The University of Manchester

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Magnetic reconnection in twisted magnetic fields in solar flares - heating, particle acceleration and observational signatures

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- Modelling energy release in unstable twisted loops
- Observational signatures
  - Thermal emission and Hard X-rays
  - Turbulent velocities
  - Radio/microwave
- Energy release in interacting twisted loops

Twisted flux ropes in the solar corona

▪Twisted magnetic flux ropes are non-potential fields providing reservoirs of free magnetic energy

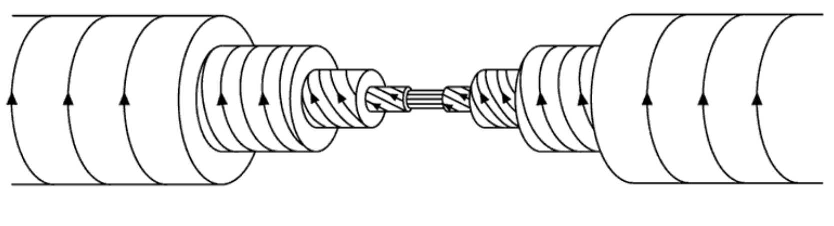
▪ Unstable twisted coronal loops can be a good alternative to the standard model, particularly in smaller flares with isolated loops

e.g. Aschwanden et al. 2009

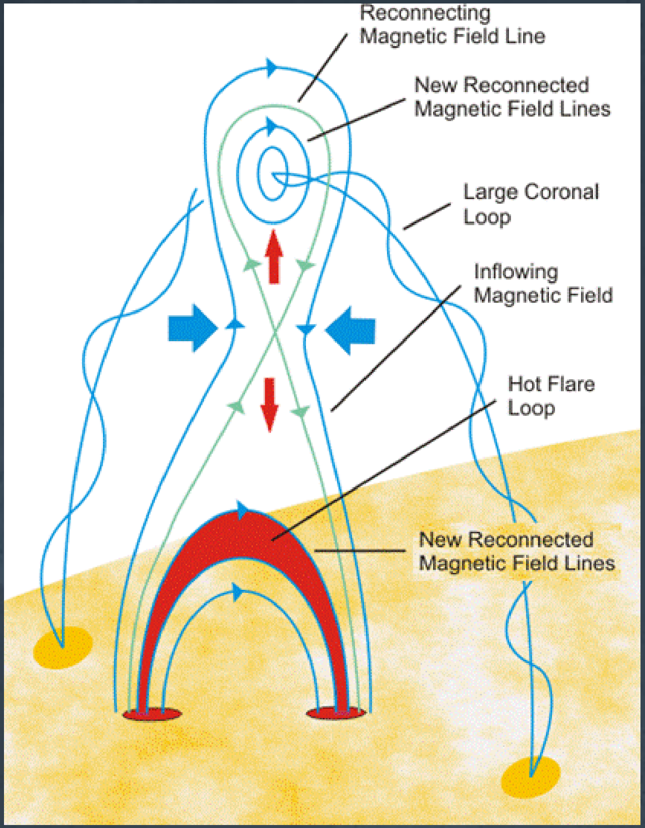
▪ In standard model, flux ropes can form due to magnetic island formation in a reconnecting current sheet with guide field *e.g. Gordovskyy et al. 2010*

▪Twist can be produced by photospheric rotation/shear motions *e.g. Brown et al. 2003*

▪Newly emerging flux is expected to have some twist *e.g. simulations by Archontis and Hood*



Interior Structure of Flux Rope



Twisted loops in flares

from Shrivastava et al 2010 ApJ

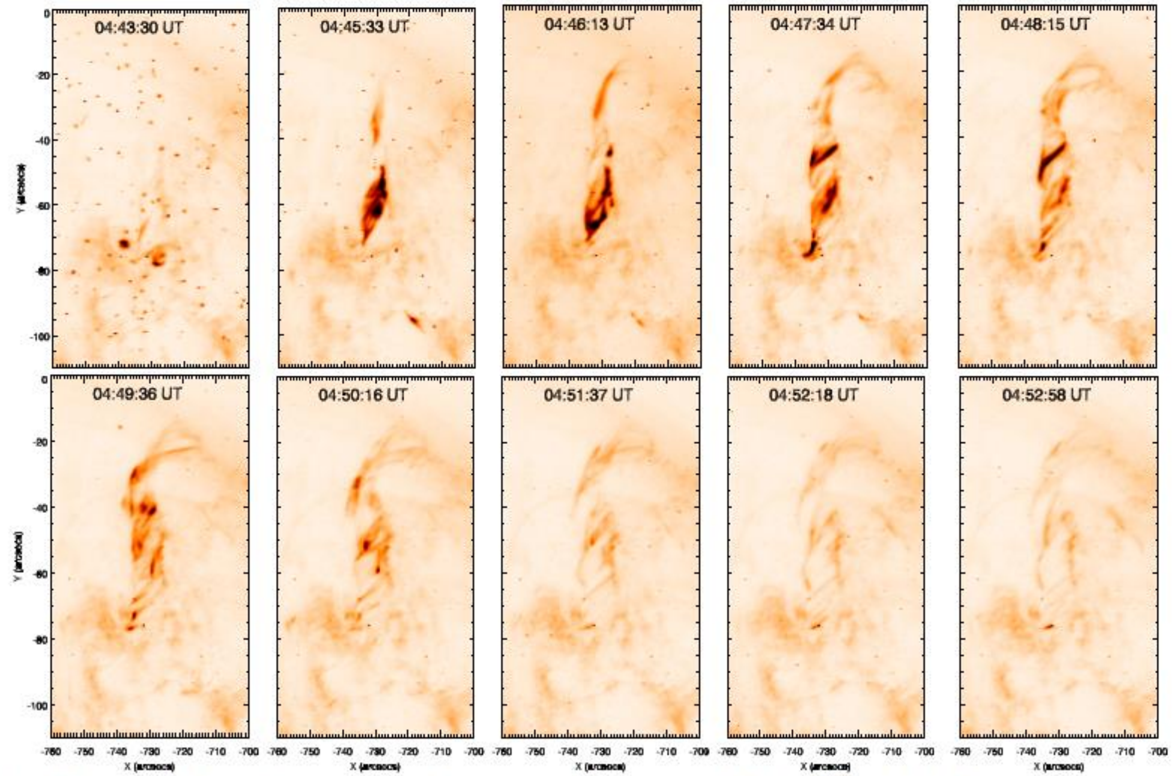
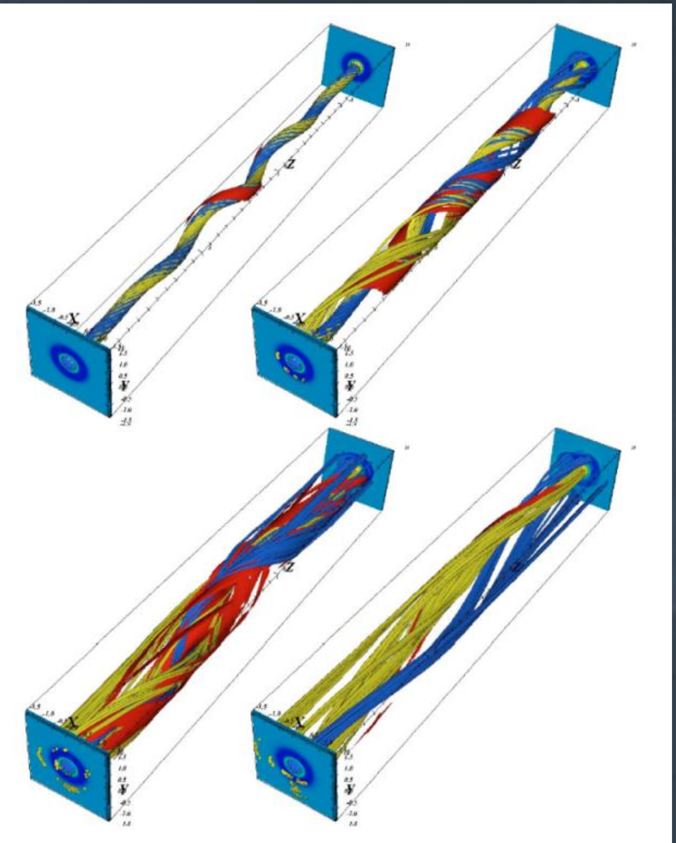


Figure 5. Time sequence of TRACE 171 Å Fe ɪx images of flaring loop in the AR 10960 during 04:43 UT–04:52 UT on 2007 June 4. The images are in reverse color and show the clear helical twist of the loop during the B5.0 flare. Note the double structure of the coronal loop top between 04:47 UT and 04:51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

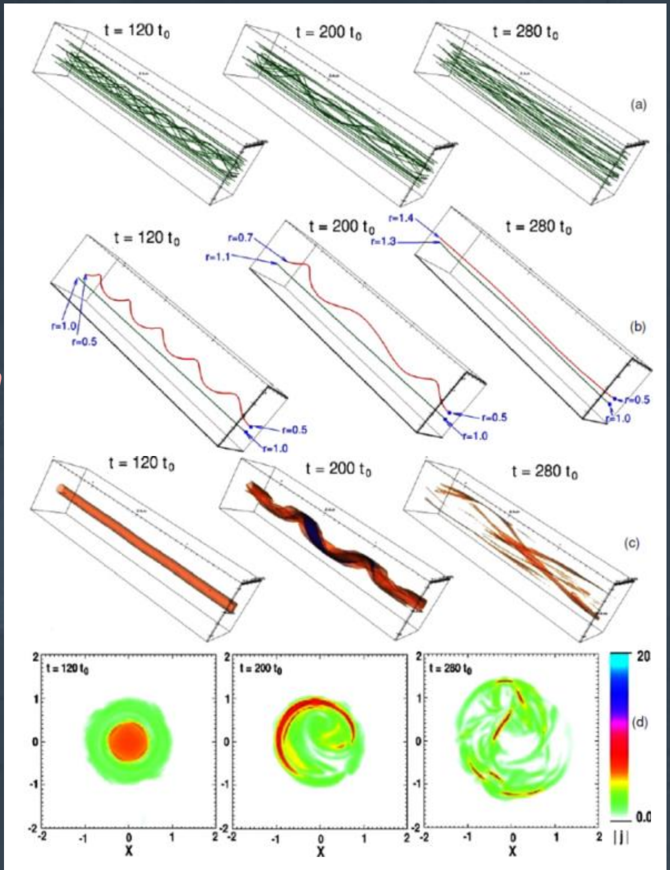
Kink instability modelling

- Ideal kink instability → fragmented current sheet in nonlinear phase
- Internal reconnection and reconnection with untwisted ambient field → untwisting of field, loop expansion
- Fast magnetic reconnection dissipates magnetic energy
- Particle acceleration throughout loop volume



Kink instability in unstable cylindrical flux ropes

Baty & Heyvaerts 1996; Browning & Van der Linden 2003; Browning et al 2008; Hood et al 2009; Botha et al, 2012; Bareford et al 2013, Bareford & Hood 2015



from Hood et al. 2009 A&A

from Gordovskyy & Browning 2011 ApJ

Observational detection of twisted loops

- Thermal emission (UV & soft X-ray, continuum and spectral lines)?
- Thermal radio?

- Non-thermal Hard X-ray?
- Non-thermal radio?

Coupled MHD and test-particle models

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

3D MHD simulations

Relativistic guiding-centre
Collisions with background plasma

Thermal emission   Field topology   Non-thermal emission

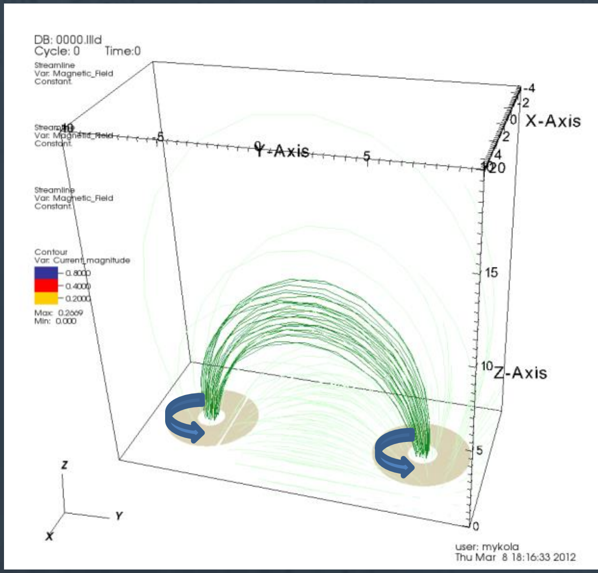
- *Gordovskyy et al A&A 2014* (loop evolution, non-thermal particles & HXR)
- *Bareford et al Sol Phys 2016* (loop geometry effects)
- *Pinto et al A&A 2016* (thermal SXR continuum, non-thermal HXR)
- *Gordovskyy A&A 2016* (EUV lines – non-thermal broadening, shifts)
- *Gordovskyy et al 2017* (thermal and non-thermal microwave)

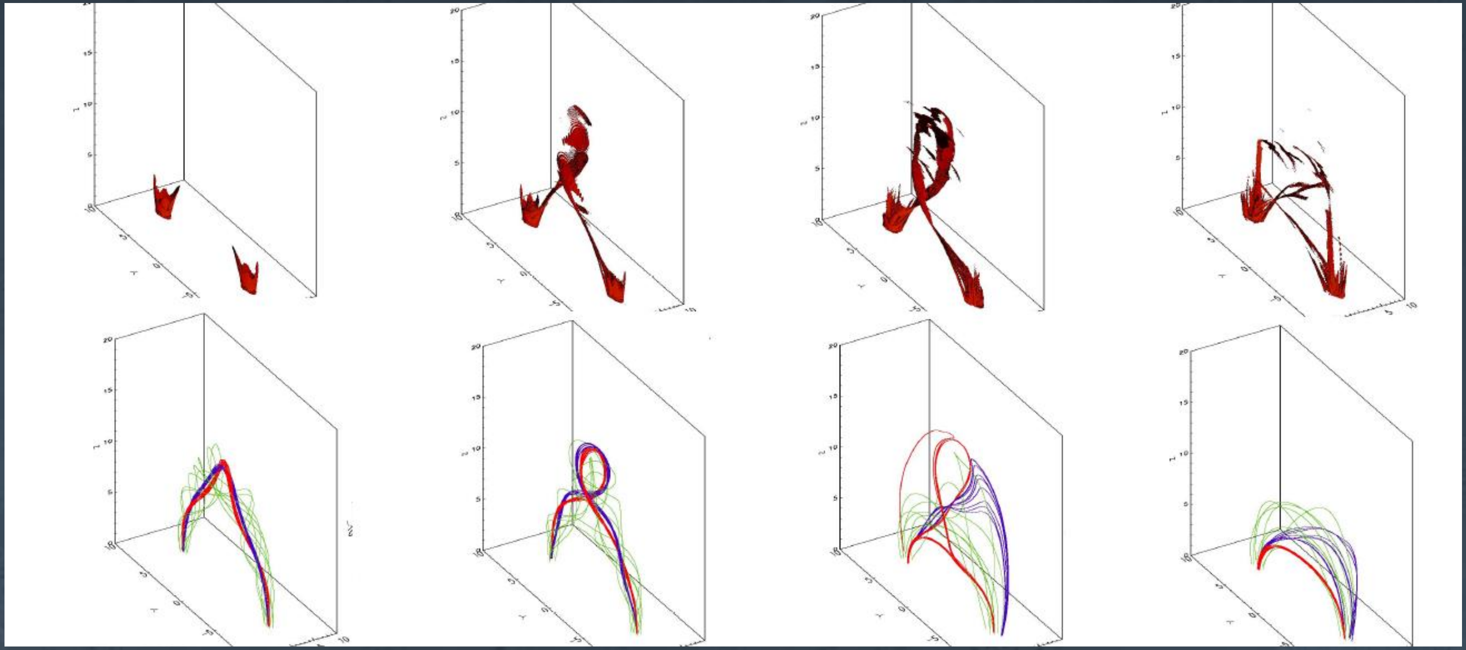
Our model

- 3D MHD with LARE3D *(Arber et al 2001)*

- anomalous resistivity triggered by ion acoustic instability

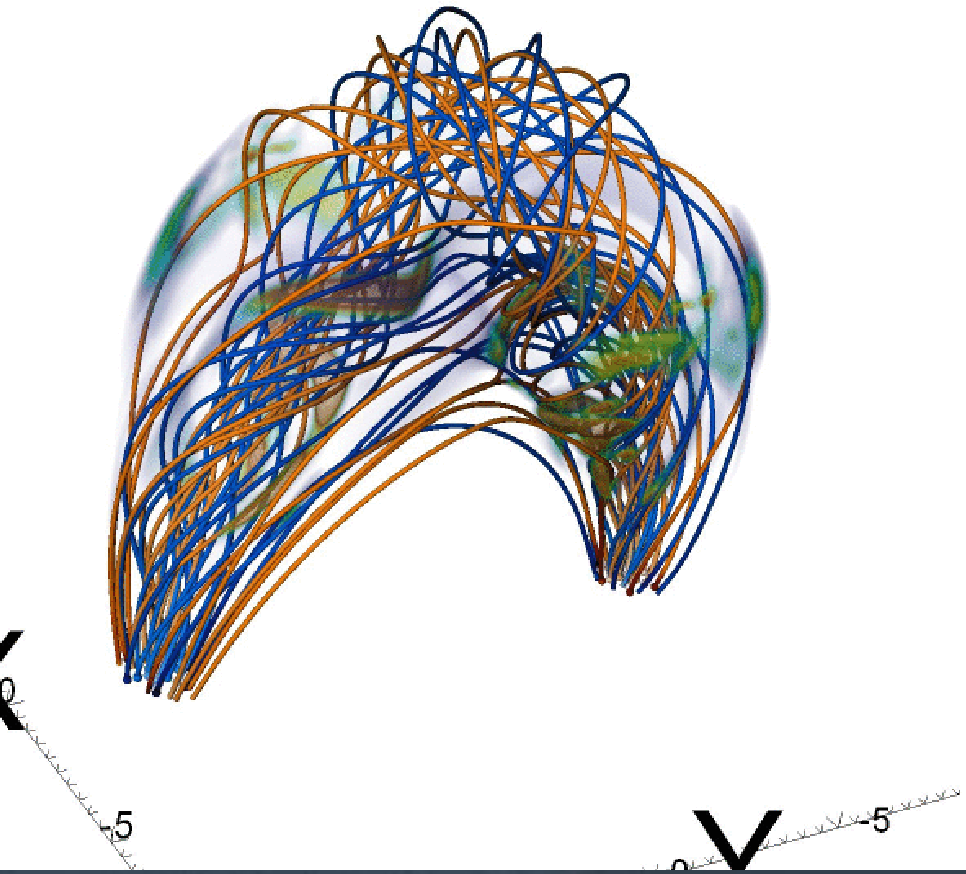
- Gravitationally-stratified atmosphere
- Bipolar magnetic region – localised rotational motions → twisted loop
- Kink instability leads to loop expansion, fragmented currents within loop, large-scale currents and reconnection

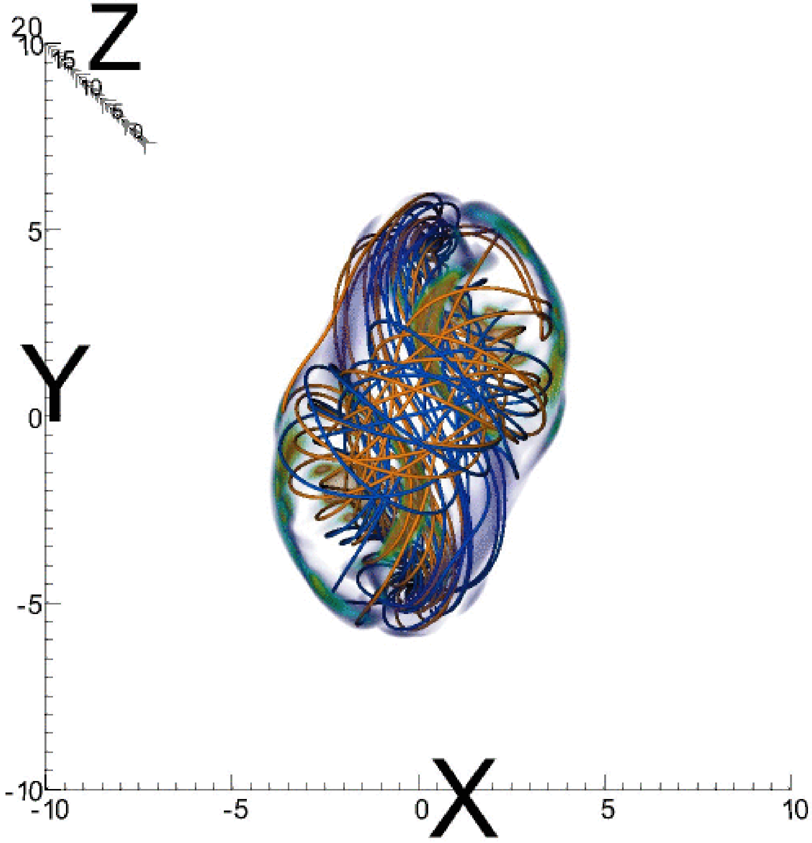




SXR thermal emission

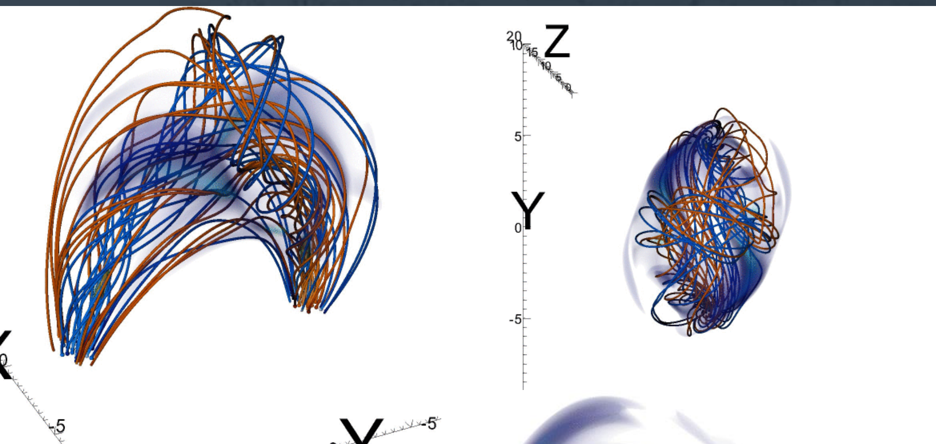
Small loop (model V), 2keV continuum emission

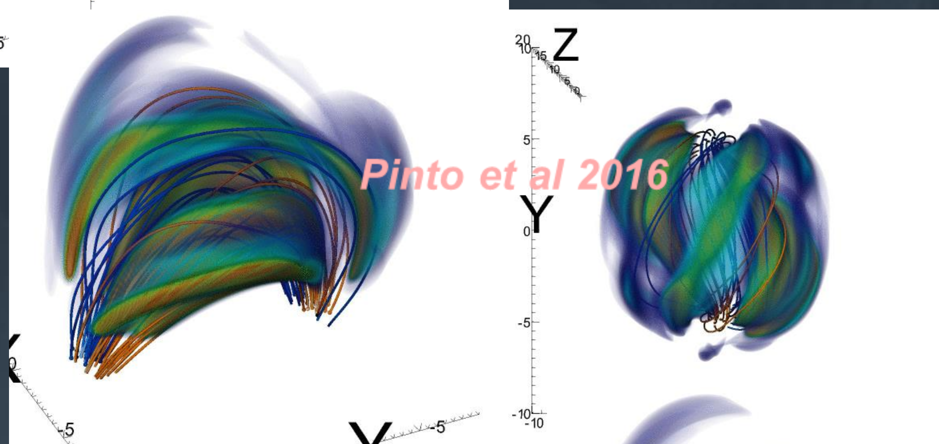


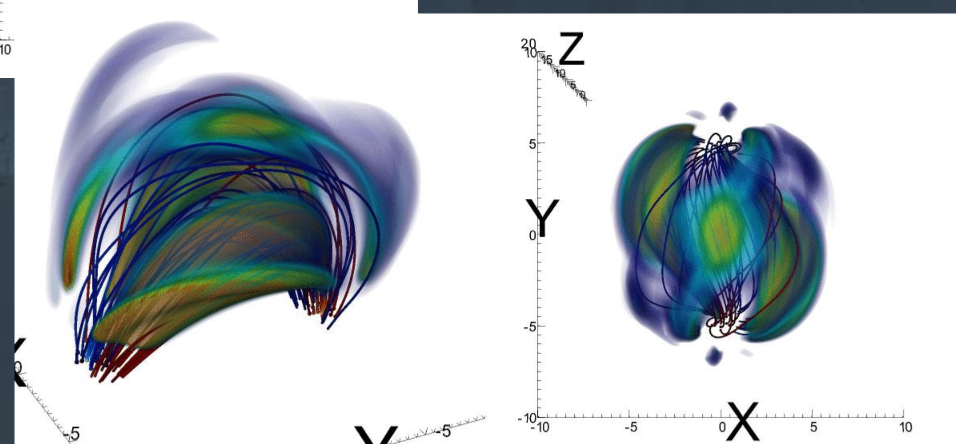


Pinto et al 2016

SXR thermal emission







Emission shows only weak signature of twist

Pinto et al 2016

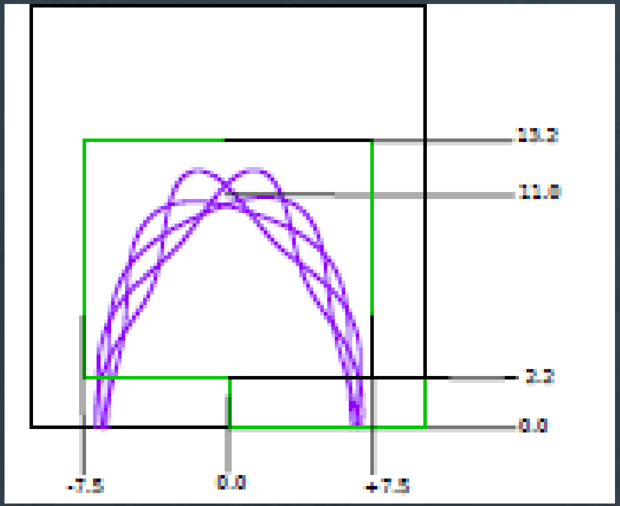
Thermal emission: velocities

Observations:

- *Doschek et al. 2008 ApJ*
- *Doschek et al. 2013 ApJ*
- *Young et al. 2013 ApJ*

- **Correlation of non-thermal velocity dispersion (line broadening) with temperature: velocity dispersion increases from 20-30 km/s at ~1MK to 100-120km/s at ~15-20MK**

- **Correlation of bulk velocity (line shift) with temperature: increases from 20-30 km/s to 300-350 km/s in the same interval**



Model – calculate line-of-sight averages of <v> and velocity dispersion in different parts of loop

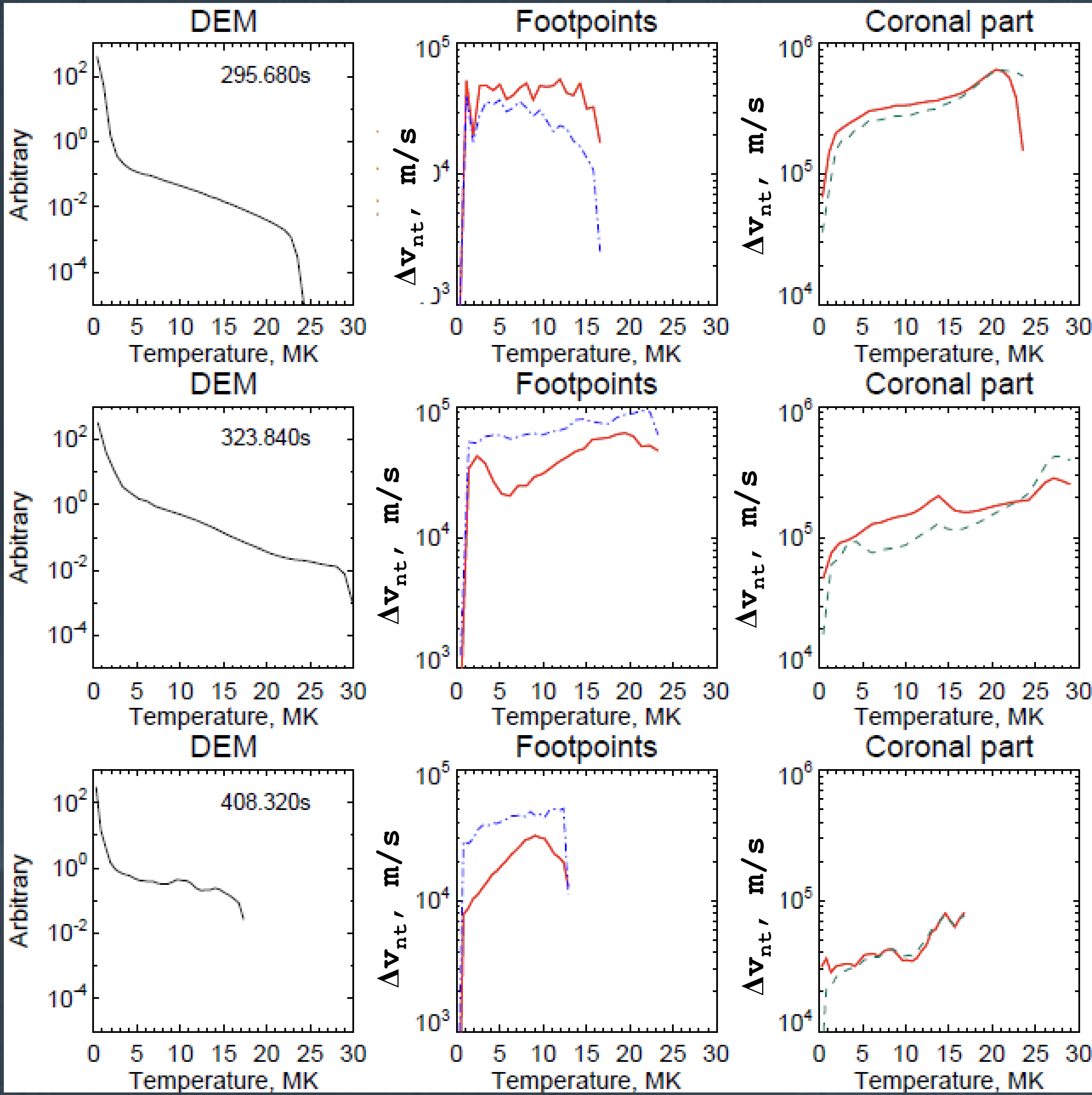
Predicted LOS velocity dispersion

Large scale loop
Strong field

Length 80 Mm

Footpoint field 1500 G

Time
↓
↓



Increasing velocity dispersion with temperature

Probably typical of all reconnection and not distinctive characteristic of twisted loops

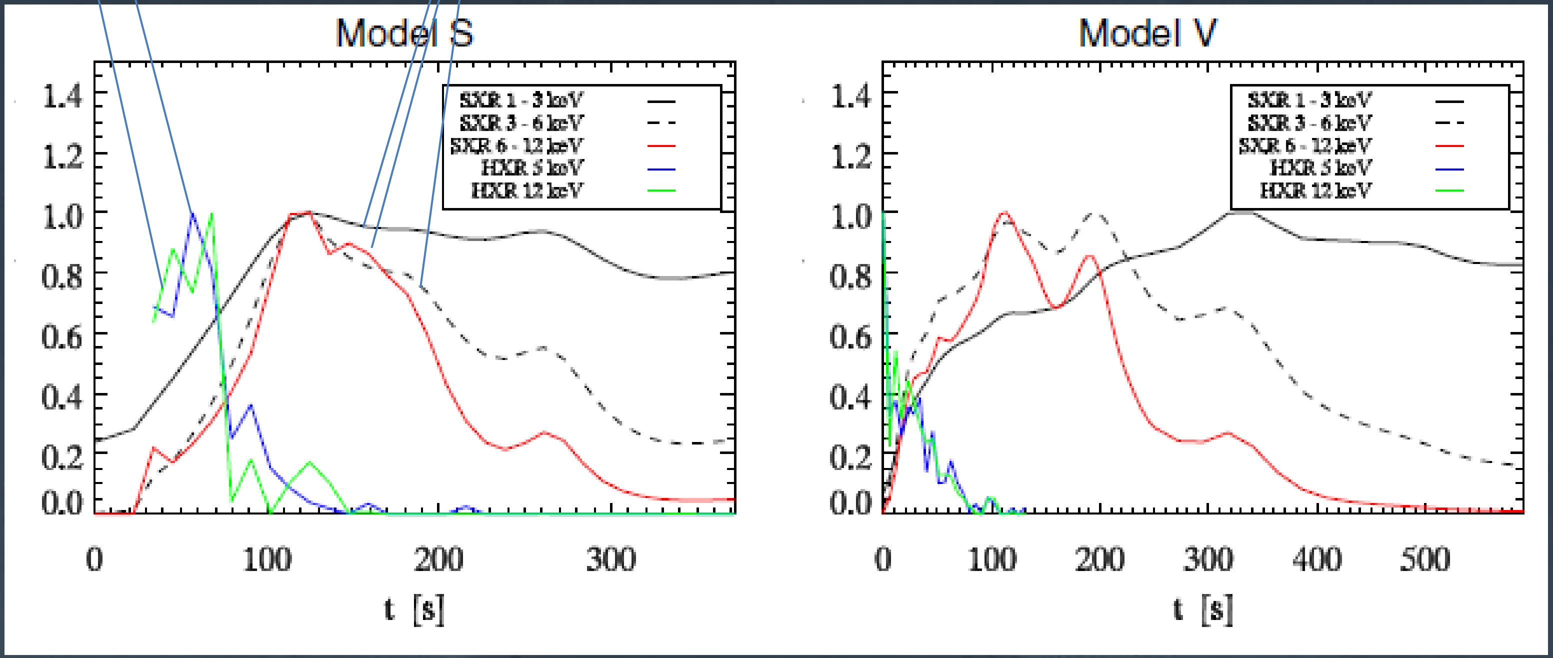
Gordovskyy et al 2016

Thermal (SXR) v. non-thermal (HXR) emission: Light curves

Neupert effect in small loops

HXR

SXR



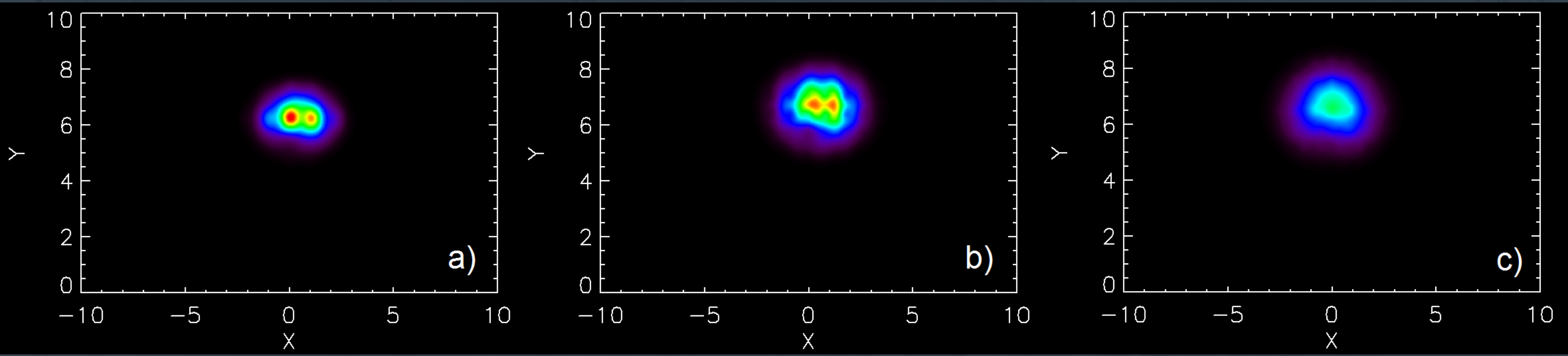
Pinto et al 2016

Non-thermal HXR emission

Onset of magnetic reconnection

Maximum dE/dt in MHD model

Decay phase



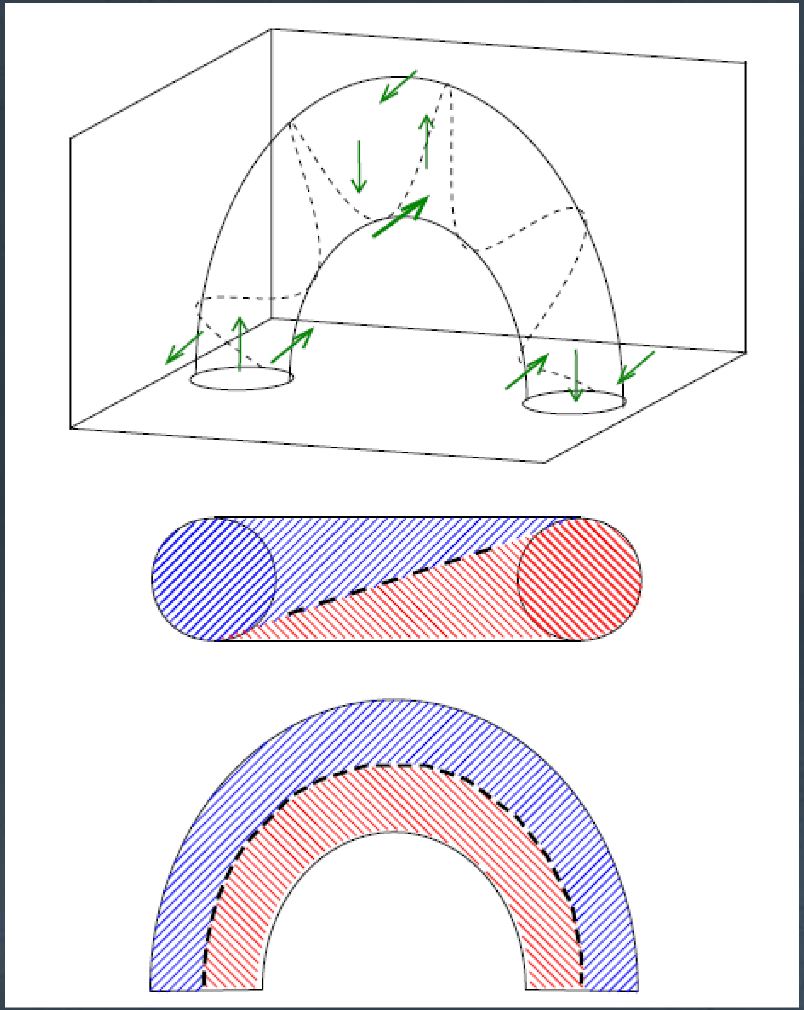
FWHM=1.9

FWHM=2.2

FWHM=2.5

- Loop cross-section increases by 50-100%
- FWHM of HXR sources increases by 20-30% (with RHESSI resolution)
- *Kontar et al 2011 ApJ* – quantitatively and qualitatively similar effect

Circular microwave polarisation pattern as a detection tool?



Polarisation pattern – Disc

Limb

- *Kuznetsov et al. 2016, Sharykin & Kuznetsov 2016*
- *Gordovskyy et al, A&A under review*

Synthetic microwave emission from twisted loops

- Is this pattern visible in "real" loop (time duration, optical thick effects, more complex field…..)?

- GX Simulator

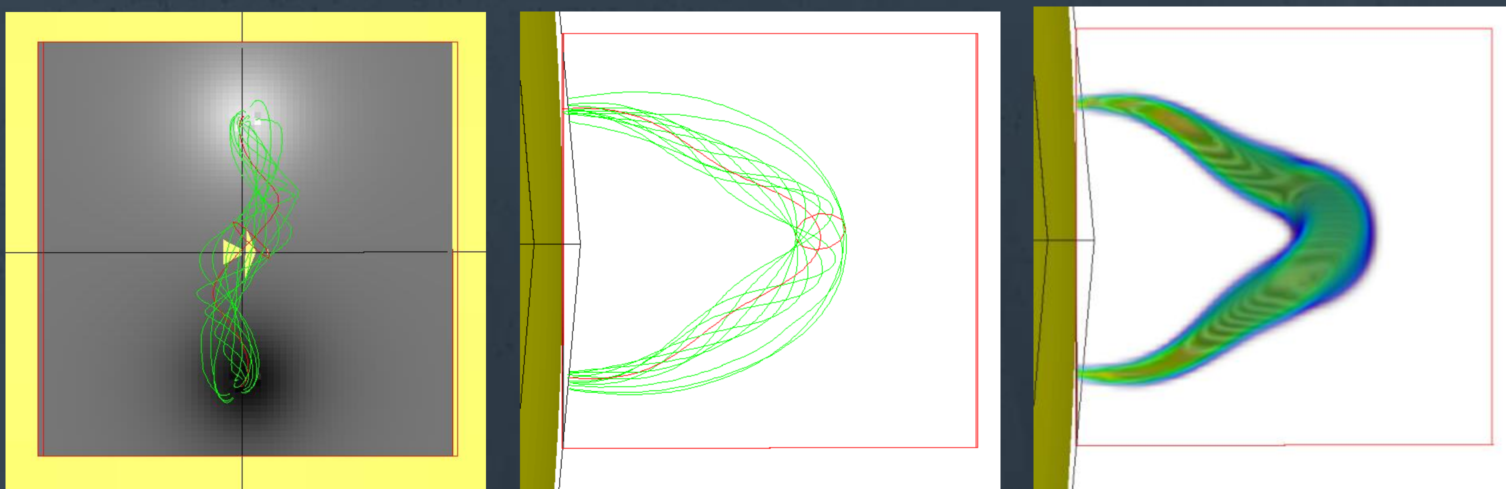
  Fleishman & Kuznetsov (2010), Nita et al. (2015)

- Magnetic field and thermal plasma density & temperature taken directly from MHD model
  - magnetic field 100-1000 G at foot-points
  - ambient plasma $n \approx 10^9 cm^{-3}$, $T \approx$ 1MK
  - hot plasma in the reconnecting loop $n \approx 10^9 cm^{-3}$, $T \approx$ 10-30 MK

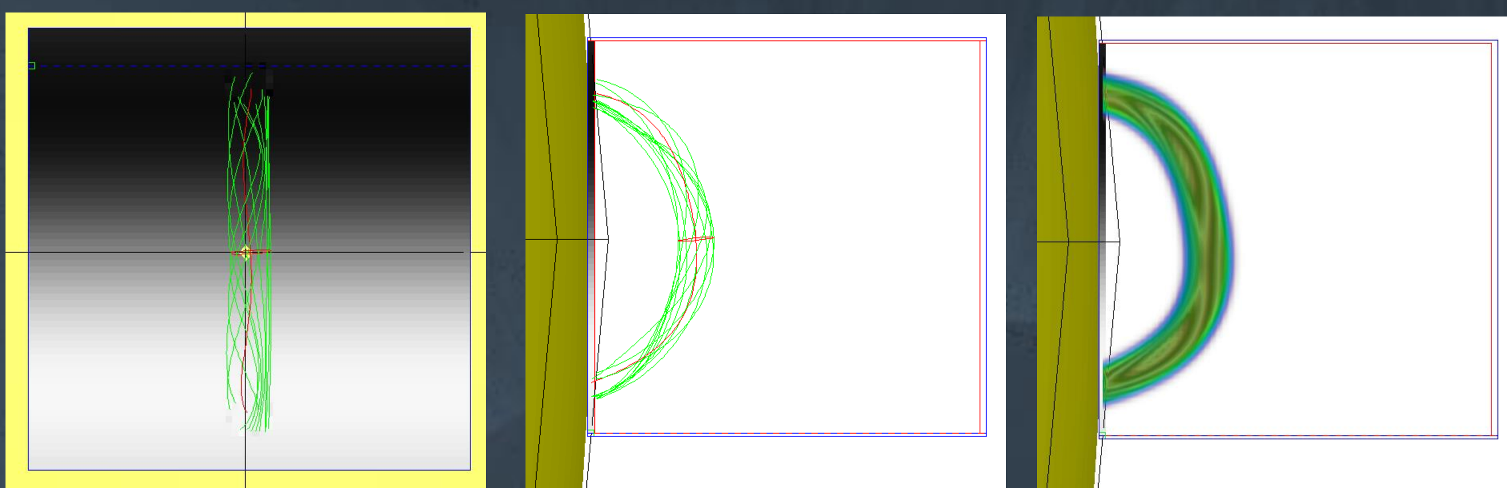
- Non-thermal electron population approximated by a single power law fitting test-particle simulations

  - $n_b \approx 5\ 10^7\ cm^{-3}$, E_{low}= 3keV, E_{up}=3 MeV, γ = 2.0-4.0

Magnetic field convergence effect

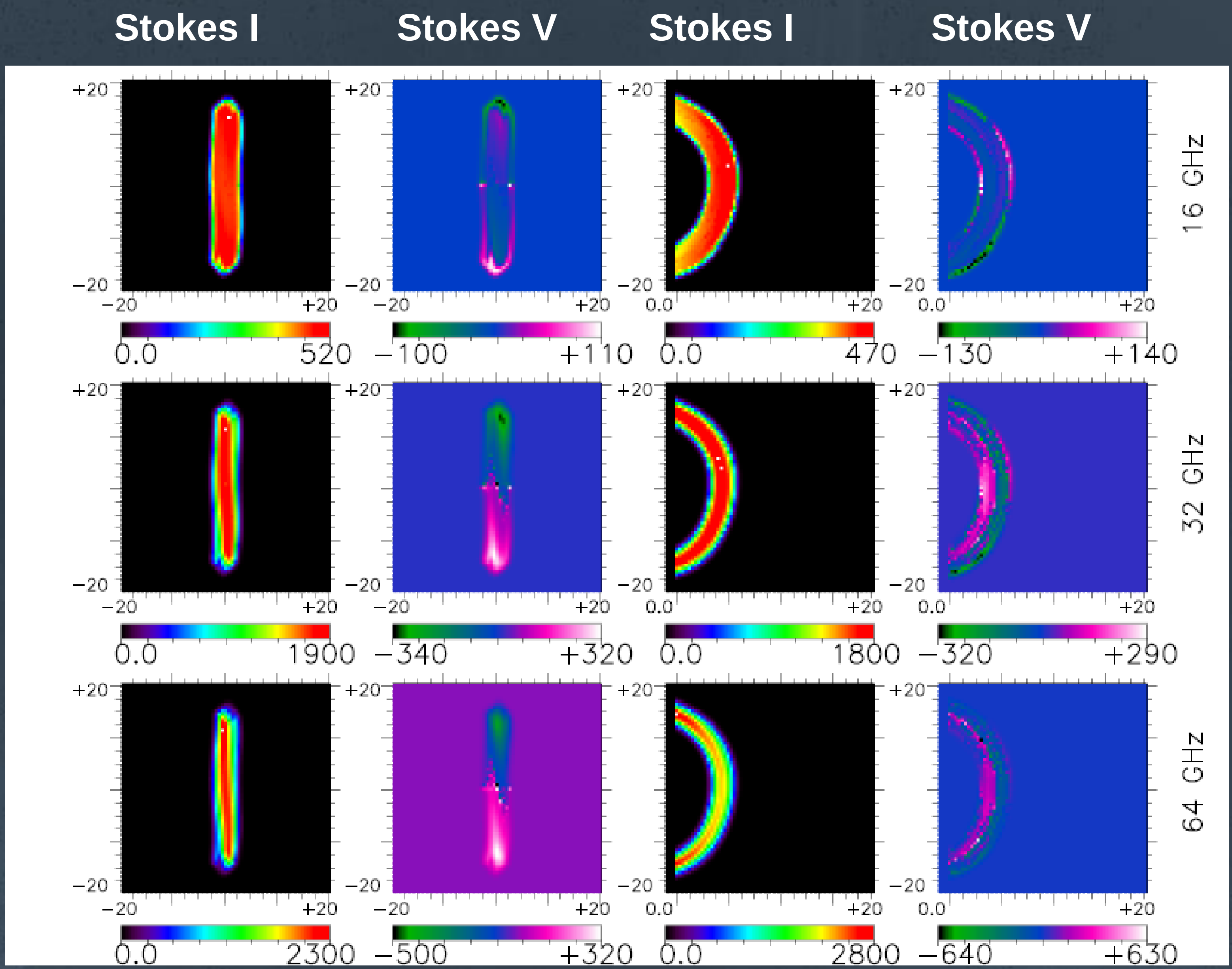


$B_{top}/B_{fp} = 10$



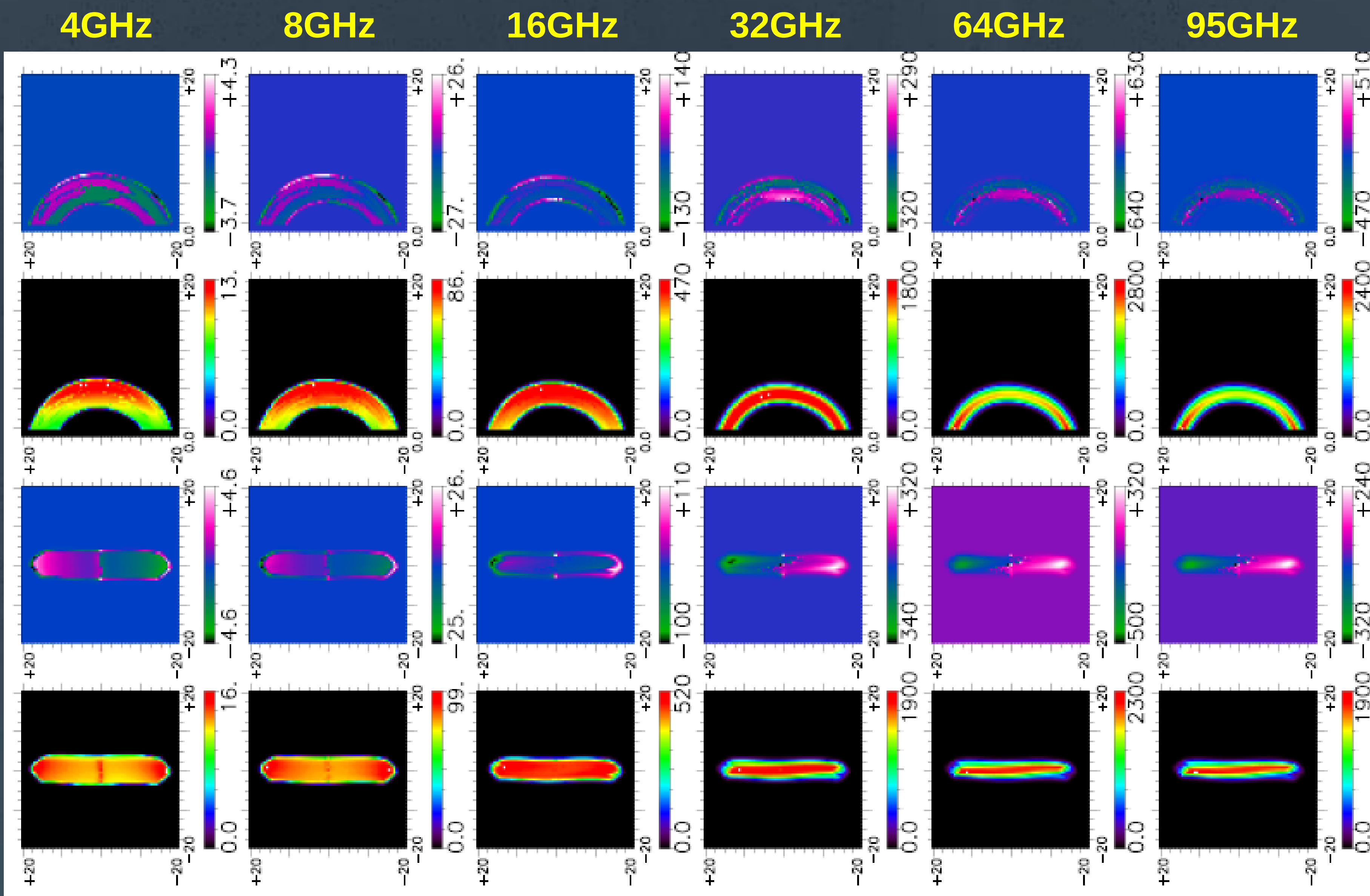
$B_{top}/B_{fp} = 2$

MW polarisation in weakly converging loop



At start of energy release

MW polarisation: frequency variation



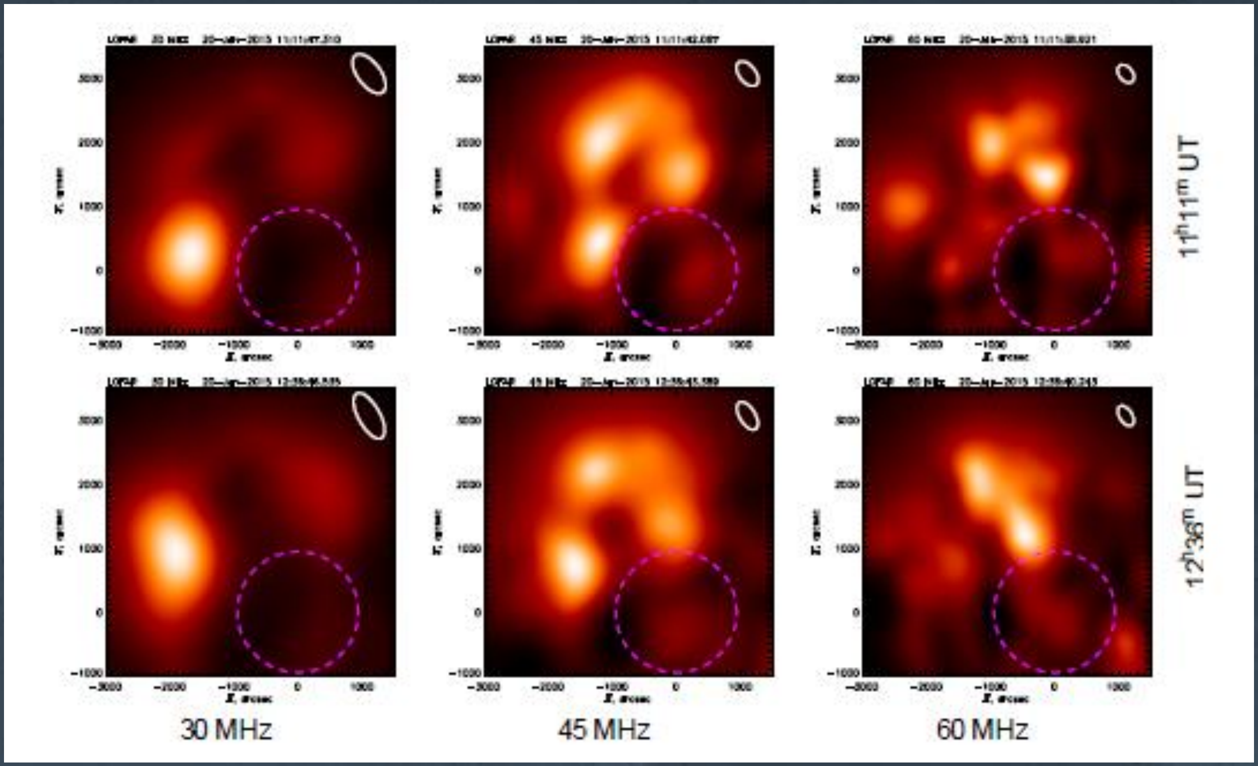
- **Thermal microwave: circular polarisation gradient across the loop should be visible, especially at the limb, although the intensity should be low**

- **Non-thermal microwave: circular polarisation gradient across the loop should be visible, however**

- **- the life-time of that pattern would be ~30-60s**
- **- visibility of the pattern would depend on loop orientation**
- **- visibility would depend on the magnetic field convergence**

LoFAR observations of giant loop

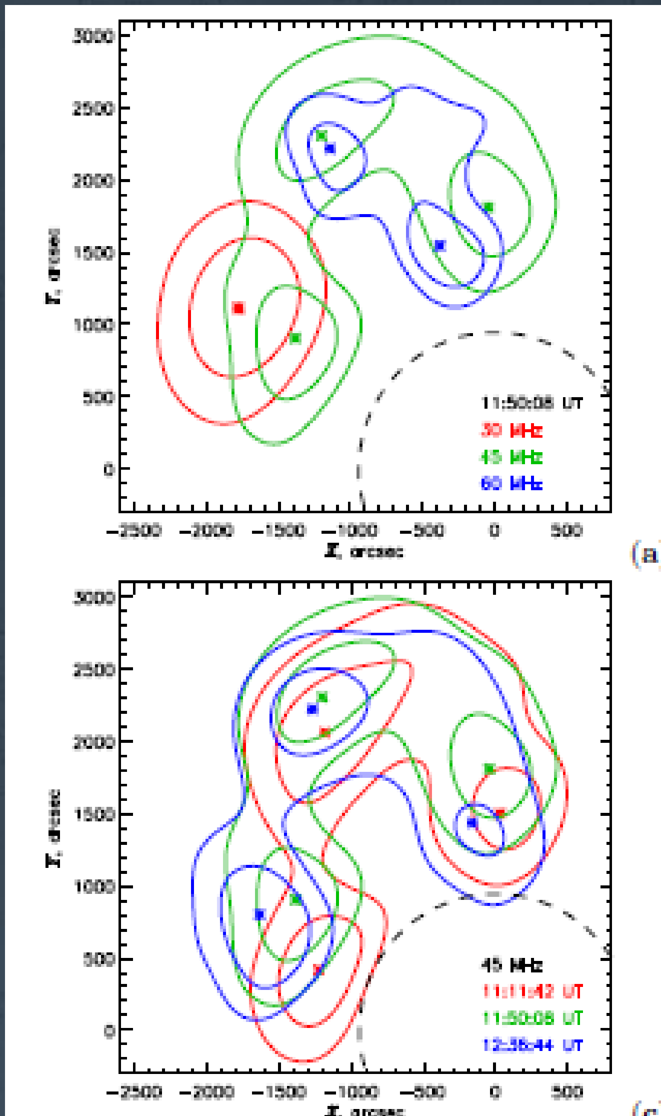
Gordovskyy, Kontar, Kuznetsov and Browning Ap J Lett submitted



- **Imaging of large-scale ~1 R_o loop in radio 30 – 60 MHz**
- **Narrow frequency range, high brightness temperature**
- **Plasma emission associated with energetic electrons (frequency ~ √density)**

$$30\ \text{MHz} \leftrightarrow 1.1\times10^{7}\ \text{cm}^{-3},\ 60\ \text{MHz} \leftrightarrow 4.4\times10^{7}\ \text{cm}^{-3},$$

Frequency variation



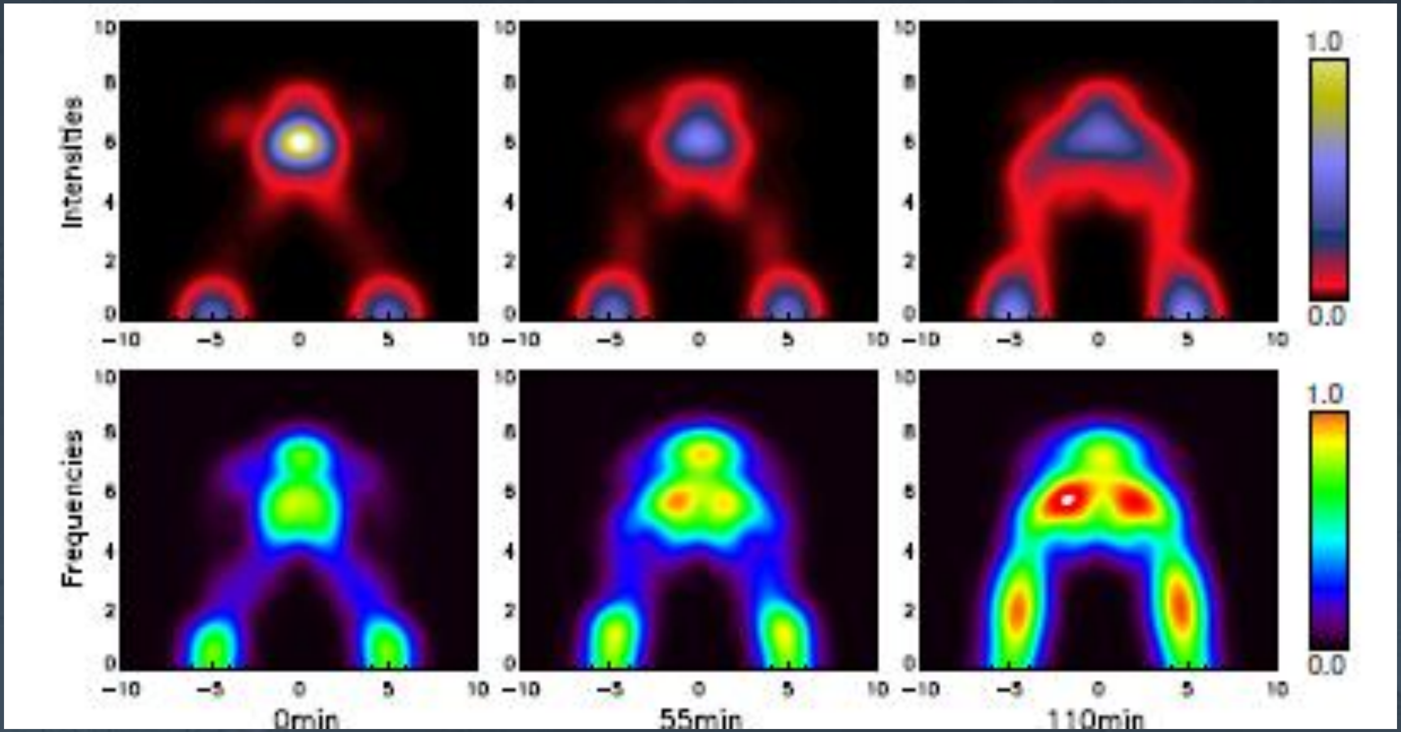
Time variation

- Distinct loop structure
- Three main sources with weak background throughout loop
- Density does not match ambient coronal stratification – but strong gradients across loop
- Some asymmetry – density increases by factor of ~4 from left to right
- No substantial expansion/motion in time

Model

- 3D MHD simulation - large-scale twisted loop with strong convergence
- Use local Ohmic dissipation rate j.E as proxy for particle acceleration
- Line-integrate - average frequency is local frequency (density) weighted by intensity

- Good agreement with many aspects of observations



Intensity

Average frequency

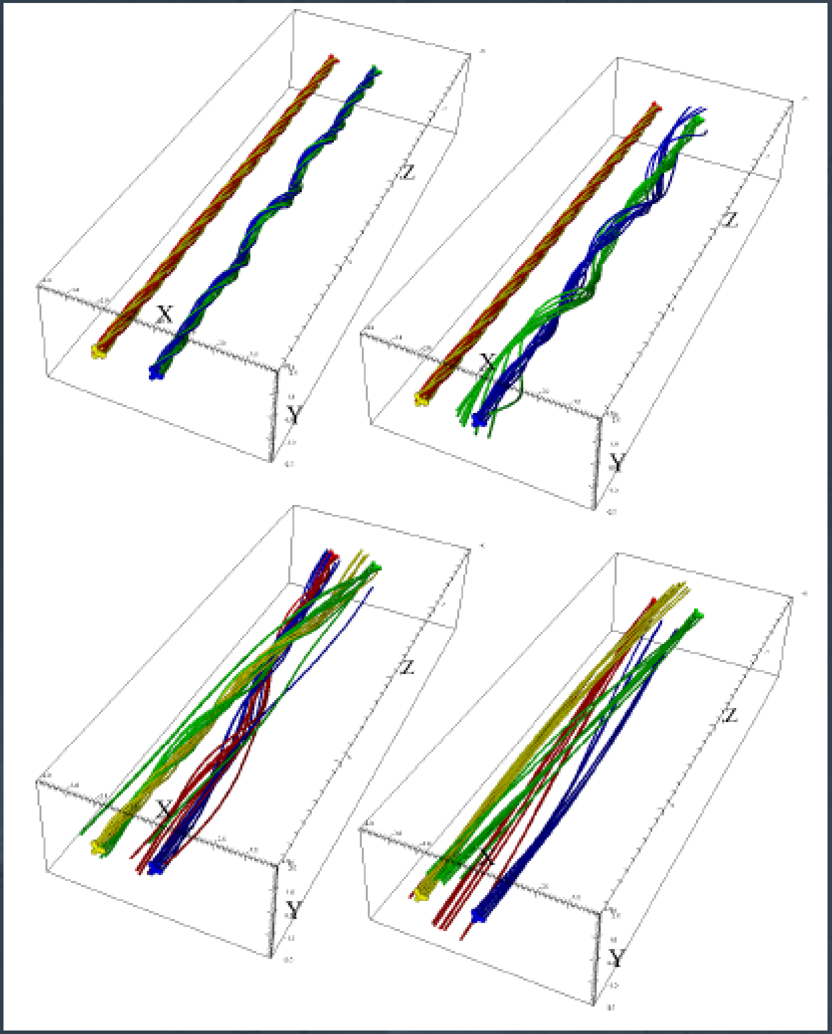
Disruption of neighbouring stable flux rope

Tam, Hood, Browning and Cargill A&A 2015

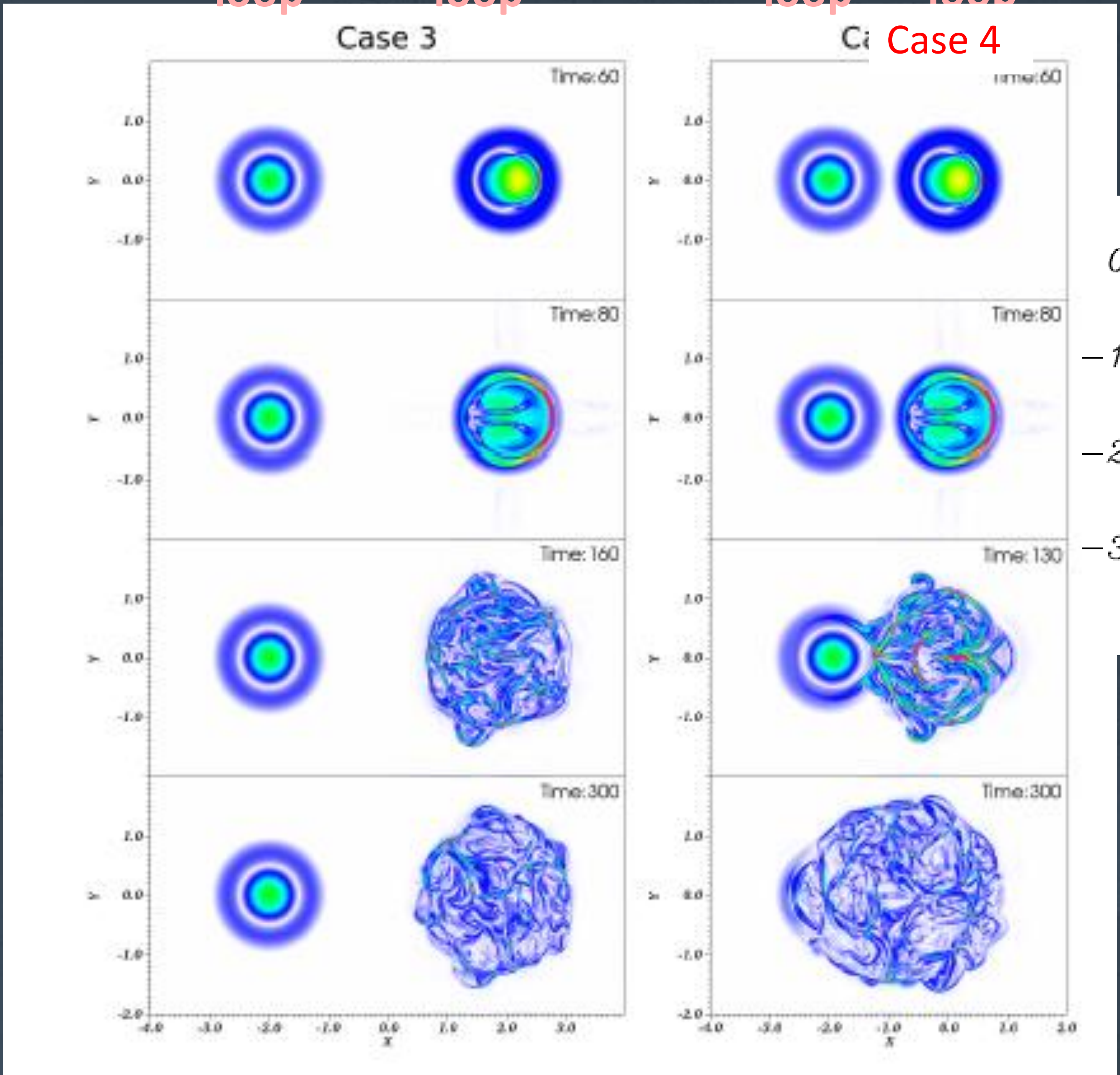
Consider adjacent zero-net - current loops

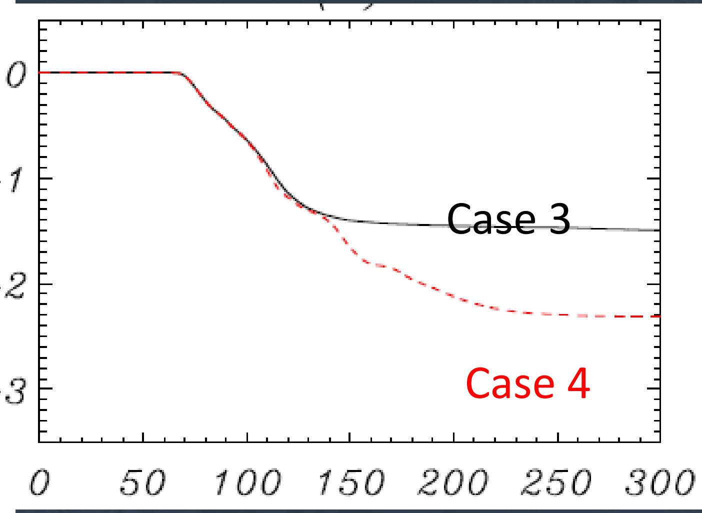
- **If the loops are sufficiently close, an unstable loop may trigger relaxation in a neighbouring stable loop**
- **In this case the two loops merge into a single (very weakly twisted) loop**

- **Releases energy stored in stable loop (as well as unstable loop)**



Stable loop Unstable loop Stable loop Unstable loop





Magnetic energy versus time

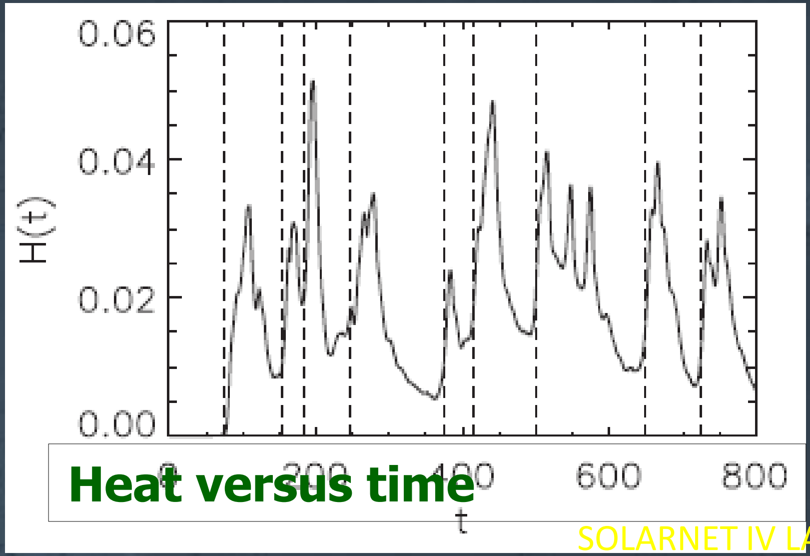
Avalanche triggered by one unstable flux rope

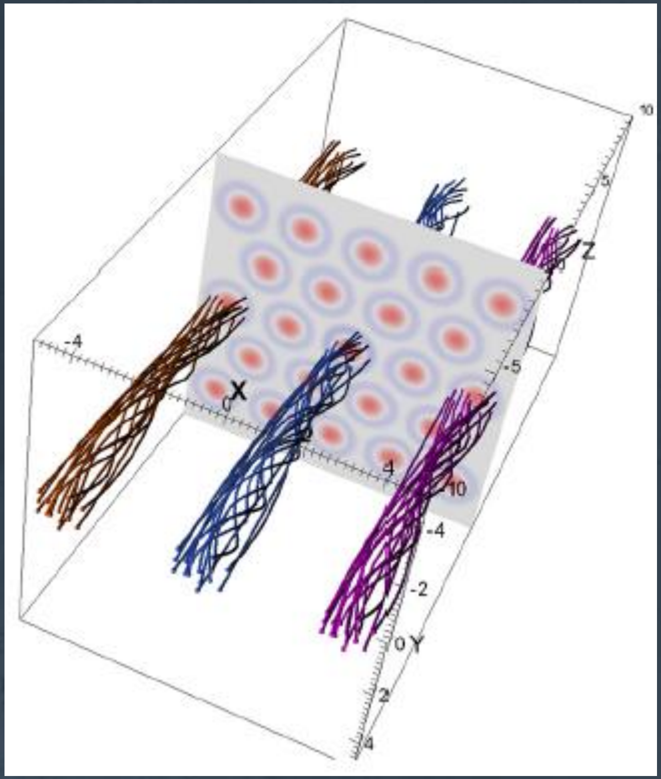
→ Under certain conditions can have an avalanche of heating events

Cf Lu and Hamilton 1881, Charbonneau et al 2001

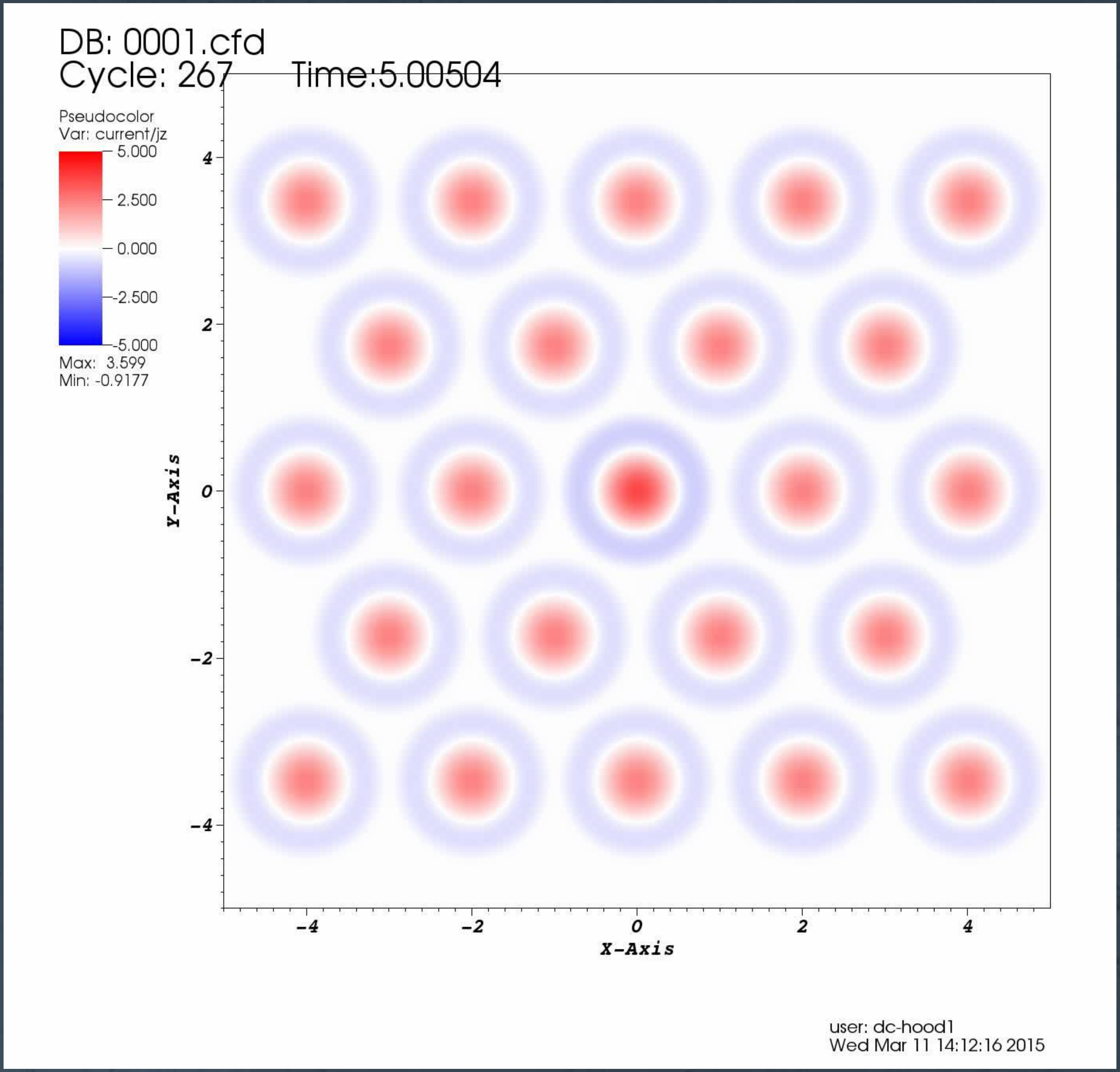
- First demonstration of avalanche - as in "cellular automaton" models - using 3D magnetohydrodynamics
- One unstable loop, 22 stable loops

Hood, B et al Ap J 16





Multiple loops - avalanche



Current in mid plane

One unstable loop,
22 stable loops

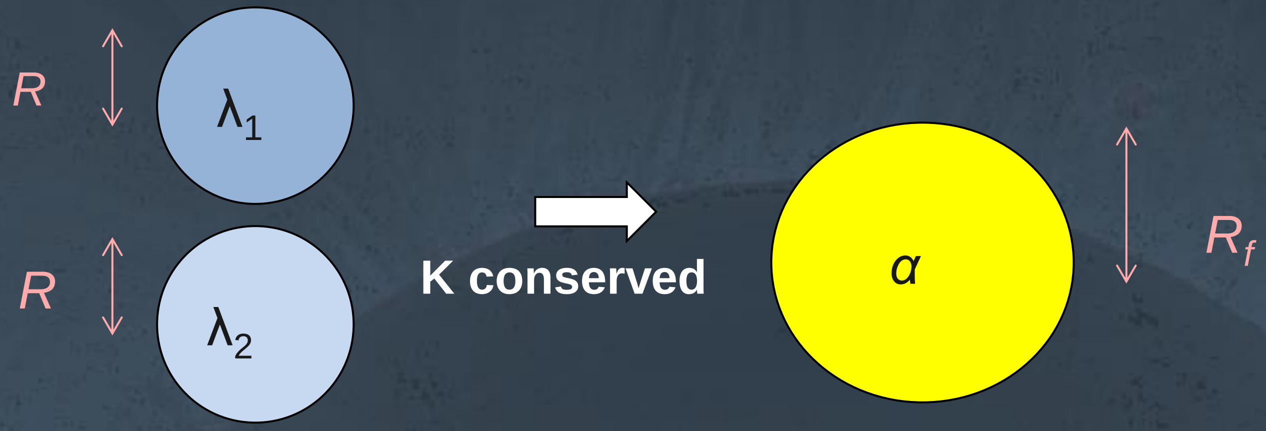
Taylor relaxation model of avalanche

- Initial force-free flux ropes (following Tam et al 2015)
- Energy *W*, magnetic helicity *K* – superposition of flux ropes
- Relax conserving helicity - individually OR merge into single cylindrical flux rope with constant-*α*

$$B_z = B_1 J_0(\alpha r), \qquad B_\theta = B_1 J_1(\alpha r)$$

$$\sum_{\text{flux ropes}} K(\lambda_i, R) = K_{\text{constant}-\alpha}(\alpha, R_f) \rightarrow \text{value of } \alpha$$

- Magnetic energy difference converted into heat

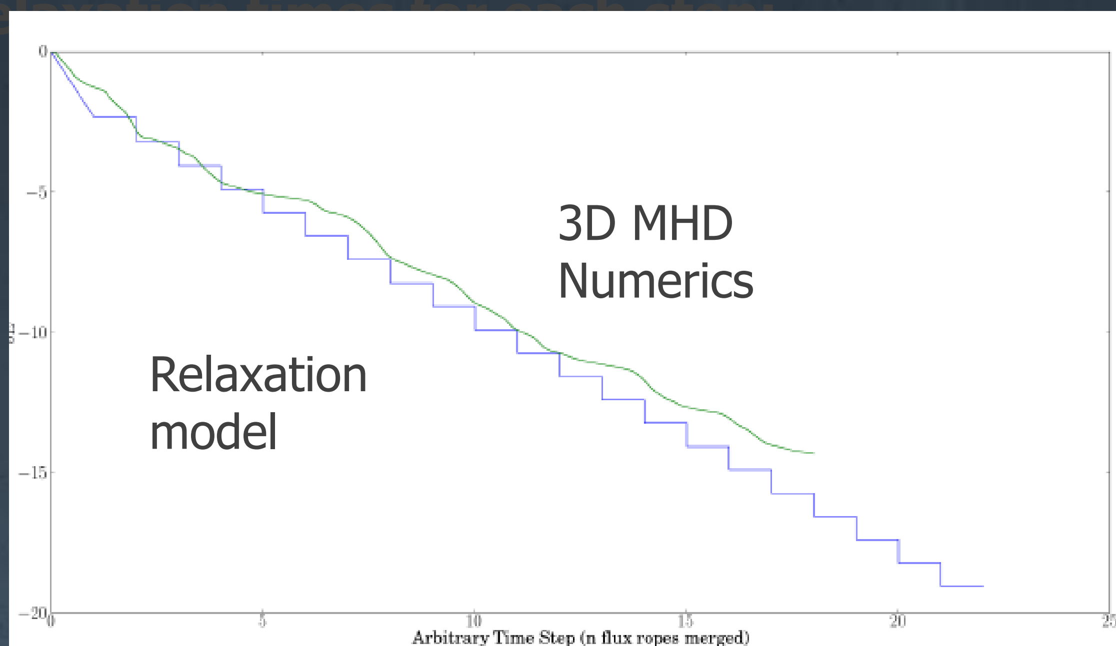


Hussein et al, 2016 A&A in press

Multi-rope relaxation model

- **Very good agreement with MHD simulations**
- **Numerical simulations are very demanding of computational resource but relaxation model is quick and easy to calculate → use relaxation model to explore wide parameter space (different loop sizes, twists, etc)**
- **Apply relaxation model to 23 loop avalanche (assuming equal re**

Energy



Time

Summary

- Twisted magnetic fields store free magnetic energy which may be released by reconnection in large-scale currents and fragmented current sheets triggered by ideal kink instability
- Modelled by coupled 3D MHD simulations and test-particles
- Predict spatial and temporal variations of thermal and non-thermal emission
- Thermal emission shows only weak twist
- Polarisation patterns of microwaves may be used to detect twisted fields in certain circumstances

- Large-scale loop structure observed by LoFAR, consistent with electron acceleration in large twisted loop

- Instability in one twisted thread may trigger energy release in many neighbouring stable threads
- First demonstration of heating avalanche using 3D MHD simulations, also relaxation model

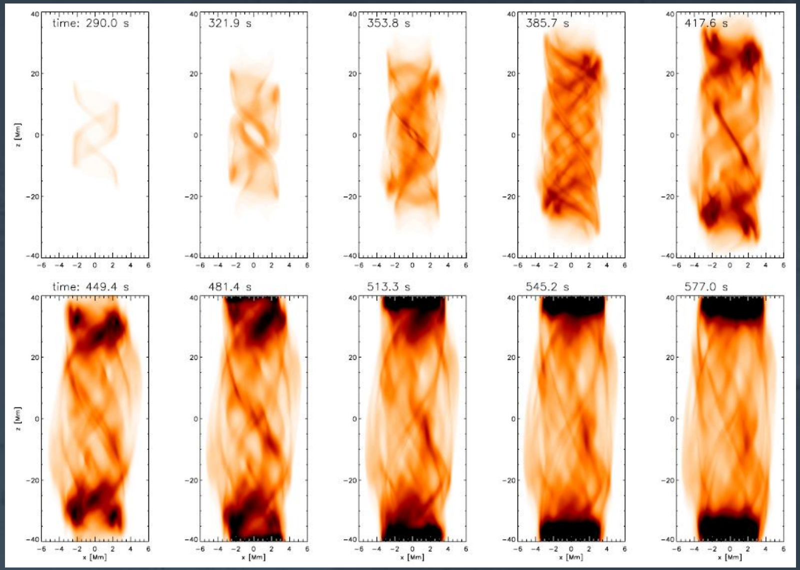
Kink instability modelling and observables

- **Field topology and thermal emission**

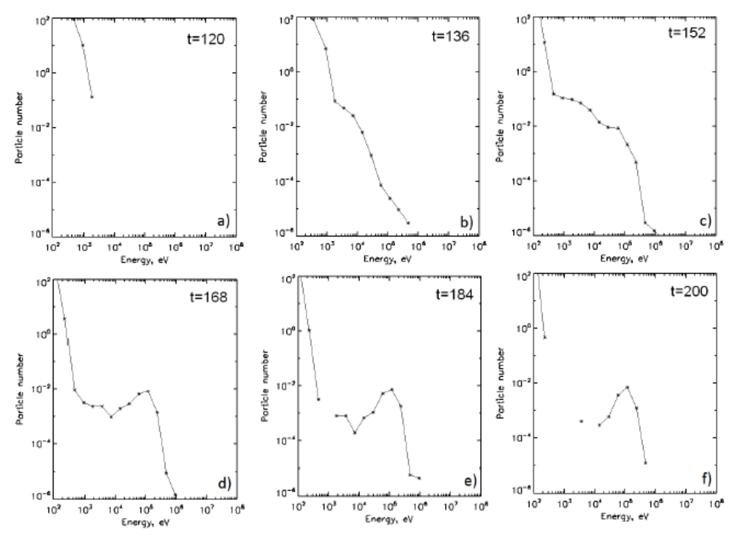
(e.g. Arber et al 1999; Botha et al 2012; Srivastava et al 2014; Pinto et al. 2015; Gordovskyy et al. 2016)

- **Non-thermal particle spectra, HXR**

(Gordovskyy & Browning 2012; Gordovskyy et al 2013, 2014; Pinto et al 2015)



from Botha et al. 2012 ApJ



from Gordovskyy et al 2013 SolPhys

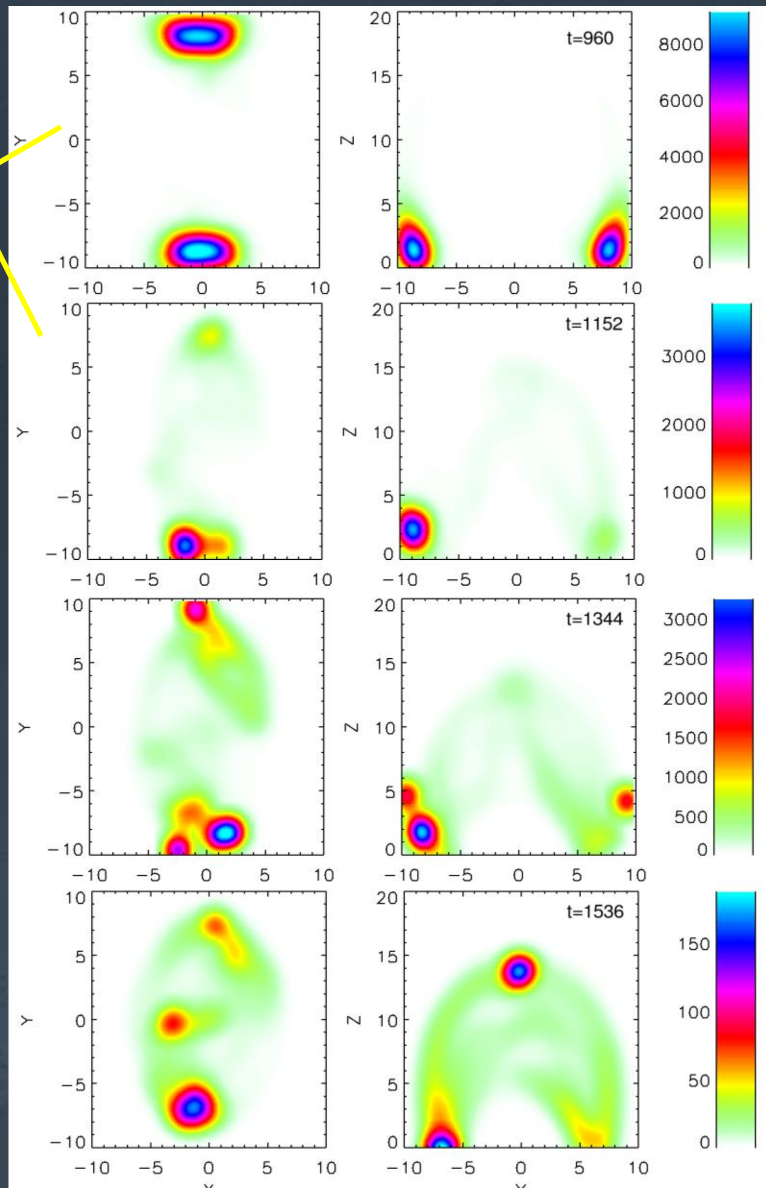
Non-thermal HXR emission

Onset of magnetic reconnection

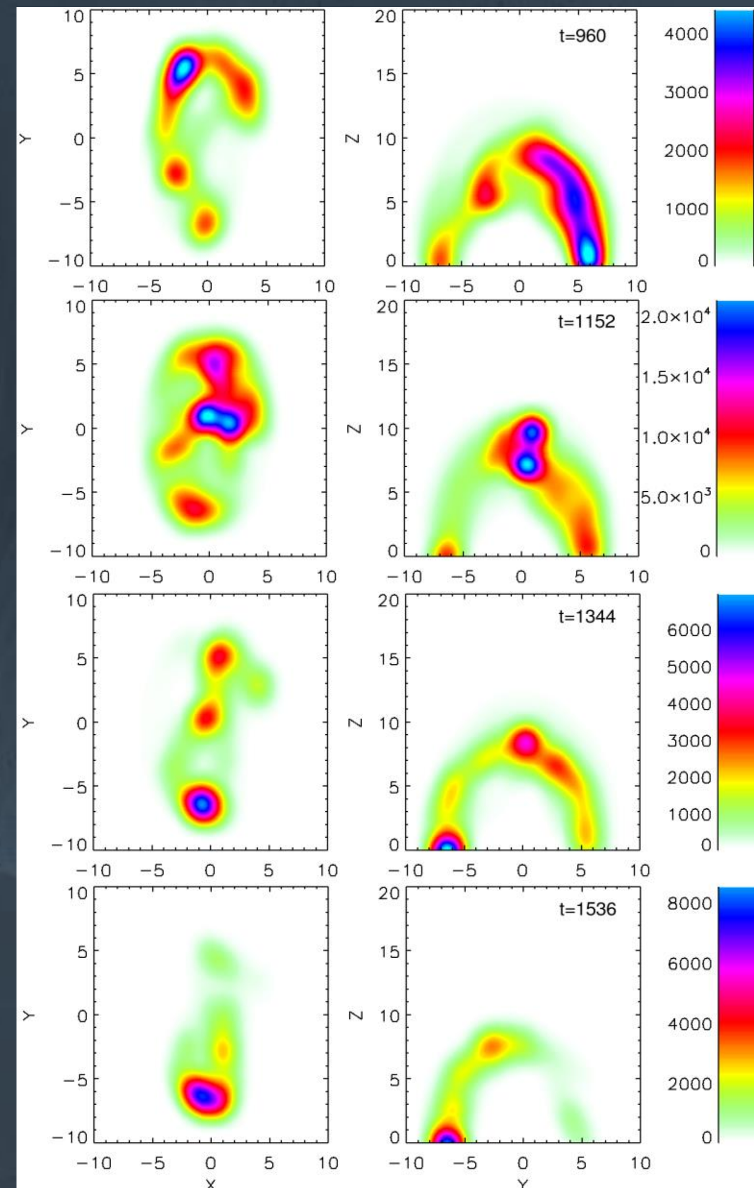
Maximum dE/dt in MHD model

Decay phase

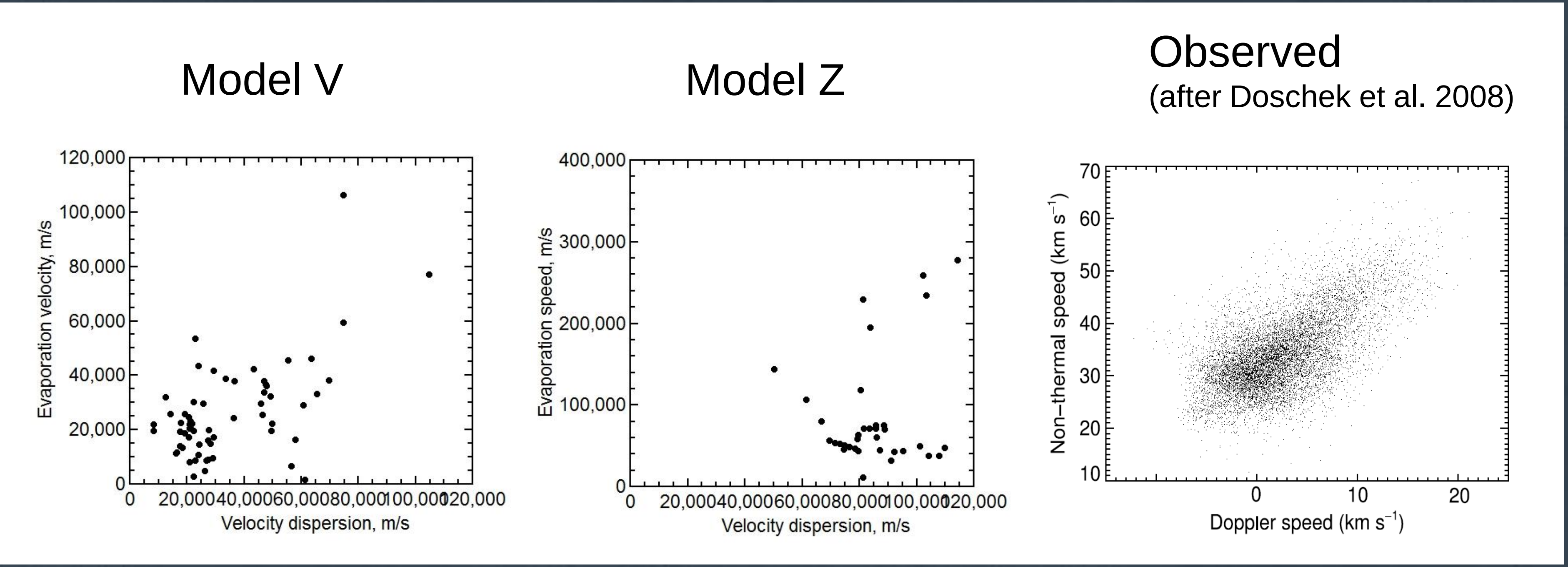
Low-density case, ε=10keV



High-density case, ε=10keV

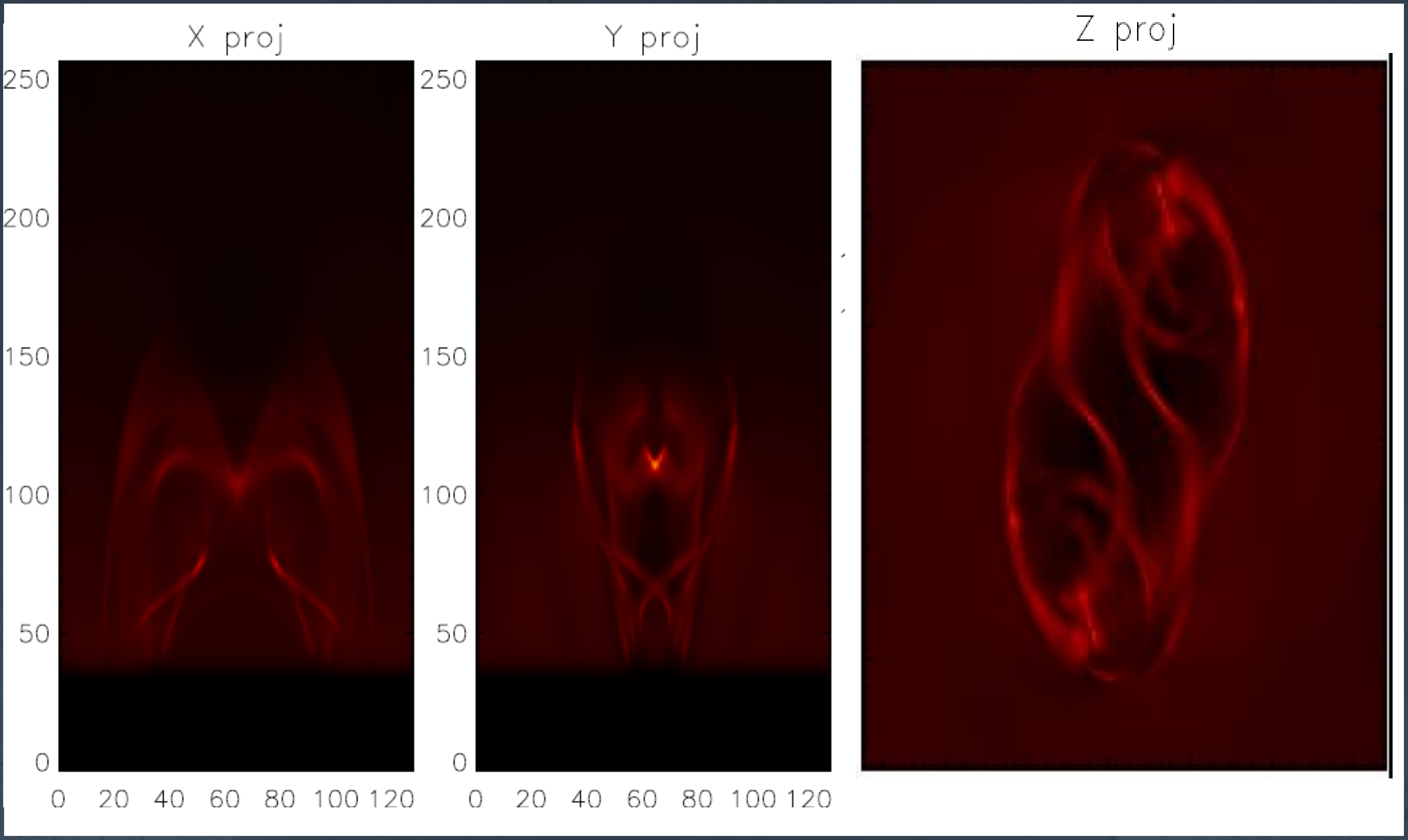


LOS velocity dispersion v. bulk LOS velocity



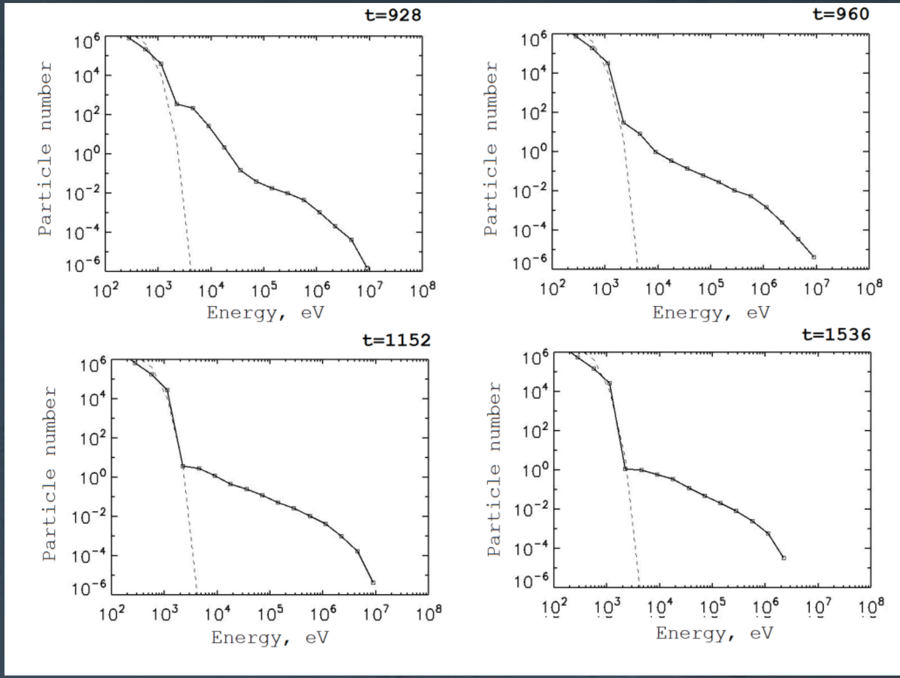
SXR thermal emission (LOS integrated)

2keV emission (near onset, large loop)

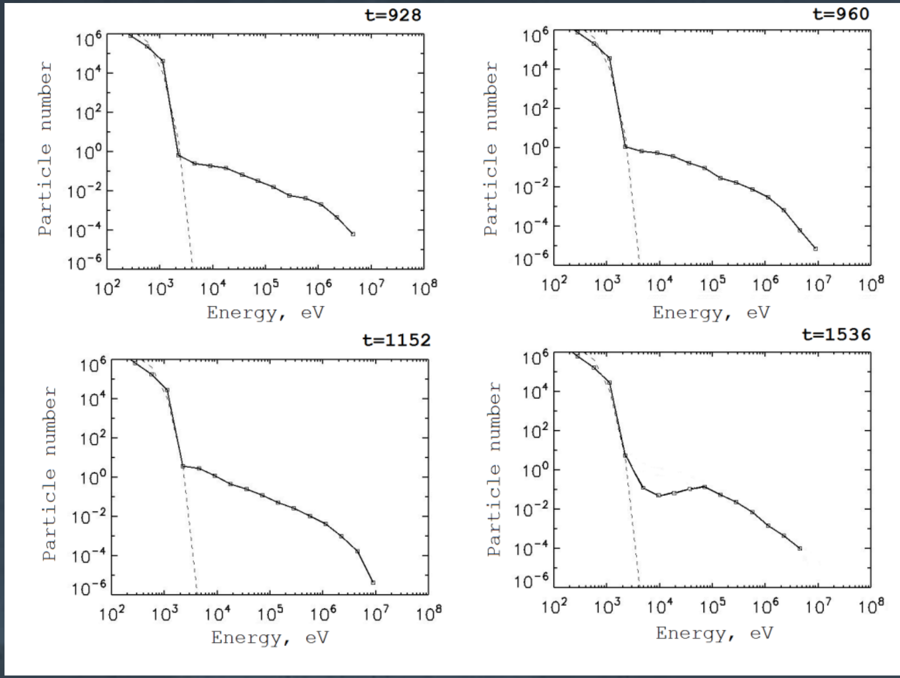


Particle kinetics: electron energy spectra

Low density loop



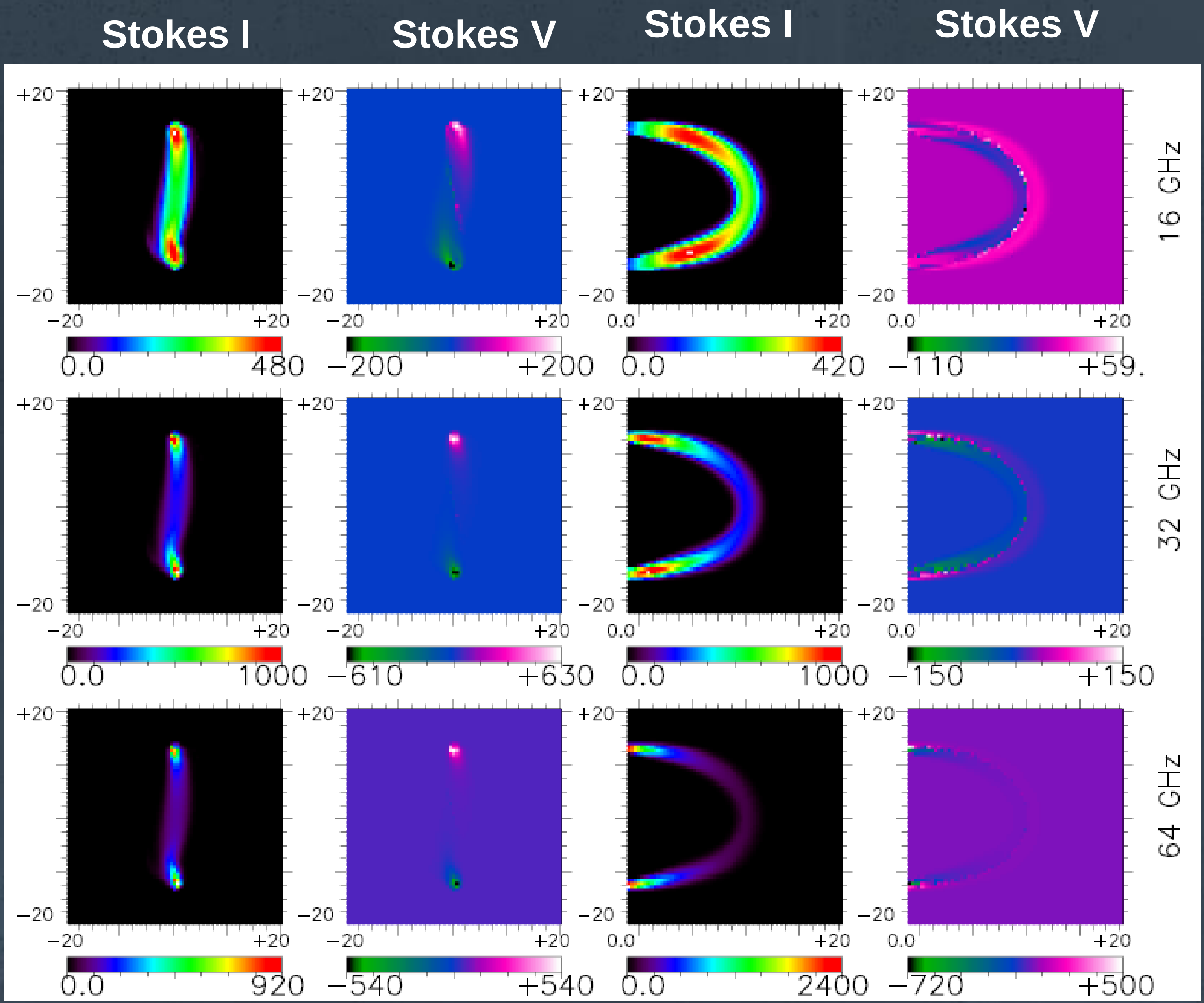
High density loop



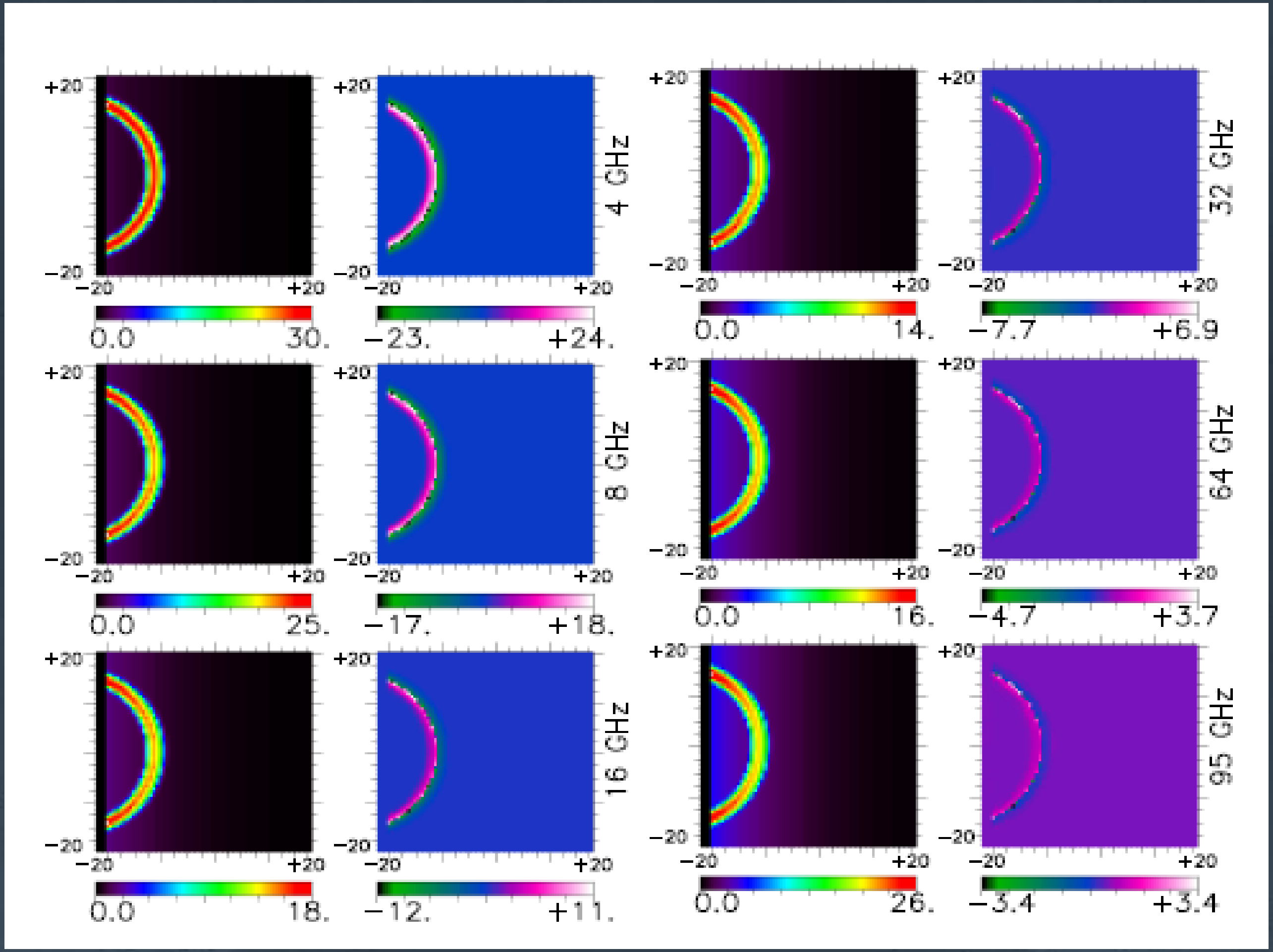
Time evolution of electron energy spectrum

MW polarisation in strongly converging loop

At start of energy release



Purely thermal MW emission



Weakly converging loop, footpoint field 360 G, time of peak temperature (about +30s after onset of reconnection)

Benchmarking relaxation model

- **To determine final radius R_f, assume magnetic pressure continuous at flux rope surface (other constraints also considered)**

$$B_z^2(R_f) + B_\theta^2(R_f) = B_z^2\ initial = B_0^2\left(1 - \frac{\lambda^2}{7}\right)$$

	Final Radius	ΔE_{MHD}	ΔE_{Taylor}
Case 1*	0.999 (each)	-3.031	-2.608
Case 2	1.412	-3.069	-3.164
Case 3*	0.999	-1.5	-1.304
Case 4	1.413	-2.3	-2.29

***Case 3 only considers one flux rope (in the Taylor model) relaxing since the first rope is stable, case 1 is twice of case 3.**

- **Good agreement between relaxation model and numerics**