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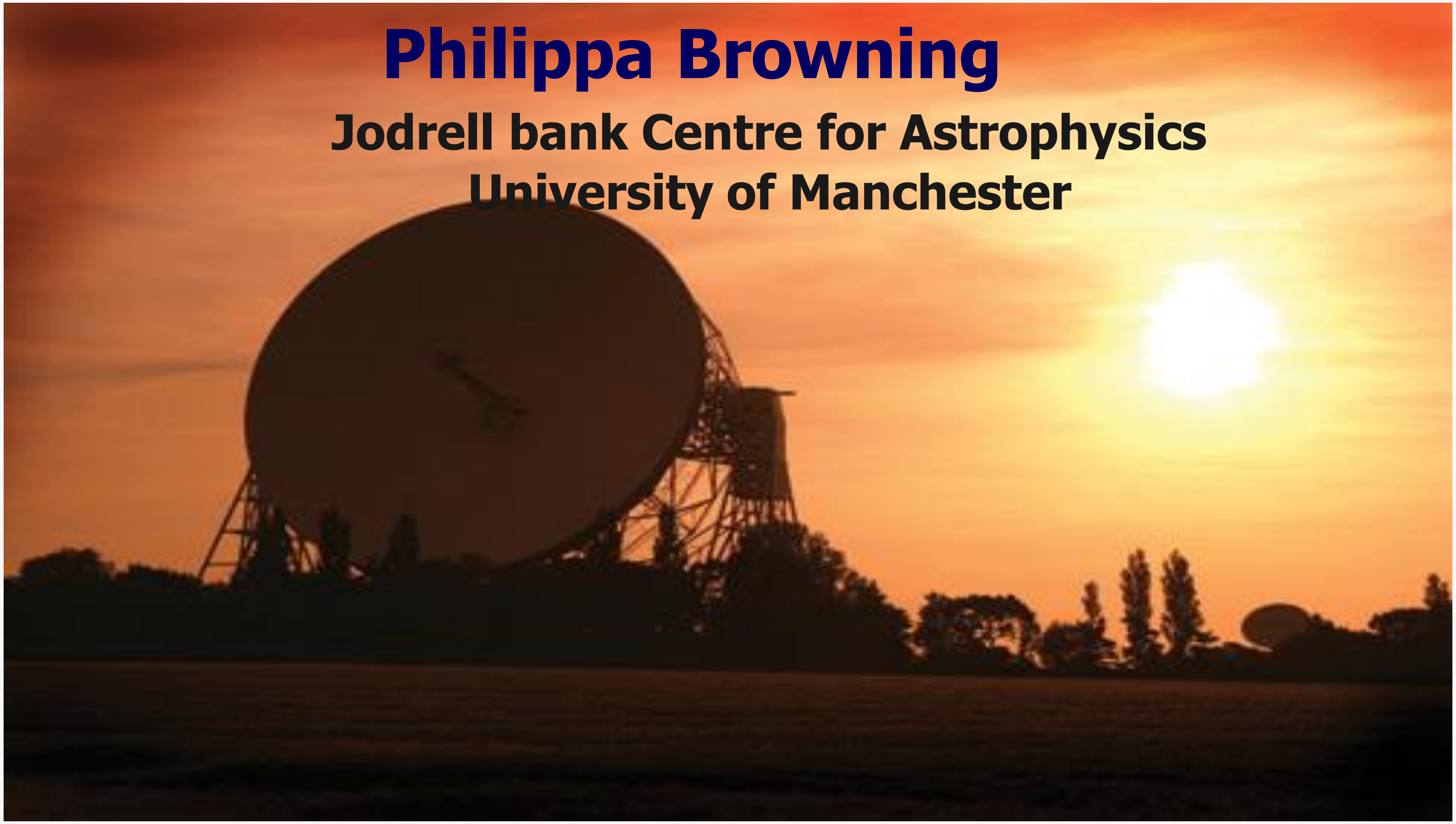
Modelling particle acceleration in solar flares



Philippa Browning

Jodrell bank Centre for Astrophysics
University of Manchester

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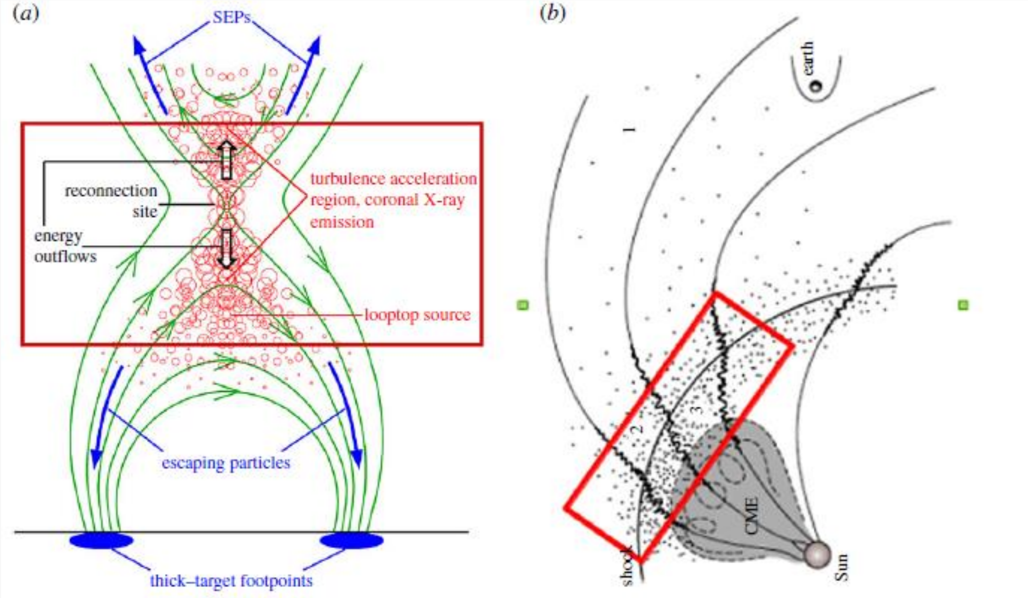
Apologies….

- **Due to limited time, I may not mention your favourite model or paper**
- **References given are illustrative rather than comprehensive**
  - **See reviews for more complete references e.g. Zharkova et al Space Sci Rev 2011, Vlahos et al Phil Trans A 2019, Dahlin Phys Plas 2020, Lin et al Phys Plas 2021**

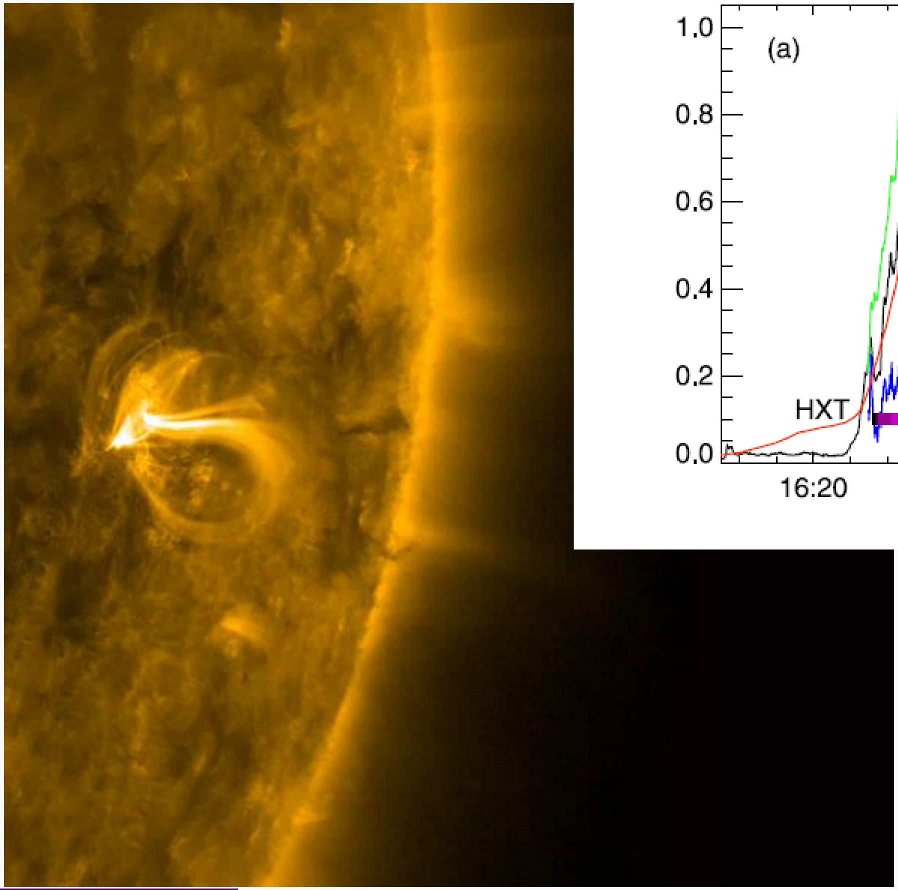
- **I will only consider acceleration at flares**
  - **CME shock acceleration not discussed here**

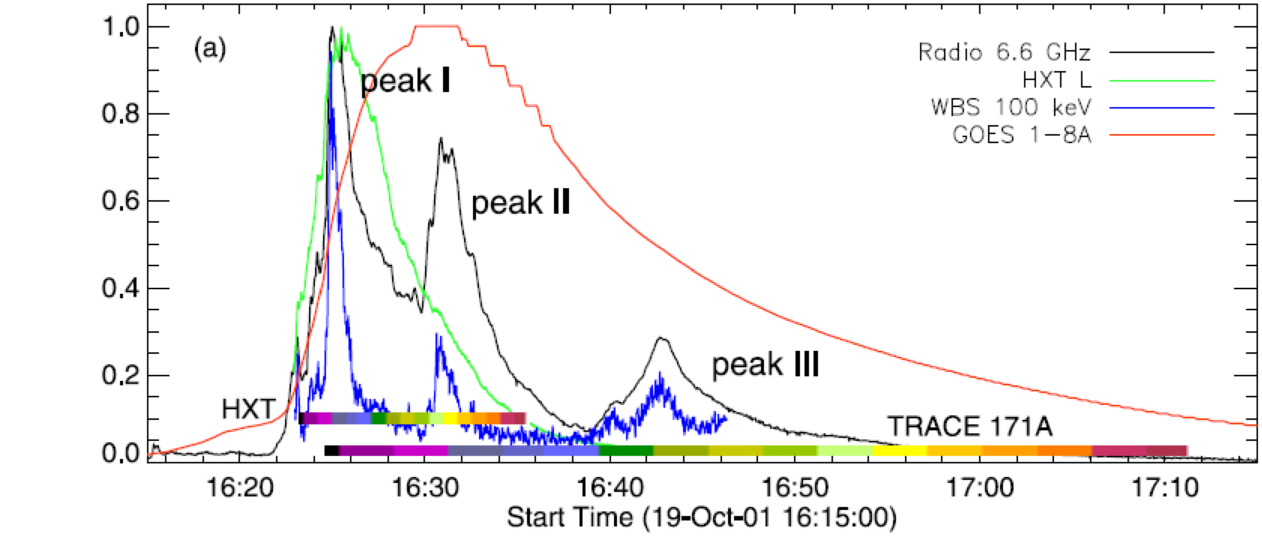


From Vlahos et al 19

Solar flares

- **Release of up to 10^{25} J over minutes/hours**
- **Emission across electromagnetic spectrum from gamma ray (large flares) to radio**



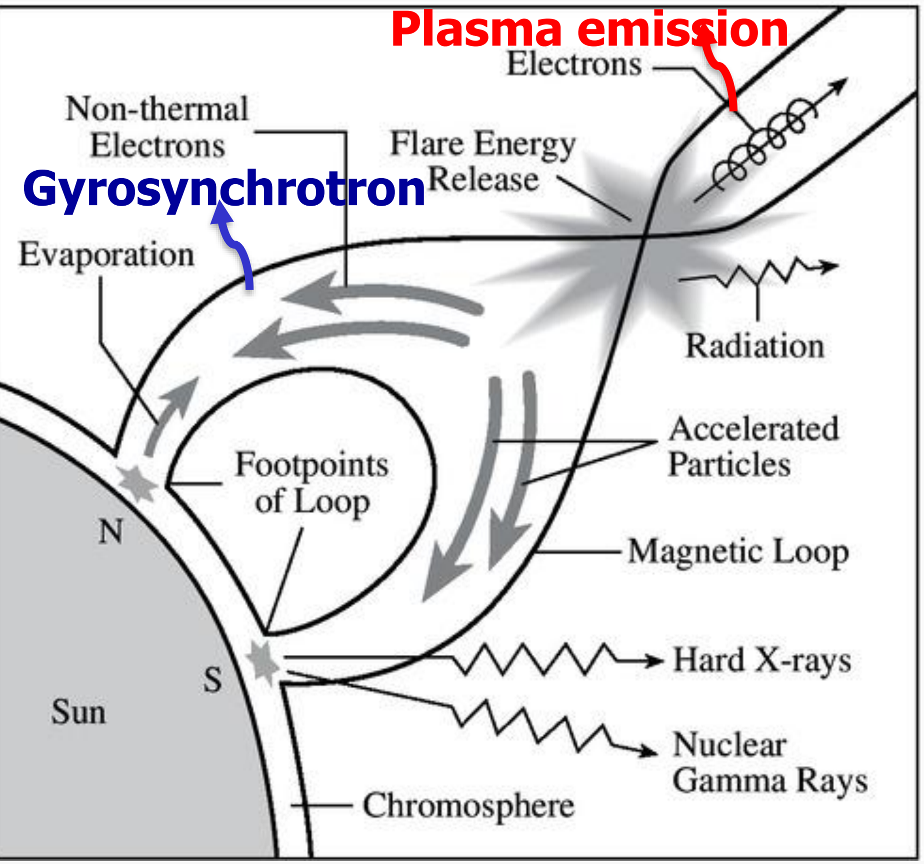


- **Plasma heated to up to 10 – 20 million degrees**
- **Also non-thermal high-energy electrons and ions**

Energetic particles in solar flares

Flares produce substantial numbers of non-thermal energetic electrons and ions – non-thermal power law tails

- **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**
  - **Emitting 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 space, may be source of Solar Energetic Particles - plasma emission (radio)**

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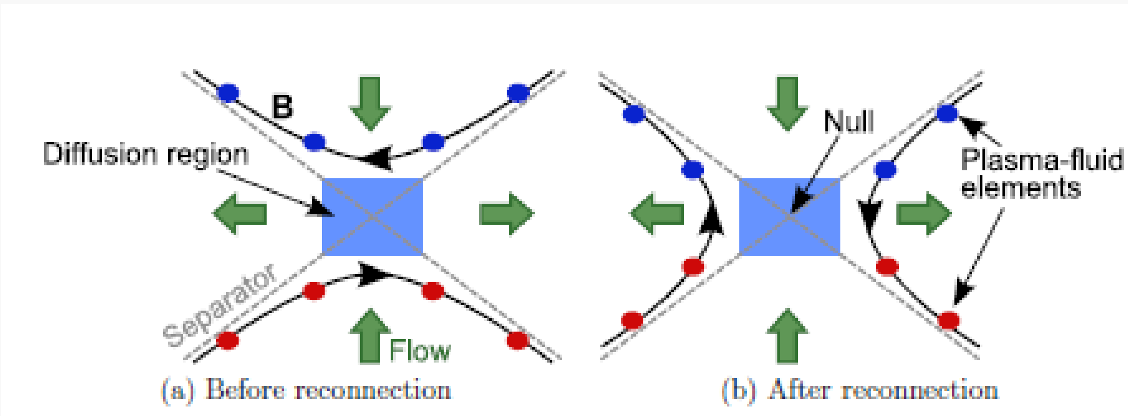
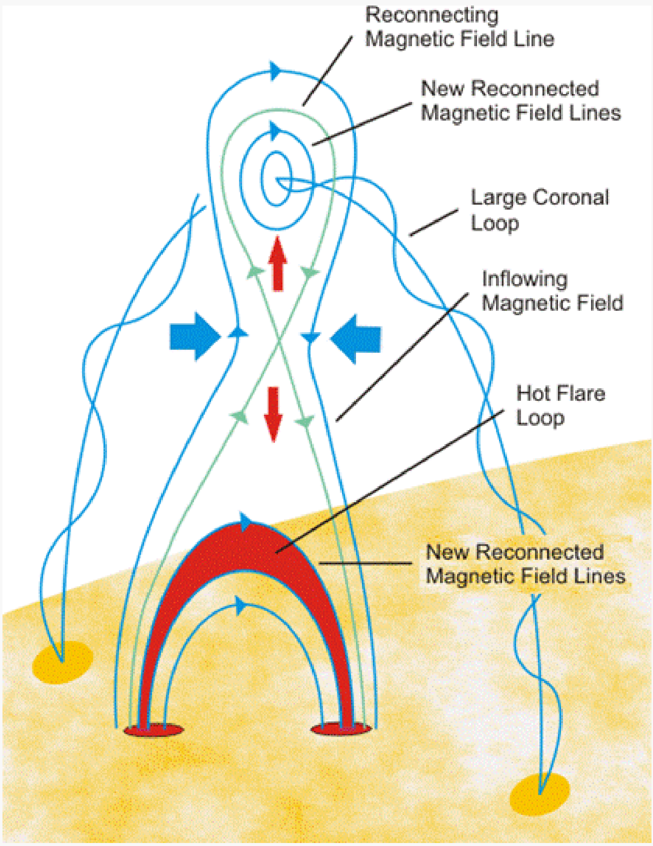
Magnetic reconnection

- **Solar flares are caused by a release of stored magnetic energy through magnetic reconnection**
- **Magnetic reconnection:**
  - **restructures large-scale magnetic field/changes magnetic topology through localised non-ideal effects**
  - **converts magnetic energy into thermal/kinetic energy**





- **MHD theory - the dissipation is through Ohmic resistivity ("Spitzer") from electron-ion collisions**
- **Collisionless reconnection - some other process locally breaks frozen-in condition**

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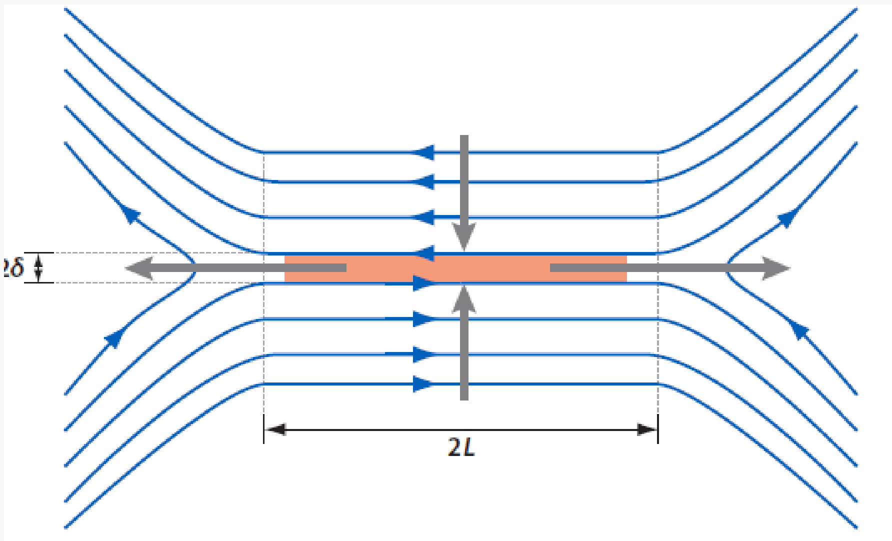
Solar flare reconnection

Classical reconnection theory

e.g. Sweet-Parker



- Ideal "outer region" - Slow inflow, fast outflow $v_o \approx v_A$
- Localised dissipative "inner region" - extended thin current sheet

3D nulls, 2D approx. with guide-field, complex topology

2D, no out-of-plane field

Transient, oscillatory

Steady

Two-fluid or collisionless reconnection

Single-fluid MHD with Ohmic resistivity

Turbulent inflows and outflows; shocks

Laminar inflow/outflow

Fragmentation; multi-scale sub-structure; plasmoids

Monolithic, simple current sheet:

Distributed current sheets

Single, isolated reconnection site

All play a role in particle acceleration

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Particle acceleration mechanisms I

- **Guiding-centre energy equation**

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

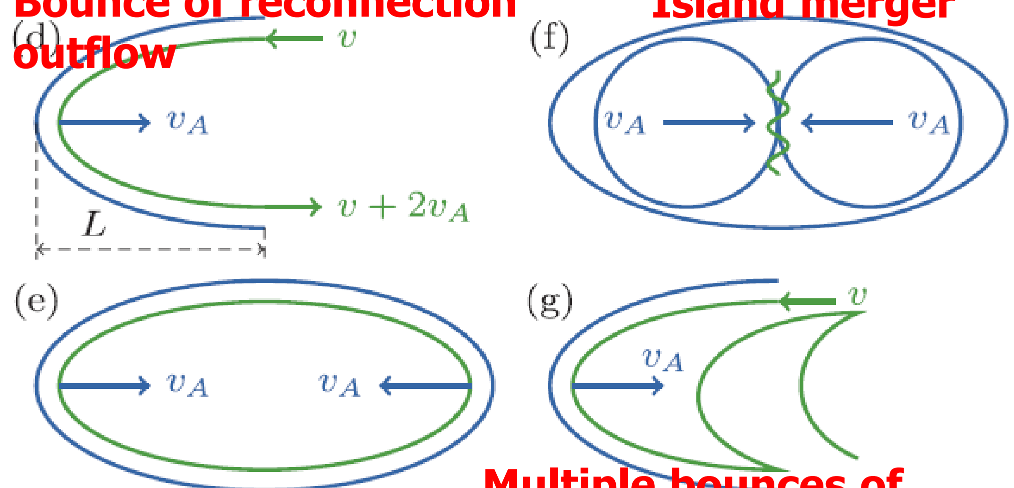
from Dahlin 2021

- **Parallel Electric field**
- **Betatron acceleration/curvature drifts**

  e.g. Vekstein and Browning 1997, Zhou et al 2015
- **Fermi acceleration**
  - **Reflection between moving mirrors**

Bounce of reconnection outflow

Island merger



Island contraction

Multiple bounces of reconnection outflow

From Li et al 2017, 2021

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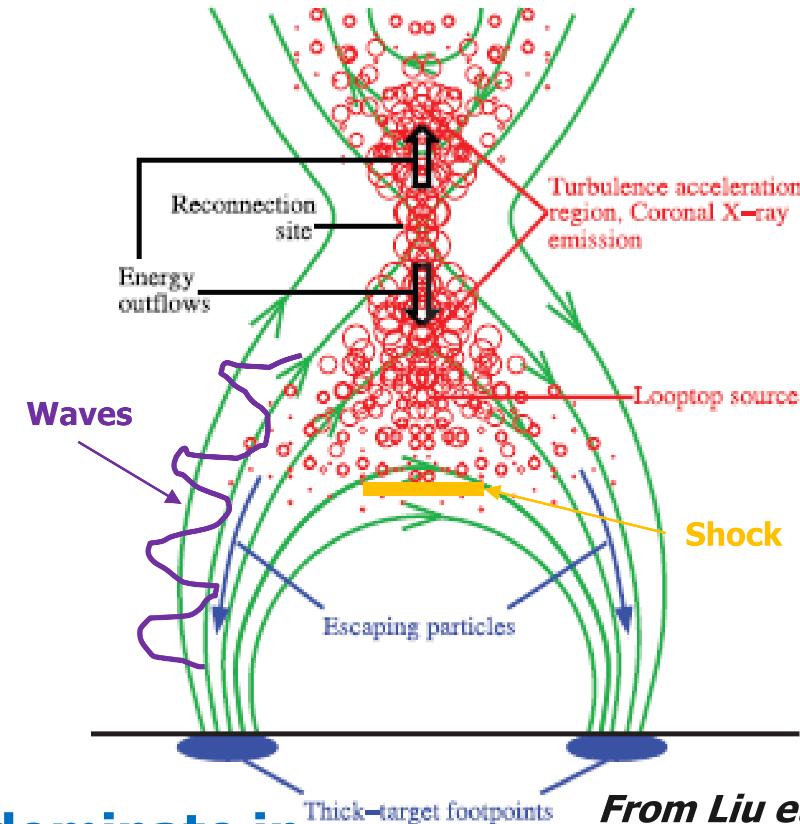
Particle acceleration mechanisms II

- 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



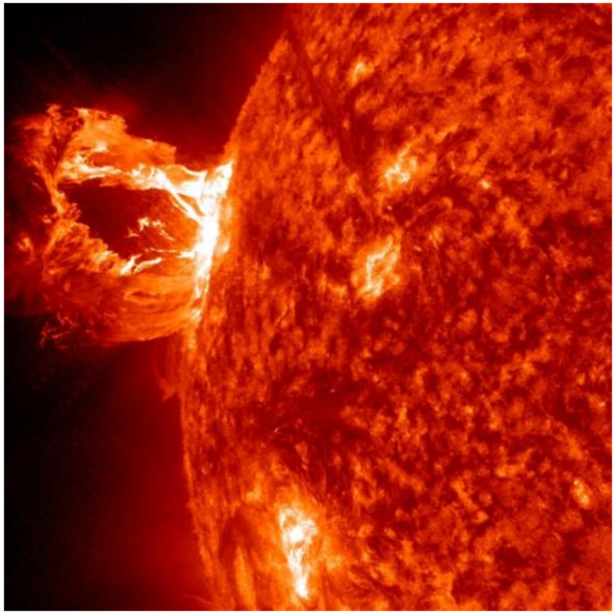
From Liu et al 2008

- It is likely that different processes dominate in different events
- There are many overlaps between the mechanisms
- "Acceleration" and "transport" inextricably linked

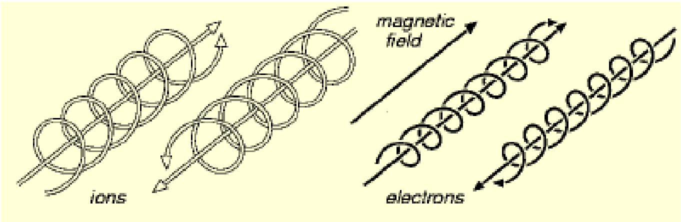
Challenges for particle acceleration modelling

- **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**

Modelling approaches

- **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

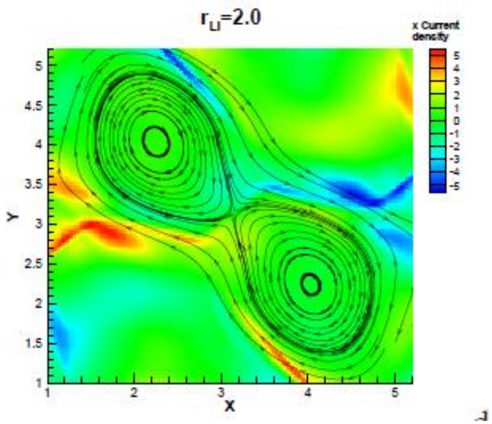
- **Cannot model global scales of flares; statistical noise**
- **Does not predict sufficient acceleration**

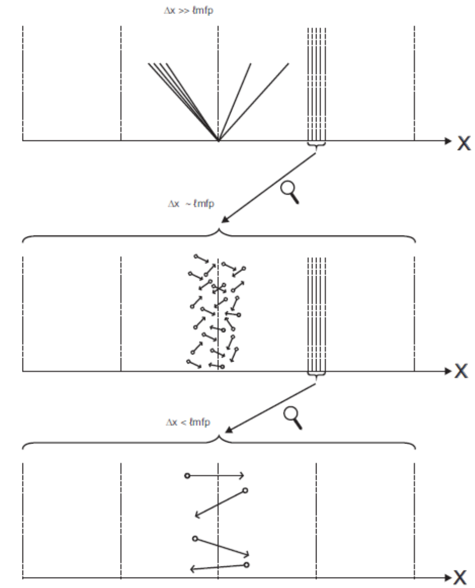
- **Other kinetic models e.g. Boltzmann equation, Fokker-Plank**

See review Gordovskyy, Browning and Pinto (2019)

- **UGKS**

Liu and Xu 2017

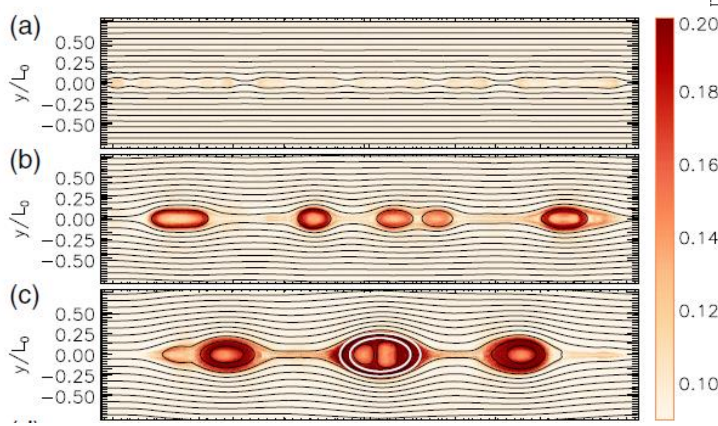


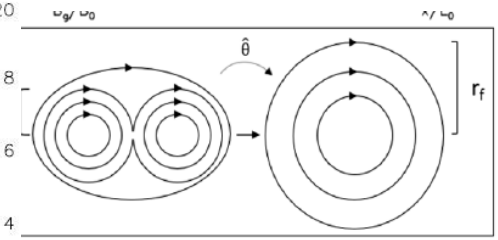


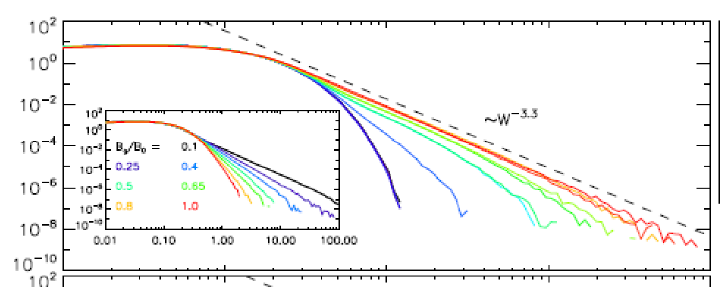
- **Kglobal**

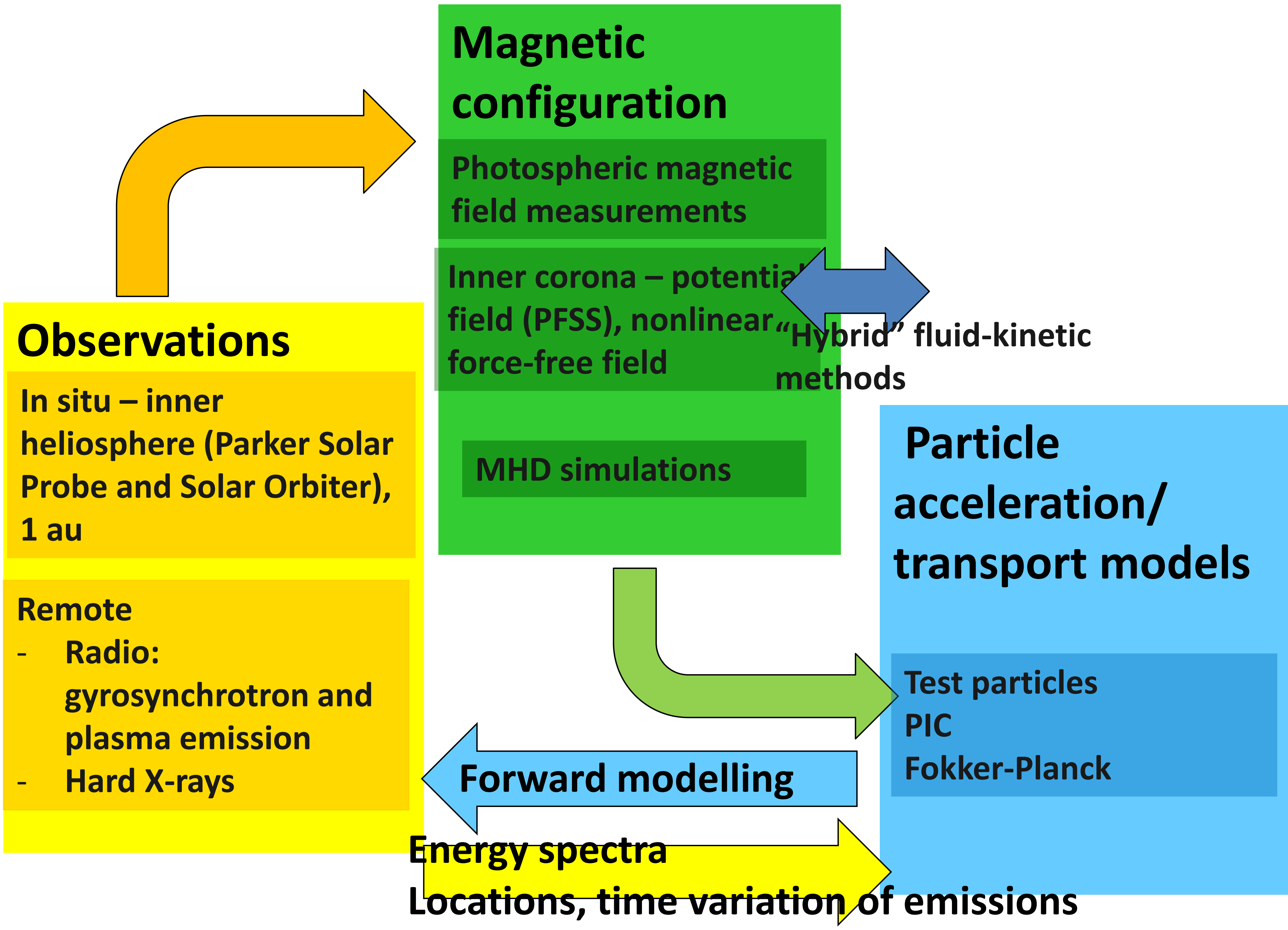
Arnold et al 2021

  - **Efficient acceleration and formation of powe law high-energy tails requires coupling between MHD and kinetic scales**
  - **Acceleration less effective in stronger guide fields**








Magnetic configuration
Photospheric magnetic field measurements
Inner corona – potential field (PFSS), nonlinear force-free field
"Hybrid" fluid-kinetic methods
MHD simulations
Observations
In situ – inner heliosphere (Parker Solar Probe and Solar Orbiter), 1 au
Remote
- Radio: gyrosynchrotron and plasma emission
- Hard X-rays
Particle acceleration/ transport models
Test particles
PIC
Fokker-Planck
Forward modelling
Energy spectra
Locations, time variation of emissions

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**

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MHD/test-particle with forward modelling

MHD

Potential field in gravitationally stratified atmosphere – twisted by footpoint motions

MHD
LARE3D

Instability results in reconnection & energy release

Test-particles
GCA code

Proton & electron populations
Relativistic guiding centre
In time-evolving fields from MHD (interpolation in **r**, t)

Velocity, density, temperature and magnetic field

Thermal emission – soft X-rays, EUV

Non-thermal emission – Hard X-rays, microwaves

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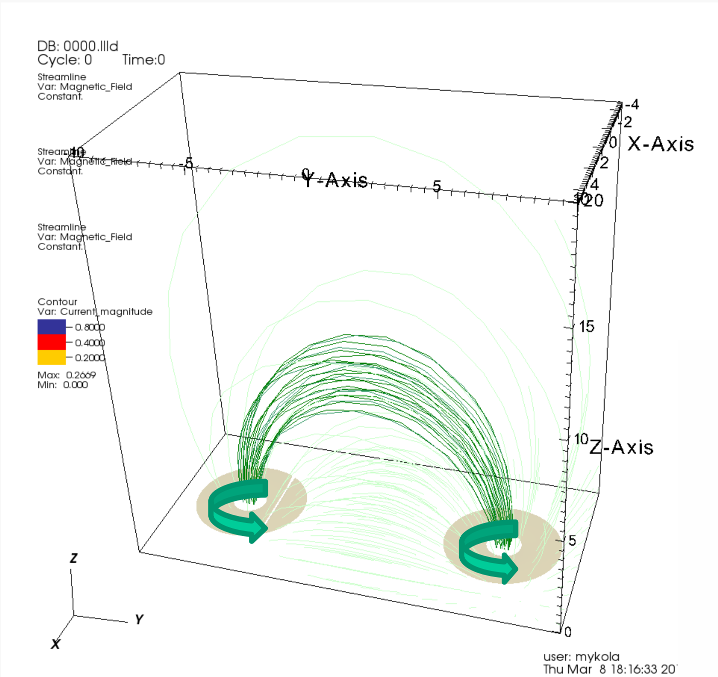
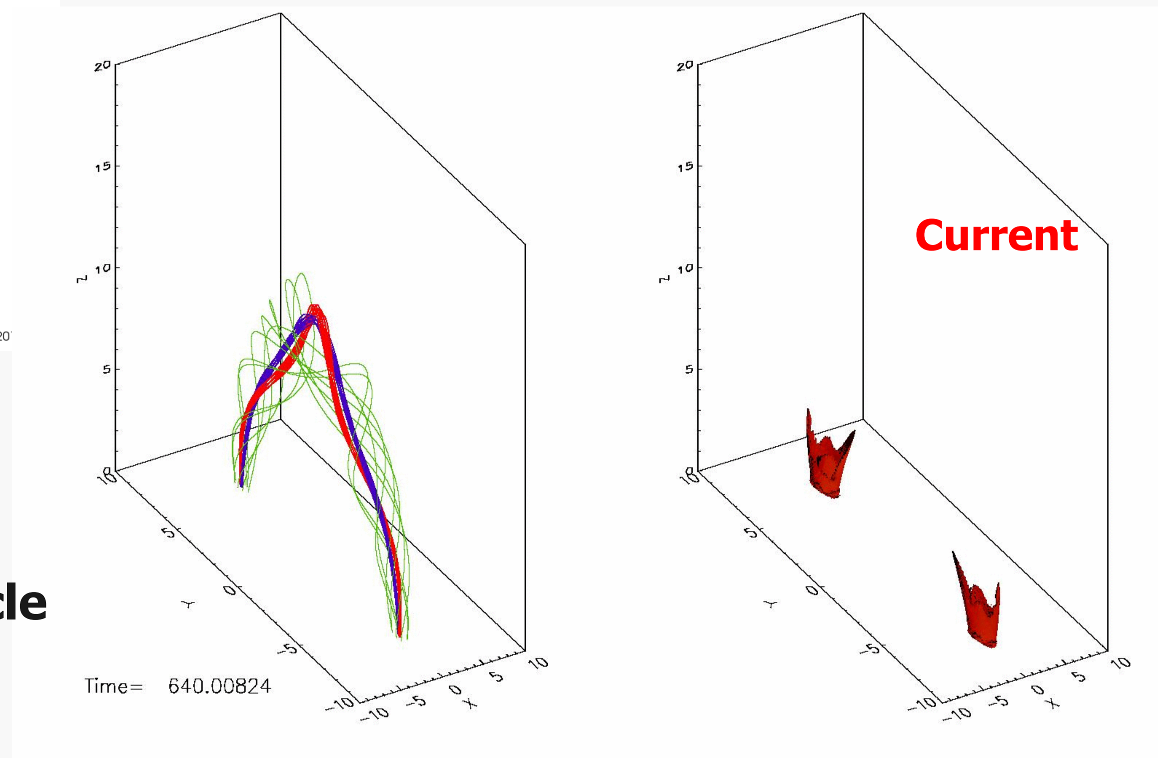
Gordovskyy, B et al 2014

Observational signatures of kink-unstable loop

- Initial "magnetic dipole" potential field → curved loop
- Stratified atmosphere



▪3D MHD simulations with anomalous resistivity
▪Initially Localised rotation at the photosphere $v_{rot} << v_A \rightarrow$ instability onset



▪Large-scale reconnection and fragmented current sheets
▪Plasma heating and particle acceleration

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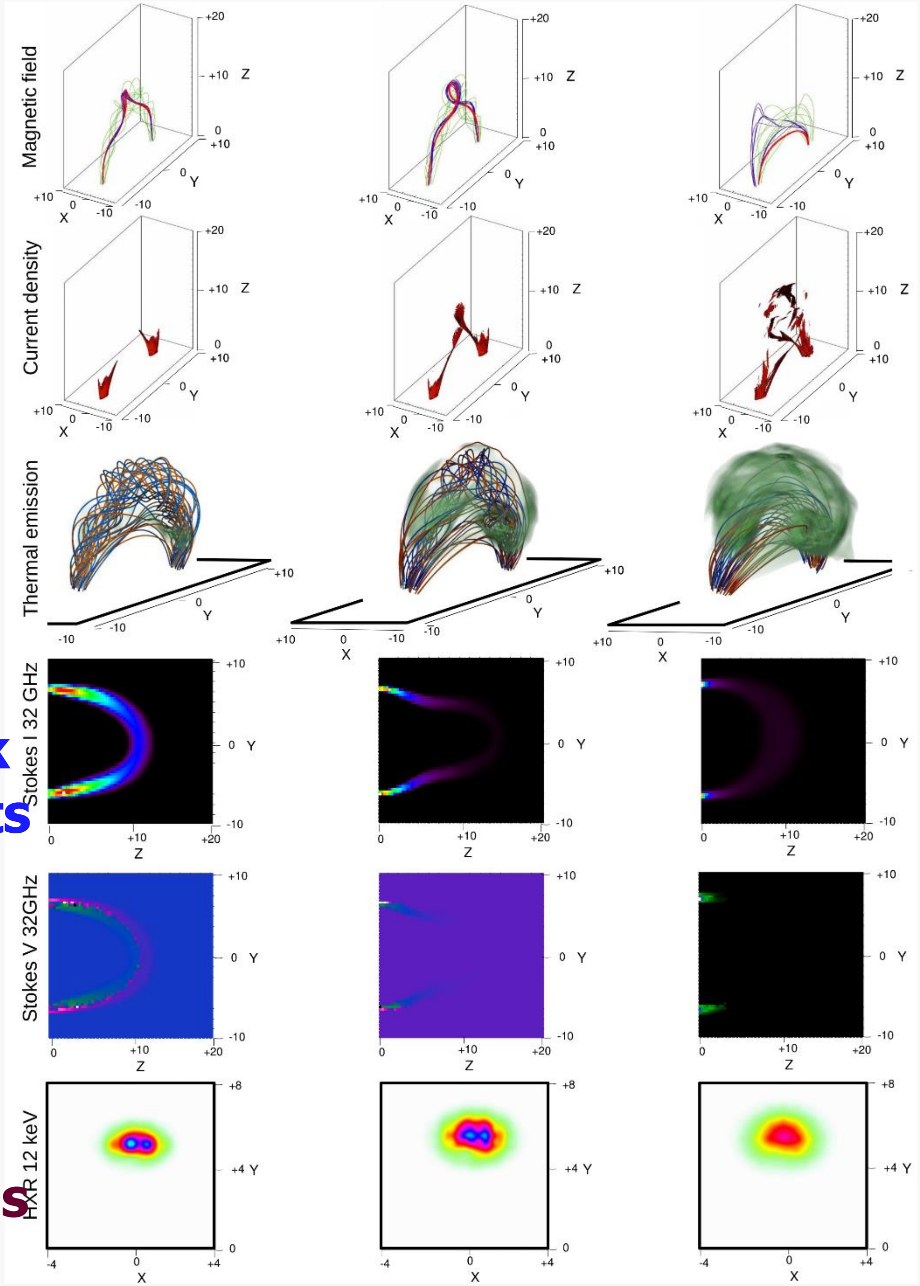
- ***Gordovskyy, Browning, Kontar & Bian 2014*** **Loop evolution, particles & Hard X rays**
- ***Bareford, Gordovskyy, Browning & Hood 2016*** **Magnetic field evolution –curvature, gravitational stratification**
- ***Pinto, Gordovskyy, Browning & Vilmer 2016*** **Thermal SXR, non-thermal HXR**
- ***Gordovskyy, Kontar & Browning 2016*** **EUV lines – Turbulent and bulk flows, non-thermal broadening, shifts**
- ***Gordovskyy, Browning & Kontar 2017*** **- Thermal and non-thermal microwave emission, circular polarisation gradient**
- ***Smith et al 2022*** **Microwave oscillations, Quasi Periodic Pulsations**



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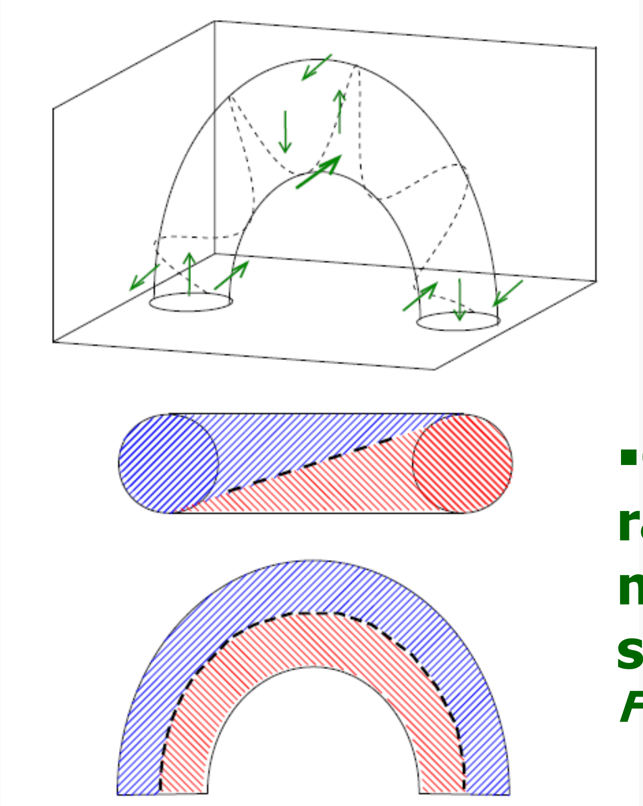
Circular microwave polarisation pattern as a twist detection tool

Microwaves due to gyrosynchrotron emission from electrons gyrating in magnetic field



- **Polarisation is parallel to line-of-sight magnetic field → twisted magnetic field gives characteristic polarisation pattern**
- **Is this observable in flaring twisted field?**

▪**GX Simulator - calculates gyro-synchrotron radiative emission/transfer from thermal and non-thermal electrons in a magnetic field structure**

Fleishman and Kuznetsov, 2010; Nita et al,2015

B, T, ρ **from 3D MHD simulations of unstable twisted loop + (parameterised) non-thermal electrons**

Gordovskky, B & Kontar A&A 2017

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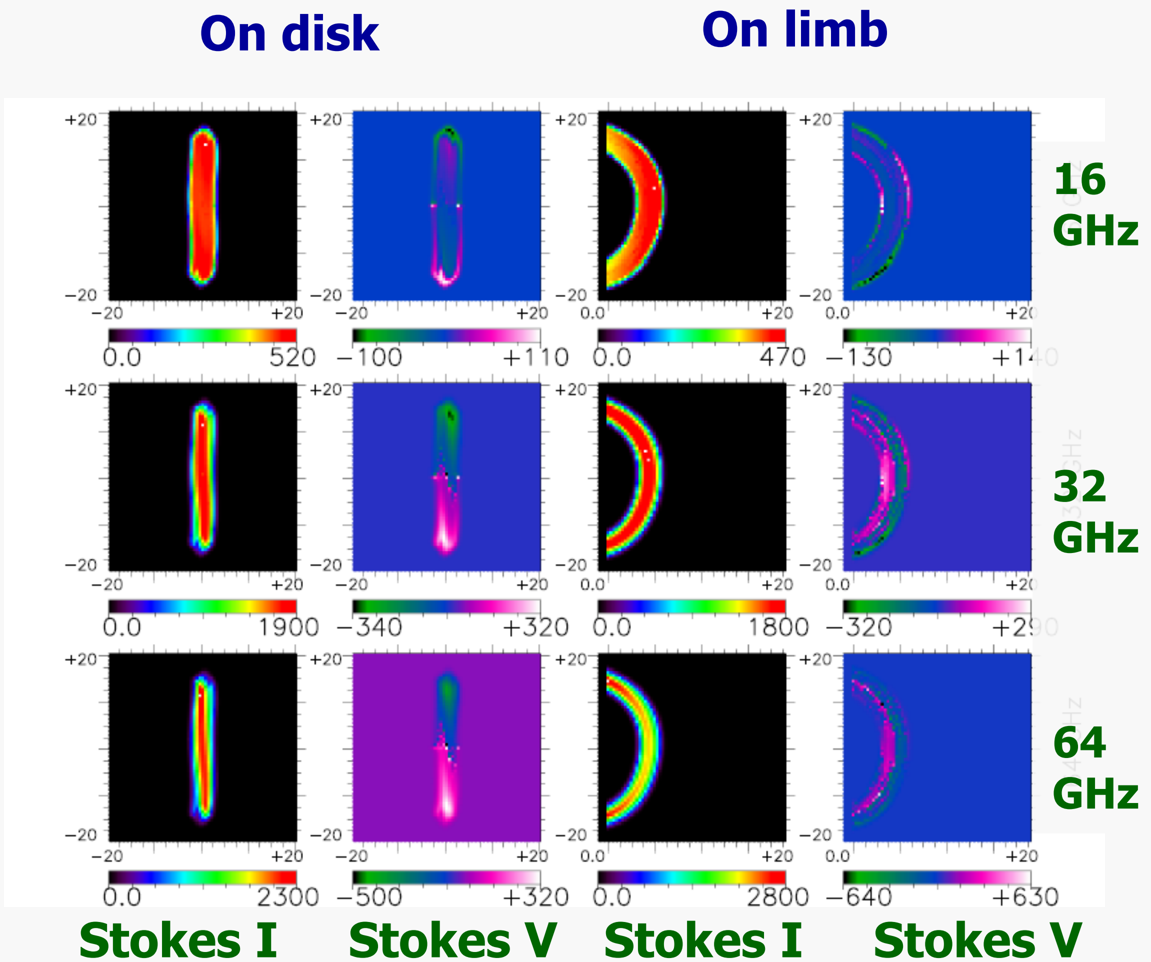
- **Polarisation pattern only observable transiently, clearest for loops observed on limb**
- **Clearest pattern for weakly-converging field**
- **Best observed in higher frequencies > 30 GHz – pattern not clear at lower frequencies since optically-thick**

Gordovskyy et al 2017

During phase of strongest reconnection



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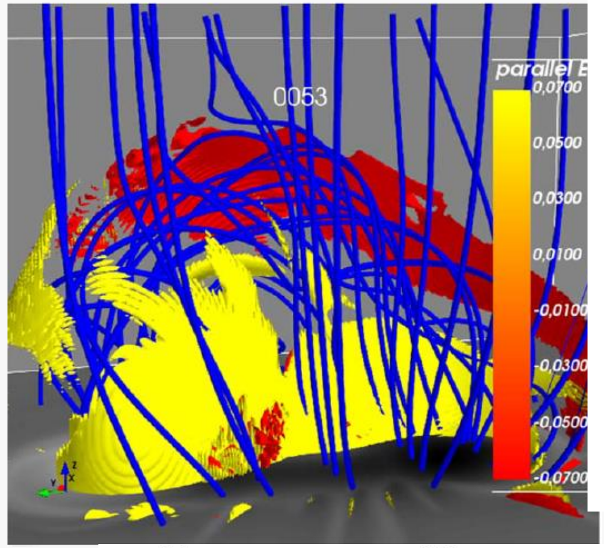
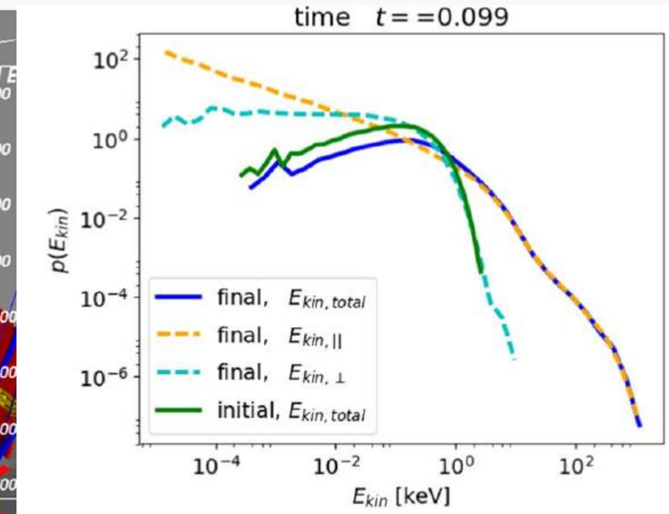
Some more MHD-TP studies

- **Emergence of twisted flux rope**

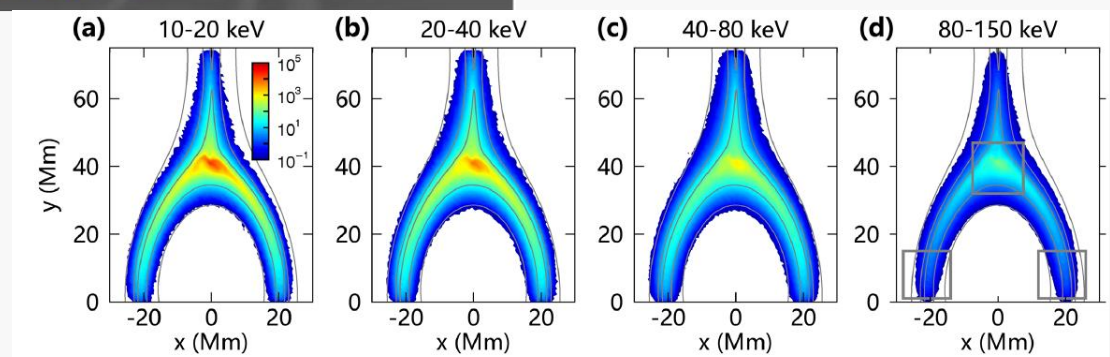
Isliker et al 2019

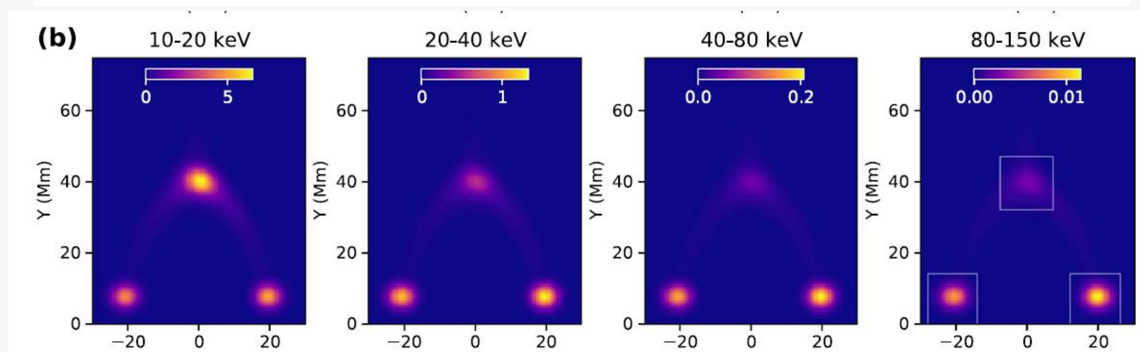
  - **3D MHD simulations with relativistic test-particles**
  - **Snapshots of MHD fields**
  - **Rapid acceleration by parallel E**





- **Connecting looptop and footpoint HXR sources**
  Kong et al 2022
  - **2D MHD with Parker transport equation for particles**
  - **Simulated HXR emission**





- **Interacting flux ropes in 2D and 3D**

Ripperda et al 2017

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Time dependence

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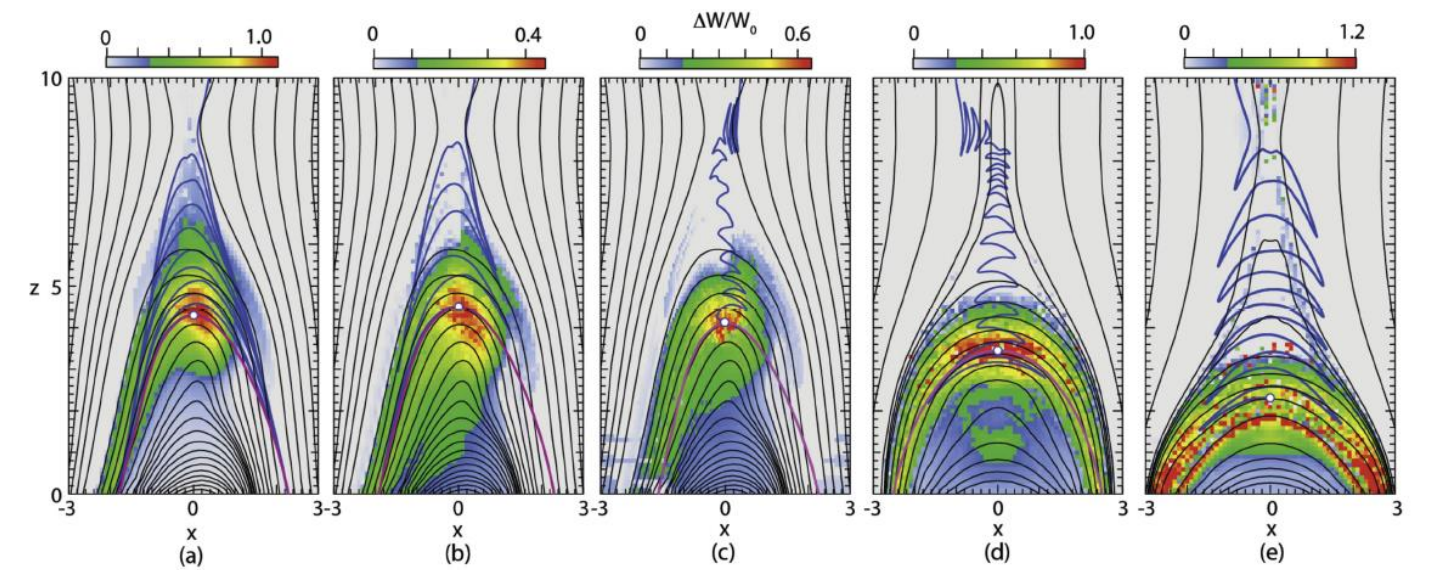
Collapsing magnetic traps

- **Acceleration in collapsing magnetic field below reconnection site – c.f. Geomagnetic substorms**

Karlicky and Kosugi 2004, Giulani et al 2005, Karlicky and Barta 2007, Grady and Neukirch 2009, Grady et al 2012, Birn et al 2017

- **Energy gain typically via factor of ~ 10 – may enhance energy of pre-accelerated particles but not a mechanism to create significant high-energy tails**



Birn et al, 2017

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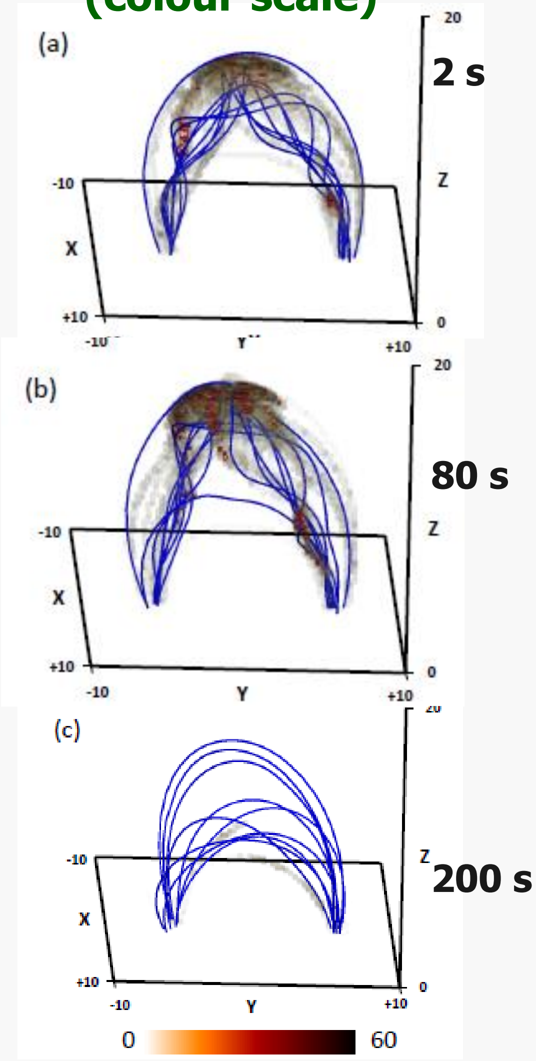
Microwave oscillations from reconnecting loop

Forward model signature in microwaves of MHD oscillations in a reconnecting twisted loop

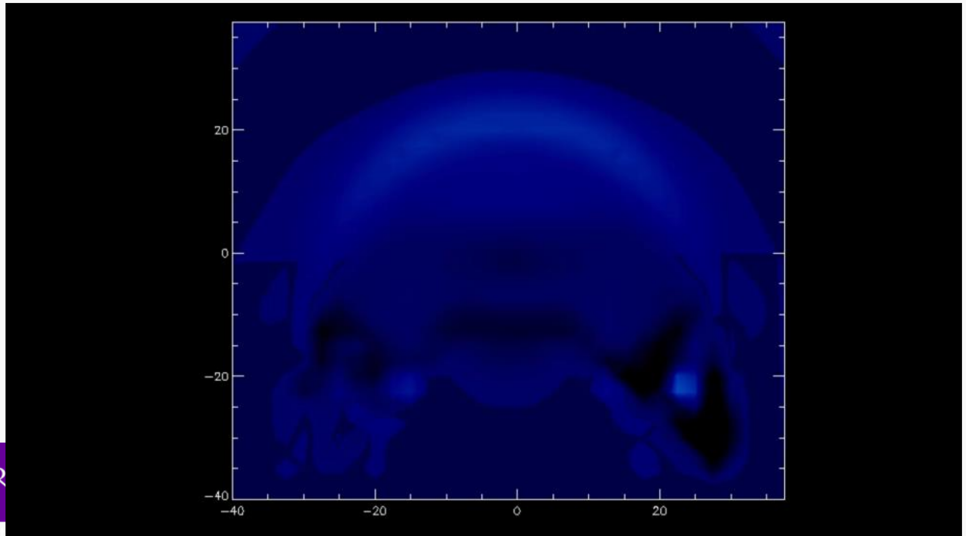
Smith, Browning and Gordovskyy (2022)

- **3D MHD simulations of kink-unstable loop → B, ρ, T, $E_{//}$**
- **Non-thermal electrons at locations of high parallel electric field, spread out along magnetic field lines (motivated by test particle results)**
- **Gyrosynchrotron emission and radiative transfer using fast GS code (Fleishman and Kuznetsov, 2010) integrated along 1D lines-of-sight**

Electric fields (colour scale)



16 GHz



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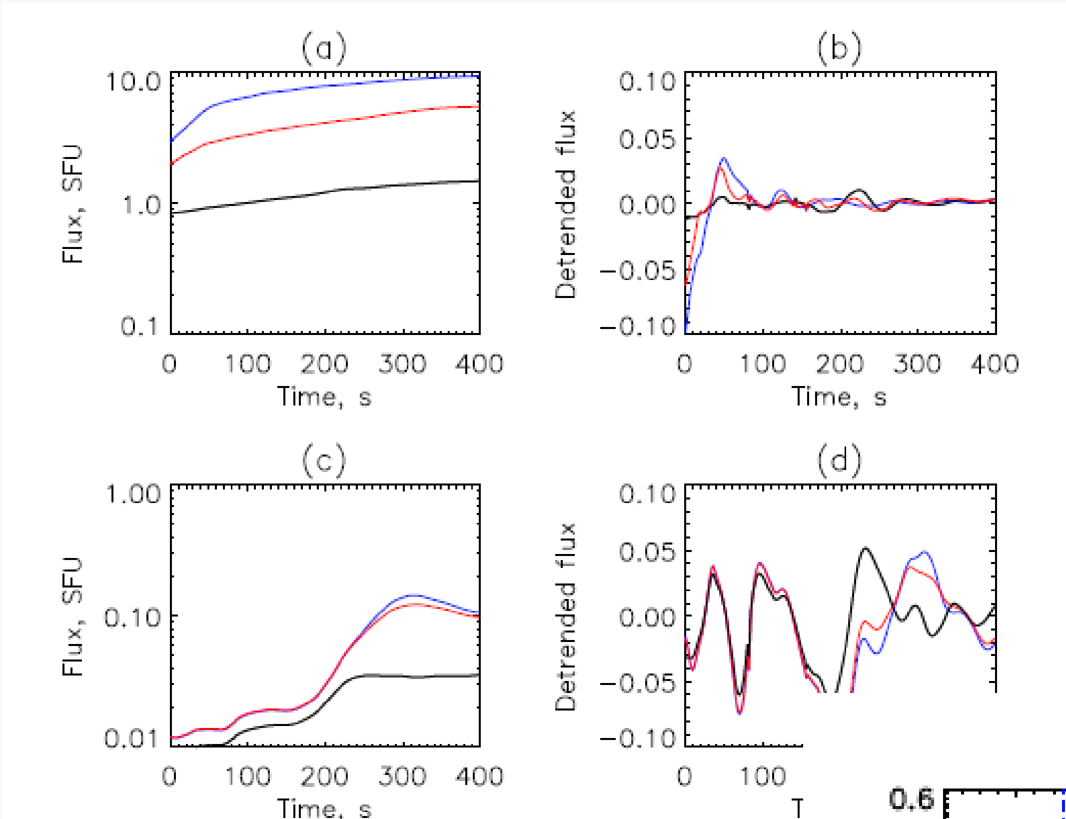
Synthesised microwave emission:
Thermal plasma – no energetic particles



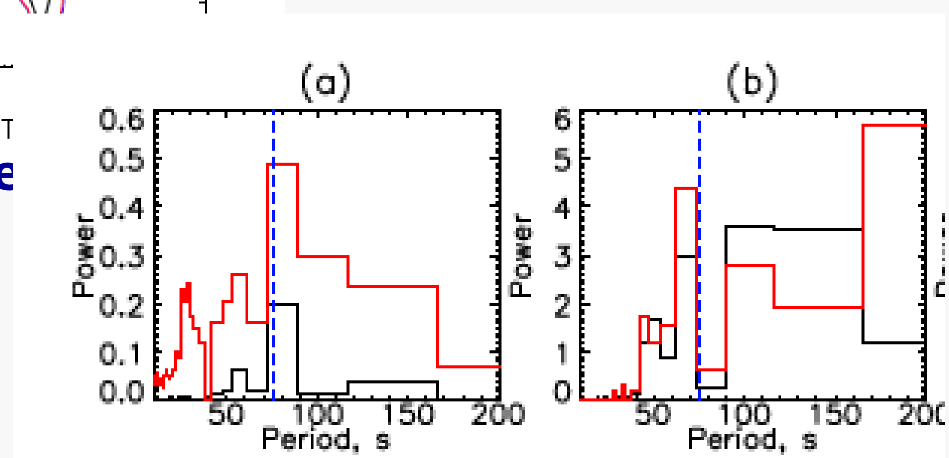
Whole domain

Loop Top

Light curve
5, 15, 30 GHz

De

5, 15 GHz



Whole domain **Loop top**

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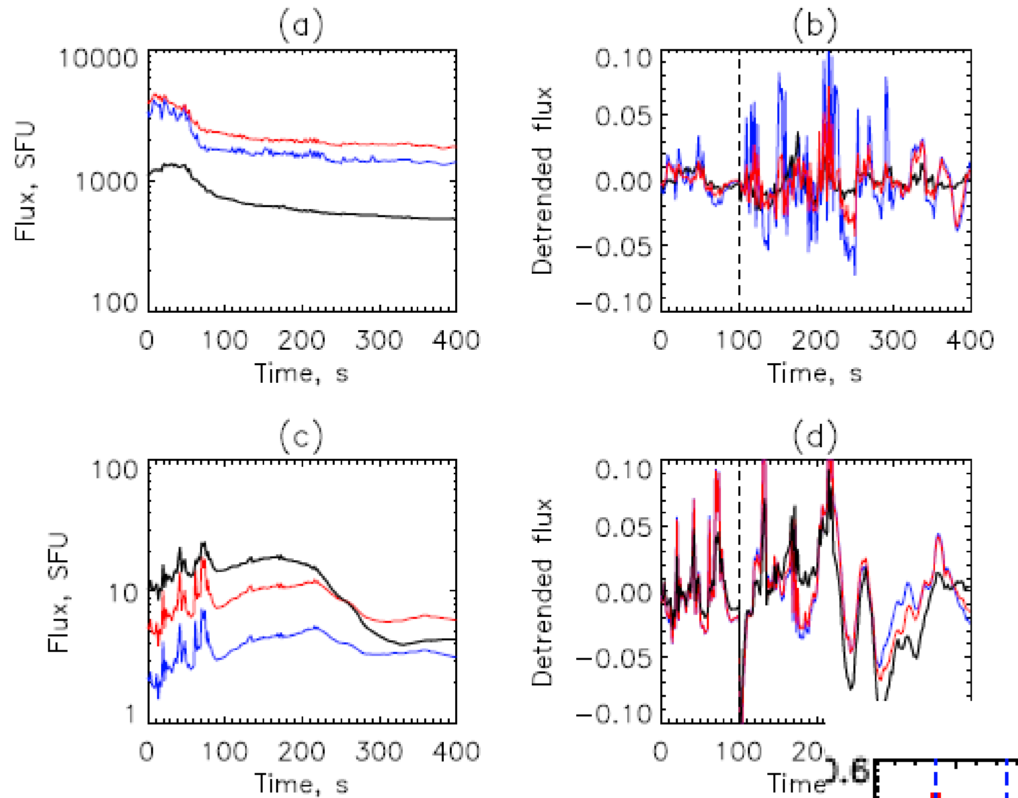
Synthesised microwave emission:
With energetic electrons

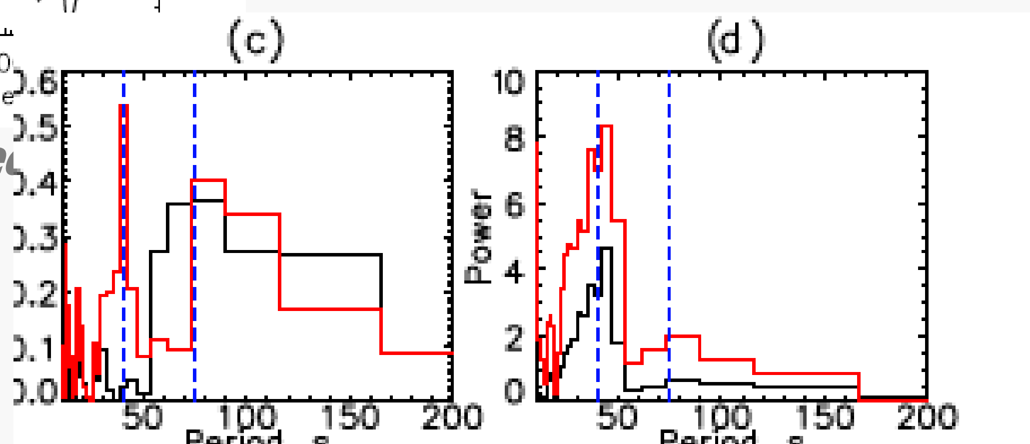


Whole domain

Loop Top

5, 15, 30 GHz

Re



Whole domain **Loop top**

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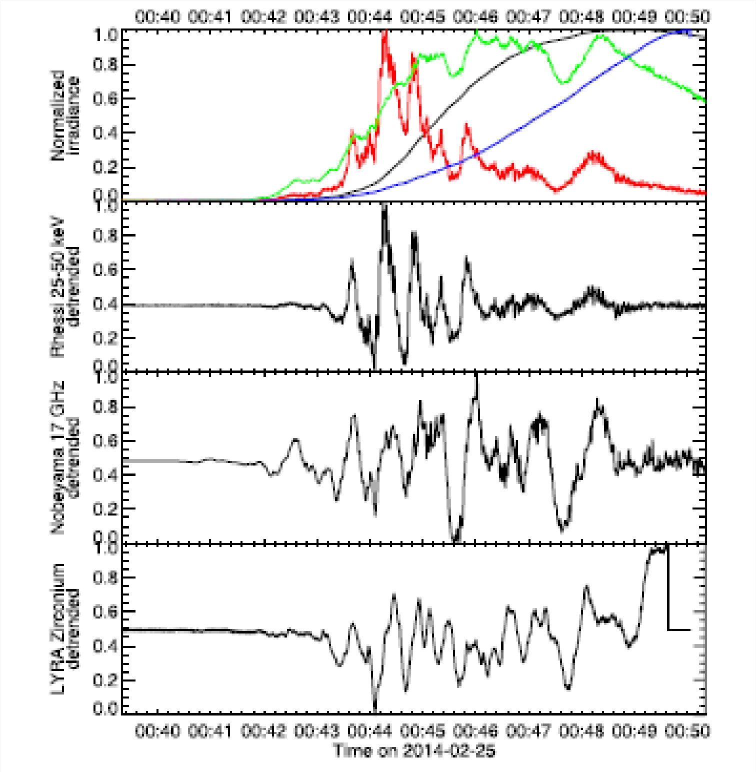
- **Slow MW oscillation period ~ 75 s observable for thermal plasma**
  - **Clearest signal for loop top**
- **Slow oscillations also observable with non-thermal particles as well as strong fast oscillations associated with localised energy parallel electric fields**
  - **switch on/off of anomalous resistivity**
- **Similar to observed Quasi Periodic Pulsations (QPPs) in observed flare emission**



Oscillations produced without any external oscillatory driver

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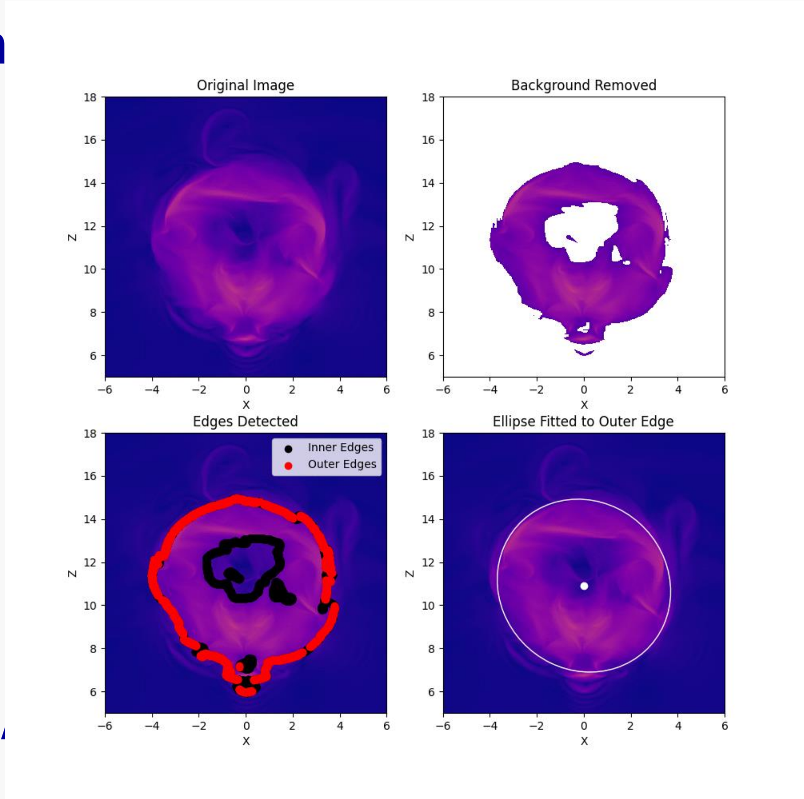
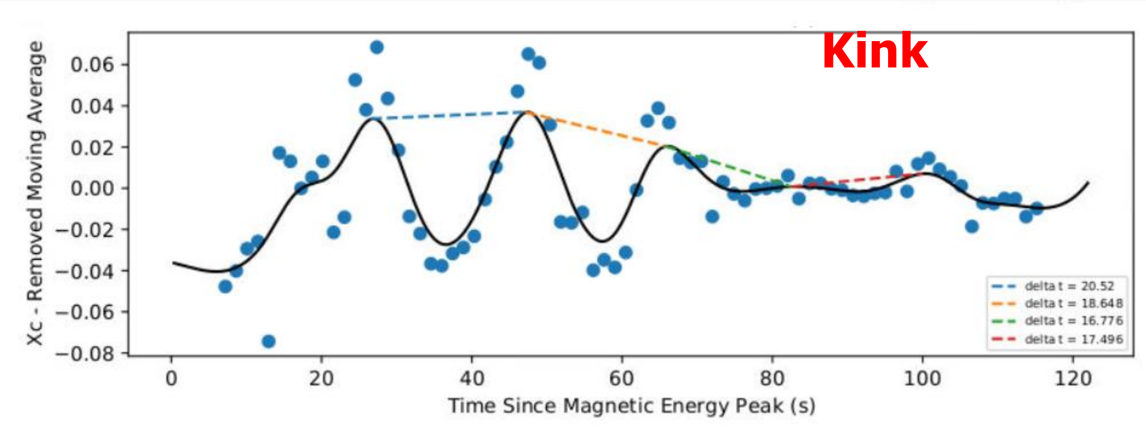
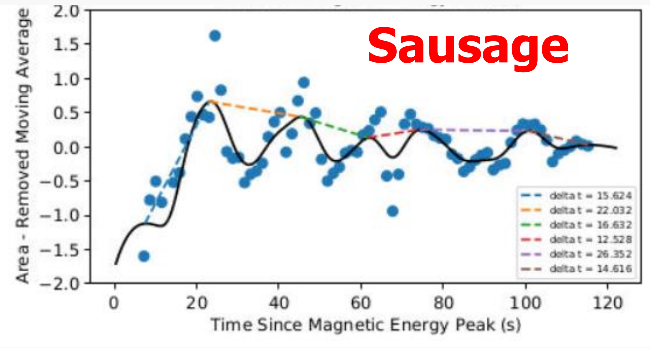
Origin of MW oscillations in kink-unstable loop

- **Identify “loop top cross-section by field line tracing**
- **Fit an elliptical boundary**
- **Identify:**
  - **Sausage Oscillations (area variations)**
  - **Kink oscillations (sideways motion of axis)**
- **Match to synthesised GS emission**

Stewart, Browning and Gordovskyy – preparation

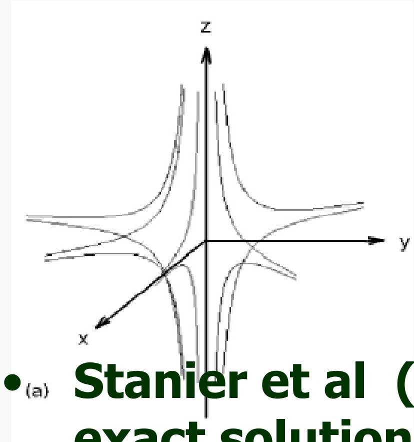




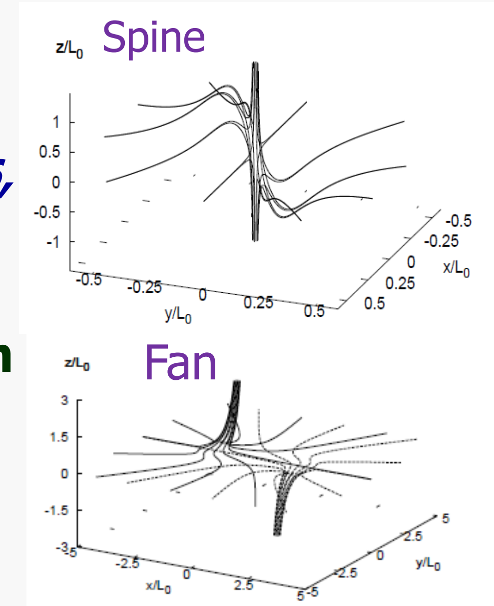


Three dimensions

Particle acceleration at reconnecting 3D nulls



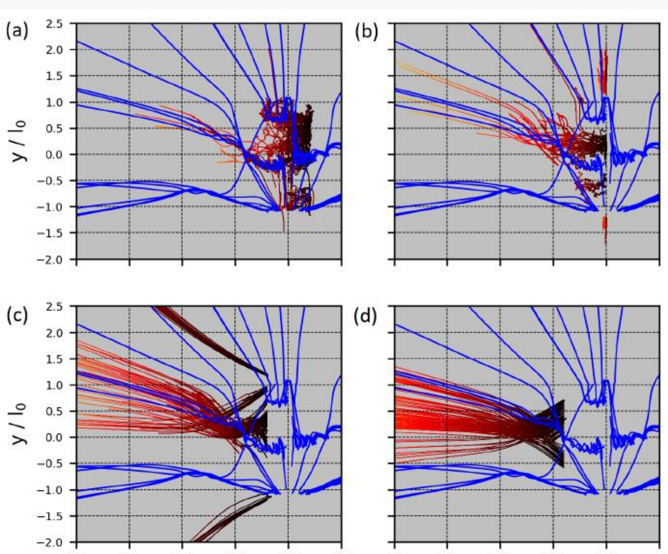
First models of ion and electron acceleration with simple field models – ***Dalla and Browning, 2005,2006, 2008; Browning et al 2010***



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

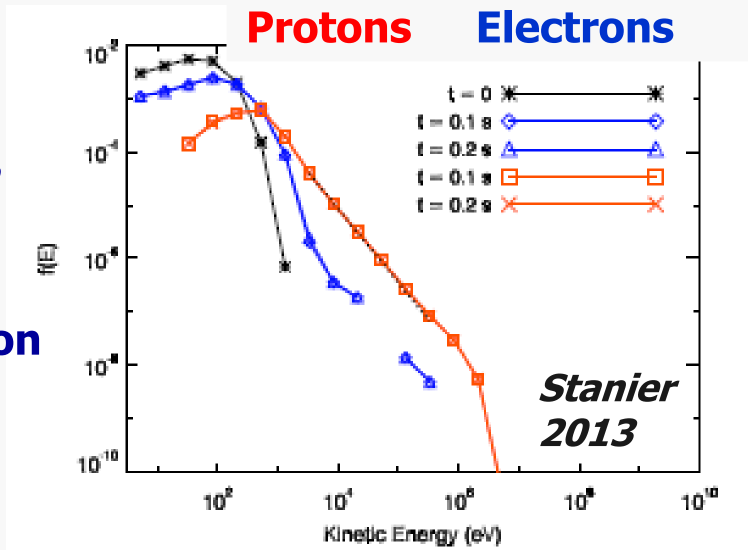
(Craig and Fabling, 1996, Craig et al 1997….)

- ***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**



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Evidence for particle acceleration at 3D nulls

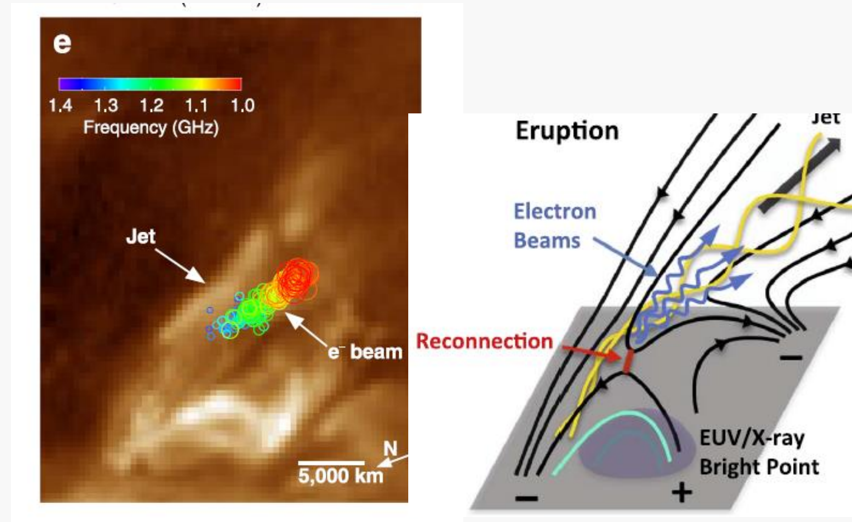
- *Chen et al 2018* - VLA observations of Type III bursts diverging from compact region in lower corona - supposed to be 3D null

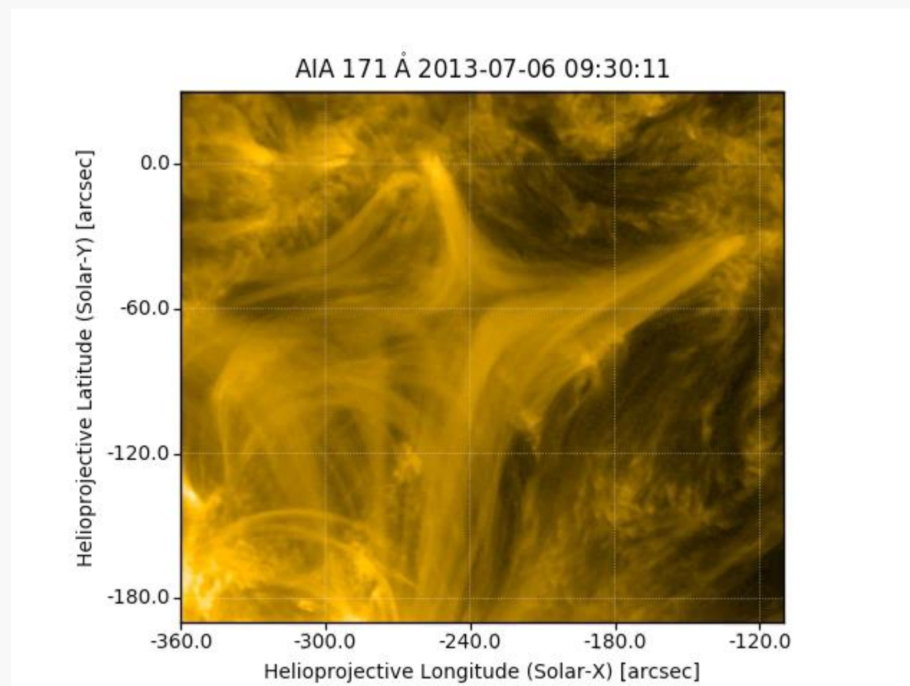
- *O'Flannagain et al A&A 2018*

- 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*





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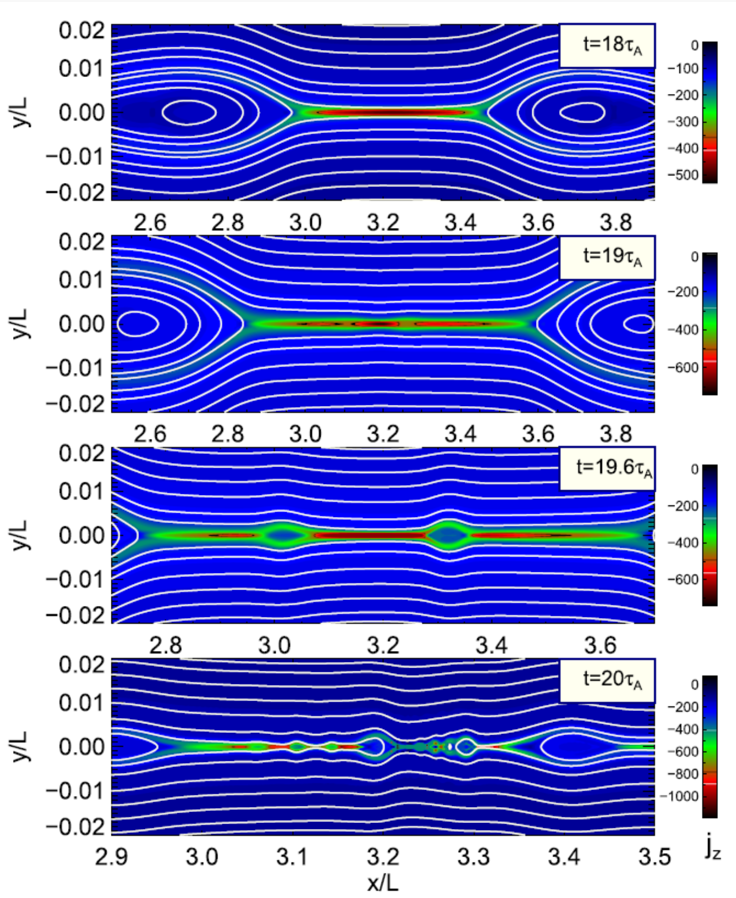
Plasmoids, fragmented current sheets and turbulence

Plasmoids

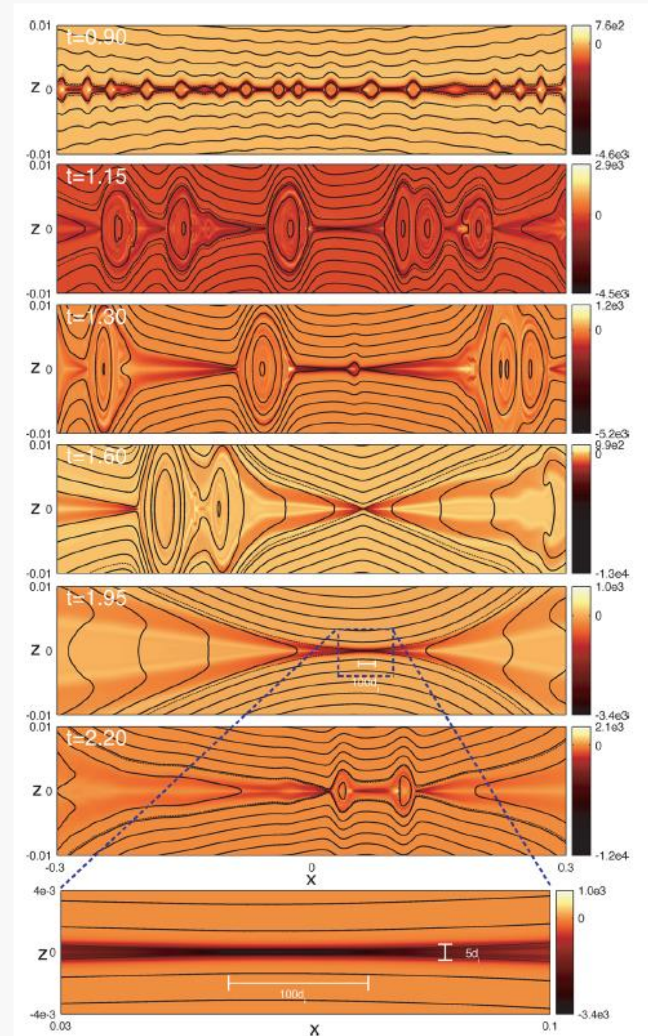


Tenerani et al Ap J 2015
MHD simulation

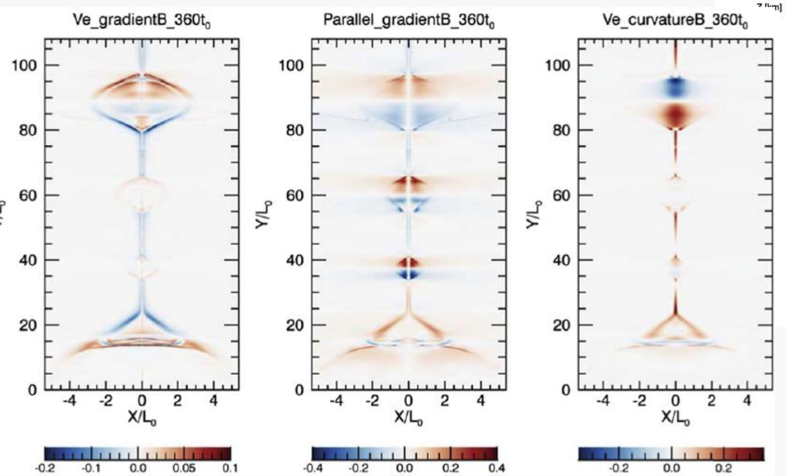
Long current sheets subject to tearing instability, break up into secondary magnetic islands or "plasmoids"

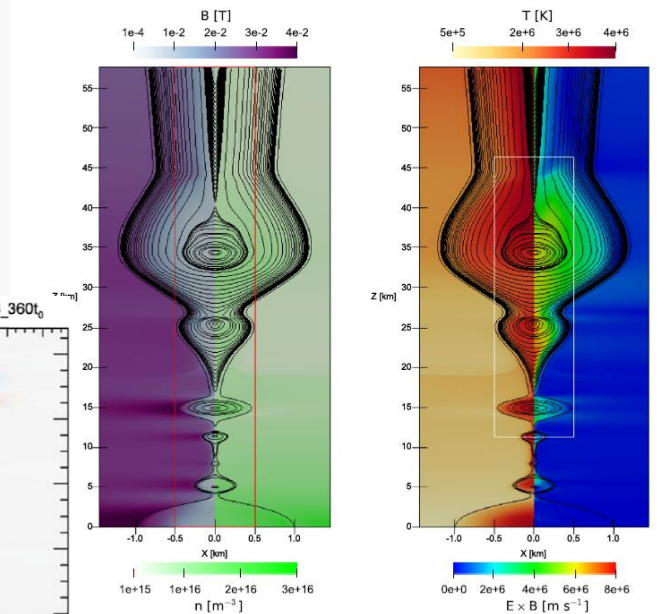
"Fractal reconnection"
Shibata and Tanuma (2001); Daughton et al , Phys Plas (2006) Loureiro et al, Phys Plas (2007); Loureiro and Uzdensky (2016)

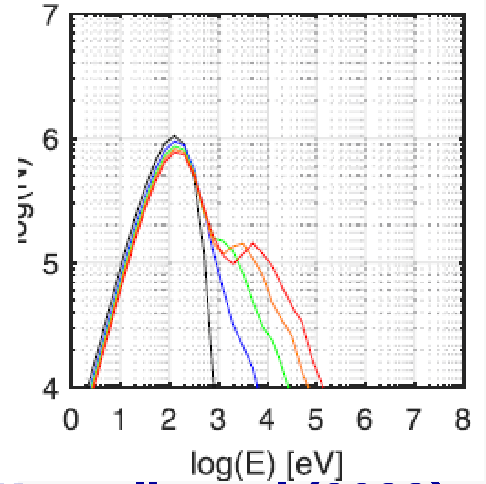
Huang et al (2011)
Hall MHD simulation



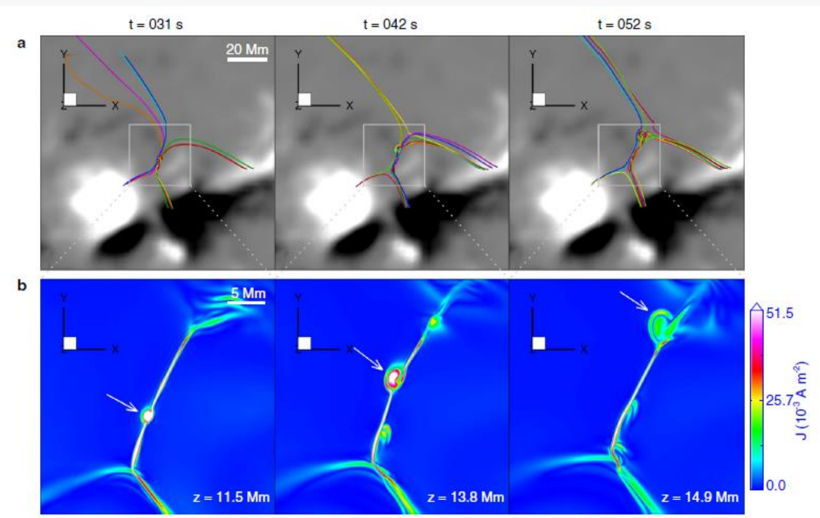
Zhou et al 2015 Electron acceleration in cascading islands – curvature drift and grad B contribute



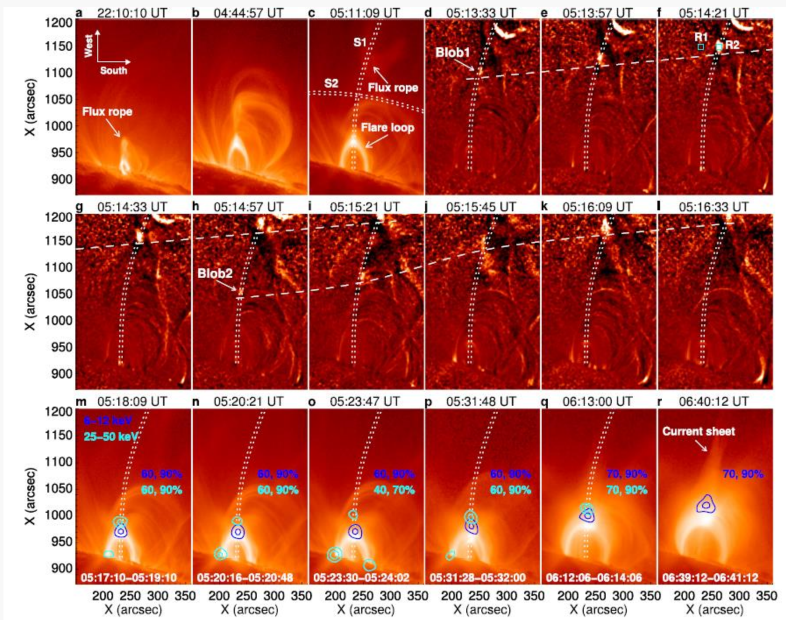




Kramolis et al (2022) – ion acceleration in flaring CS with plasmoids – preferential acceleration of heavy ions



Lu et al 2022, Yan et al 2022 – evidence of plasmoids in flares



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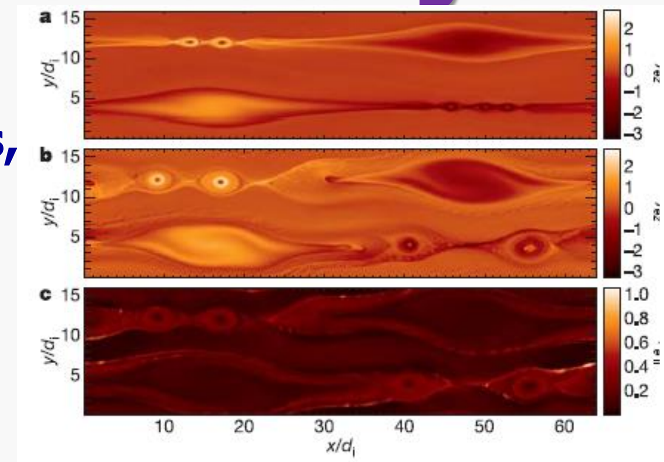
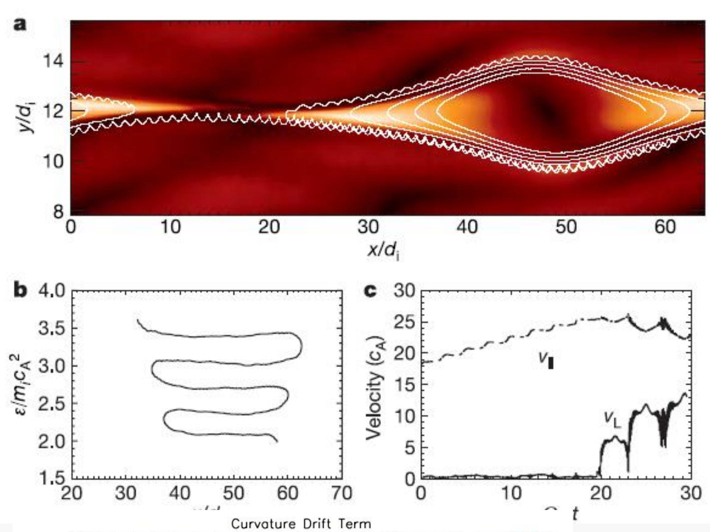
Contracting islands

Drake et al 2006

- **2D PIC simulations, no guide field**
- **Electrons are energised by repeated episodes of Fermi acceleration in contracting islands**

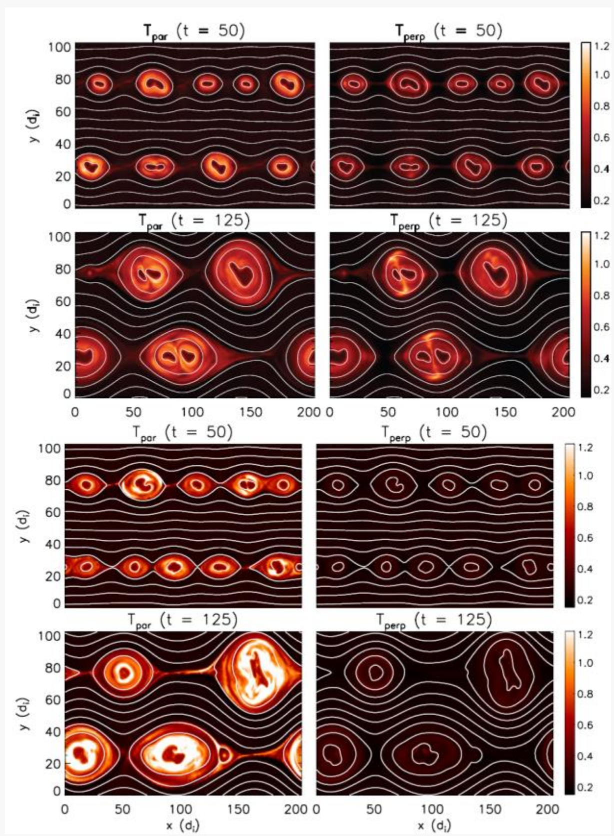


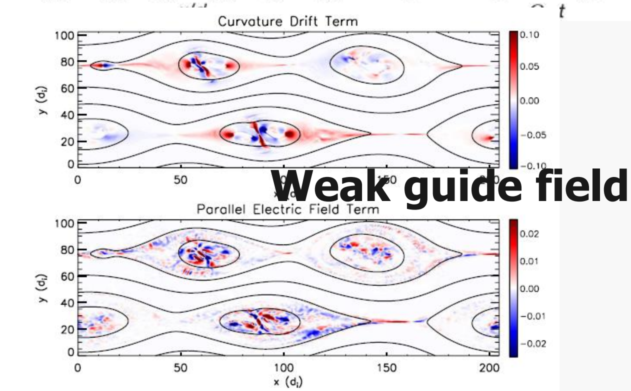


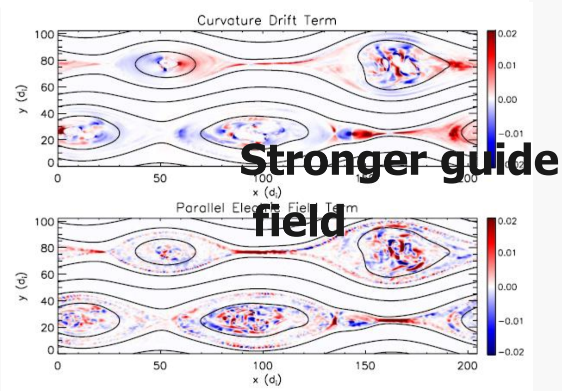
- **Effect of guide field:**

Dahlin et al 2014

- **As guide field increases, acceleration by parallel E increases relative to curvature drift**



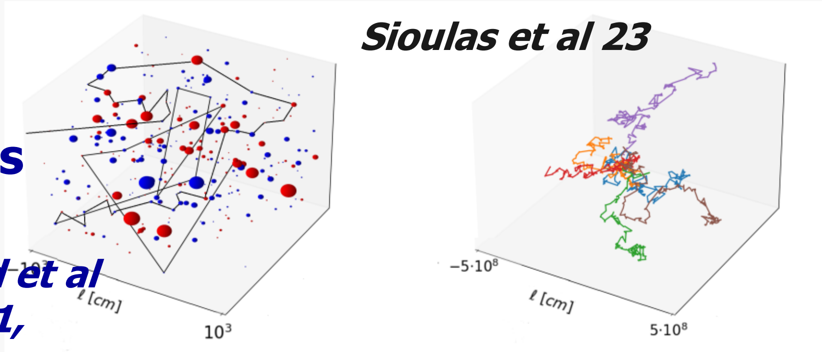




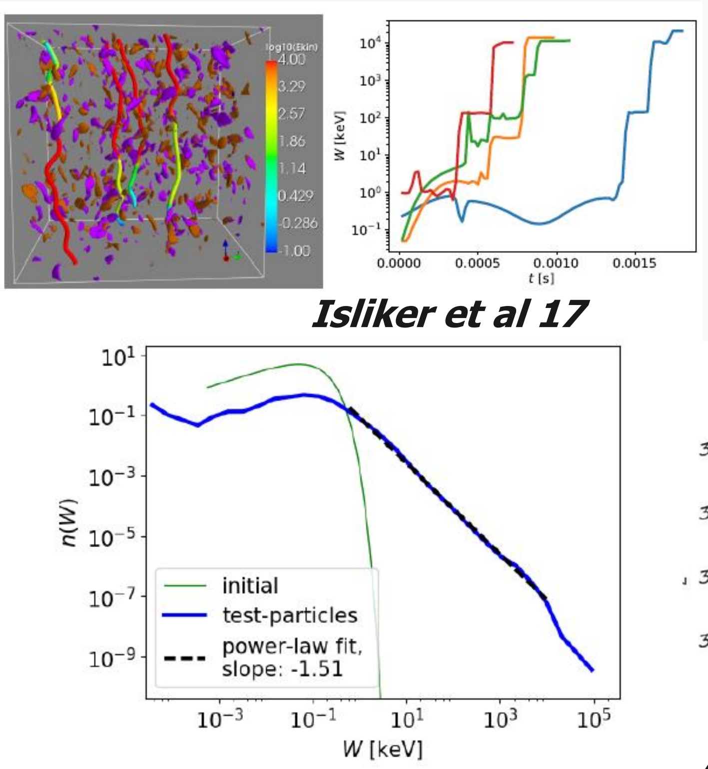
Fragmented current sheets

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

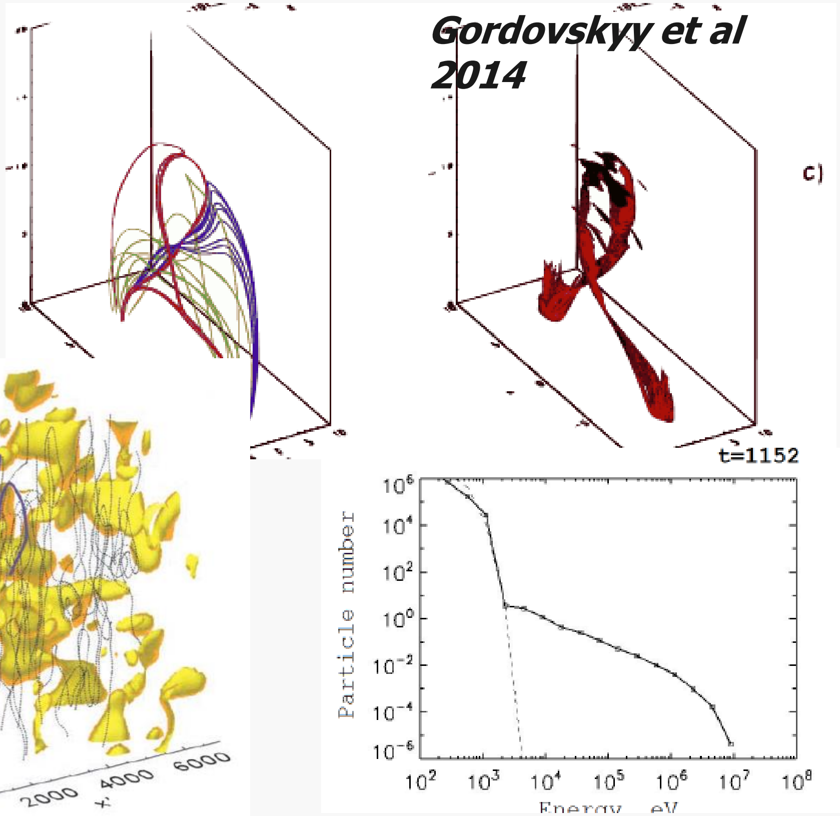
e.g. *Arzner and Vlahos 2004, Turkmani et al 2005, Hood et al 2009, Cargill et al 2012, Gordovskyy and Browning 2011, Isliker et al 2017, Sioulas et al 2023*



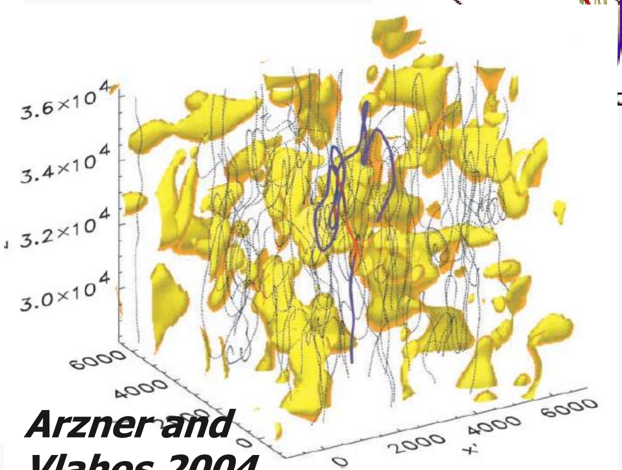
Sioulas et al 23



Isliker et al 17



Gordovskyy et al 2014



Arzner and Vlahos 2004

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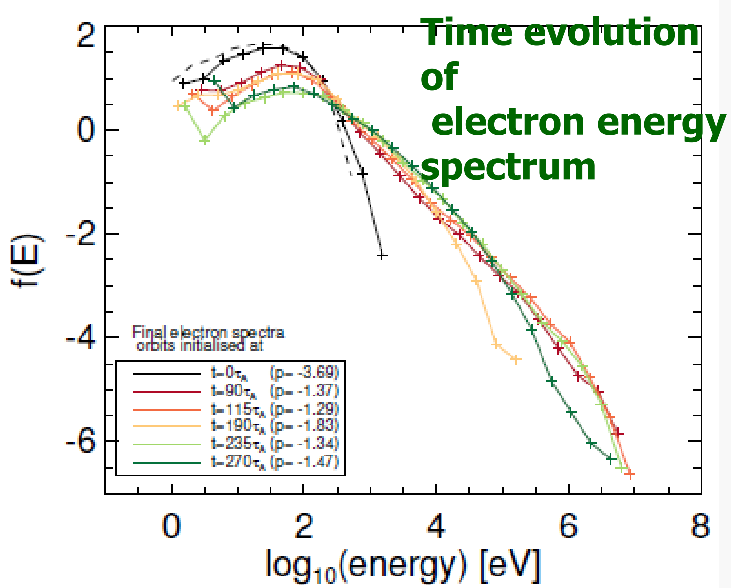
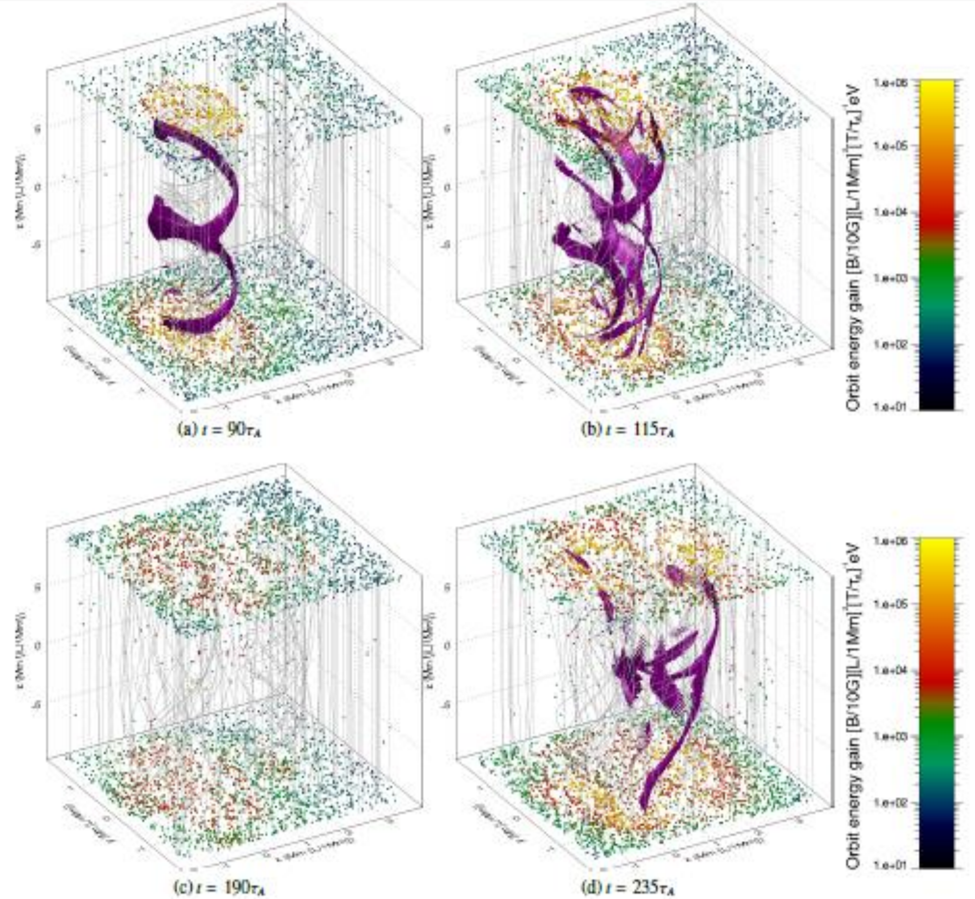
Particle acceleration in flux rope avalanches

Threlfall, Hood and Browning 2018

- **Test particles in interacting pair of loops – one unstable, one stable**
- **Highly-fragmented current sheet**

Time evolution of electron energy spectrum





- **Acceleration of protons and electrons - filling both loops eventually**
- **Non-thermal tail of energetic particles up to ~ 1 MeV**

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Turbulence

- **Turbulence on MHD and kinetic scales affects reconnection - earing and reconnection can lead to turbulence and multiple islands, current fragmentation**

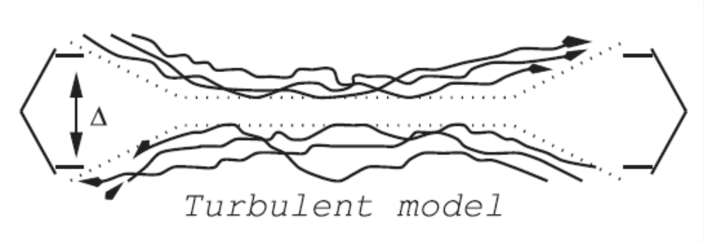
See review Browning and Lazarian 2013

- **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)



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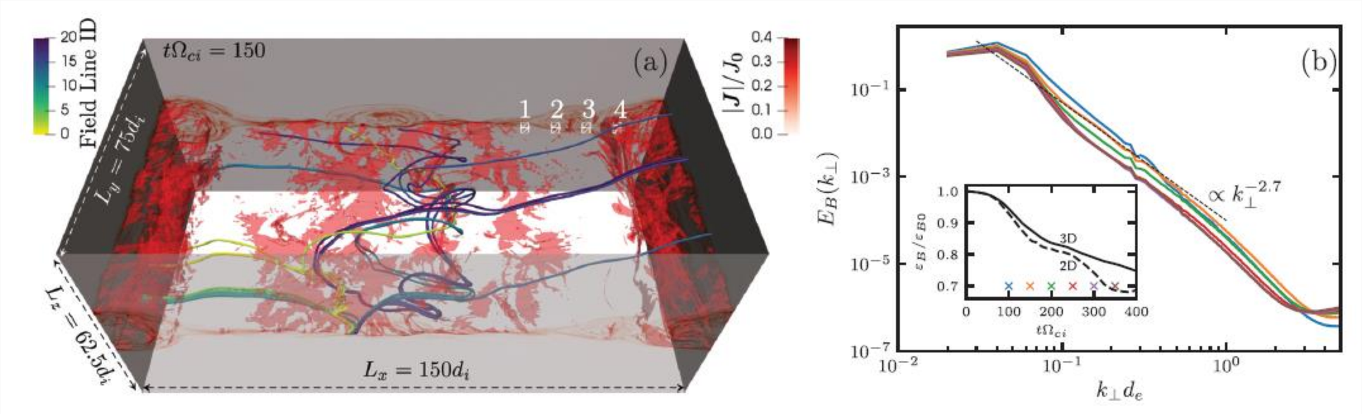
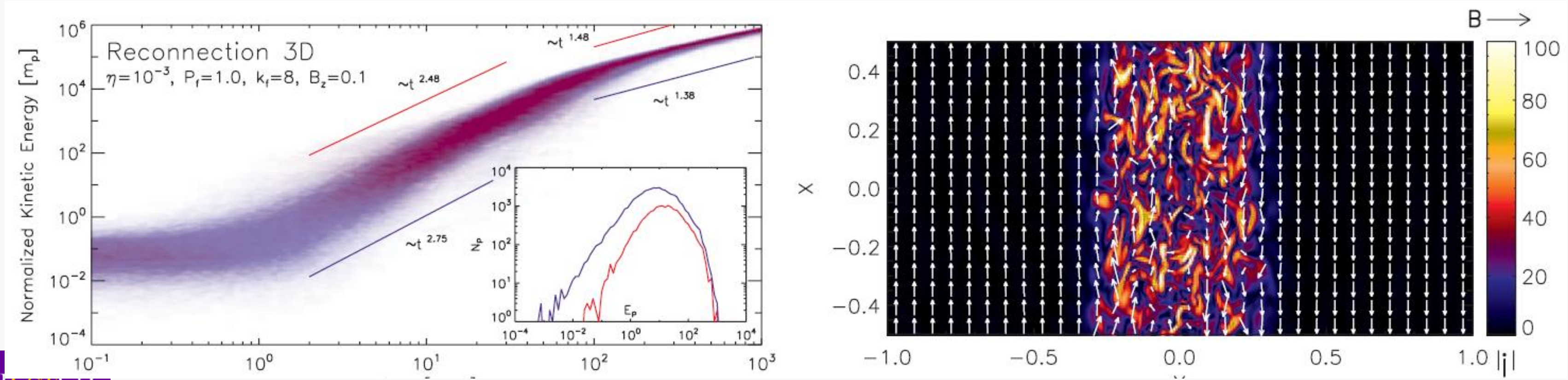
- **3D turbulence with stochastic magnetic fields allow particles to access regions of high acceleration repeatedly**
  - **Acceleration more effective in 3D than 2D**

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

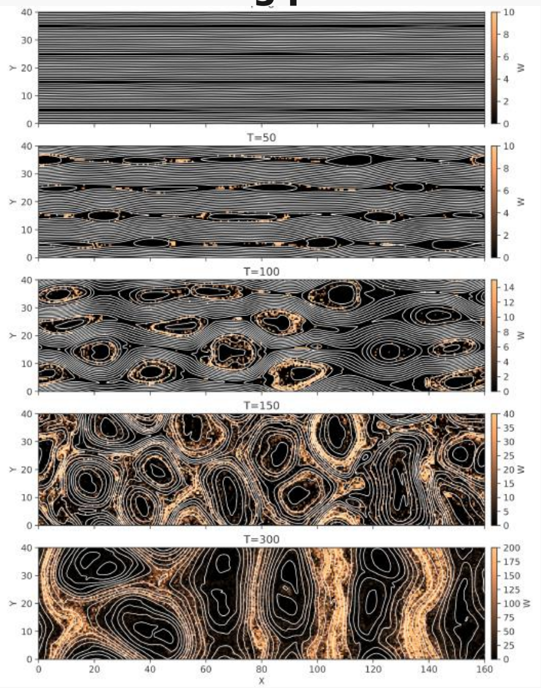
– **MHD-Test Particle**

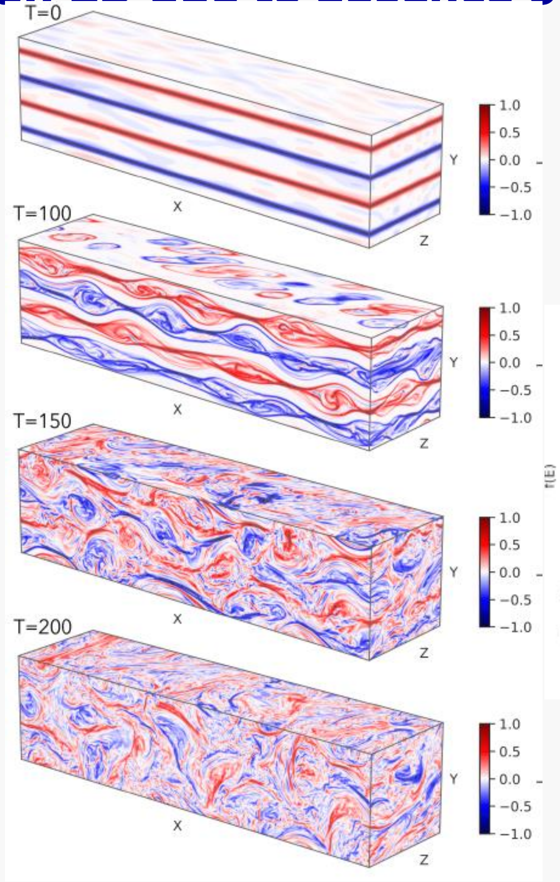
Nakanotani et al 2022

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

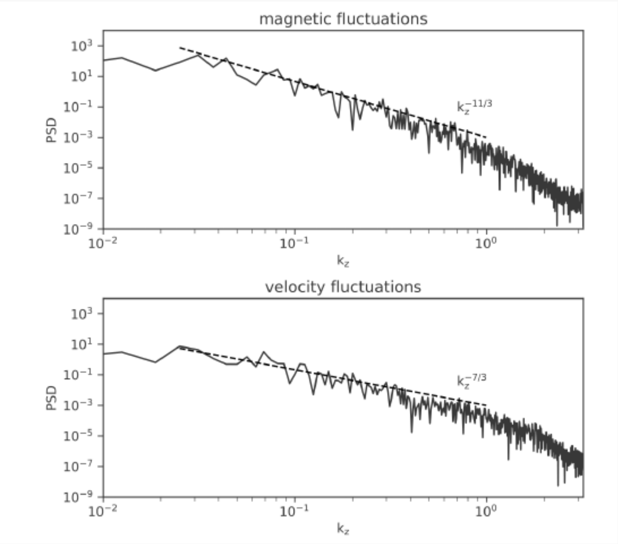
- **Superdiffusion in particle energy**

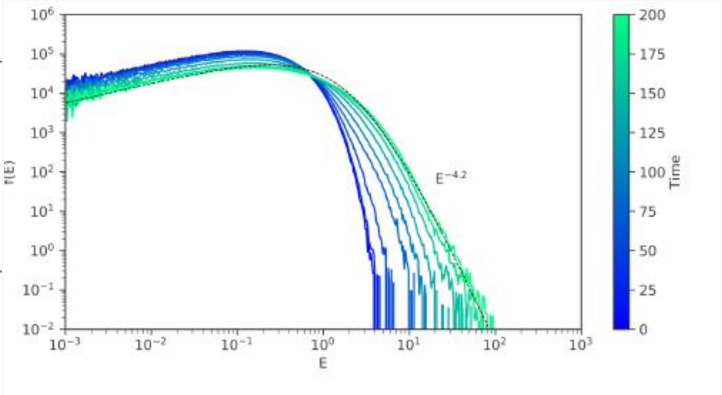
2D – showing particles





3D





Particle energy spectrum 3D

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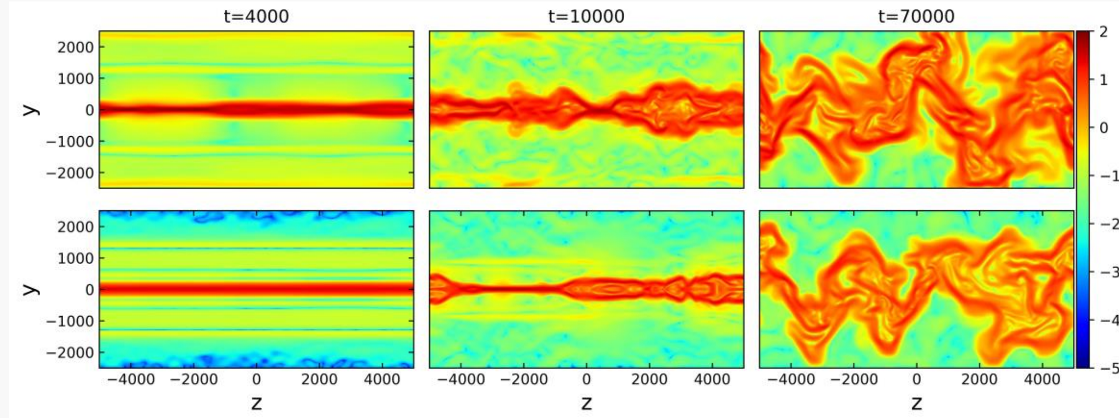
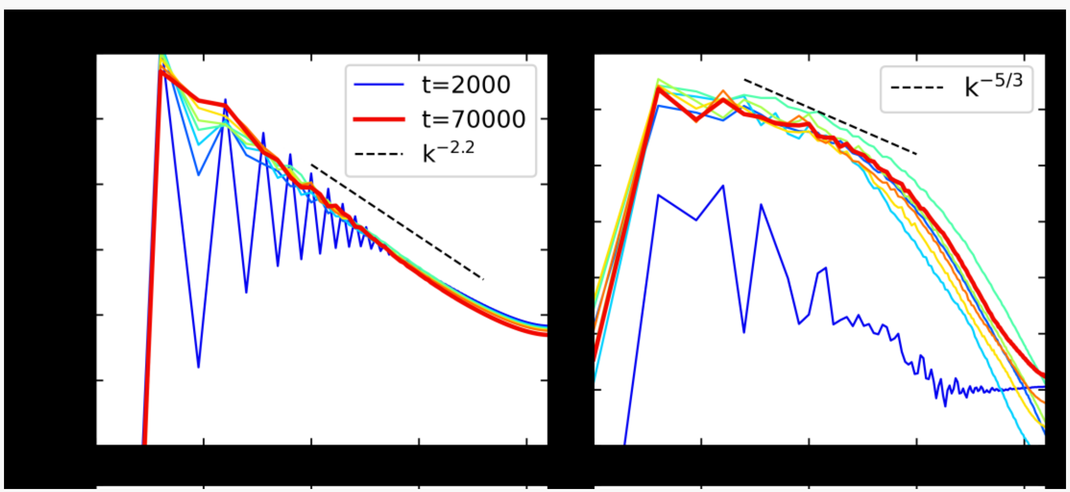
Turbulence and particle acceleration in MHD-PIC model

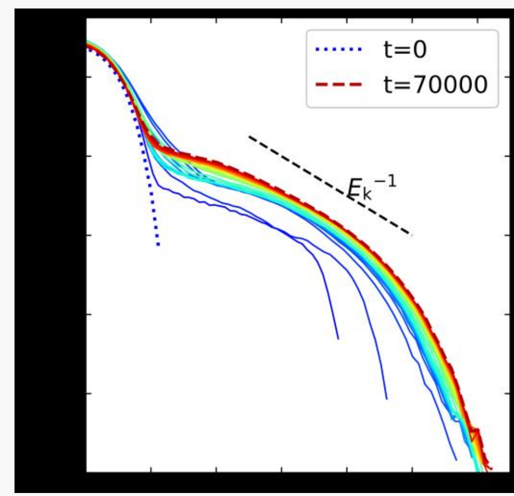
- **Turbulent state in reconnecting current sheet from combination of fragmentation (plasmoids) and Kelvin-Helmholtz**
- **Turbulence in transition scale between MHD and kinetic**



Liang et al 2023



B ***v***



Particle energy spectrum

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Integrating particle acceleratiom models with observations – modelling actual flares

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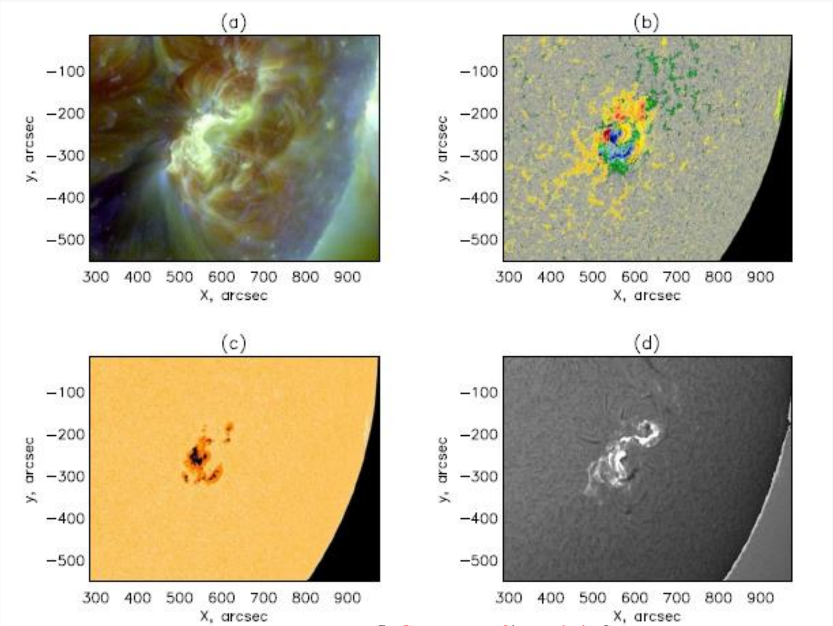
Modelling an individual solar flare

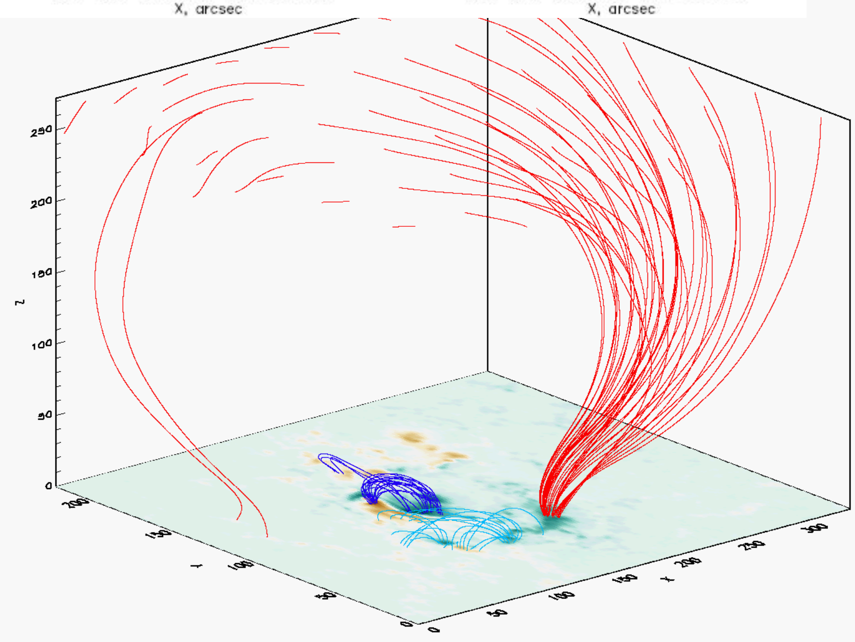
Gordovskky, B, Inoue, Kontar, Kusano and Vekstein 2020

- **Flare September 6th 2017**
- **Magnetic field from nonlinear force-free field extrapolations using vector magnetogram and 3D MHD simulation**

Inoue et al (2018)



- **Test-particles – ions and electrons – with GCA code**
- **Calculate precipitation of energetic particles and forward-model HXR**



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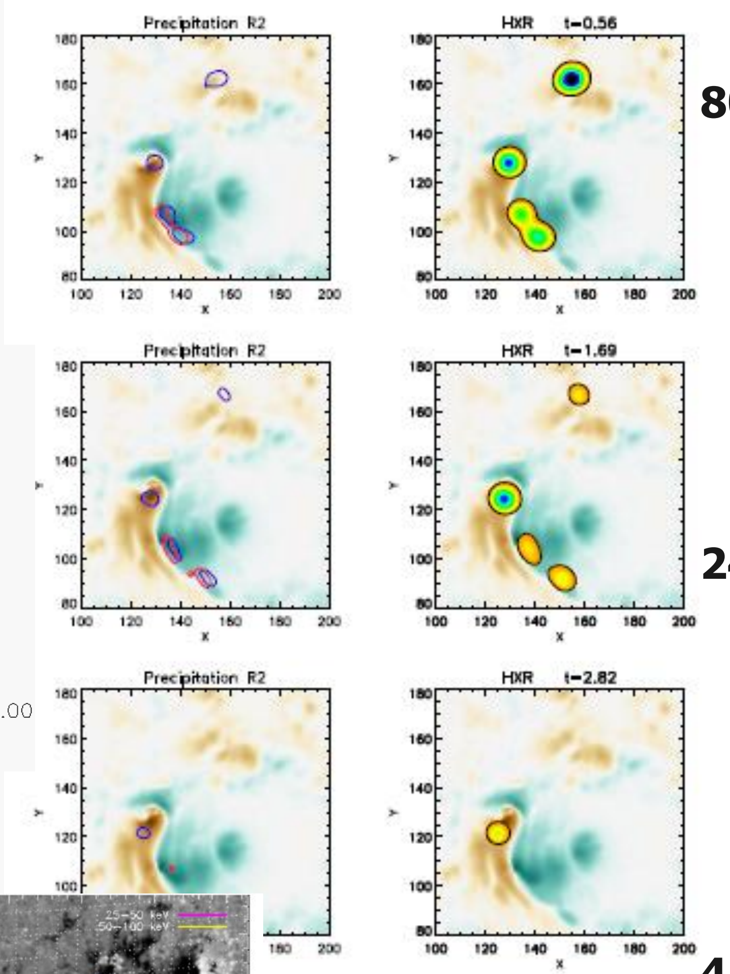
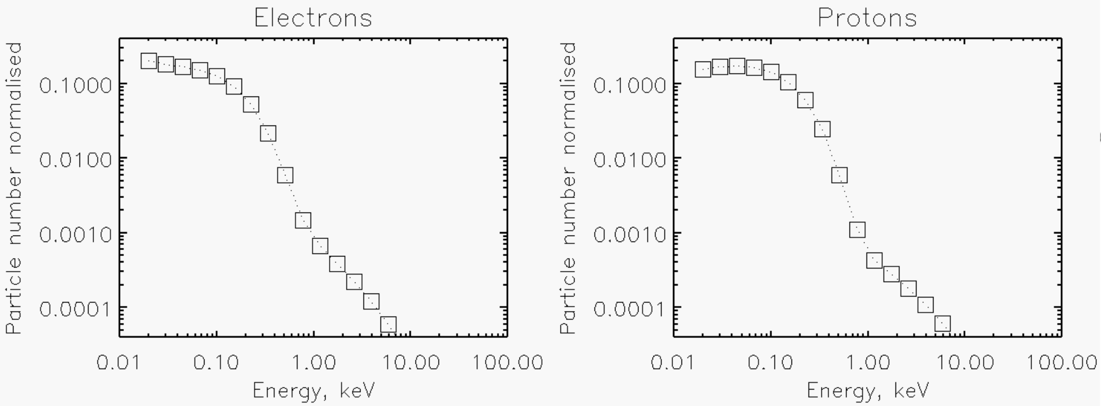
Electron/ion impact on chromosphere and Hard X-rays

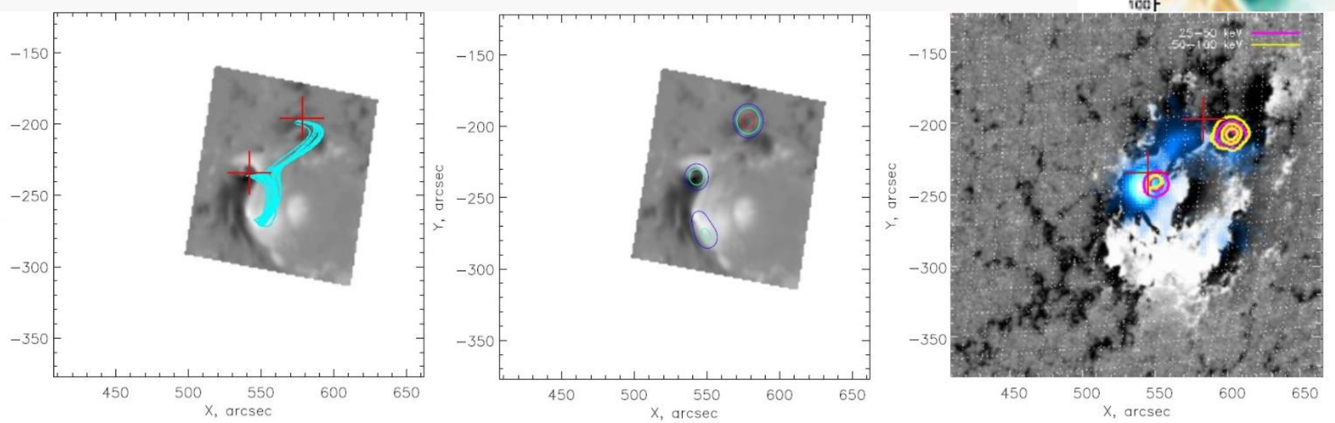


80 s

249 s

415 s





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9 – 12 keV pink

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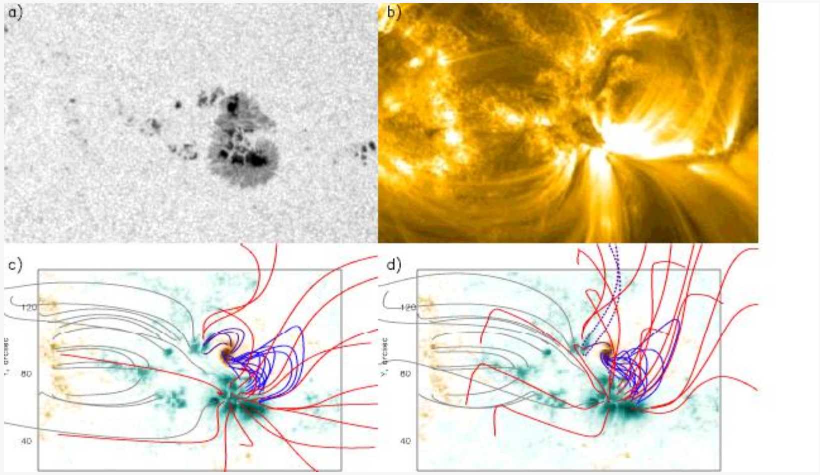
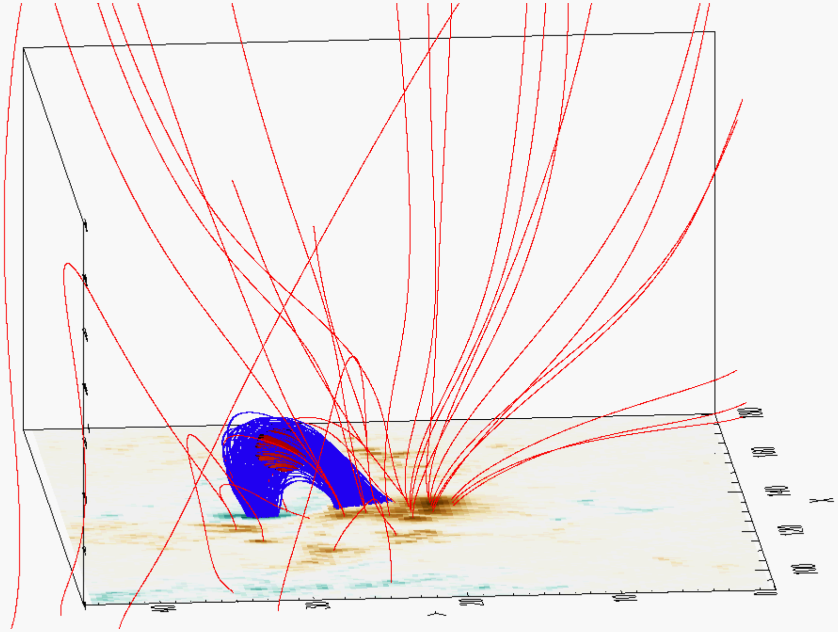
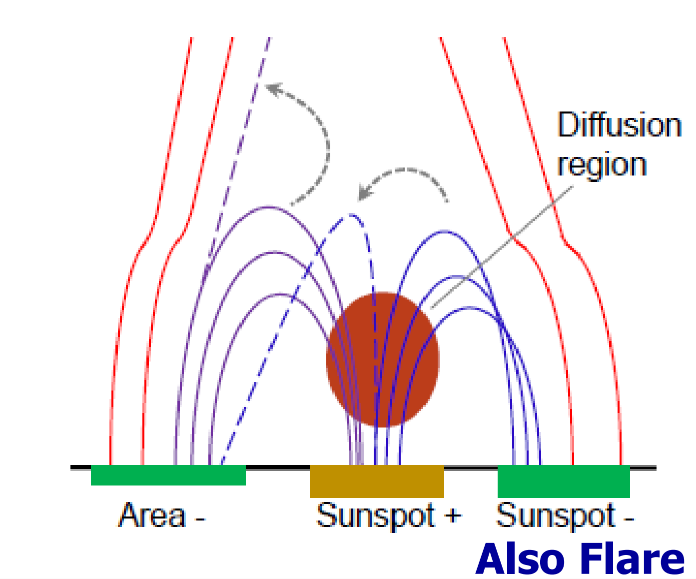
Particle precipitation and escape in flares

- How do energetic electrons/ions escape into heliosphere from flares and what fraction of particles escape?
- What is relationship between properties (energy spectra, time profiles) of precipitating and escaping particle populations?

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







Also Flare 2: M-class flare, 19/6/2013

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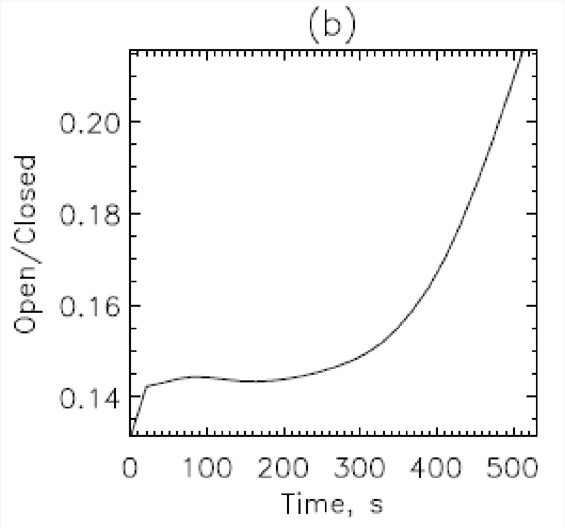
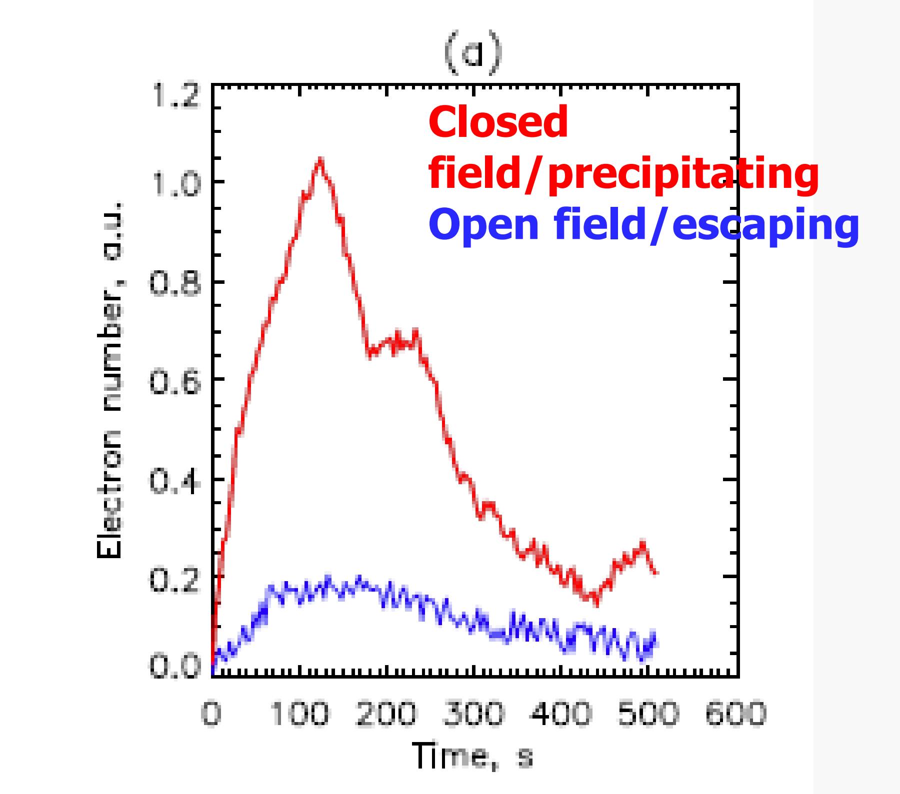
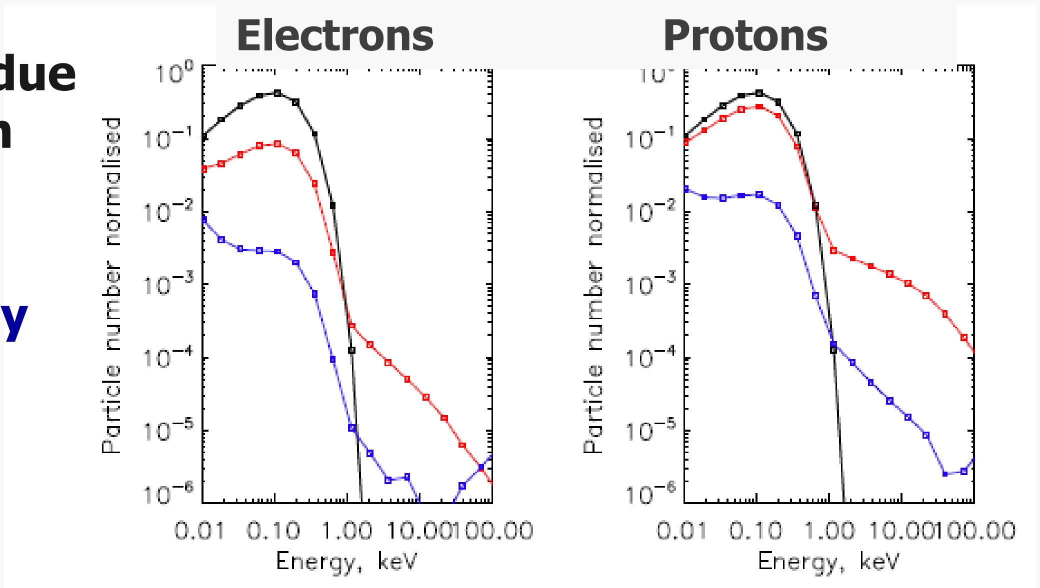
Gordovskyy et al ***Mon. Not Roy Astr Soc*** **in press**

- **Open flux increases with time - interchange reconnection**





- **Particles mainly accelerated due to strong electric fields in closed magnetic field but some escape due to interchange reconnection with open field**
- **Escaping/precipitating particles populations have different energy spectra and time profiles**
  - **C.f. observations *Krucker et al (2007), Klein and Dalla (2017)***



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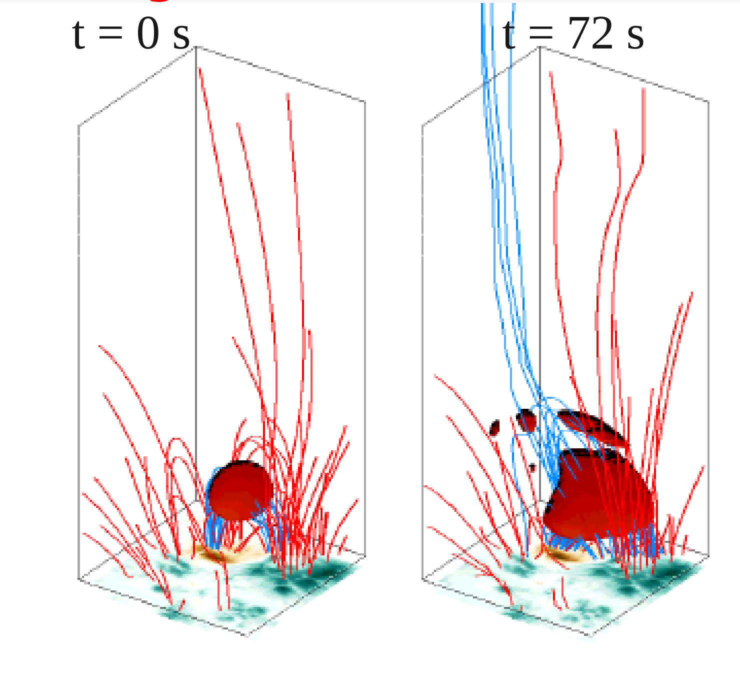
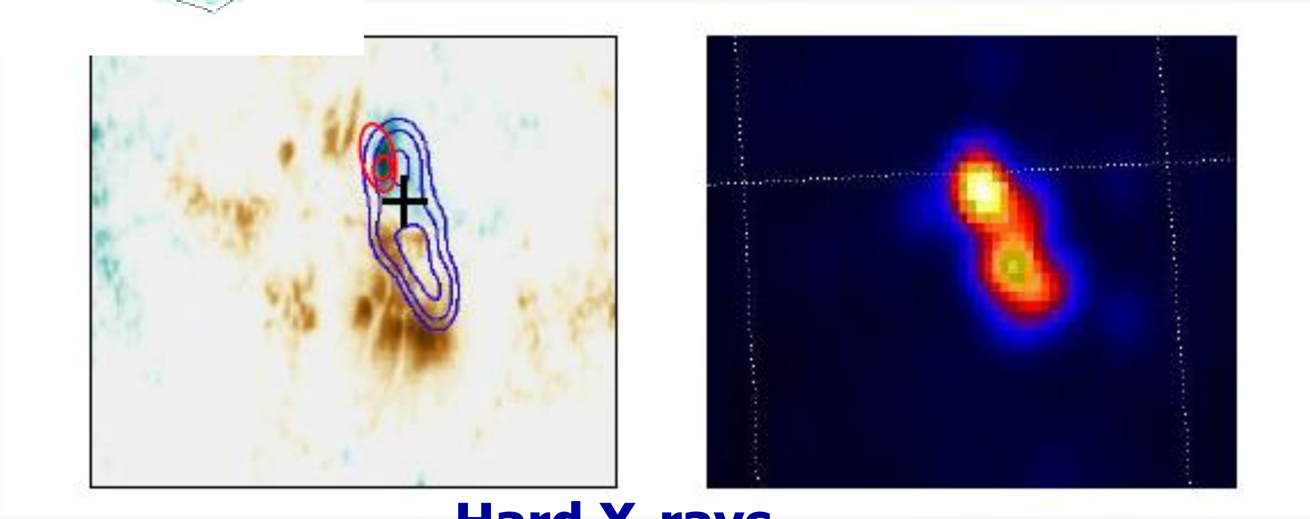
Electron trajectories & magnetic field lines



Electron escape and precipitation



Hard X-rays

Modelled

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Summary and final thoughts

- Particle acceleration in solar flares arises ultimately from magnetic reconnection – which is turbulent, 3D, time-dependent etc - in contrast to classical models
- Proper understanding of particle acceleration and transport requires models bridging huge range of spatial and temporal scales from global to kinetic
- Magnetic field structure is complex – current sheets may be fragmented, turbulence interacts with reconnection…
- Mechanisms include direct acceleration in current sheets, contracting or merging islands, turbulence and stochastic fields, waves
- Radio observations are a key diagnostic of accelerated electrons and will help to resolve questions concerning particle acceleration

Looking forward to considerable progress on this topic within Working Group 2

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