Evidence of magnetic field switch-off in PIC simulations of collisionless magnetic reconnection with guide field

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Motivations

- what's the long term evolution of collisionless magnetic reconnection? Petschek-like or multiple X-points?

  Observational evidence in both directions in the solar wind, e.g. [Gosling07] vs [Eriksson14]

  → we see plasmoids first, then Petsheck-like exhaust

- if Petschek-like evolution, can we see in fully kinetic simulations the Switch Off Slow Shocks (SO-SS) that Petschek expected [Vasyliunas75]?

  Long history of searching for SO-SS in kinetic simulations (intro in [Liu 12, Innocenti15])

- Petschek reconnection is a collisional concept. What's the relation with collisionless (i.e. kinetic) reconnection?

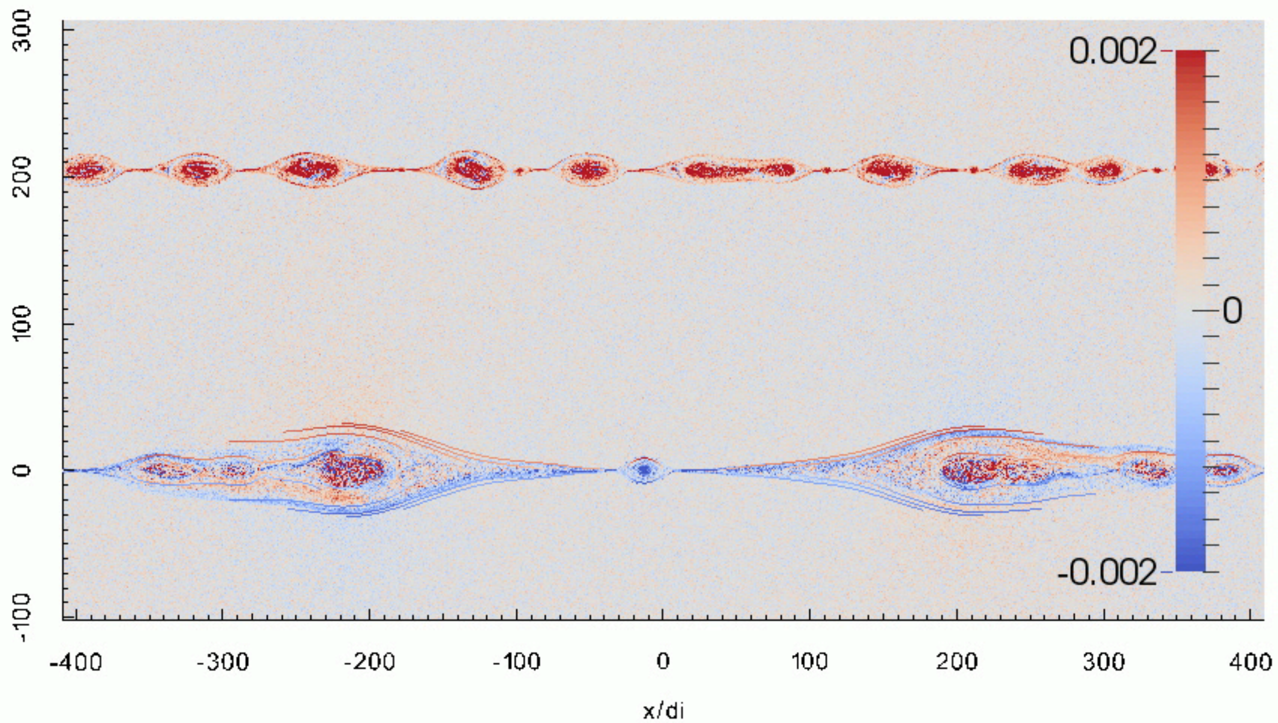
→ the multi scale problem

Large scale, long term evolution of a 2D3V collisionless magnetic reconnection simulation

upper layer: unperturbed, plasmoid chain* develops from $\sim$ 180 $\Omega_{ci}t$ onwards

lower layer: GEM-like perturbation [Birn01], goes directly into non ideal regime of reconnection [Karimabadi05]

$J_{ze}\ \frac{4\pi e d_i}{m_i \omega_{pi}}$, Time: 250 $\Omega_{ci}t$

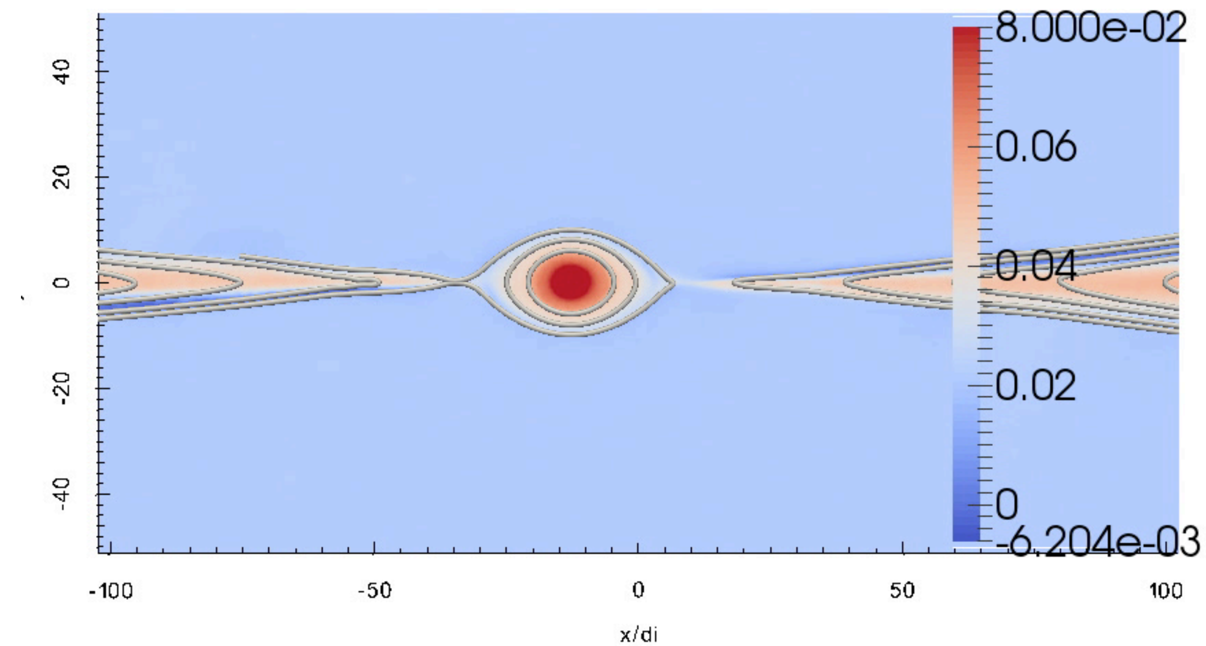


a moderate guide field, Bg=0.3 B0 (corresponds to $\sim$ 0.035 B0 for mr=1836, 0.35-1 nT for the tail), opposes the firehose instability [Karimabadi99, Lee13]

→ different evolution than [Liu12]

Before proceeding: closer look at the X point

$B_z \frac{e}{m_i \omega_{pi}}$, Time: 250 $\Omega_{ci}t$



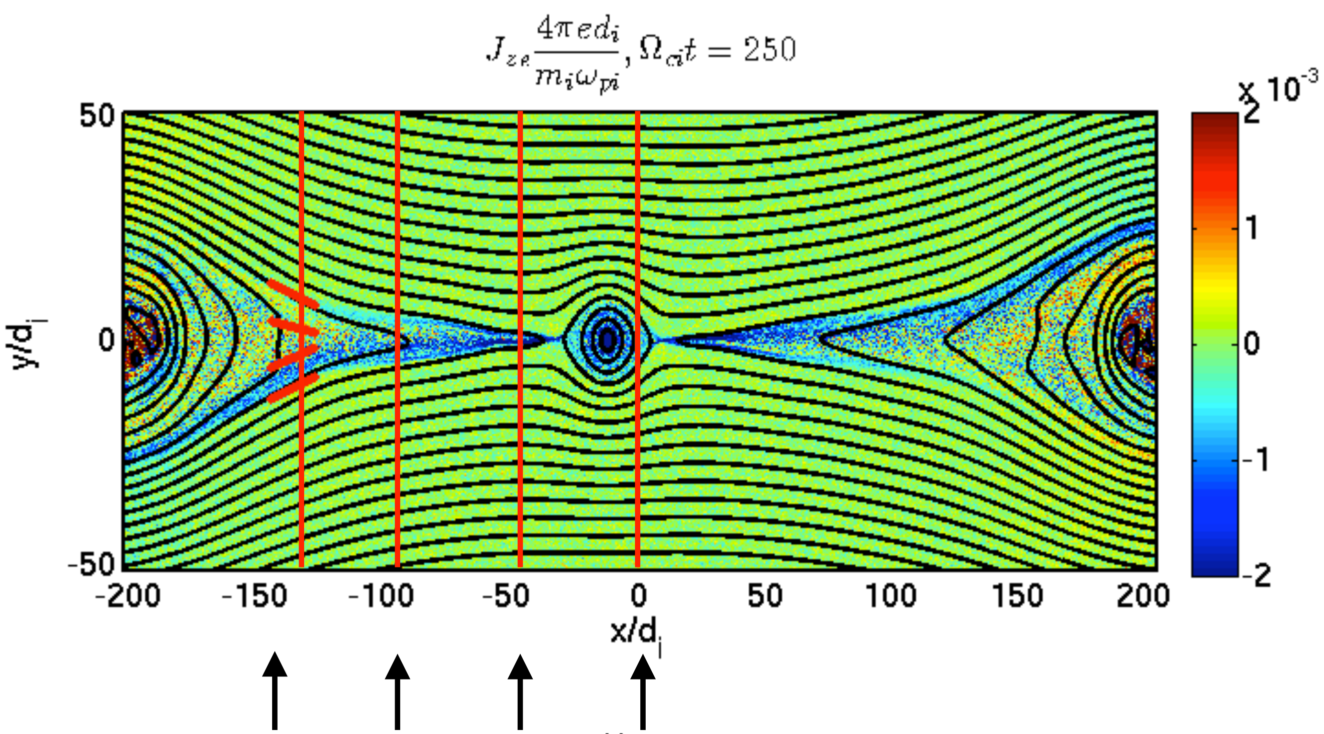
Medium-size plasmoids are emitted in the leftwards exhaust from $\sim$ 90 $\Omega_{ci}t$ until a monster plasmoid [Uzdensky10, Loureiro12] forms at $\sim$ 160 $\Omega_{ci}t$

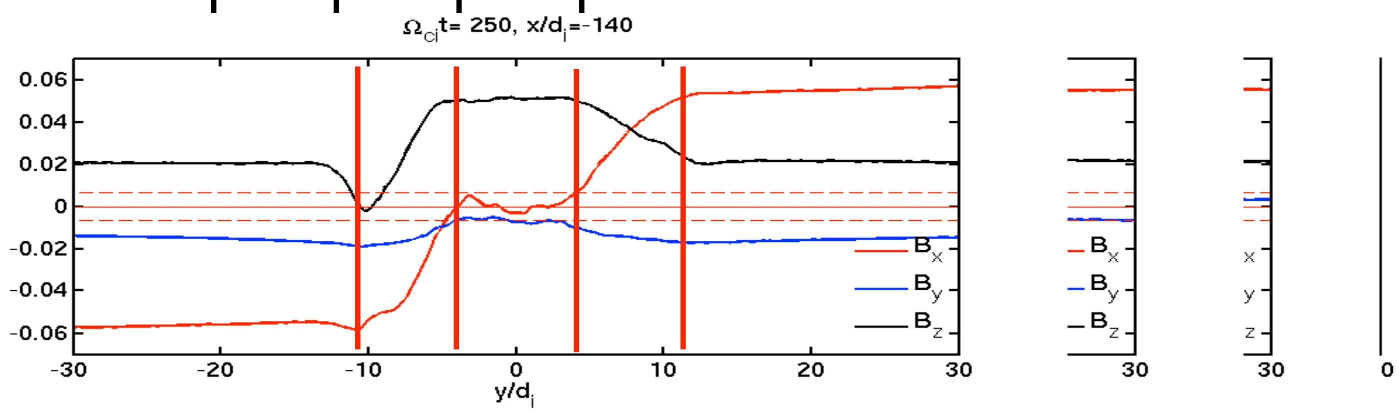
Simulation parameters

2D3V, $L_x/d_i \times L_y/d_i$ = 891.2 x 409.6
$dx/d_i = dy/d_i$ = 0.1, dt = 0.01Ω_{ci}
m_r=25, L_H/d_i = 2, T_i/T_e=1, $v_{th,e}/c$ = 0.16667
double periodic BC
simulation done with iPic3D [Markidis10]

* Loureiro07-12, Lapenta08, Daughton06, Drake06, Markidis13, Lin08

Looking for an area of (in plane) magnetic field switch-off



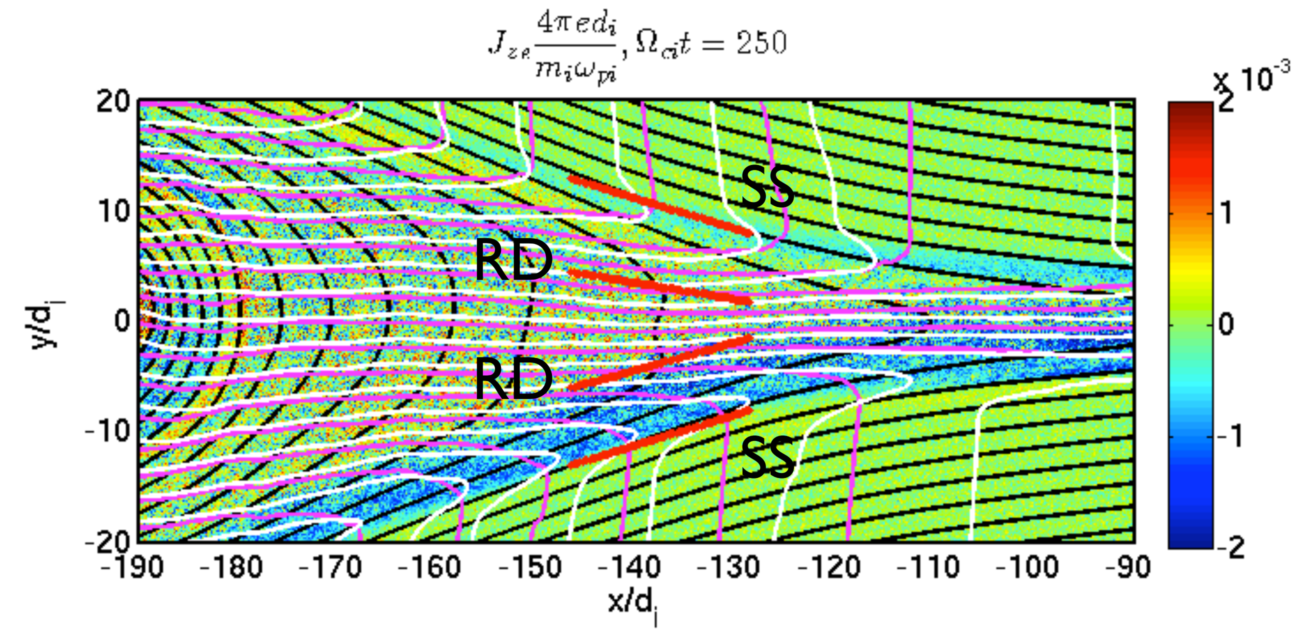


At large distances [Higashimori12] from the X point/monster plasmoid, $B_x \sim B_{T1}$ (in plane tangential component) forms a plateau around $\sim$0.

The plateau/ switch off area moves outwards embedded into the exhaust and covers growing % of it (see below for the rightwards exhaust)

time $[\Omega_{ci}]$	length $[d_i]$	% of the exhaust
180	12.5	11 %
200	16.3	12.7 %
220	26.3	17.6 %
240	31.3	18.4 %

Closer look at the switch-off area:



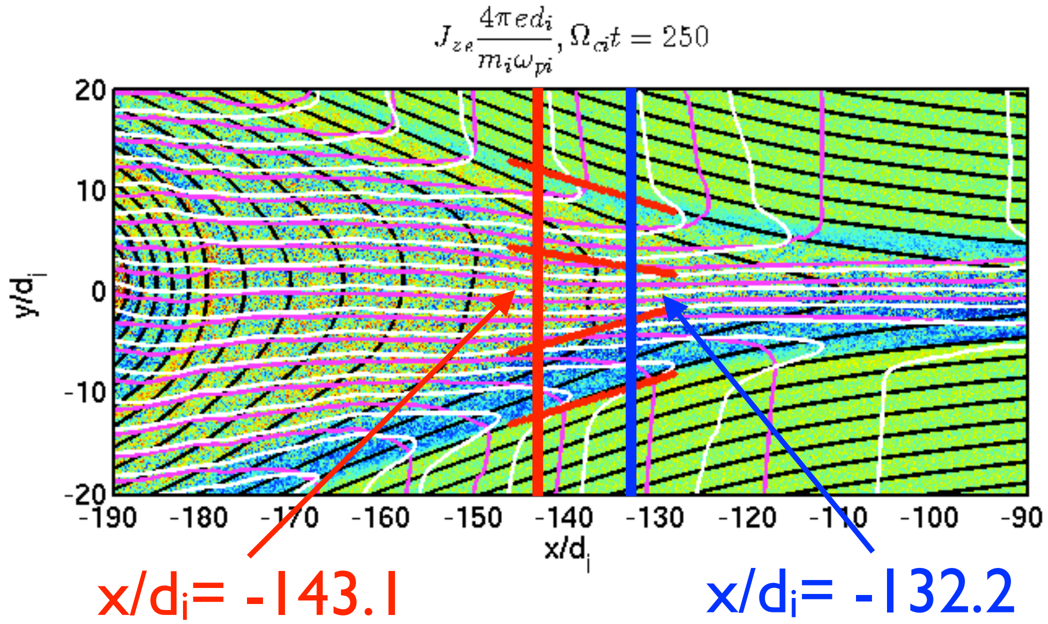
We identify two structures in correspondence with the SO areas, i.e. two back-to-back Slow Shock/ Rotational Discontinuity structures

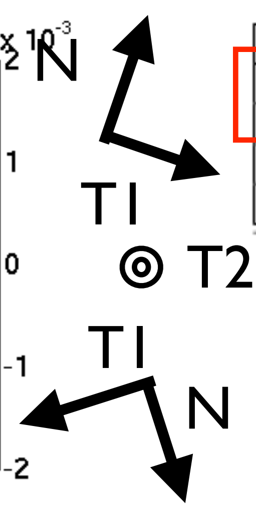
[Liu12] observes two SSs and a rotational wave in 2D3V PIC simulations, no switch off because of firehose instability

[Whang98,04] sees SS/RD in Wind (solar wind) and Geotail (magnetosphere) data

is this structure already observed?

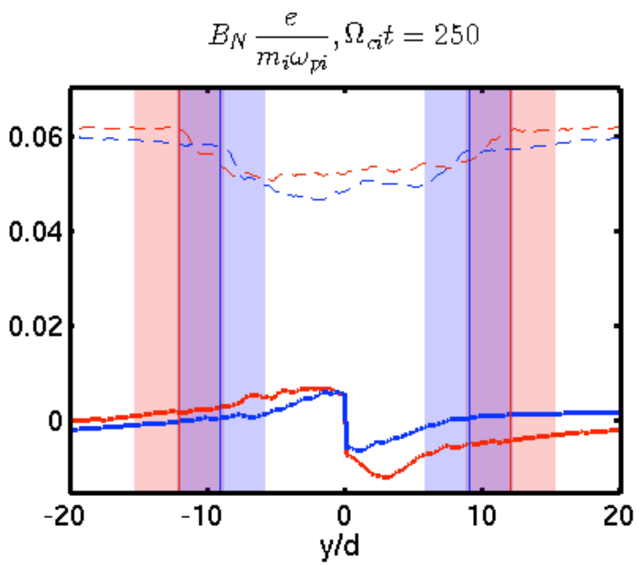
Identification of the external transitions as Slow Shocks/ 1

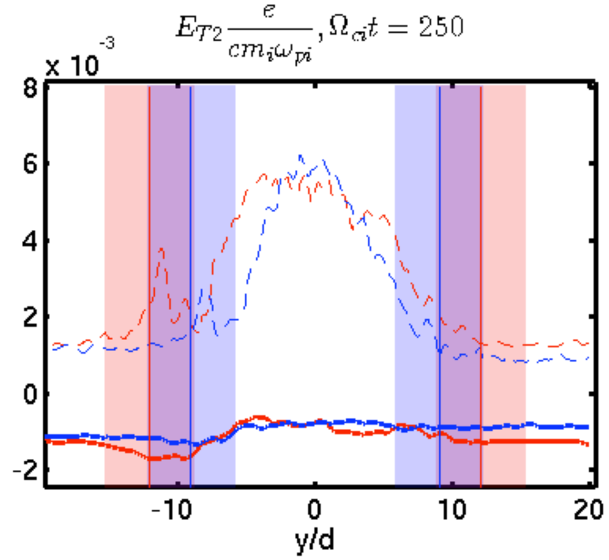


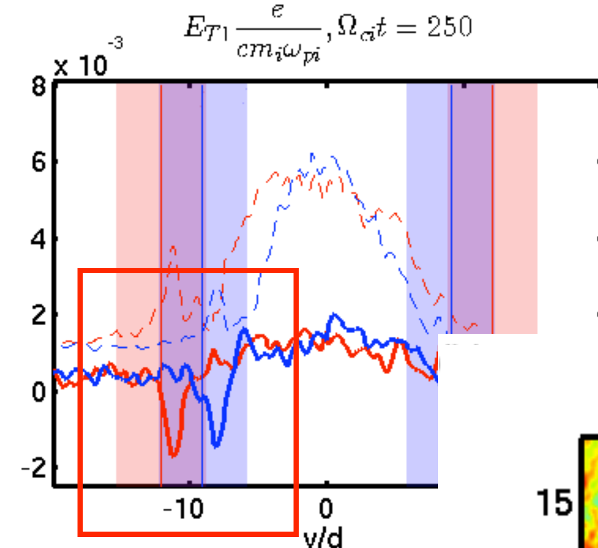


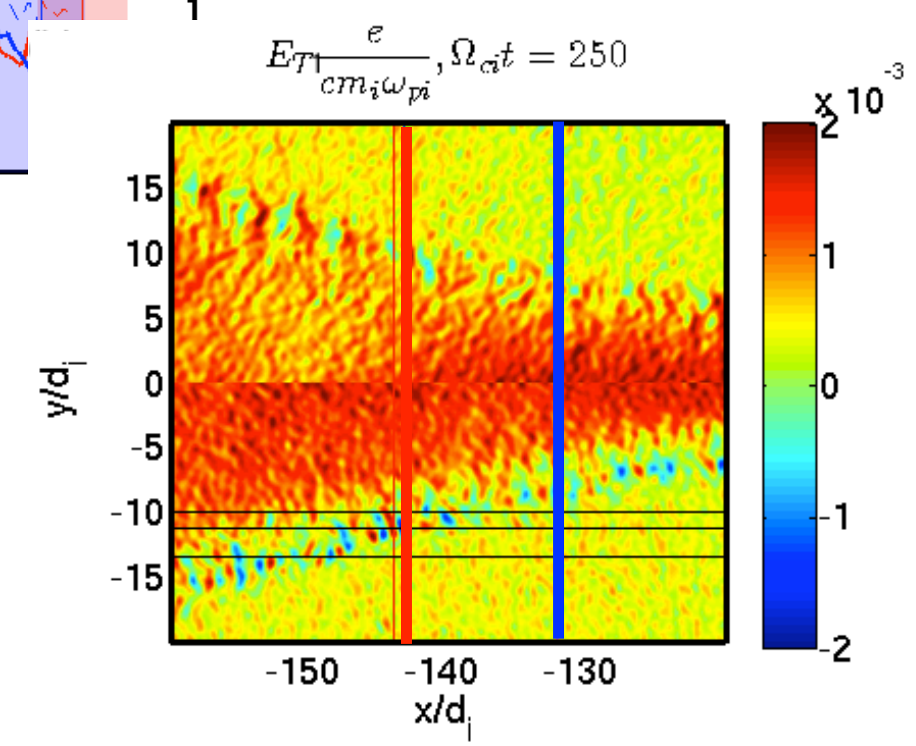
	v_{dHT}/c	N	T1
upper SS	$(-0.0911, 0.0080, -0.0366)$	$(0.26903, 0.96313, 0)$	$(0.96313, -0.26903, 0)$
lower SS	$(-0.1177, -0.0129, 0.0407)$	$(0.26903, -0.96313, 0)$	$(-0.96313, -0.26903, 0)$
upper RD	$(-0.098, 0.0079, -0.0382)$	$(0.14915, 0.98881, 0)$	$(0.98881, -0.14915, 0)$
lower RD	$(-0.1118, -0.0103, 0.0498)$	$(0.24381, -0.96982, 0)$	$(-0.96982, -0.24381, 0)$

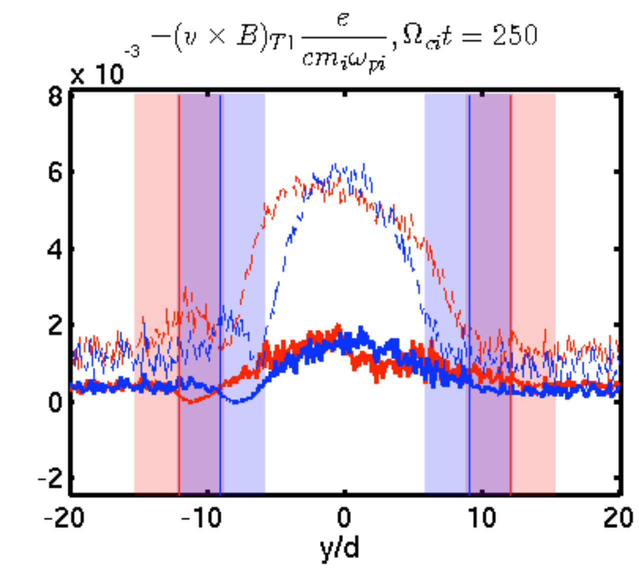
of the Rankine-Hugoniot jump relations [Goedbloed04], we check preliminarily $[B_N]=0$, $[\mathbf{E}_T]=0$ for validation purposes; width of the discontinuities: $\Delta/2= d_{i,loc}$ [Treumann09], $d_{i,loc}/d_i=3.25$







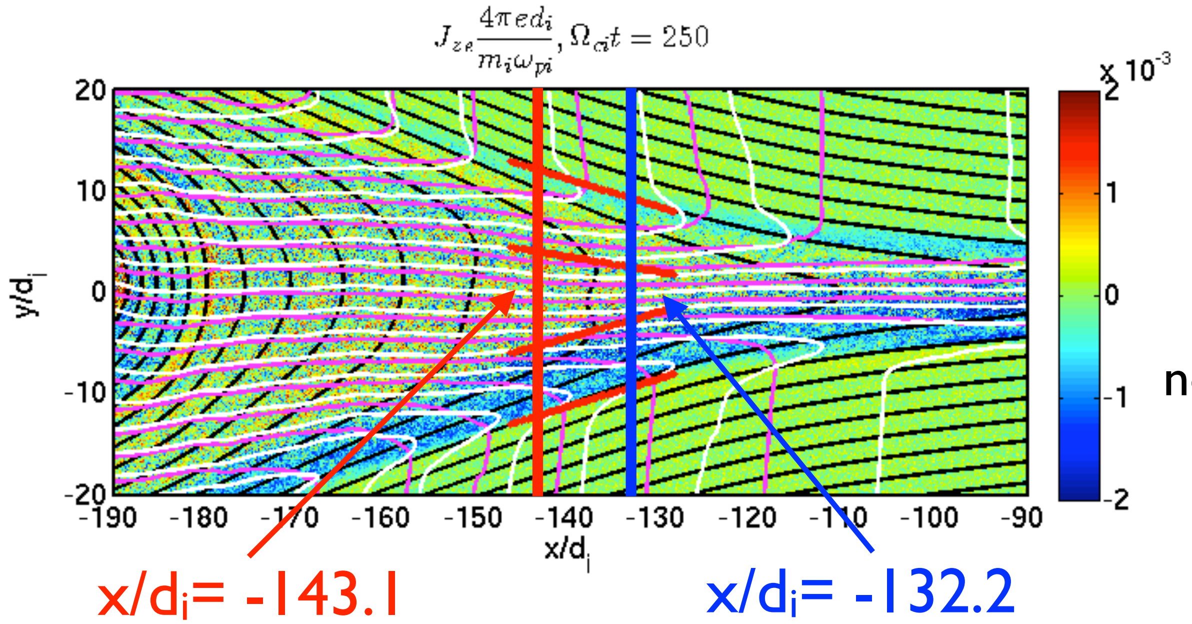




the traces in E_{T1} are electron holes [Drake03, Lapenta11, Divin12] in the lower separatrix (there, $E_{T1} \sim E_{par}$)

we are looking for fluid structures, but the simulation is kinetic!

Identification of the external transitions as Slow Shocks/ 2



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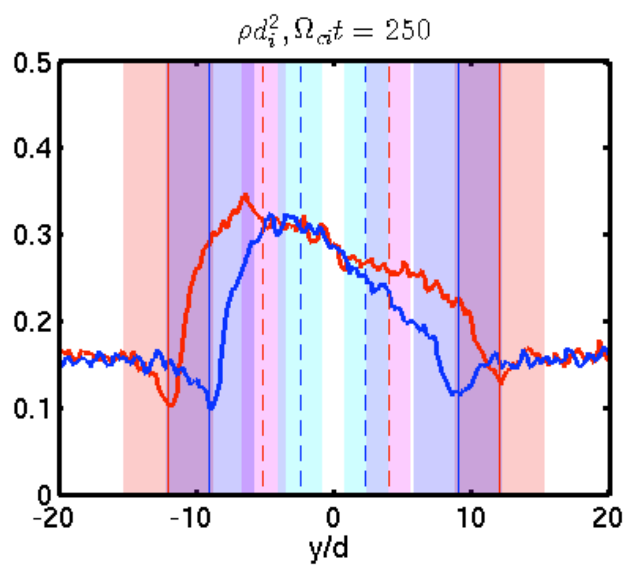
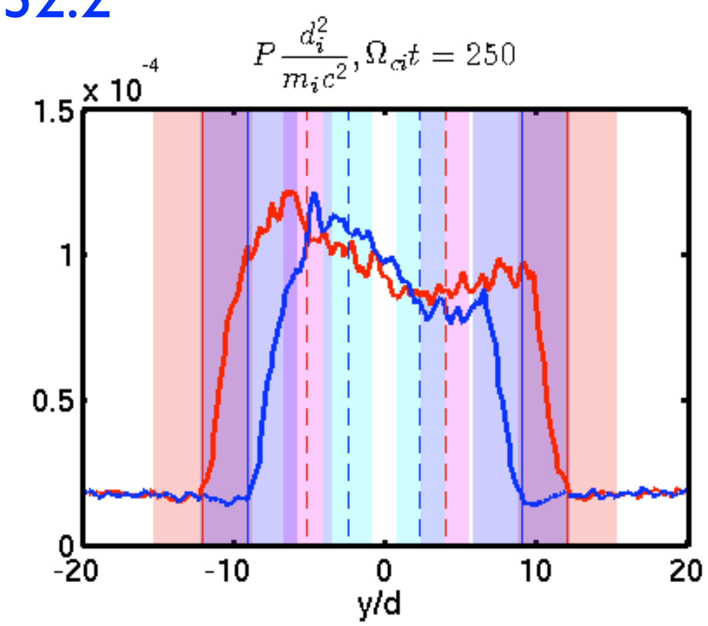
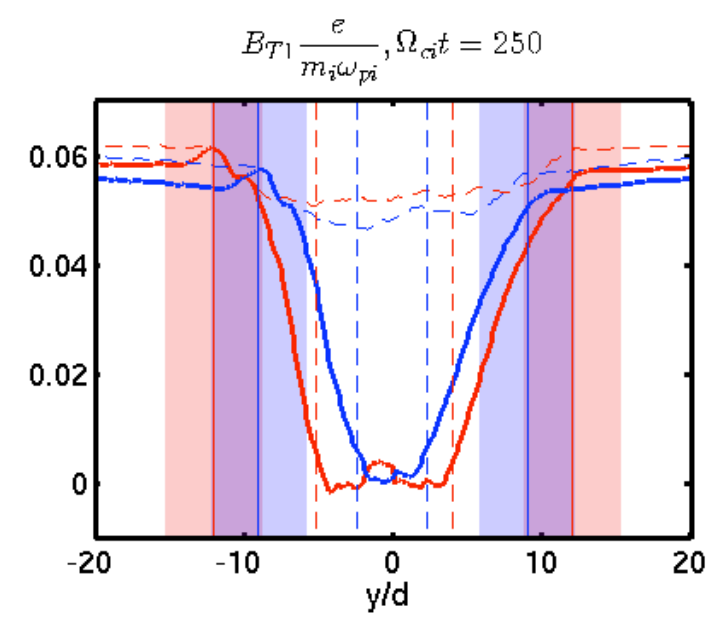
now let's check for density and pressure increase, reduction of B_{T1}

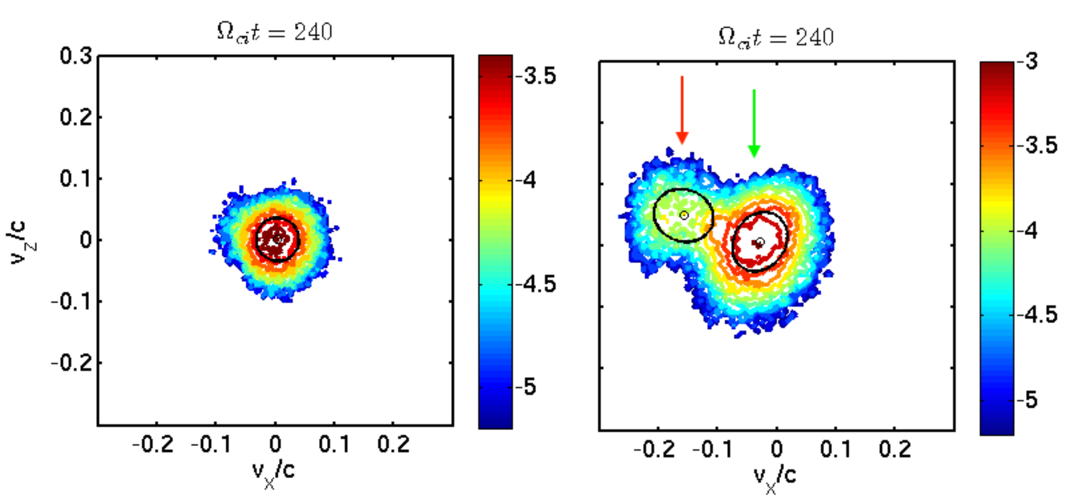
B_{T1} is reduced, but not switched off: this is NOT a SO-SS



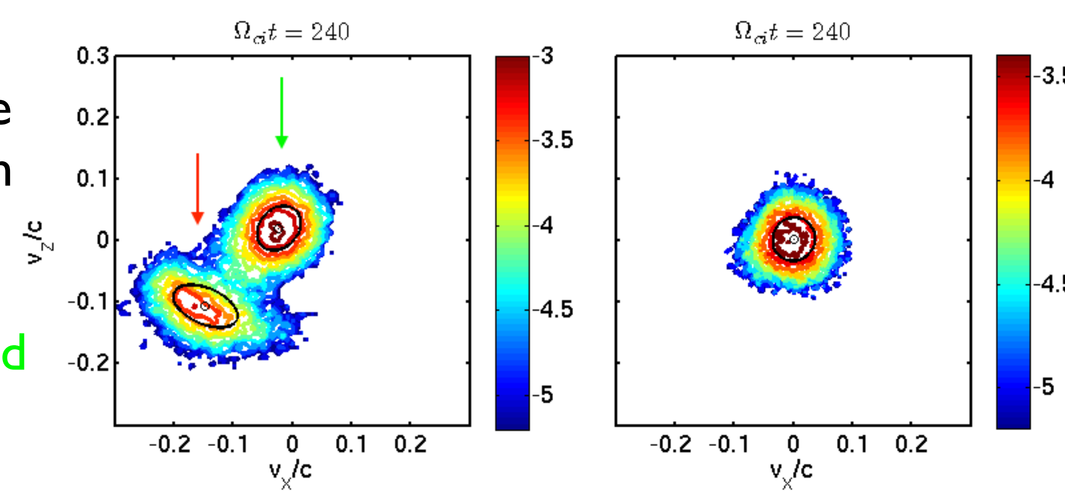




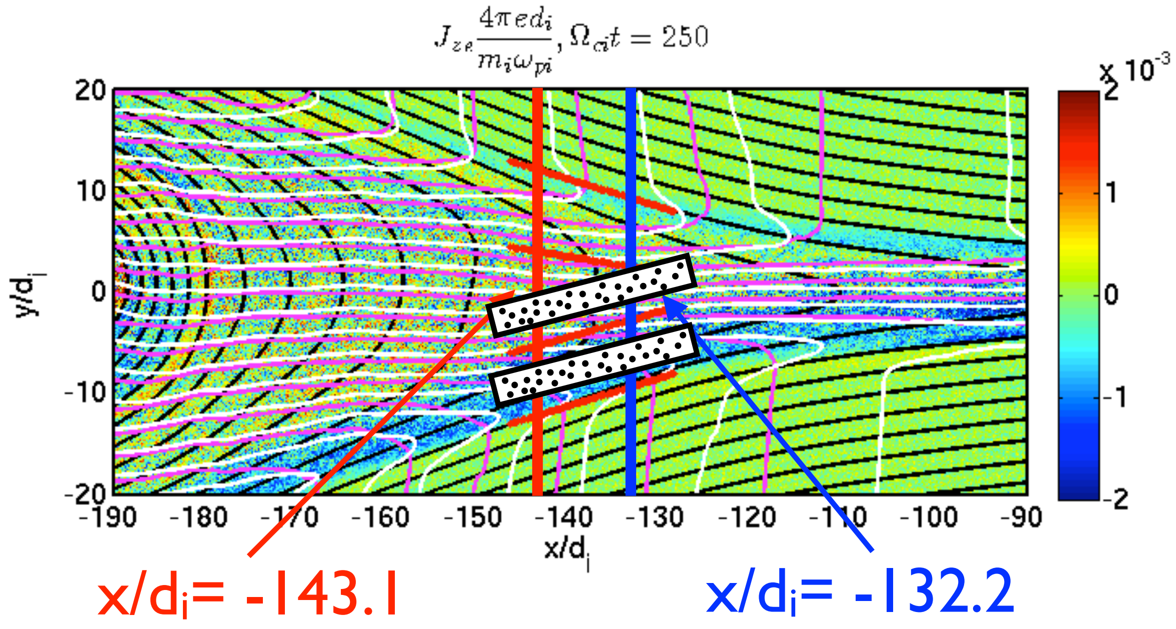
A measure of the (asymmetrical) ion heating while crossing the separatrices



just downstream the separatrices, two ion populations: separatrix current and ions just captured



Identification of the internal transitions as Rotational Discontinuities (-*like*)



The internal transitions are identified as Rotational Discontinuities (RDs) through the *generalized* Walén [Retinò05] test, since ions are not magnetised upstream and the plasma carries large currents [Scudder99, Le14]

Steps:

1. calculation of the fluid velocity U in the deHoffman-Teller frame [Khrabrov89]

U= v-V$_{\mathrm{HT}}$

$$V_{\mathrm{HT}} = \mathrm{K}_0^{-1}\left\langle \boldsymbol{E}^{(m)} \times \boldsymbol{B}^{(m)} \right\rangle$$

$$K_{\mu\nu}^{(m)} = B^{(m)2}\left(\delta_{\mu\nu} - \frac{B_\mu^{(m)} B_\nu^{(m)}}{B^{(m)2}}\right) \equiv B^{(m)2} P_{\mu\nu}^{(m)}$$

m: 'observations' → 100 couple of points randomly generated up- (U) and down- (D) stream at distance $0.5<d/d_i<2$

2. calculation of $\Delta\mathbf{U}_{T,obs}$ vs $\Delta\mathbf{U}_{T,th}$ [Retinò05] keeping the plasma anisotropy into account (α factor [Paschmann98])

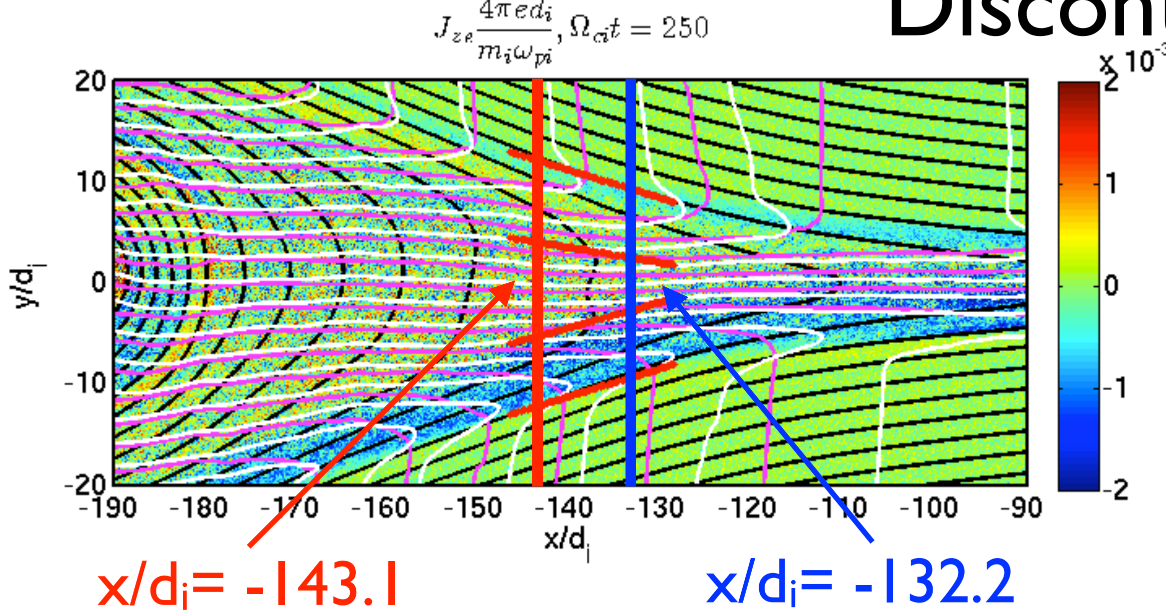
$$\Delta\mathbf{U}_{T,obs} = \mathbf{U}_{T,D} - \mathbf{U}_{T,U}$$

$$\Delta\mathbf{U}_{T,th} = \pm\left[(1-\alpha_U)4\pi\rho\right]^{-1/2} \cdot \left[\mathbf{B}_{T,D}(1-\alpha_D) - \mathbf{B}_{T,U}(1-\alpha_U)\right]$$

$$\alpha \equiv \frac{(P_\parallel - P_\perp)}{(B^2/4\pi)}$$

3. evaluation of results through R= $|\Delta\mathbf{U}_{T,obs}|/|\Delta\mathbf{U}_{T,th}|$, angle

Identification of the internal transitions as Rotational Discontinuities (*-like*)



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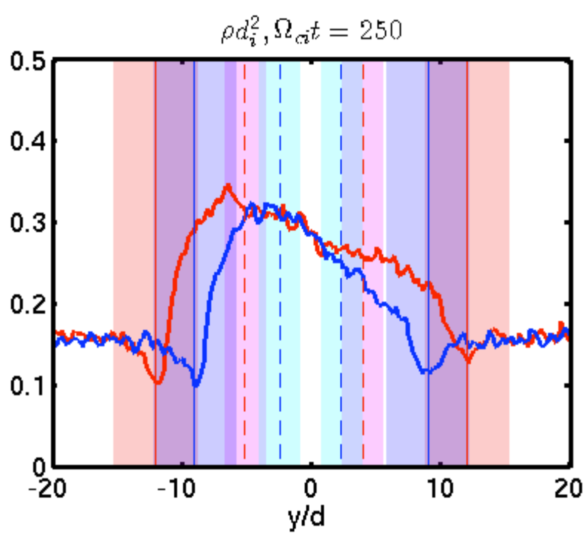
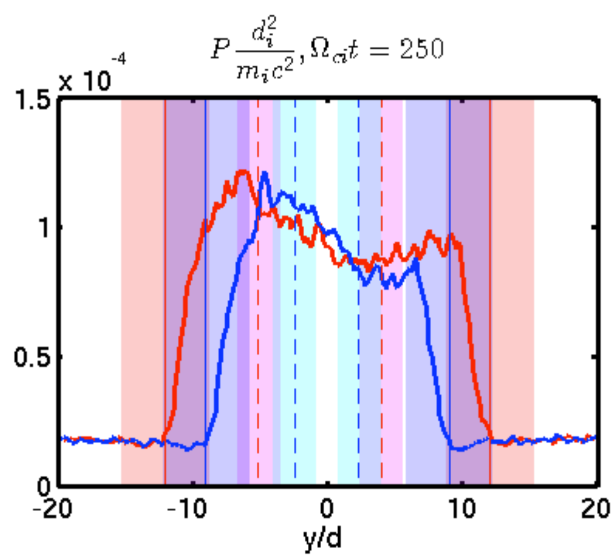
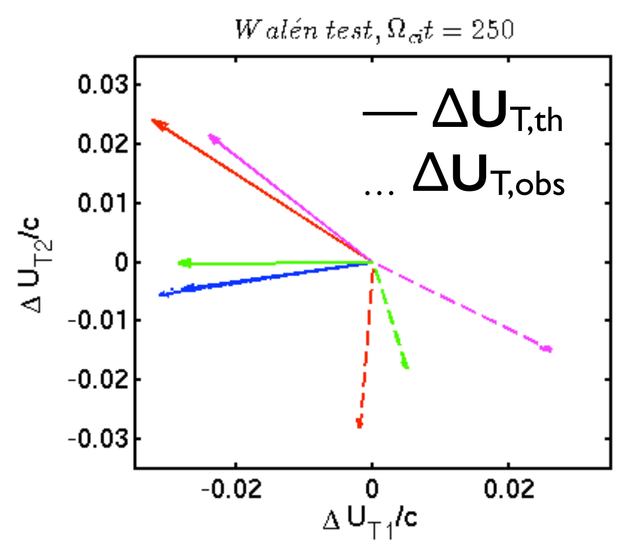
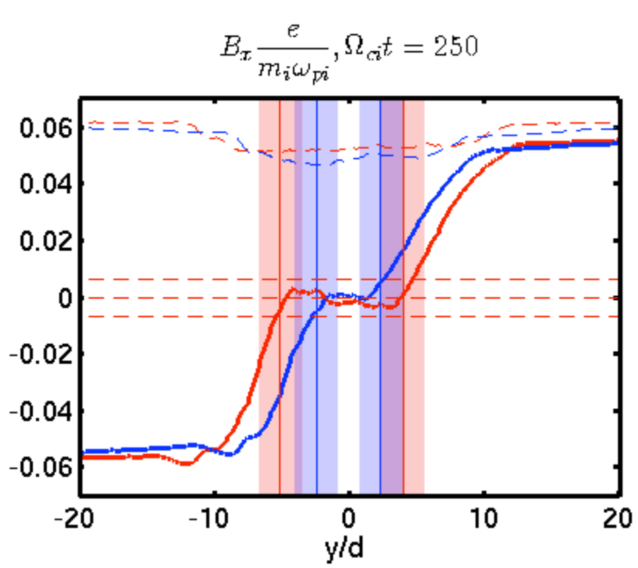
RDs do not compress or heat the plasma: δρ and δP minimum with respect to SS values (but keep into account kinetic processes, e.g. formation of density cavities)





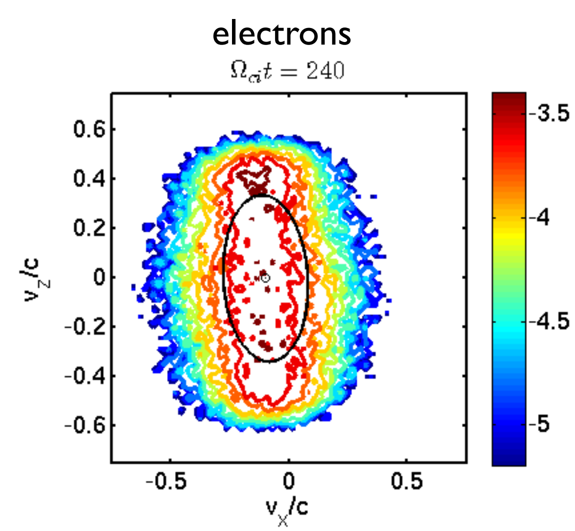


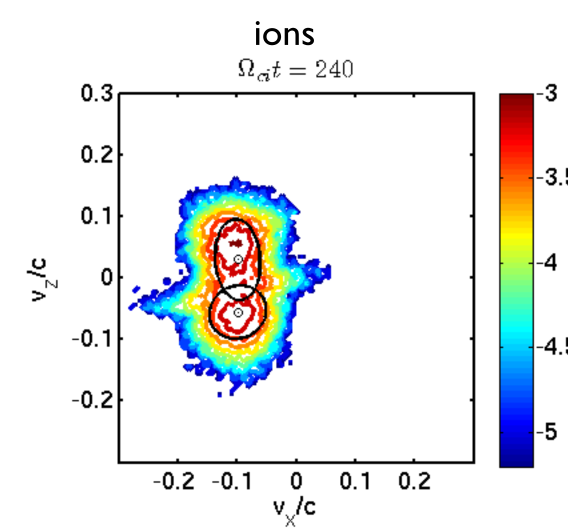
transitions at x/d_i= -132.2 give excellent results at the *generalized* Walén (R=0.93, 1.12, θ= 168, 0.7), less good results at x/d_i= -143.1



The internal Rotational Discontinuities switch-off the in-plane tangential component of the magnetic field ($B_{T1} \sim B_x$)

What is the phase space for the particles species within the switch-off region?





Kinetic aspects of the SS/RD structures

1. measure of *ion* slippage [Goldman15]

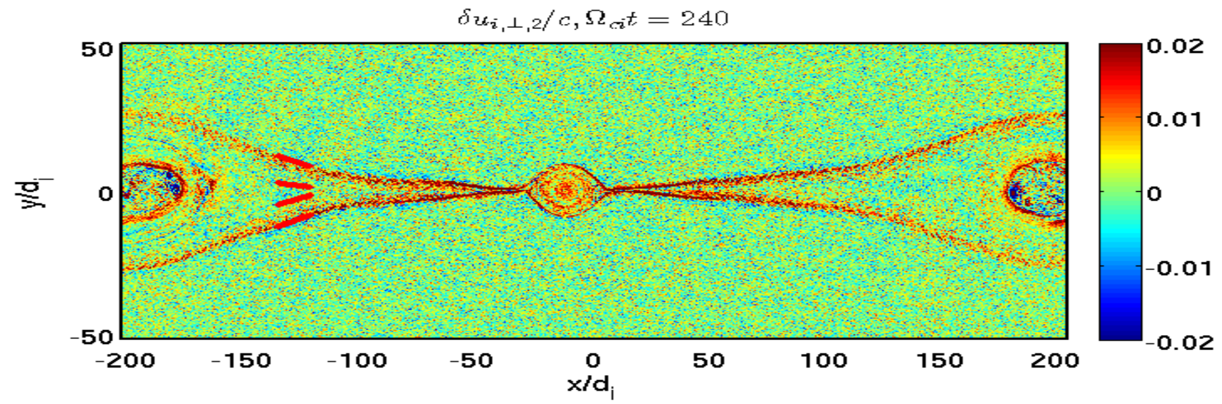
$$\delta u_{s,\perp,1} = v_{s,\perp,1} - E_{\perp,2}/|\mathbf{B}|$$

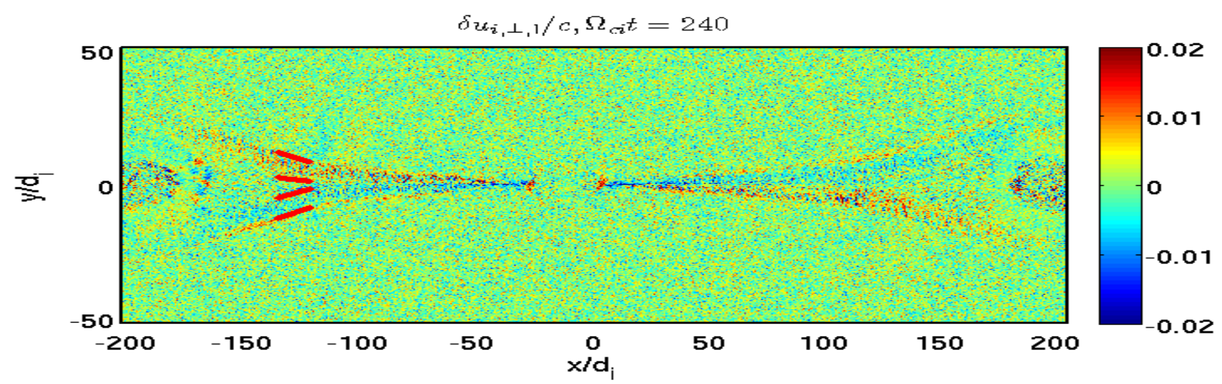
$$\delta u_{s,\perp,2} = v_{s,\perp,2} + E_{\perp,1}/|\mathbf{B}|$$

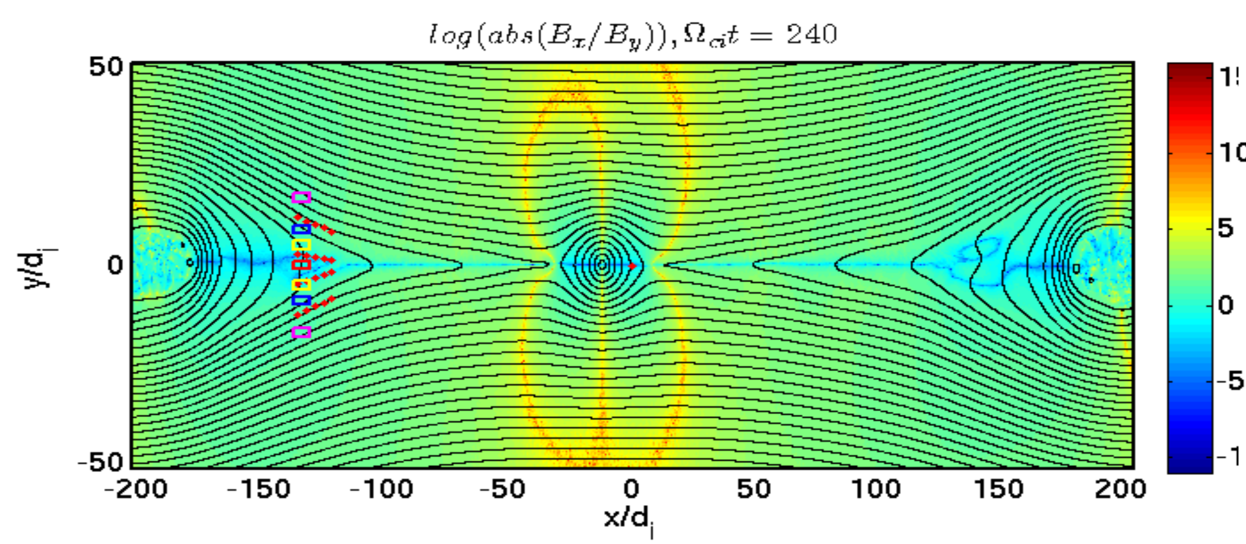
$$\mathbf{e}_{\perp,1} \rightarrow \mathbf{B} \times \mathbf{e}_z$$

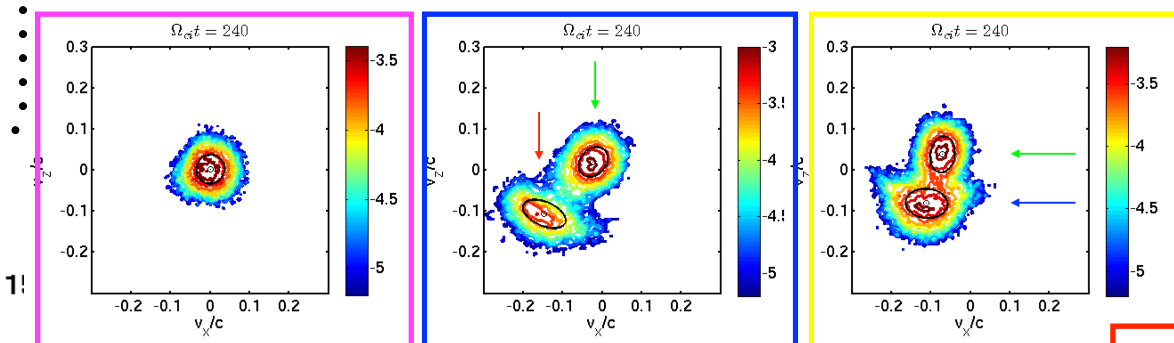
$$\mathbf{e}_{\perp,2} \rightarrow \mathbf{B} \times \mathbf{e}_{\perp,1}$$

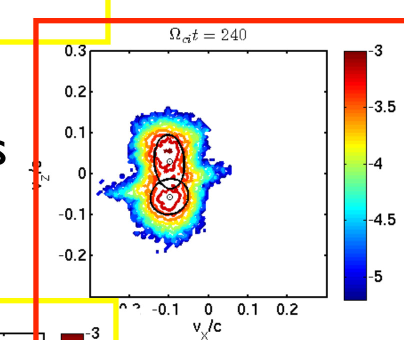
Areas of interest for slippage: separatrices and dipolarization fronts and their upstream (expected); upstream the rotational discontinuities



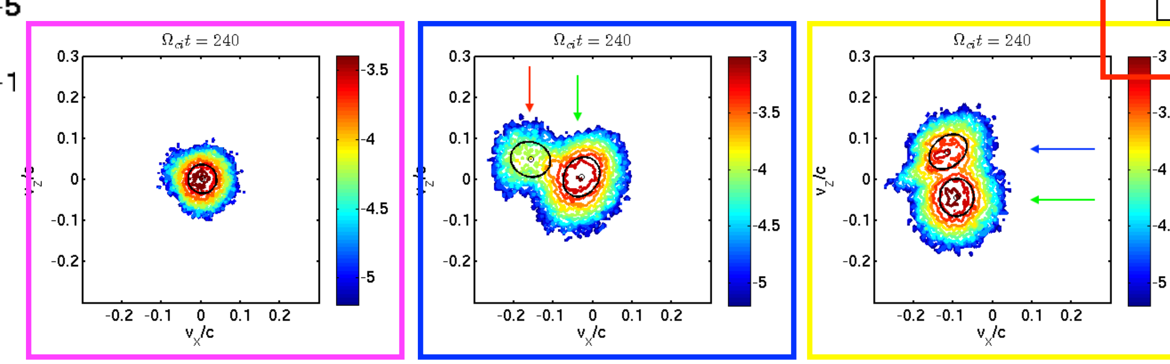








2. kinetic particle distribution signatures (see talks yesterday)



ion population: separatrix current, ions captured into the exhaust recently or closer to the X point

Conclusions and future work

- we examined the long term evolution of large domain 2D3V PIC simulations of collisionless magnetic reconnection seeded by a GEM-like perturbation
- we observed t

Thank for you your attention

ith the formation of

- in the exhausts, compound Petschek-like Slow Shock/ Rotational Discontinuity structures switch off the in plane component of the tangential magnetic field

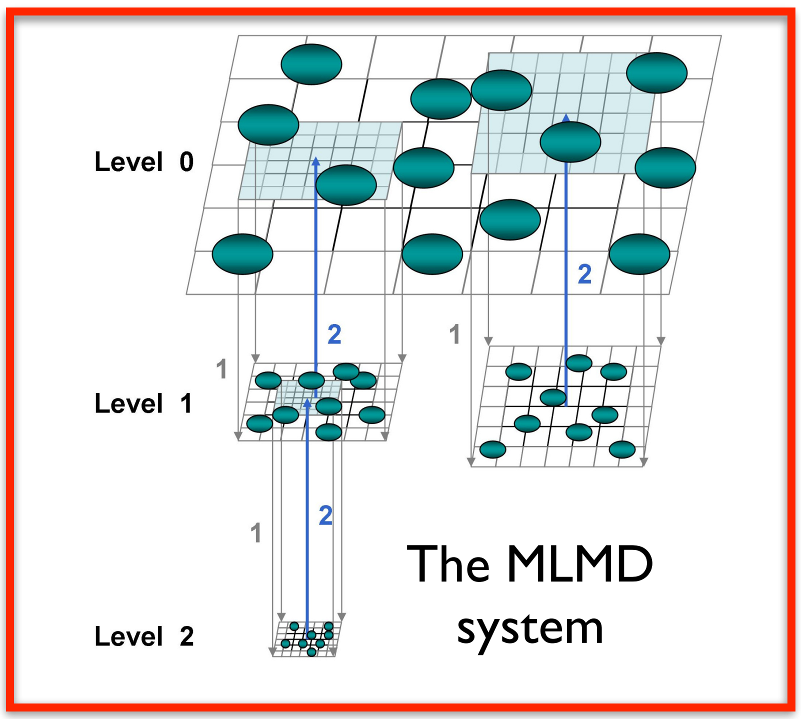
Check my poster on the Multi-Level Multi-Domain method, a semi-implicit adaptive method for PIC simulations (tested on reconnection & turbulence)

Reference: Innocenti et al, *Evidence of magnetic field switch-off in collisionless magnetic reconnection*, ApJL, accepted (uploaded on ResearchGate)

The Multi-Level Multi-Domain method: a fully kinetic semi-implicit adaptive method for PIC simulations

Multi-Level Multi-Domain simulations of Electron Diffusion Regions in magnetic reconnection are as much as 70 times cheaper than their "traditional" PIC counterparts

The entire domain is simulated with ion scale resolutions; higher (electron scale) resolution is used in selected, smaller regions, e.g. in the Electron Diffusion Region

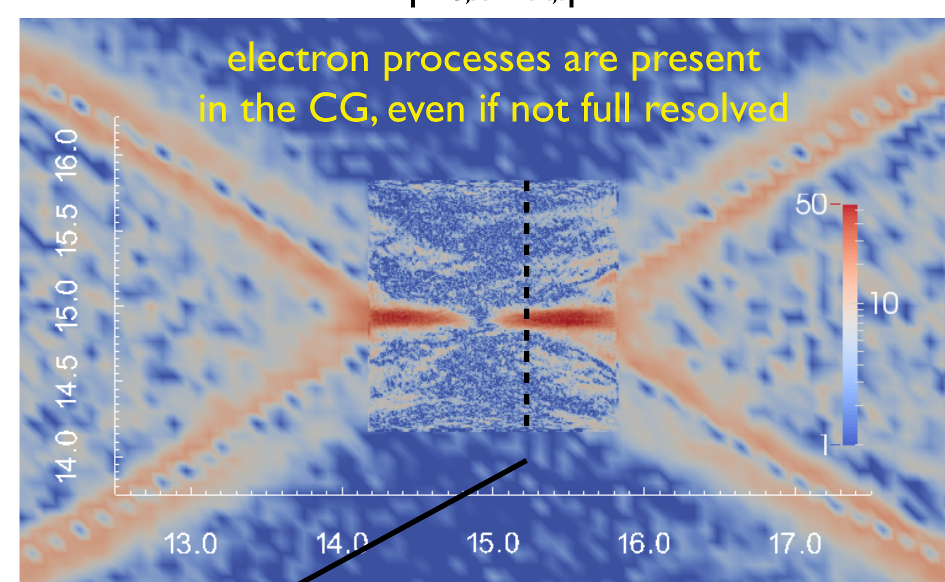


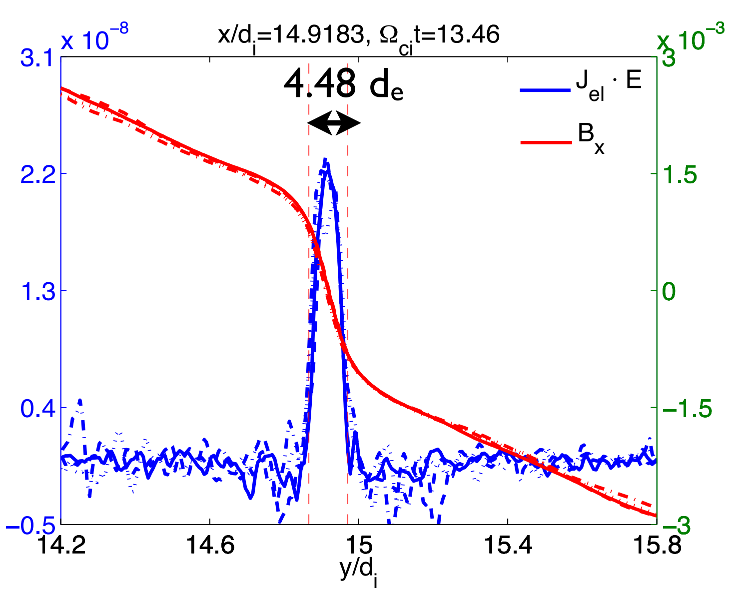
An exercise: measurement of the velocity of the electron jets ejected at the X point, $V_{e,x}/V_{A,i}$, with $V_{A,i}$ the ion Alfven speed

$L_x/d_i = L_y/d_i = 20$
$m_r = 1836$
RF=12
TR= 1 → 6
$dx_{CG} = 0.078\ d_i$
$dx_{RF} = 0.28\ d_e$
$dt_{CG} = 0.05 \rightarrow 0.3\omega_{pi}^{-1}$

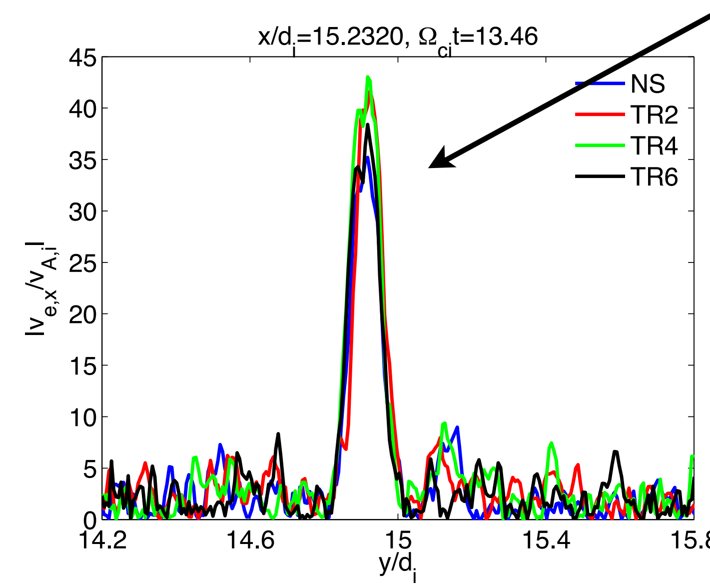
very cheap realistic mass ratio simulations!!!

$|V_{e,x}/V_{A,i}|$





calculation of the ion Alfven speed: identification of the Electron Diffusion Region with the J.E method



electron jet velocity, normalized to the ion Alfven speed

Innocenti et al., 2013
Bect et al, 2014
Innocenti et al., 2015