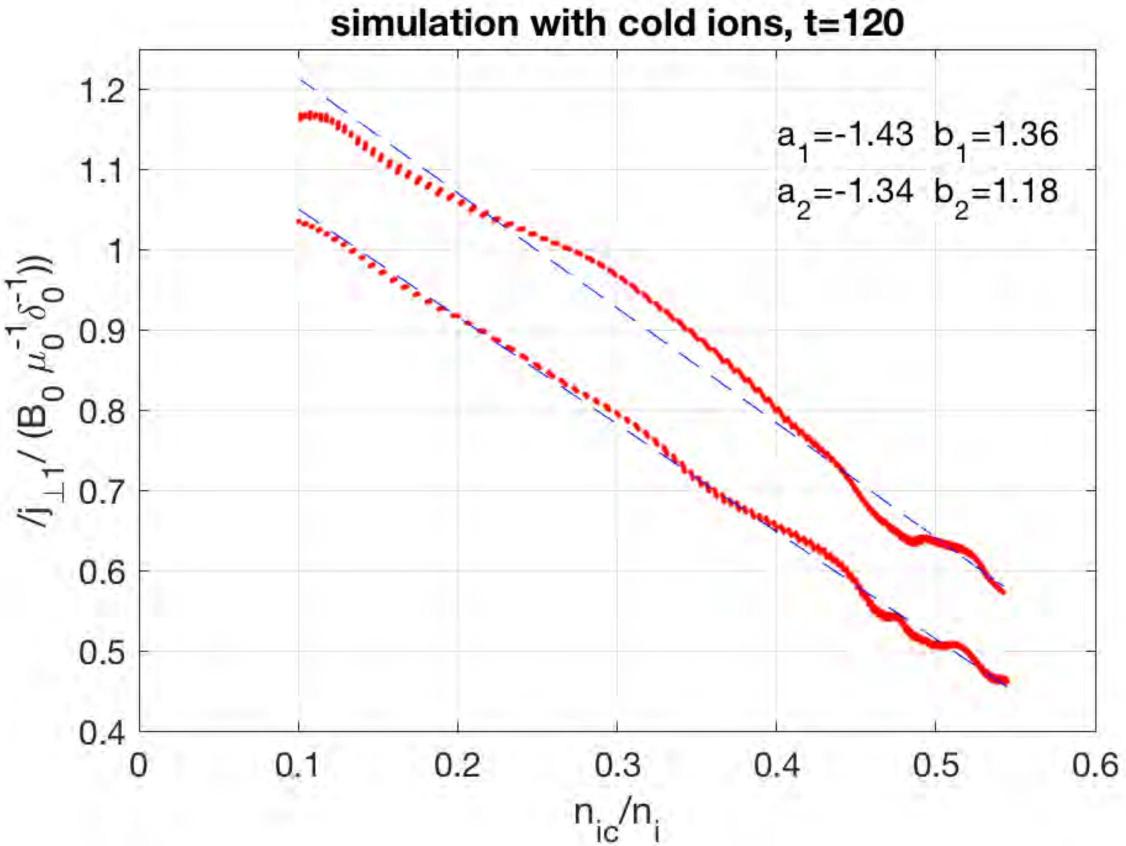
Ohm’s law terms along the separatrix



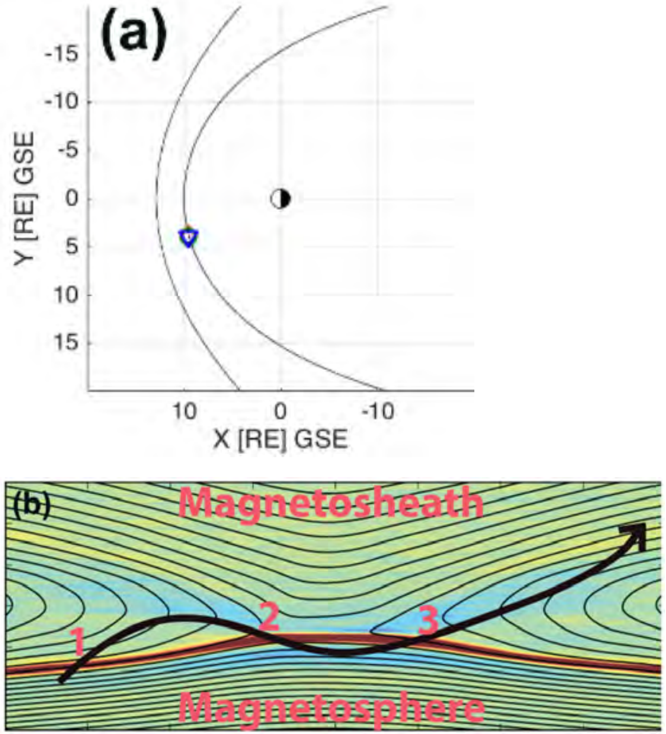
J_{perp} reduction as a function of n_{ic}/n



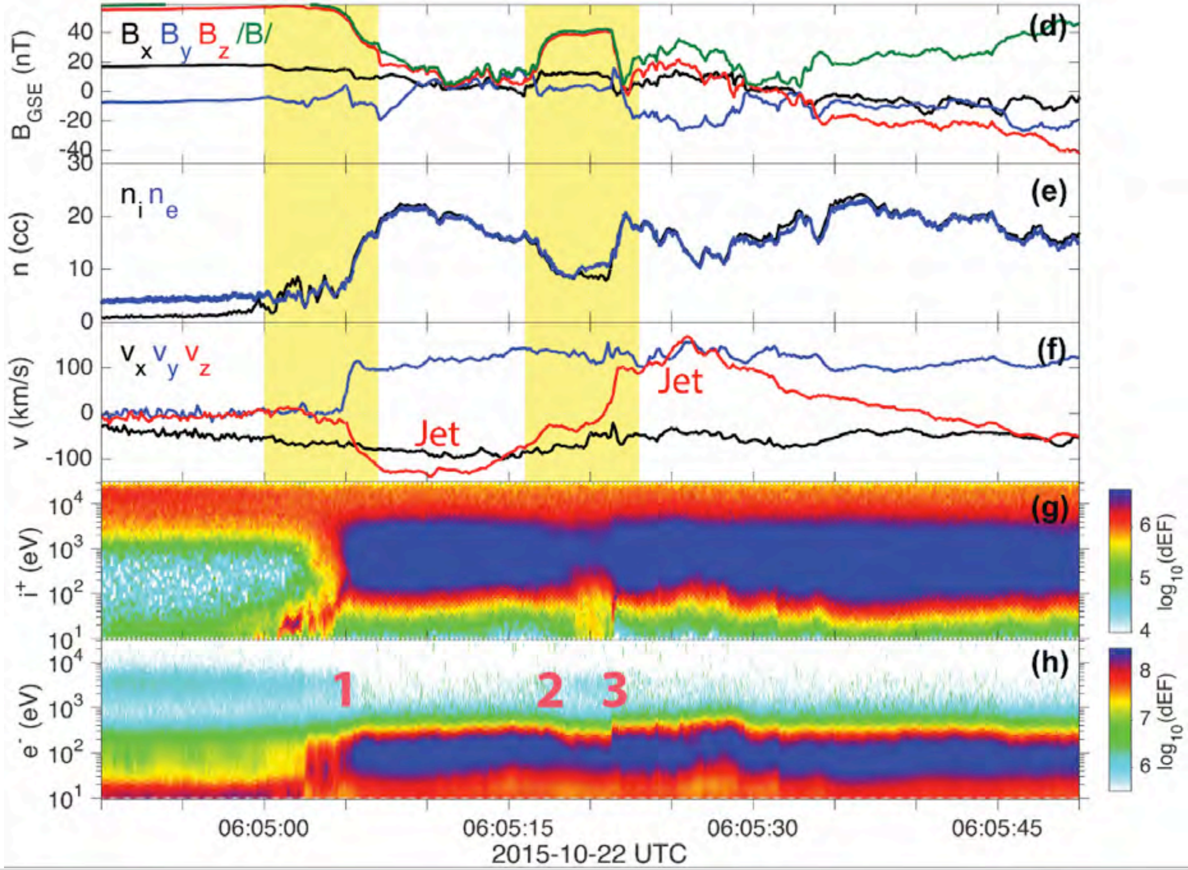
Toledo-Redondo+, GRL (2018)



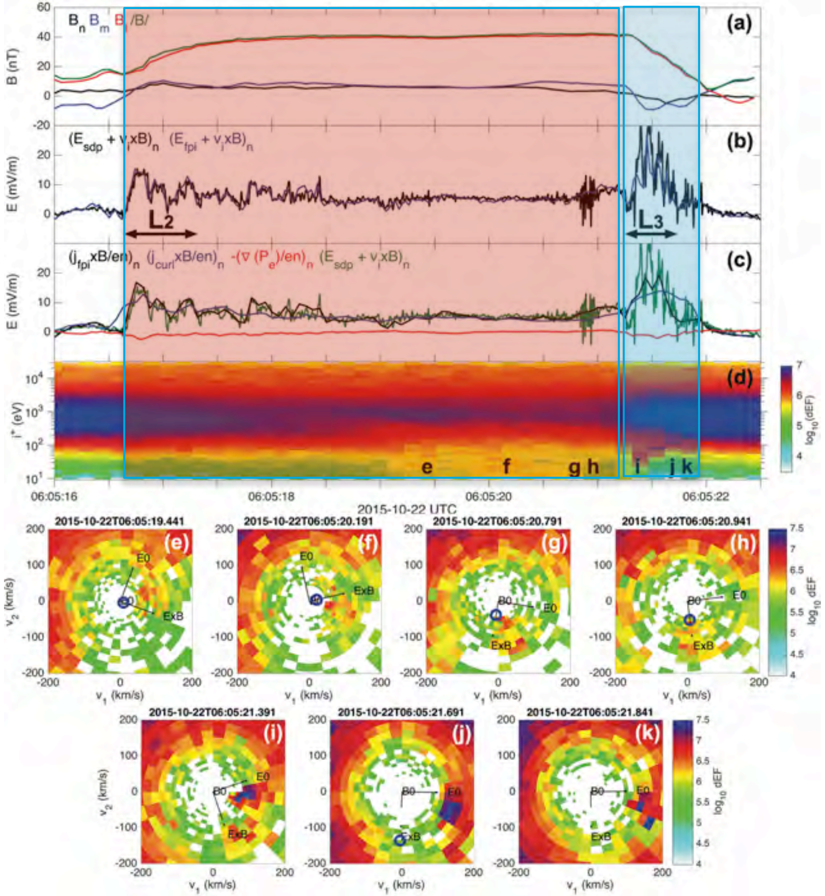
Cold ion diffusion region

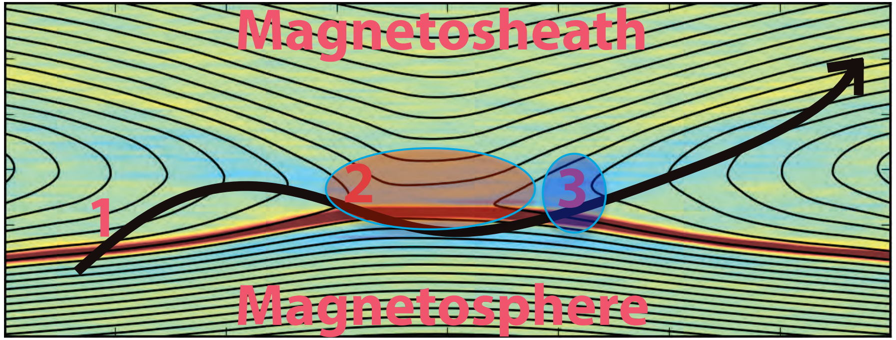


Toledo-Redondo+, GRL (2016a)



Cold ion diffusion region

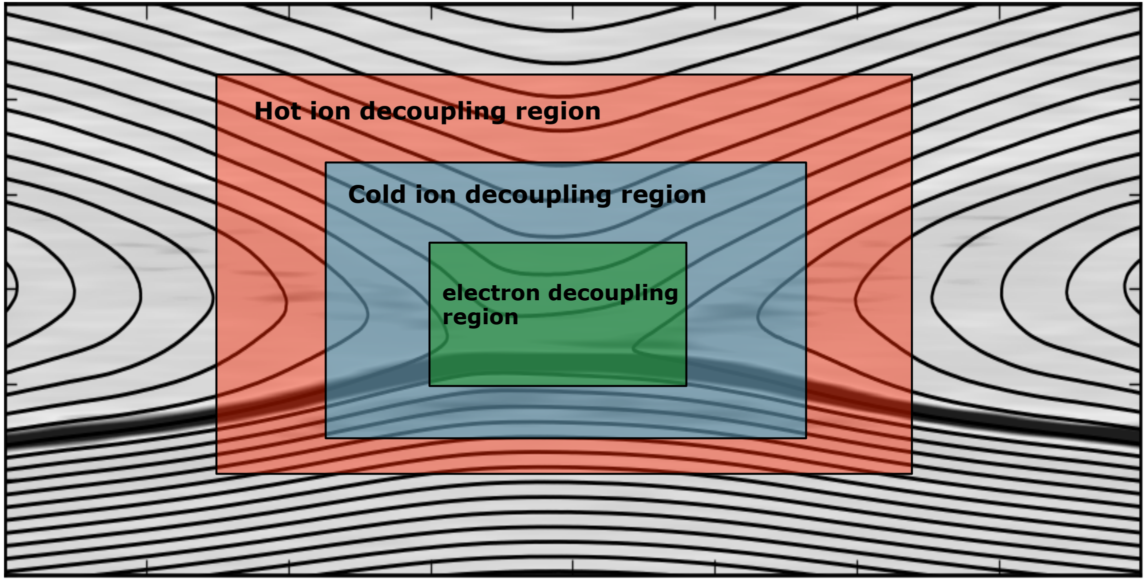




A layer (cIDR) embedded in the IDR is found where **cold ions are demagnetized and accelerated parallel to E**. The width of the layer is of the cold ion gyroradius. Outside the cIDR, in the hIDR, cold ions follow ExB.

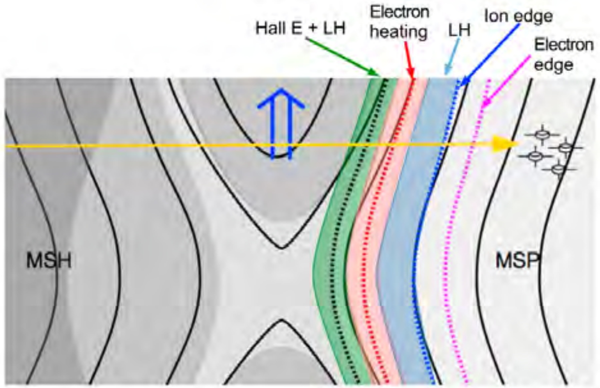
Toledo-Redondo+, GRL (2016a)

Cold ions introduce a new length-scale

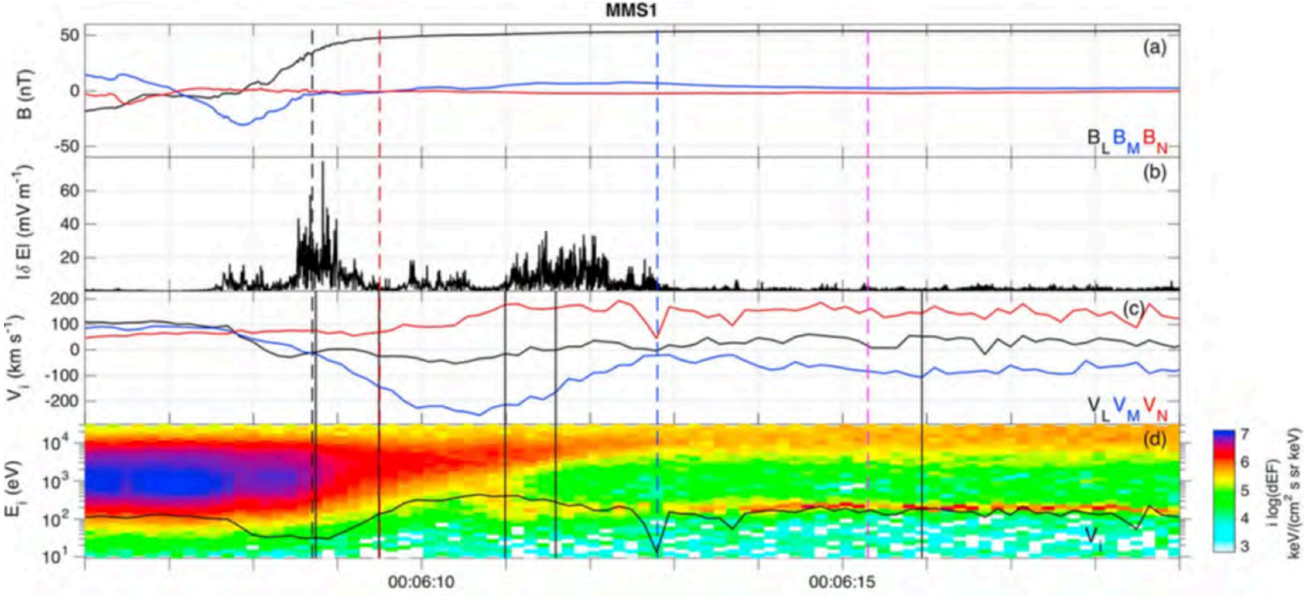


Toledo-Redondo+, GRL (2016a)
Divin+, JGR (2016)

Lower Hybrid waves at the separatrix owing to cold ions

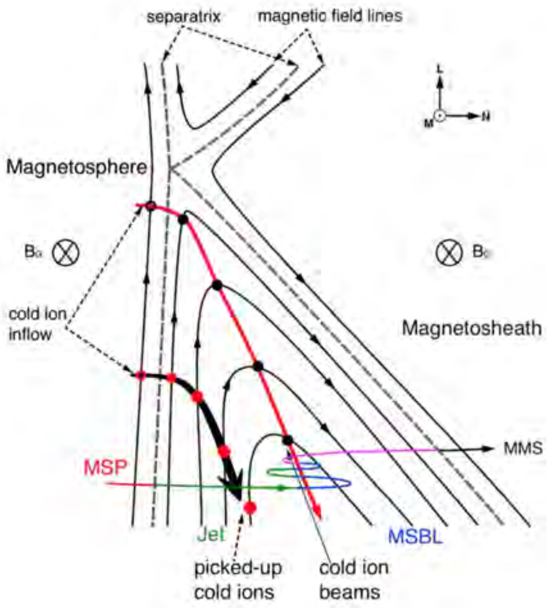


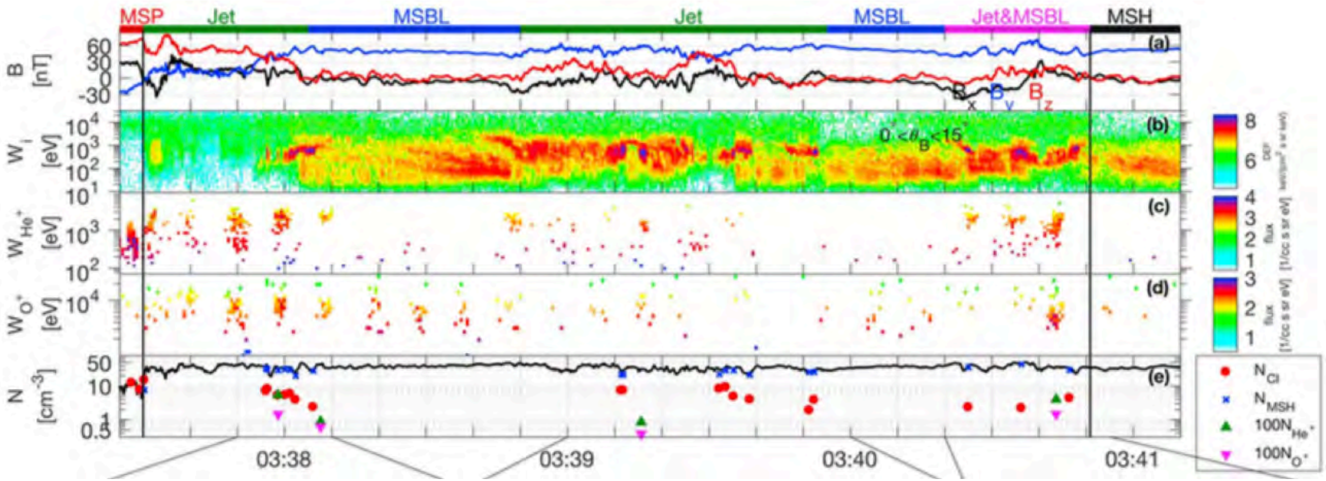
The relative motion between the magnetized cold ions and the magnetosheath ions favours **an ion – ion drift instability** at the separatrix that generates **lower hybrid drift waves**. These waves can **heat the cold ions** and demagnetize them.



Graham+, JGR (2017)

Cold ions inside the exhaust region

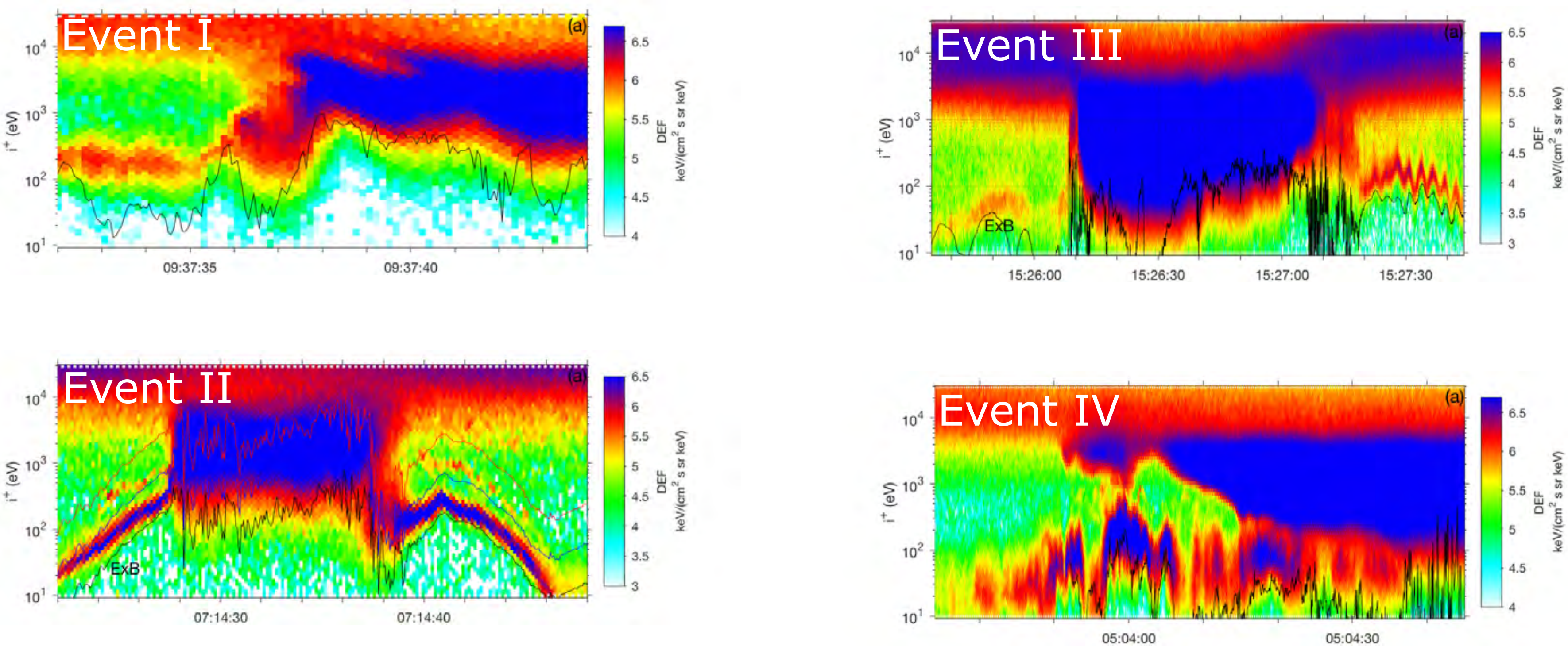




Cold ion beams can be found **inside reconnection exhausts** without much heating. A plausible explanation is that **they crossed the magnetopause close to the X line**.

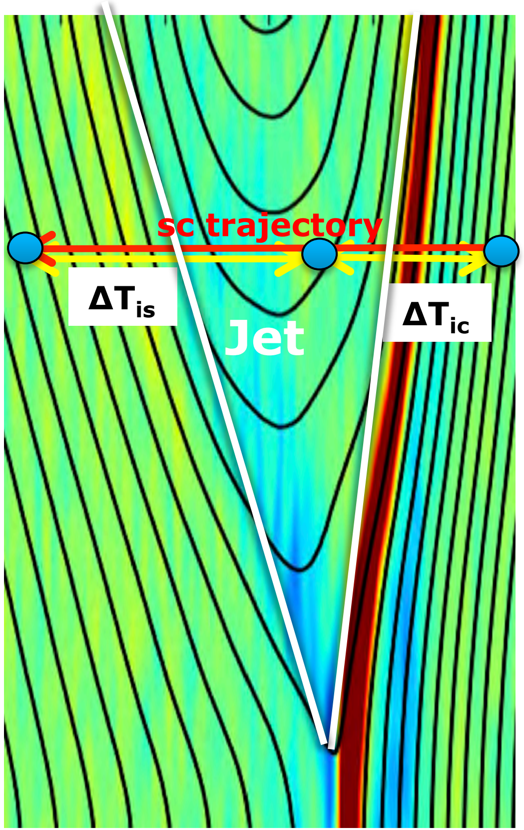
Li+, JGR, [2017]

Cold ion heating by magnetic reconnection



Toledo-Redondo+, JGR, (2017)

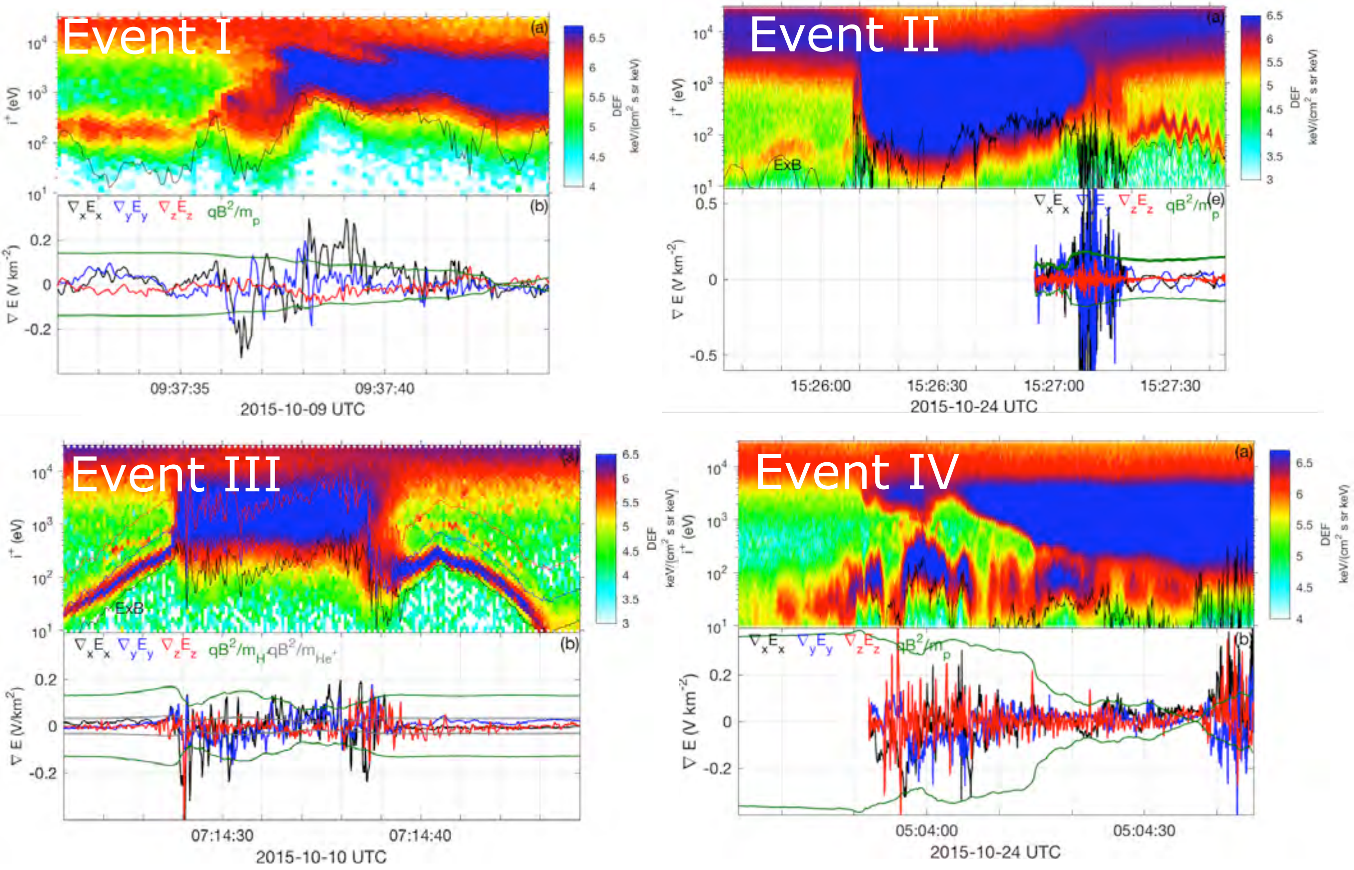
Energy budget of magnetic reconnection



$$\rho_{ic} = \frac{\Delta T_{ic} n_{ic}}{\Delta T_{ic} n_{ic} + \Delta T_{is} n_{is}}$$

Event	ρ_{ic}
I 2015-10-09	20% (H^+)
II 2015-10-24 Inb	08% (H^+)
III 2015-10-10	20% (H^+) 07% (He^+)
IV 2015-10-24 Out	No cold ion heating

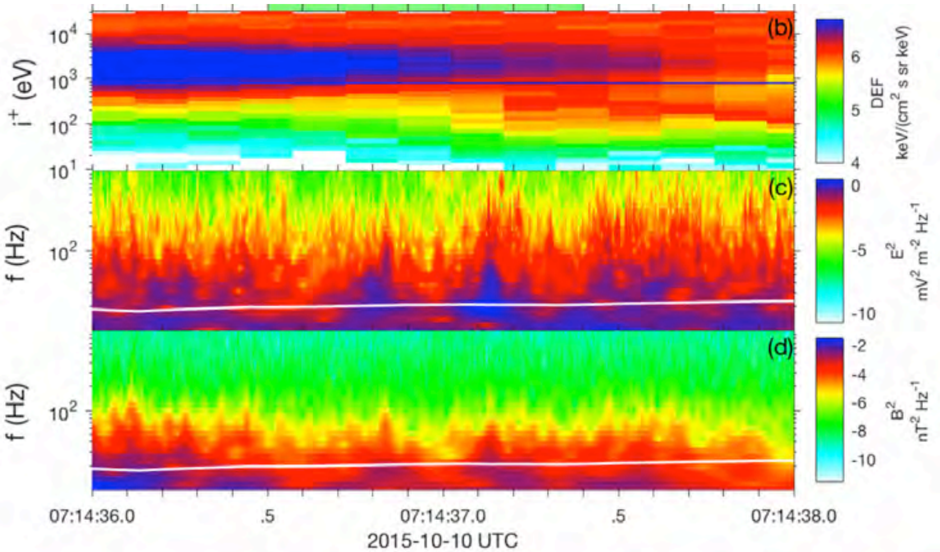
Heating mechanism I: E field gradients



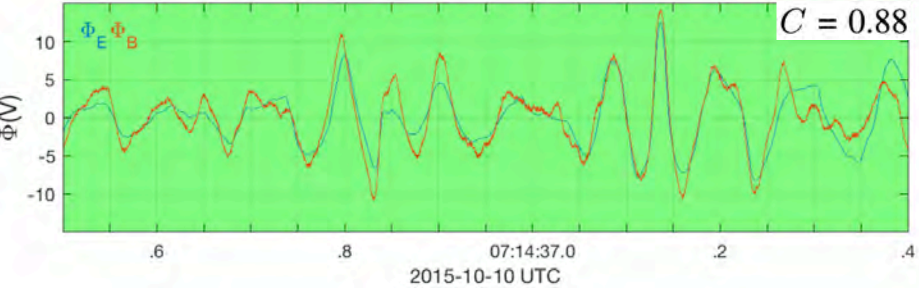
$$/\nabla \mathbf{E}/ > qB^2/m$$

Toledo-Redondo+, JGR, [2017]

LHDW in association with cold ion heating



Observation of LHDW in the region where cold ion heating occurs



$$\Phi_B = \frac{B}{qn\mu_0}\delta B_{||}$$

$$\Phi_E = \int \delta \mathbf{E} dt \cdot \mathbf{v}_{ph}$$

Toledo-Redondo+, JGR, [2017]

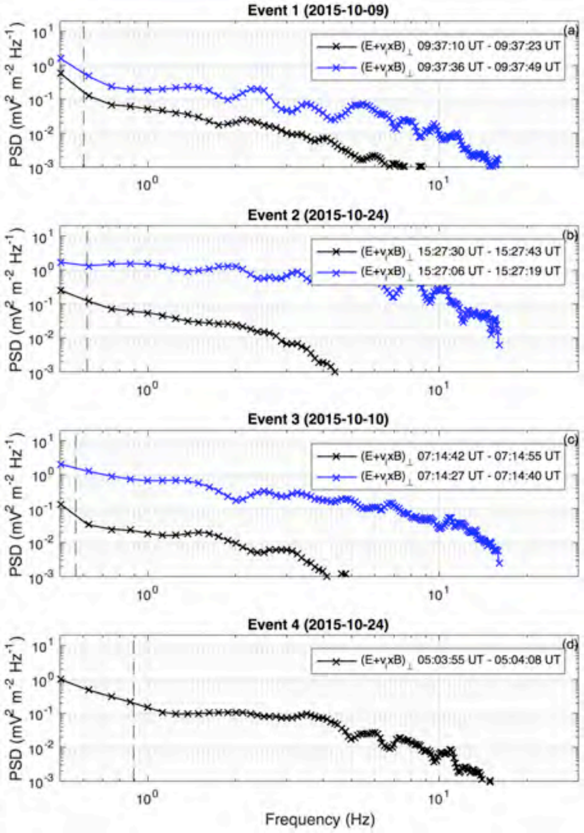
Heating mechanism II: Waves close to ion frequency

EMIC and/or LHDW can transfer energy to the cold ions by resonant interactions.

$$\frac{dW}{dt} = P_i \frac{q^2}{2m}$$

Chang+, GRL, [1986]
André+, GRL, [1994]

Toledo-Redondo+, JGR, [2017]



Event	Heating rate* Inside region	Heating rate* Outside region
I 2015-10-09	7 eV/s	2 eV/s
II 2015-10-24 Inb	15 eV/s	1 eV/s
III 2015-10-10	15 eV/s	0.5 eV/s
IV 2015-10-24 Out	No heating	2 eV/s

* 20% of the available energy was considered

Summary - Conclusions

- **Cold plasma from the ionosphere modifies the solar wind – magnetosphere coupling**. This can have implications at **global scales**, for instance space weather research.

- Cold ions **mass load** the magnetosphere and **reduce the reconnection rate**.

- They introduce **new microphysics** owing to their small gyroradii and can facilitate, for instance, **LHDW, cIDRs,** or the **generation of plasmoids**.

- Reconnection can spend **20%** or more of the heating **energy** into **heating the cold ions,** when present. The heating is related to non-adiabatic processes (**waves** and **E field gradients**).

- **Cold plasma** interactions with solar wind are **common** in **unmagnetized planets** (e.g. Mars), or in **giant planets** with active Moons (Jupiter, Saturn). Implications for **exoplanetary systems**.

Thanks for your attention