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The University of Manchester

Magnetic reconnection, relaxation and particle acceleration in unstable twisted coronal loops

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- **The solar corona, flares and coronal heating**
  - **Twisted fields in the corona**
- **Reconnection and particle acceleration in unstable cylindrical twisted loops**
  - **MHD and test particles in a single cylindrical loop**
- **Realistic loop models and observational signatures**
  - **Curved loops, thermodynamics and forward modelling**
- **Beyond the single loop model**
  - **Repeated heating events and multiple loops**
  - **Towards complex topologies (3D null points)**

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The solar corona

- The corona is the hot ($T \approx 10^6 - 10^7$ K) tenuous outer atmosphere of the Sun
- c.f. photosphere, $T \approx 6000$ K

- Highly dynamic and structured plasma dominated by magnetic field $\beta << 1$

[redacted]

SDO – EUV emission and photospheric magnetic field

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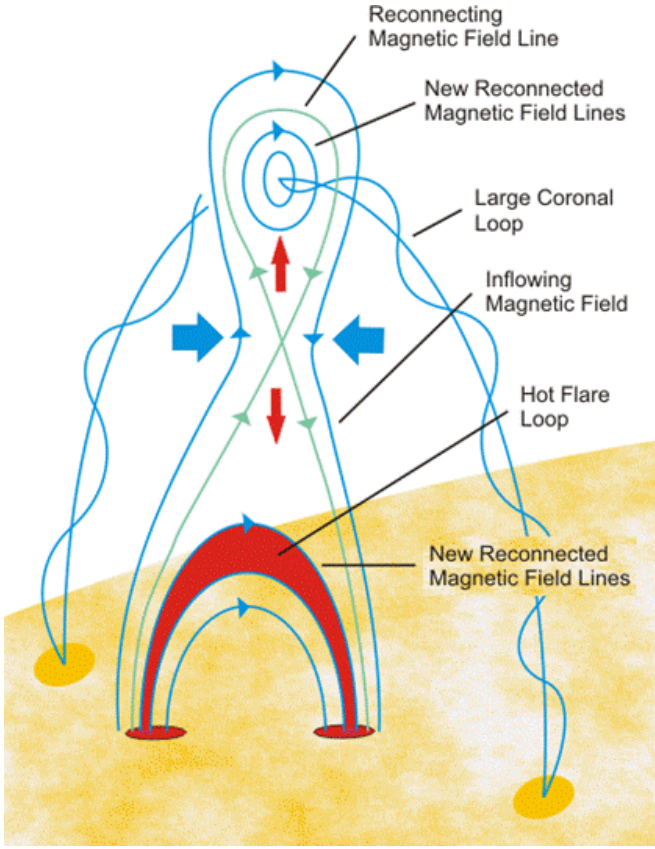
Solar flares –
magnetic reconnection in action

X class flare
September
2014



- **Solar flares are dramatic events releasing up to 10^{25} J of stored magnetic energy over minutes/hours – strong brightening in soft x-rays**
- **Plasma heating and non-thermal energetic particles - signatures across the em spectrum from gamma rays to radio**
- **Primary energy release process believed to be magnetic reconnection**

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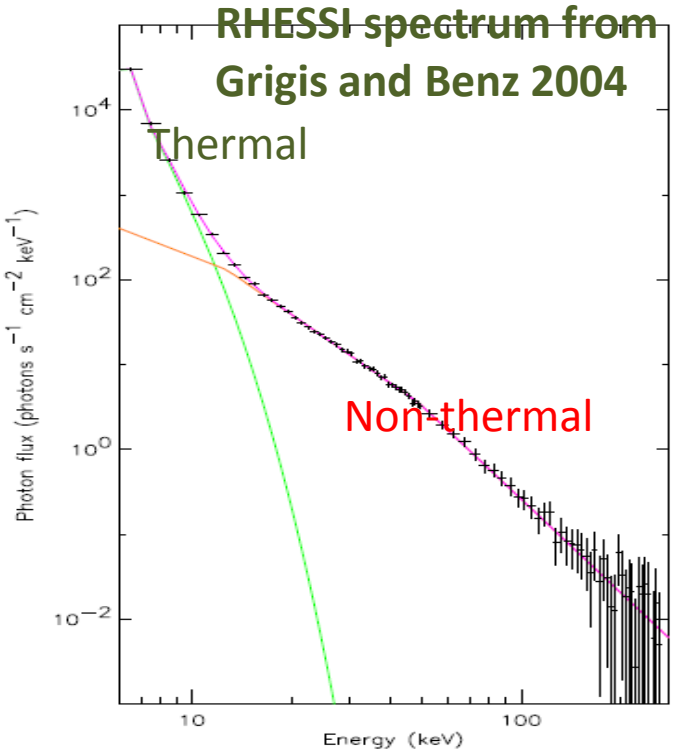
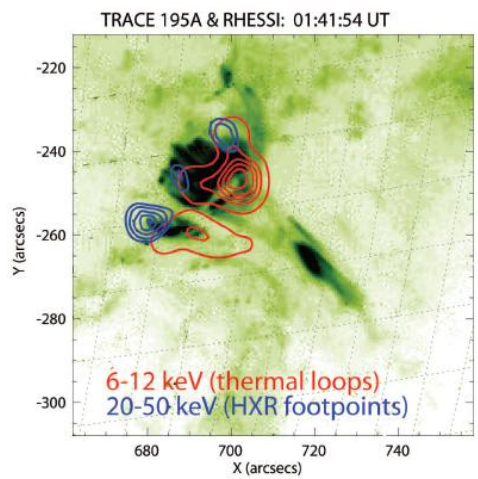
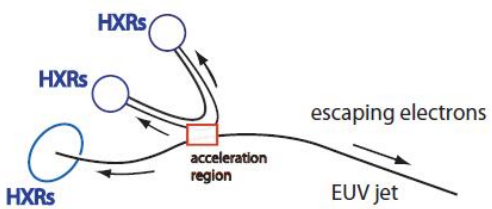
Energetic particles in solar flares

Flares produce substantial numbers of non-thermal energetic ions and electrons

- **Up to 50% of flare energy in non-thermal particles**
- **May propagate down to solar surface where they impact on dense chromosphere emitting bremsstrahlung - " Collisional Thick Target Model" CTTM**
  - **Hard X-ray emission e.g. RHESSI**
- **Or along open field lines into space, may be source of Solar Energetic Particles and contribute to "space weather"**
  - **Radio/microwave emission**







RHESSI Hard X-rays and SXR Schematic (right) from Vlahos et al 2009

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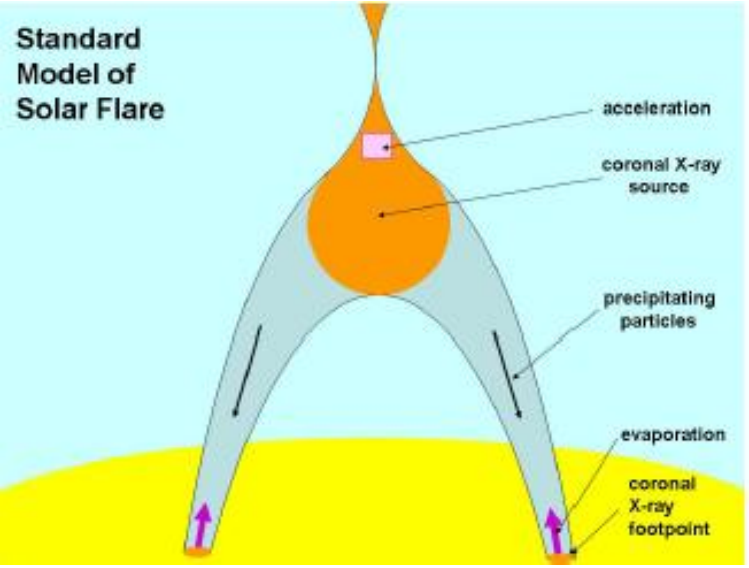
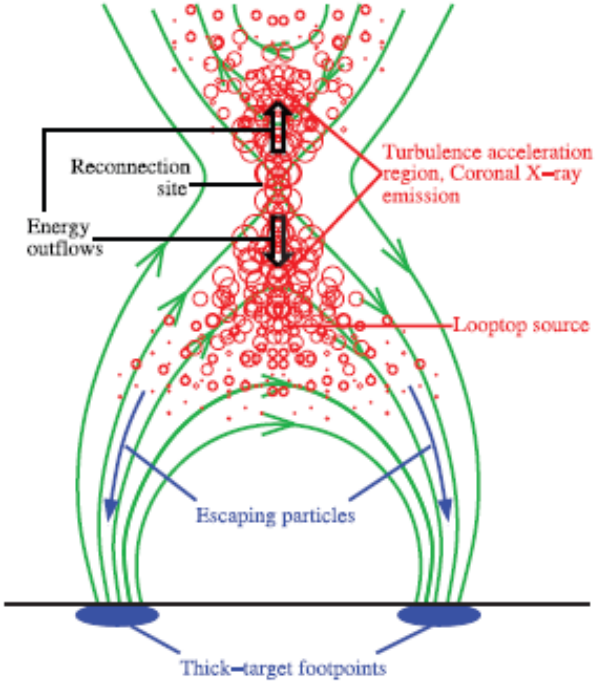
Particle acceleration mechanisms

- **Strong candidate for particle acceleration is direct electric field in reconnecting current sheet (at loop top in "standard model")**
- **Also proposed - waves, turbulence, shocks**
- **Difficulties with standard model and "Collisional Thick Target Model" - acceleration in highly-localised monolithic coronal current sheet *e.g. Brown et al 2009***
  - **Number problem, intense beam....**



From Liu et al 2008



- **May be alleviated by chromospheric (re-) acceleration and/or distributed or stochastic acceleration *e.g. Vlahos et al 2009***
- **Here bring together elements of "reconnection" and "stochastic" models - reconnection closely linked to turbulence e.g. *Browning and Lazarian, 2013***

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Coronal heating and nanoflares

- **Need heat source to balance losses due to conduction and radiation (T over 10^6 K)**
- **Sub-surface motions shuffle the footpoints of the coronal magnetic field → free magnetic energy in the corona**
- **For slow driving, field evolves through equilibria - free energy associated with static currents**

$$\mathbf{j} \times \mathbf{B} = 0$$

SDO Coronal loops Oct 26-29 2014

•Magnetic reconnection may dissipate this energy efficiently in highly-conducting coronal plasma

•Corona may be heated by combined effect of many small "nanoflares" (*Parker 1988)*

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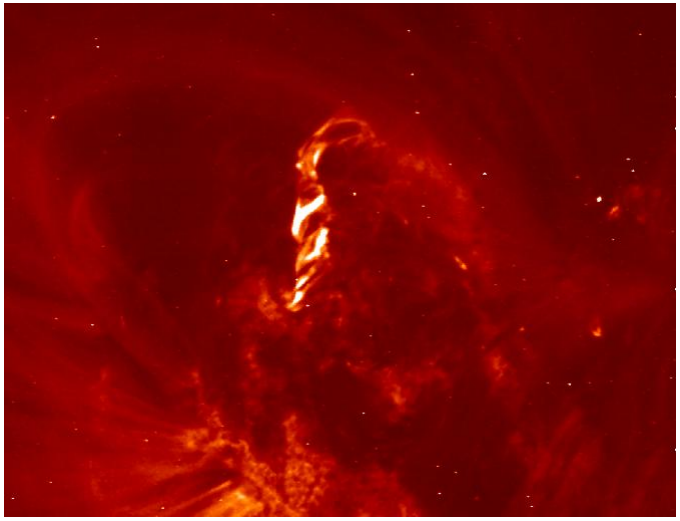
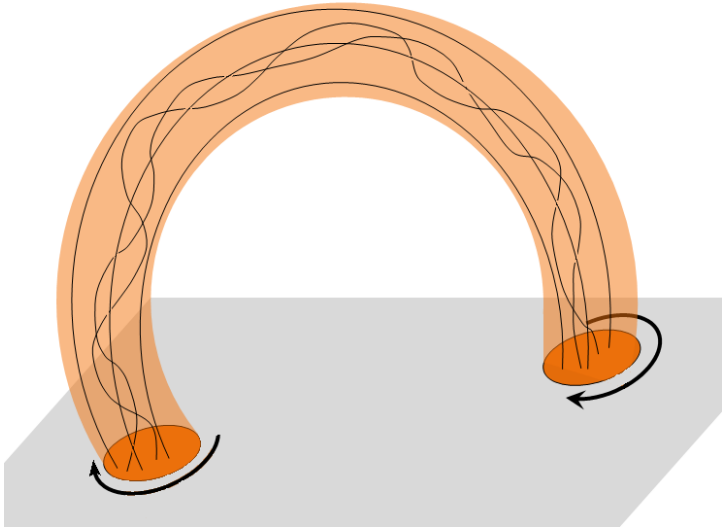
Twisted fields in the corona

- Non-potential coronal fields due to emergence of current-carrying flux and/or photospheric footpoint motions
- Twisted loop are observed directly in EUV *e.g. Song et al. 2008; Raouafi et al. 2009*
- Reconstructed coronal field often shows substantial twist

e.g. Regnier & Amari 2004;Malanushenko et al 2011

- Free magnetic energy associated with currents





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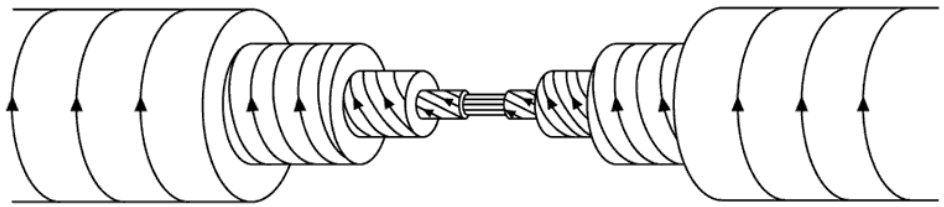
Twisted flux ropes



Interior Structure of Flux Rope

Ubiquitous structure in laboratory, space and astrophysical plasmas
•*Russell et al (eds)* Physics of magnetic flux ropes, AGU 1990
•Plasma Physics and Controlled Fusion Special Issue June 2014

- **Coronal Mass ejections and erupting filaments**
- **Solar coronal loops and flares**
- **Solar and stellar interiors – dynamos**
- **Planetary magnetospheres and solar wind**
- **Basic plasma physics lab experiments**
  - **e.g. LaPD Gekelman et al 2014; Moser and Bellan, 2012; RSX Sears et 2014....**
- **Spheromaks**
  - **e.g. Brown, Browning et al Space Sci Rev 2013**
- **Tokamaks, Reverse Field Pinches etc**

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Reconnection and particle acceleration in unstable twisted cylindrical loops

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Energy release – relaxation theory

•**Relaxation to a minimum energy state conserving total magnetic helicity *(K)***
Taylor 1974

$$K = \int_V \mathbf{A} \cdot \mathbf{B} dV$$

From Wiegelmann Liv Rev Sol Phys

•**Relaxed state is constant-*α* or linear force-free field**

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \qquad \alpha = \mu_0 j_{//} / B$$

•**Solar coronal field releases free magnetic energy as heat during relaxation from nonlinear force-free field** *Heyvaerts & Priest 1984*

- **Helicity is invariant in ideal MHD**
- **Magnetic reconnection destroys individual flux tube helicities**
- **Global helicity still approximately conserved in presence of small-scale reconnection – helicity dissipation much less than energy dissipation**

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How does relaxation happen in the corona?

- Heyvaerts-Priest assumed continuous relaxation with (unknown) timescale
- But relaxation is likely to be an intermittent process
- How far can free energy build up before onset of relaxation ?

→ heating rate

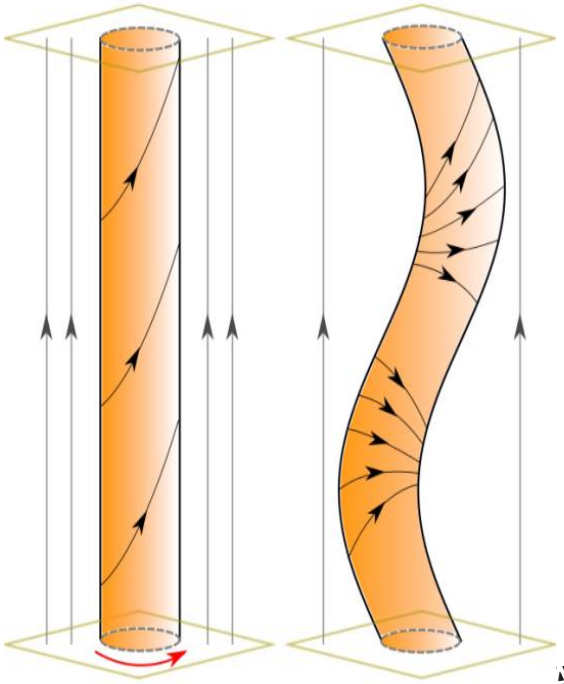
•Proposed that a possible trigger for relaxation is the onset of kink instability in a twisted coronal loop

Browning and Van der Linden 2003

•Helicity-conserving relaxation during nonlinear phase of kink instability

$$W_{heat} = W_{inital} - W_{relaxed}(\alpha)$$

where α determined by helicity conservation and $W_{initial}$ evaluated at ideal kink instability threshold



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Kink-unstable twisted cylindrical coronal loop

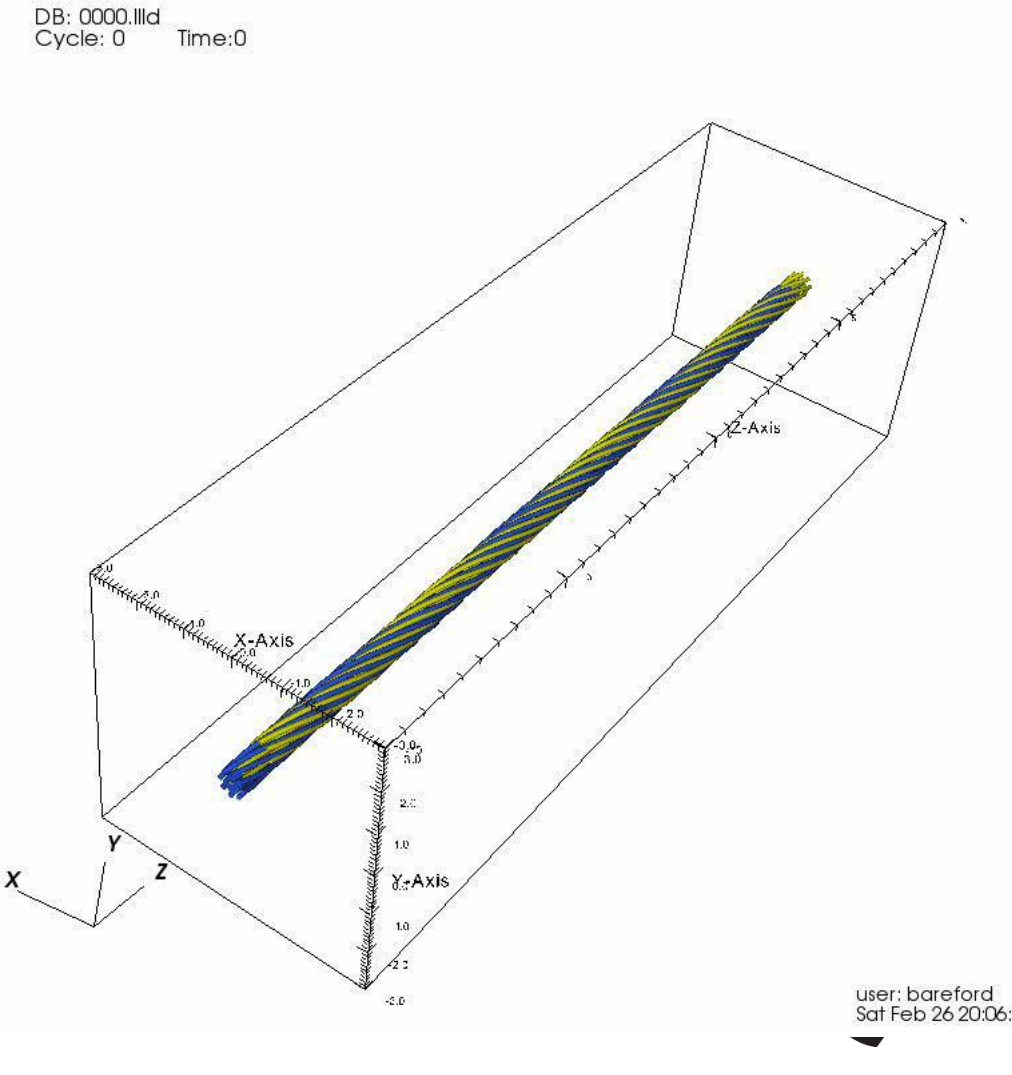
- **Solve 3D MHD equations with Lagrangian-Remap code LARE3D**

Arber et al 2001

- **Previous work considered initial cylindrical nonlinear force-free equilibrium with *α(r)* linearly unstable to ideal kink**

Browning et al 2008, Hood et al 2009, Bareford et al 2013

- **Helicity conserved much better than energy**
- **Final state close to "constant-α" minimum energy state and energy release well approximated by relaxation theory**



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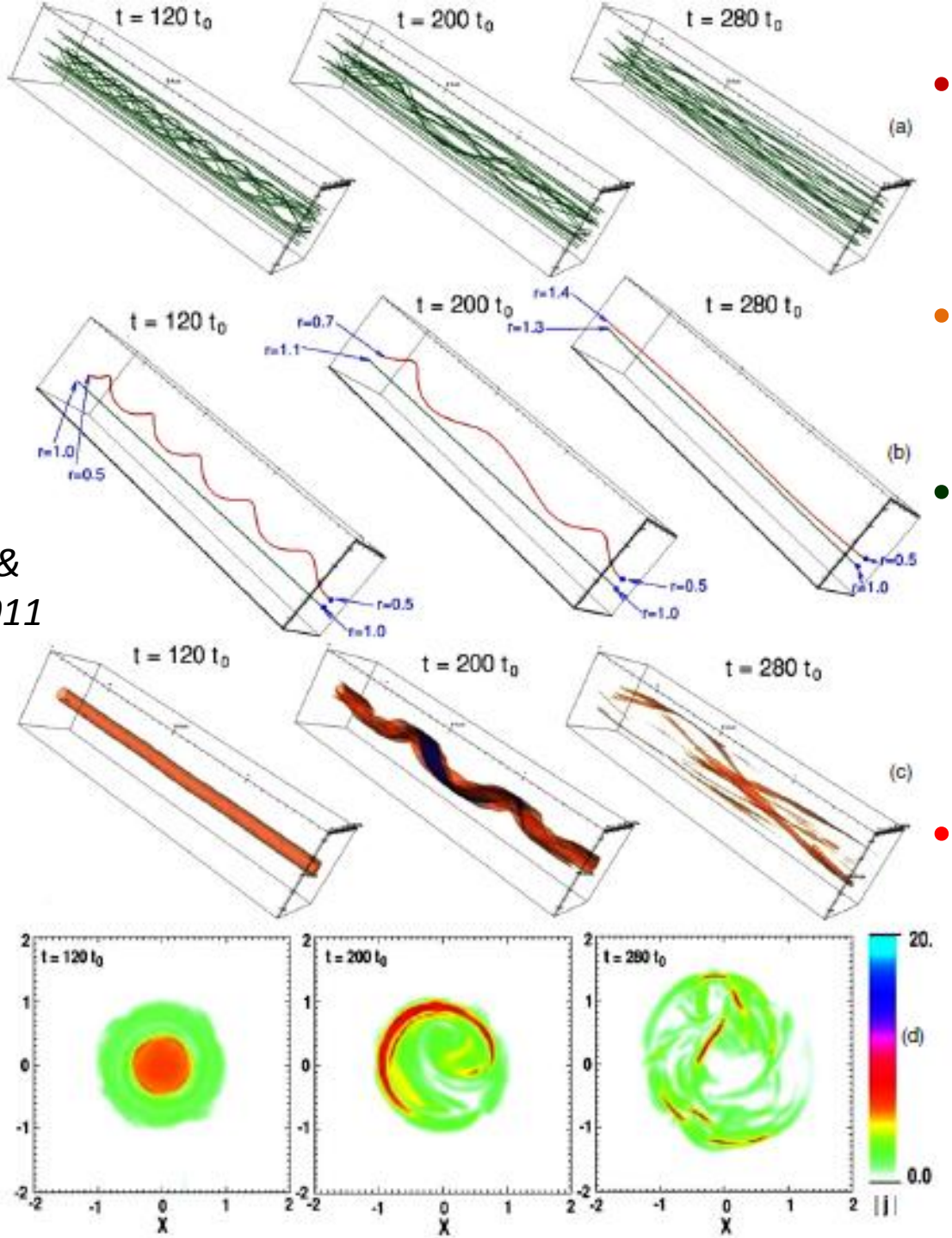

Gordovskyy & Browning 2011

- **Helical current ribbon forms at quasi-resonant surface of linear kink**
- **Current sheet stretches and fragments**
- **Reconnection within loop and with surrounding axial field → loop expansion and "untwisting" of field**
- **Mixing of α-profile (relaxation to constant-α) due to multiple reconnections**

Particle acceleration and transport in unstable twisted loops

- **Test particles coupled to 3D MHD loop simulations**
- **Relativistic guidlng-centre equations with time-evolving E and B - fields interpolated in (*x,y,z,t*)**
- **Particles efficiently accelerated throughout loop volume by fragmented current sheet → distributed acceleration region, avoiding some problems of "standard flare model"**

Gordovskyy and Browning 2011, 2012

- **Recent work incorporates Coulomb collisions of test particles with background plasma – mainly in dense chromosphere**
- **Energy loss**

  Removes high energy electrons, softens spectrum
- **Pitch-angle scattering**

  Improves confinement of energetic particles since allows mirroring at footpoints

  Gordovskyy et al 2013

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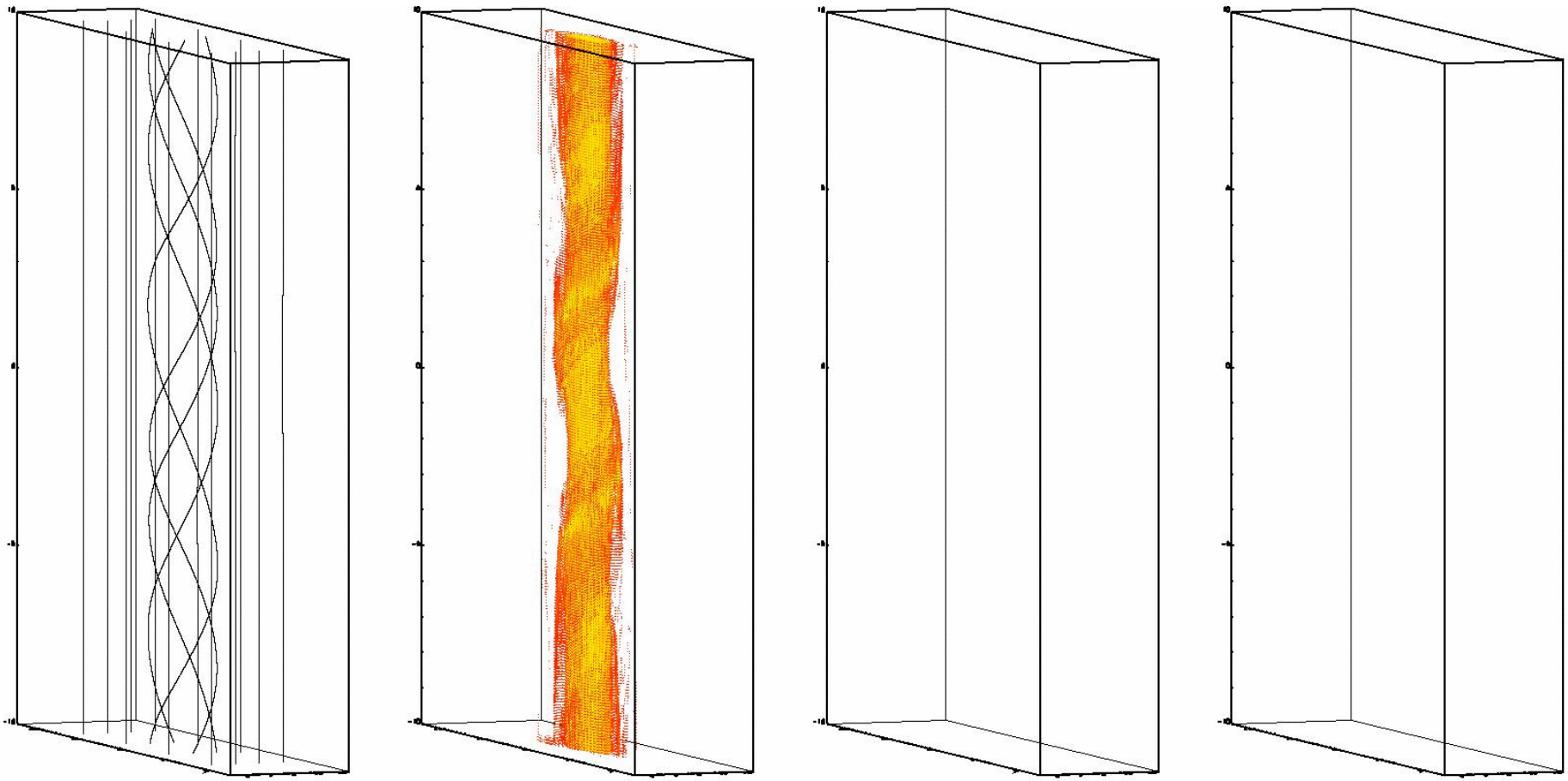
Particle distribution in space – cylindrical loop

Particles accelerated throughout loop volume by repeated encounters with fragmented current sheet *Gordovskyy and Browning 2011, 2012*

Magnetic field **Current density** **Protons** **Electrons**



E = 100keV...1MeV

E > 1MeV

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Realistic loop models and observational signatures

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Towards realistic models – methodology

Potential field in stratified atmosphere

MHD

Derivation of twisted loop configuration (ideal phase)

Magnetic reconnection triggered by kink (resistive phase)

Test-particles

Proton & electron trajectories

Energy spectra, pitch angles, spatial distributions

Thermal emission **Field topology** **Non-thermal emission**

- **Solve 3D MHD equations using LARE3D (Arber et al, 2001) with thermal conduction - anomalous resistivity above critical current**
- **Test particle calculations using relativistic guiding-centre equations including collisions with background plasma**

Gordovskyy, Browning, Kontar and Bian Sol Phys 2014
Gordovskyy, Pinto, Browning and Vilmer in preparation

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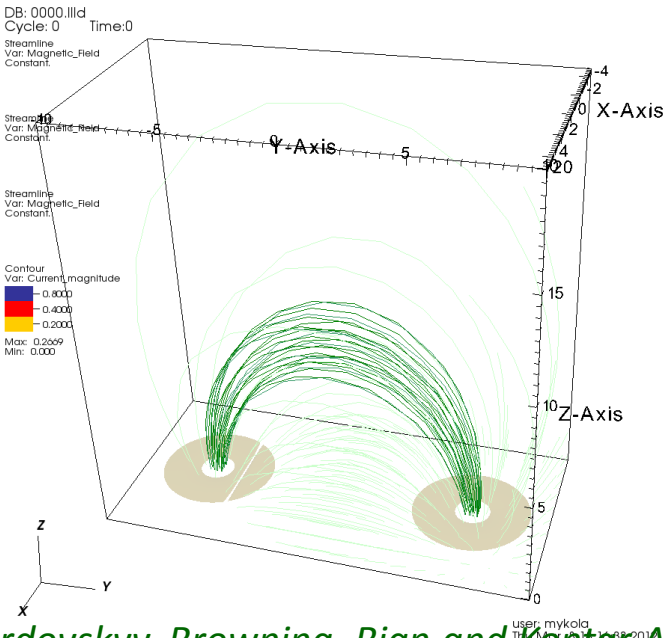
Evolution to unstable twisted loop

- **Initial potential field corresponding to a "magnetic dipole" located under the photosphere**



- **Use ideal MHD and apply "localised" rotation at the photosphere $v_{rot} << v_A$**
- **Wait for it to kink**

- **"Switch on" resistivity before instability onset**
- **Anomalous resistivity above critical current due to ion acoustic instability**

$$j_{crit} \propto \rho\sqrt{T}$$

- **Gravitationally-stratified atmosphere**
- **Energy equation with conduction and optically-thin radiation**

Gordovskyy, Browning, Bian and Kontar A&A 2014
Bareford, Gordovskyy, Browning and Hood 2014 in preparation
Pinto, Gordovskyy, Browning and Vilmer 2014 in preparation

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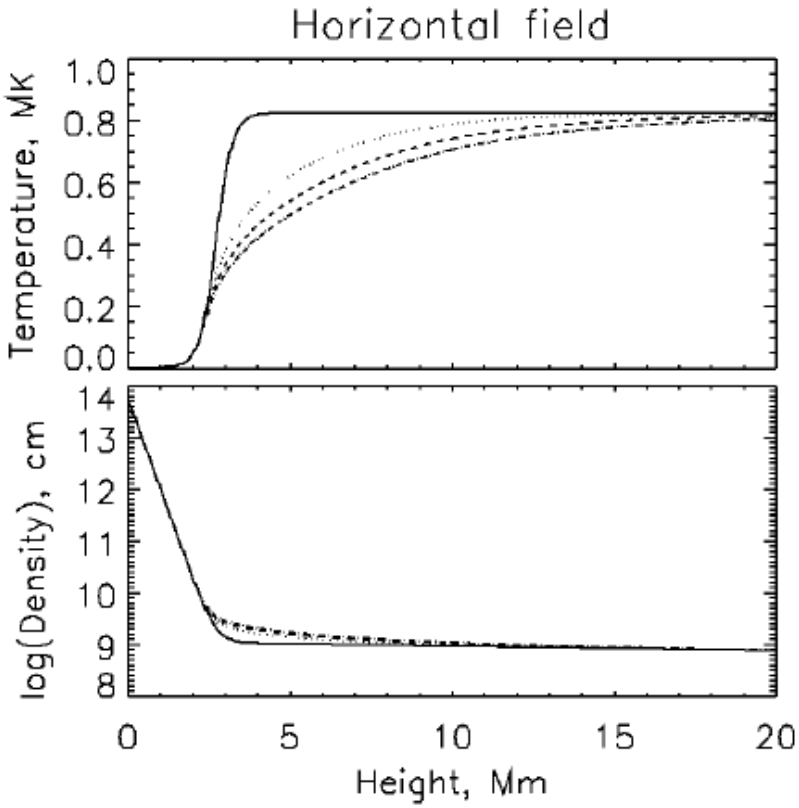
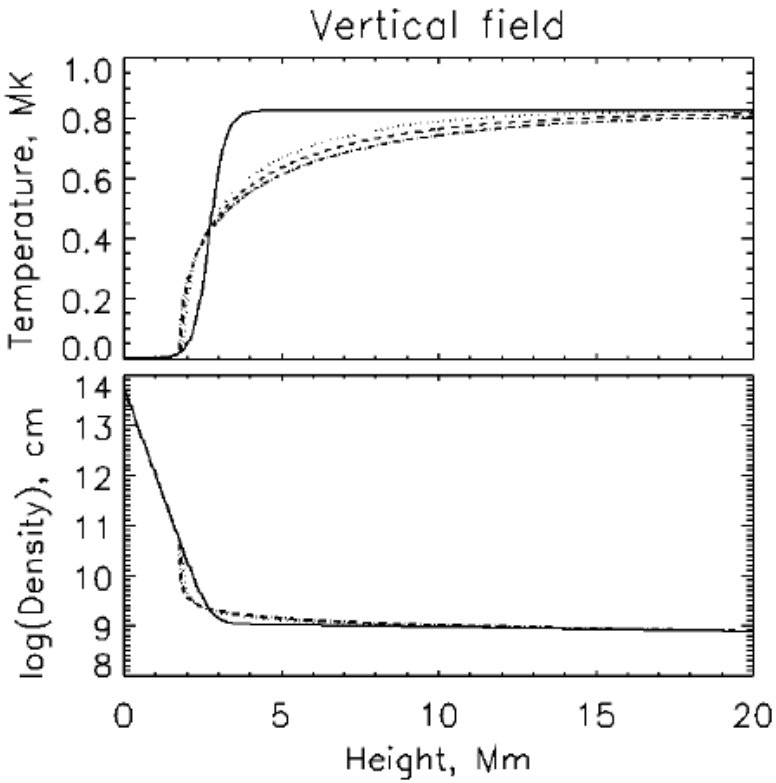
Initial atmosphere

- Chromosphere to corona
- Evolve temperature and density to quasi-equilibrium before twisting loop
- Temperature profile affected by non-isotropic thermal conduction



Loop midplane



Above footpoints

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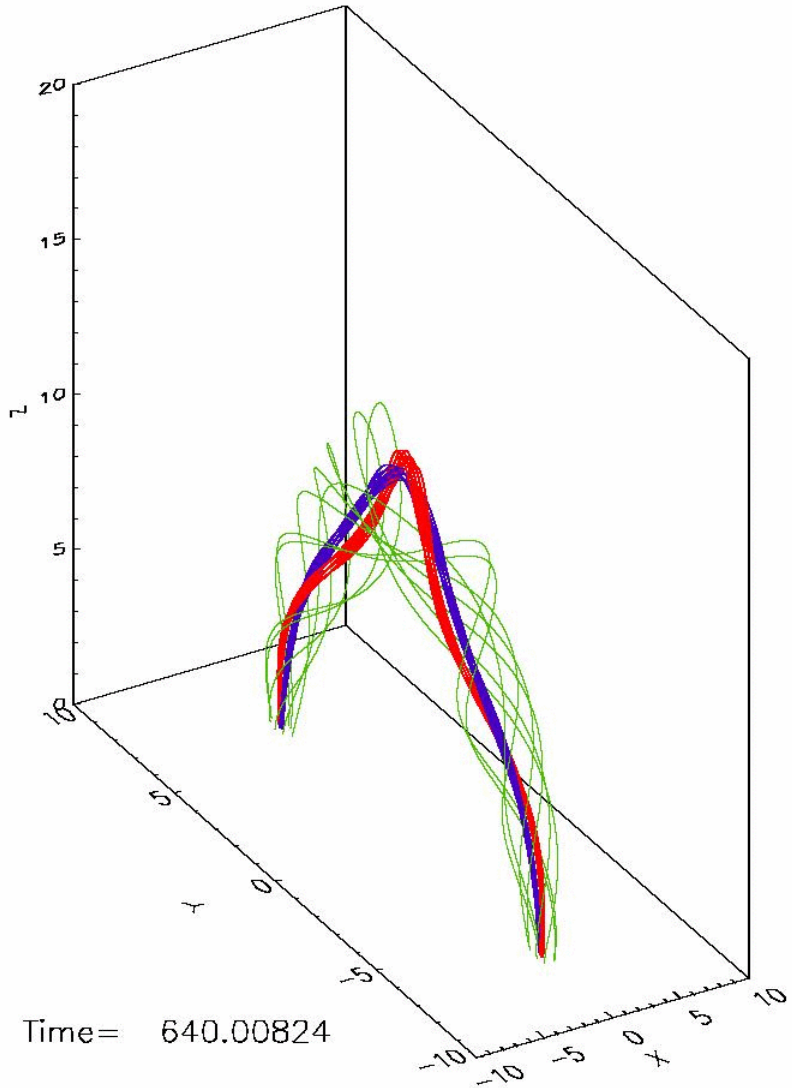

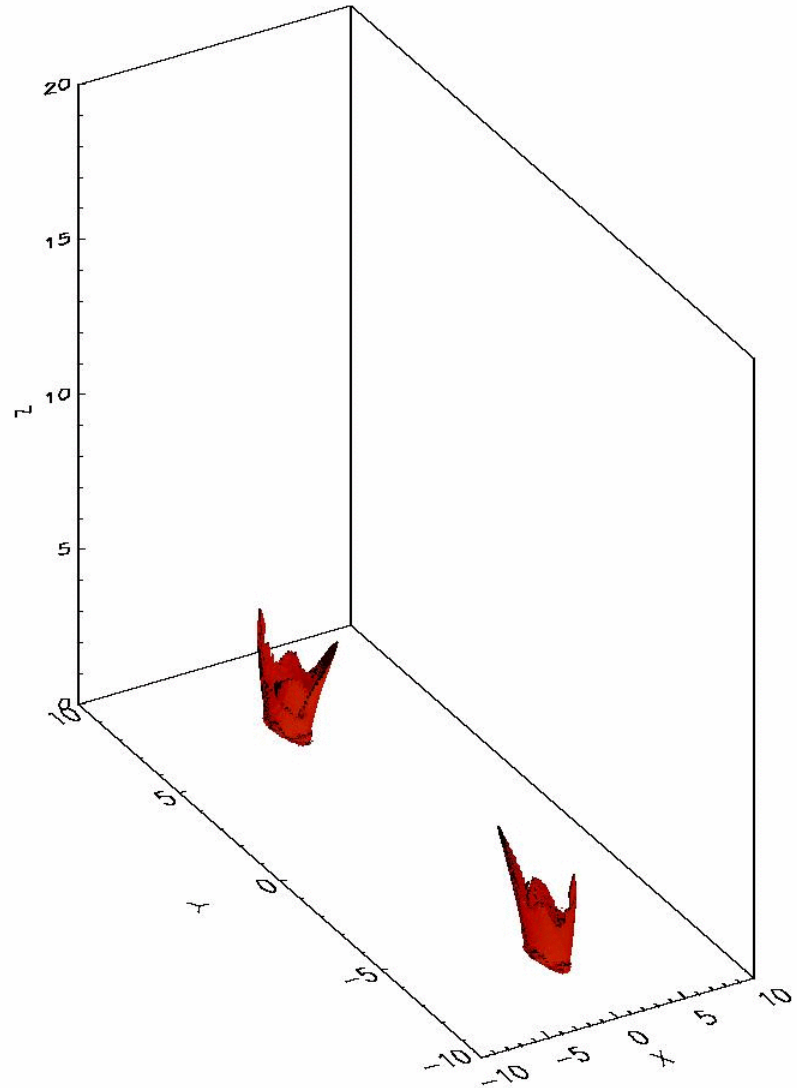

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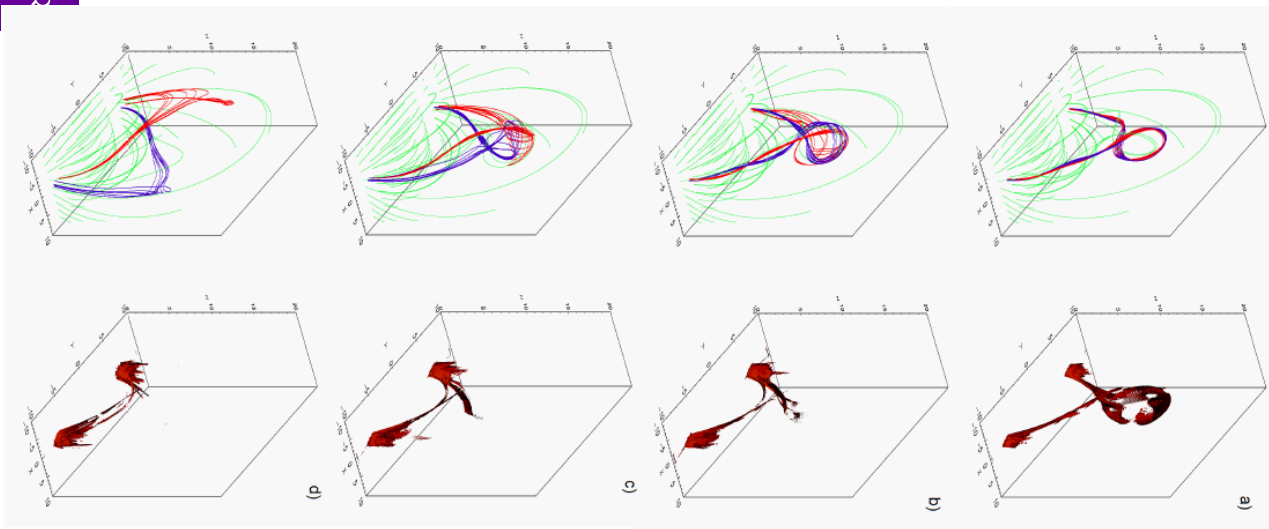
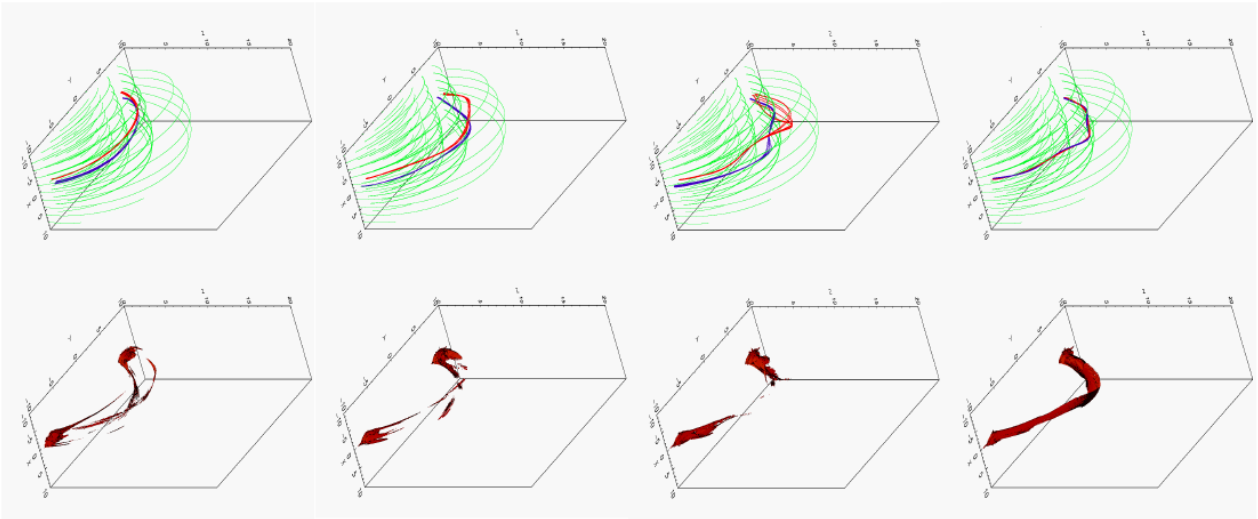
Strongly-converging loop

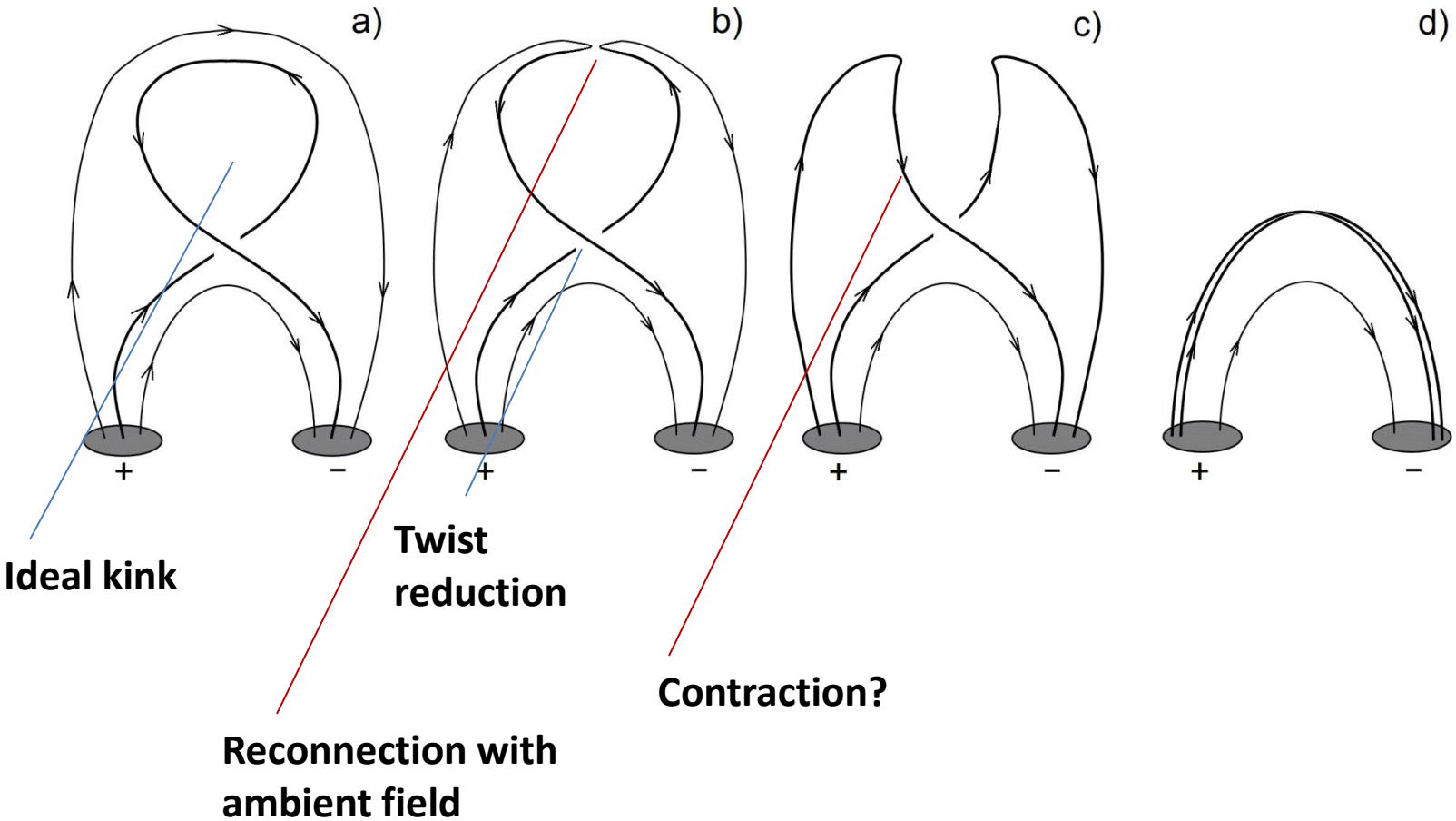


Weakly-converging loop



Curved loop – topology evolution

- Change of connectivity during magnetic reconnection in twisted loop



- Overlaying field prevents eruption (see also Torok & Kliem 2005)

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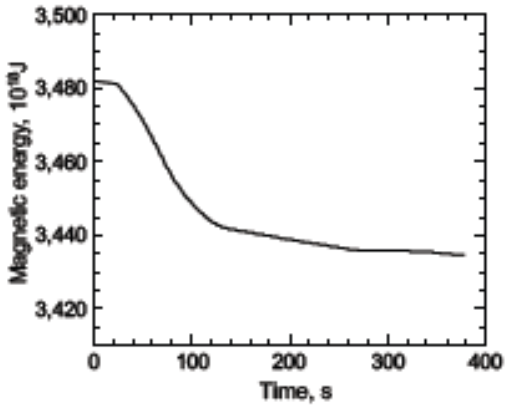
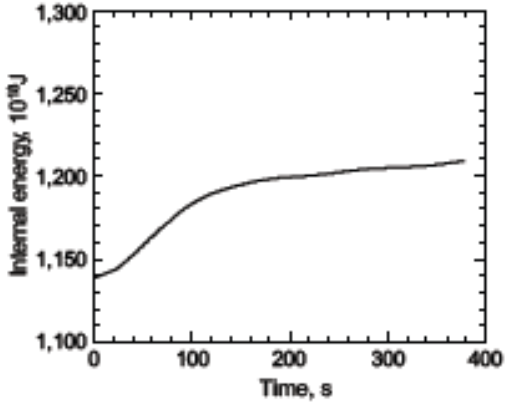
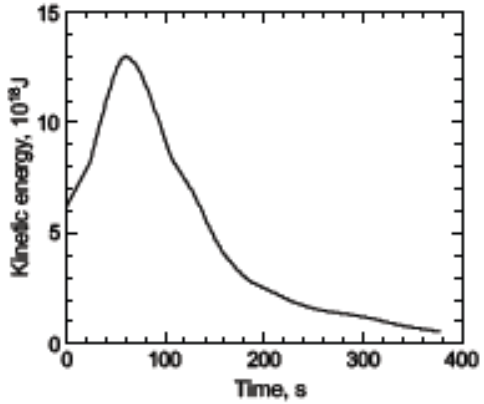
Energy release and heating



Magnetic energy



Internal energy



Kinetic energy

Time from onset of instability

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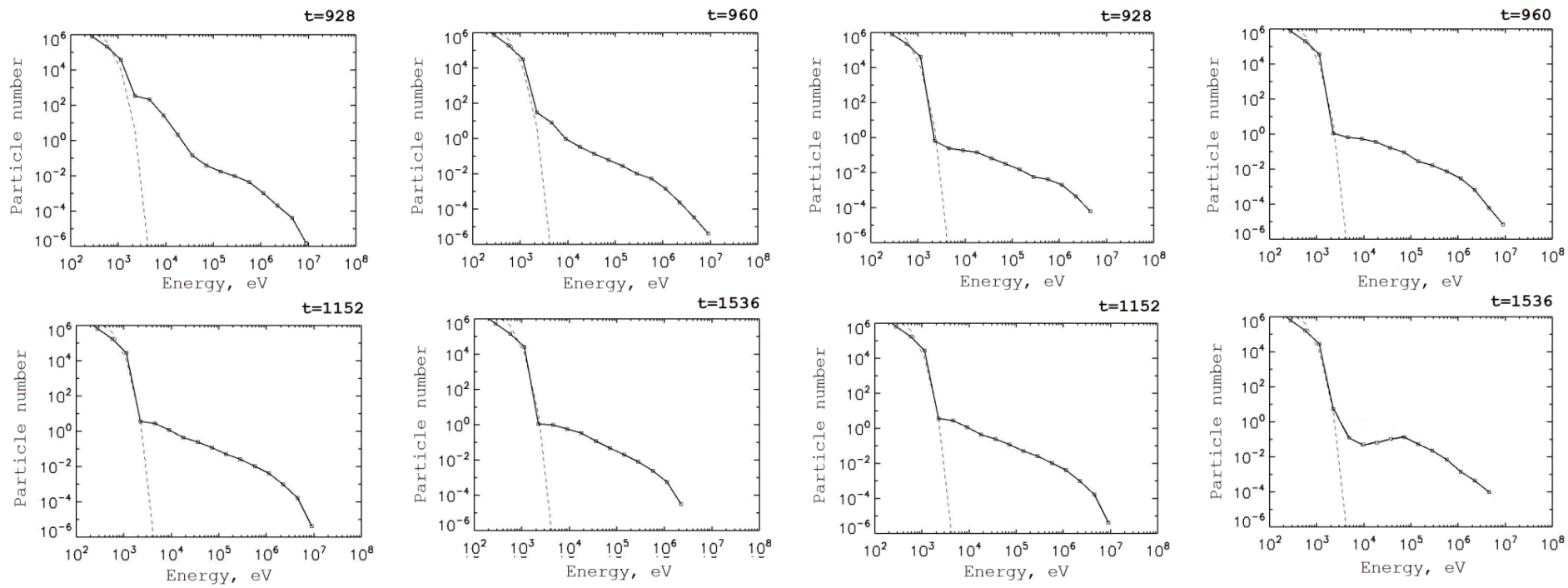
Particle energy spectra – curved loop

Time evolution - electrons

Low density **High density**



Gordovskyy et al 2014

MHD without density stratification

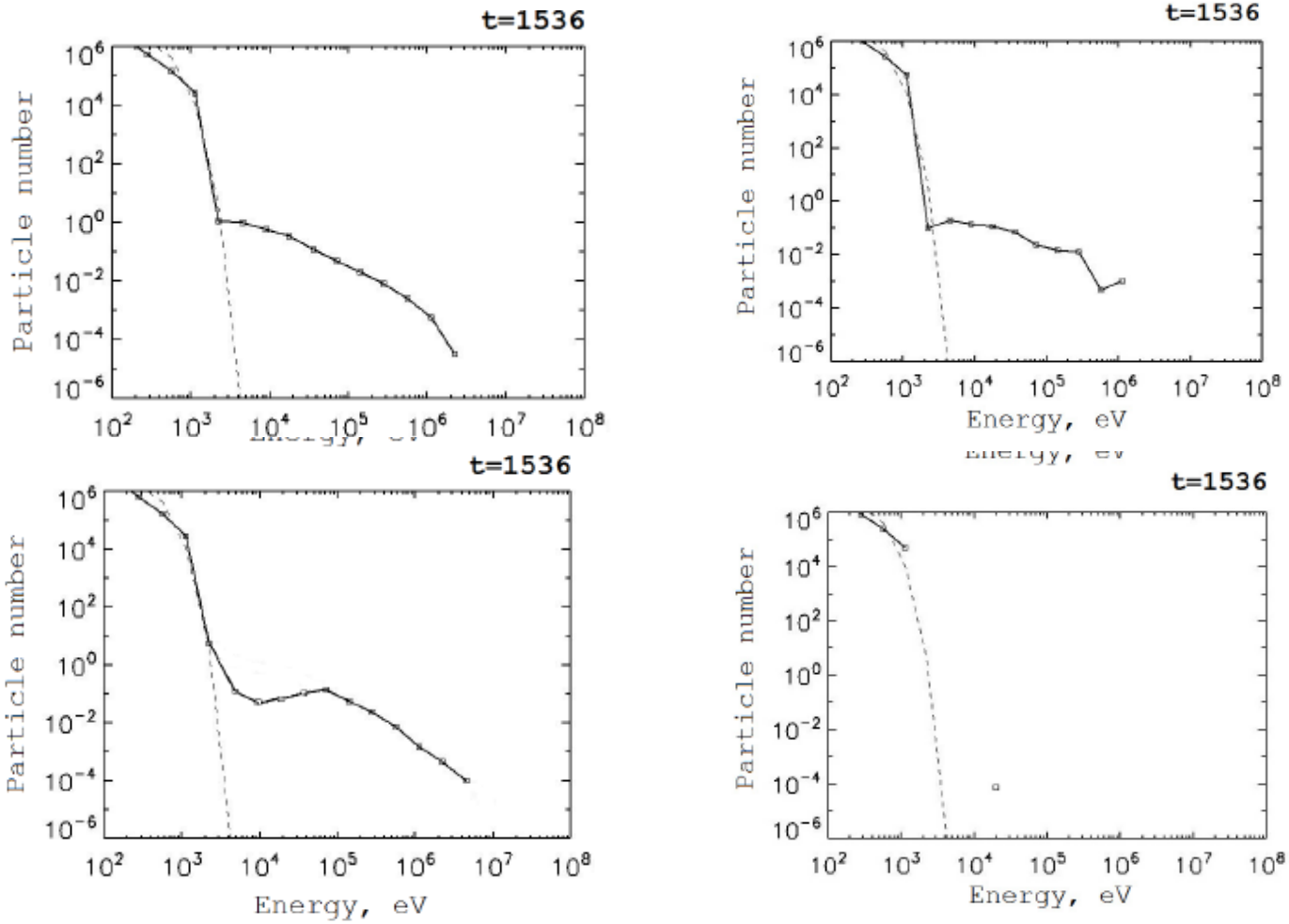
Particle energy spectra – curved loop

Towards end of reconnection

Electrons **Protons**

Low density loop

High density loop



Gordovskyy et al 2014

MHD without density stratification

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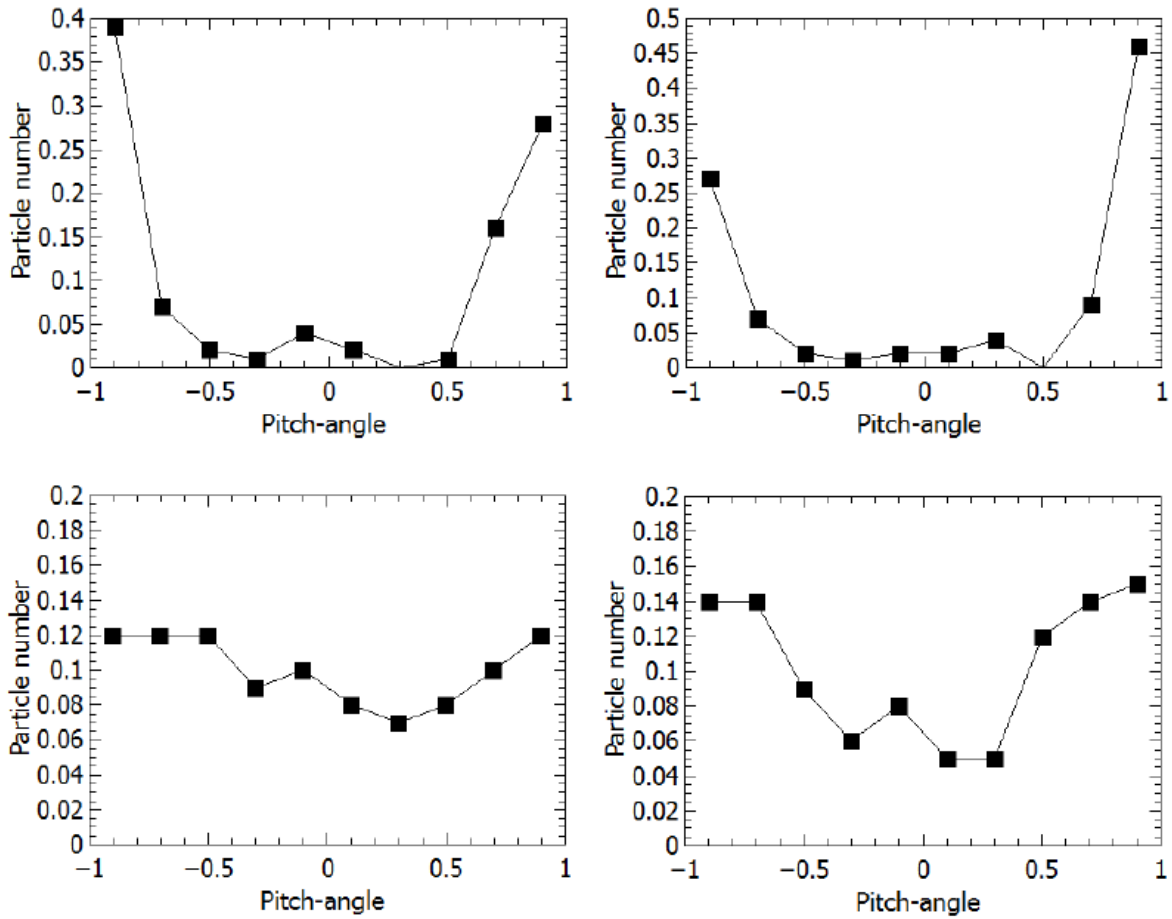
Pitch angle distributions

during main reconnection phase

Low density

High density



Electrons **Protons**

DC electric fields create strong anisotropic pitch angle distributions – mainly parallel

Gordovskyy et al 2014

MHD without density stratification

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Acceleration efficiency

	Low-density model	High-density model
Electrons	7%	4%
Protons	6%	1%

- **Small fraction of particles accelerated (to > 1 kEV) – validates use of test particles**
- **Energy transferred to non-thermal ions/electrons around 6-8% of released magnetic energy (low density model)**
- **Protons more strongly affected by collisions (for same energy) – proton acceleration suppressed in high-density loop**

Gordovskyy et al 2014

MHD without density stratification

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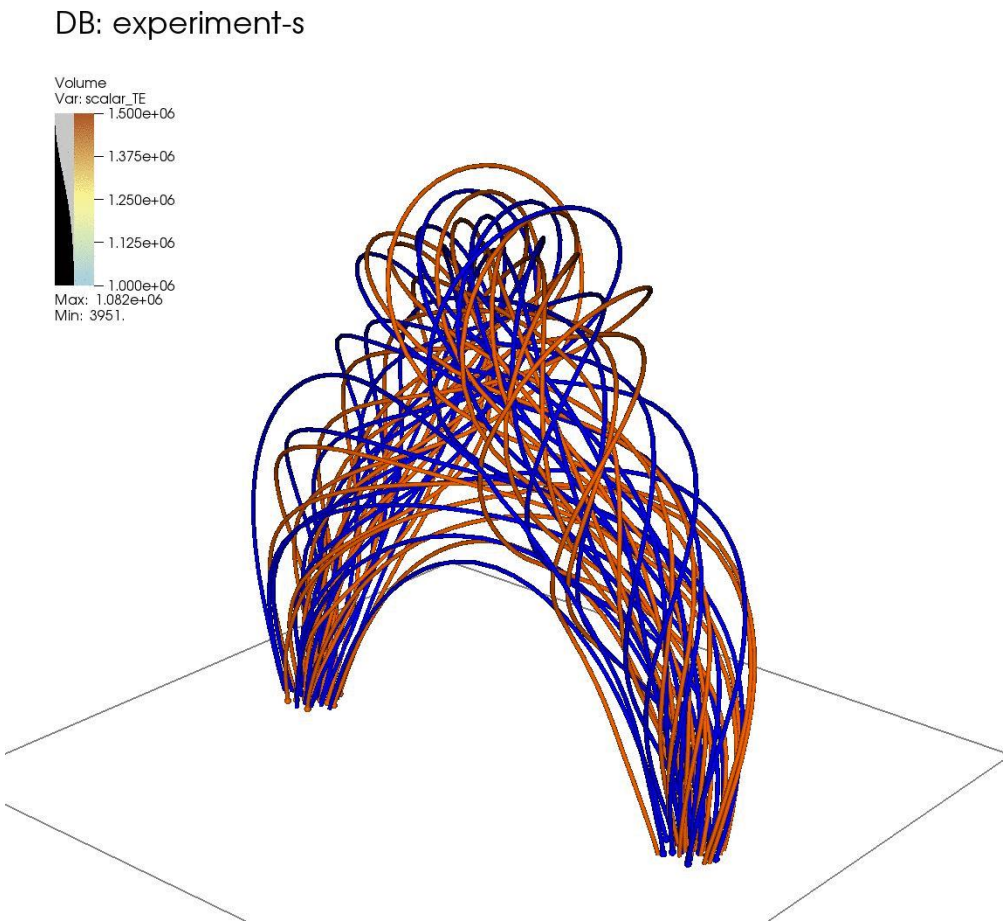
Temperature distribution



Pinto, Gordovskyy, Browning and Vilmer

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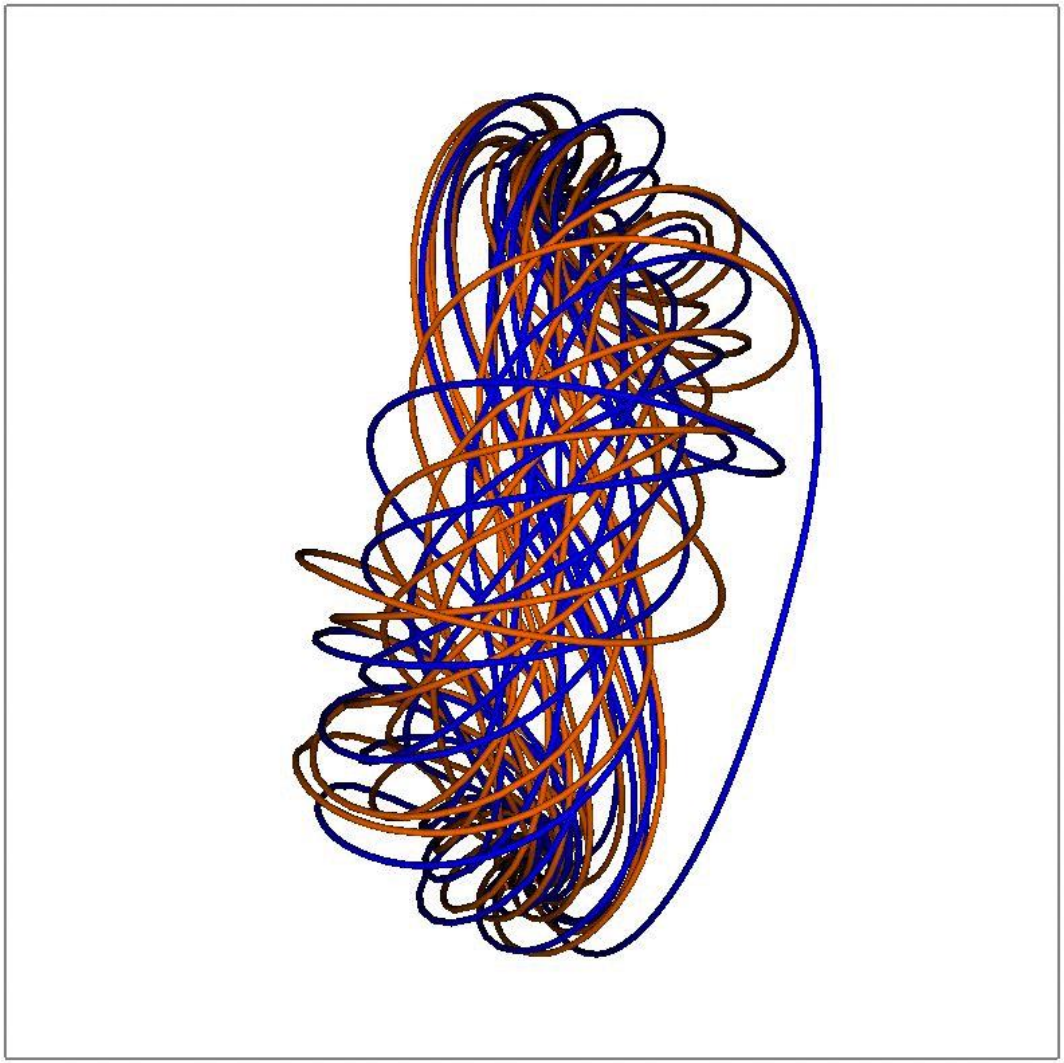
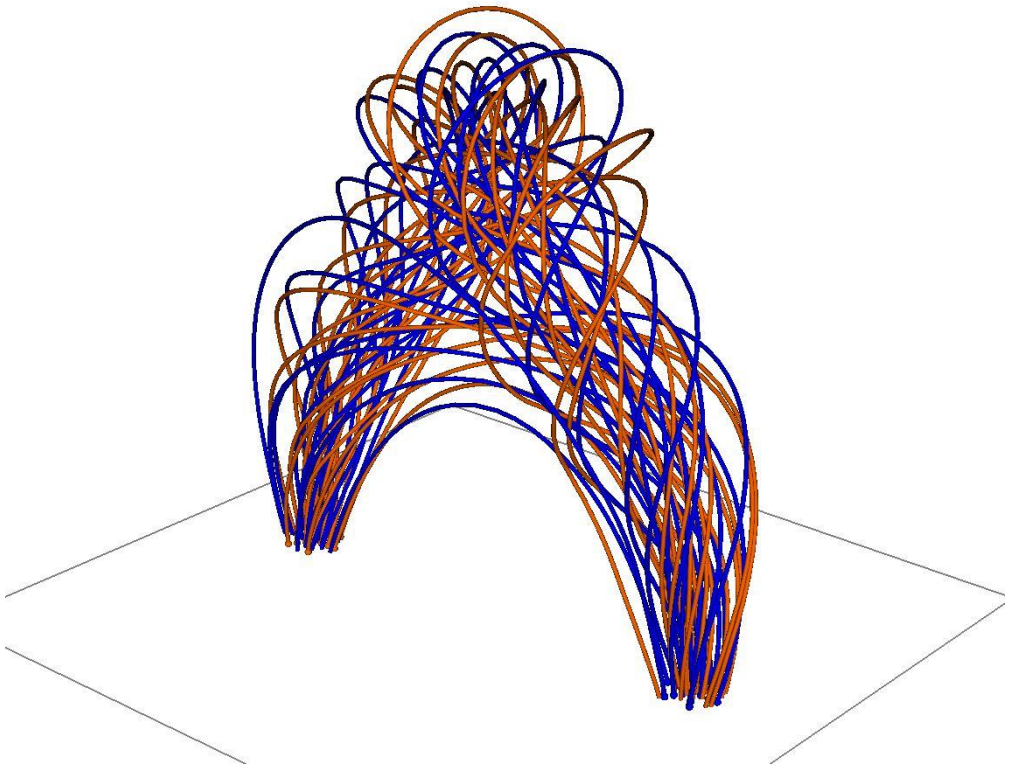
DB: experiment-s

Temperature distribution



Synthesised thermal emission

DB: experiment-s



- **2 keV continuum emission**
- **Structures in emission are not strongly twisted despite highly-twisted initial magnetic field → we do not expect often to "see" twist**

Pinto, Gordovskyy, Browning and Vilmer

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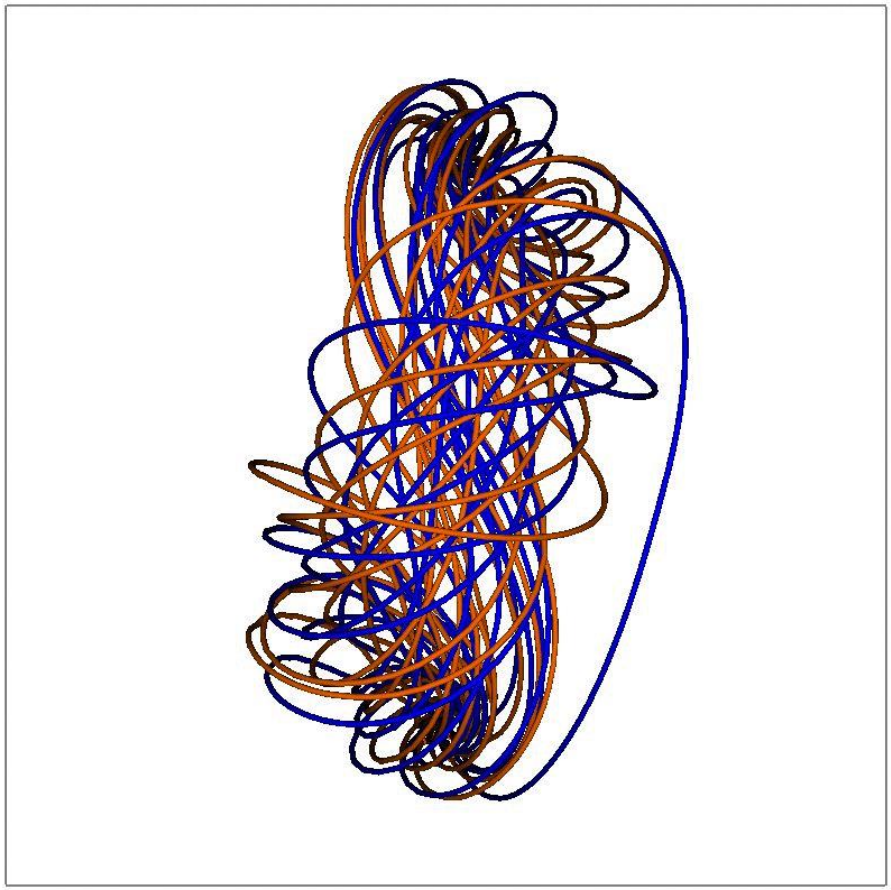
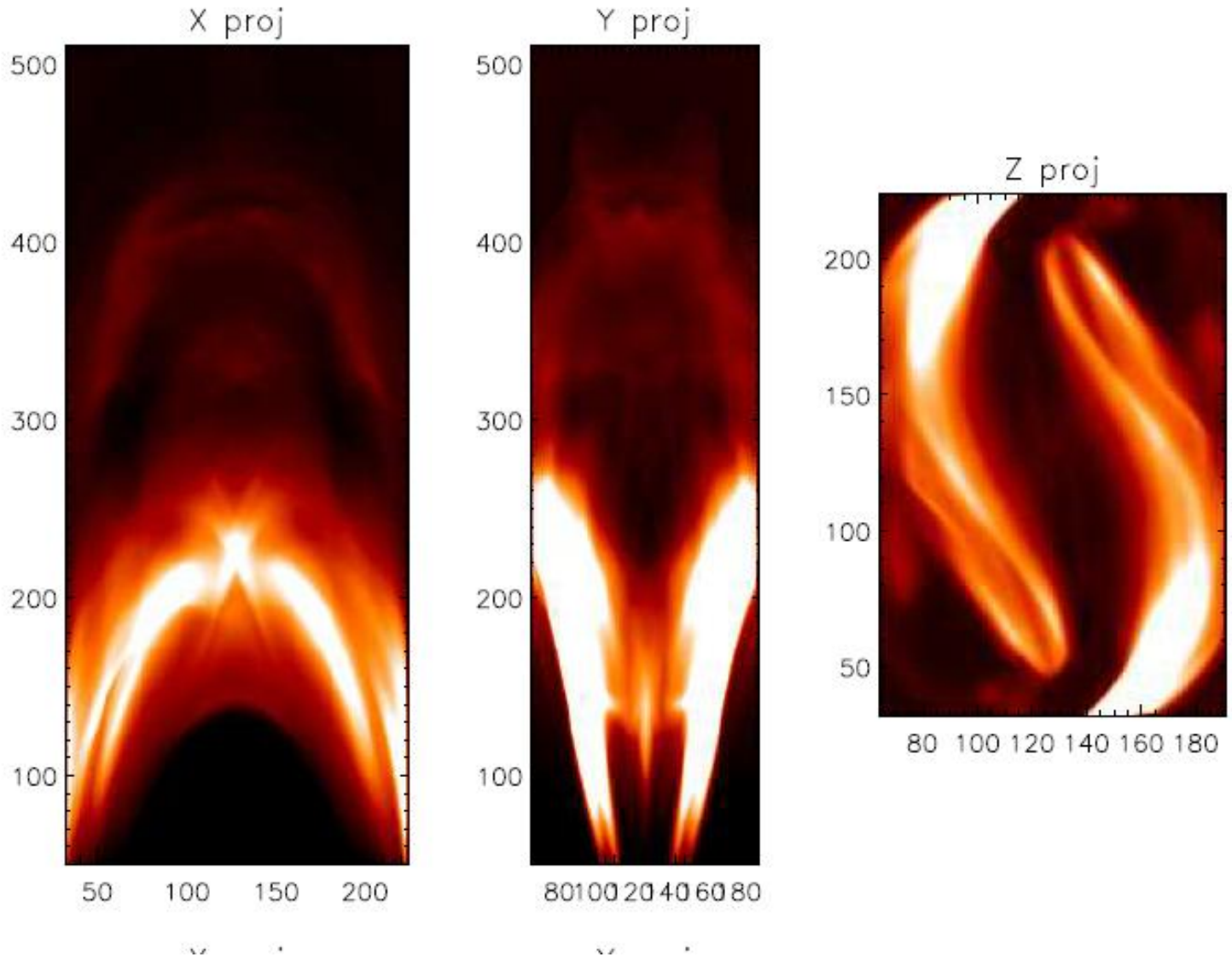
Synthesised thermal emission

DB: experiment-s



Synthesised thermal emission - image



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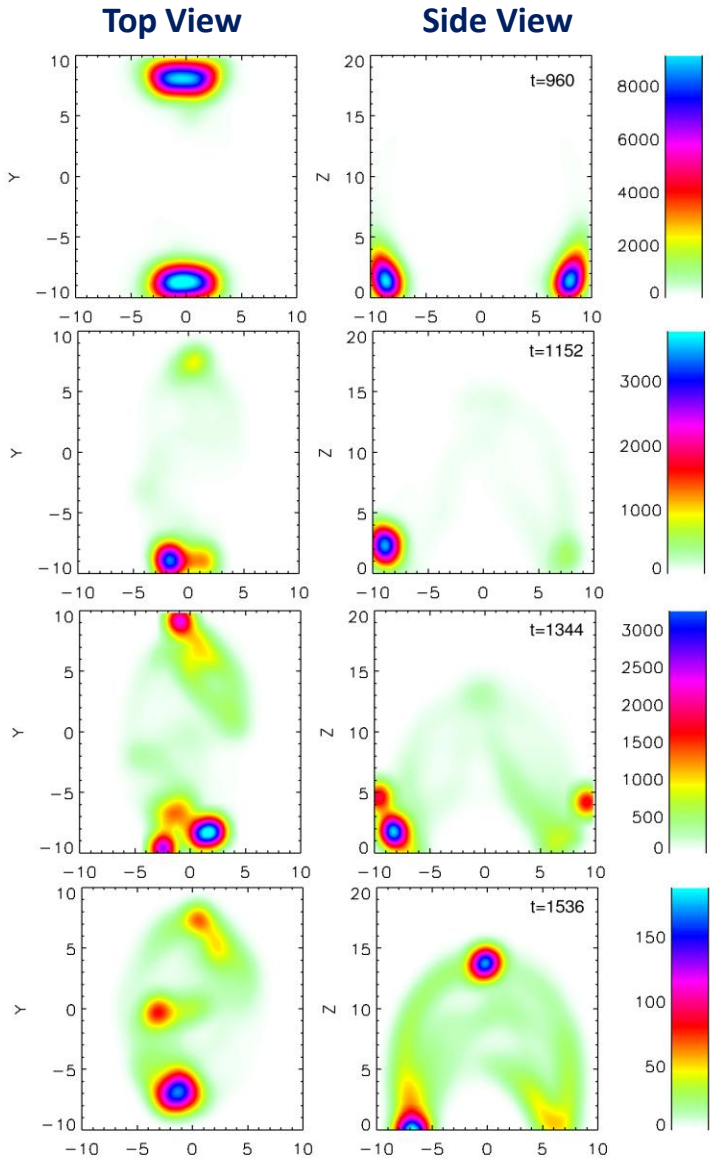
Energetic particles and Hard X-ray emission

- Synthesise spatial and temporal dependence of Hard X-ray emission, compare with RHESSI observations



Synthesised HXR ε=10keV

Gordovskyy et al 2014

~ 30s after kink

Onset of reconnection

~ 120s

Maximum dE/dt in MHD model

~ 220s

Decay phase

~ 320s

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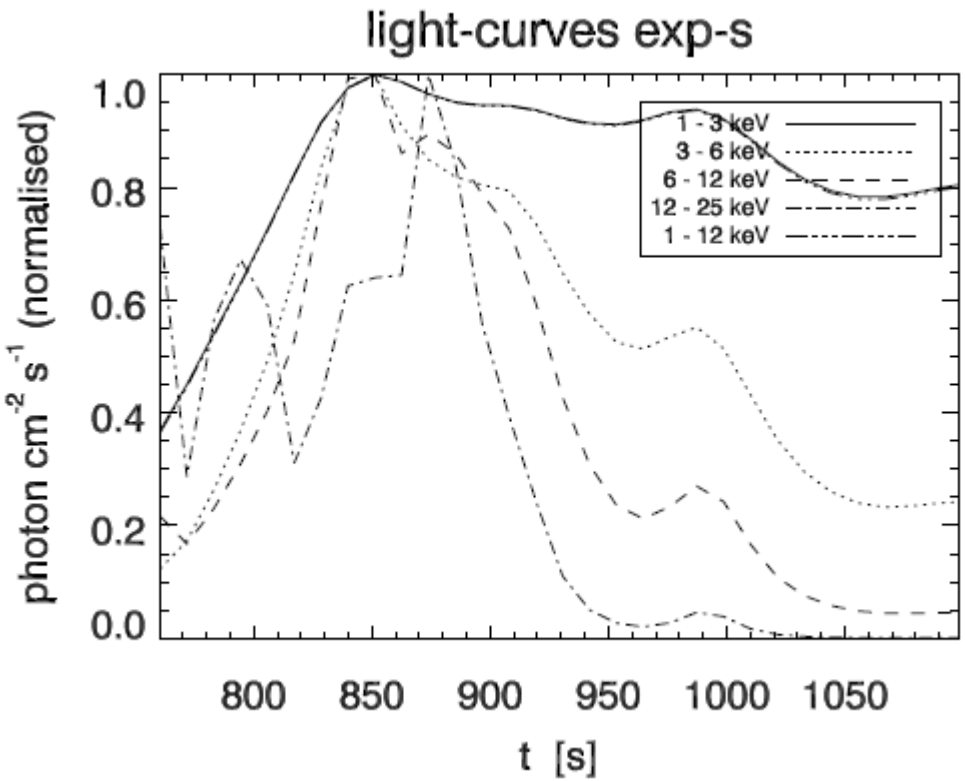
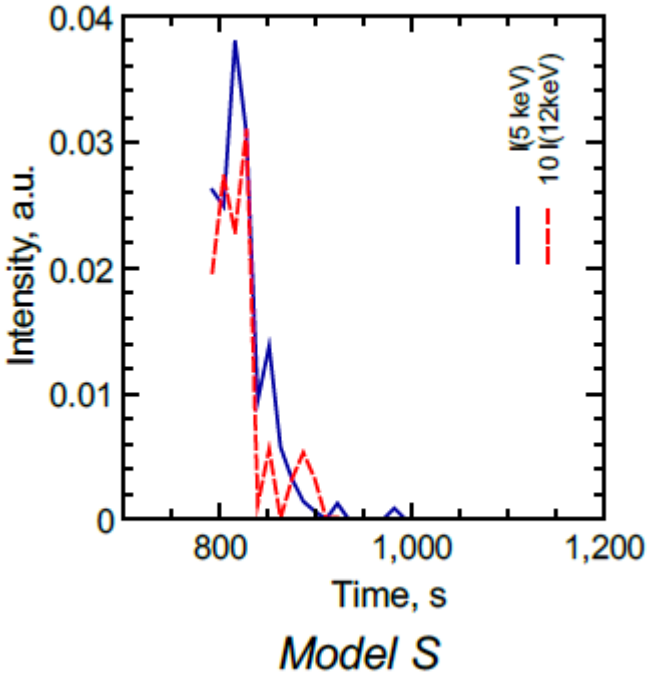
Synthesised light curves





Thermal emission "Soft X rays"- different energy bands

Non-thermal emission "Hard X rays"

Note higher energy bands shorter duration and "spikier"

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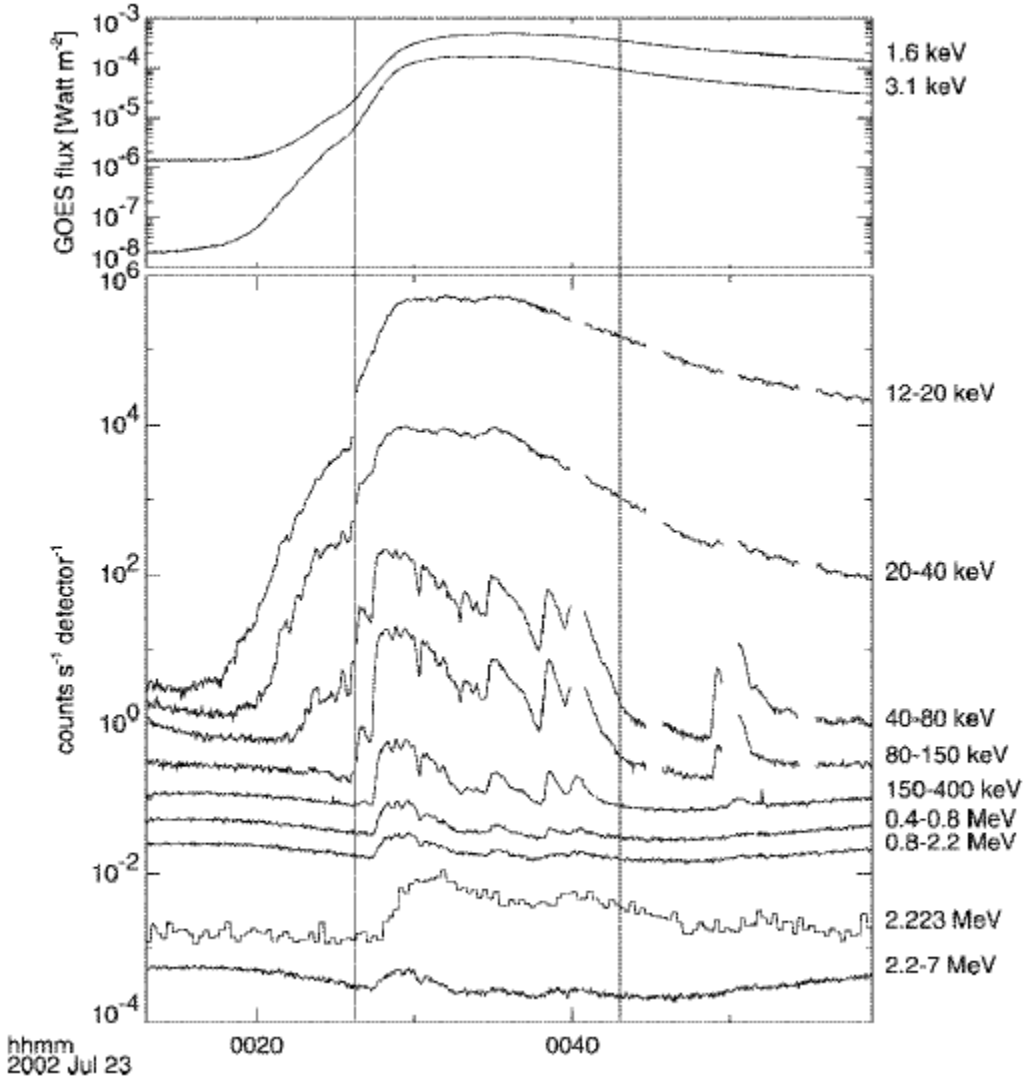
RHESSI light curves



(For much larger flare!)

Lin et al 2003

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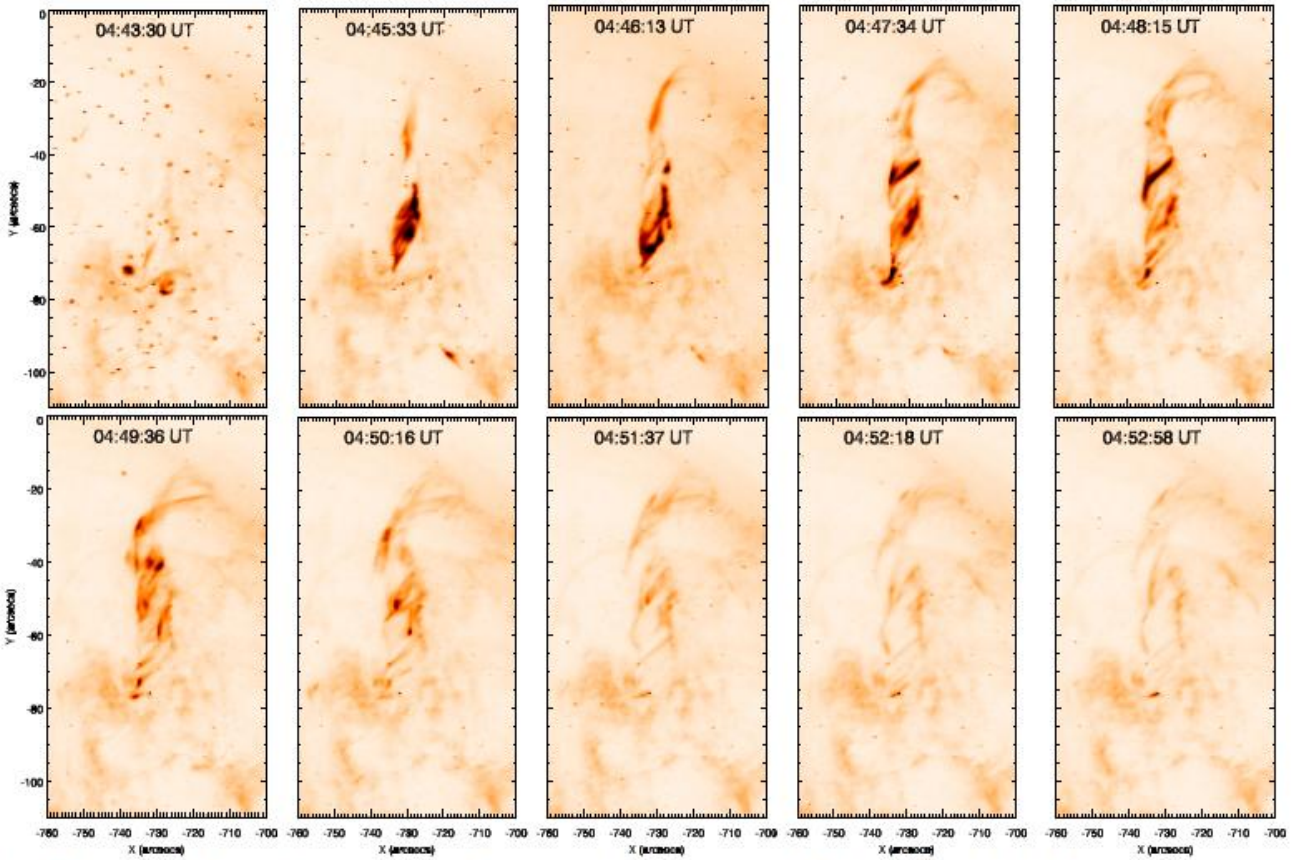

Figure 5. Time sequence of TRACE 171 Å Fe IX images of flaring loop in the AR 10960 during 04:43 UT–04:52 UT on 2007 June 4. The images are in reverse color and show the clear helical twist of the loop during the B5.0 flare. Note the double structure of the coronal loop top between 04:47 UT and 04:51 UT near $(X,Y) = (-720, -20)$.

Srivastava, et al. 2010, ApJ

- **Compact self-contained flare**
- **Kink instability in the strongly twisted loop?**

See also e.g. Liu et al 2013, Song et al 2014, Yan et al 2014

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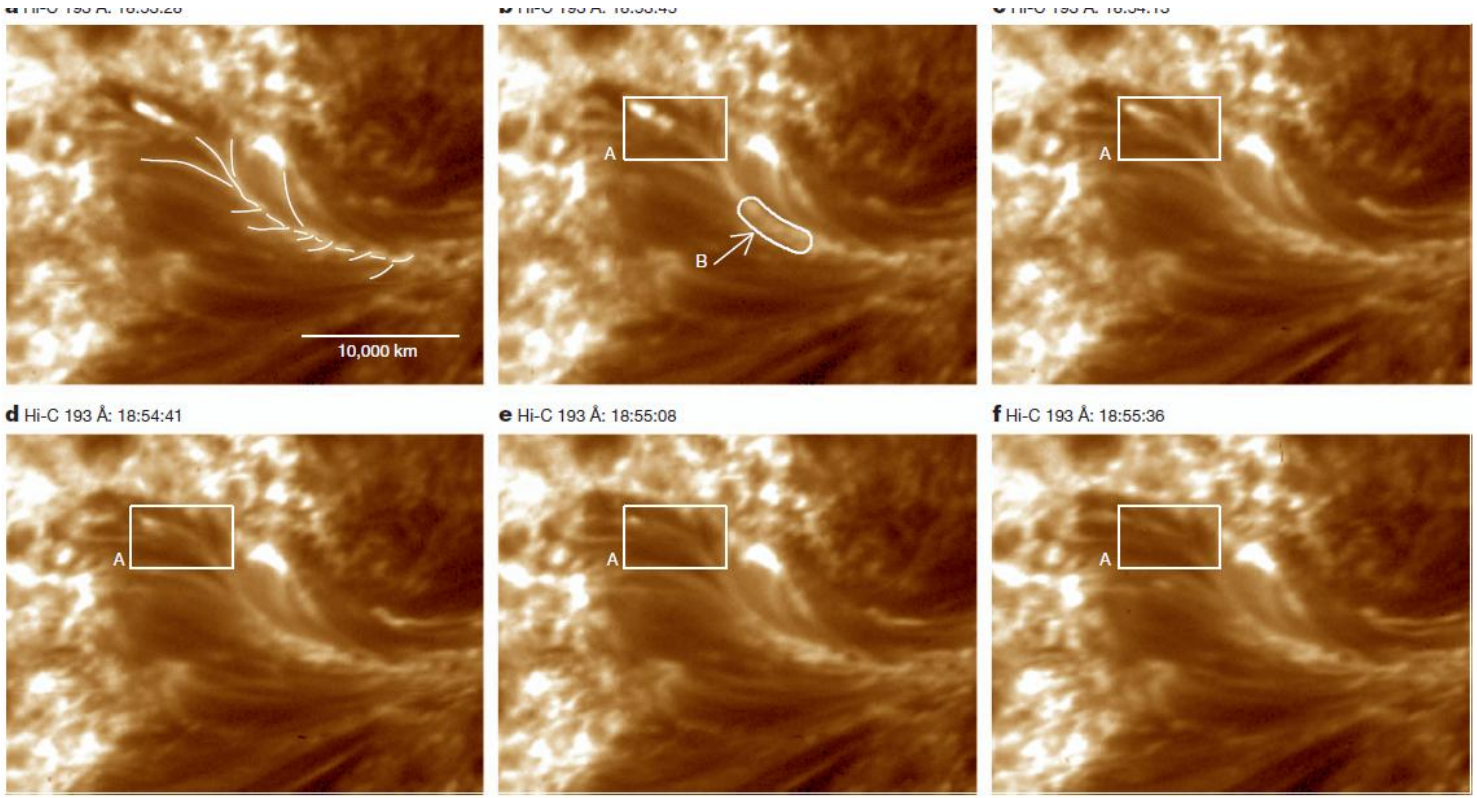
- **Hi-C results show unwinding of twisted or braided field**

Cirtain et al 2013

- **Consistent with simulations of kink-unstable twisted loops**

Cargill 2013



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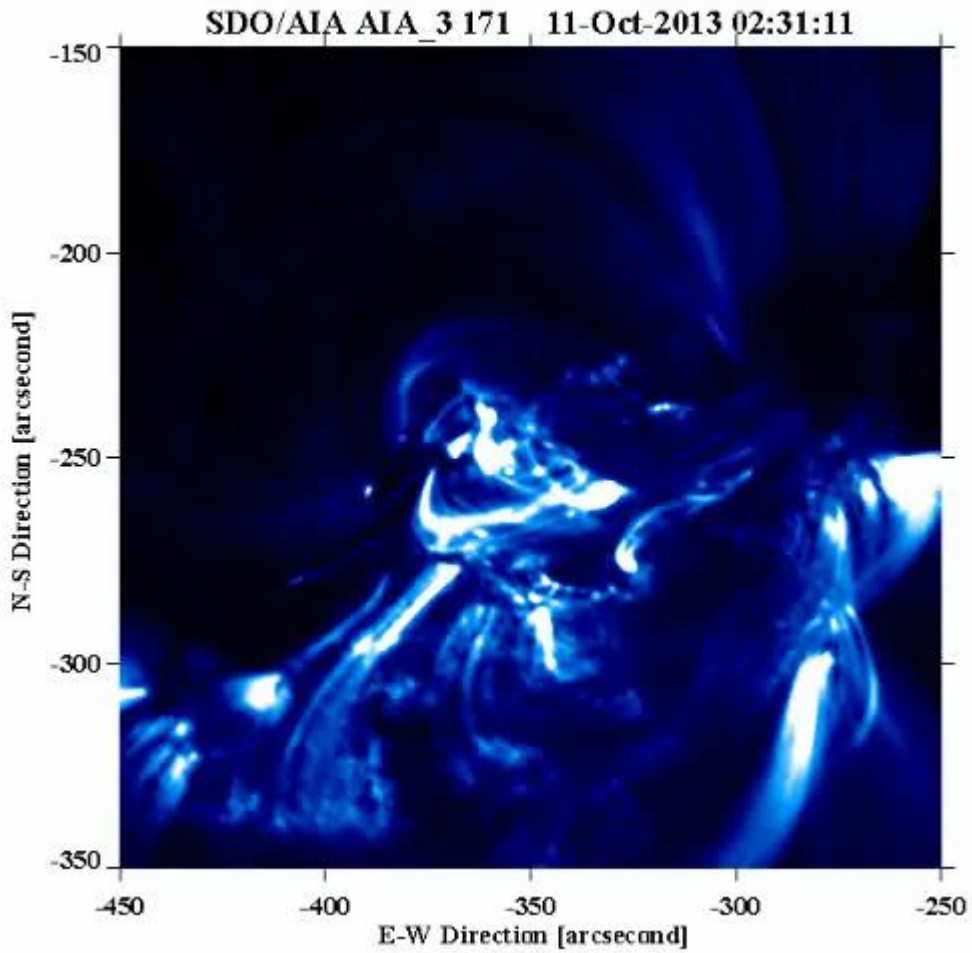

SDO video thanks to Yan Xu

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Beyond the single loop model

– Repeated heating events and multiple loops

– Towards complex topologies

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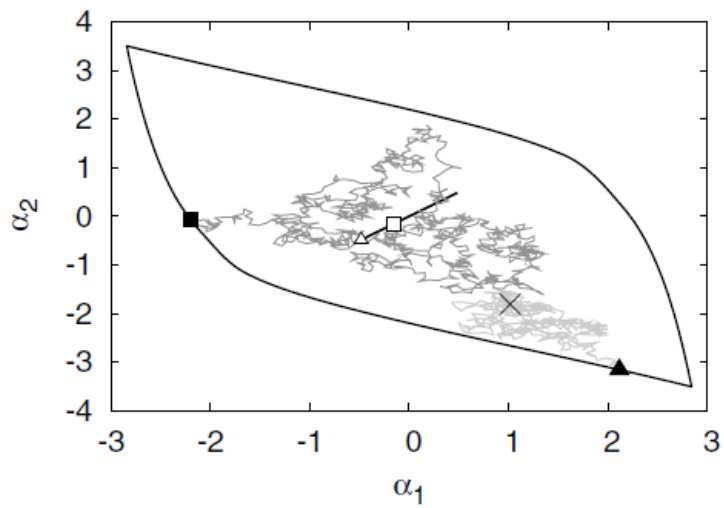
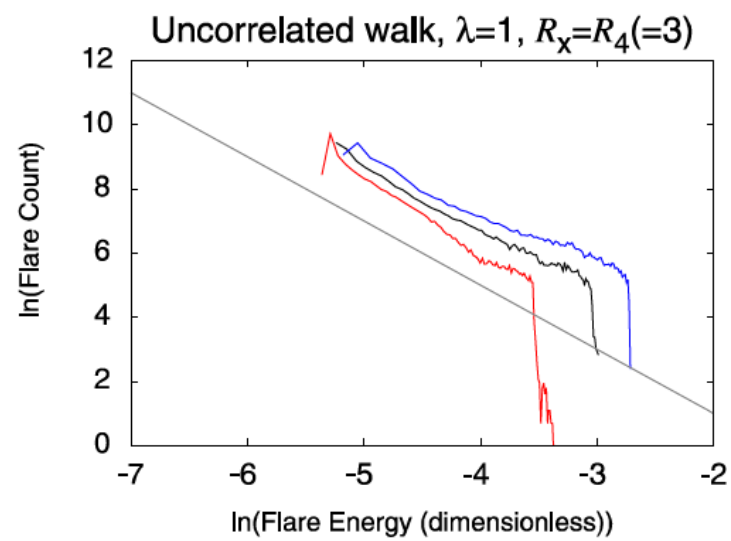
Distributions of heating events and nanoflares

- **Using relaxation theory, may evaluate energy released as heat for a wide range of initial current profiles, marginally-unstable to ideal kink**

•Random photospheric footpoint motions generate range of current profiles - family of analytical models parameterised by piecewise constant $\alpha(r)$
•Energy release depends on current profile at onset of ideal instability
•Repeat many times, building distribution of heating events

Bareford et al 2010, 2011





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Implications for coronal heating

- **Estimate Poynting flux of energy from photosphere to corona**

$$F = \left|\mathbf{E}\times\mathbf{B}/\mu_0\right| = B_v B_h v_{phot}/\mu_0$$

$$B_v \approx 100\ \mathrm{G},\ v_{phot} \approx 1\ \mathrm{km\ s^{-1}}$$

where $\mathbf{B_v}$ and $\mathbf{B_h}$ are vertical/horizontal magnetic field

- **In order to match required coronal heating flux , require sufficiently large $\mathbf{B_h}$ i.e must be sufficient stored free energy for effective heating**

Parker 1983

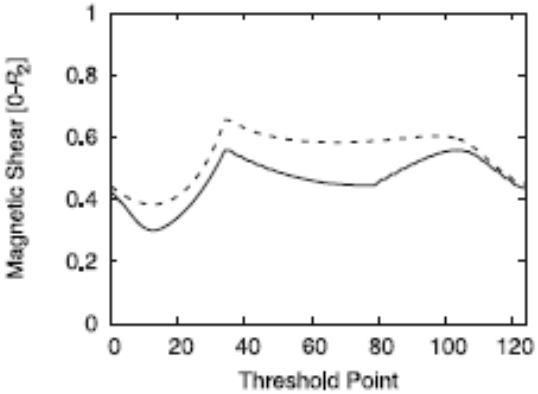
- **For relaxation nanoflare model, estimated heating flux is**

$$F \approx \frac{81\pi}{2\mu_0} R_c B_c^2 \frac{\langle \delta W^* \rangle}{N\tau} \approx 3\times10^7\ \mathrm{erg\ cm^{-2}\ s^{=1}}$$

adequate for Active Region Heating

- **Model predicts shear angle $B_h/B_v \approx 0.4$**

matching above requirement



From Bareford et al 2010

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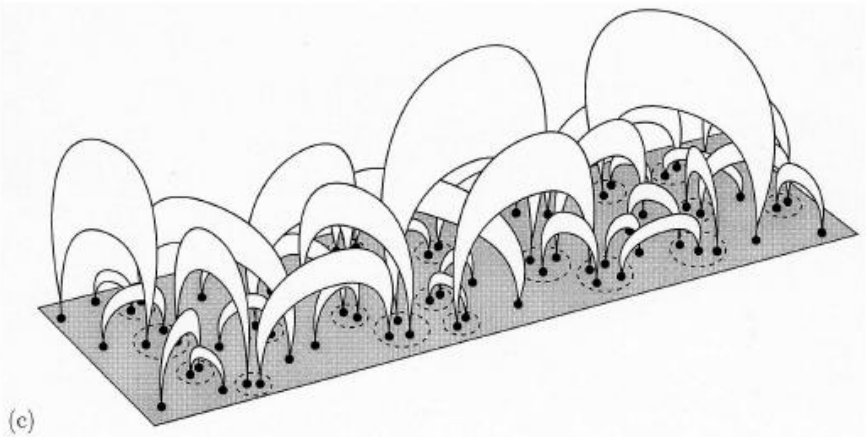
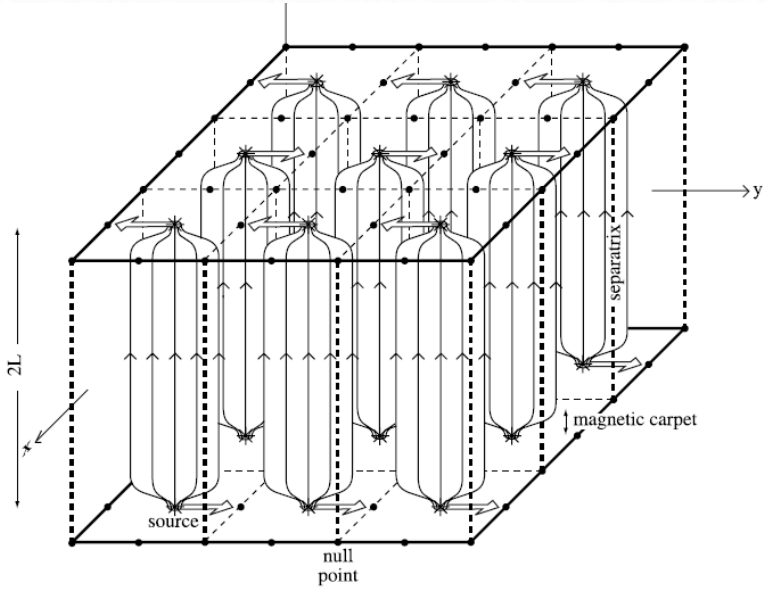
Interacting coronal loops – multi-thread structures

- **Coronal loops may contain multiple threads**
- **Either due to discrete photospheric flux sources – flux tube tectonics (*Priest et al 2002*) or due to complex pattern of photospheric motions "braiding" within a single flux tube**





Consider here:

- **Merging of two or more flux ropes carrying net current**
- **Destabilisation of one (or more) flux rope by a kink-unstable neighbour –**

potentially leading to an avalanche

- **Repeated heating events with random driving**

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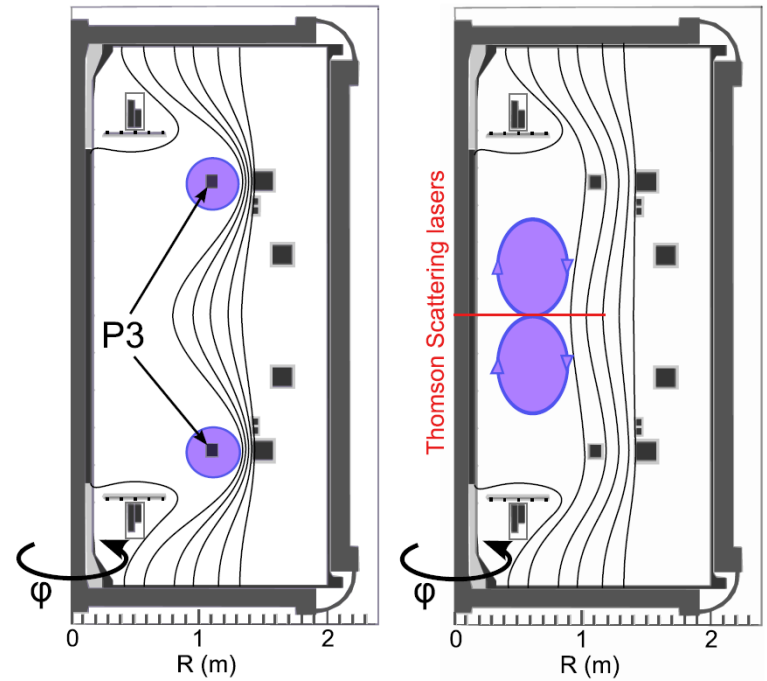
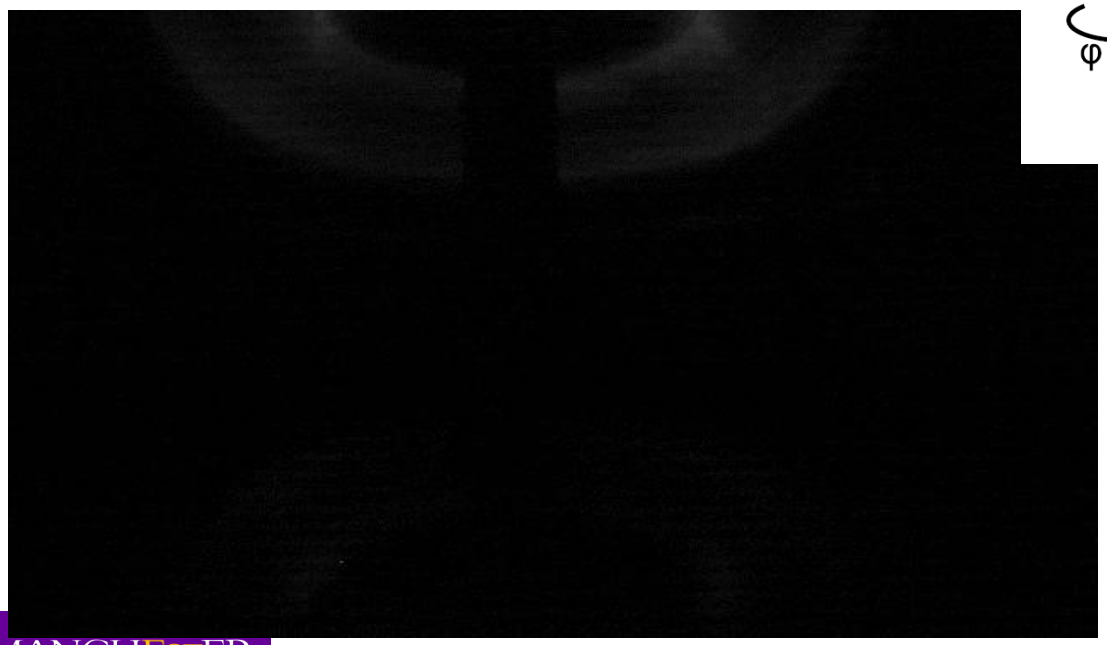
Merging-compression startup in MAST

- **One of several plasma start-up methods used in MAST spherical tokamak was merging-compression:**
  - **Two plasma rings "flux ropes" with parallel current attract & merge, forming plasma torus with single set of closed flux surfaces**





Opportunity to study magnetic reconnection in well-diagnosed high temperature plasma with strong guide field - similar parameter regime to solar corona

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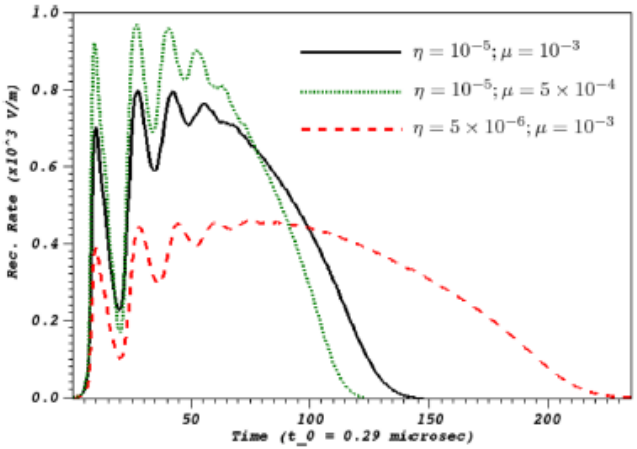
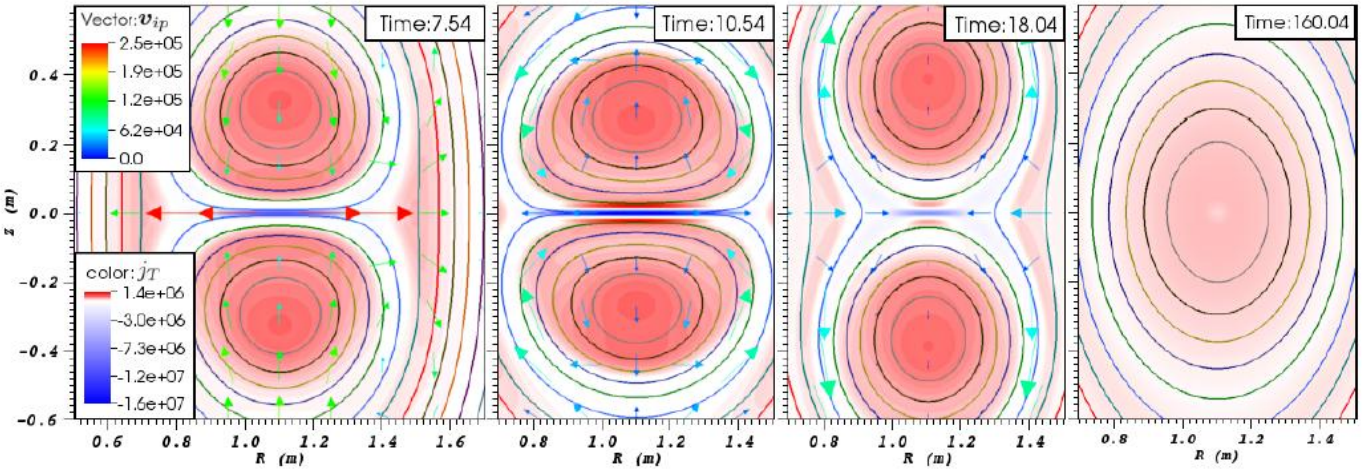
Merging of two twisted flux ropes

- Consider two identical adjacent twisted flux ropes carrying net current
- These attract – current sheet is formed at interface due to reversing azimuthal field component
- Subsequently reconnect, forming a single twisted rope





Resistive MHD simulation of two merging flux ropes in MAST spherical tokamak

Stanier et al 2013,
Browning et al 2014

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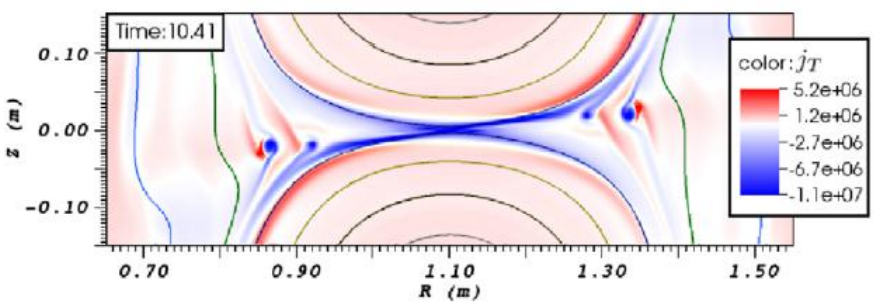
Hall MHD simulations of merging flux ropes

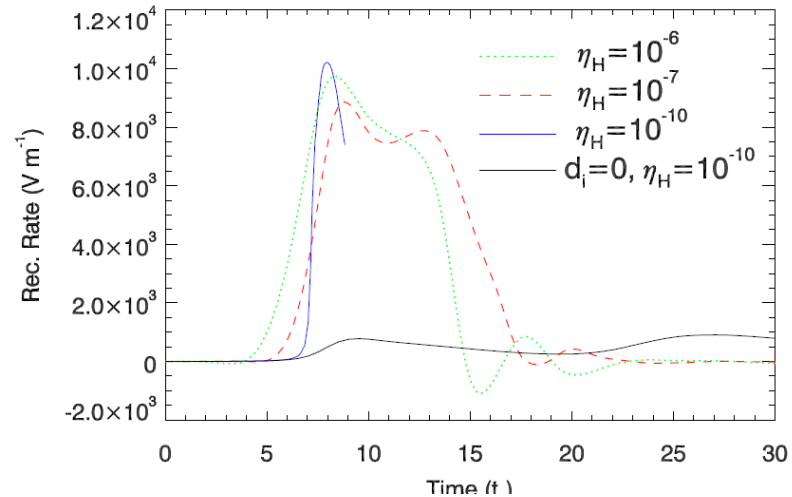
- Large ion skin depth in MAST plasmas →Hall MHD simulations (with hyper-resistivity)
- Hall MHD reconnection much faster than resistive MHD – peak reconnection rate insensitive to hyper-resistivity
- Current sheet tilts → asymmetric ion outflow jets

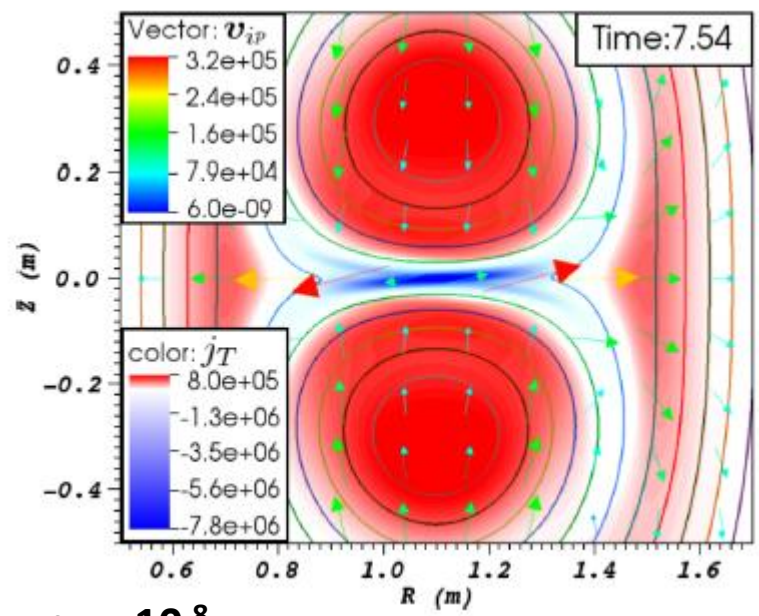
$\eta_H = 10^{-9}$

- At lower η_H current sheet fragments into series of islands



- At lowest values $\eta_H = 10^{-10}$ outflow opens leading to fast reconnection





$\eta_H = 10^{-8}$

Stanier et al 2013

MAST merging and solar plasmas

Quantity	Solar flare	MAST merging-compression
Typical values		
Global length	$L \sim 10^7$ m	$L = 1$ m
Ion species	Hydrogen	Deuterium
Magnetic	$B \sim 0.01$ T	$B_p = 0.1$ T, $B_T = 0.5$ T
Temperature	$T \sim 100$ eV	$T = 10$–1000 eV
Density	$n \sim 10^{15}$ m^{-3}	$n = 5 \times 10^{18}$ m^{-3}
Dimensionless		
Plasma-β	$\beta = 10^{-4}$–10^{-2}	$\beta_T = 10^{-4}$–10^{-2}, $\beta_p = 10^{-3}$–10^{-1}
Lundquist number	$S = 10^{12-14}$	$S = 10^{4-7}$
Non-MHD		
Ion skin-depth	$d_i = 10$ m	$d_i = 14.5$ cm
Ion gyro-radius	$\rho_i = 0.1$–1 m	$\rho_i = 0.15$–1.5 cm
Current-sheet		
Sweet–Parker width	$\delta_{SP} = 1$–10 m	$\delta_{SP} = 0.03$–1 cm
δ_{SP}/d_i	0.1–1	0.002–0.07

- **T_e, T_i & β values similar**
- **Coronal *S* values are higher than those in MAST, but latter much higher than any other reconnection experiments**
- **Predicted current sheet length scales in flares are comparable to ion skin depth – suggests that two-fluid effects should be taken into account when estimating reconnection rates in flares**

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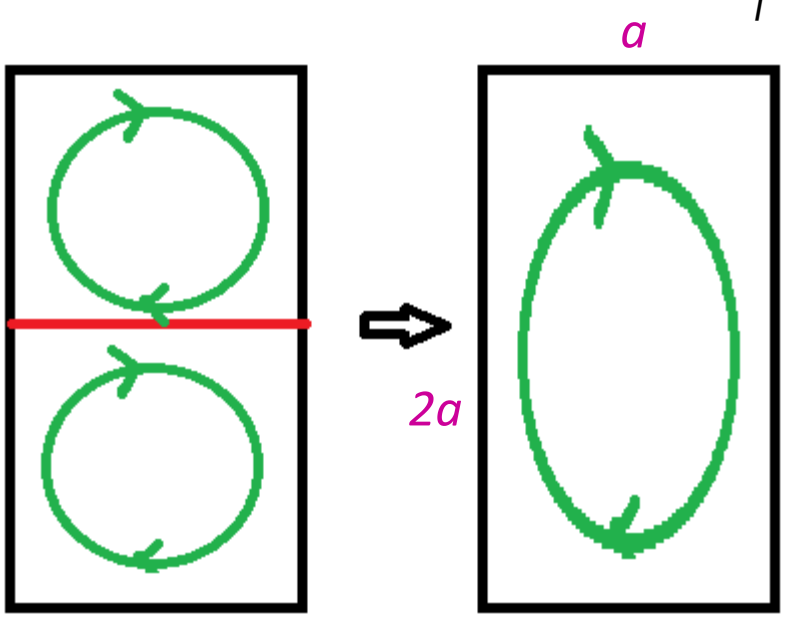
Relaxation model of merging flux ropes

Browning et al PPCF 2014

- **Rectangular boundary a X 2a**
- **Two initial identical flux ropes a x a, each with linear force-free internal current profile, $\alpha = \alpha_i$ separated by current sheet**
- **Not minimum energy state due to current sheet**
- **Relaxation to a single flux rope $\alpha = \alpha_f$ determined by conservation of helicity and axial (toroidal) flux**

$$\nabla \times \mathbf{B} = \alpha_f \mathbf{B}$$



$$\Phi_t = \int_A B_\phi dRdZ = \oint_b \mathbf{A} \cdot d\mathbf{r}$$

Taylor 1974

$$K = \int_V \mathbf{A}.\mathbf{B} dV$$

Helicity conserved

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- **Solution of Grad-Shafranov equation**

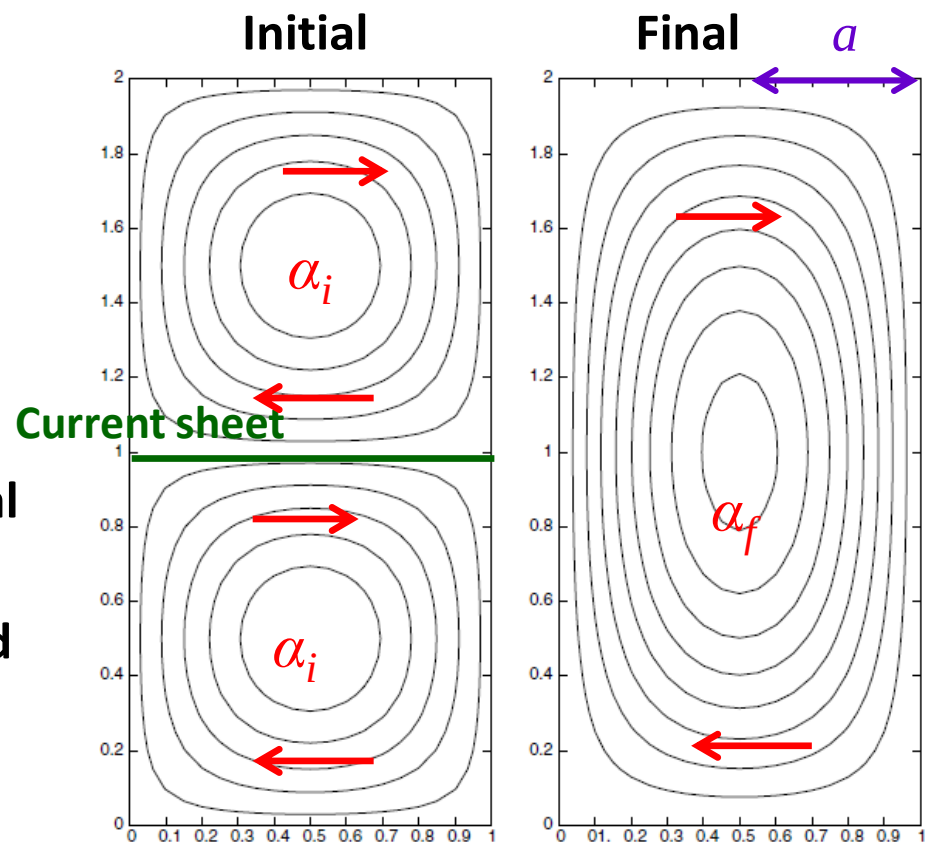
$$\frac{\partial^2\psi}{\partial R^2}+\frac{\partial^2\psi}{\partial Z^2}+\alpha^2\psi=0$$

$$\psi=\psi_b\left[1+\sum_{m,n}a_{mn}\sin\left(\frac{m\pi R}{a}\right)\sin\left(\frac{n\pi Z}{b}\right)\right]$$

where a_{mn} determined from GS equation using orthogonality

- **For both initial field (b =a) and final field (b= 2a)**
- **Final α_f determined by helicity and flux conservation**

Azimuthal field lines B_x B_y
Also axial field component B_z



- **Energy *W***

$$W(\alpha;a,b)=\frac{ab\psi_b^2}{2\mu_0}\left[\alpha^2+\sum_{m,n\,\mathrm{odd}}\left\{\frac{a_{mn}^2}{4}\left(\frac{m^2\pi^2}{a^2}+\frac{n^2\pi^2}{b^2}+\alpha^2\right)+\frac{8a_{mn}\alpha^2}{\pi^2 mn}\right\}\right]$$

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Relaxation model of merging coronal flux ropes

- **Dimensionless energy release/per unit length *ΔW* scales roughly quadratically with initial flux rope current α_i**

$$\Delta W^* \approx 0.1(\alpha_i R)^2$$

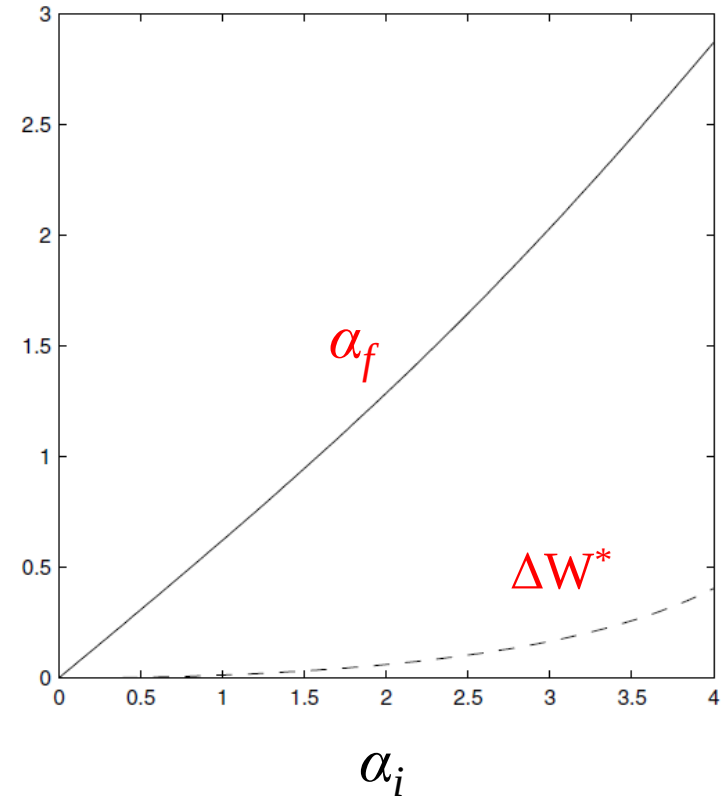
- **Estimate heating as**

$$W_{heat} \approx 0.1 \frac{1}{\mu_0} \alpha_i^2 B^2 R^4 L$$

$$B = 0.01 \text{ T}, R = 1 \text{ Mm}, L = 10 \text{ Mm}$$

$$\alpha \approx 2\Phi / L \text{ - take weak twist } \Phi = \pi$$

$$\Rightarrow W_{heat} \approx 10^{19} \text{ J}$$



- **Gives average temperature rise ΔT**

$$\left(4R^2 L\right) 2 \frac{3}{2} nk\Delta T = W_{heat} \; ; \quad \text{taking } n = 10^{15} \text{ m}^{-3} \Rightarrow \Delta T \approx 10^7 \text{ K}$$

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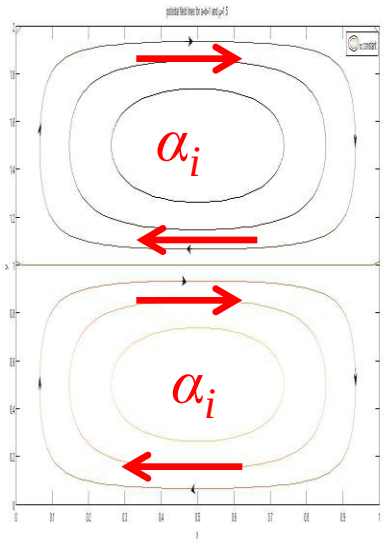
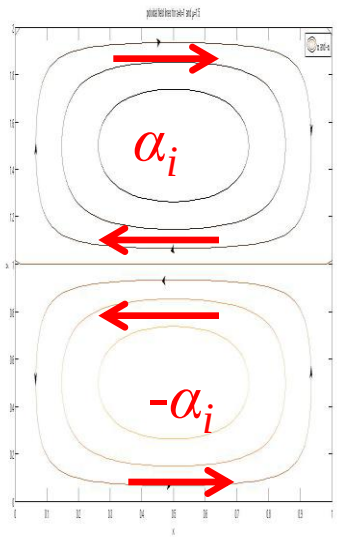
Merging tubes – varying twist direction

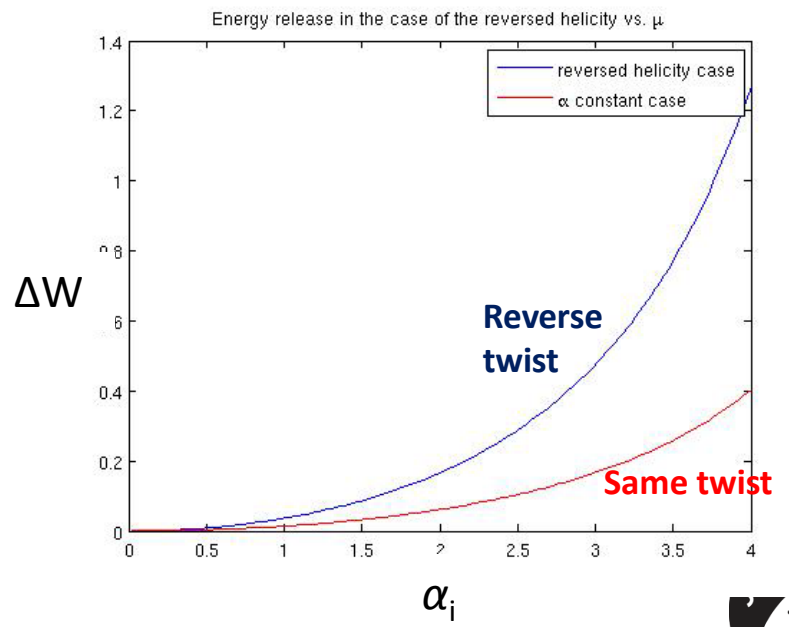




Same twist
"co-helicity"
→ $\alpha = \alpha_f$

Reverse twist
"counter-helicity"
→ $\alpha = 0$

- **If loops have opposite twist but same axial field, reconnection is much less likely (unless strongly perturbed?) since azimuthal fields are parallel at interface**
- **But free energy is much greater since minimum energy state is potential**



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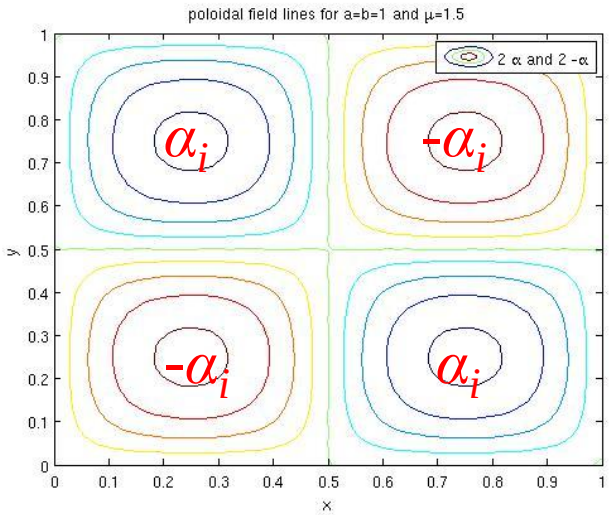
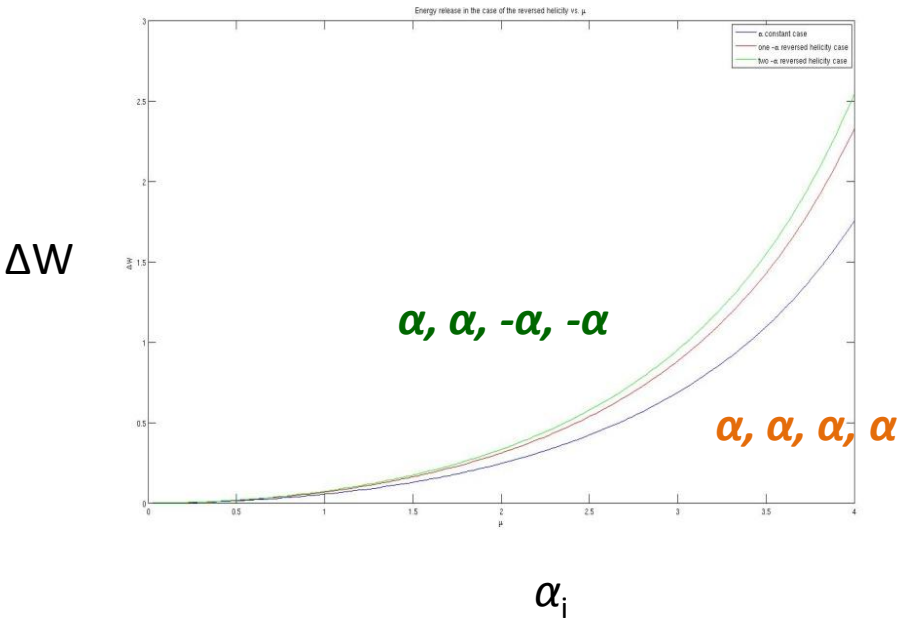
Relaxation of multiple merging coronal loops

- **Consider n twisted loops merging**
- **May merge completely into single loop or partially (less energy release)**





n = 4 – consider all cases of equal/opposite twist:

α, α, α, α ***Least energy release***

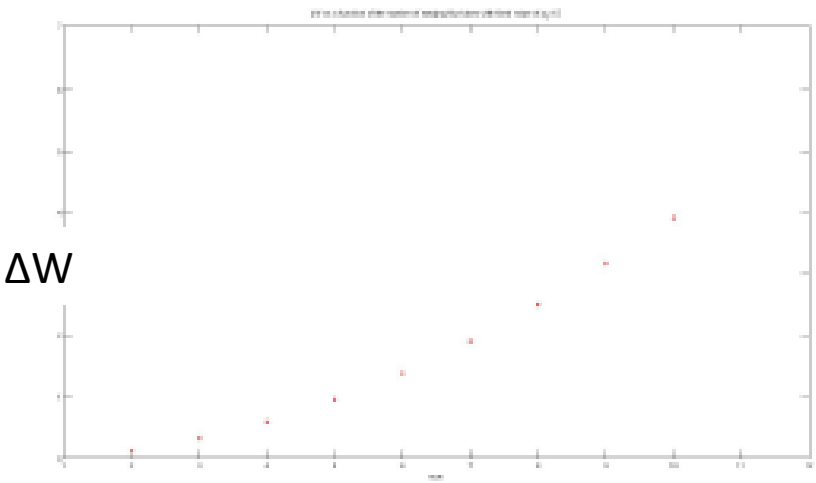
α, α, α, -α

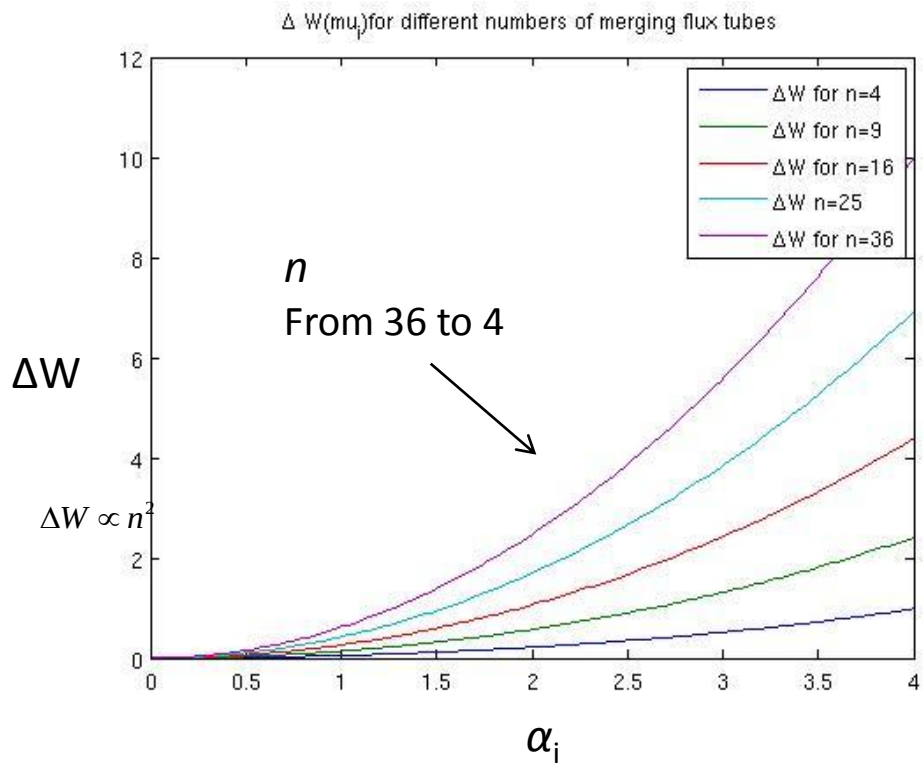
α, α, -α, -α ***Greatest energy release***

Lucini MSc thesis 2014

Multiple merging tubes

- **Energy release is increases as number of flux tubes within a given volume increases**
- **Due to increasing number of current sheets**





$$\Delta W \sim n$$

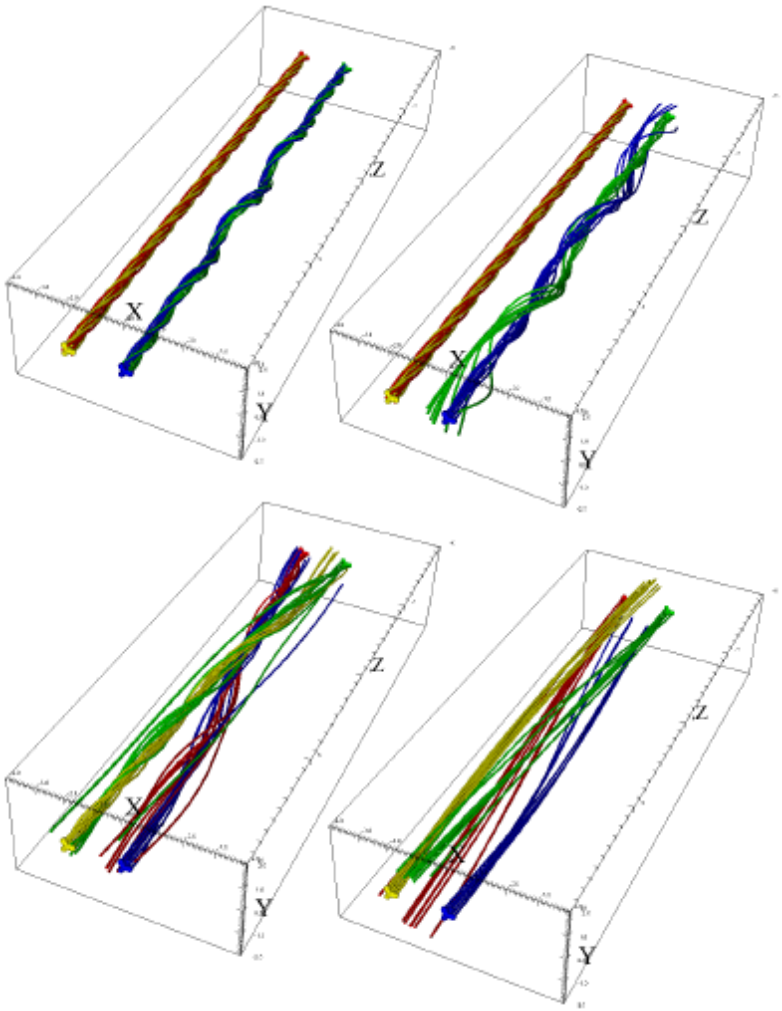
“Avalanche”- disruption of neighbouring stable loop

Tam, Hood, Browning and Cargill (in preparation) 2014

- **Consider adjacent zero net current loops**
- **If the loops are sufficiently close, an unstable loop may trigger relaxation in a neighbouring stable loop**
- **In this case the two loops relax into a single (very weakly twisted) loop**

→ Under certain conditions can have an avalanche of heating events

Cf Lu and Hamilton 1881, Charbonneau et al 2001



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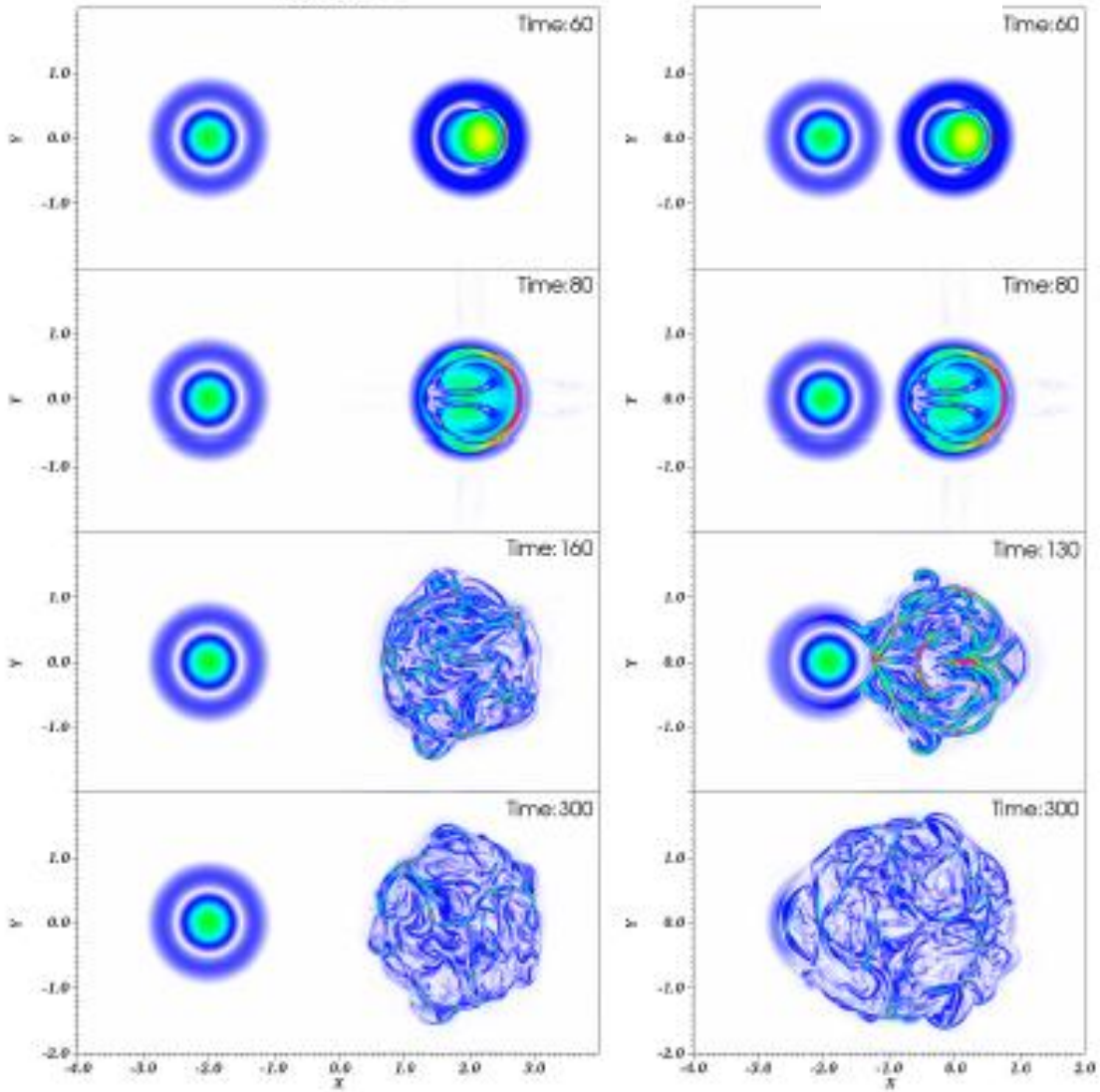
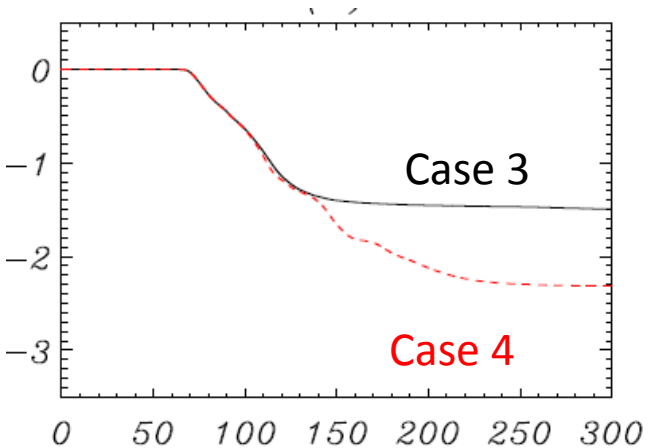
Stable loop **Unstable loop** **Stable loop** **Unstable loop**

Case 3 Case 4





Magnetic energy versus time

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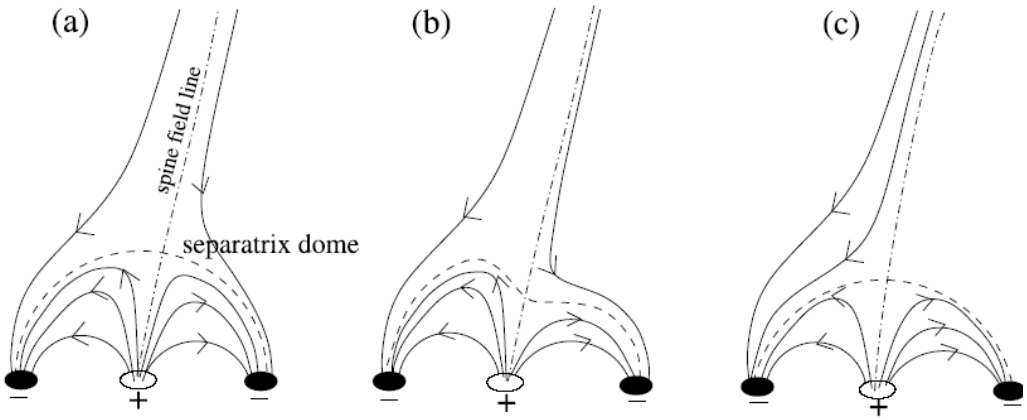
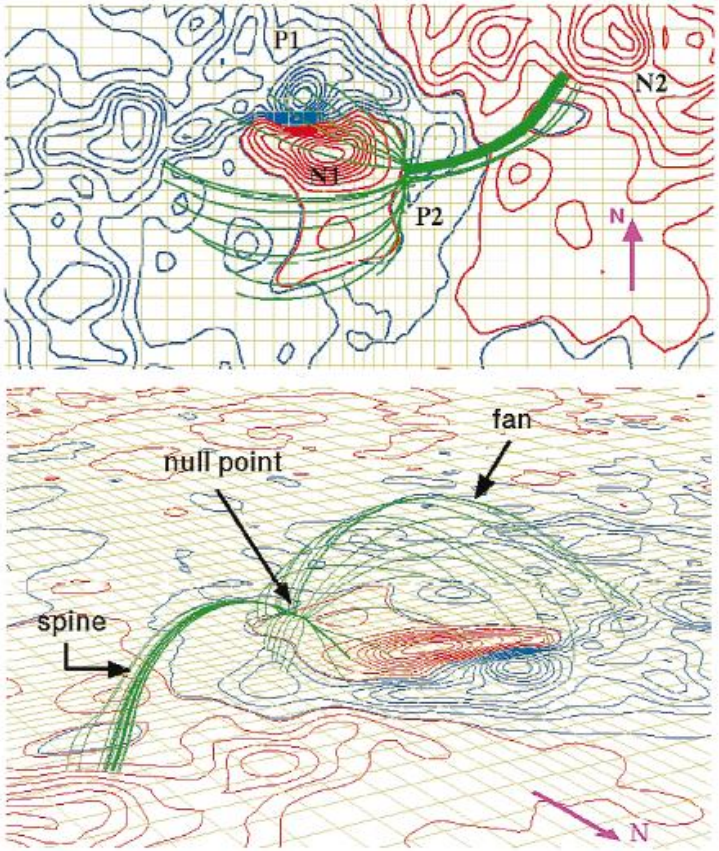
3D null points in reconstructions of coronal field in flares



Fletcher et al 2001



Also:

Filippov, 1999, DesJardins et al 2009, Sun et al 2012, Sun et al 2014...

Data-driven simulation of flare ribbons with coronal null point *Masson et al 2009*

Also in magnetosphere e.g. Xiao et al 2006...

Aulanier et al 2000

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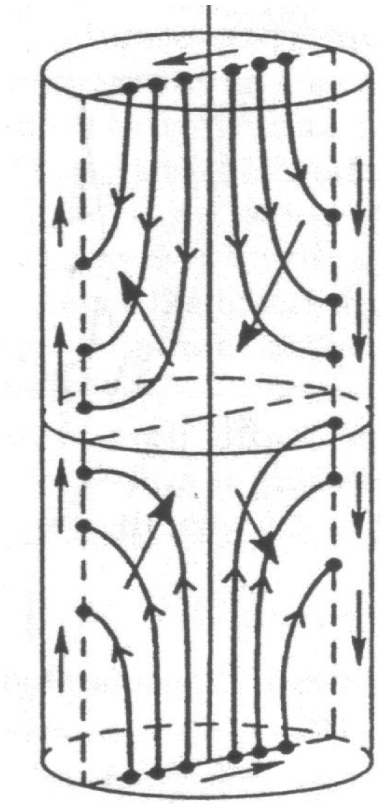
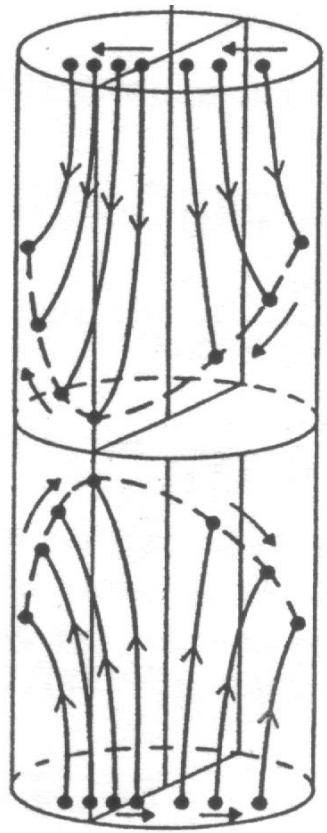
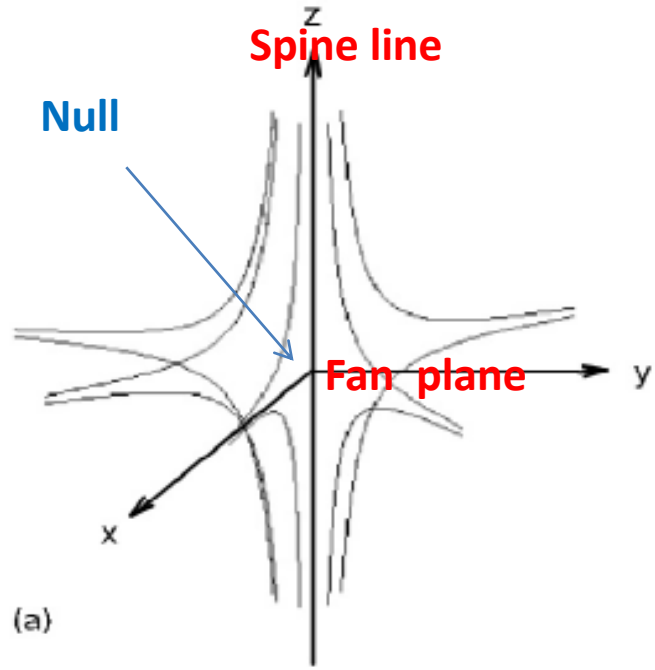
3D null points and reconnection





Spine reconnection Fan reconnection

From Priest and Titov 1996



- Priest and Titov (1996) - **kinematic** solutions of **outer ideal reconnection region**
- Singularities (current tubes/sheets) at spine line or fan plane

Particle acceleration at reconnecting 3D nulls

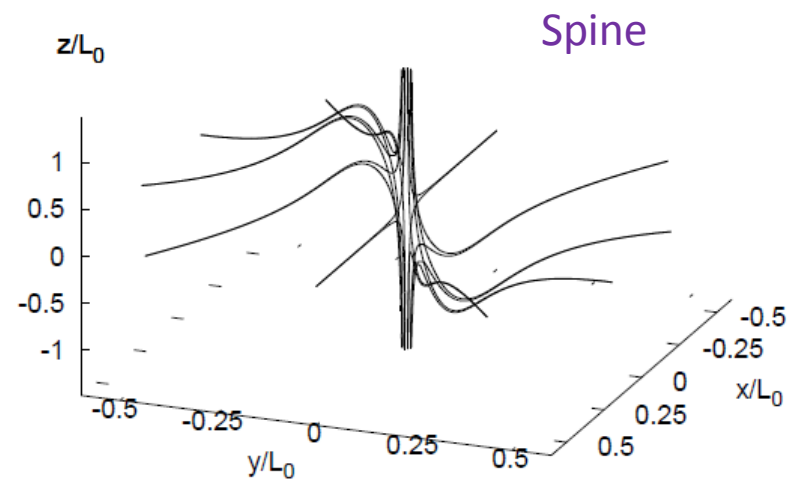
- **Fields from simple models of outer ideal reconnection region – *Dalla and Browning, 2005,2006, 2008; Browning et al 2010***
- **Numerical simulation of 3D null – convective electric field only – *Guo et al (2010)***
- **Stanier et al use background fields from exact solutions of steady MHD equations (Craig and Fabling, 1996, Craig et al 1997....)**

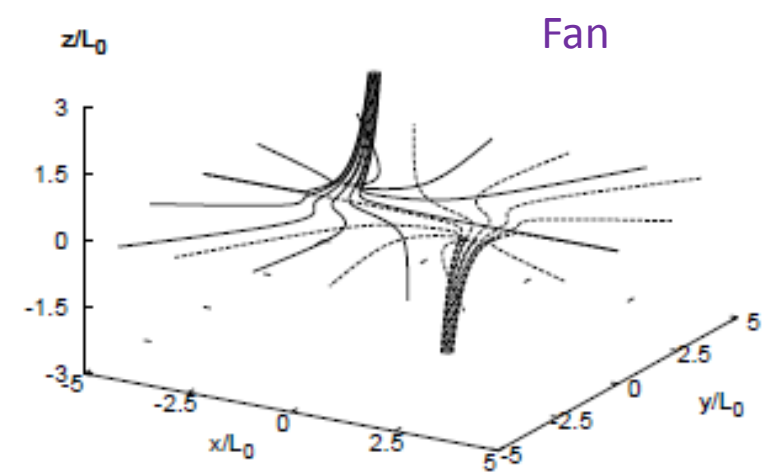
$$\boldsymbol{B} = \lambda \boldsymbol{P} + Q(x,y)\hat{\boldsymbol{z}},$$

$$\boldsymbol{v} = \boldsymbol{P} + \lambda Q(x,y)\hat{\boldsymbol{z}},$$

Potential null + reconnection field

***Q* expressed in terms of Kummer functions**





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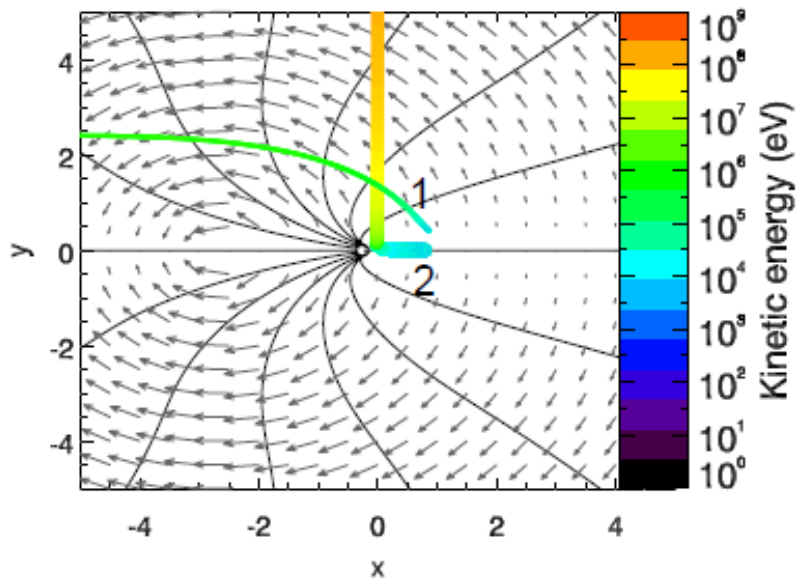
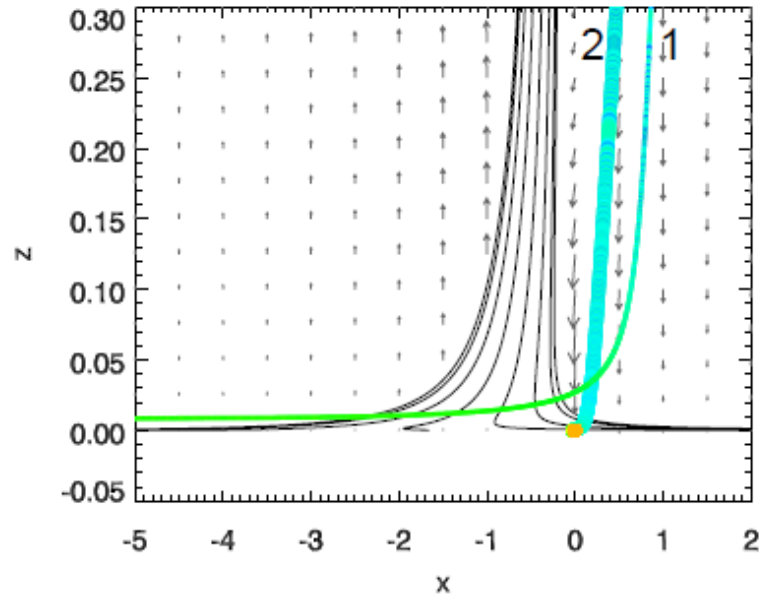
Proton trajectories in fan reconnection

– self-consistent C&F fields

- **Electric field from E = -v X B - ηj**
- **Calculate test particle trajectories for ions using full Lorentz equations**

Stanier et al A&A 2012





- **Typical energetic proton "1" – remains magnetised – gets close to current sheet but does not enter it**
- **Proton "2" enters current sheet and is directly accelerated – not ejected**
- **C.f. approximate solution near null *Litvinenko 2006***

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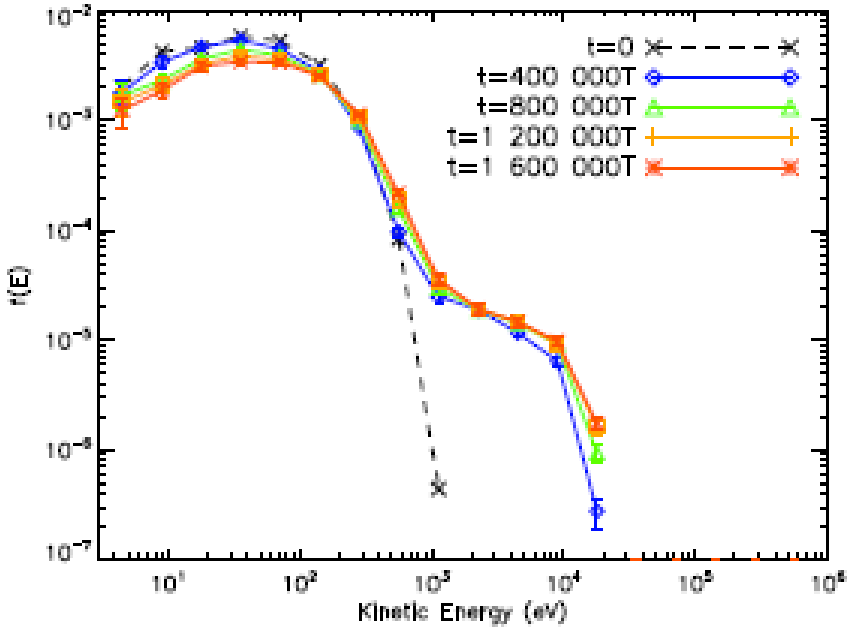
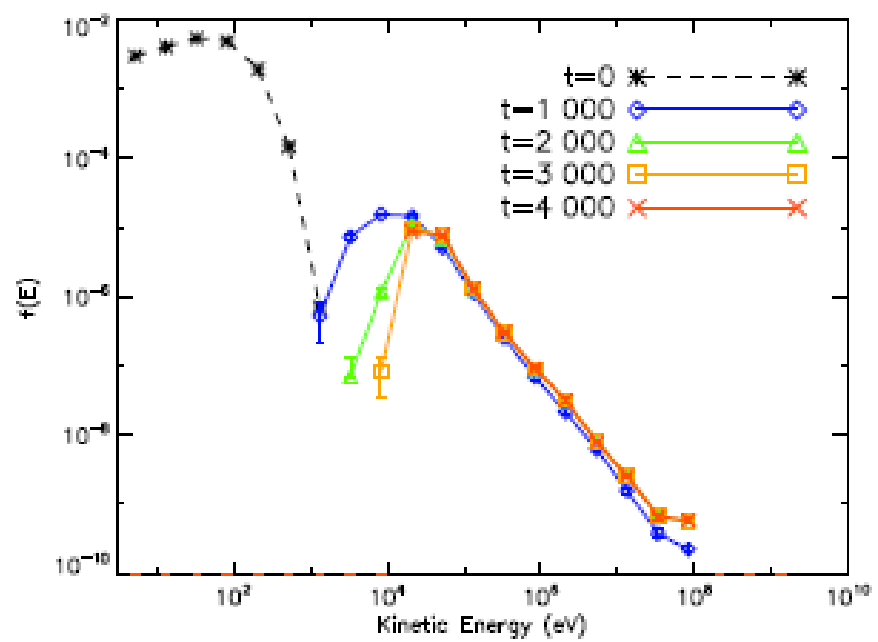
Proton energy spectra

Stanier et al A&A 2012





Spine case –

Some acceleration but rather weak due to "flux pile up" limits on electric field, small volume of spine reconnection region

Fan case –

Almost all particles accelerated, mainly due to strong electric drift

Unbounded current sheet

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Electron acceleration

- **Developed new "switching" particle solver:**
  - **Full Lorentz equations when Larmor radius too large**
  - **Guiding-centre when Larmor radius small**
- **5000 electrons in C&F fan reconnection field, initially Maxwellian 86 eV, random pitch angles and gyrophase, uniformly distributed at global distance *L* from null**

- **Two populations – those with initially y < 0 are trapped close to spine and do not reach current sheet region – those with y > 0 are accelerated at low latitudes and escape**
- **Trapped population behaviour is caused by "reverse" parallel electric fields outside current sheet - effect on electrons is much stronger than for protons (~ 1/*m*)**
- **Undertake simulations with much lower - and more realistic – values of *η* to reduce effect of reverse electric field**

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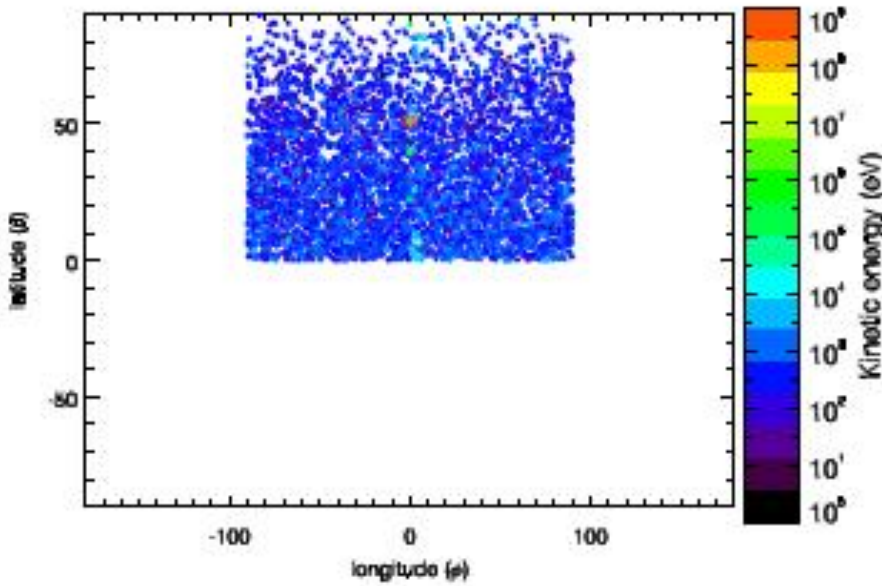
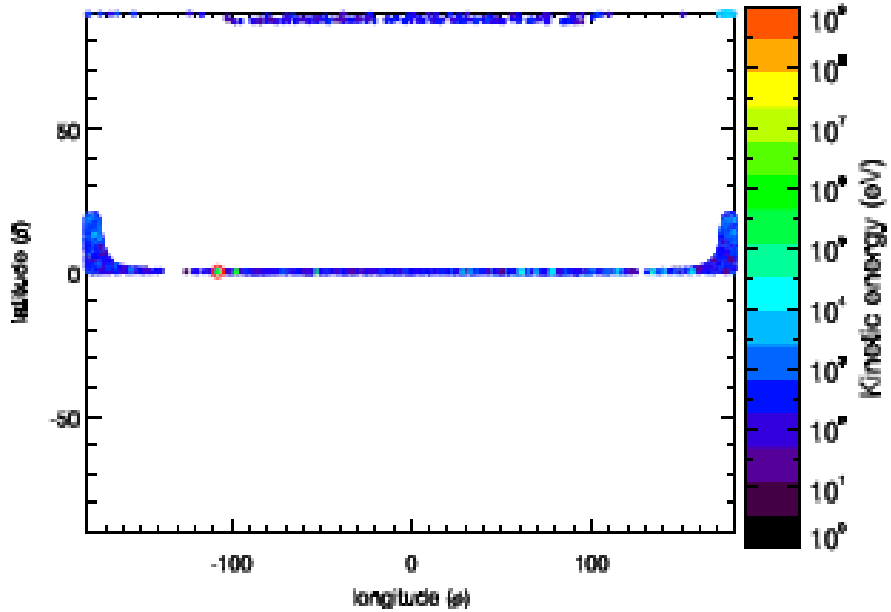
Energies and positions of electrons – reduced resistivity

$\eta = 10^{-10}$ $\alpha = B_s = 5$





Initial positions
Colour coded by final energy

Final positions
Colour coded by final energy

Highest energy electron (red circled) gets to 0.23 MeV

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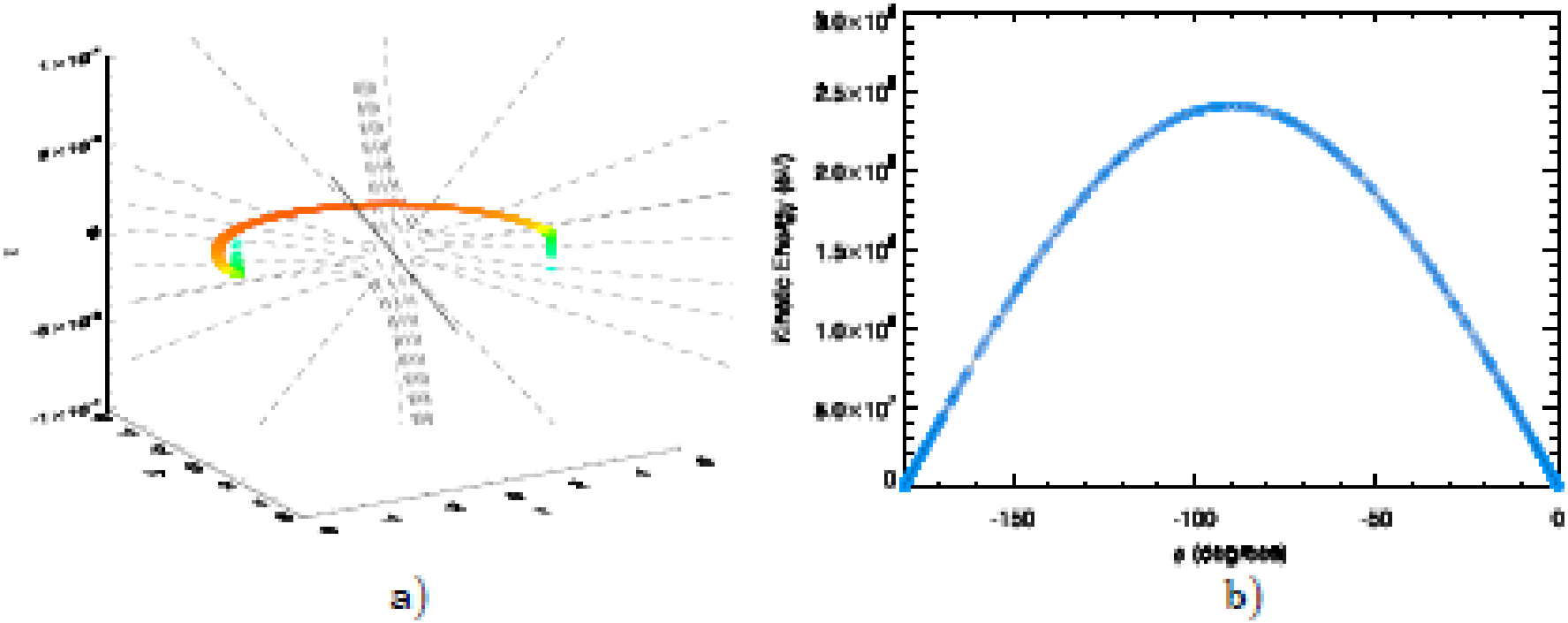
Electrons started in current sheet



$t = 10^7 \ T_{c,e}$

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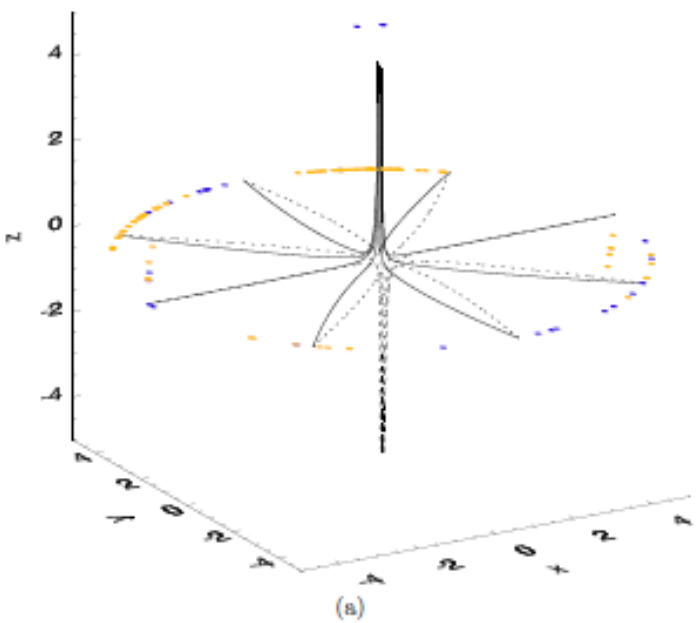
Observational predictions

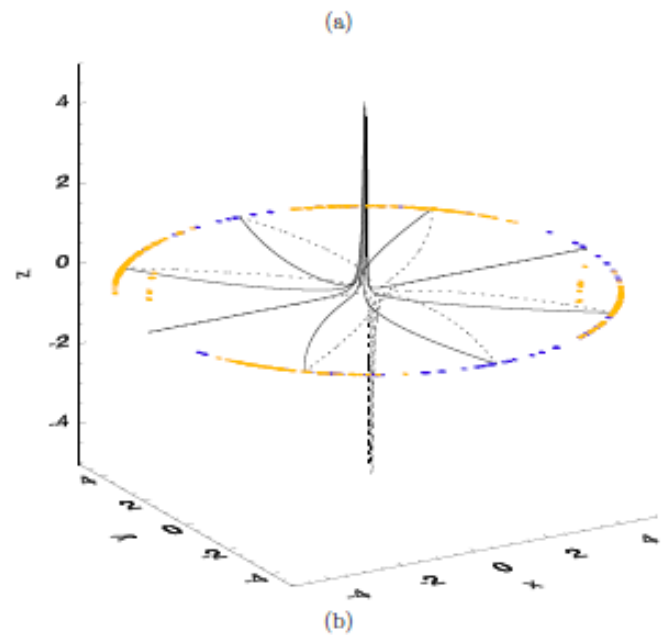
– spatial locations of high-energy protons (> 1 MeV, orange) and electrons (> 10 keV, blue)

$\eta = 10^{-10}$ $\alpha = B_s = 5$

$\lambda = 0.5$ t = 0.4 s



$\lambda = 0.25$ t = 0.2 s



Protons

Electrons

Varying shear parameter λ

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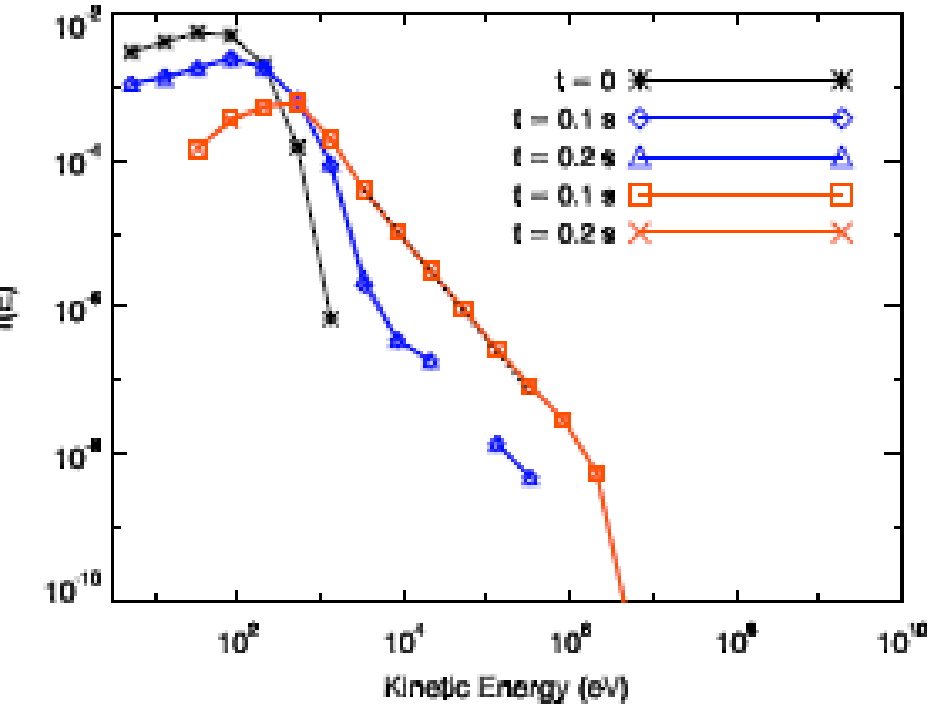
Energy spectra

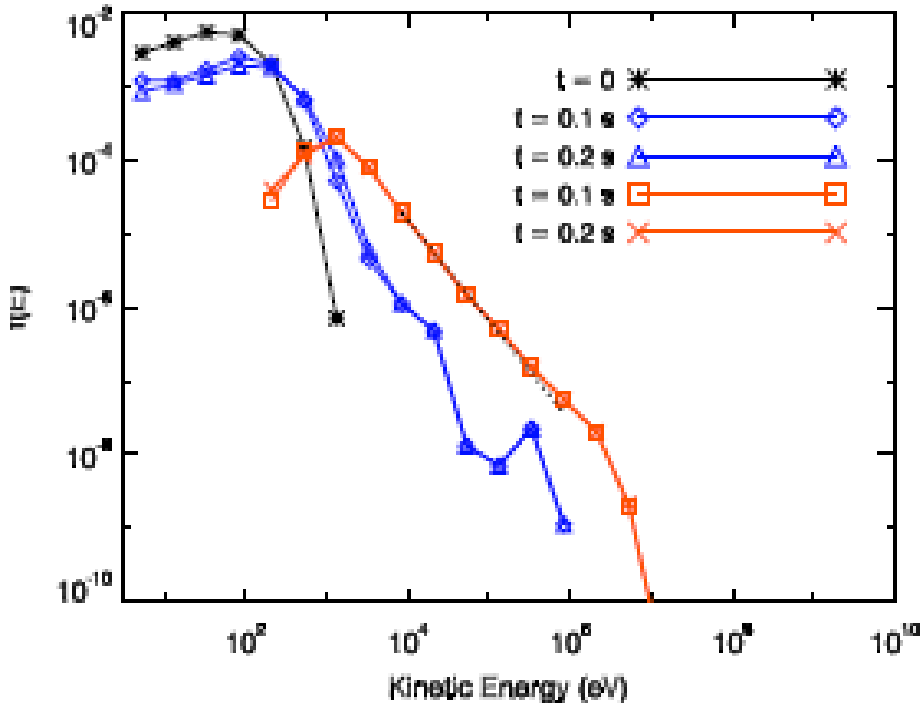
– protons (red) and electrons (blue)

$\eta = 10^{-10}$ $\alpha = B_s = 5$

$\lambda = 0.5$



$\lambda = 0.25$



Protons

Electrons

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Summary

- The solar corona may be heated to millions of degrees by dissipation of stored magnetic energy through multiple magnetic reconnections
- Relaxation and release of stored magnetic energy may be triggered by ideal kink instability in twisted coronal loops
- 3D numerical simulations show formation of fragmented current sheet with multiple reconnections in nonlinear phase of kink instability
- Fast reconnection in the fragmented current sheet results in plasma heating and particle acceleration distributed throughout the loop volume
- We have simulated this in realistic curved coronal loops twisted by footpoint motions – representing a confined flare - and calculated observable signatures
- Repeated driving and relaxation gives a distribution of heating events of different magnitudes – may be power laws
- Instability in one loop may trigger relaxation in an unstable neighbour leading to an "avalanche" of heating events - heating may also result from merging of twisted filaments
- As a first step to more complex topologies, we have investigated particle acceleration at 3D magnetic null points

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