Magnetic Reconnection in the Solar-Terrestrial program

Roch SMETS (LPP),
Nicolas Aunai (LPP),
and a lot more...

AstroSim - Lyon, October 2018

Frozen-in theorem

Let's consider $\mathbf{K}$ along the magnetic field $\mathbf{B}$: $\mathbf{K} \times \mathbf{B} = 0$

For an ideal Ohm's law $\mathbf{E} = -\mathbf{V}_i \times \mathbf{B}$, one can show $d_t(\mathbf{K} \times \mathbf{B}) = 0$

$\rightarrow$ The magnetic field is frozen in the plasma : they are co-moving together & keep coupled

A particle cannot jump from a magnetic field line to another : no reconnection

deHoffmann-Teller frame

Non-relativistic Lorentz transform : $\mathbf{E}' = \mathbf{E} + \mathbf{V}_{R'/R} \times \mathbf{B}$

One can define $V_{HT} = (\mathbf{E} \times \mathbf{B})/B^2$: In this frame, the (perpendicular) electric field is null, so particle keep gyrate around a same field line through time.

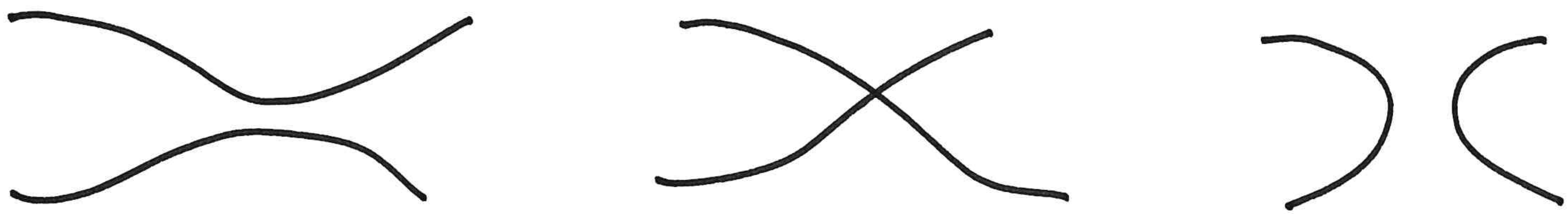
In the HT frame, a magnetic field line is non-moving

For ideal MHD : $V_{HT} = V_{\perp}$ so plasma & magnetic field are frozen one into the other

To allow $d_t(\mathbf{K} \times \mathbf{B}) \neq 0$, one needs $\mathbf{\nabla} \times \mathbf{E}_{\|} \neq 0$

Reconnexion in ideal MHD ?

In ideal MHD, magnetic connecions are conserved, except eventually where $\mathbf{B} = 0$



• Either the electric field is null, so lines of forces do not cross separatrices

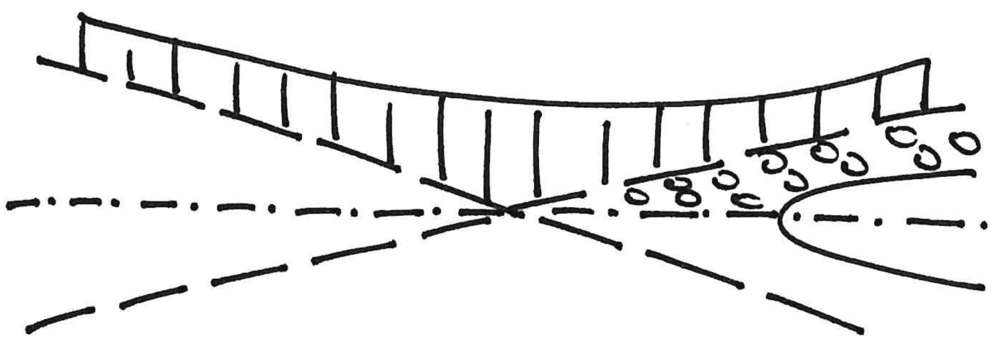
• Or the plasma velocity must be discontinuous, for $\mathbf{E} \neq 0$, which is forbidden by its inertia

Reconnection rate : definition

Amount of magnetic flux across a closed surface : $\oint \mathbf{B}\, d\mathbf{s}$

The reconnection rate is the time derivative of this quantity

$$\frac{\partial}{\partial t} \oint \mathbf{B}\, d\mathbf{s}$$



Using Faraday eq. & Stokes theorem, the reconnection rate is $\mathbf{E} = -\partial_t A$

Ohm's law (electron momentum equation)

$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} + \frac{1}{qn}\mathbf{J} \times \mathbf{B} + \frac{m}{q} d_t \mathbf{V}_i - \frac{m}{nq^2} d_t \mathbf{J} - \frac{1}{nq} \boldsymbol{\nabla} . \mathbf{P}_e + \eta \mathbf{J} - \eta^{\star} \Delta \mathbf{J}$$

(1) : ideal term iscales like V_i/V_A

(2) : Hall effect scales like kl_p

(3) : electron inertial effect scales like ω/Ω_e

(4) : electron inertial effect iscales like $kl_p\omega/\Omega_e$

(5) : electron compressibility scales like $k\rho_{Le}v_{the}/V_A$

(6) : resistivity (dissipative term)

(7) : hyper-viscositA (dissipative... depends on scale)

What if 3D ?

Asks Sophie Masson...

Very large scales phenomenon, needing a MHD description

$\rightarrow$ Micro-Physics can hardly be considered because of scales discrepencies

$\rightarrow$ Plasms weakly collisional close to the photosphere

$\rightarrow$ Bounded problems where boundary conditions are important

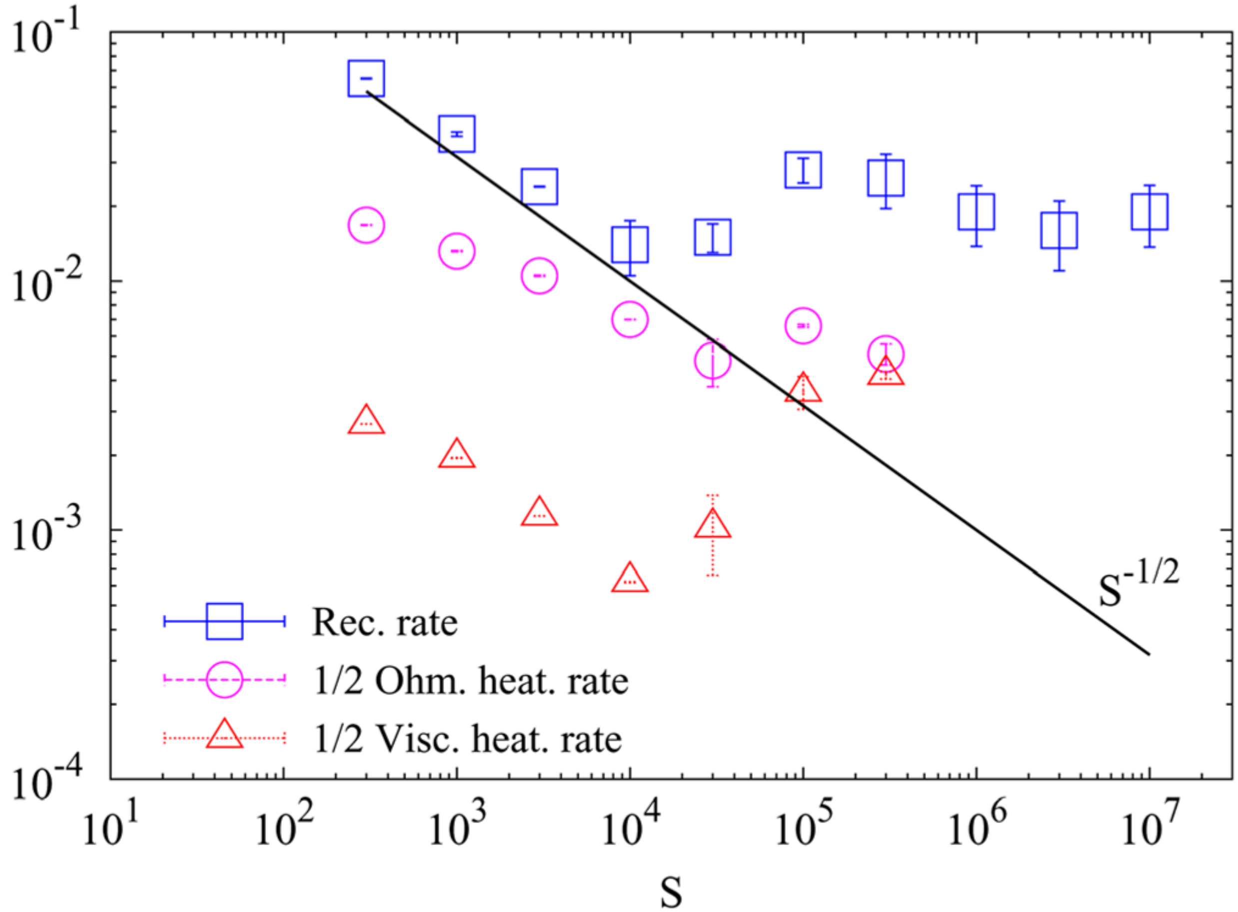
- Numerical works are oftenly using resistive MHD

Fast reconnection killed by small Lundqvist nbr ?

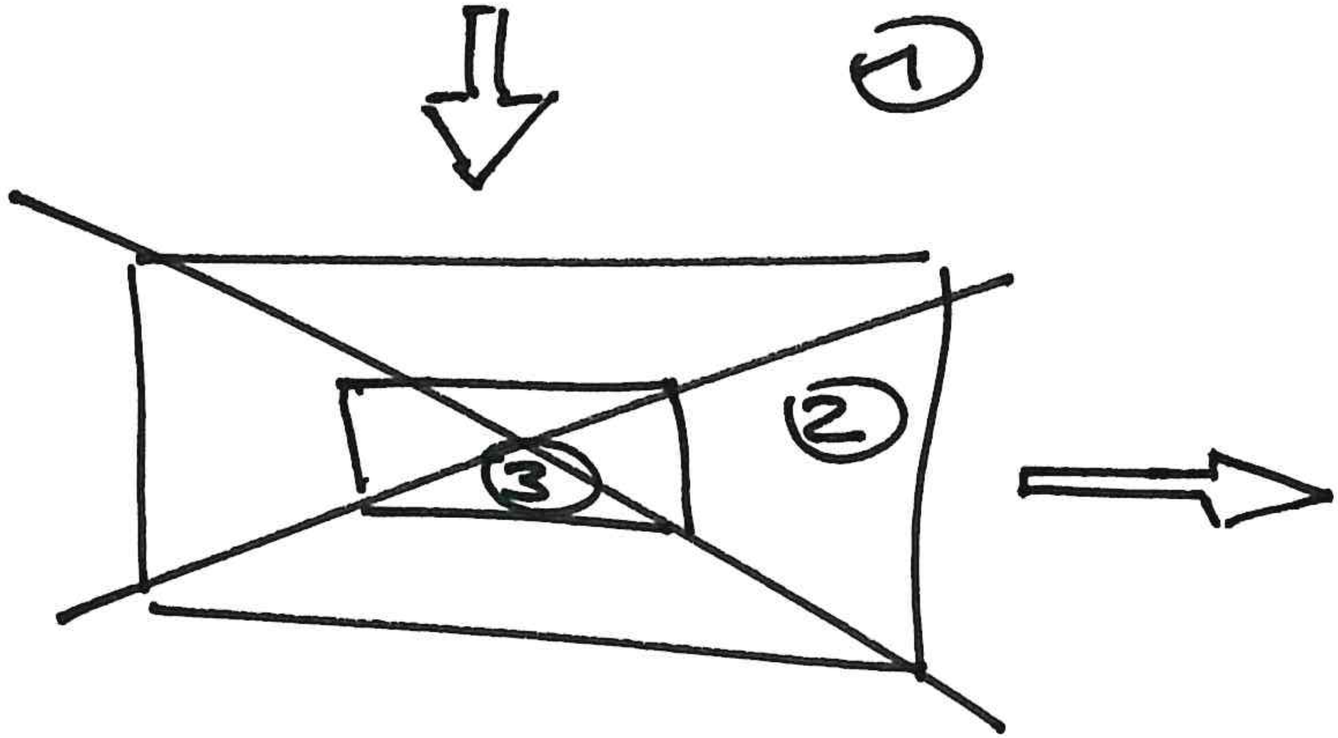
In Sweet-Parker model, reconnection rate scales as $S^{-1/2}$:

$\rightarrow$ reconnection should be quenched in collisionless media...

Loureiro et al, 2012

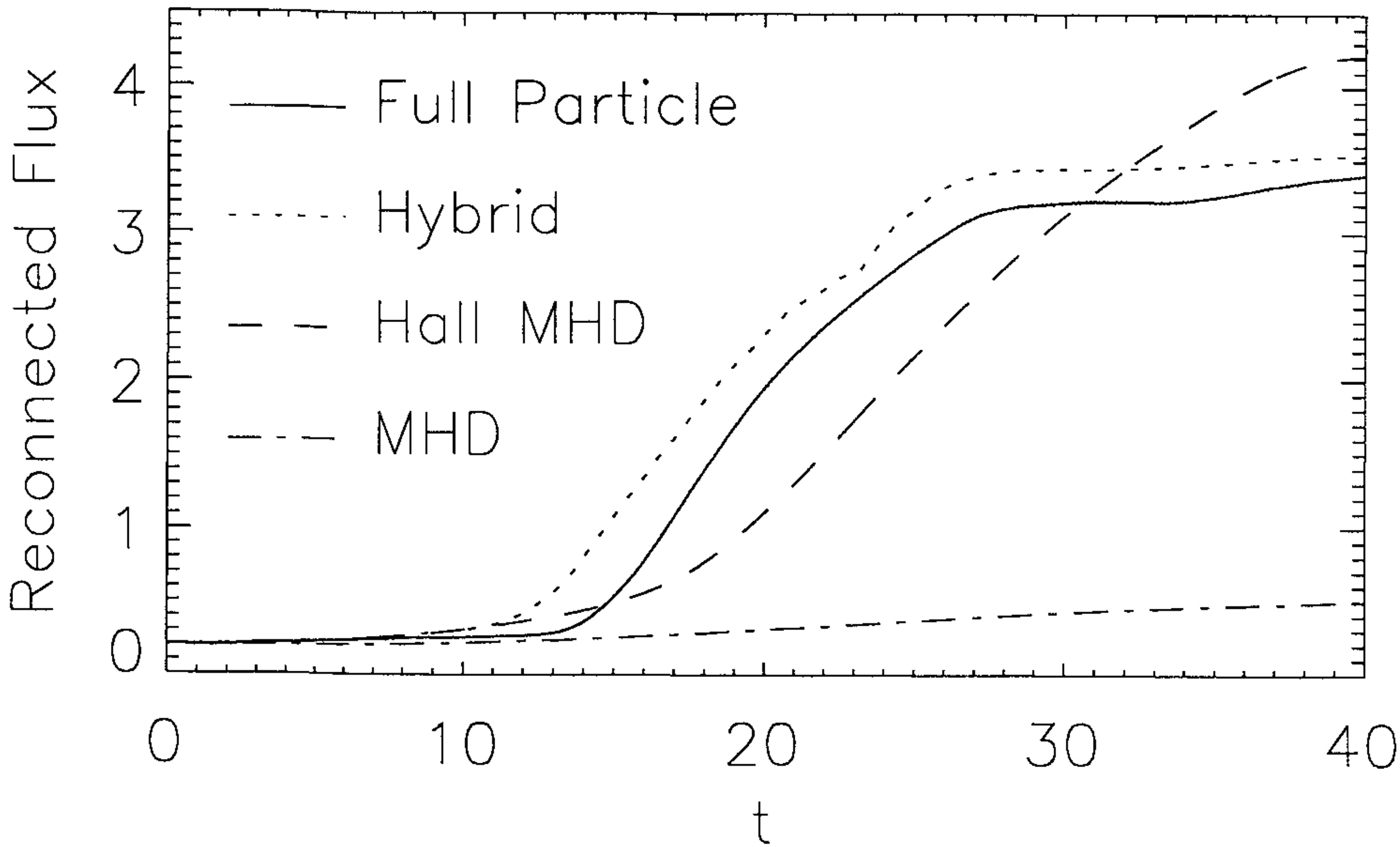


2D reconnection : out-of-plane electric field



1. Ideal MHD : $\mathbf{E} = -\mathbf{V}_i \times \mathbf{B}$
2. p^+ Diff. region : $\mathbf{E} = (\mathbf{J} \times \mathbf{B})/en$
3. e^- Diff. region : $\mathbf{E} = -\boldsymbol{\nabla}.\,\mathbf{P}_e/en$

Fast Reconnection : Hall effect [GEM Challenge, 2001]



→ Hall effect governs the reconnection rate

Numerical simulation of plasmas

Self-consistant electromagnetic fields :

$\mathbf{B}$ from $\partial_t \mathbf{B} = -\boldsymbol{\nabla} \times \mathbf{E}$ (always)

- in MHD : $\mathbf{E} = -\mathbf{V}_i \times \mathbf{B}$
- in two-fluid & hybrid : complete Ohm's law ($\mu_0 \mathbf{J} = \boldsymbol{\nabla} \times \mathbf{B}$)
- in full-PIC : $c^{-2} \partial_t \mathbf{E} = \boldsymbol{\nabla} \times \mathbf{B} - \mu_0 \mathbf{J}$ (+ Poisson correction)

$\rightarrow$ So need density and current density from plasma equations (or ion flow in MHD)

3 possible approaches

• MHD and 2-fluid : set of fluid equations

+ closure (need an hypothesis) and eq. on $\mathbf{E}$

• Hybrid : p^+ as macroparticles $\rightarrow$ kinetic effects,

e^- as a massless fluid (closure)

• full-PIC : both p^+ & e^- are macroparticles

(strong constraints on mass ratio & c/V_A)

$\rightarrow$ Vlasov codes are unaffordable in 3D...

Set of equations for hybrid models

$$
\begin{aligned}
d_t \mathbf{x}_i &= \mathbf{v}_i \\
d_t \mathbf{v}_i &= \mathbf{E} + \mathbf{v}_i \times \mathbf{B} - \eta \mathbf{J} \\
\partial_t \mathbf{B} &= -\boldsymbol{\nabla} \times \mathbf{E} \\
\mathbf{J} &= \boldsymbol{\nabla} \times \mathbf{B} \\
\mathbf{E} &= -\mathbf{V}_p \times \mathbf{B} + N^{-1}(\mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla}.\, \mathbf{P}_e) + \eta \mathbf{J} \\
P_e &= N T_e
\end{aligned}
$$

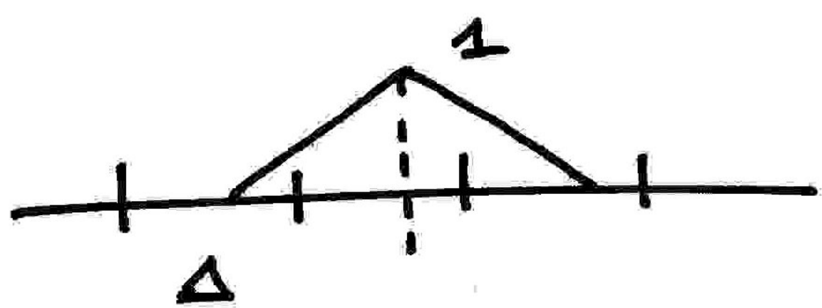
$\rightarrow$ Electric field has electrostatic component

$\rightarrow$ no need of Poisson correction (and Laplacian to invert)

- How to define n and $\mathbf{V}_p$ from collections of $\mathbf{x}_i$ & $\mathbf{v}_i$

How to manage macro-particles ?

- A macro-particle is representative of a set of particle...
- In a statistically acceptable way (nrb of part per cell)
- A macro-particle has finite size, more or less “diffusive”
- The size of the macro-particle depends on the mesh size
- macro-particles flow one through the other



→ Fluid moments depend on assignment function

How to manage macro-particles ?

Shape factor :

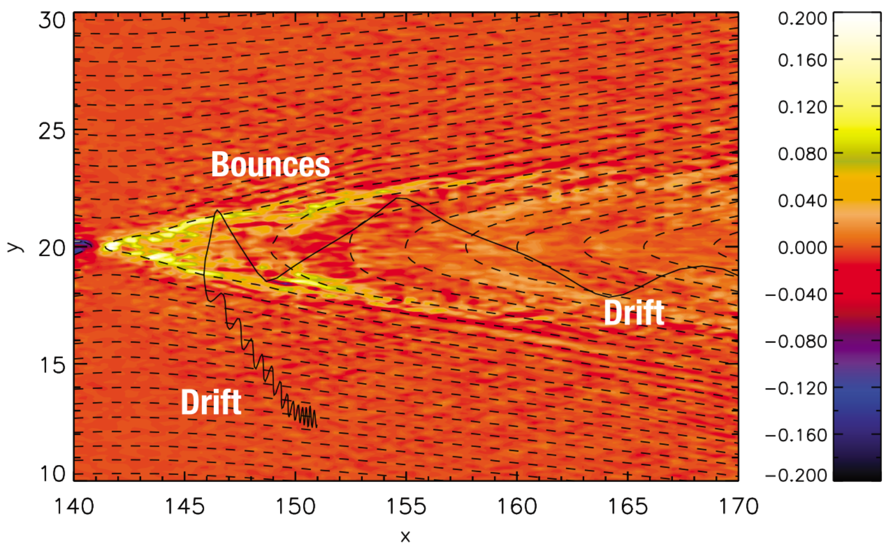
$S(x)$ are *b-splines* of order 1, 2, 3... or more ?

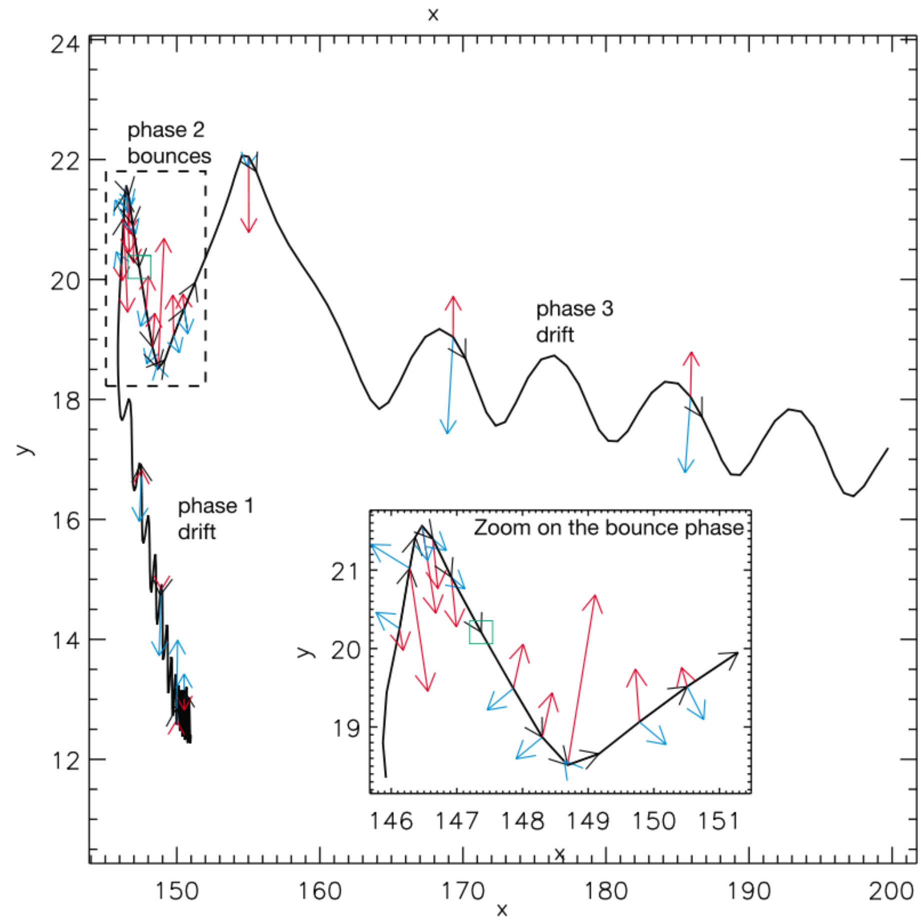
$$
\begin{aligned}
N(x) &= \sum_{i=0}^{N-1} S(\mathbf{x} - \mathbf{x}_i) \\
\mathbf{V}_p &= \sum_{i=0}^{N-1} S(\mathbf{x} - \mathbf{x}_i)\mathbf{v}_i/N
\end{aligned}
$$

$\rightarrow$ Only defined on grid points

$\rightarrow$ and convolution product for 2- and 3-dimensions

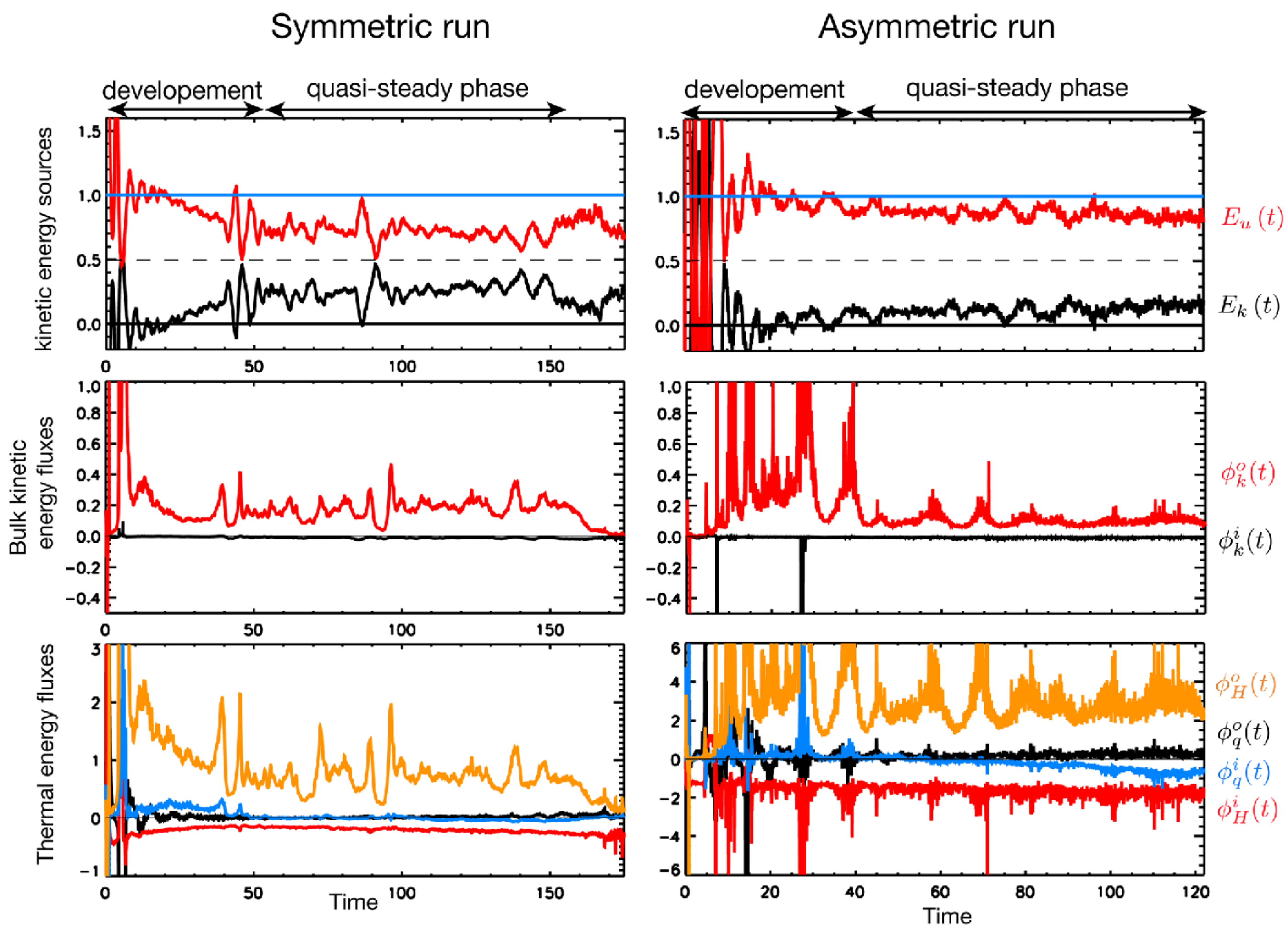
Bounce motion : Aunai et al., 2011





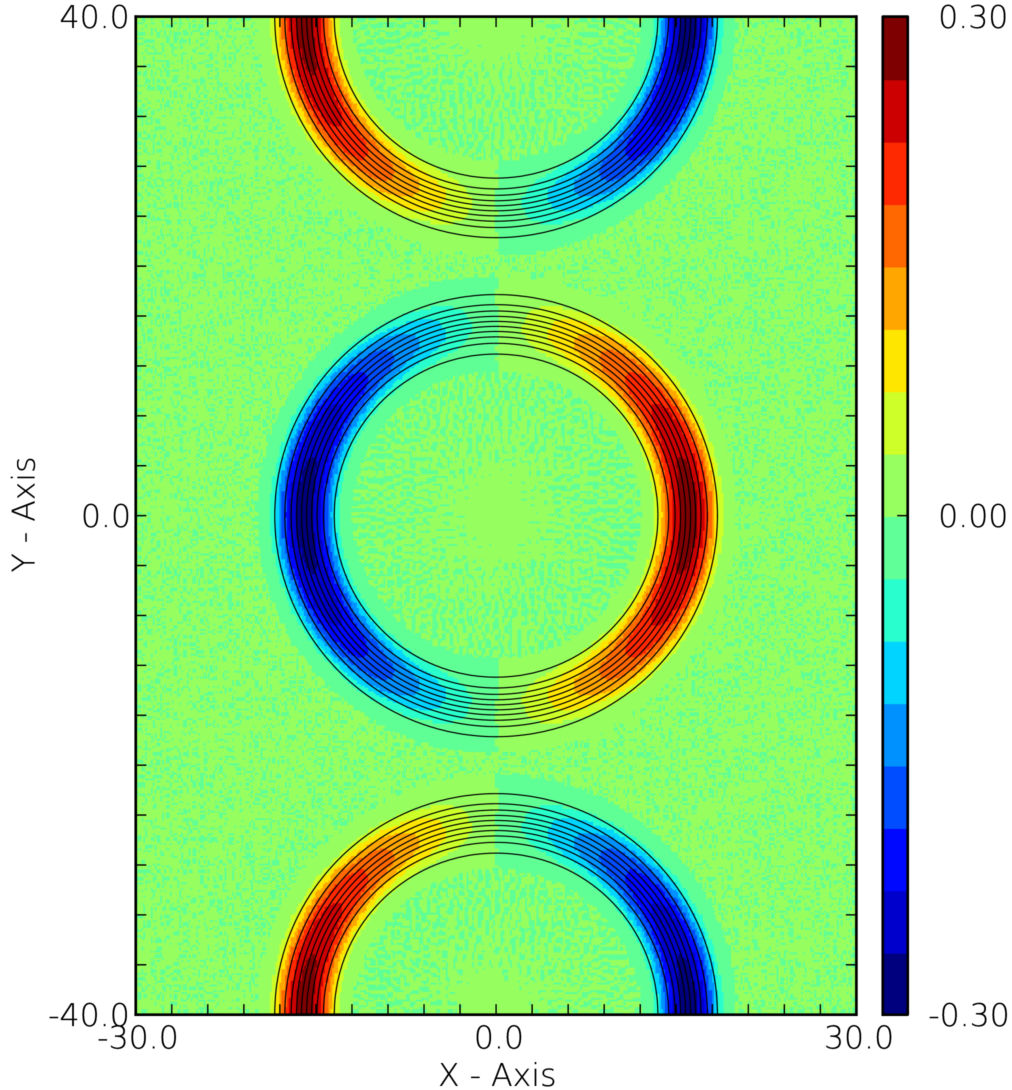
→ bounce motion of the ions is associated to the Hall electric field (electrostatic) and not to the magnetic field

Energy budget : Aunai et al., 2011

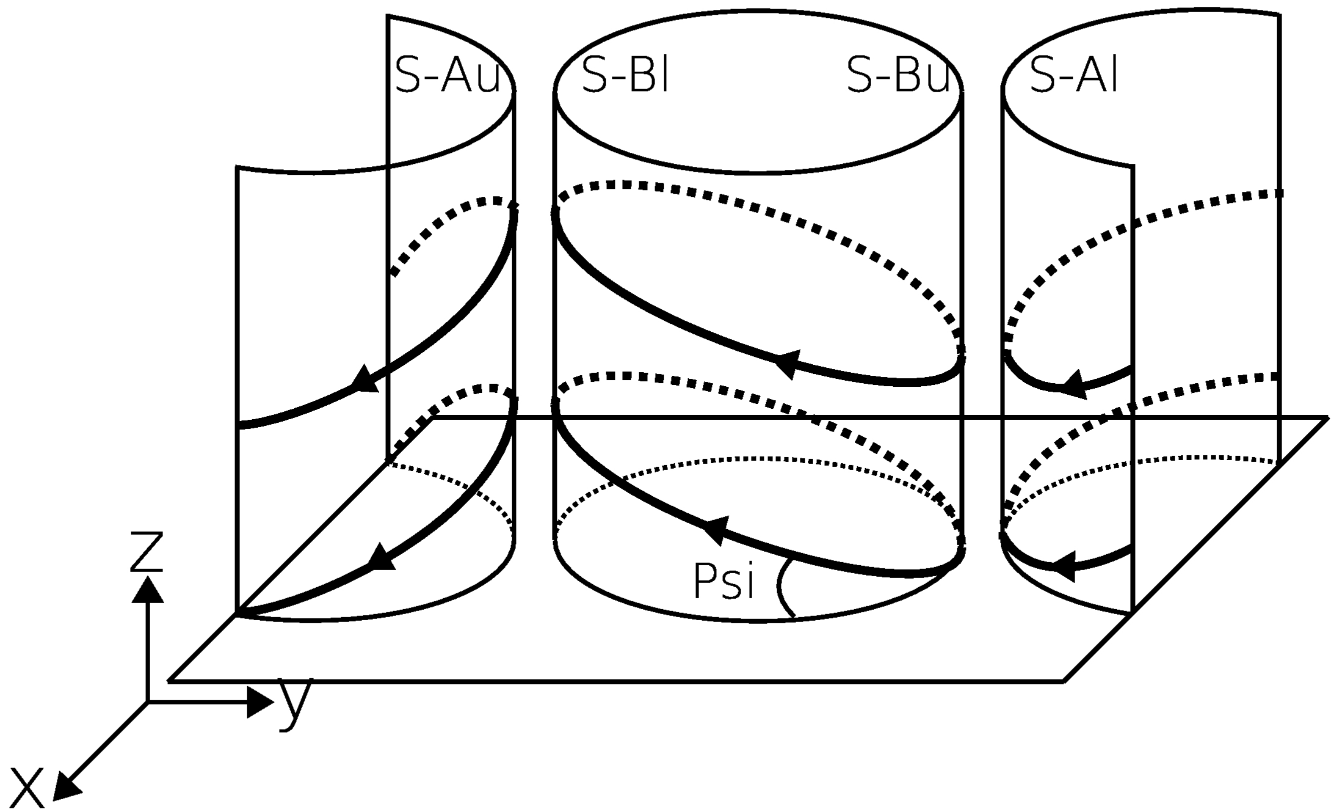


→ Thermal energy is larger than bulk energy (outflow)

Reconnexion mediated by High Power lasers : t=0



When folding targets [Smets et al., 2014]

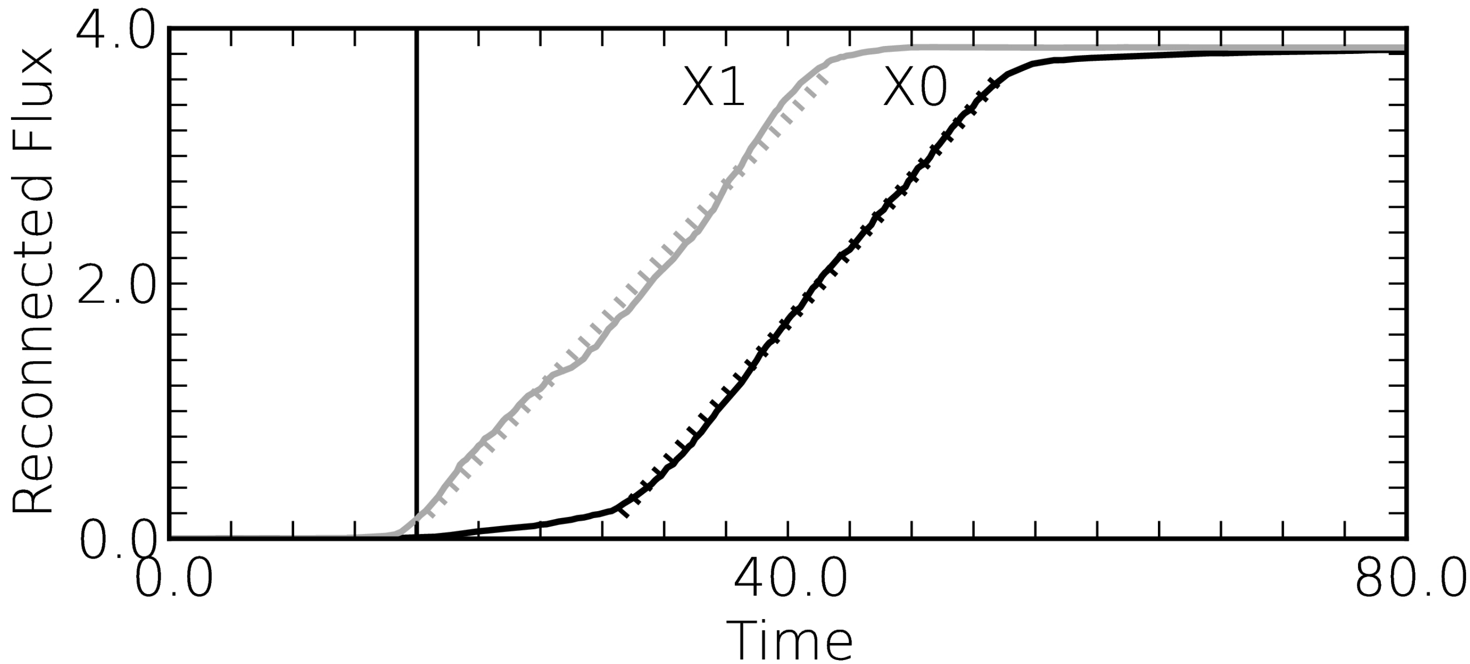


Initial out-of-plane magnetic field : Quadripolar structure

→ Reconnection rate depends on sallient/reverse angle

→ 6 shots scheduled on LMJ/PETAL : spring 2019

Reconnected flux

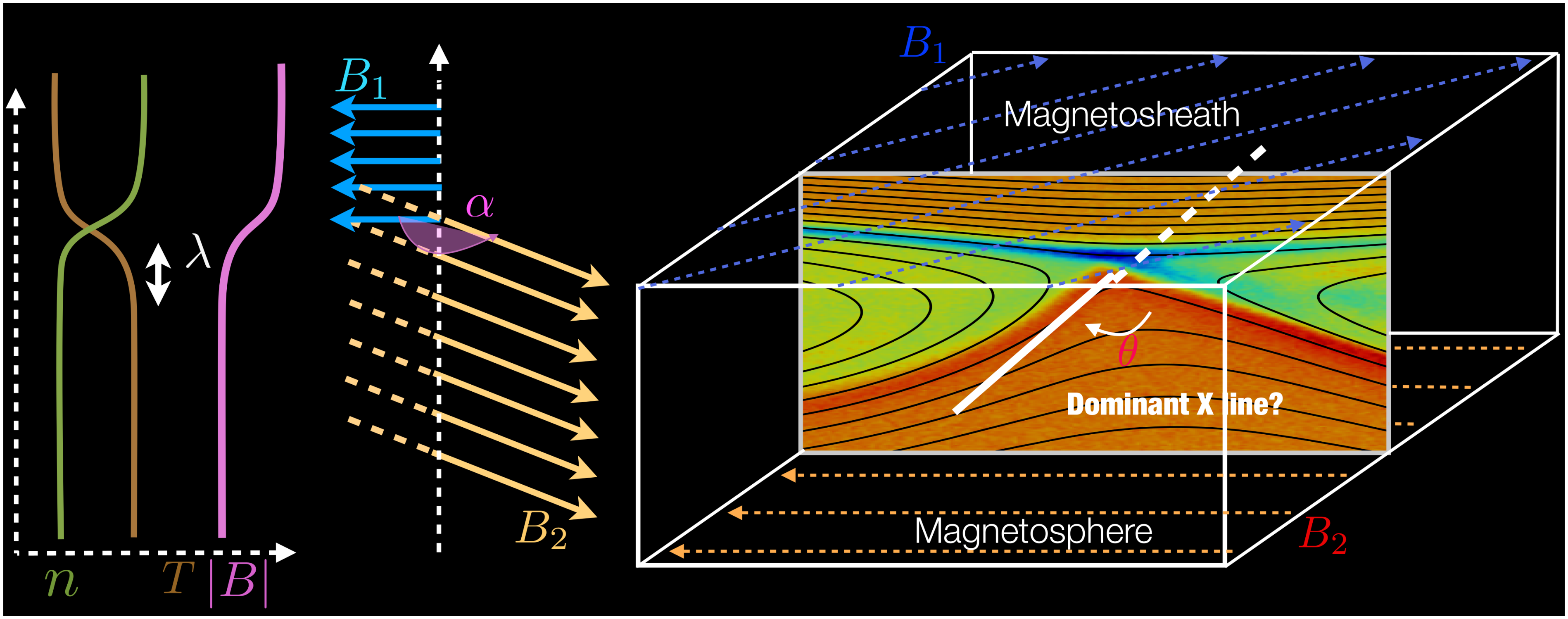


$\longrightarrow$ B_Z develops prior the reconnection onset (t=16)

$\longrightarrow$ Same reconnection rate at each loci (slope of A_Z)

$\longrightarrow$ Time lag between the 2 onsets of reconnection

Local X-line orientation : [Aunai et al., 2016]



$\rightarrow$ Reconnection rate depends on the 2D simulation plane

$\rightarrow$ It is maximum in the plane defined by bisector of upstream fields

Coming soon : PHARE

Parallel Hybride code using Adaptive-Mesh-refinement

Developped across LPP & LERMA :
Space plasmas, Lab. astrophysics, ISM...

small team (3 persons) hopefully growing

$\rightarrow$ aims at being state-of-the-art for Petascale... Exascale
1D version begining of 2019, 2D end of 2019,
and then 3D...

Which kind of AMR ?

• It could have been "cell-based" (see P. Kestner & P4est)

$\rightarrow$ Nice because refined only in the needed cells

$\rightarrow$ But we have particles to manage...

and self-forces appear for $\partial_t S(x) \neq 0$

• So it is "patch-based"

$\rightarrow$ refine in a given patch (of given geometry)

a (refinement) level is a collection of patches

eases the parallelization

What about self-forces ?

Multi-Level-Multi-Domain techniques :

Innocenti et al., 2013

- A corse level existe for the WHOLE simulation domain

- Patches exist at finer levels (with finer particles)

$\rightarrow$ the entry flux is dictated by next coarser level

so a refinement operator exist for BOTH fields & particles

$\rightarrow$ the outgoing flux is... outgoing !

- No $\partial_t S(x)$, only fine living patches

$\rightarrow$ Make sure levels are "physically coherents"

What else ?

• The electric field coming from Ohm's law,
no simple leap-frog
$\rightarrow$ Predictor-Predictor-Corrector scheme *kuntz et al., 2013*

• *Yee* grid

• Non-relativistic *Boris* pusher (80% of CPU)

$\rightarrow$ Abstract base classes as interface for various solver, grid, electron closure, *b-spline* order, dimension...

Written in C++17

FOR(mula)TRAN(slation) tuned for numerical operation...

Now, most of the code is software engeneering

C++ combines low-level optimized code &

high-level abstract code

smart pointers (memory leaks), STL for containers...

of course, data encapsulation, polymorphism, inheritance

Design pattern

“general reusable solution to a commonly occurring problem within a context in software design”

Needed to code factoring, avoid bugs, ease lecture...

Strategy, Factory...

Interpolator for 1, 2, 3D and 1, 2, 3 & 4^{th} order ?
$\rightarrow$ Bridge

Projet management & Documentation

- Redmine :

provides issues, doc, wiki, Gantt, calendar, forum, files...

- Doxygen :

generate the documentation (for devlopers) automatically from comments in the code

UML diagrams are also included

Unit, integration & validation Tests (GoogleTest)

• Unit tests : aims at testing a "unitary component", basically a method, or a class

• Integration tests : be sure that a whole chain of components is well integrated

• Validation tests :

- functional... a given function is fulfilled
- "solution"... the solution of a given problem is reached
- associated to performance & robustness

→ Test driven developement when needed

Version Control System

- RhodeCode : manage repositories "@HOME", with Git or Hg, pull request, forks, gists

- Git : allow `diff`, `reset`, `blame`, `diff`, `stash`

- Workflow : uses local branches, repositories like `upstream`, `origin`, ...

- pull request : pieces of codes are integrated after peer review

→ Agile method, extreme coding...

Continuous Integration

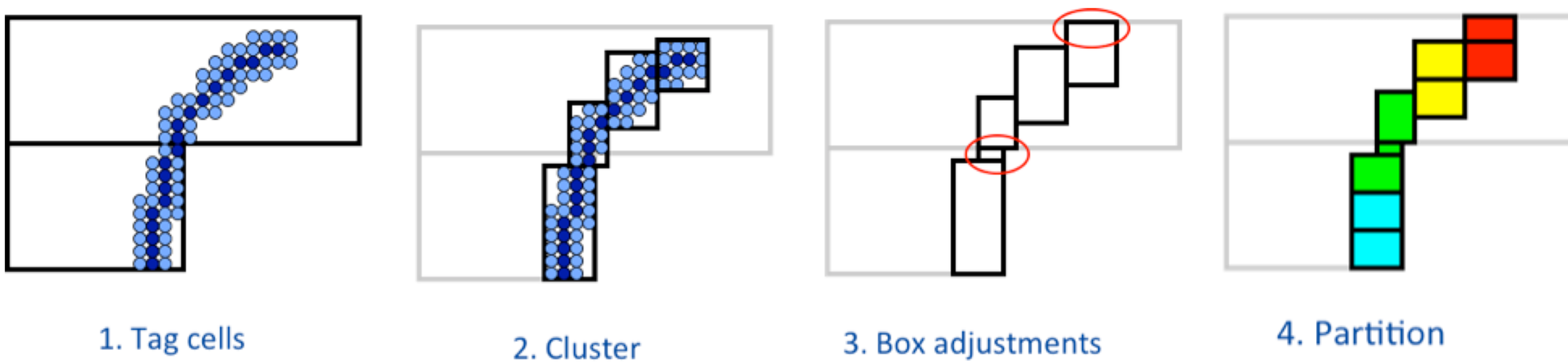
After a commit from contributor :

- `clang-analyze` & `cppcheck`
- coding style & documentation
- unit & integration tests
- compilers & libraries (portability)
- `push` on official repository

→ using a local "TeamCity"

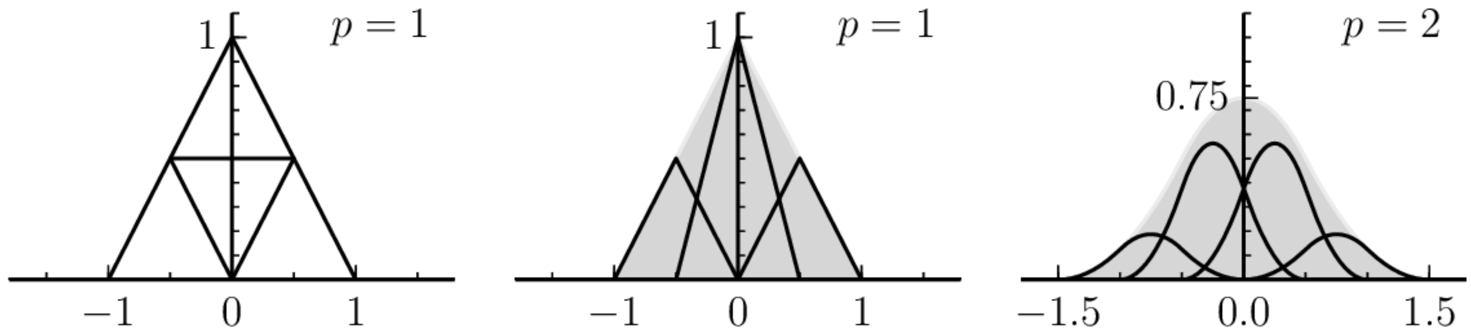
A library for AMR : SAMRAI

Developped at LLNL, manage plenty of nice features :

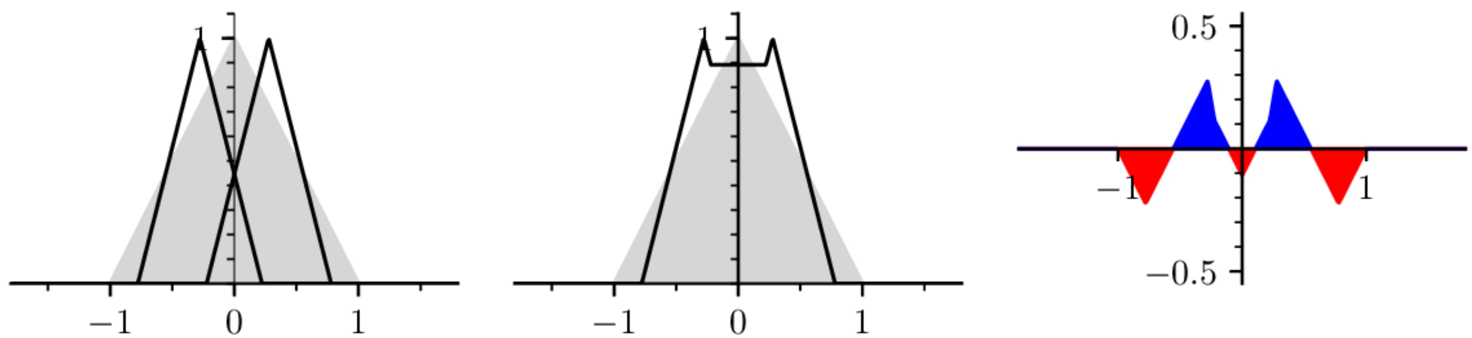


"patch based", dynamic mesh refinement, user defined data, load balancing, interface to solver libraries, visualization support,... & open source !

splitting method for particles : [Smets et al. 2018]



$\rightarrow$ exact solution... eventually expensive



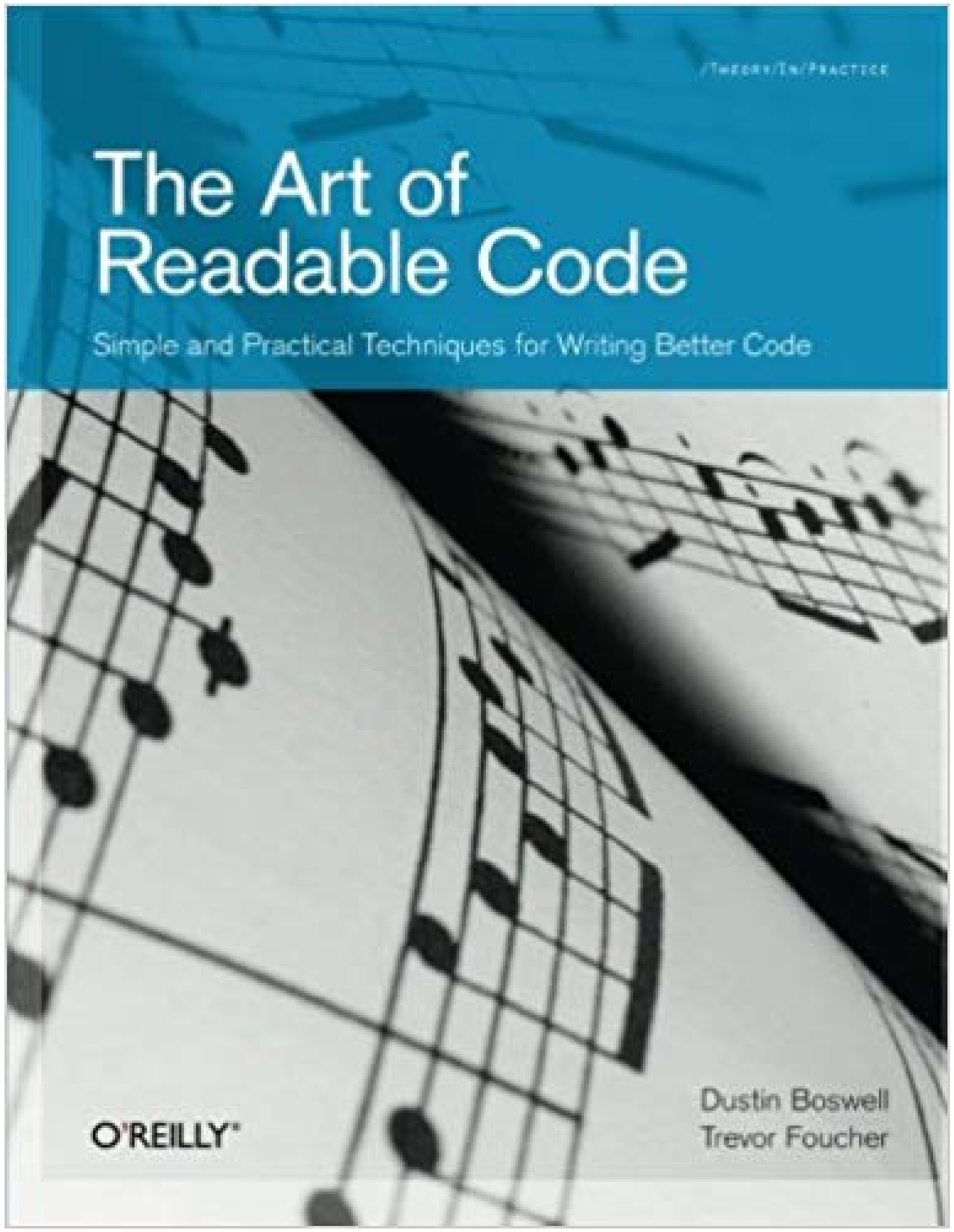
$\rightarrow$ approximate solution results from optimisation

Concluding remarks

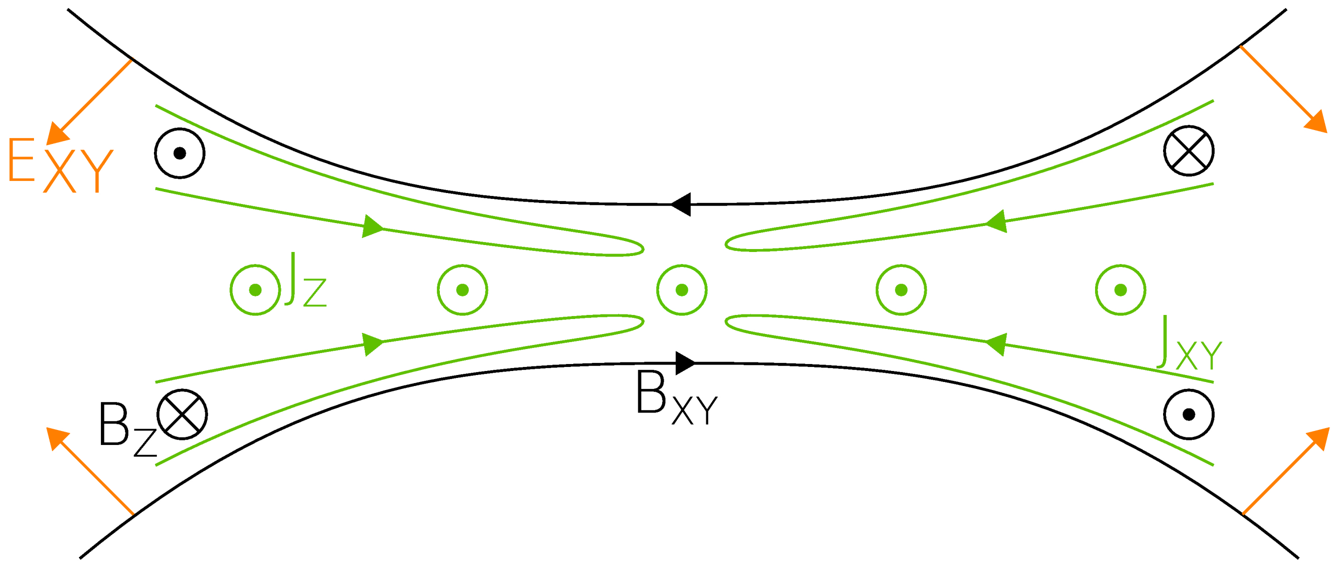
- Wee need software engineering
- We need collaborations
- We need open source codes
- We need engineer in HPC
- We need money

$\rightarrow$ But we already have computers...

For each new PhD student...



About the Hall effects



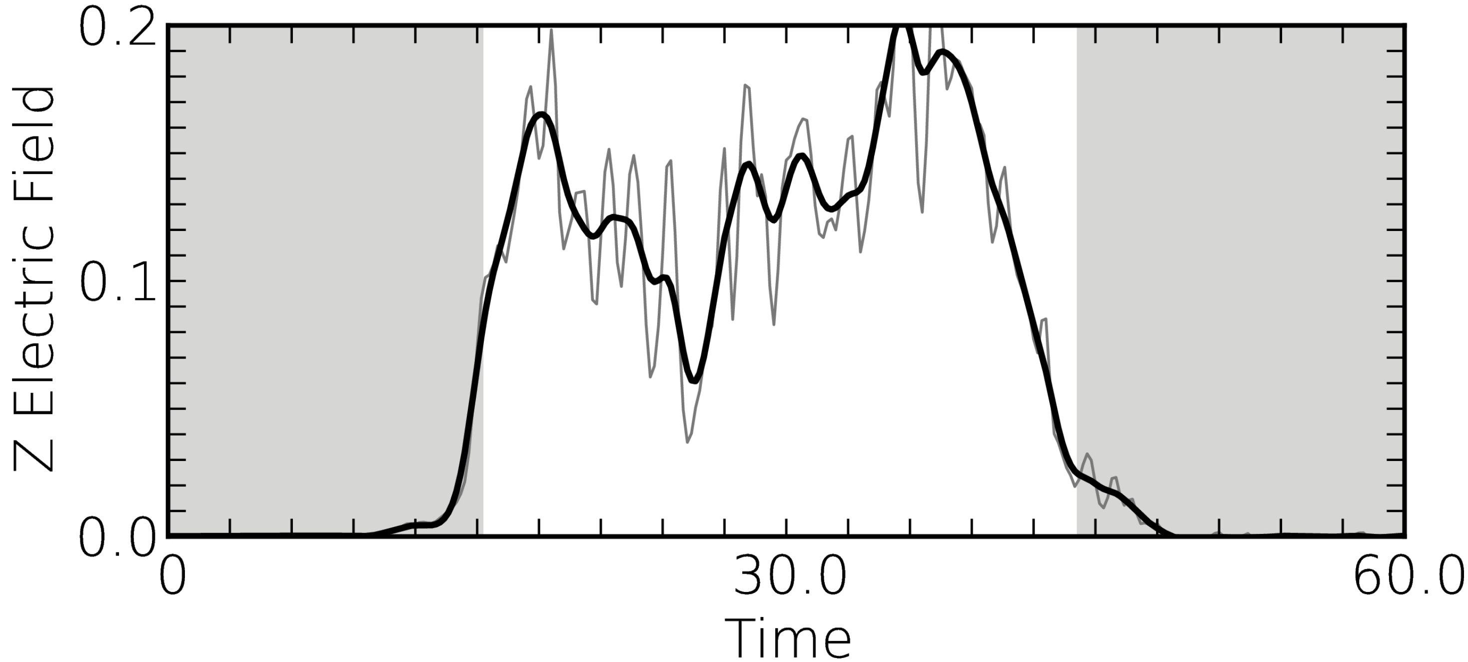
- (Hall) E_{XY} electric field associated to J_Z and B_{XY}
- J_Z grows at the tip of each loops when colliding

$\rightarrow$ quadrupolar B_Z grows because E_{XY} is no more curl-free

- J_{XY} associated to this out-of-plane magnetic field

$\rightarrow$ Carried by electrons (protons are demagnetized)

Reconnection Rate

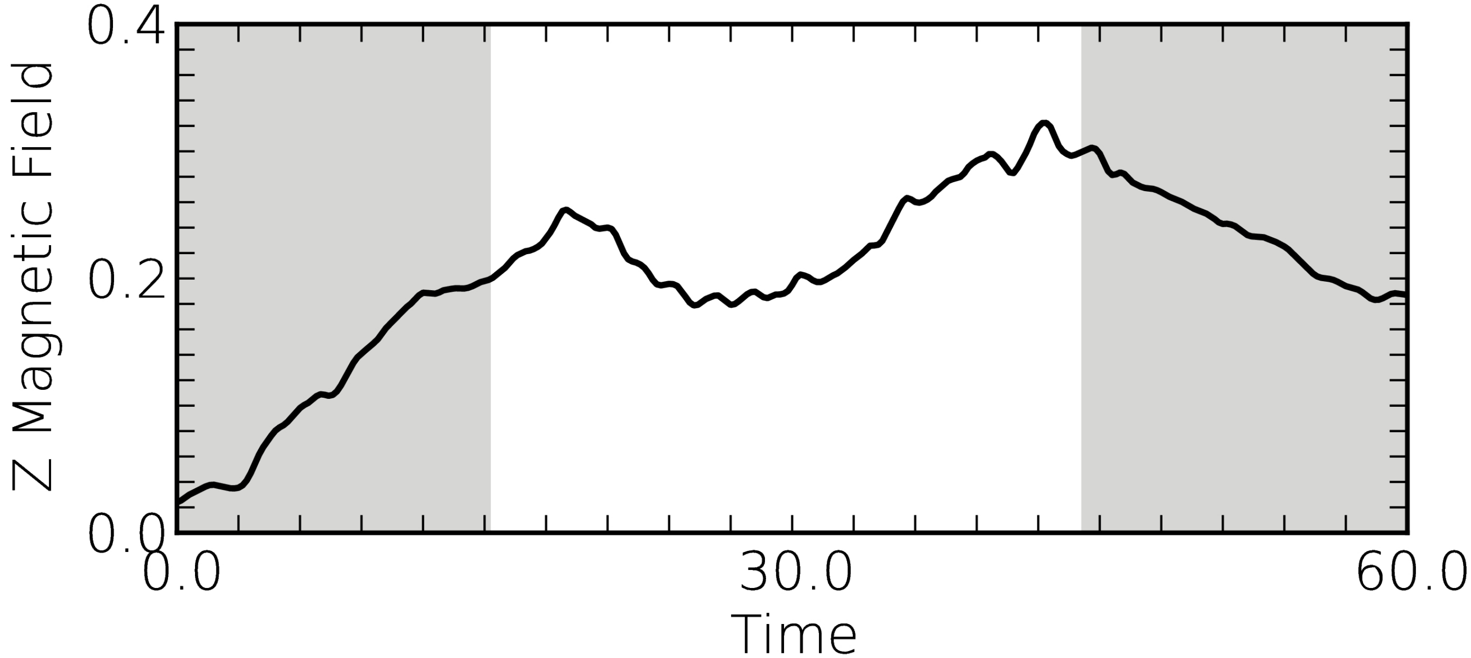


Slope of the reconnected flux : $E_Z = -\partial_t A_Z$

Reach the “holly” value of 0.2...

$\longrightarrow$ The outflow speed is aroud 0.2 times the (upstream) Alfvén speed (not yet normalized)

Out-of-plane quadrupolar (Hall) Magnetic Field



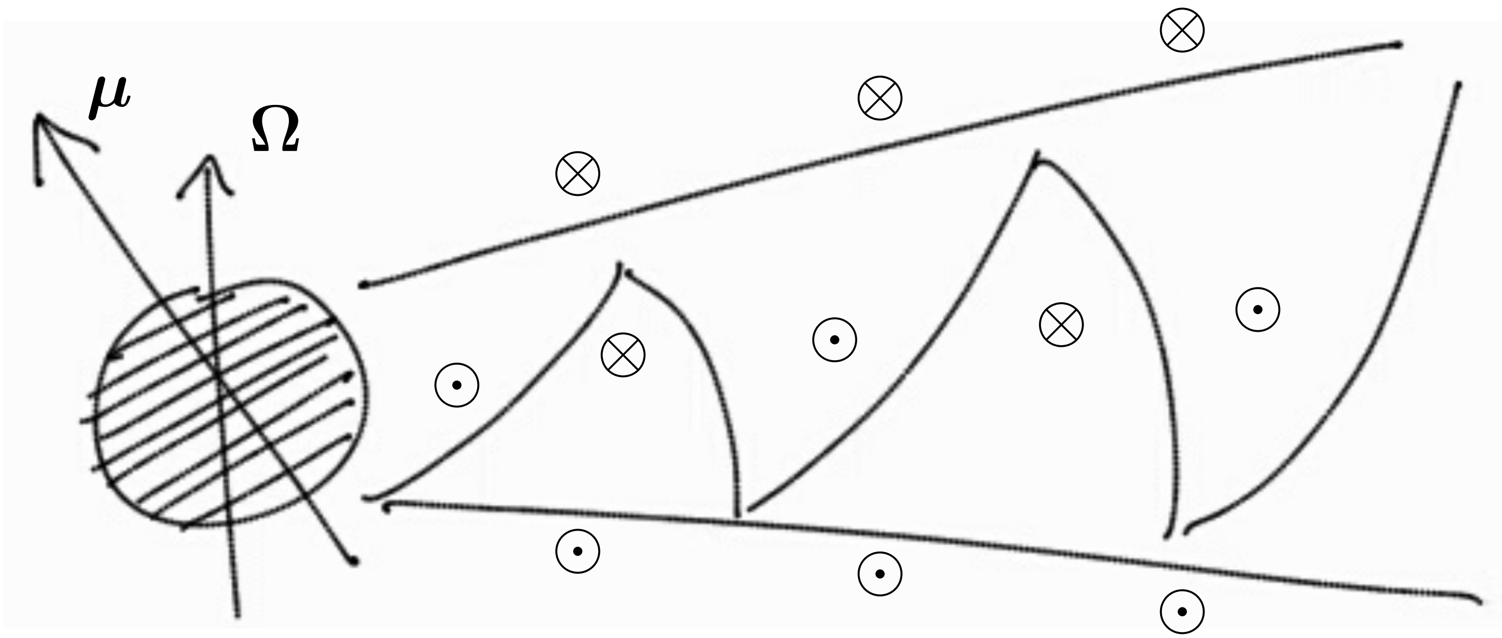
Its value clearly increases prior the reconnection onset

$\longrightarrow$ Can not be a consequence of the reconnection process

Double hump structure like the one of the E_Z component

$\longrightarrow$ Close connection between these two components

Striped pulsar wind [Bogovalov, A&A 1999]

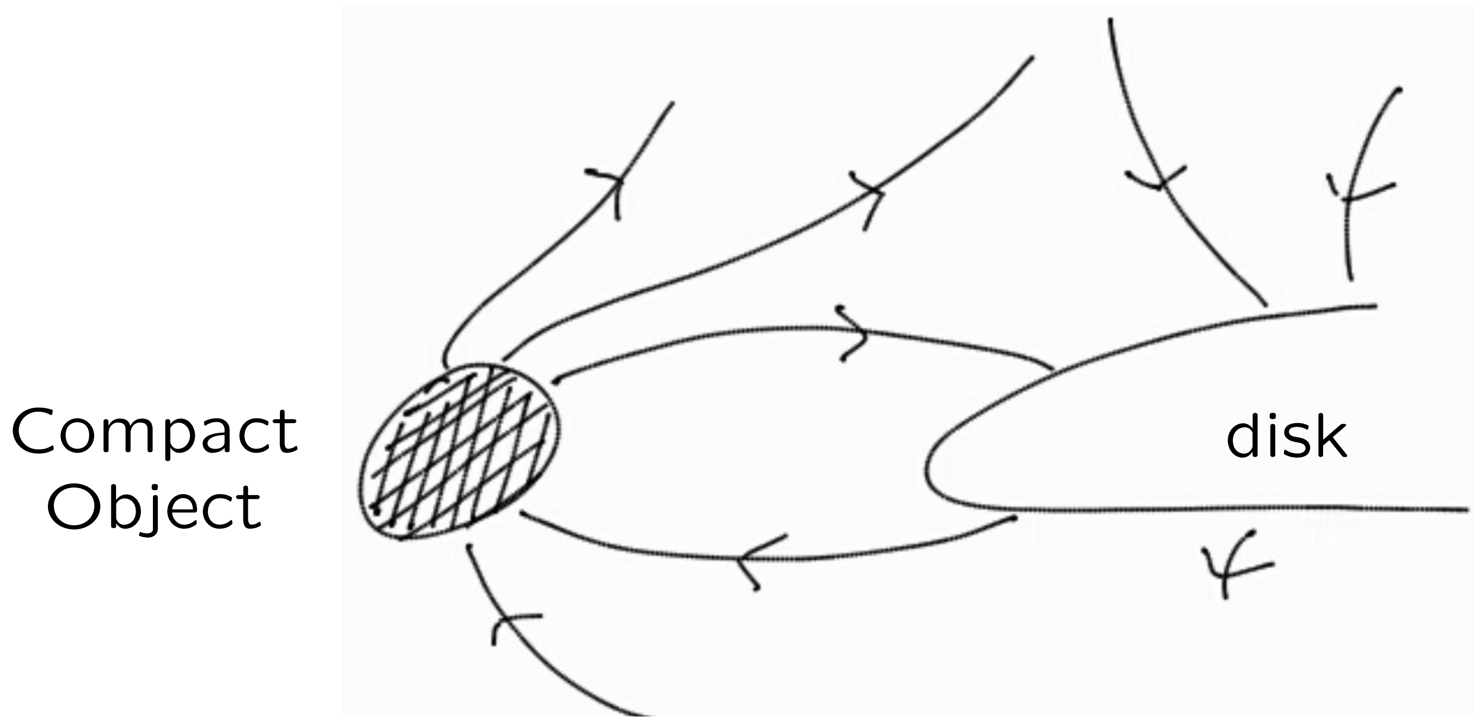


Ultra-relativistic pair-plasmas ($\gamma \sim 10^3$, $\sigma \sim 10^4$)

(collisionless) Shock-driven reconnection

$\rightarrow$ EM energy to synchrotron emmitting electrons (X & γ)

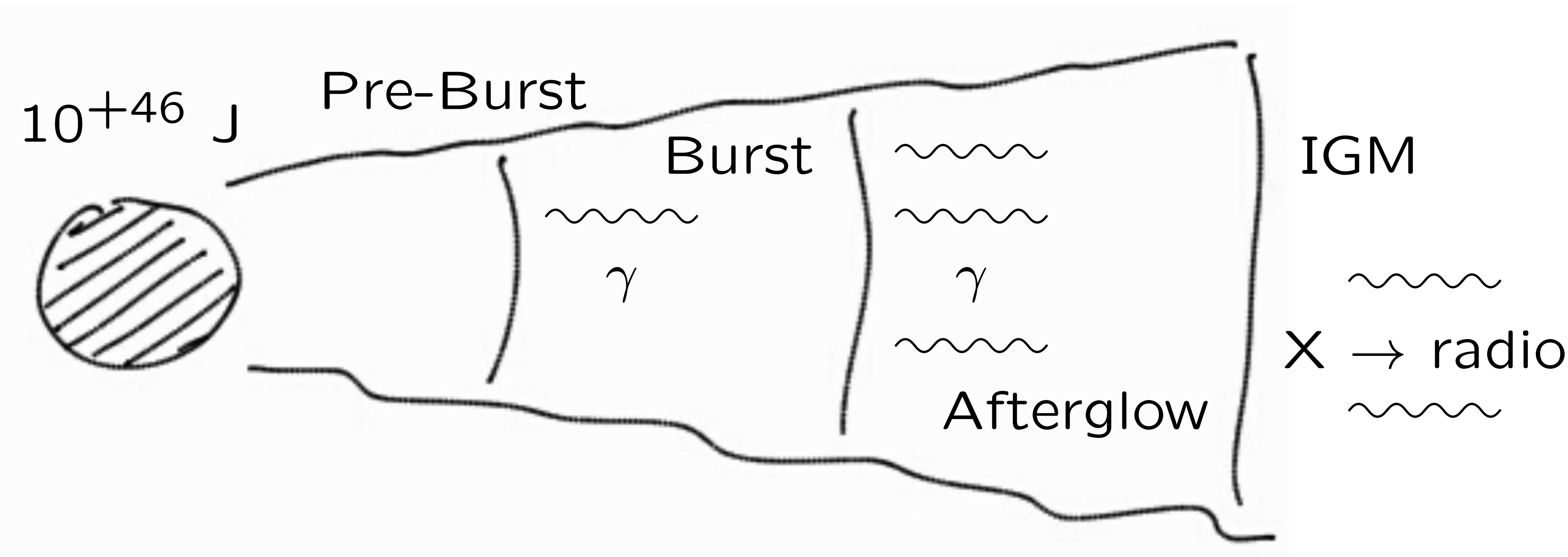
Accretion disks [Gouveia dal Pino & Lazarian, 2005]



Can explain the steep power-law state of photons for $\beta \leq 1$

$\rightarrow$ Could be extended to AGNs & YSOs,

γ **ray bursts (Fireball model)** [Thompson, 1994]



Ultra-relativistic with $\beta \leq 10^{-4} \rightarrow f(\gamma) \propto \gamma^{-p}$ with $p \sim -2.2$

$\rightarrow$ Associated $p \sim -1.6$ for synchrotron photons