Particle acceleration in solar flares: phenomenology and modelling

Mykola Gordovskyy
University of Manchester

Key constraints/requirements deduced from observations

	ELECTRONS	**IONS**
Total energy budget	**~10^{23} – 10^{24} J**	
Total particle number (v > 0.1c)	up to 10^{35}	10^{34}?
Energy spectra	power-law $\gamma \approx 2 - 7$	power-law $\gamma \approx 2 - 4$?

- **Corona v. IPS**

  - IPS electron spectra are harder, same spectral index for protons *(see Lin 2005; Krucker et al. 2007)*
  - different sources for IPS and coronal particles acceleration?

- **Spatial and temporal evolution:**

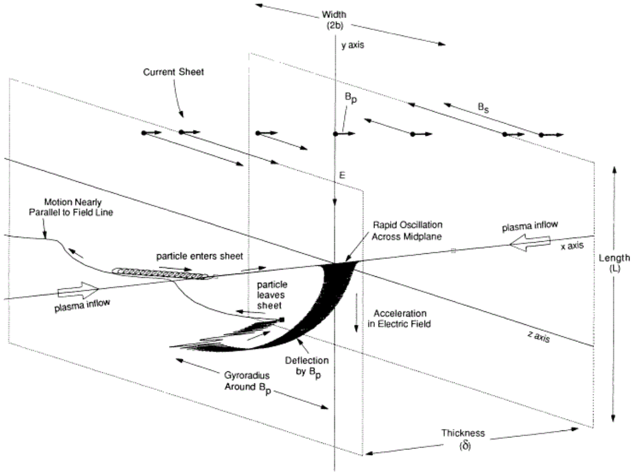
  - soft-hard-soft variation of HXR spectra *(Grigis & Benz 2004, 2005; Battaglia & Benz 2006; Liu & Fletcher 2009)*
  - pulsations in HXR intensity *(Aschwanden et al. 1990; Dabrowski & Benz 2009; Nakariakov & Melnikov 2009)*
  - γ-ray emission spatially separated, with temporal delay *(e.g. Hurford et al. 2006)*
  - height-energy dependence for HXR emission *(e.g. Battaglia & Kontar 2011)*
  - expansion of HXR sources? *(see Kontar et al. 2011)*

Acceleration by DC electric field

- There are many studies dedicated to this mechanism in 2D and 3D geometries *(e.g. Speicer 1965; Martens & Young 1991; Zhu & Parks 1993; Litvinenko & Somov 1993, 1995; Heerikhuisen et al. 2001; Browning & Vekstein 2001; Zharkova & Gordovskyy 2004; Petkaki & MacKinnon 2004; Wood & Neukirch 2005; Dalla & Browning 2008; Gordovskyy et al. 2011; Stanier et al. 2012)*

- Acceleration occurs due to (parallel) electric field in a "solid" regular current with high electric resistivity ($E_{||} = \eta j$)

- Energies are determined either by guiding & transversal field components or by the length of the current layer *(see e.g. Litvinenko 1996)*



From *Martens & Young 1991 ApJS*

- Large-scale E → Plasma oscillations → Radio-emission ? correlated with HXR

- Waves/ ? turbulence → Anomalous resistivity → High $E_{||}$ magnitude

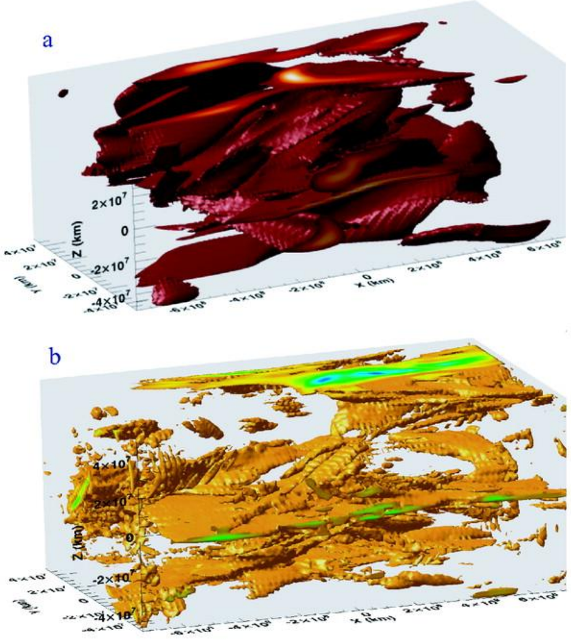
- Large-scale stationary CS → Low resistivity → Negli ? gible $E_{||}$

Stochastic acceleration

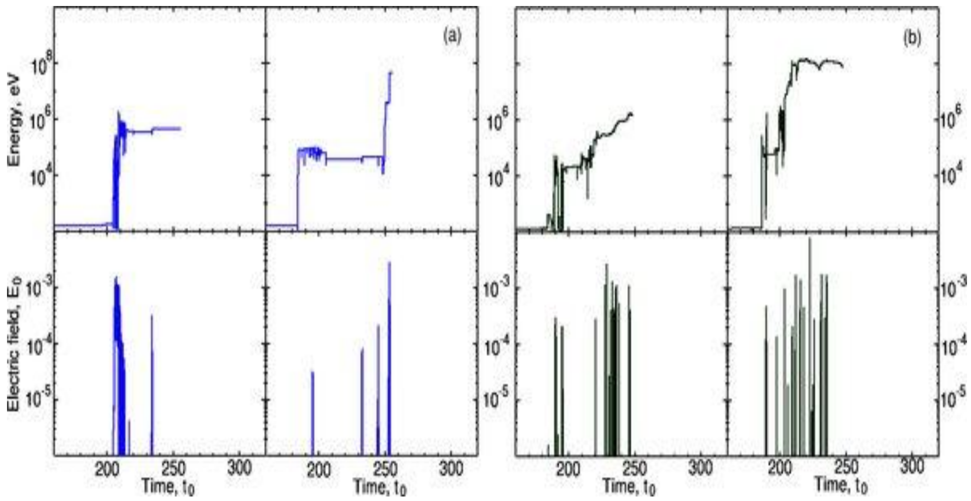
- Resonant and non-resonant acceleration by low-frequency MHD and kinetic waves *(e.g. Miller et al. 1996; Pryadko & Petrosian 1997;Vainio 2000; Bykov & Fleishman 2009; Bian et al. 2010; Fleishman & Toptygin 2013)*

- (See *Petrosian 2012* for review; *Bian et al. 2012* – formal classification; *Kontar et al. 2017* – role turbulence in flares)

- Acceleration by large-scale “filamentary” electric field appearing due to fragmentation of some global current structure *(Turkmani et al. 2005, 2006; Cargill et al. 2006; Gordovskyy & Browning 2011; Gordovskyy et al. 2012)*

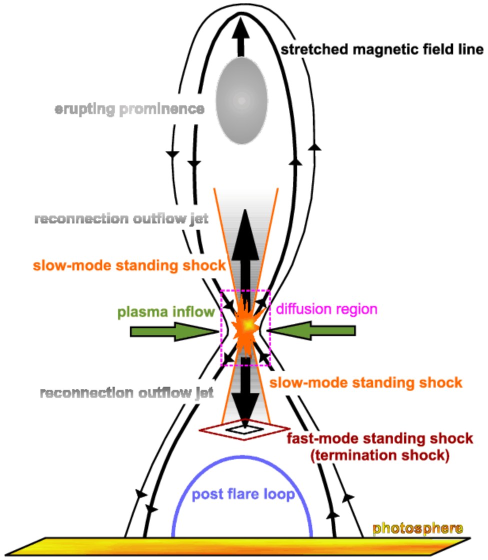


From *Turkmani et al. 2005 A&A*

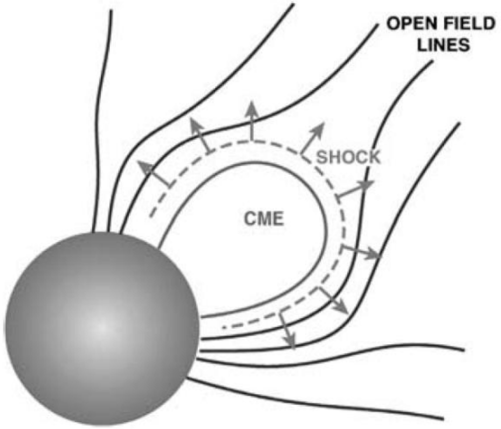


From *Gordovskyy & Browning 2012 ApJ*

Acceleration on shock fronts



From Mann et al. 2009 A&A



From Giacalone & Kota 2006 SSRw

- Quick particle acceleration (up to GeV/s) with high ion acceleration efficiency

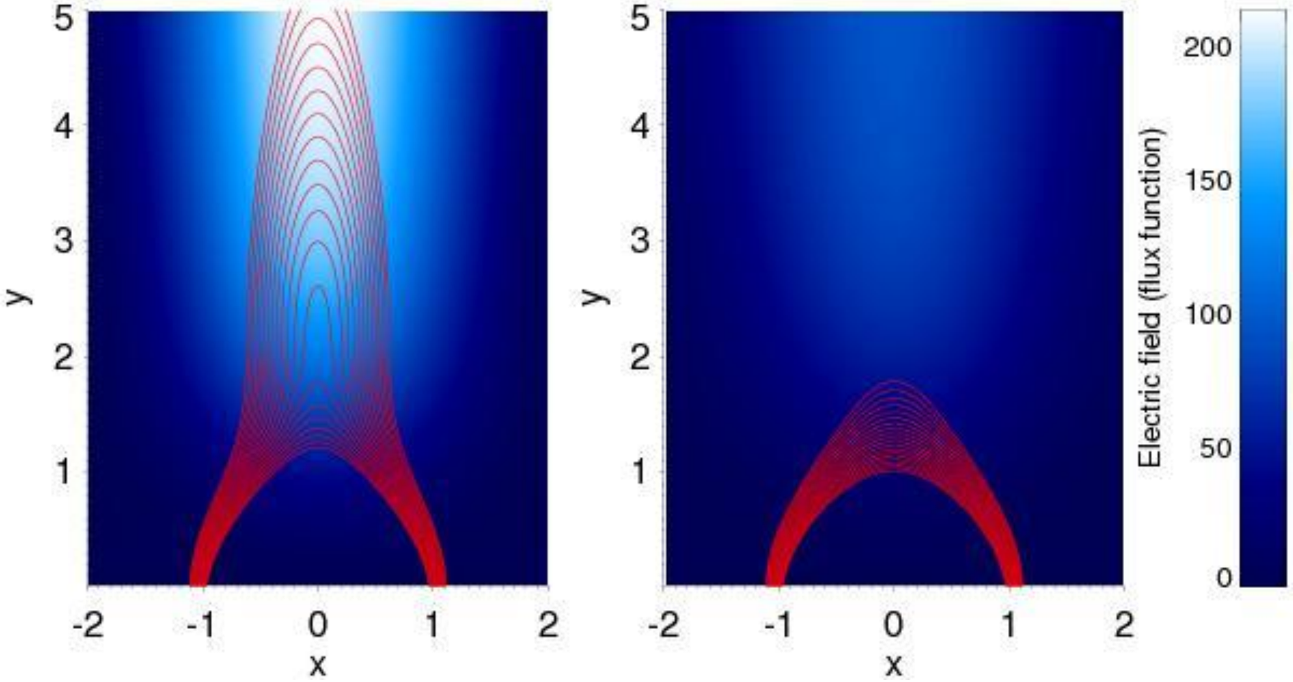
- Shocks are believed to be the main mechanism for accelerating particles ejected into IPS *(see e.g. Aschwanden 2012; Reames 2012)*

- Termination shocks can accelerate particles in the downstream region in solar flares *(Aurass & Mann 2004; Mann et al. 2009; Warmuth et al. 2009; Fan & Giacalone 2012)*

- Stationary shocks in a reconnection region can produce “bulk plasma acceleration” (outflow jets) *(see e.g. Strachan & Priest 1994; Voitenko 1998)*

Acceleration in collapsing magnetic traps

- see *Bogachev & Somov 2001; Karlicky & Kosugi 2004; Grady & Neukirch 2009; Grady et al. 2012*

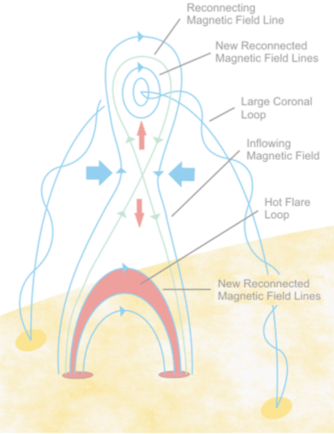


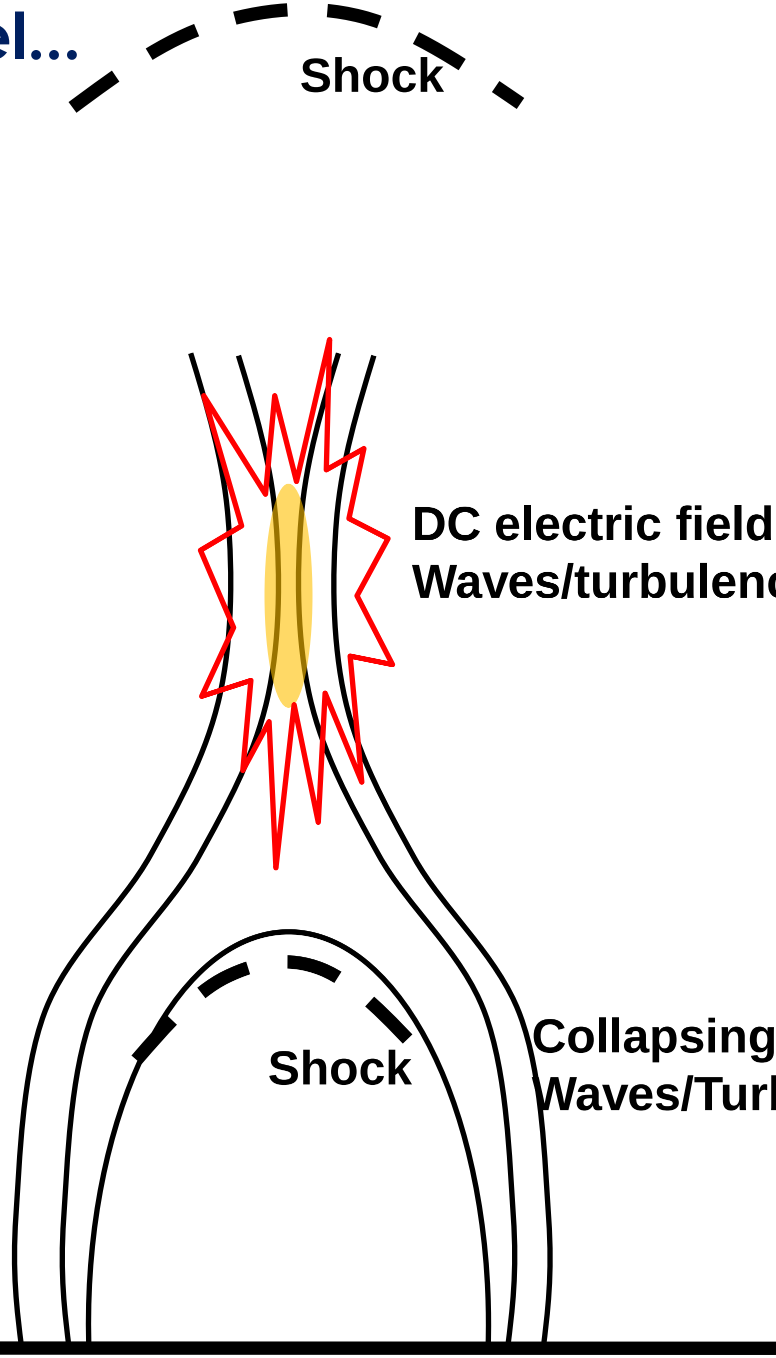
From *Giuliani et al. 2005 ApJ*

- Very modest energies of accelerated particles: ~10-50 kT, i.e. ~1-5 keV for the corona

- Number of accelerated particles can be very high, comparable to the total particle number

“Standard” model...



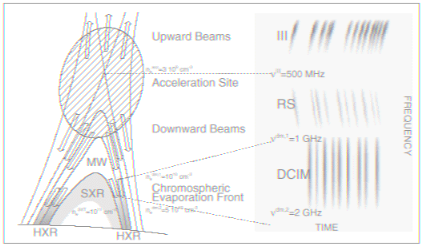


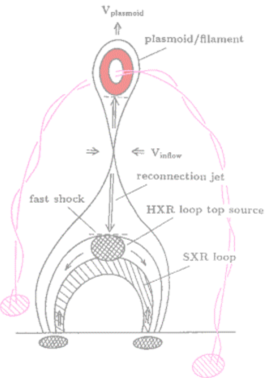
Shock

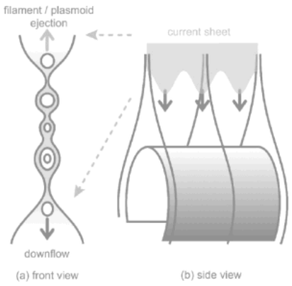
DC electric field
Waves/turbulence

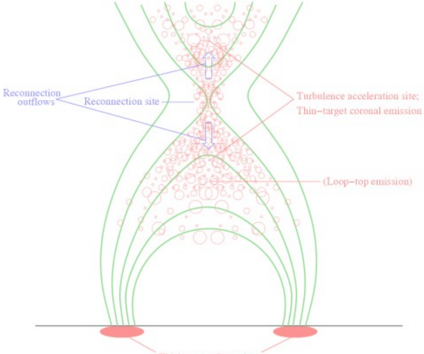
Collapsing magnetic trap
Waves/Turbulence

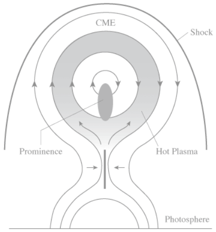
Shock

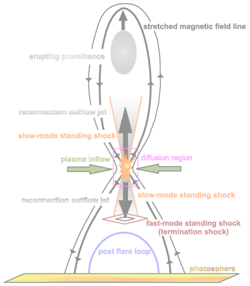












… and its problems

- "Electron number problem" in the "standard model":

  - Thermal/non-thermal energy partition is not fully clear *(e.g. Fleishman et al. 2015; Warmuth & Mann 2016)*

  - up to 10^{36} electrons need to be energized *(see e.g. Brown & Emslie 1988; Brown et al. 2009)* – equivalent ~10-100 Mm^3

  - electron flux up to $10^{20}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ or energy flux up to 10^{11} erg $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ – strong return current electric field (unless neutralized by ions) would stop electrons before they reach *photosphere (e.g. Knight & Sturrock 1977; Diakonov & Somov 1988; Zharkova & Gordovskyy 2005)*

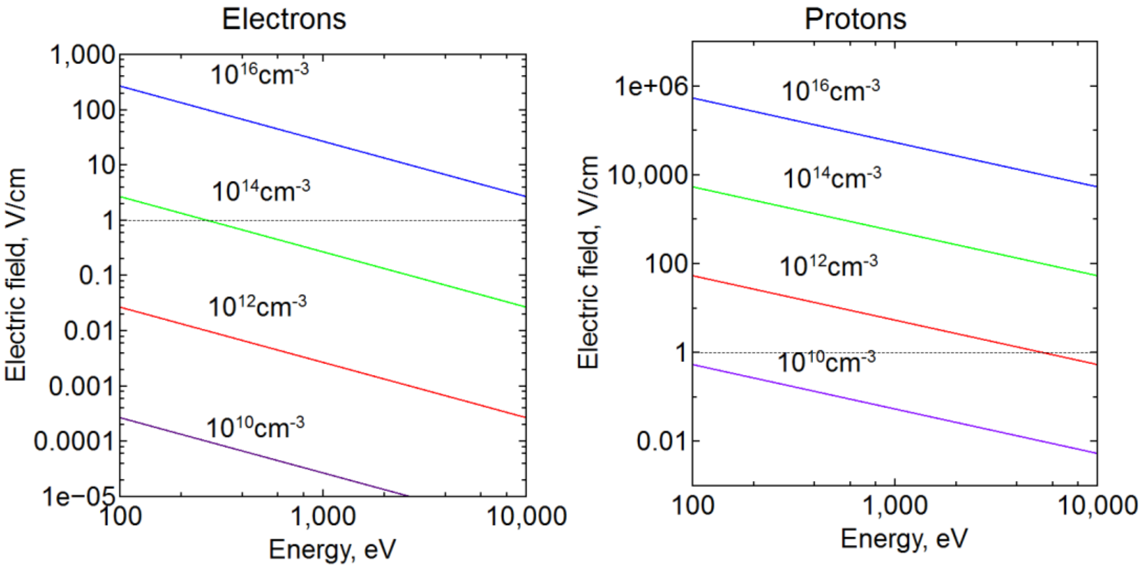
- Modification to standard model: acceleration along with transport

Re-acceleration & Distributed acceleration

- Particle acceleration distributed within flaring region (rather than localized in a small volume somewhere in the corona) can help to reduce transport losses and produce number of electrons comparable with observations

- Re-acceleration in dense transition region & chromosphere can reduce the number of required electrons *(Brown et al. 2009)* and reduce transport energy losses if electrons are accelerated locally

- "Weak" acceleration mechanisms may be important



- Stochastic acceleration by waves propagating from the reconnection site

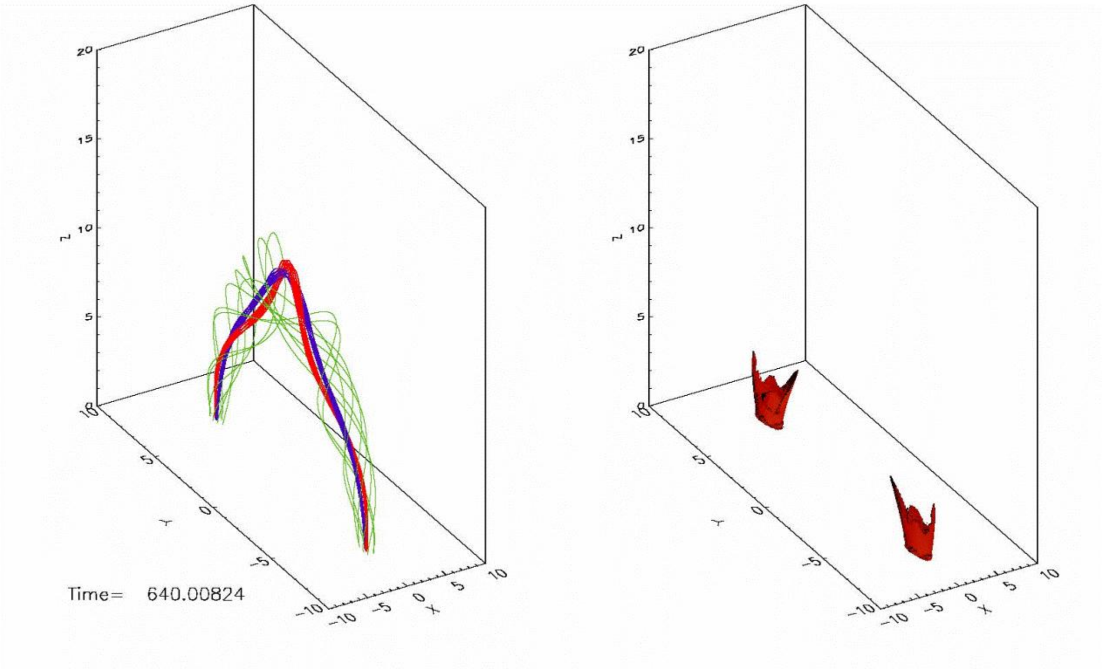
- Large-scale fragmented electric field due to magnetic field stress or twist

Twisted and braided coronal magnetic fields

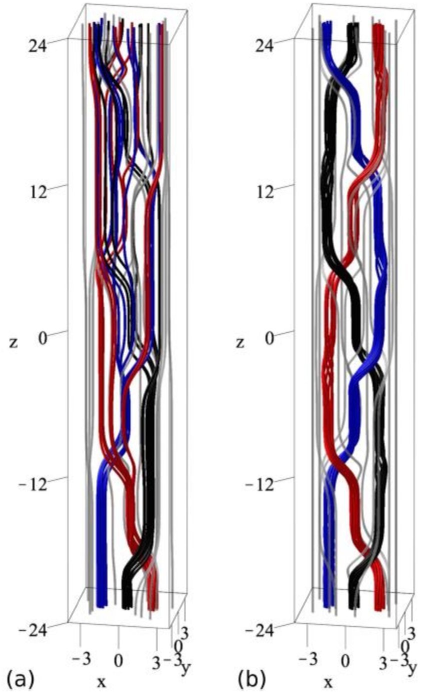
- Both twisted and braided magnetic fields contain excess magnetic energy that can be released

- Strongly twisted coronal loops can be kink unstable; kink instability can trigger fast magnetic reconnection and energy release *(e.g. Batty & Heyvaerts 1996; Browning & Van der Linden 2003; Browning et al 2008; Hood et al 2009; Gordovskyy & Browning 2011, 2012; Bareford & Hood 2015)*

- Braided field is likely to be more stable, but it should be more ubiquitous *(Yeates et al. 2010; Wilmoth-Smith et al. 2010; Pontin et al. 2011, 2017)*



Gordovskyy et al. 2011, 2012



From *Pontin et al. 2017*

Twisted and braided coronal magnetic fields

- Twisted loops are often observed in solar flares either as ropes in major flares or as main elements in small flares *(see e.g. Raouafi et al. 2009; Shrivastava et al. 2010)*
- Magnetic twist can be detected using MW polarisation *(Sharykin & Kuznetsov 2016; Gordovskyy et al. 2017)*
- Braided magnetic fields are not easily detectable

From *Shrivastava et al 2010*

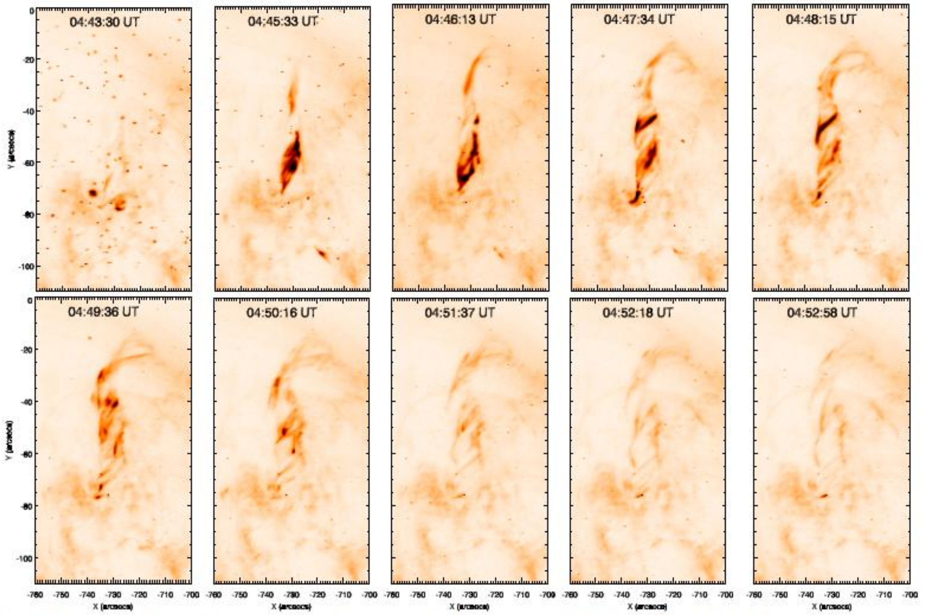
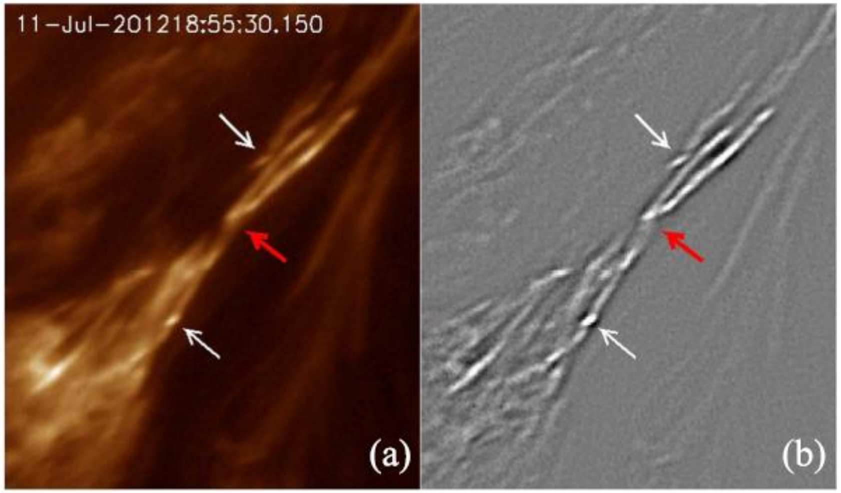
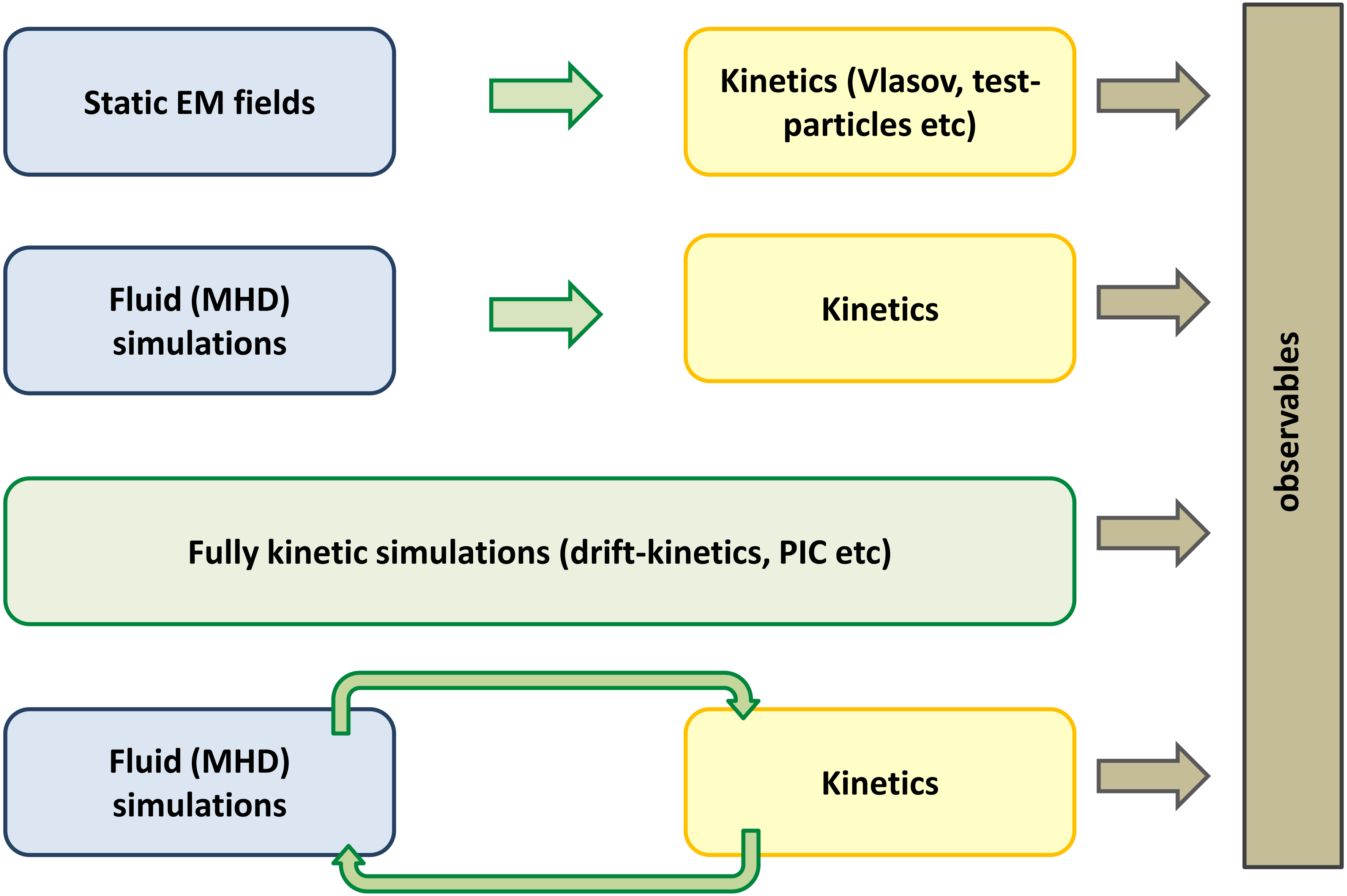


Figure 5. Time sequence of TRACE 171 Å Fe ix images of flaring loop in the AR 10960 during 04:43 UT–04:52 UT on 2007 June 4. The images are in reverse color and show the clear helical twist of the loop during the B5.0 flare. Note the double structure of the coronal loop top between 04:47 UT and 04:51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

From *Pontin et al. 2017 ApJ*



Theoretical modelling of particle acceleration in solar flares



Static EM fields

Kinetics (Vlasov, test-particles etc)

Fluid (MHD) simulations

Kinetics

Fully kinetic simulations (drift-kinetics, PIC etc)

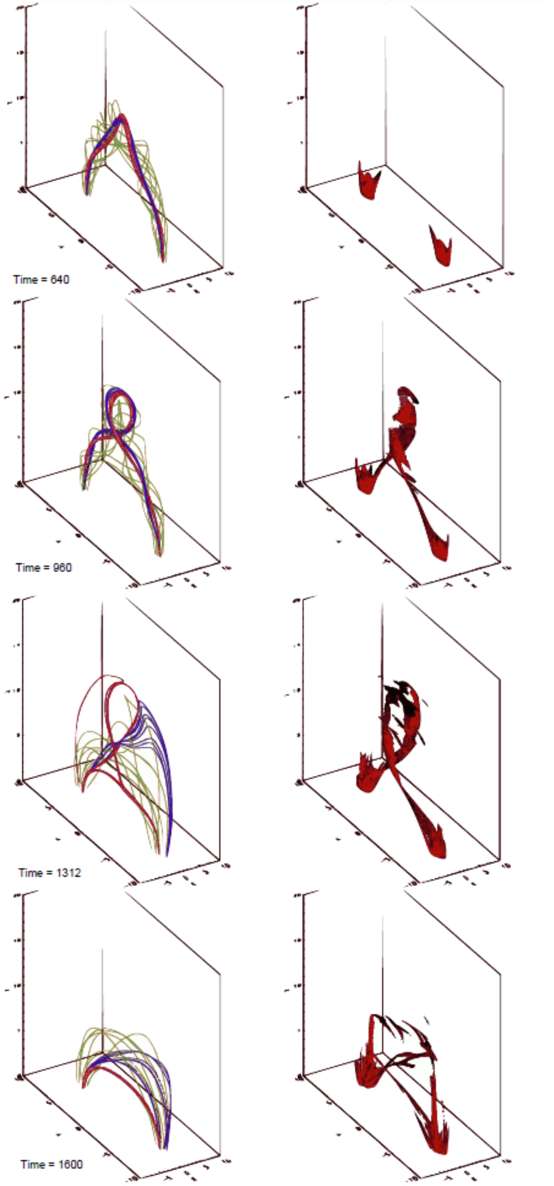
Fluid (MHD) simulations

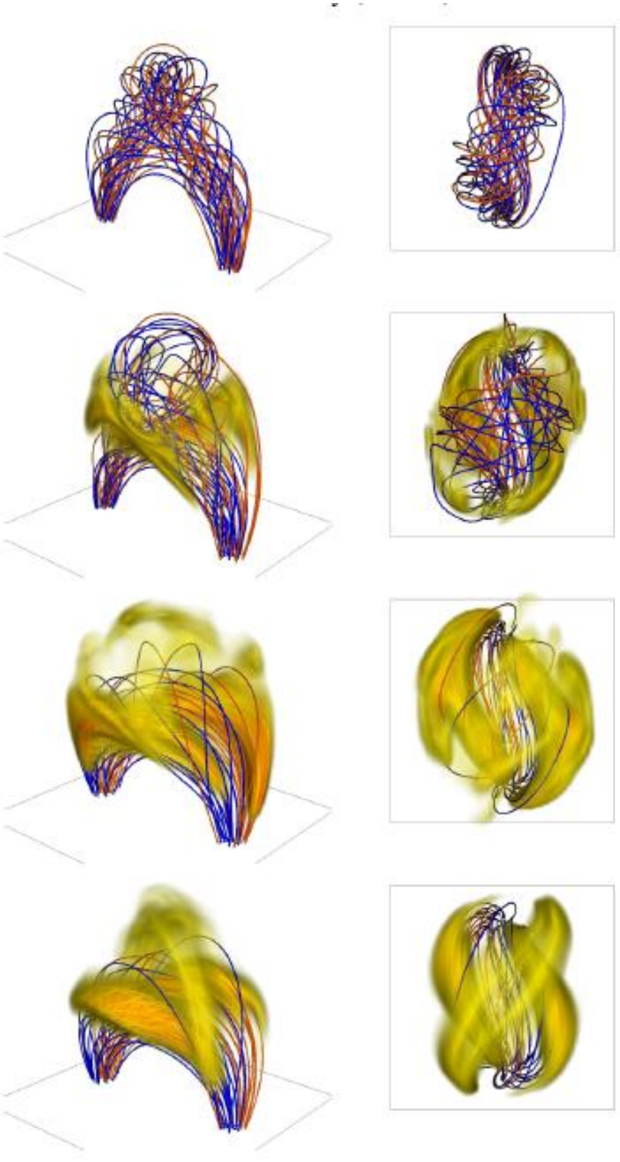
Kinetics

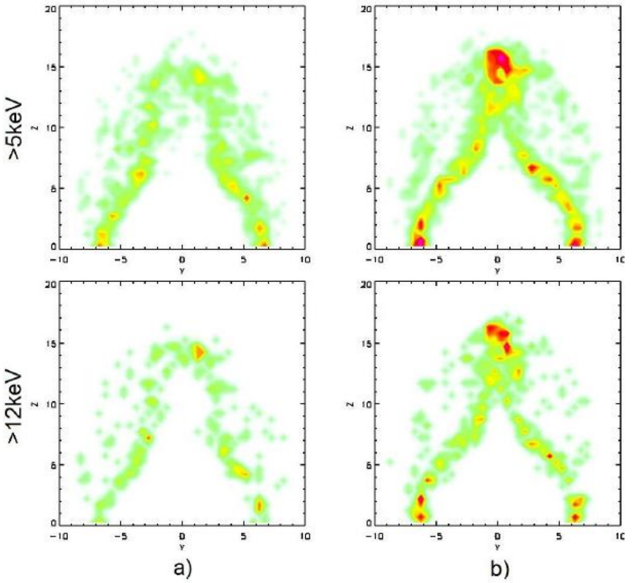
observables

Combined MHD-test-particle modelling

Gordovskyy et al. 2010, 2011, 2014; Pinto et al. 2016; Riperda et al. 2017; Threfall et al. 2017

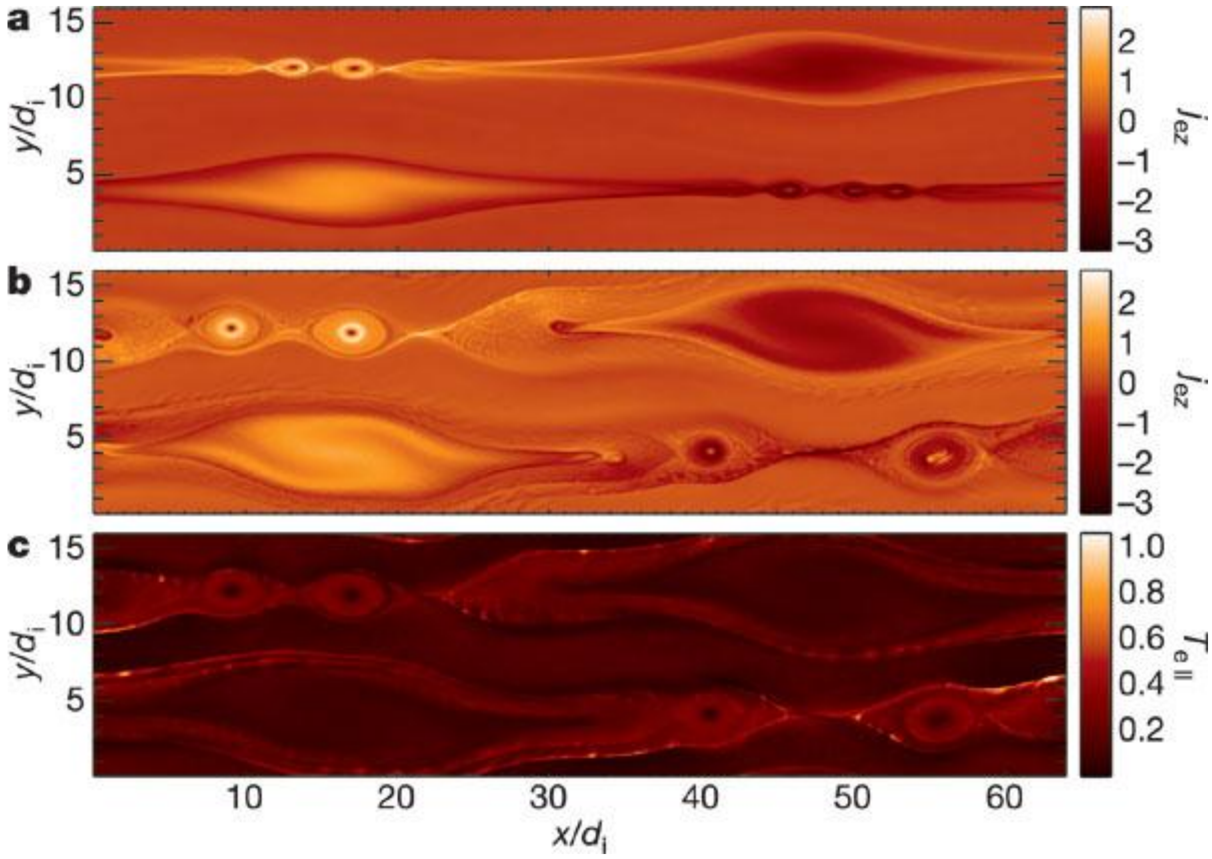






Fully kinetic modelling

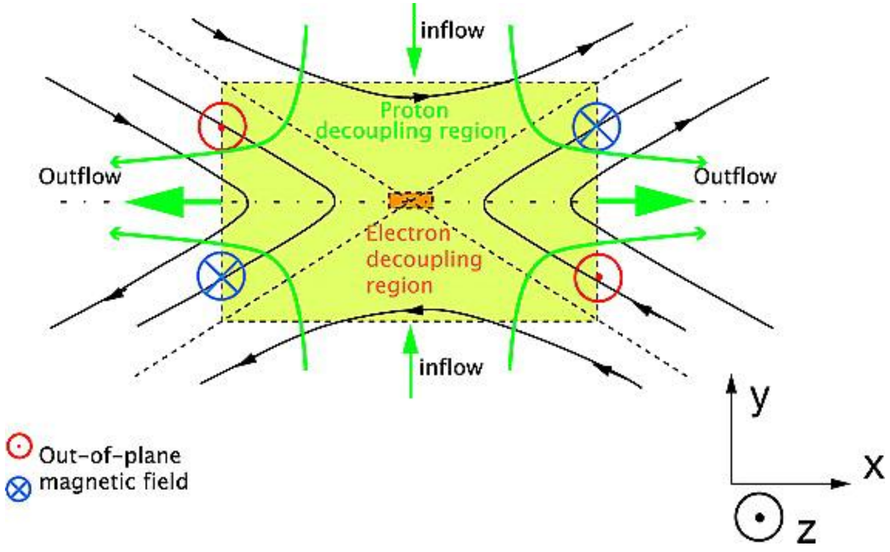
Drake et al. 2006 (and other studies by Drake, Swisdak & co.); Siversky & Zharkova 2008

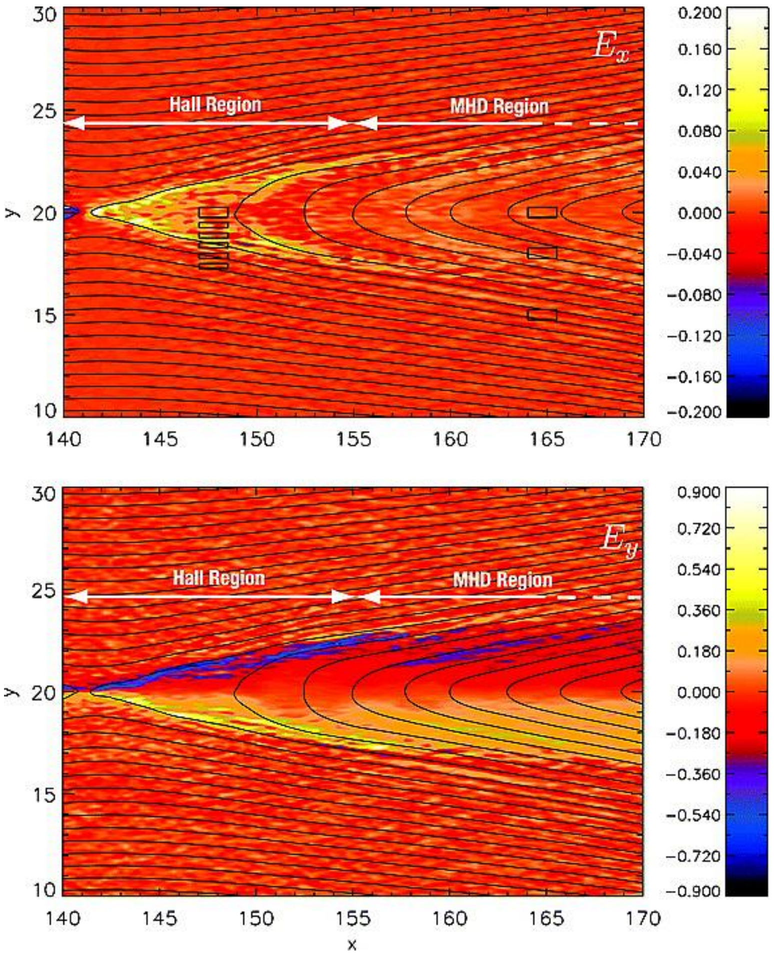


From *Drake et al. 2006*

Hybrid modelling

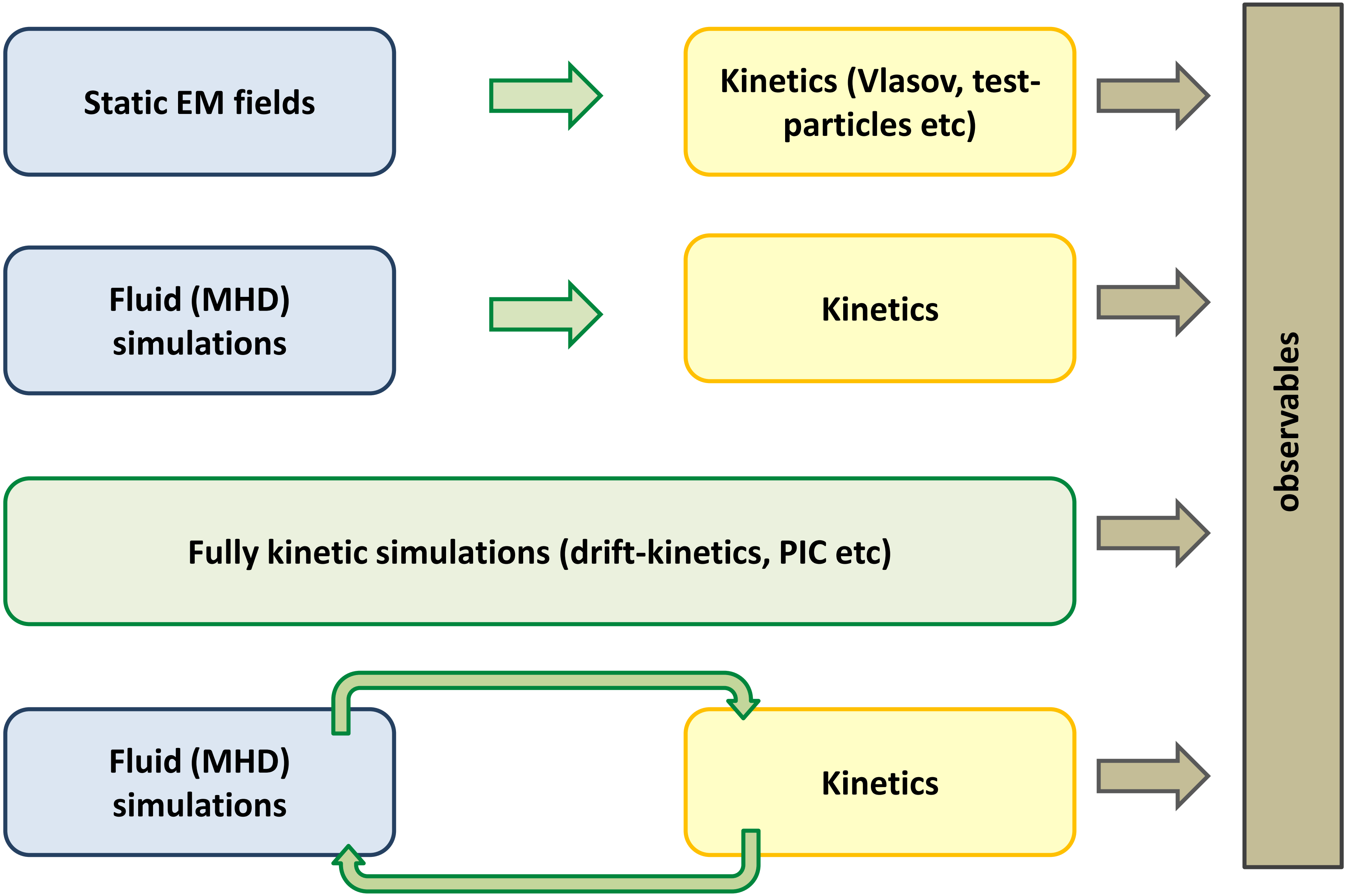
Aunai et al. 2011; Giacalone et al. 2012; Gordovskyy & Browning 2016





From *Aunai et al. 2011*

Theoretical modelling of particle acceleration in solar flares



Static EM fields

Kinetics (Vlasov, test-particles etc)

Fluid (MHD) simulations

Kinetics

Fully kinetic simulations (drift-kinetics, PIC etc)

Fluid (MHD) simulations

Kinetics

observables