Face 2 Face talk on common features and differences of MR in space and fusion plasmas

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Moderator: Francesco Pegoraro

1. Definition

Magnetic reconnection involves two features:

- a topology change → non-magnetic free energy that was already available is released because a topological constraint is broken

- an energy source → the energy that is transferred to the plasma in the form of heat and/or non thermal particle acceleration is generally attributed to the "burning" of the magnetic energy only

What definition best fits your field and how to blend these two points of view?

Definition of MR is mostly consistent across Space, astrophysical and Laboratory plasma

- Magnetic reconnection (MR) refers to changes in the linking of magnetic field lines.
- The topological definition includes diffusive(slow) processes like the nonlinear growth of the tearing mode but the “MR” label is more often used for phenomena much more rapid than current diffusion, $V \gg V_A/S$
- Rapid changes are enabled by the occurrence of a localized parallel component of the electric field
- The conversion of magnetic into thermal energy is of less interest in fusion than:

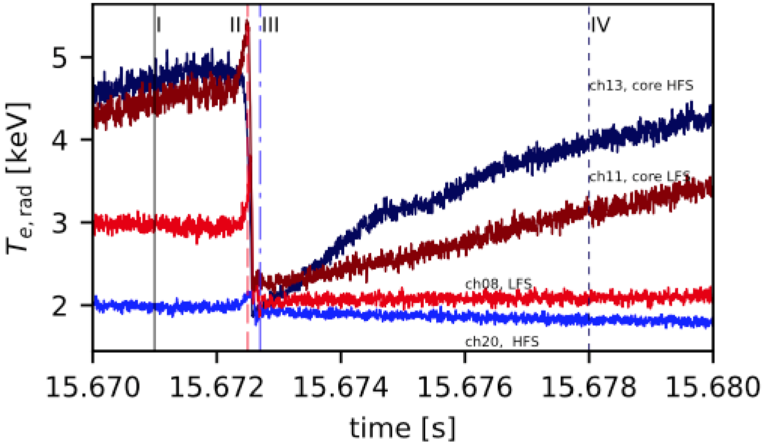
(i) The production of runaway electrons;

(ii) The loss of energetic fusion products;

(iii) The effect on confinement

Types of Magnetic Reconnection

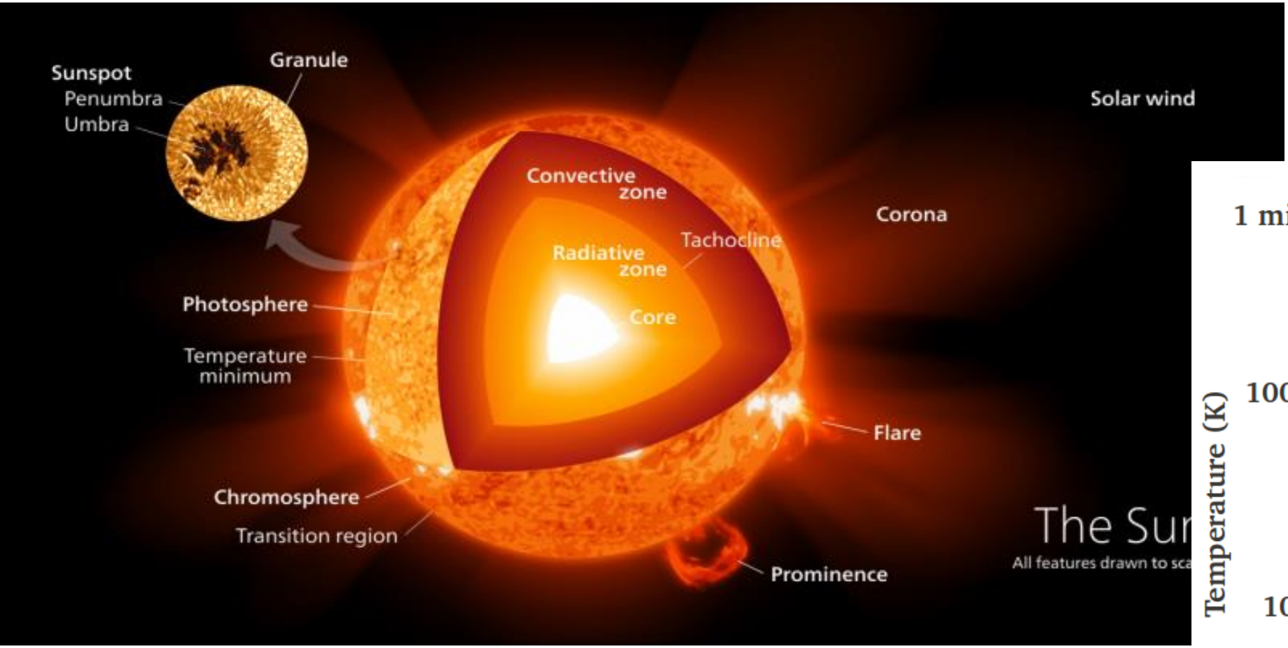
- Forced vs. Free MR
  - Forced when rate is controlled by ”external” process, e.g. chromospheric motion, turbulence or an experimentalist
- Line-tied MR
  - Pertains to field lines anchored in a dense medium, e.g. a conducting vessel or the chromosphere
- 3D vs 2D MR
- Guide-field or Null-point MR



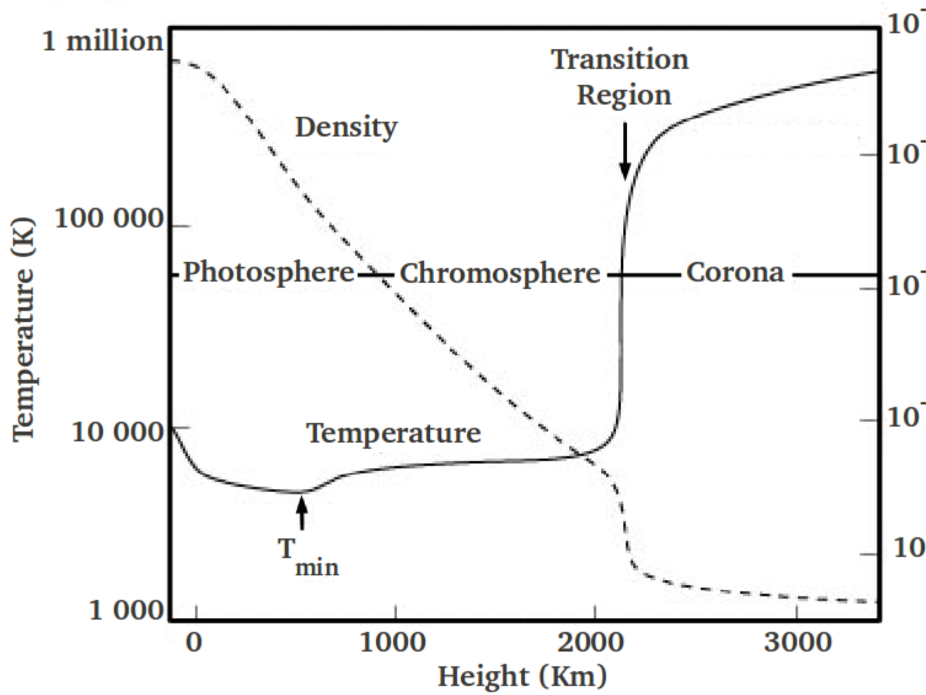
Magnetic reconnection event in W7-X stellarator

Introducing the Sun

Before answering questions, let's introduce the Sun and where reconnection happens….

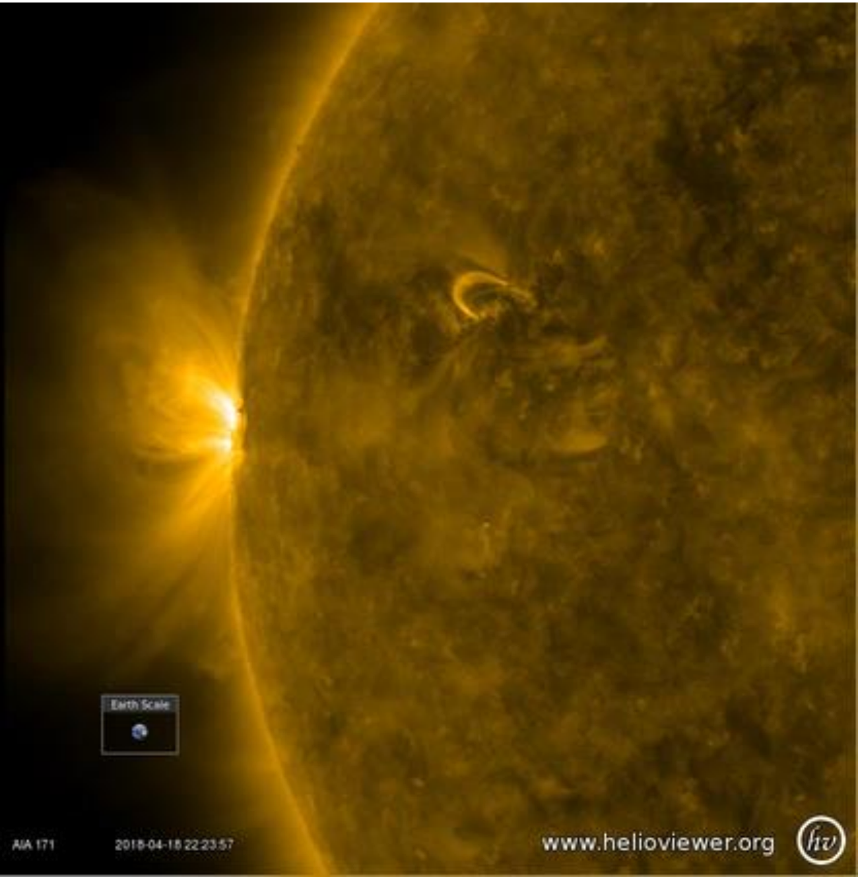


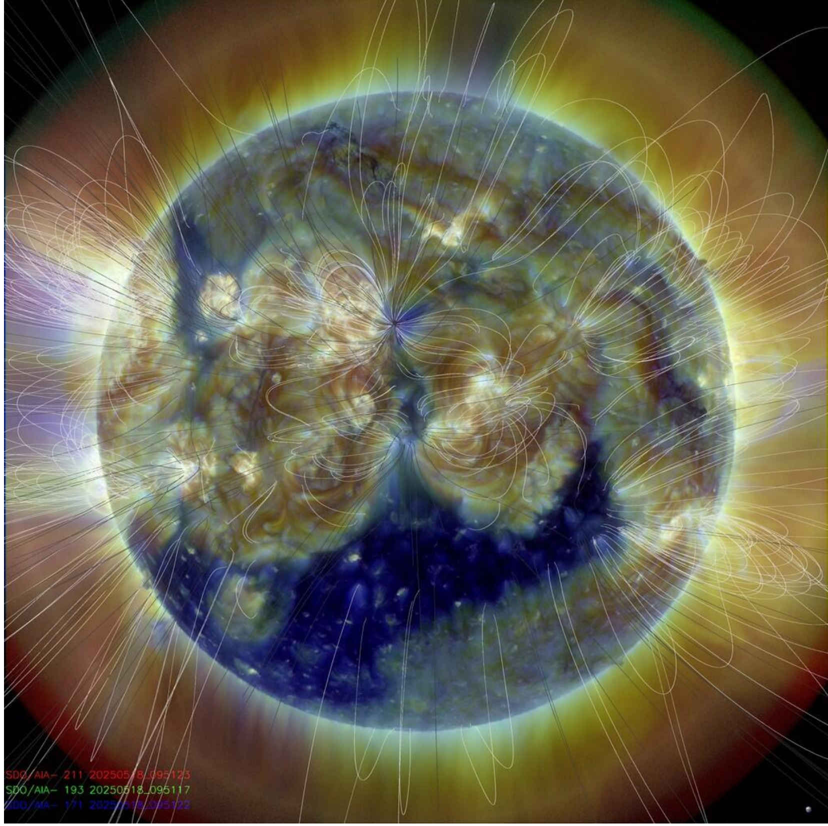
From Lang 2001



Corona –
Hot, tenuous outer atmosphere
~ 1 million K
(photosphere ~ 6000 K

Images
SDO/AIA

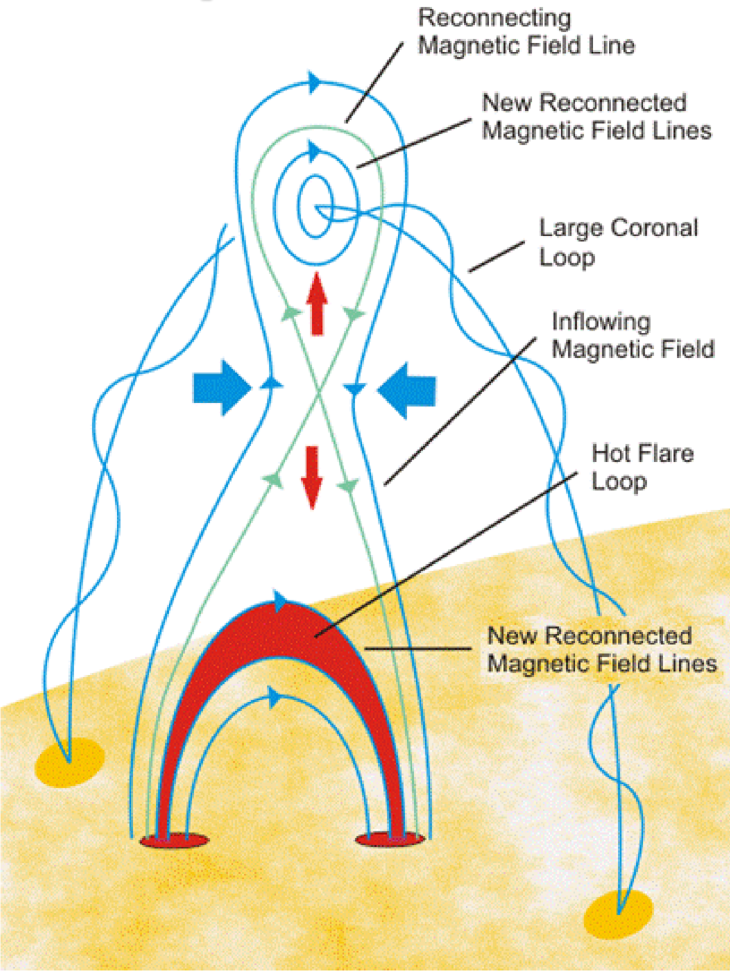




- Strongly- magnetised
  $\beta << 1$
- Highly structured and dynamic
  - Many coronal loops

Magnetic reconnection in the solar atmosphere

- **Solar flares**
  - **Rapid release of stored magnetic energy**
- **Coronal Mass Ejections**
- Heating of solar corona
  - Maybe due to combined effect of many nanoflares
  - Multiple magnetic reconnections in tangled coronal magnetic field
- Chromospheric and photospheric reconnection
  - e.g. Chromospheric heating, Ellerman bombs
  - Need to consider partial ionisation, two fluid effects etc
- Also in heliosphere



Change of topology or energy release?

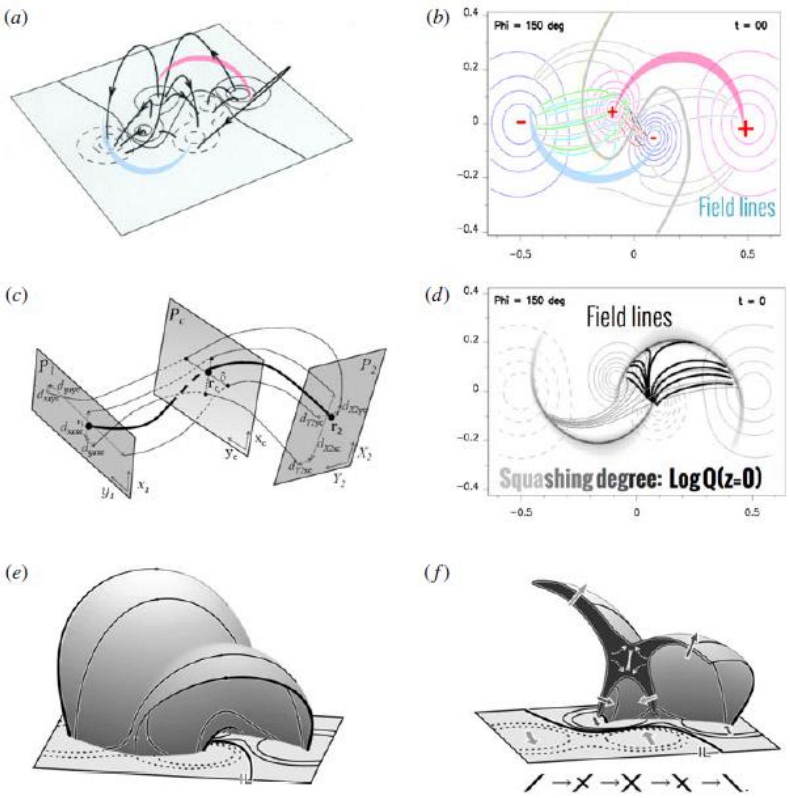
Both definitions are appropriate in solar corona – and closely linked

- Corona has complex magnetic topology - defined by "magnetic skeleton" dependent on distribution of magnetic flux sources at photospheric surface
- Magnetic nulls, separatrix surfaces divide regions of different magnetic connectivity, separator field lines; Quasi-Separatrix layers (strong field line divergence)

Henoux and Somov 1987; Demoulin et al 1992, Bungey et al 1996

- Reconnection changes field line connectivity
- Magnetic free energy is stored and released in flares (large-scale to manoflares) and eruptions
- Input of magnetic energy from photospheric footpoint motions twisting or braiding coronal field
- Also in 3D may define reconnection as presence of localised parallel electric field $\int E_{para} dl \neq 0$

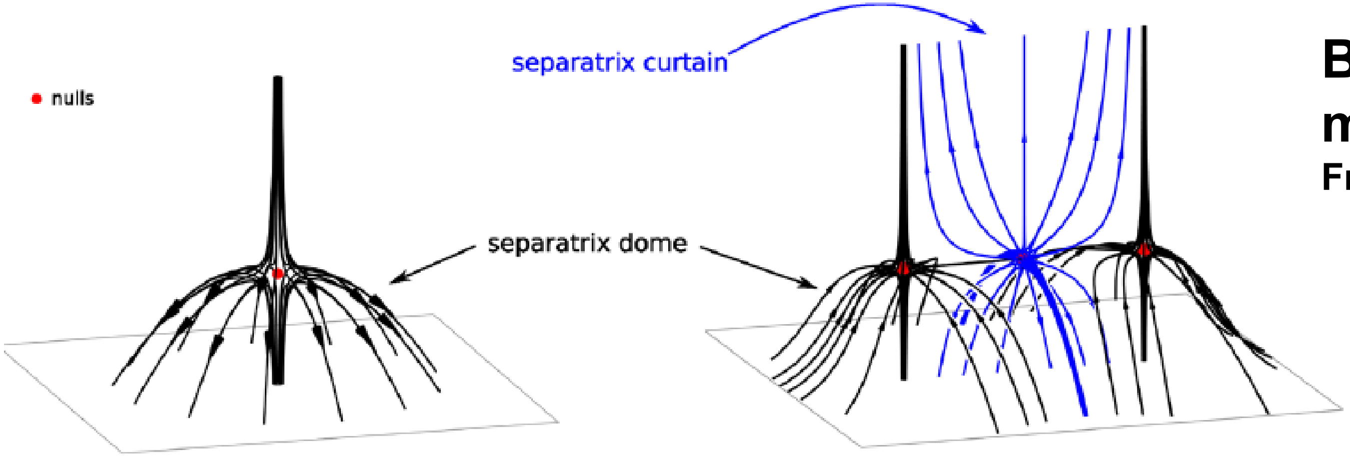
Schindler et al 1988



From Janvier 2017

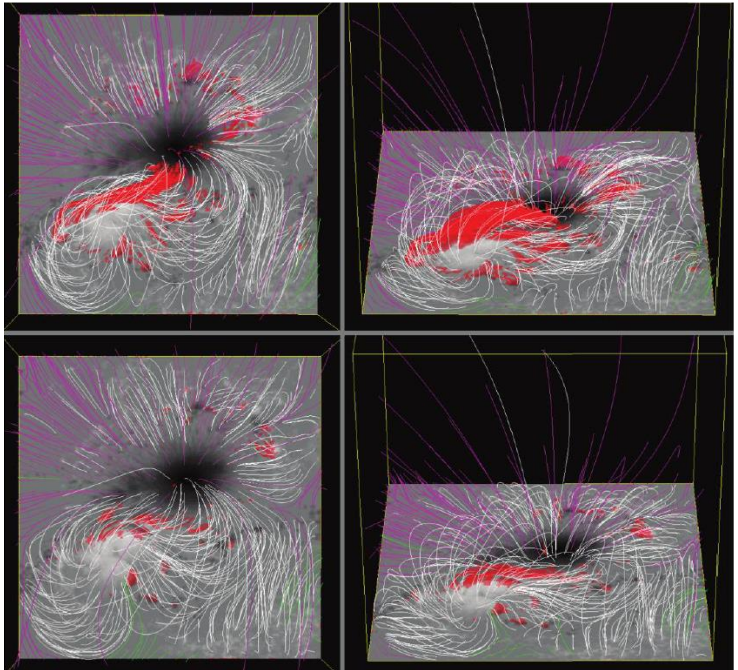
Building blocks of coronal magnetic topology

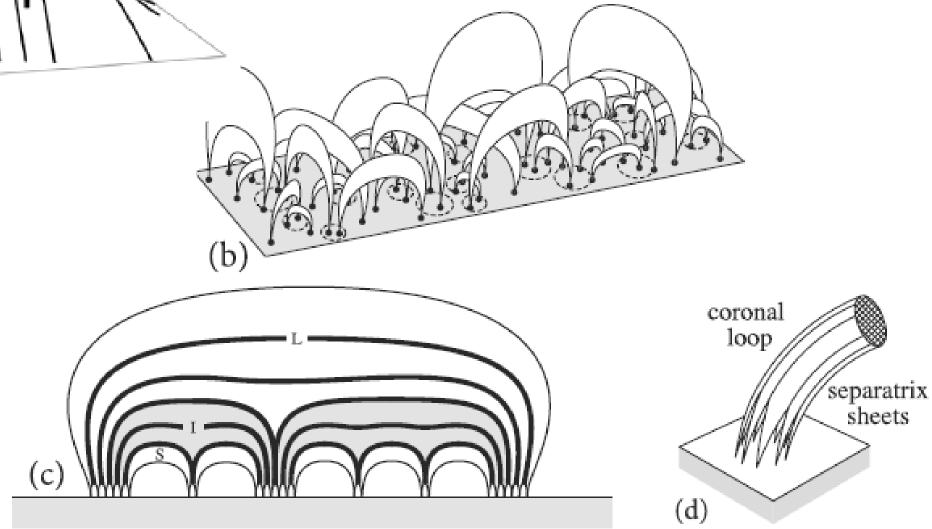
From Pontin and Priest 2022



Magnetic field before and after X3.4 flare (nonlinear force free field). Energy reduction ~ 10^{25} J

Schrijver et al 2008





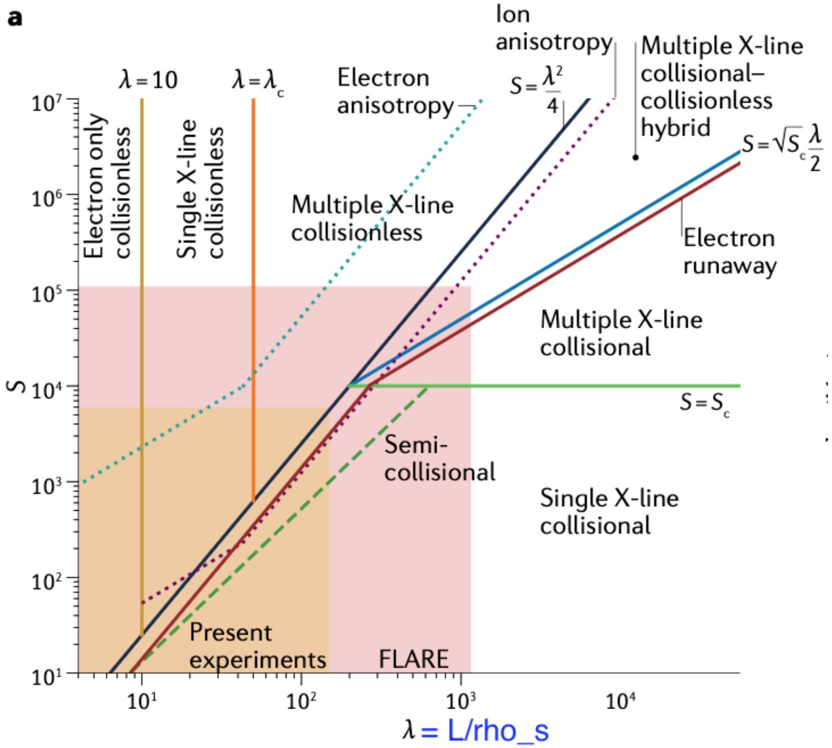
Coronal magnetic field rooted in many discrete photospheric flux sources → "flux tube tectonics"

From Priest 2002, 2014

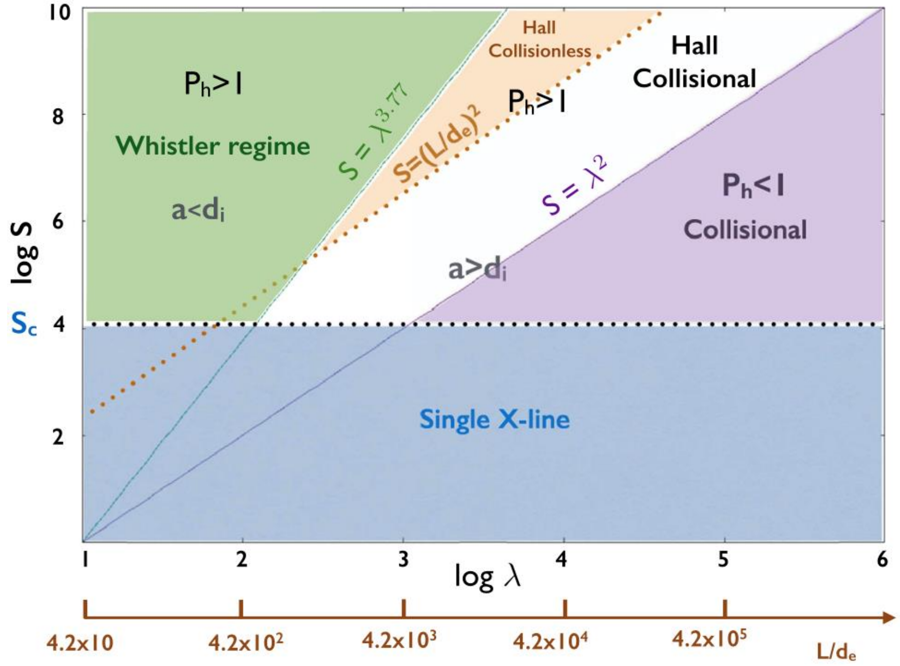
2. Scales

On which charateristic spatial and temporal scales does MR occur in your field?

Scales



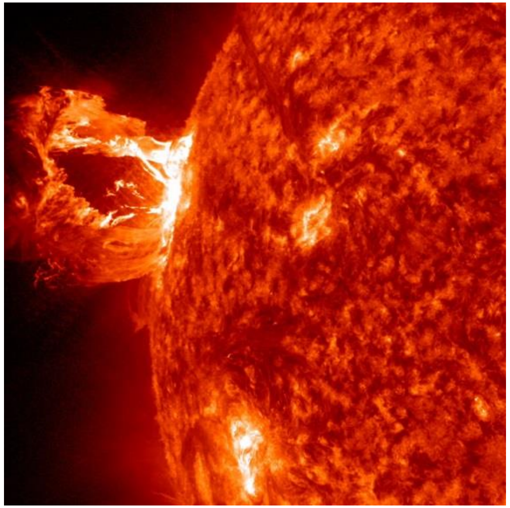
H. Ji, W. Daughton et al., Nat. Rvw. Physics 2022



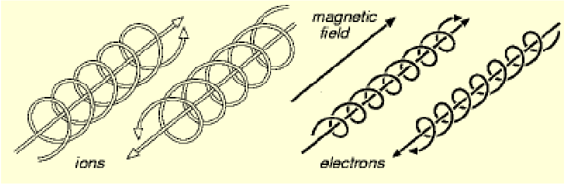
Pucci, Velli & Tenerani Ap. J. 2017

- Large scale phenomena ~ 10^8 m described well by fluid models - magnetohydrodynamics (MHD)

- Small kinetic plasma scales are significant for key physics e.g. reconnection dissipation, particle acceleration

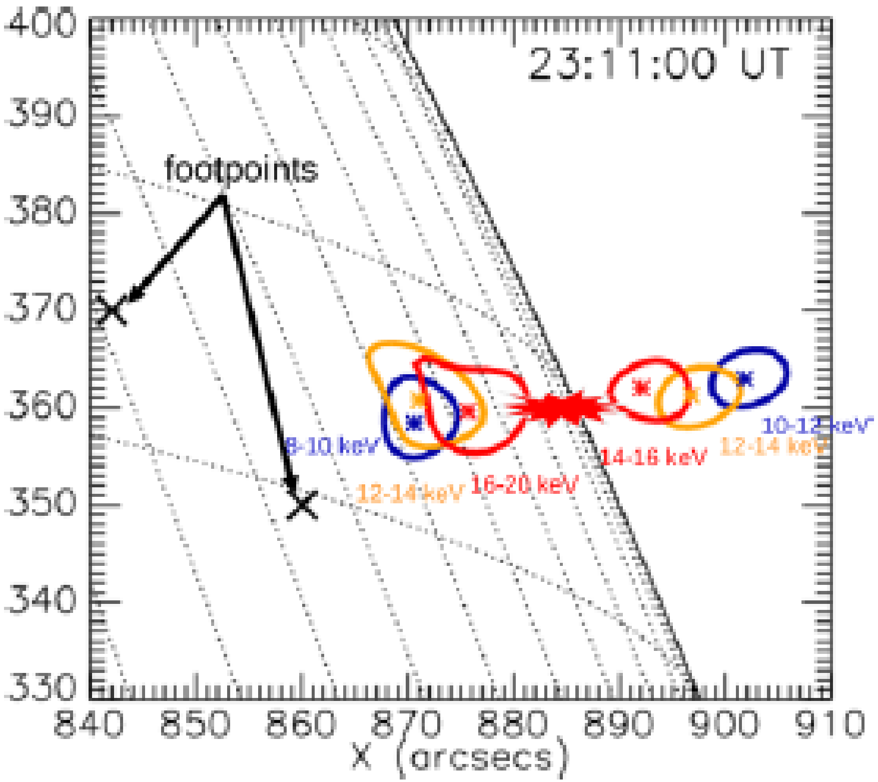


Ion Larmor radius ~ 0.1 – 1 m
Ion skin depth 10 m
Electron scales even smaller



- Non-Maxwellian distribution functions associated with energetic particles cannot be accounted for by MHD

Flare current sheet



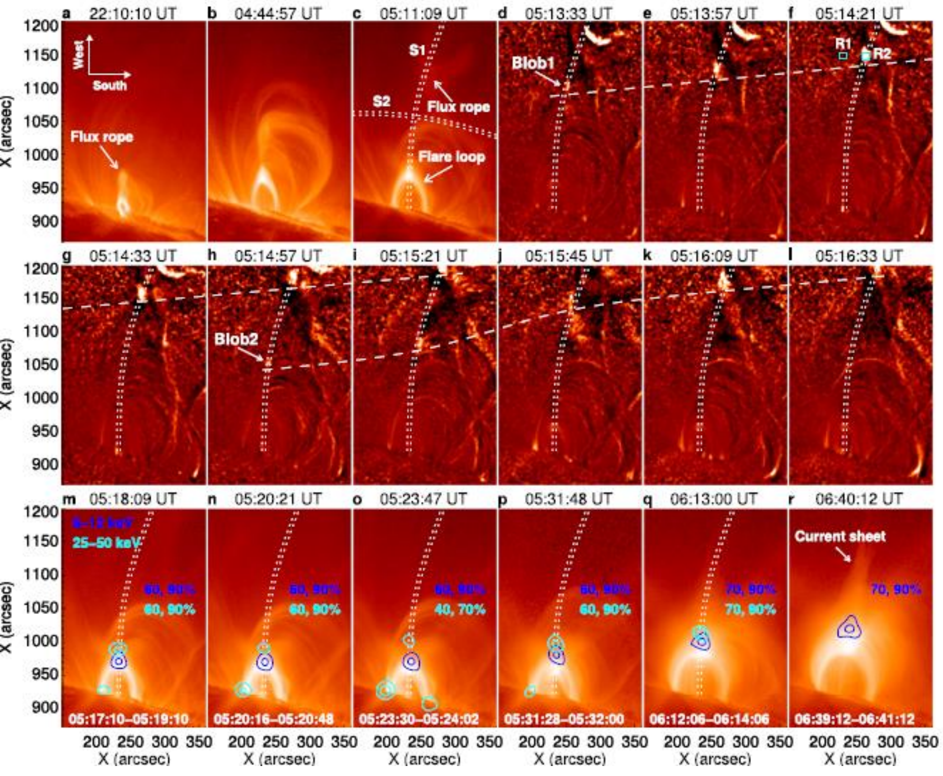
- **Suggests current sheet between HXR sources**

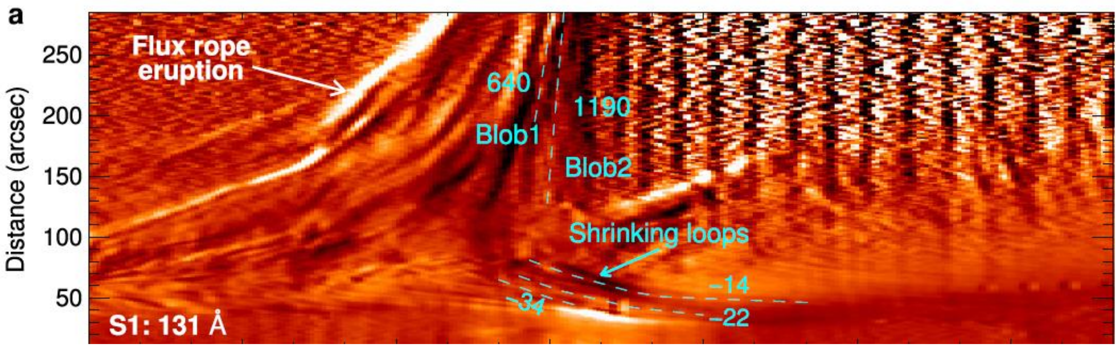
Sui and Holman Ap J 2003

Length of current sheet ~ 30 arcsec ~ 20 Mm

Substructure in current sheet - plasmoids

Lu et al 2022
Length ~ 200 arcsec ~ 14 Mm





Modelling approaches across scales

- MHD + Test-particles

+ Widely-used, easy to implement/interpret, predictive capability

- Ignores feedback of particles on fields, requires ad hoc anomalous resistivity

- Hybrid models – many possibilities e.g.
  - Standard "hybrid" has particle ions, fluid electrons – not very useful for flare particle acceleration
  - Unified Gas Kinetic Scheme - multiscale *Liu and Xu 2017*
  - KGLOBAL – MHD + nonthermal electrons – assumes energisation only due to Fermi reflection in contracting islands *Arnold et al 2021*
  - PLUTO MHD code has "cosmic ray" hybrid particle module, with some feedback effects *Bai et al 2015, Mignone et al 2018*

- Particle-in Cell

+ Many codes available, fully self-consistent, models local effects

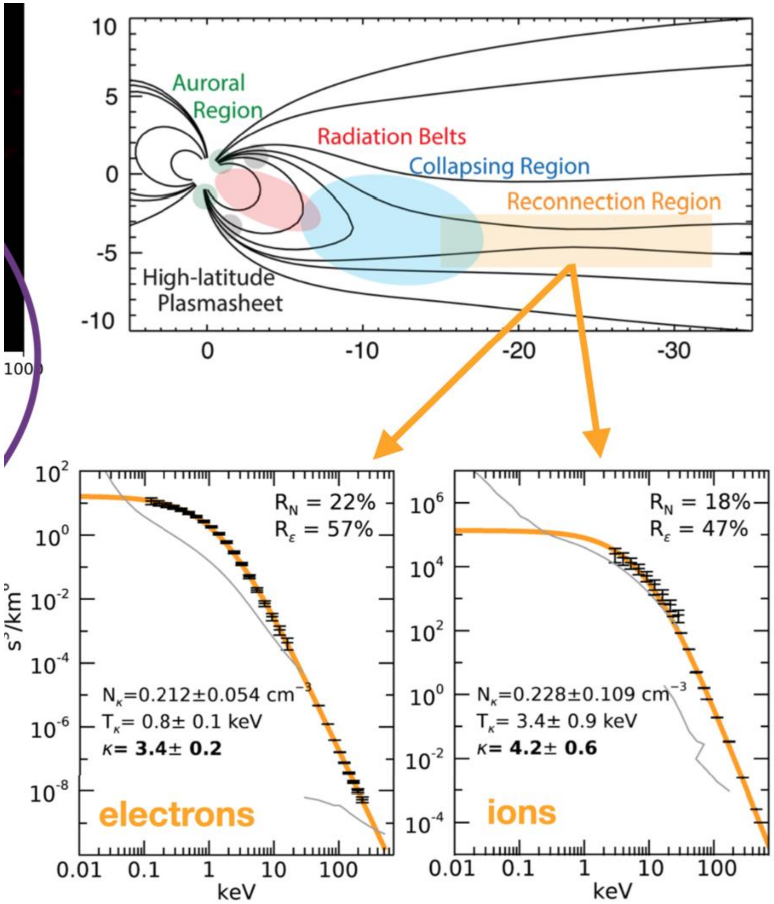
- Cannot model global scales of flares; statistical noise
- Does not predict sufficient acceleration

- Other kinetic models e.g. Boltzmann equation, Fokker-Plank

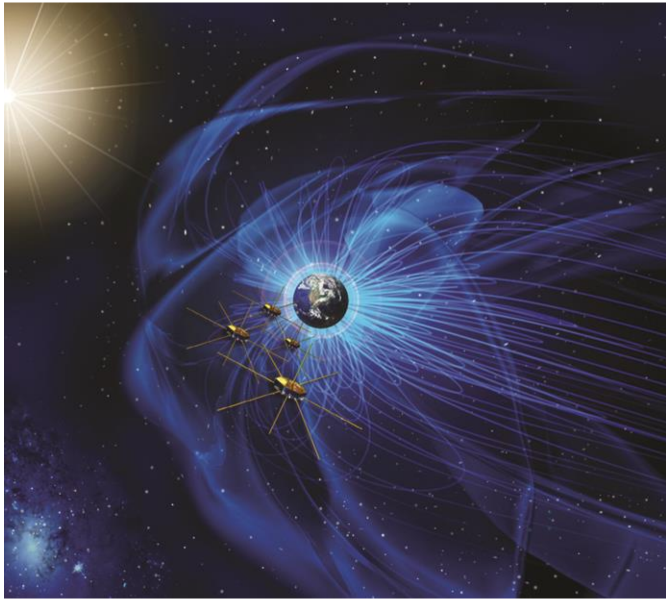
See review Gordovskyy, Browning and Pinto (2019)

Reconnection across heliosphere

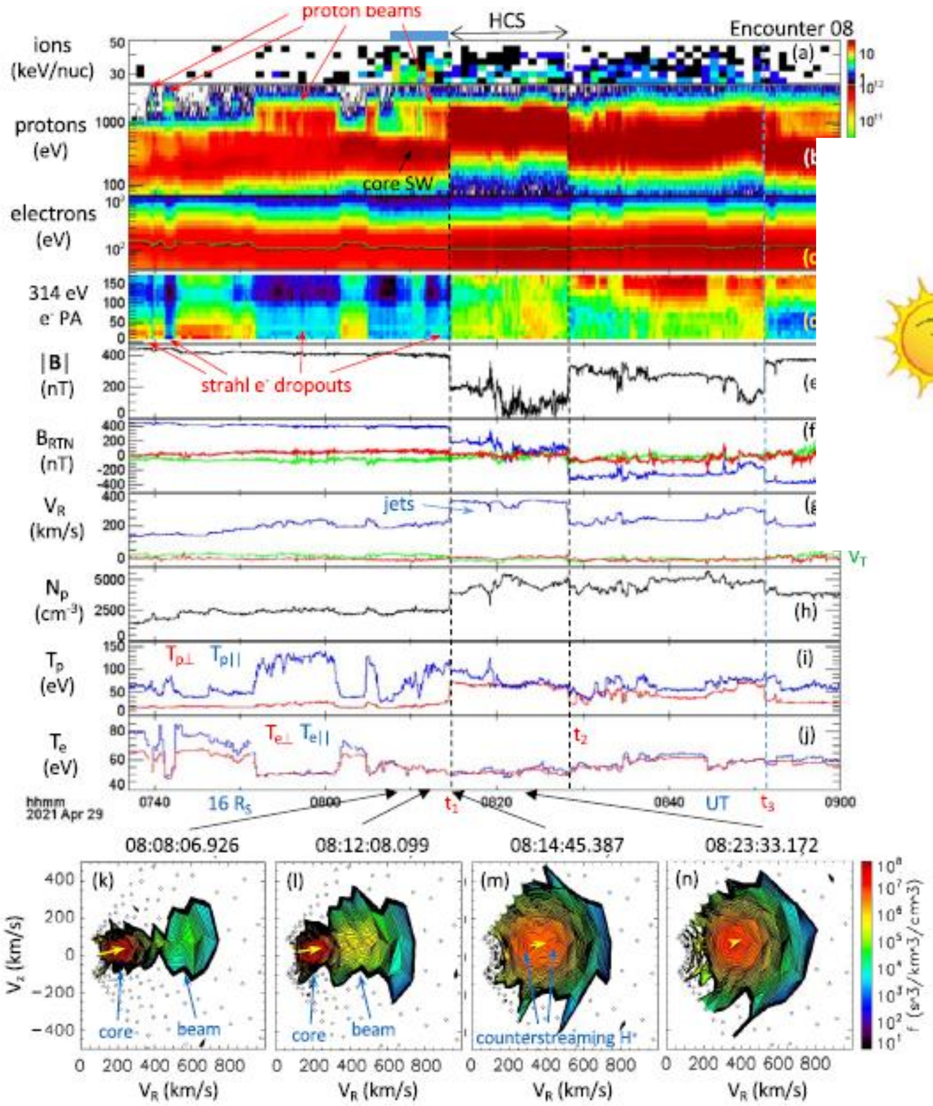
Solar wind
Solar wind planetary magnetosphere interactions
Magnetospheric substorms
Mainly collisionless reconnection

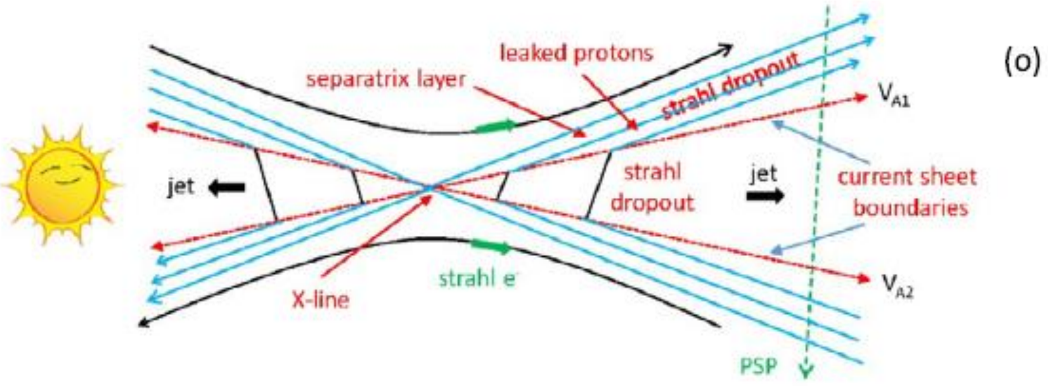


From Oka et al 22, Drake et al 25



Magnetospheric Multiscale Mission Spacecraft separation ~ 10 – 400 km Electron scales





Parker Solar Probe Reconnection in heliospheric current sheet at 16 R_{sun} showing energetic ion generation

Drake et al 2025

3. Energetic particles

On MR as a particle energy source:

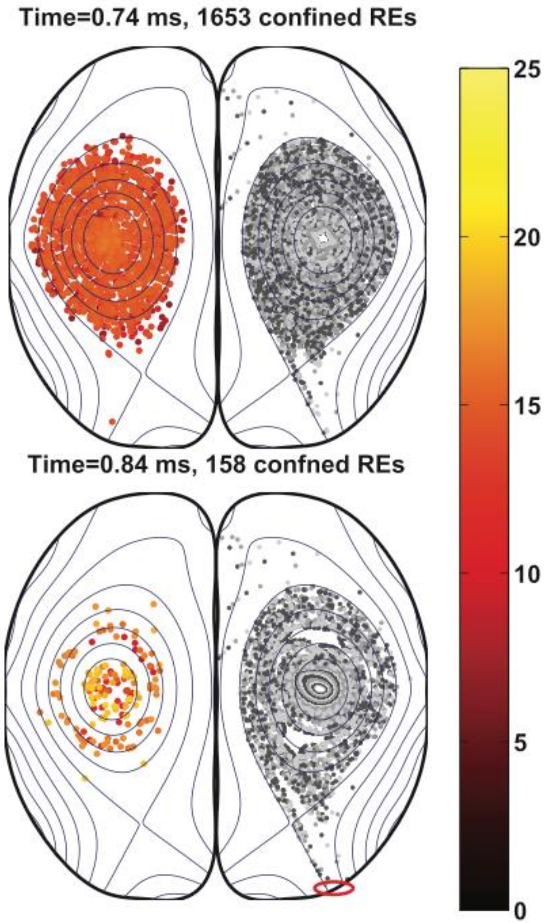
How MR affects energetic particles in your field?

Which is the trademark of MR respect to other acceleration mechanisms in space plasmas?

How fusion devices can cope with runaways electron beams?

Energetic Particles

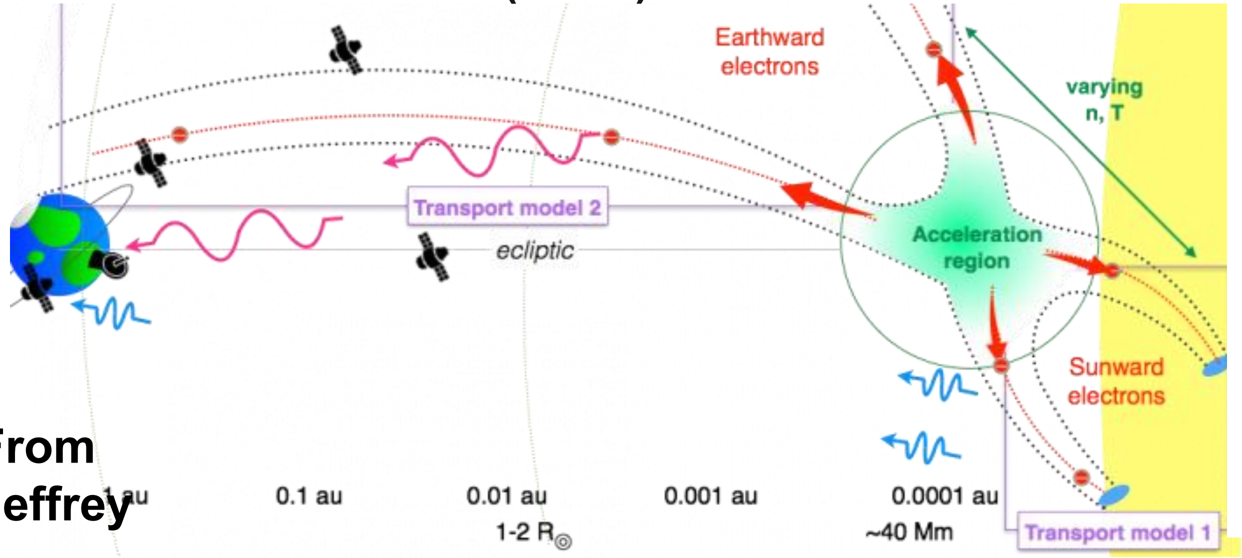
- In Magnetic fusion, reconnection produces field-line braiding that reduce thermal confinement, resulting in a thermal quench.
- The thermal quench increase the electric field through E=ηJ
- The rising E creates runaway electrons (RE) that present a danger to the vessel walls.



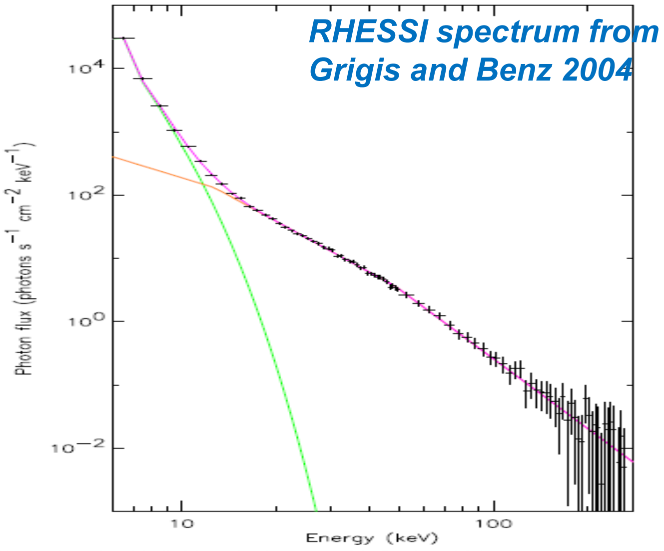
V A Izzo et al., PPCF 2012,

Particle acceleration in solar flares

- Flares produce substantial numbers f energetic electrons and ions
  - Fraction of non-thermal electrons at peak of impulsive phase ~ 0.01 – 0.02 (Kontar et al 2023) or ~ 1 Fleishman et al (2022)
- May propagate down to solar surface impacting on dense chromosphere
  - Emit bremsstrahlung (Hard X-rays) and ion nuclear line emission (gamma rays)
  - Electrons gyrating in magnetic field emit gyrosynchrotron (microwaves)
- Or along open field lines into heliosphere
  - Plasma emission (radio)



From Jeffrey



Particle acceleration mechanisms

- Guiding-centre energy equation

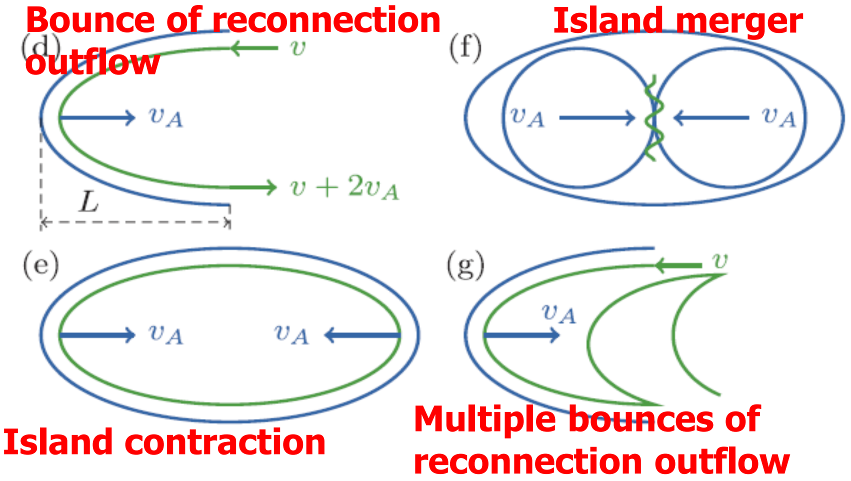
$$\frac{d\epsilon}{dt} = qE_{\parallel}v_{\parallel} + \frac{\mu}{\gamma}\left(\frac{\partial B}{\partial t} + \mathbf{u}_{\mathrm{E}}\cdot\nabla B\right) + \gamma m_e v_{\parallel}^2(\mathbf{u}_{\mathrm{E}}\cdot\boldsymbol{\kappa}),$$

from Dahlin 2021

- Parallel Electric field
- Betatron acceleration/curvature drifts

  e.g. Vekstein and Browning 1997, Zhou et al 2015

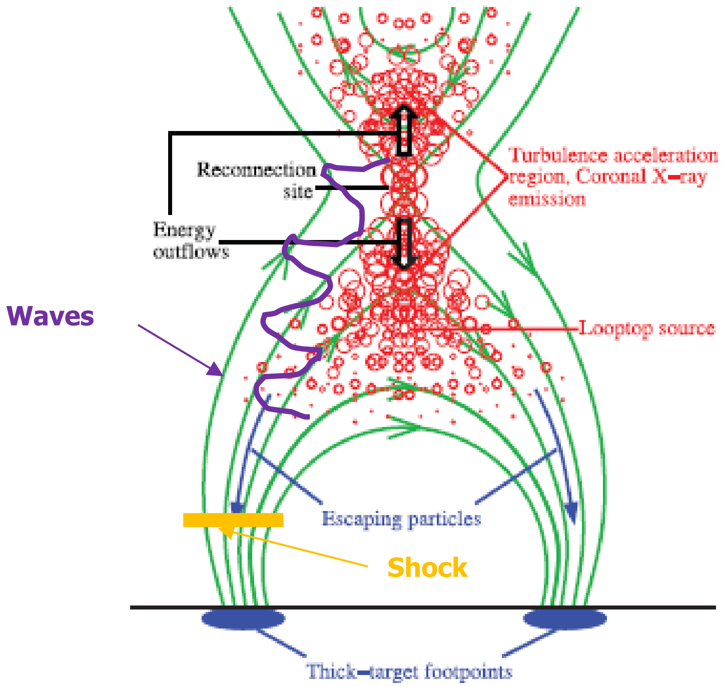
- Fermi acceleration
  - Reflection between moving mirrors



From Li et al 2017, 2021

Particle acceleration in flares

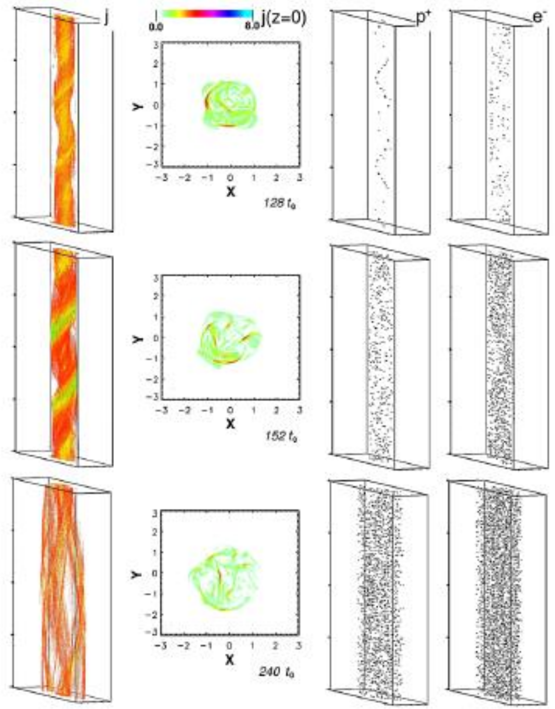
- Direct electric field in reconnecting current sheet - at loop top in "standard model"
    - X point acceleration
    - Distributed current sheets
- Turbulent reconnection outflows
- Collapsing or merging magnetic islands (plasmoids, flux ropes)
    - Collapsing magnetic traps
- Termination shock
- Large-scale waves
    - Inertial Alfven waves



From Liu et al 2008

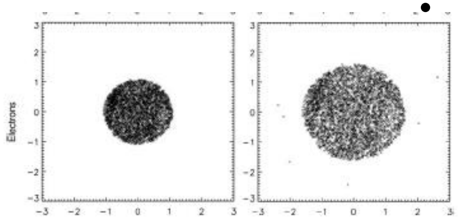
Review Zharkova et al Space Sci Rev 2011

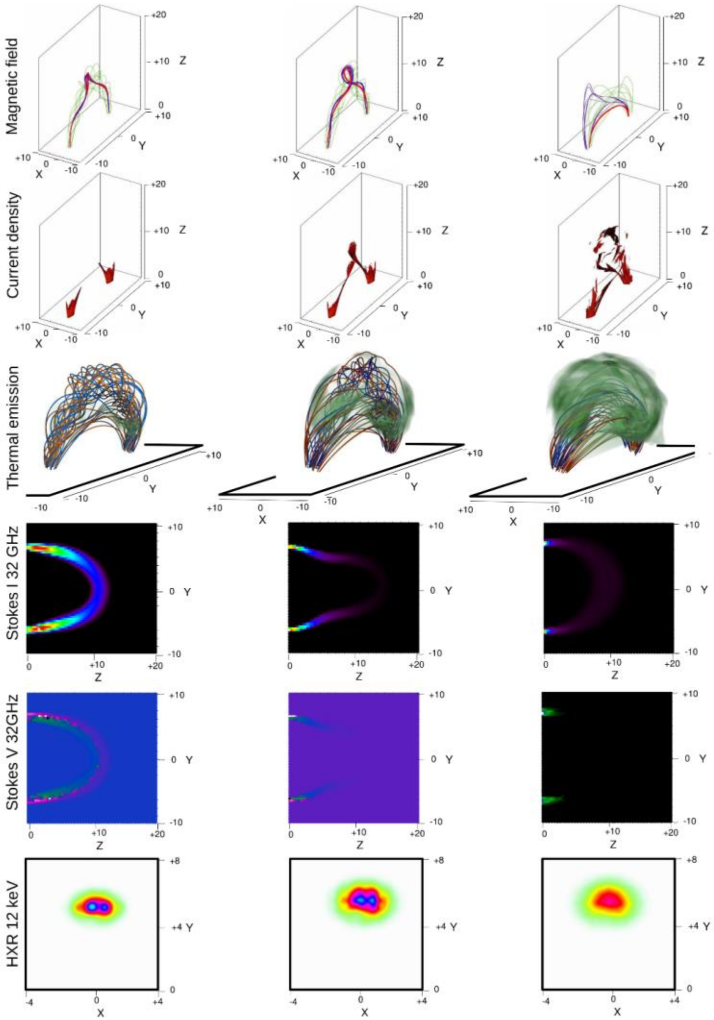
Particle acceleration in unstable twisted loop



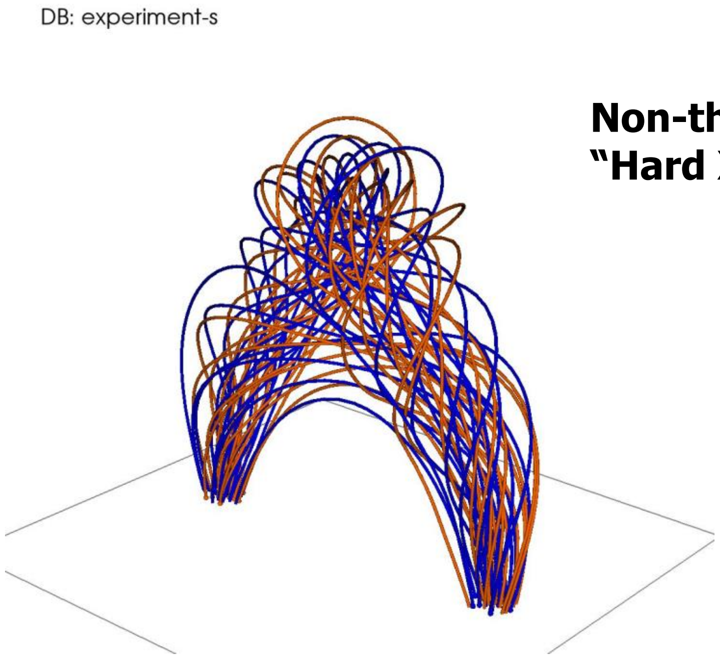
- Investigate by integrating test particles with 3D MHD simulations
- Electrons and ions accelerated by strong electric fields in fragmented current sheets
- Forward model observables of thermal plasma and non-thermal electrons – including Hard X-rays and microwave intensity/polarisation
- Gordovskyy et al 2014, 2017, Pinto et al 2016, Smith et al 2022, Stewart et al 2025

Gordovskyy and B, 2012



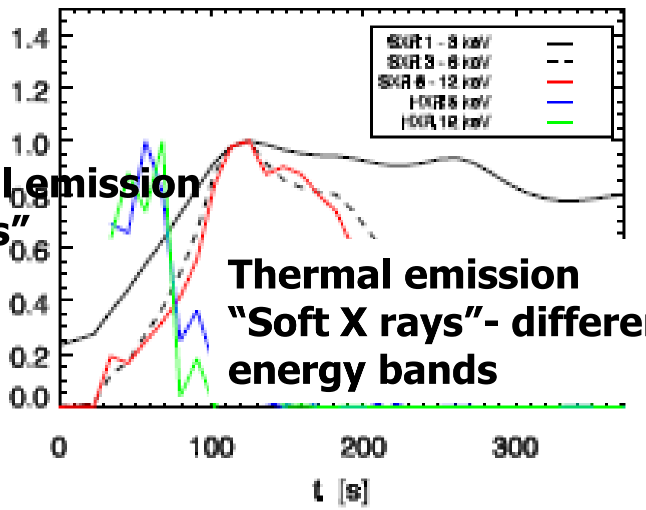


Synthesised emission in twisted loop



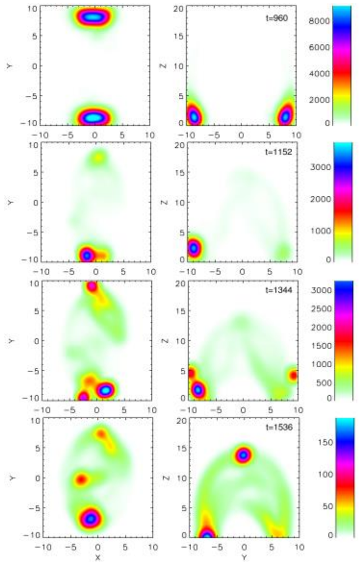
2 keV continuum emission

Pinto et al 2016



Non-thermal emission
"Hard X rays"

Thermal emission
"Soft X rays"- different energy bands

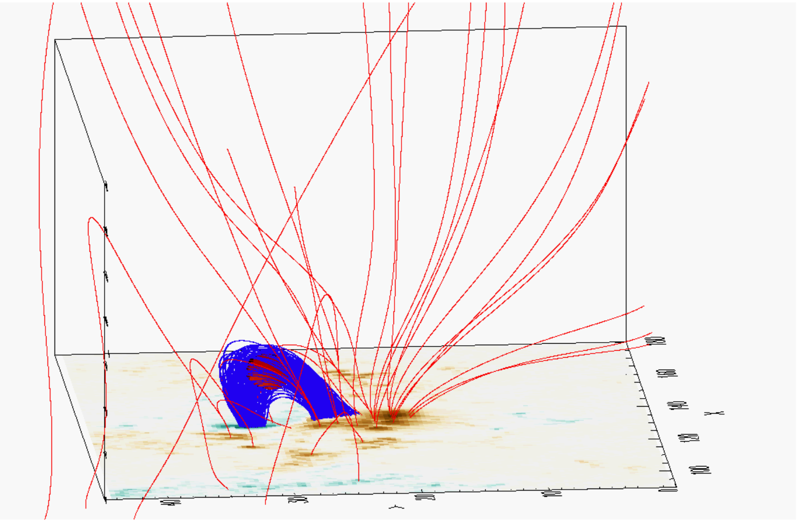


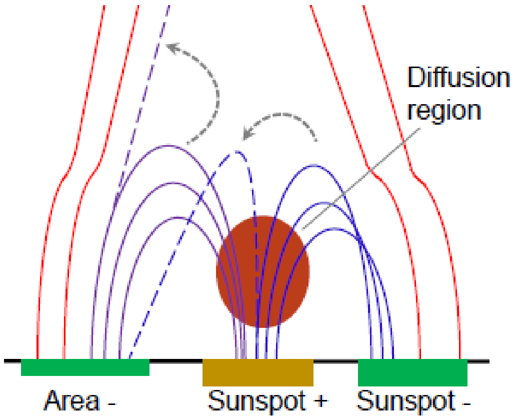
Synthesised HXR
ε=10keV
Gordovskyy et al 2014

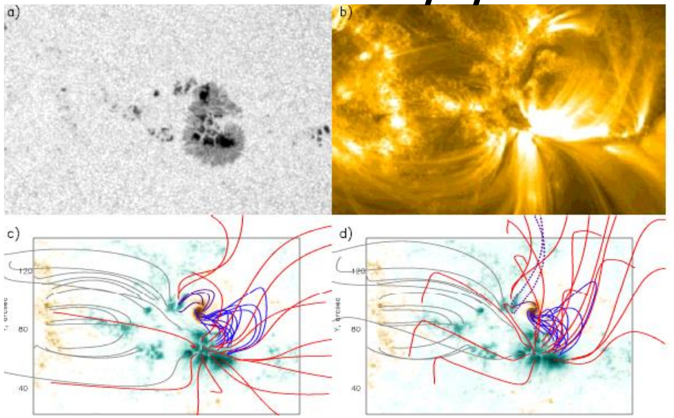
Data-driven modelling of particle precipitation and escape in flares

How do energetic electrons/ions escape into heliosphere from flares and what fraction of particles escape?

Flare 1: X-class flare 26/9/2011







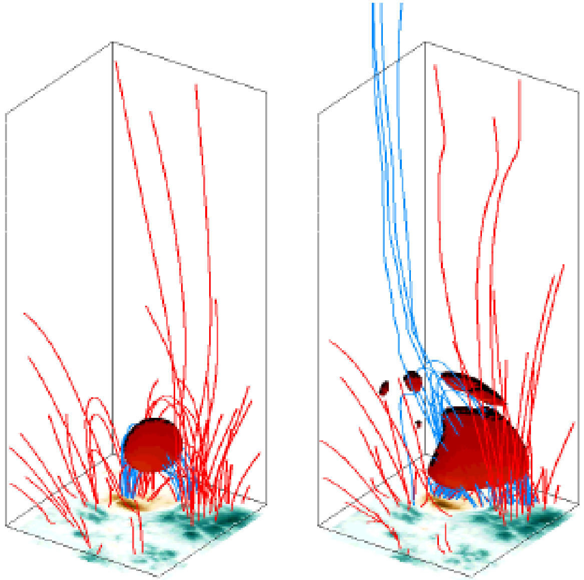
- Initial field from force-free field with observed magnetograms – 3D MHD simulations + test particles for energetic electric/ions
- Open flux increases with time - interchange reconnection between open and closed flux
- Particles mainly accelerated due to strong electric fields in closed magnetic field but some escape due to interchange reconnection with open field

Gordovskyy et al *Mon. Not Roy Astr Soc 2023*

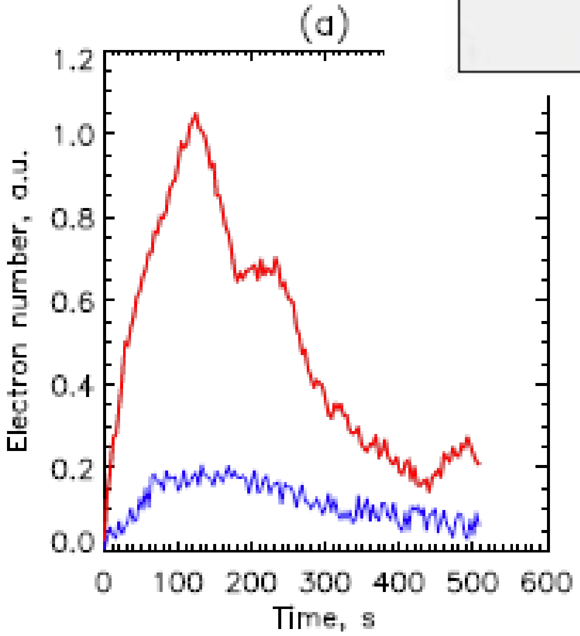
Electron escape and precipitation

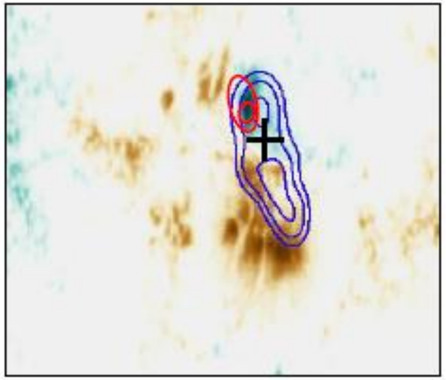
Electron trajectories & magnetic field lines

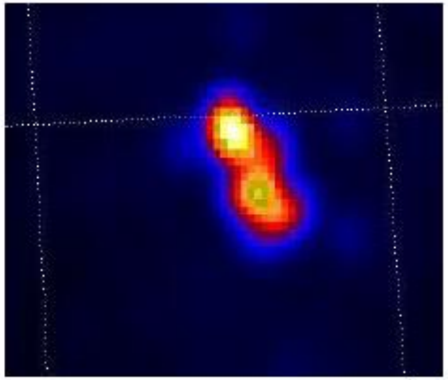
t = 0 s   t = 72 s



Escaping/precipitating particles populations have different energy spectra and time profiles







Hard X-rays

Modelled   **RHESSI**

Closed field/precipitating
Open field/escaping

4. Topological aspect

On MR as a topological change:

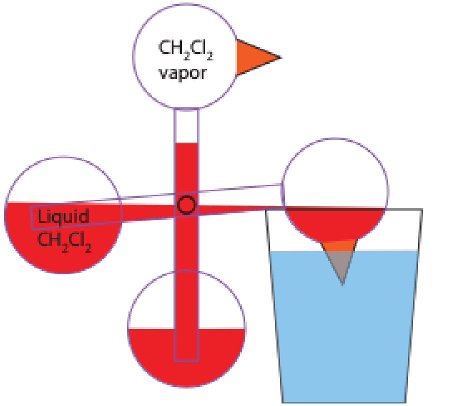
How large must the (local, global) magnetic energy reservoir be in order to account

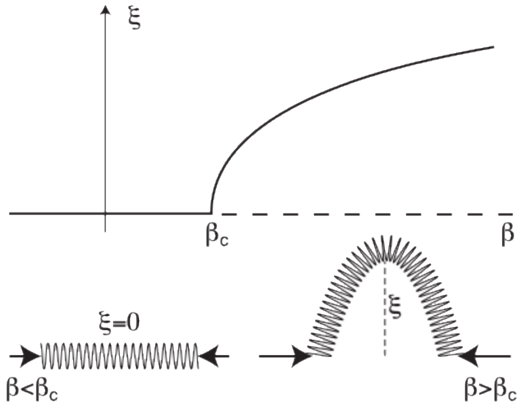
1) for the maximum energy of the accelerated particles that are observed?

2) observed disruptions?

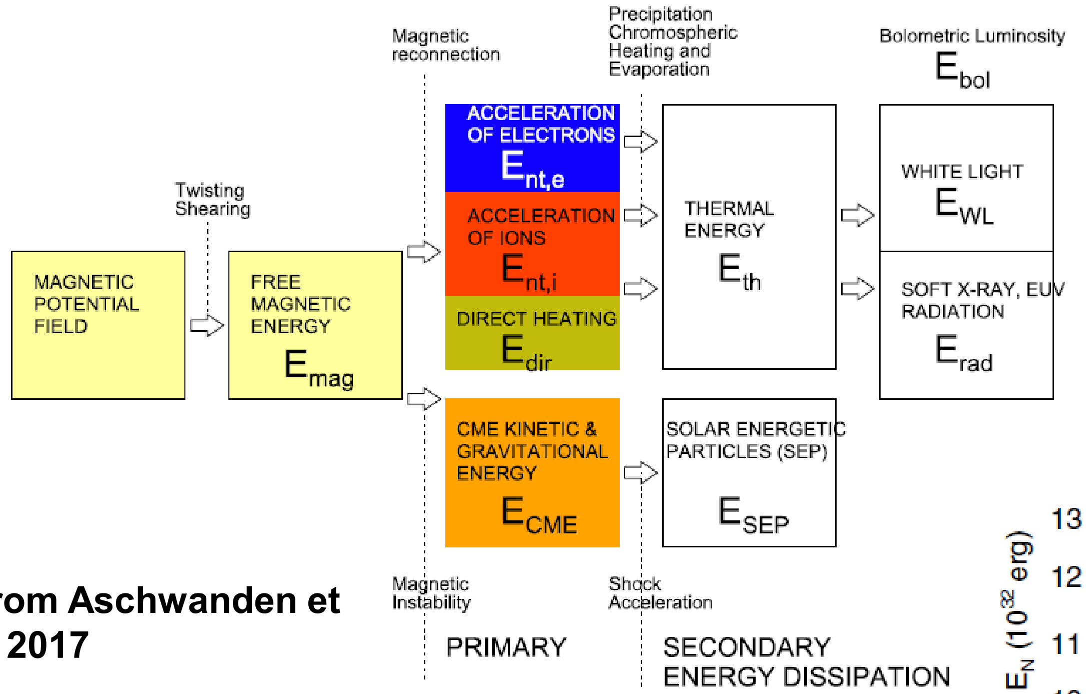
Topological aspects: Explosive nature of Magnetic Reconnection

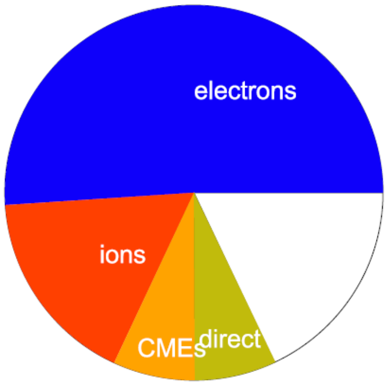
- Ideal MHD theory predicts slow evolution into bifurcated states: it offers a "drinking bird" paradigm that is at odds with observations.
- In particular, two shortcomings of ideal MHD that MR theory is called upon to describe are
  1. Absence of saturation
  2. Presence of a trigger
- The "fast-slow" nature of normal plasma evolution breaks down.





Energy release in solar flare up to 3×10^{25} J

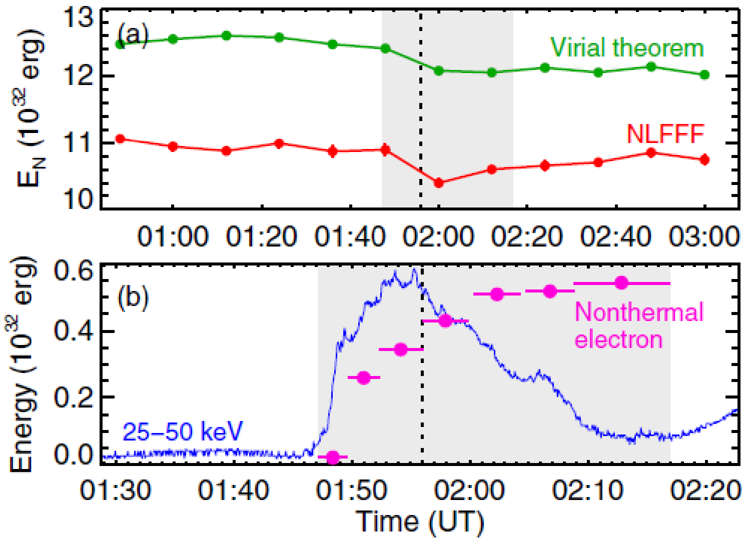




Elec/magnetic energy = 0.51+0.17
Ions/magnetic energy = 0.17+0.17
CME/magnetic energy = 0.07+0.14
direct/magnetic energy= 0.07+0.17

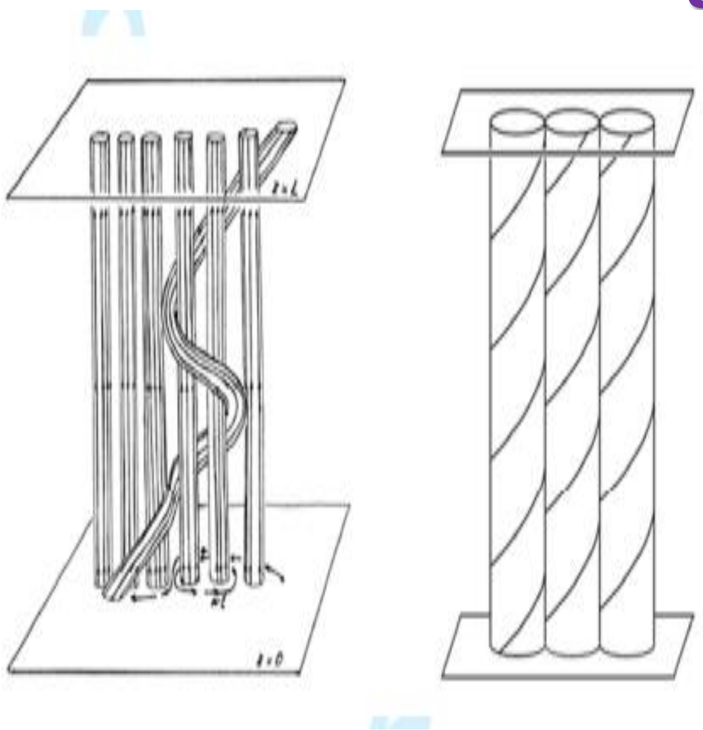
ENERGY CLOSURE :
Sum/magnetic energy = 0.87+0.18

From Aschwanden et al 2017

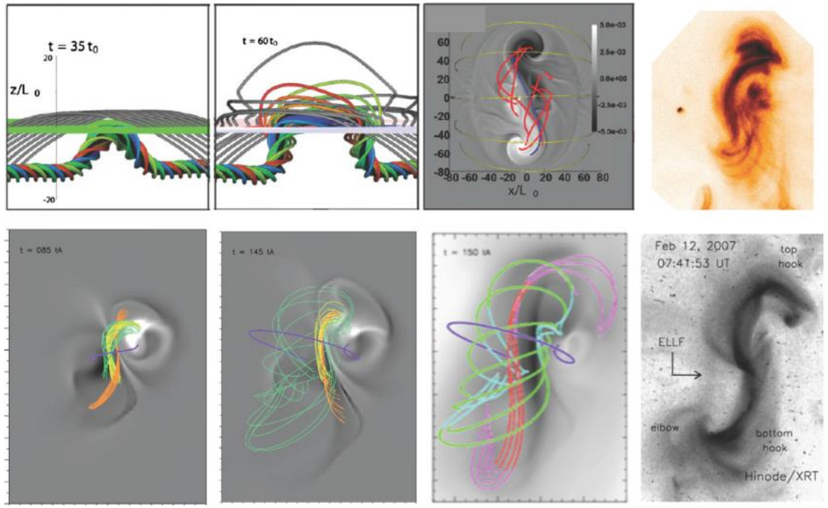


From Sun et al 2012

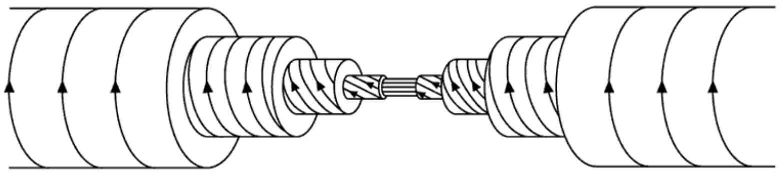
Twisted and braiding of magnetic fields



- **Energy is built up in coronal magnetic field through photospheric footpoint motions which shear, twist or tangle the fieldlines**
- **Force-free fields j X B = 0 has free magnetic energy above potential state associated with currents**



- **Flux ropes are reservoirs of magnetic energy**



Coronal flux rope generation by flux emergence or photospheric driving
Aulanier et al 2010, Leake et al 2013, Janvier et al 2015

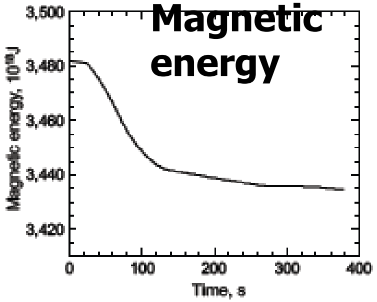
Energy release in twisted flux ropes

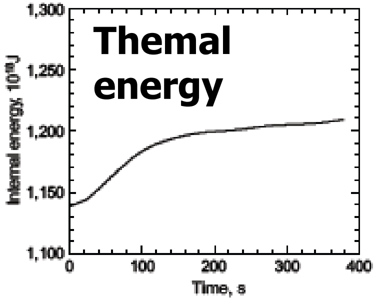
Energy release through reconnection triggered by onset of ideal kink instability

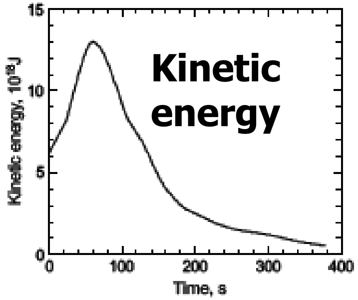
- **3D MHD simulations of nonlinear kink in instability in cylindrical flux rope**

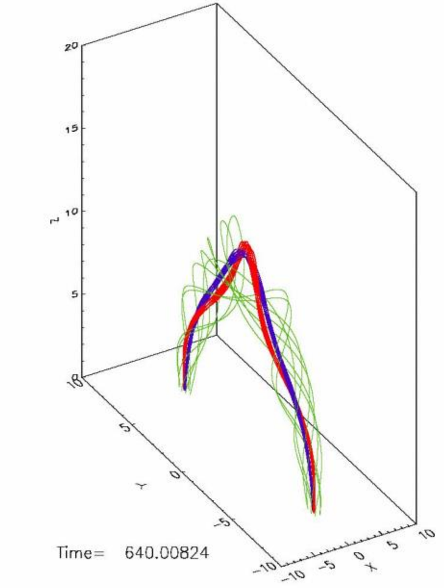
Browning et al, 2008, Hood et al 2009, Gordovskyy et al 2014, Pinto et al 2016

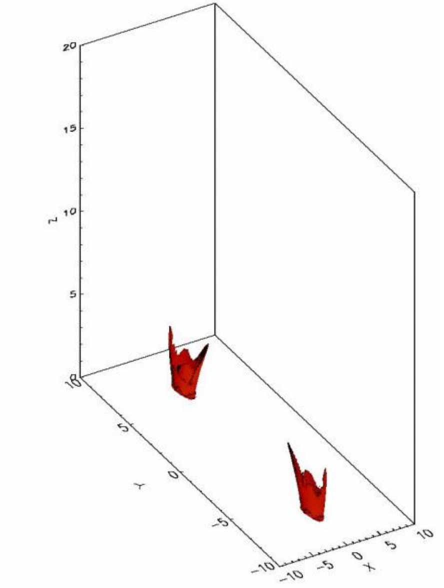
- **Current sheet fragments - reconnection at many sites throughout loop volume**
- **Release of magnetic energy leads to plasma heating – helicity-conserving Taylor relaxation**

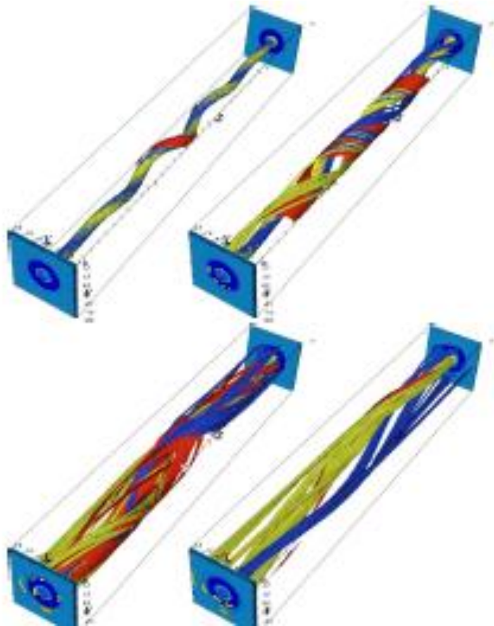


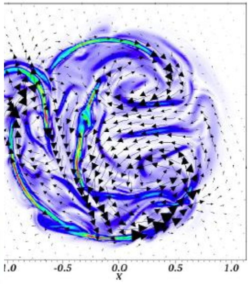












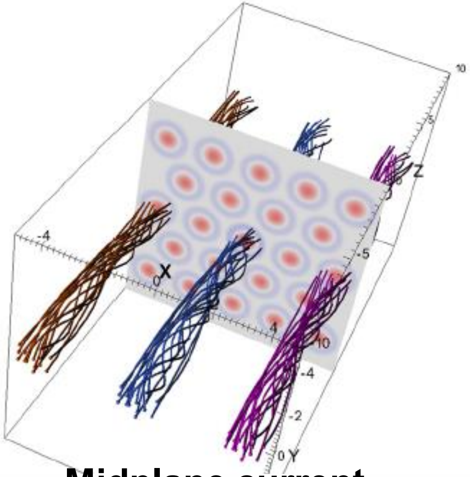
Heating avalanches and coronal heating

- Instability in one twisted magnetic flux rope may drive instability and reconnection in stable neighbours – a heating "avalanche"

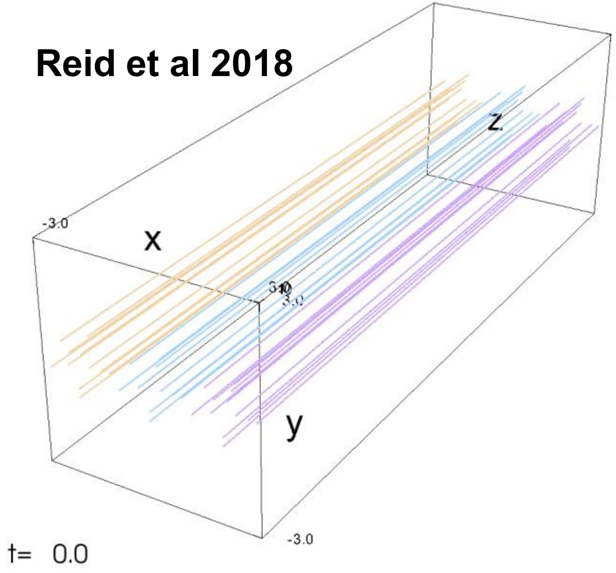
Tam et al, 2015, Hood et al 2016

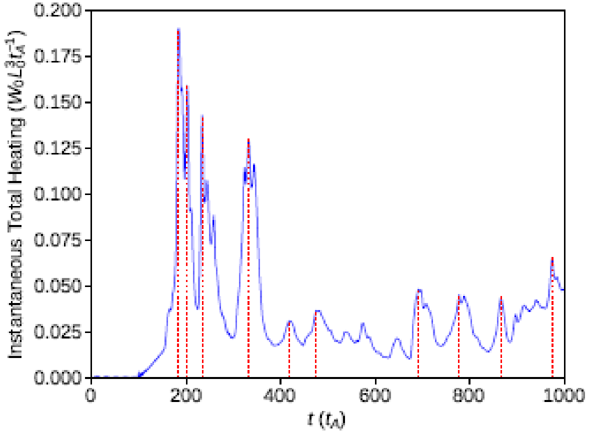
- Repeated heating events in case of continuous footpoint driving

Reid et al 2018

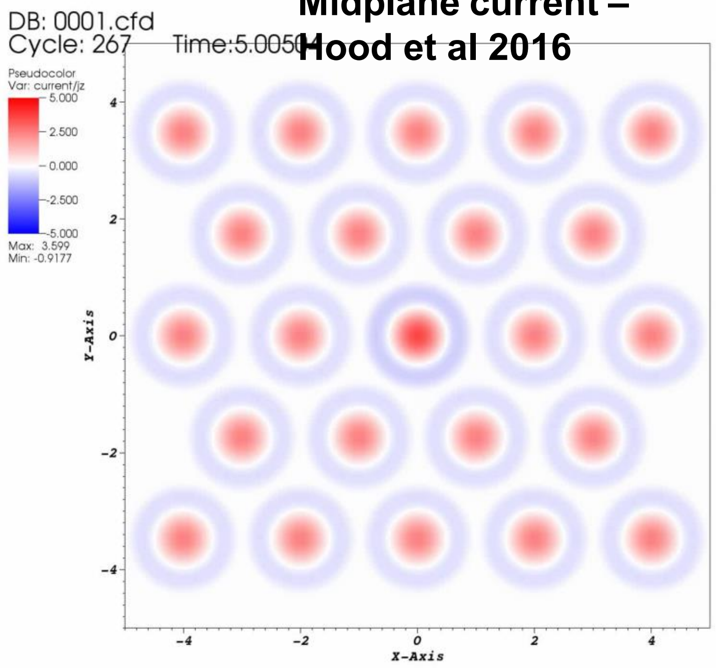


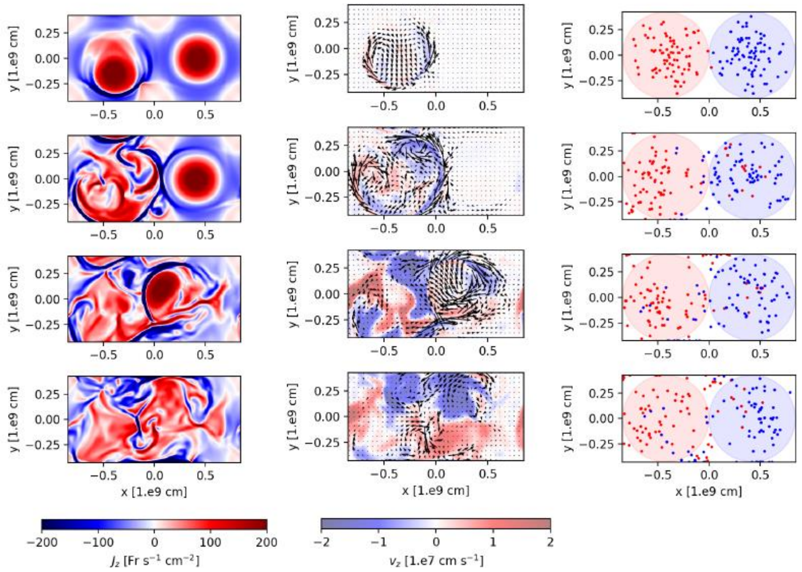
Reid et al 2018



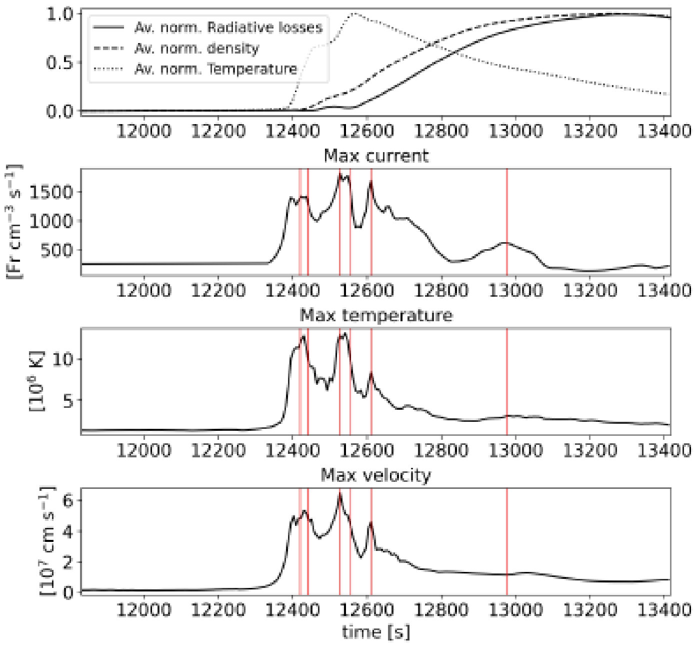


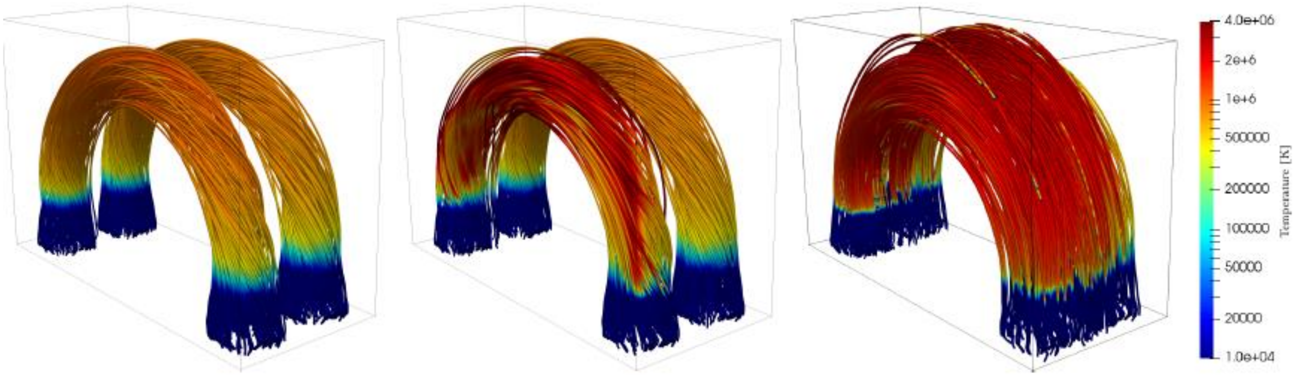
Midplane current – Hood et al 2016





Radiative losses, density, temperature and velocity in multi-strand loop
Cozzo et al 2023

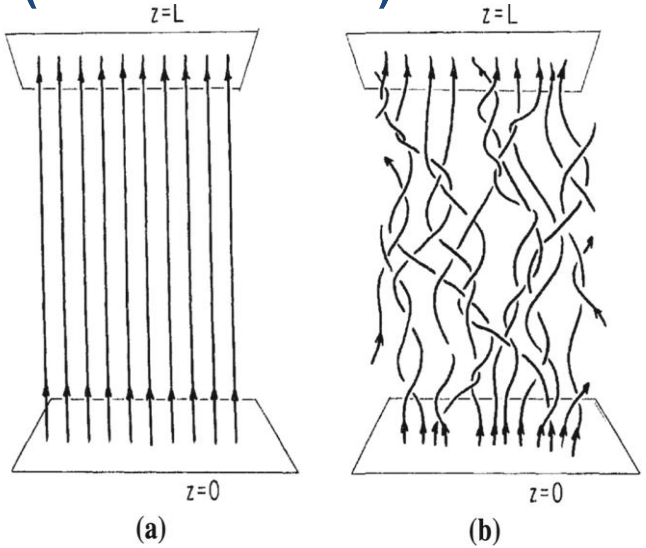




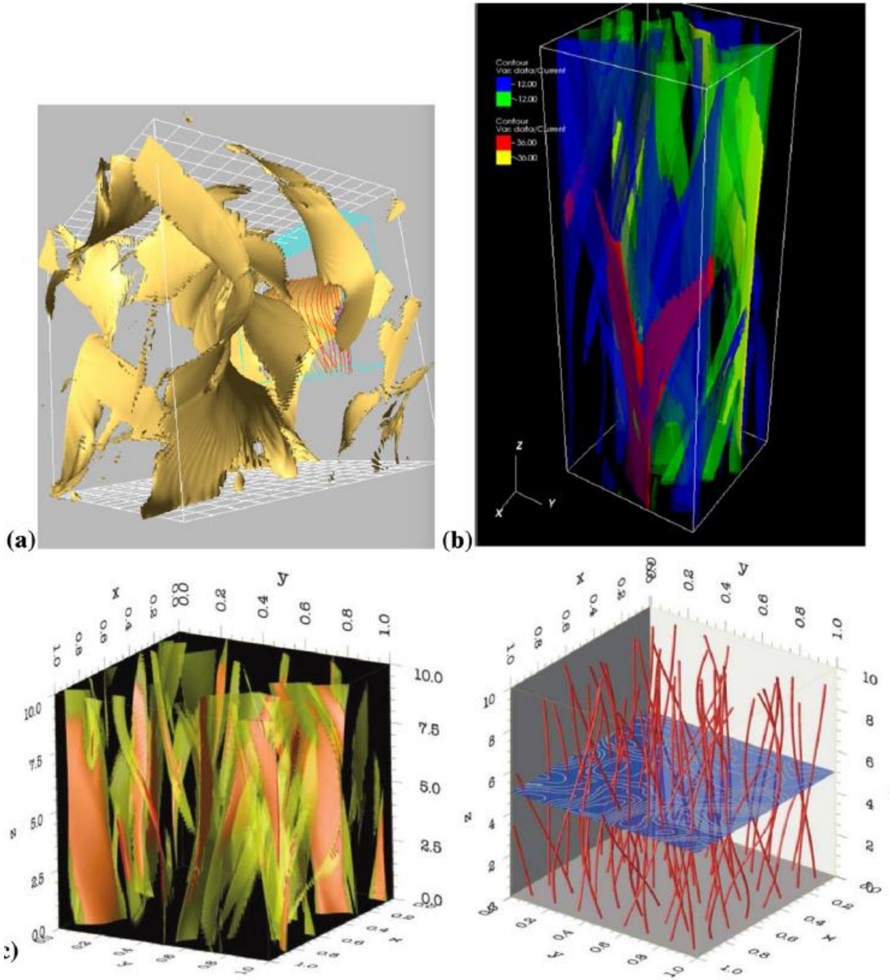
Cozzo et al 2024

Braiding of magnetic fields

Parker (1972) proposed that a smooth field perturbed by footpoint motions will relax to an equilibrium containing current sheets (discontinuities)



Tangling of magnetic fields by footpoint motions
Parker 1994

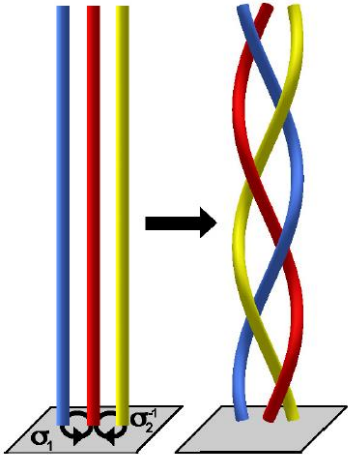


Statistical steady states achieved in 3D MHD flux braiding simulations – dissipation by reconnection balances energy input from footpoints

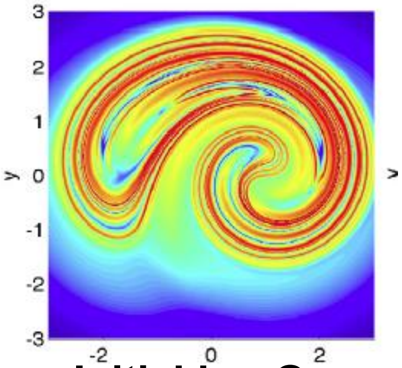
From Pontin and Hornig 2020 (Galsgaard and Nordlund, 1996, Rapazzo et al, 2007, 2008, Ng et al 2012)

Numerical simulations of braiding

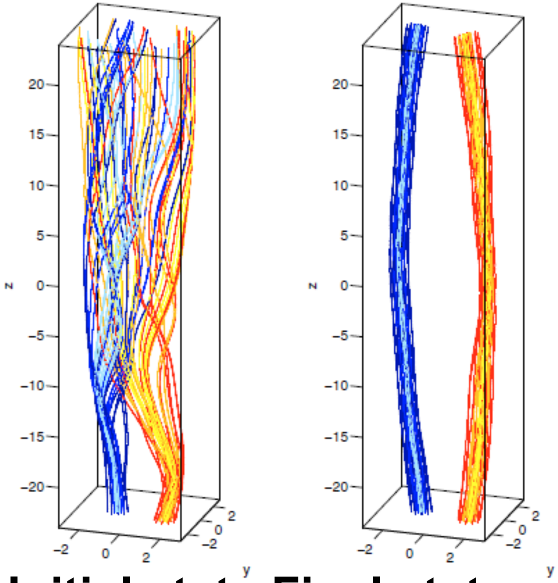
Initial braid by imposing twists
Relax to equilibrium then 3D MHD simulations
Wilmot-Smith et al 2010, 2012, Pontin et al 2011



Zero net-current braid

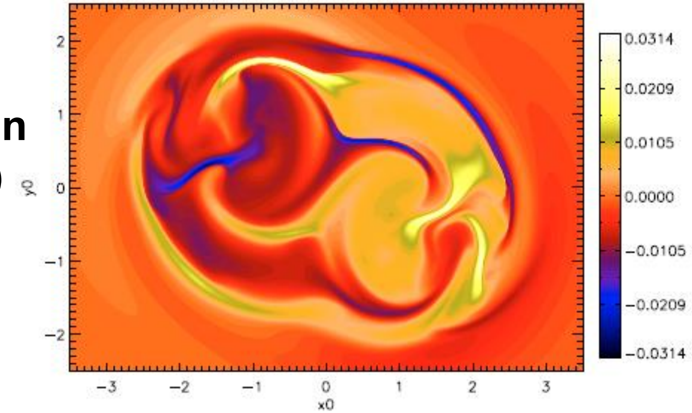


Initial log Q map (Q is "squashing factor" of field lines)



Initial state Final state

Reconnection rate $E_{//}$ (t=50)



- Fragmented current layers develop, reconnection at many sites
- Field "unbraids", with partial relaxation to two flux ropes with weak opposite twists
- Magnetic energy is released, plasma heats

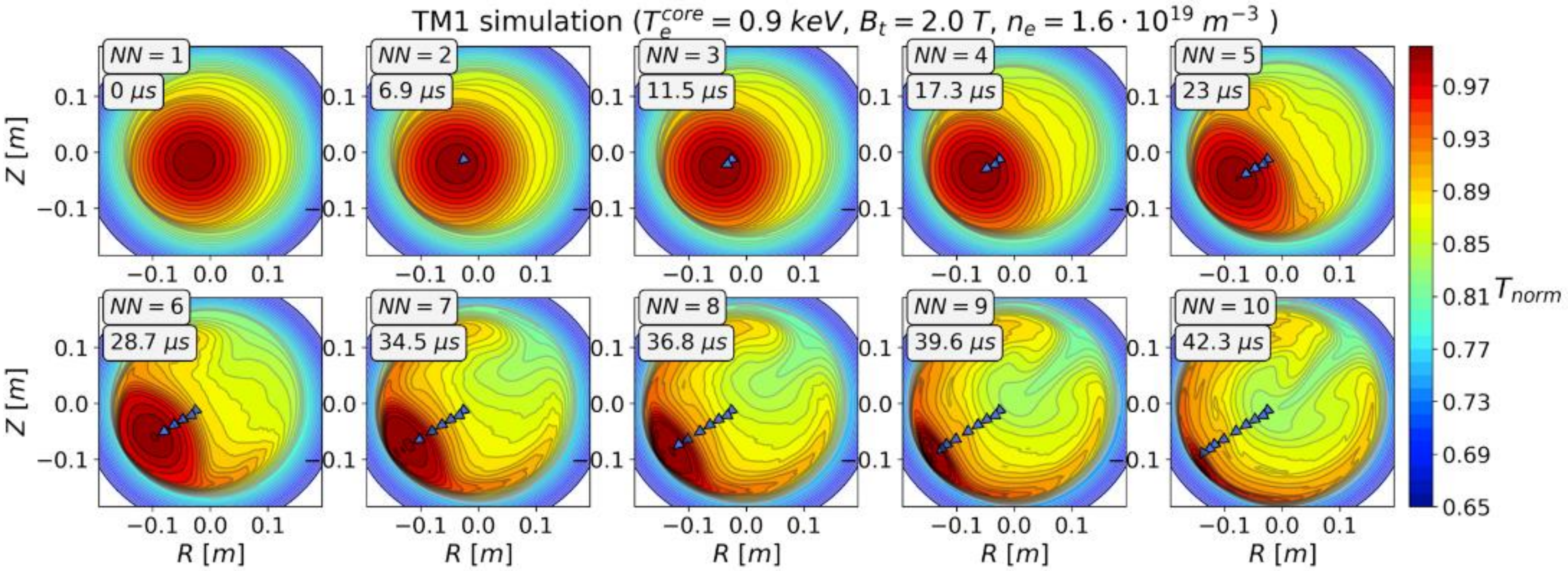
5. Geometry

2D or not 2D?

Most of the analytical and numerical investigations even in space and in relativistic astrophysical contexts involve 2D configurations (or geometries that are effectively two dimensional) even in the absence of a guide field

To which extent in your field you can rely on a 2D picture?

Geometry

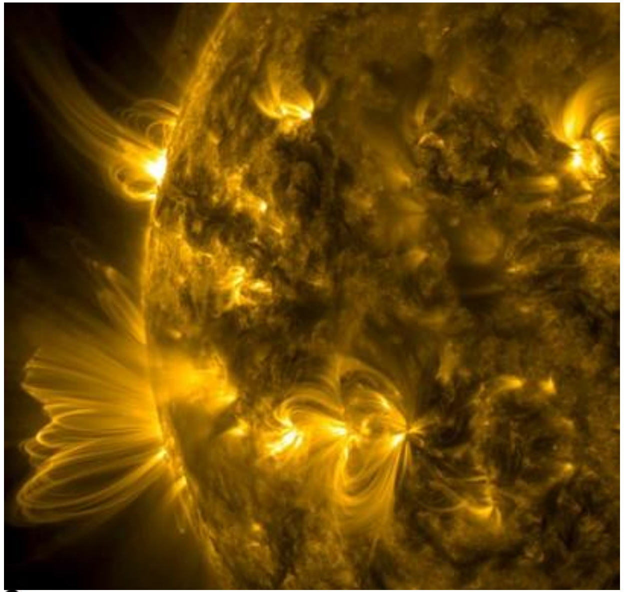


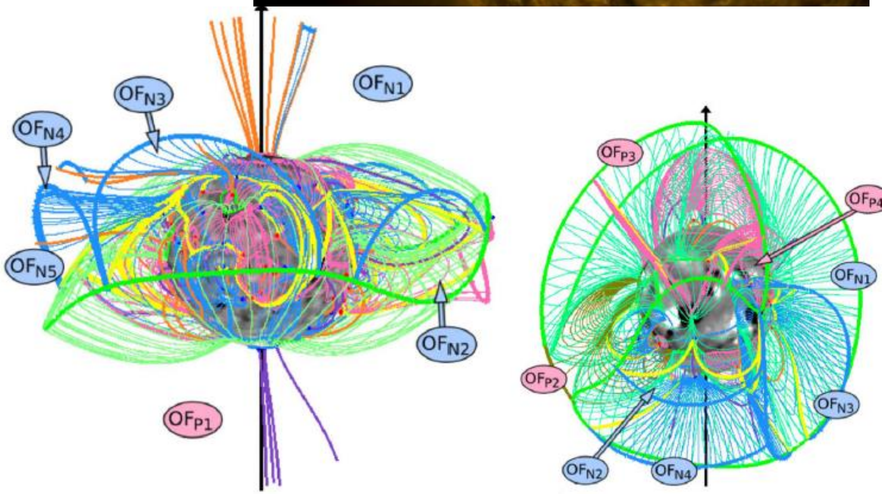
- Sawtooth crash in AUG. In magnetic fusion 3D effects matter but are seldom determinative: a 2D picture gives good predictions.

The solar corona is 3D!

- Coronal magnetic fields lack symmetry and have complex topology
- Generated by multiple photospheric flux sources
- Twisting, braiding and emerging flux generate 3D structure
- Reconnection can occur in 3D magnetic fields at 3D nulls, also separators and other locations including QSLs
- 3D reconnection differs in many fundamental ways from 2D paradigm

Reviews - Pontin 2011, Janvier 2015, Pontin and Priest 2022

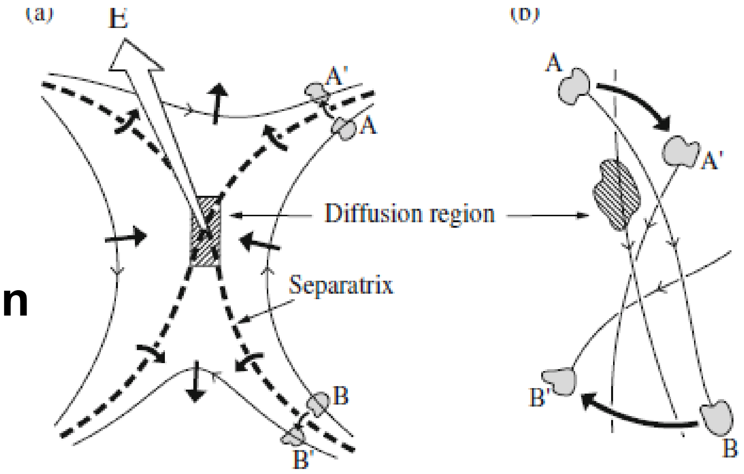


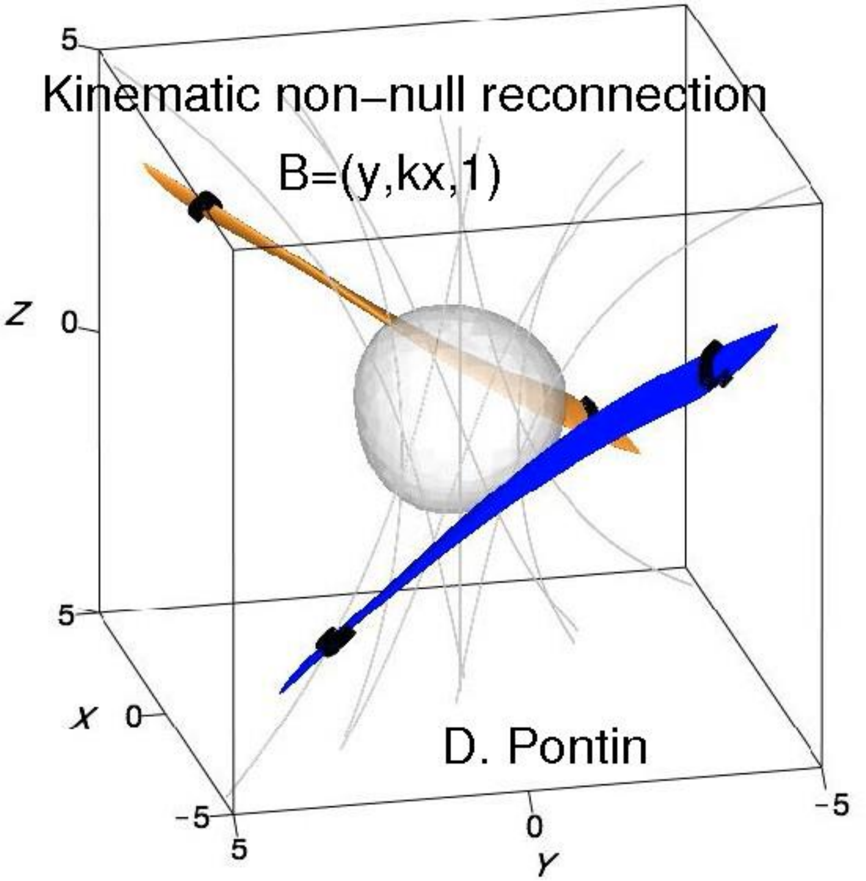


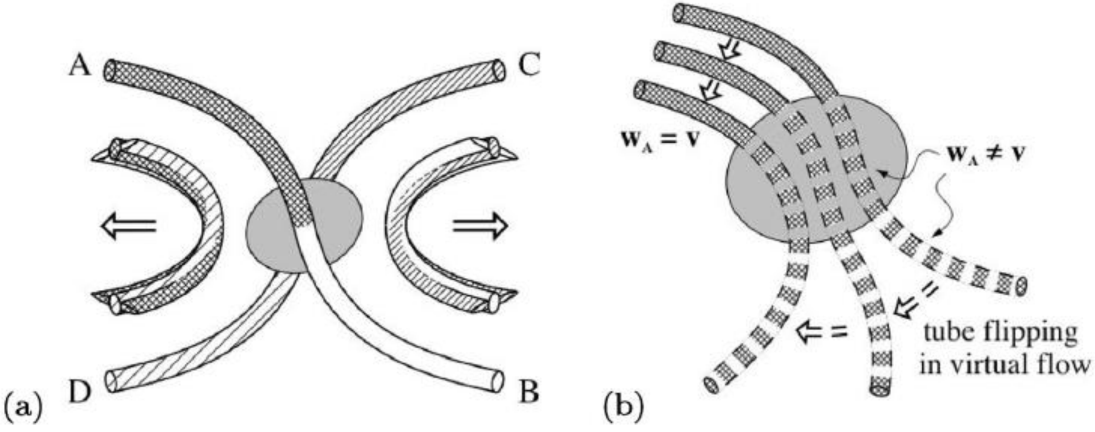
Magnetic topology at solar minimum and solar maximum Showing Open Field regions with +/- polarity; seperators; separatrix surfaces; nulls. Linking to heliospheric current sheet
Platten et al 2014

2D vs 3D reconnection

Priest 2019



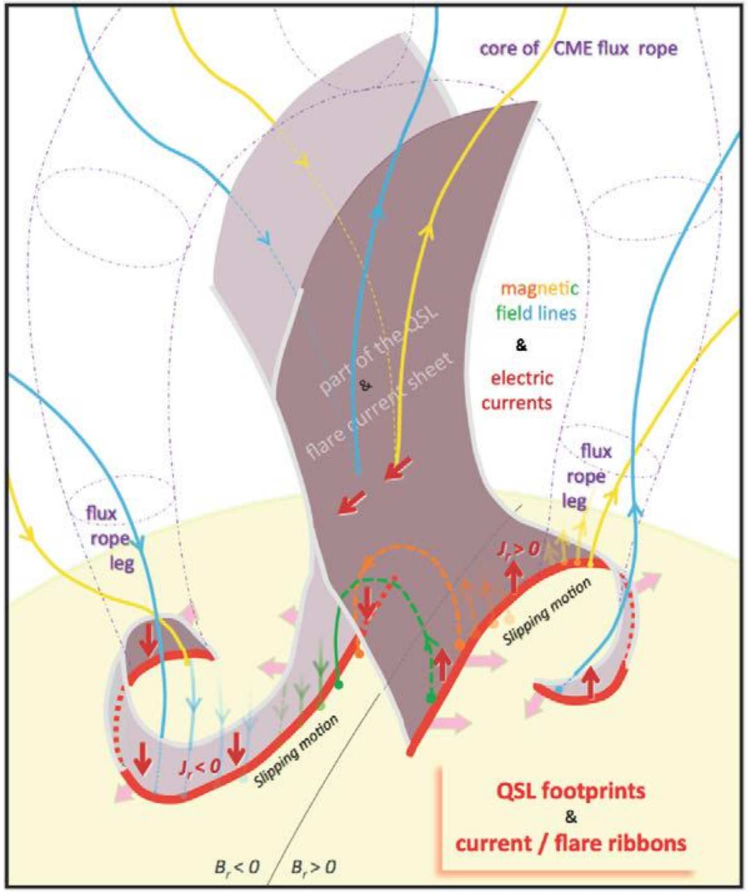


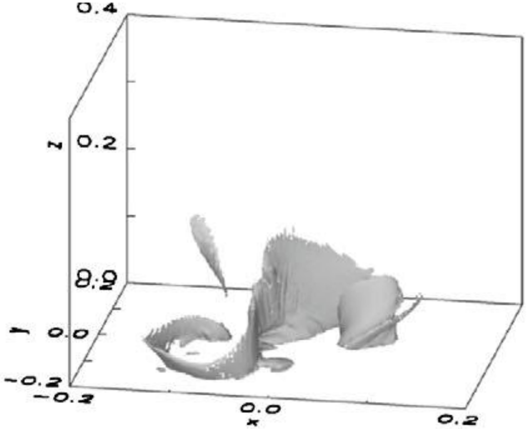


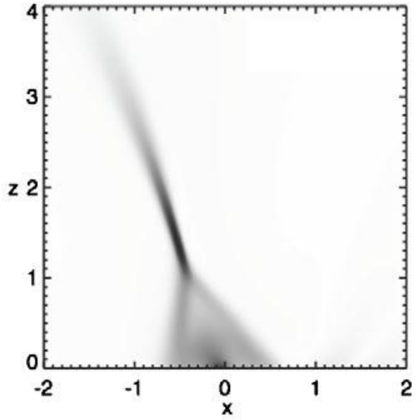
Priest et al, 2003; Hornig and Priest, 2003; Pontin 2011; Pontin and Priest 2022

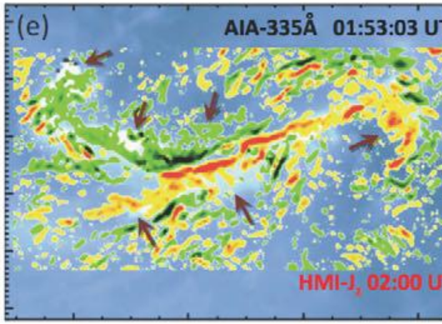
3D solar flare model

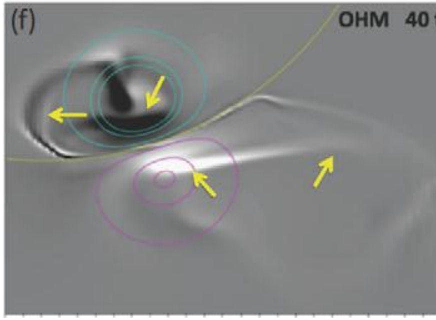
Janvier et al 2014





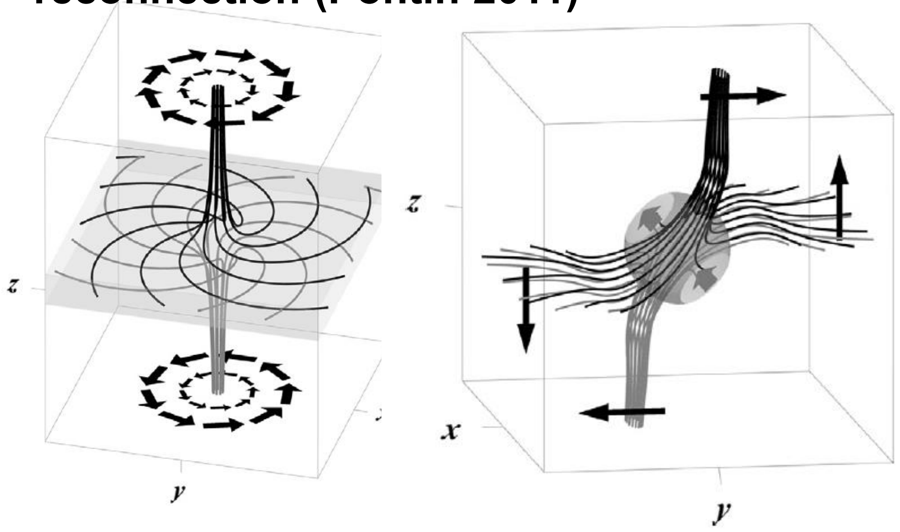




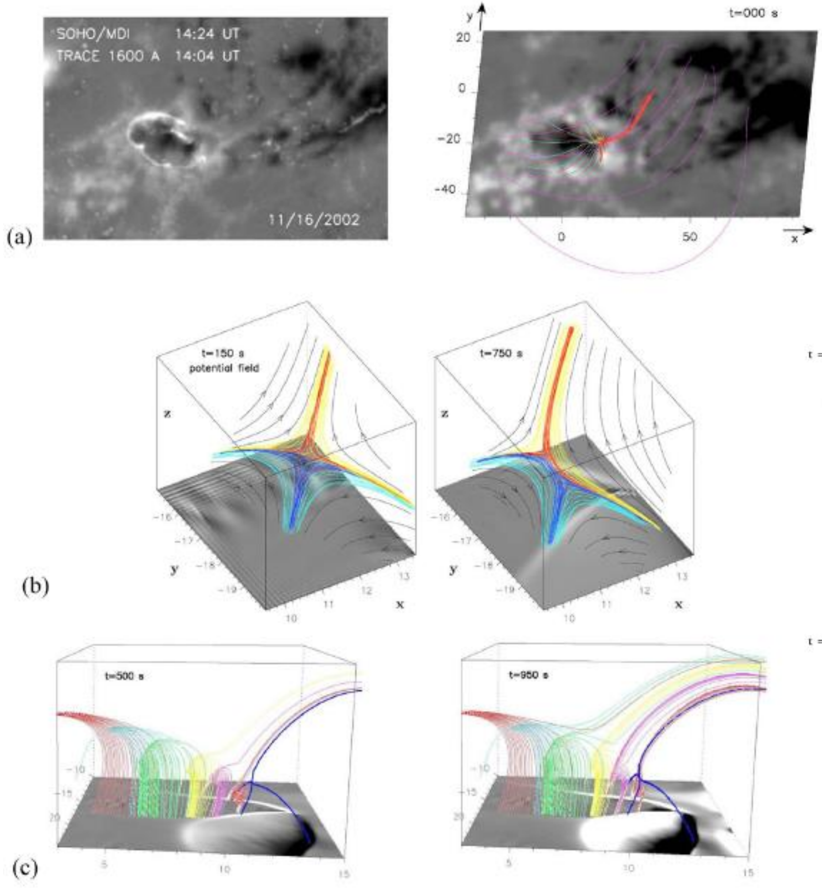


Reconnection at 3D nulls

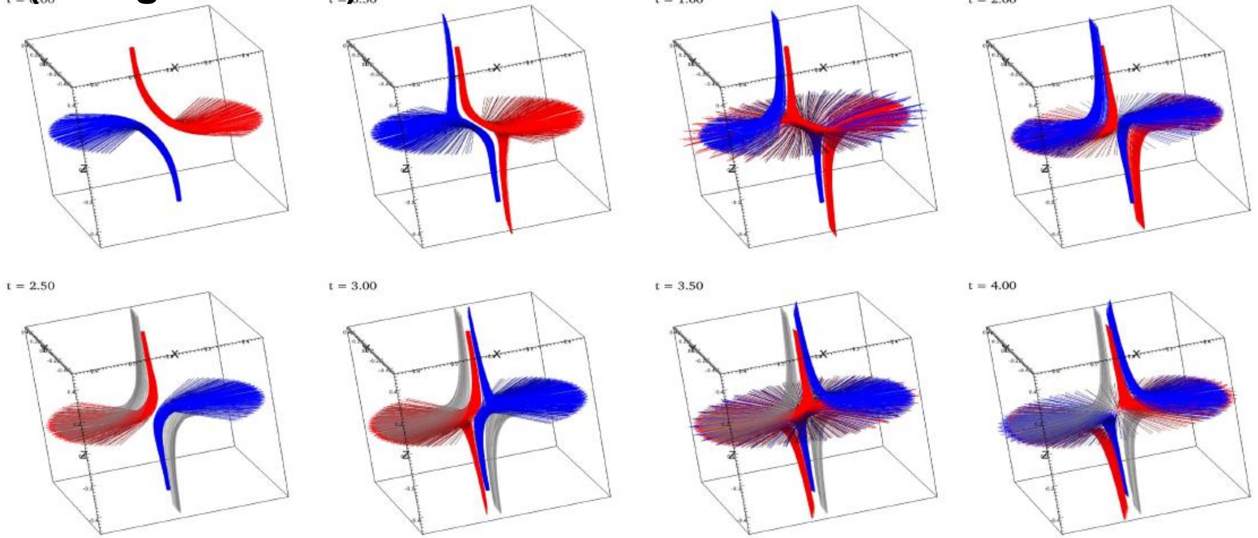
Torsional fan reconnection and spine fan reconnection (Pontin 2011)



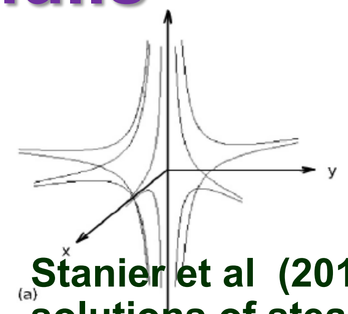
Null point reconnection in a flare (Masson et al 2009)



Oscillatory spine-fan reconnection at 3D null (Thurgood 2017)

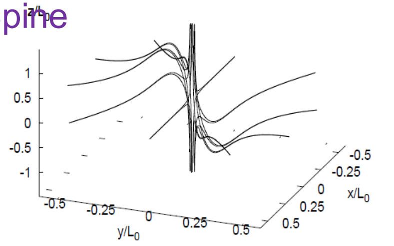


Particle acceleration at reconnecting 3D nulls

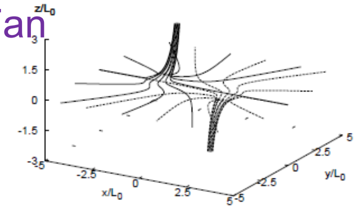


First models of ion and electron acceleration with simple field models – *Dalla and Browning, 2005,2006, 2008; Browning et al 2010*

Spine



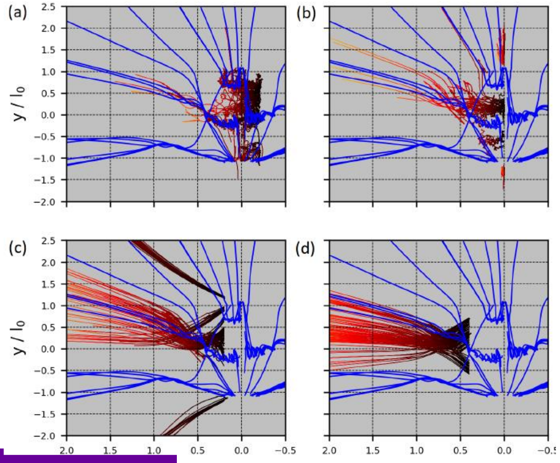
Fan



- **Stanier et al (2012, 2013) use background fields from exact solutions of steady MHD equations**

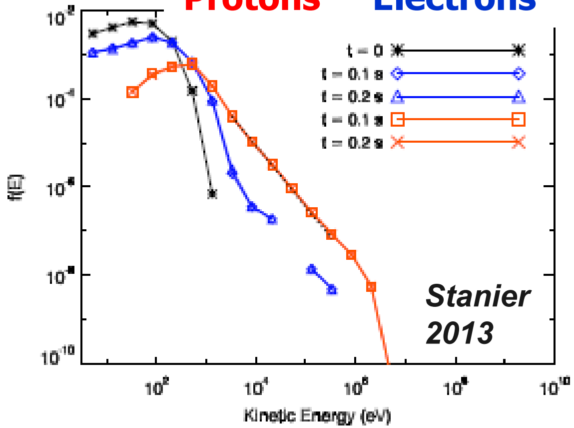
(Craig and Fabling, 1996, Craig et al 1997....)

- ***Threlfall et al (2015)* 3D separator reconnection – 2 nulls**



Protons in 3D MHD simulation of reconnecting null *Pallister and Pontin 2019*

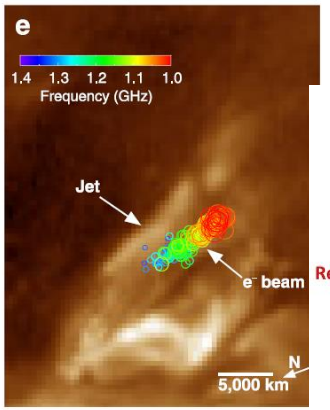
- **Initially strong energetic population**
- **In later phases current sheet fragments, power law tail**

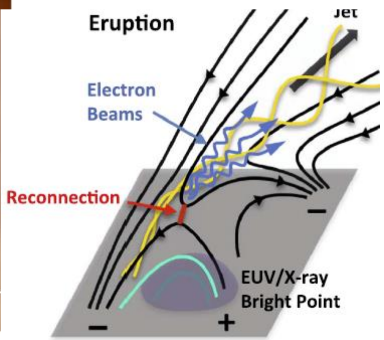


MANCHESTER 1824

Evidence for particle acceleration at 3D nulls

- *Chen et al 2018* - VLA observations of Type III bursts diverging from compact region in lower corona - supposed to be 3D null

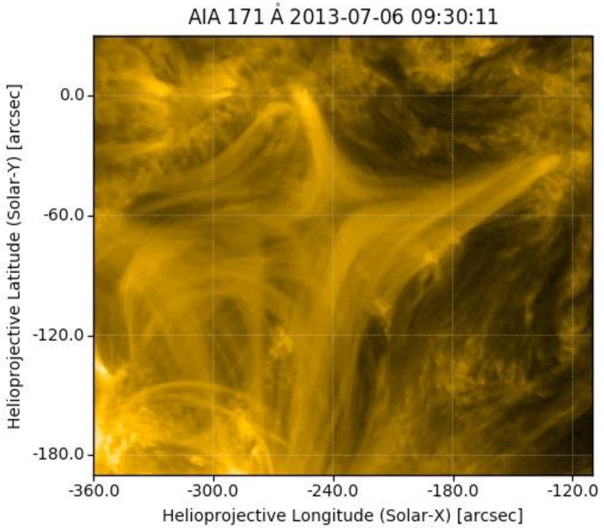




- *O'Flannagain et al A&A 2018*

- NRH observations of Type I radio source associated with collapsing 3D magnetic null

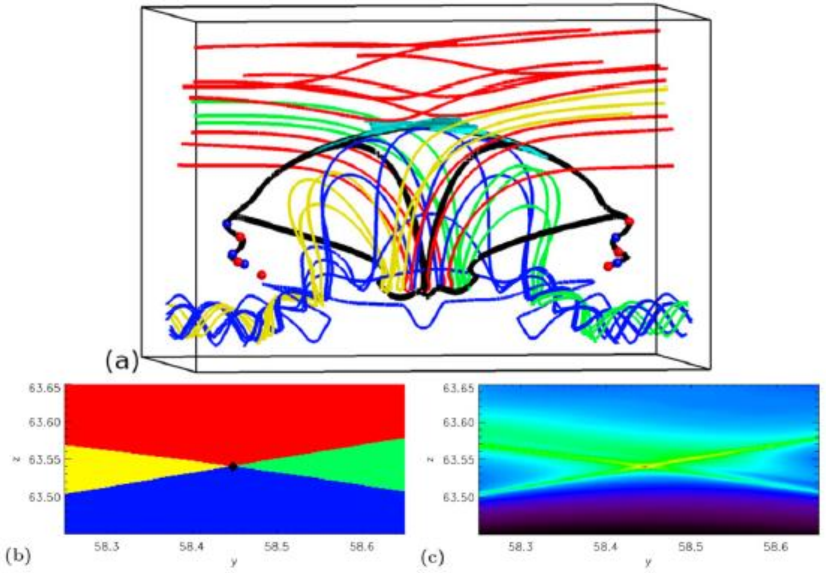
- Variation of radio emission interpreted as increase/decrease of electron acceleration due to decrease/increase of magnetic field



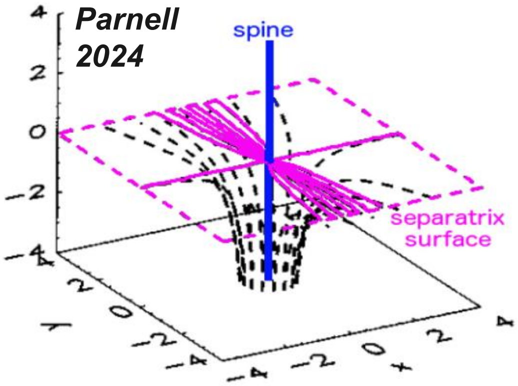
- And in laboratory experiment – *Chesny et al 2021*

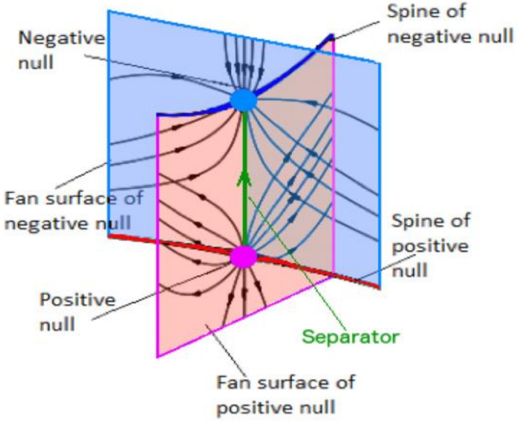
Separator reconnection

Separator field lines link magnetic nulls

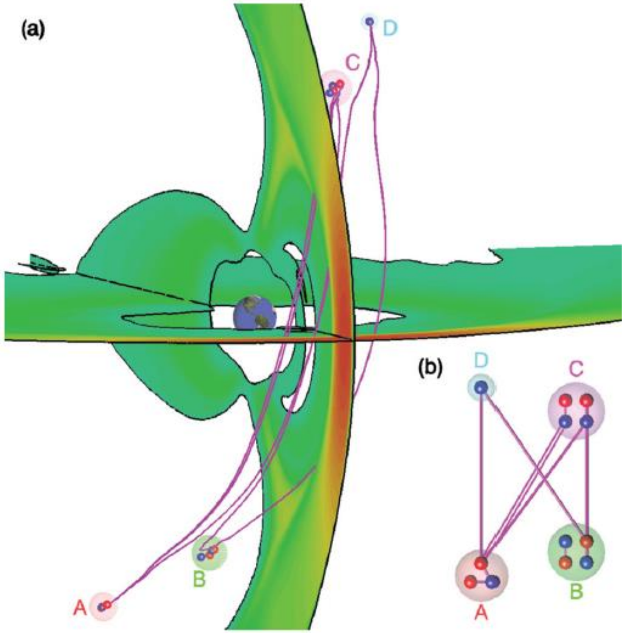


Separators and topological structure in flux emergence simulation- showing field line connectivity and parallel electric field
Parnell et al 2010, 2024





Topology of dayside magnetopause
Haynes and Parnell, 2010, 2024



6. Turbulence

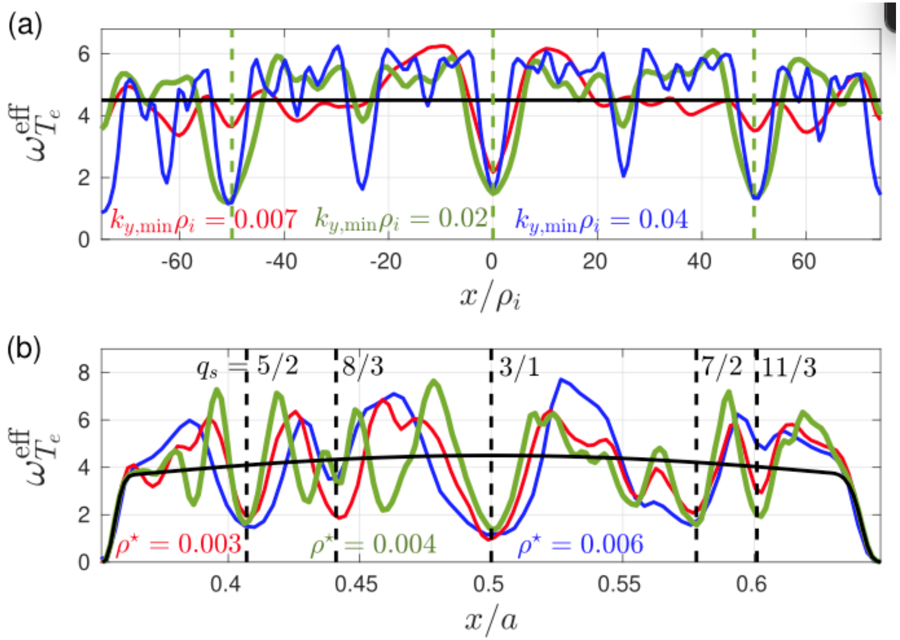
MR and turbulence:

Recent numerical investigations have analyzed the role on magnetic reconnection in the turbulent spectrum of weakly dissipative plasmas. On the other hand the interaction of MR and turbulence is relevant for transport processes.
Is there corresponding observational evidence from space plasmas? From the solar wind? From fusion?

How MR influences turbulence and viceversa in your field?

Turbulence

- Magnetic reconnection can be a source of turbulence in the form of the micro-tearing mode, which is believed to be important in the edge transport barrier in tokamaks.
- Turbulence in magnetic fusion is dominantly electrostatic but at prevailing beta, the unstable interchanges drive stable tearing modes resulting in magnetic braiding.
- The effect of turbulent fluctuations on the reconnection rate is an open question.
- Magnetic reconnection can also be a source of turbulence in the plasmoid reconnection regime.



Time-averaged ω_T as function of radial coordinate. (Ajay C.J., B.F. McMillan and M.J. Pueschel, NF2023)

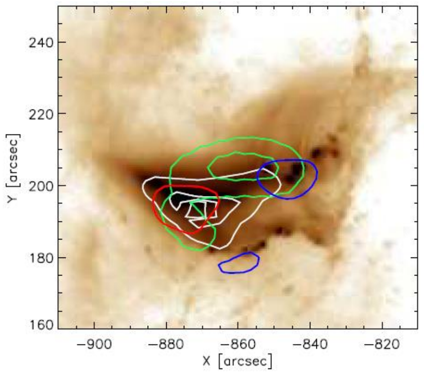
Space Sci Rev (2013) 178:325–355
DOI 10.1007/s11214-013-0022-6

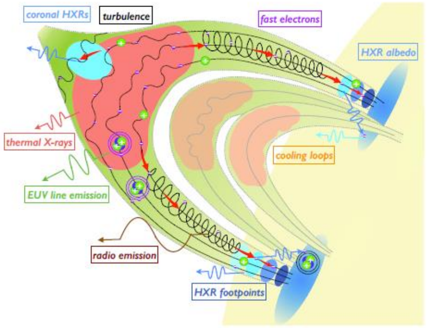
Notes on Magnetohydrodynamics of Magnetic Reconnection in Turbulent Media

Philippa Browning · Alex Lazarian

- Turbulence can generate fast reconnection in MHD
- Kinetic turbulence within current sheet can create anomalous resistivity
- "Strong turbulence" naturally arises in solar corona with fragmentary current sheets – leads to particle acceleration
- Turbulence in fast reconnection outflows accelerates particles

Turbulence



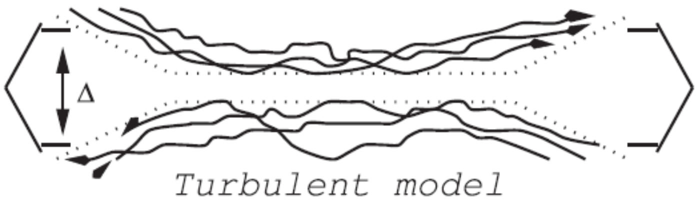


Turbulence in solar flare (Kontar et al 2017) Energy content ~ 10^{21} J, dissipated in a few s

- **Turbulence on MHD and kinetic scales affects reconnection - earing and reconnection can lead to turbulence and multiple islands, current fragmentation**
- **Many models consider turbulence as a source of particle acceleration**
  - **but evidence from tokamaks that stochastic fields also proposed to remove electrons from acceleration sites and reduce acceleration**

McClements 2019

- **Processes are different in 2D versus 3D**
- **Also depends on magnitude of gyroradius relative to current sheet width**



Turbulent reconnection inflow leads to fast reconnection (Lazarian and Vishniac 1999)

Anomalous resistivity

- **If $v_e \gg c_s$(electron drift velocity exceeds ion sound speed), then ion acoustic waves interact strongly with particles**
- **Happens if current layer is sufficiently narrow**
- **These microstabilities give effective larger resistivity, broadening current layer until drift velocity drops below critical value – "anomalous resistivity"**

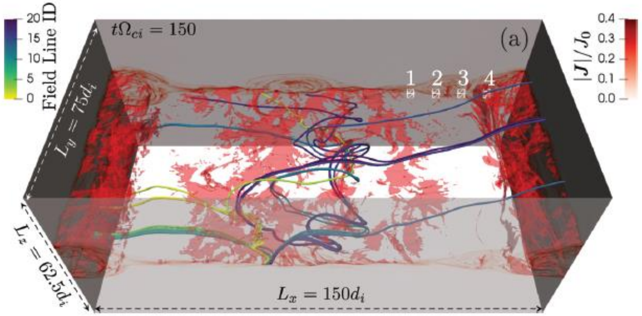
- **More generally, anomalous resistivity is an effective resistivity arising from micro-scale instabilities/turbulence such as Lower-Hybrid Drift Instability (e.g. *Ricci et al Phys Plas 2005*)**

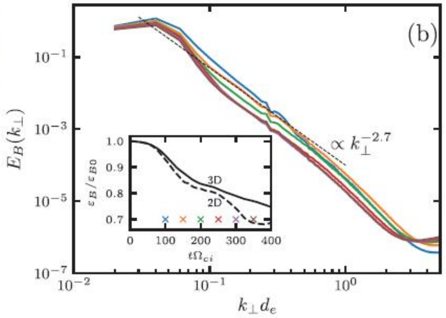
- **Predictions of resistivity from kinetic simulations e.g. *Huba et al GRL (1977)*; *Buchner and Elkina Phys Plas (2006)***

- **A means to bridge kinetic and global scales**

- **3D turbulence with stochastic magnetic fields allow particles to access regions of high acceleration repeatedly**
  - **Acceleration more effective in 3D than 2D**

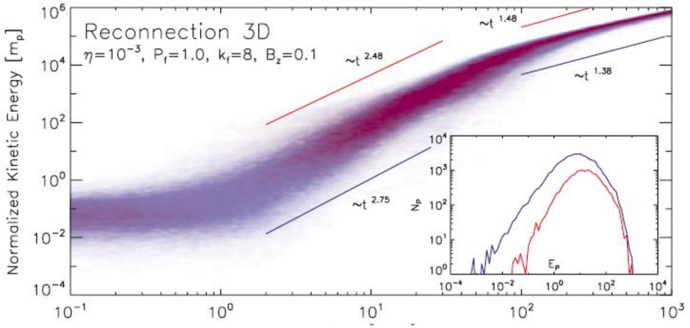
Li et al 2019, 2021

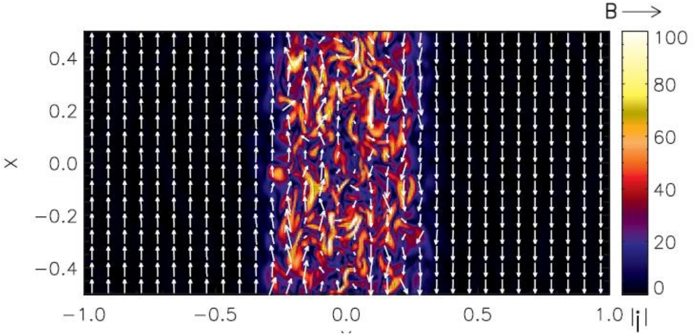




- **Particle acceleration in Sweet-Parker with 3D turbulent current sheet**
  - **First order Fermi acceleration between reconnection inflows**

de Gouevia dal Pino and Lazarian 2005, *Kowal et al 2012*



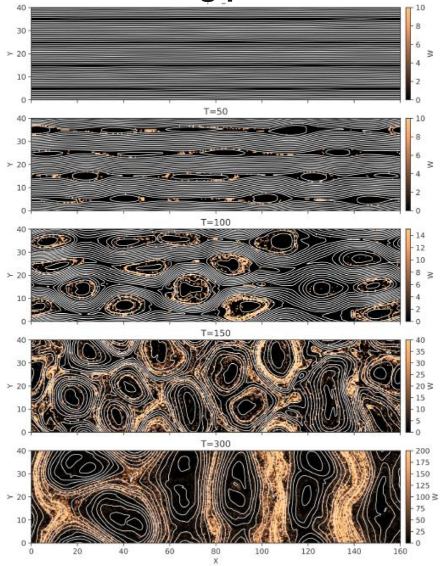


Turbulence and particle acceleration from multiple CS in 2D and 3D (MHD test particle)

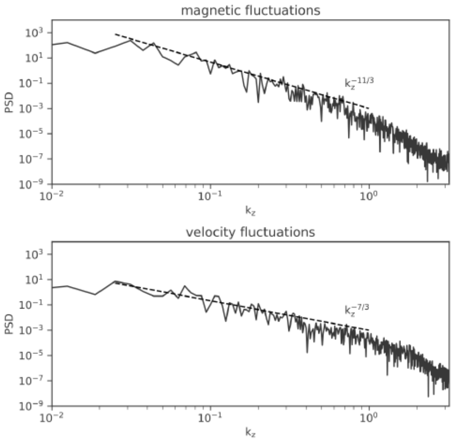
Nakanotani et al 2022

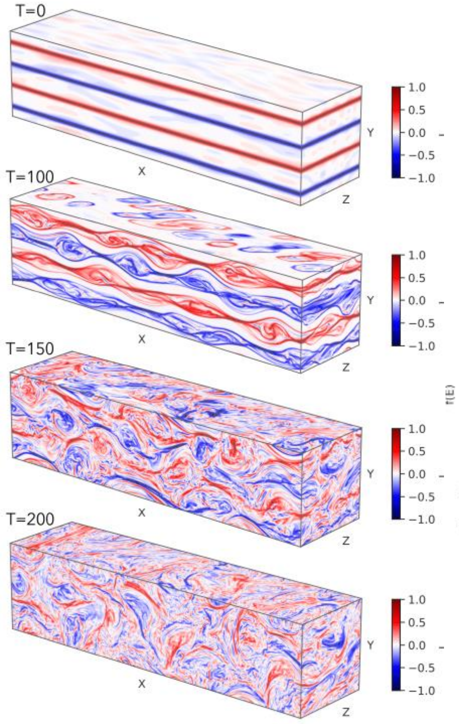
- **Efficient acceleration in contrast with kinetic simulations**
- **3D less effective than 2D due to absence of trapping**

2D – showing particles

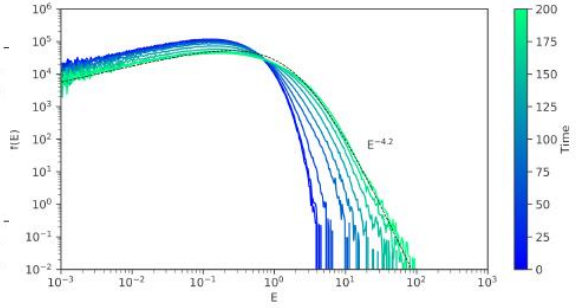


- **Superdiffusion in particle energy**





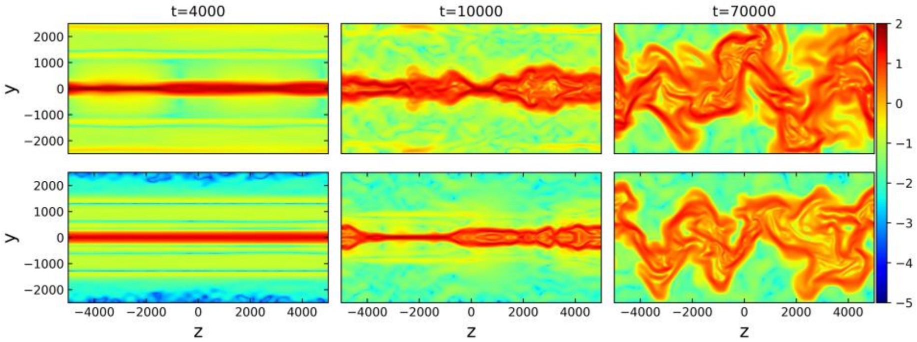
3D



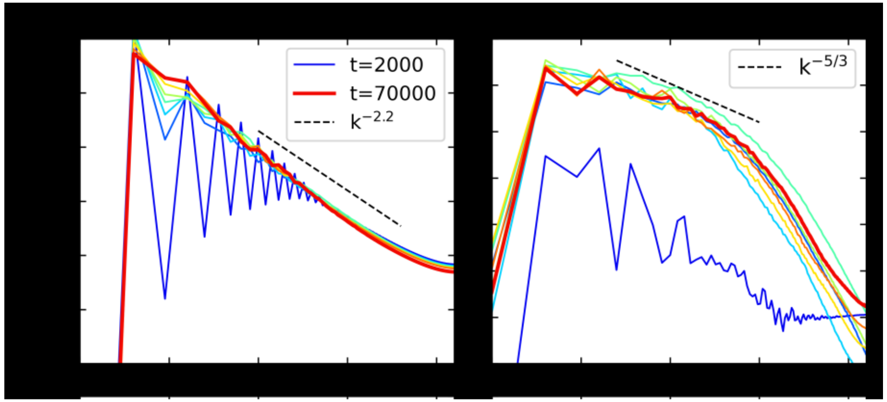
Particle energy spectrum 3D

Turbulence and particle acceleration in MHD-PIC model

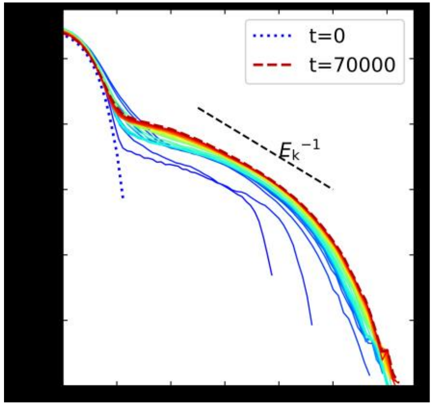
- **Turbulent state in reconnecting current sheet from combination of fragmentation (plasmoids) and Kelvin-Helmholtz**
- **Turbulence in transition scale between MHD and kinetic**



Liang et al 2023



B ***v***



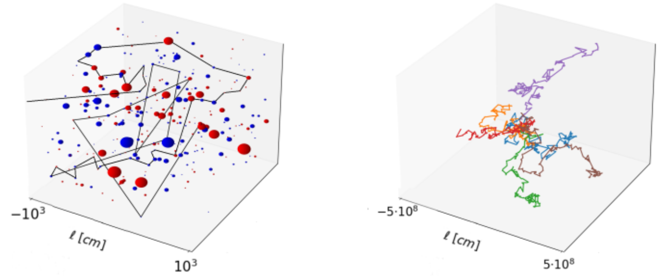
Particle energy spectrum

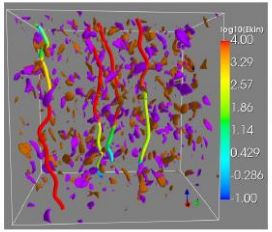
Fragmented current sheets – strong turbulence

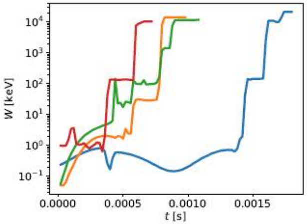
Turbulent reconnection with many CSs distributed throughout volume is a natural state giving efficient particle acceleration as particles interact with multiple CS

e.g. Arzner and Vlahos 2004, Turkmani et al 2005, Hood et al 2009, Cargill et al 2012, Gordovskyy and Browning 2011, Isliker et al 2017, Sioulas et al 2023

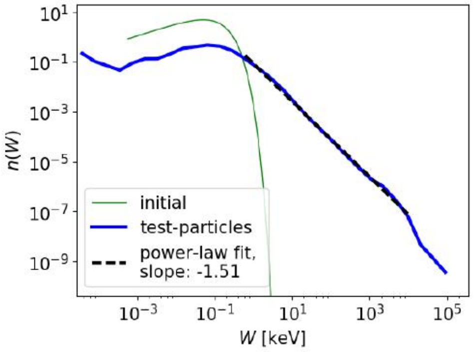
Sioulas et al 23

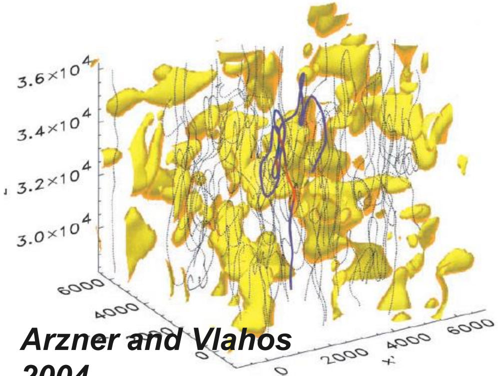






Isliker et al 17





Arzner and Vlahos 2004

Gordovskyy et al 2014