Magnetic Reconnection Drivers of Solar Eruptions

J. T. Dahlin

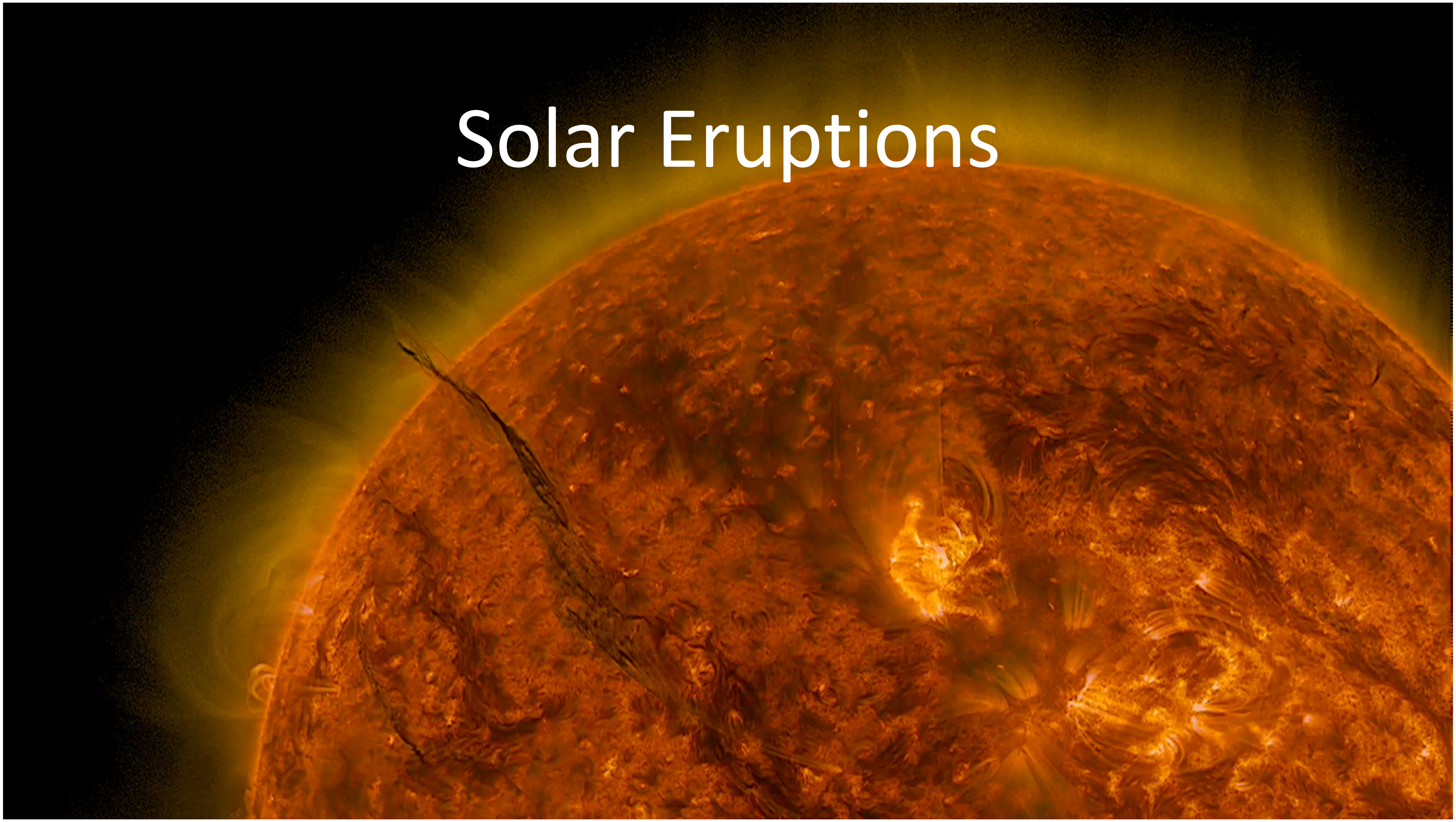
S. K. Antiochos, C. R. DeVore

J. F. Drake, M. Swisdak

Feb 14, 2019

PPPL Heliophysics Seminar

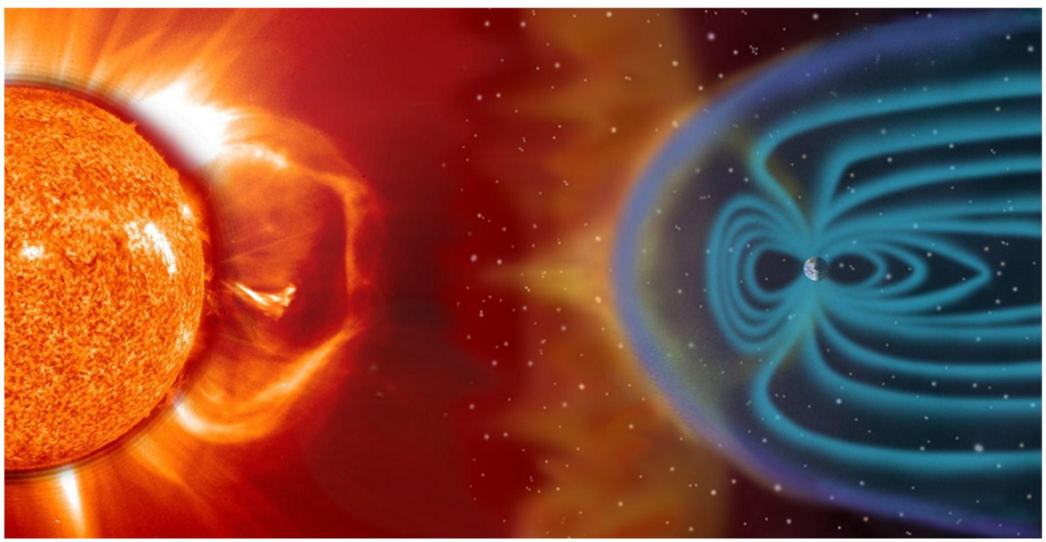
Solar Eruptions

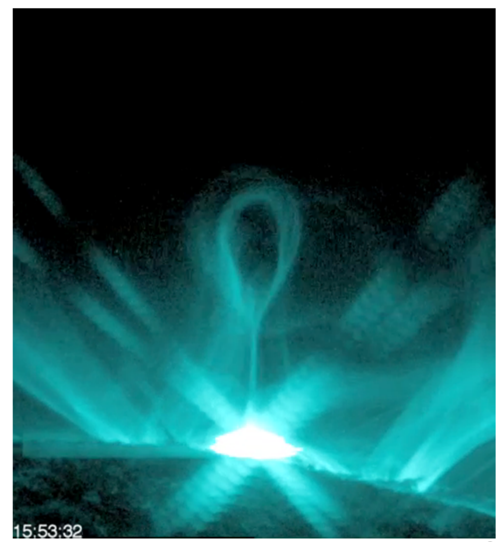


- Coronal mass ejections (CMEs), eruptive flares, coronal jets
- Explosive release of plasma and magnetic fields into the solar wind
- Spectacular example of self-organization and explosive energy release

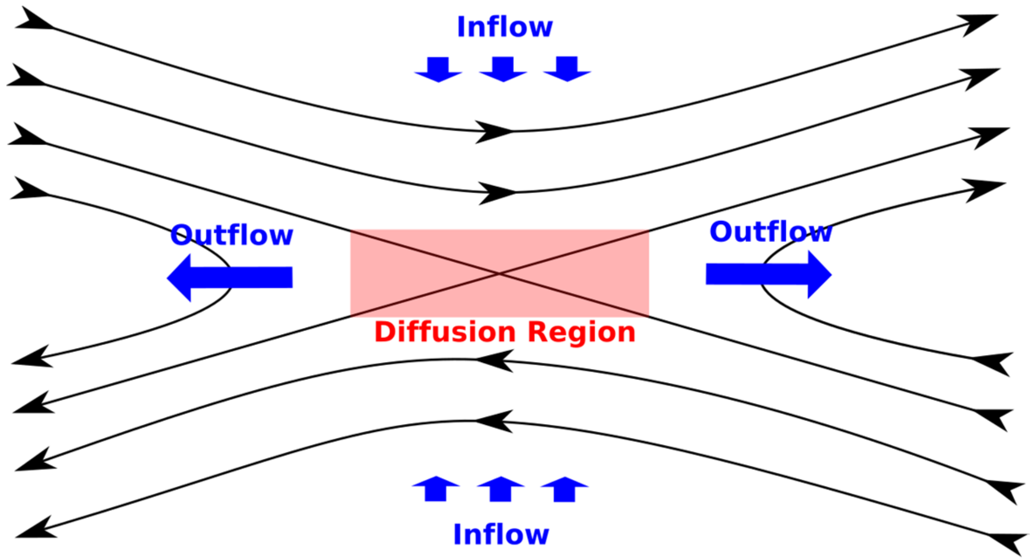
CMEs/Eruptive Flares

- CMEs: ejection of plasma & magnetic fields into the solar wind
  - Generate shocks, drive geomagnetic storms
- Flares: explosive solar reconnection that heats coronal plasma, accelerates particles
  - Cause sudden ionospheric disturbances (communication and navigation impact)
- Most energetic phenomena in the solar system (largest events $>10^{32}$ erg)
  - Only plausible energy source is the magnetic field
- **What powers a solar eruption?**





Magnetic Reconnection



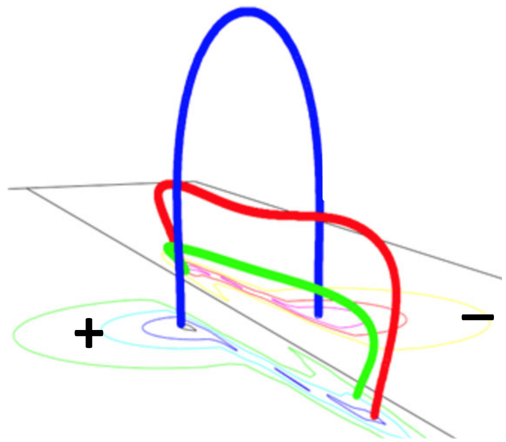
- Essentials
  - Magnetic field lines are **‘reconnected’** in localized dissipation region
  - **Magnetic tension** expels reconnected field, driving energy conversion
- Products
  - **Magnetic energy release -** Bulk flows, heating, energetic particles
  - **Topology change –** Plasma mixing, merging of magnetic structures

Outline

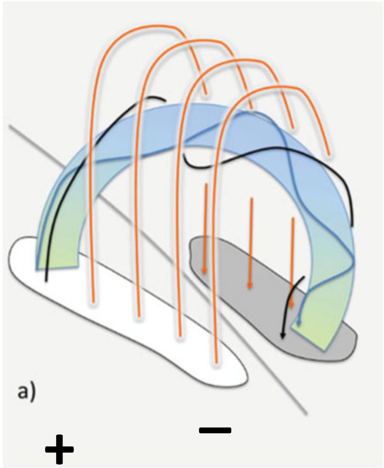
- What drives magnetic energy storage & explosive release in the solar corona?
  - Magnetic reconnection is involved, but does it trigger an eruption or is it driven by an ideal process?
  - To determine the trigger, we perform an end-to-end MHD simulation that self-consistently generates the pre-eruptive field
- Three reconnection roles during the eruption
  - Small-scale reconnection mediates energy buildup via inverse helicity cascade
  - External "breakout" reconnection disrupts force balance
  - Internal "flare" reconnection explosively ejects built-up shear
- Application: **"Why are flares such efficient particle accelerators?"**
  - Kinetic simulations demonstrate the role of the guide field in particle acceleration – moderate (~1) is most efficient
  - Of the three types of reconnection, only the flare occurs with a moderate guide field

Filament Channels

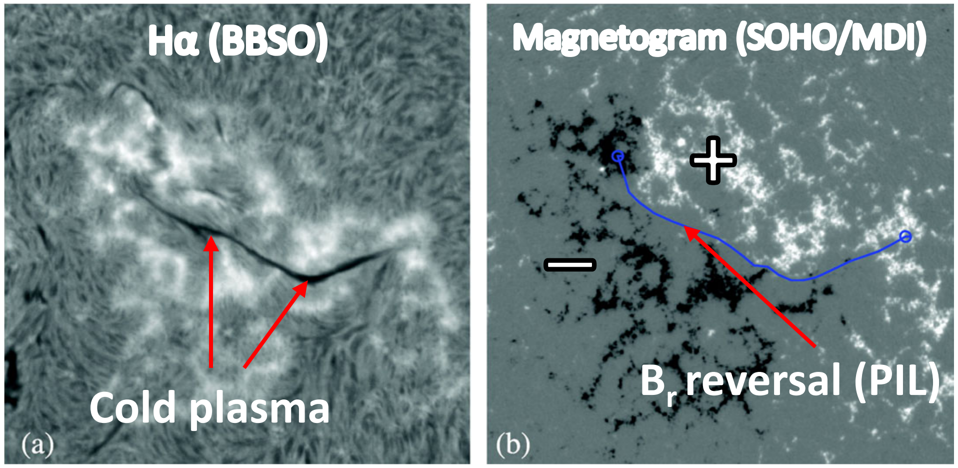
- All CMEs/eruptive flares (and possibly jets) originate from coronal filament channels
- Magnetic field configuration above polarity inversion lines (PILs) where B_r reverses
  - Often associated with coronal filaments (cold plasma suspended in the hot corona)
- Two generic configurations:
  - Sheared arcade
  - Coronal flux rope
- Force balance: tension of overlying field restrains magnetic pressure of shear field



Sheared Arcade (Antiochos 1994)



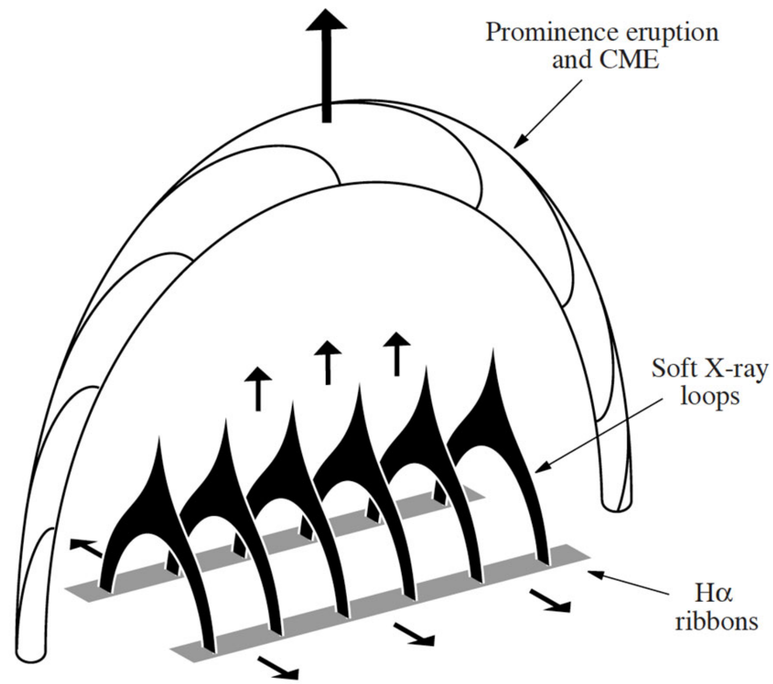
Flux Rope (Klein 2018)



Bobra et al., 2008

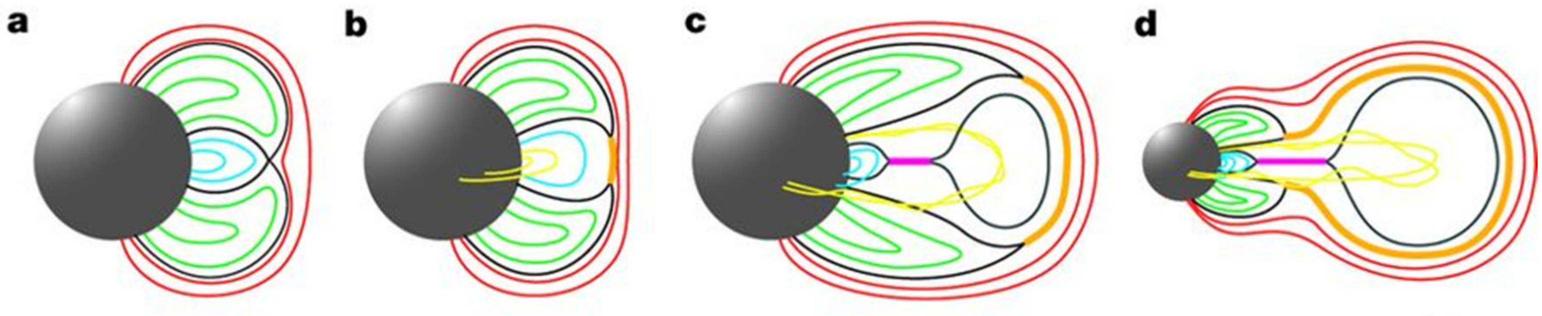
Generic Scenario for Solar Eruptions

1. Energy builds up in form of a filament channel
2. Trigger destabilizes force balance
3. Eruption ejects shear
4. Flare reconnection closes field back down



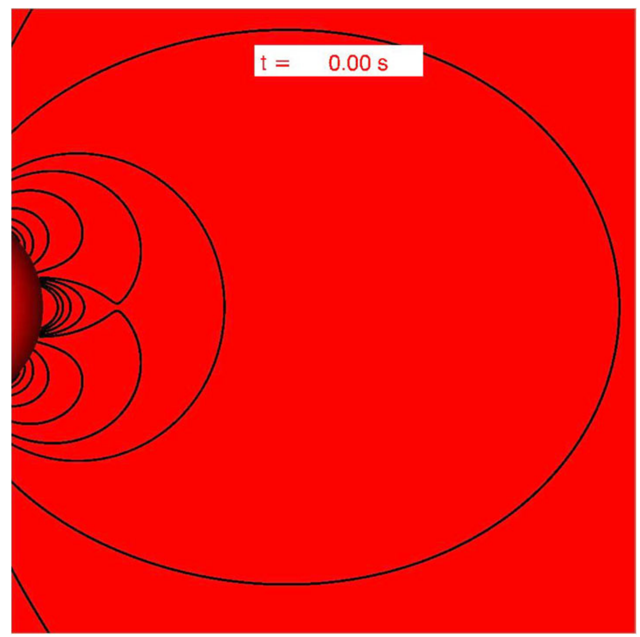
Priest & Forbes, 2001

Breakout Model (Antiochos et al., 1999)



Wyper et al., 2017

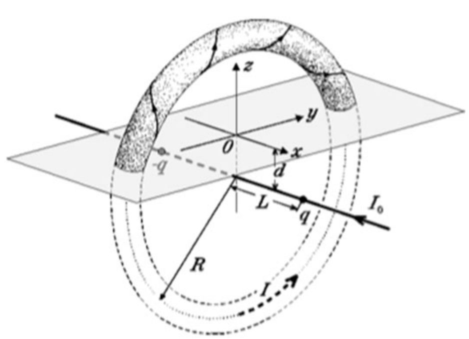
1. Energy builds up in the form of a **filament channel** consisting of a force balance: pressure of **sheared field** and tension of **overlying field**
2. **"Breakout" reconnection** above the filament channel removes overlying flux and destabilizes force balance
3. **Flare reconnection** ejects shear, generates a flux rope & closes down **overlying field**

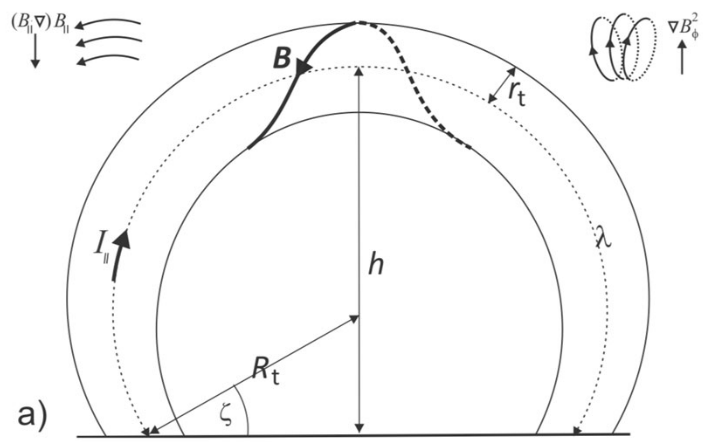


Guidoni et al., 2016

Ideal Instability

- Energy builds up in the form of a highly-twisted coronal flux rope restrained by overlying field
- Configuration exceeds ideal instability threshold, driving a runaway force imbalance between flux rope forces (e.g. hoop stress) and overlying field
  - E.g. torus, helical kink instability, “loss of equilibrium”
- Flare reconnection driven by ideal dynamics closes field back down





Green et al., 2018

Modeling the Pre-Eruptive Field

- What triggers an eruption: reconnection or an ideal dynamics?
  - Both involved, but a matter of cause and effect
  - Important for predicting an eruption
  - Mechanism depends on the pre-eruptive field structure (sheared arcade or flux rope)?
- Challenge to accurately observe/model filament channel field
  - Few direct observations, coronal field must be extrapolated from photosphere/chromosphere
  - Extrapolation is especially challenging for small-scale structures with strong currents
- Can we *self-consistently* generate the pre-eruptive field?
  - **How do filament channels form?**

Notable Filament Channel Properties

- Common field morphology in both active regions & quiet sun
  - Suggests a **ubiquitous** energy source/formation process
- Chirality of helicity structures is ordered by hemisphere
  - E.g. left-handed corkscrew (northern) vs. right-handed (southern)
  - Up to 90% of erupting filaments follow the hemispheric patterns (Ouyang 2017*)*

Magnetic Helicity

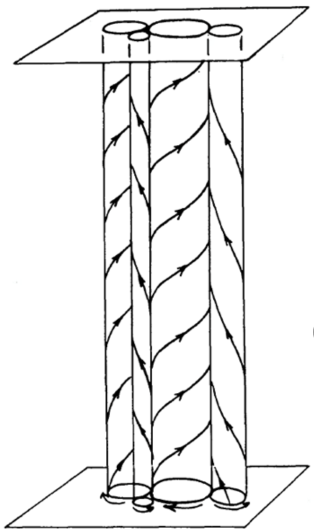
- Measure of the twist and linkage of magnetic field
- Two key properties
  - **Conserved under reconnection** (Taylor 1974)
  - Undergoes **inverse cascade** from small to large spatial scales mediated by reconnection

$$H = \int_V \mathbf{A} \cdot \mathbf{B} \, dV$$

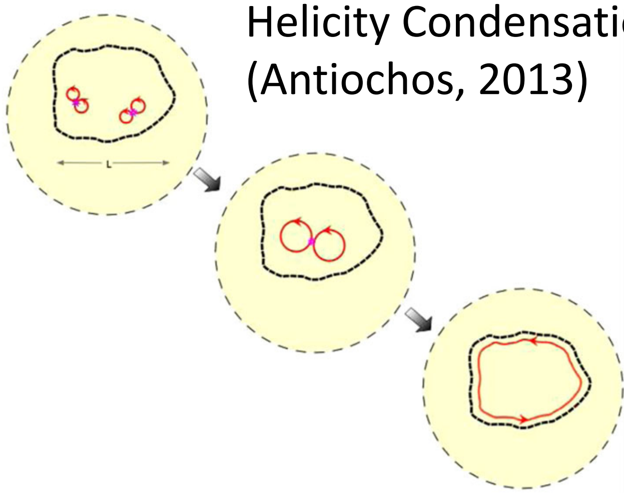
$$H_R = \int_V (\mathbf{A} + \mathbf{A_p}) \cdot (\mathbf{B} - \mathbf{B_P}) \, dV$$

Wiegelmann & Sakurai 2012

Helicity Condensation Model

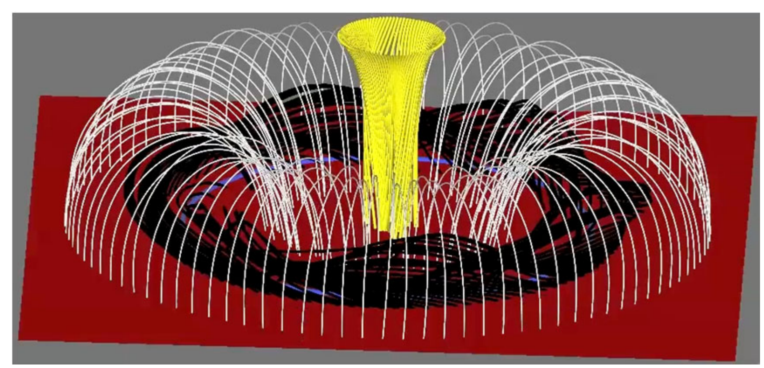


Nanoflare Reconnection (Parker, 1983)



Helicity Condensation (Antiochos, 2013)

- Turbulent convective flows inject small-scale twist (helicity) into corona
- Reconnection via "nanoflares" reconfigures magnetic field, transferring structure to larger scales
- Helicity 'condenses' at magnetic boundaries (PILs) to form filament channels

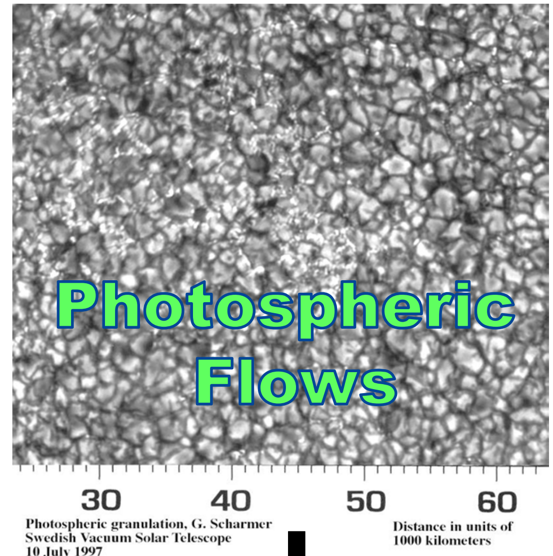


MHD Simulations (Knizhnik et al., 2017)

Two Ingredients for Filament Channel Formation

1. Inject free energy into corona via small-scale photospheric flows
2. Concentrate free energy along PIL in form of shear

Photospheric Granulation (SST)



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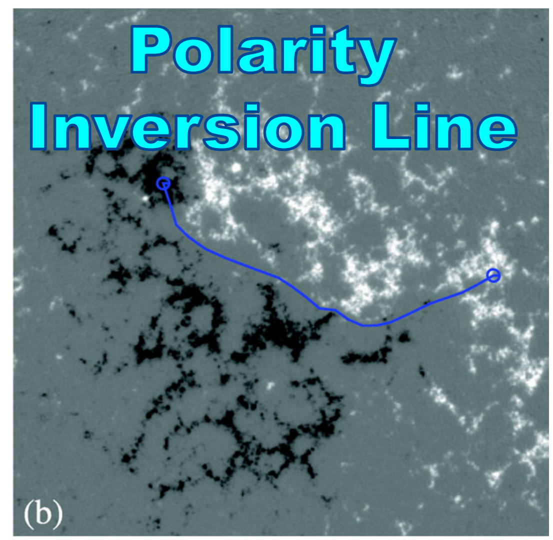


SOHO/MDI Magnetogram

ARMS—Adaptively Refined Magnetohydrodynamics Solver

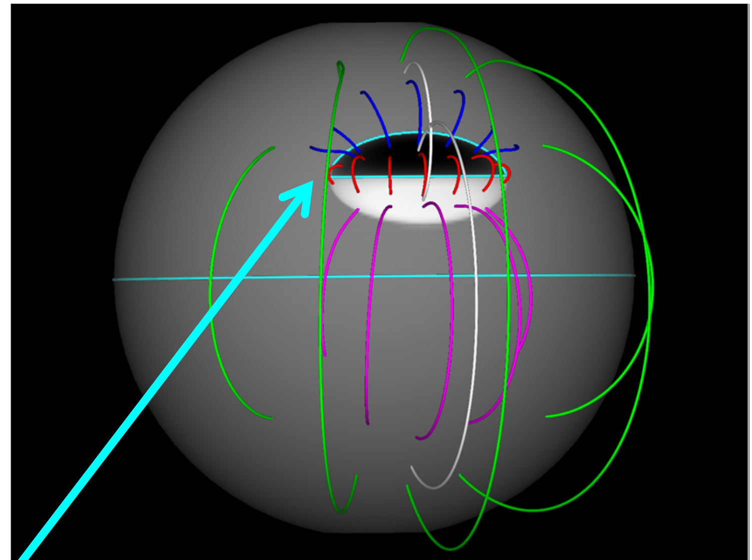
- Solves 3D ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = \frac{1}{4\pi} (\nabla \times \vec{B}) \times \vec{B} - \rho \vec{g} - \nabla P$$

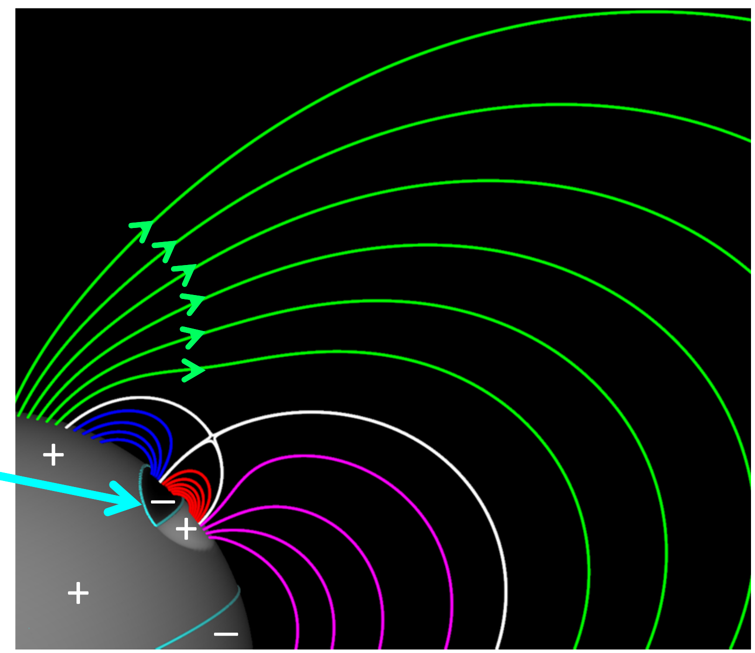
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$$

- Adaptive mesh, static atmosphere



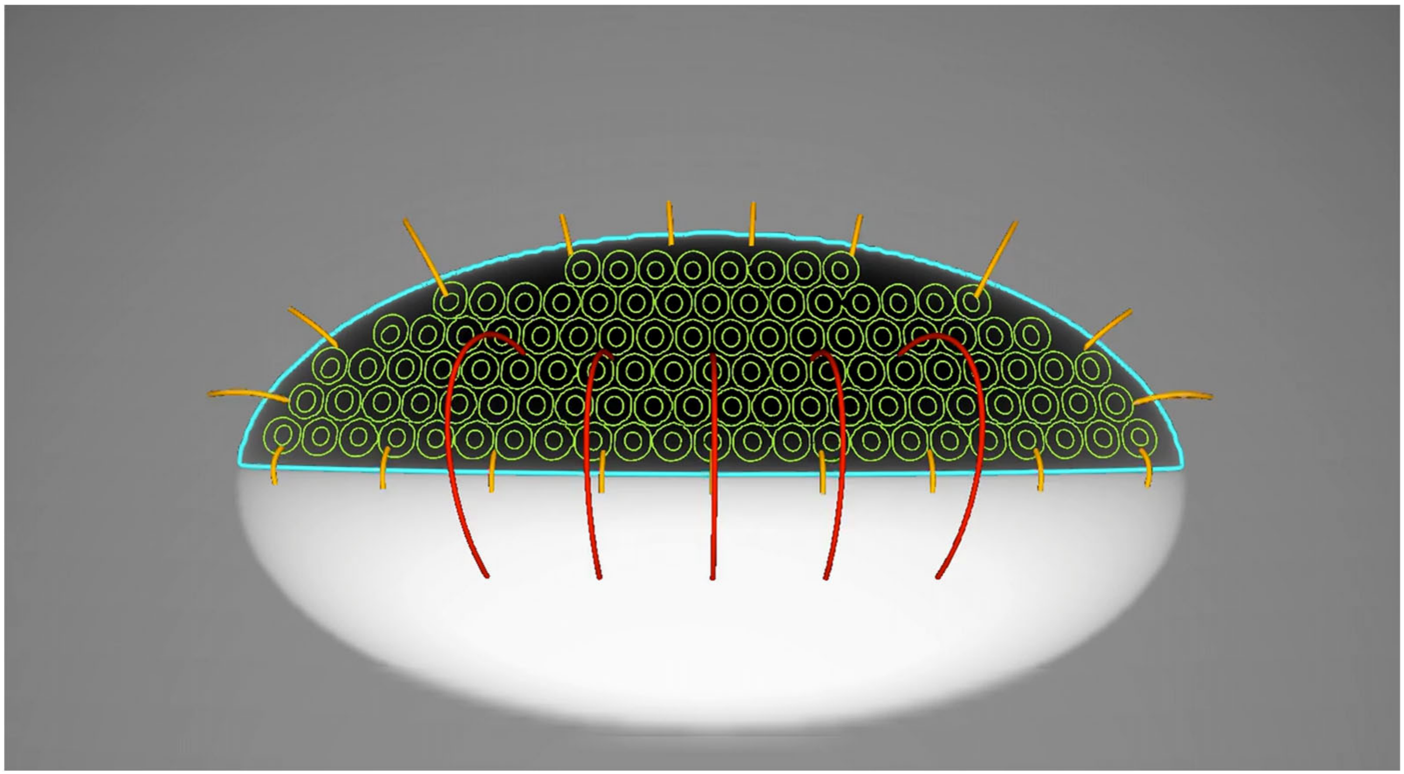
Initial Configuration

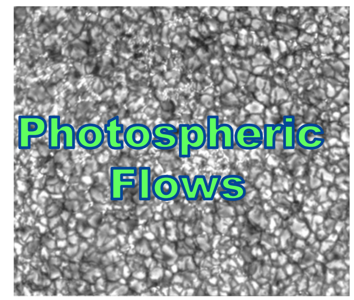
- **Solar dipole + active region**
- **Multipolar ("breakout") topology**
- **Polarity Inversion Line (PIL)** encircles **minority polarity**
- Potential field (minimum energy state)



Filament Channel Formation

- Driver: ~100 surface twist flows inside PIL
- Sheared arcade forms
  - Strongly sheared core field
  - Weakly sheared overlying field





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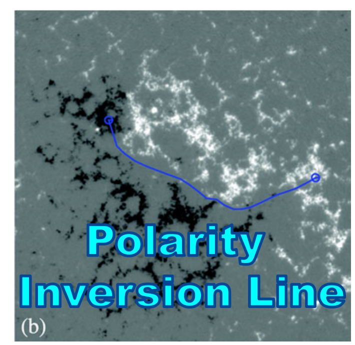
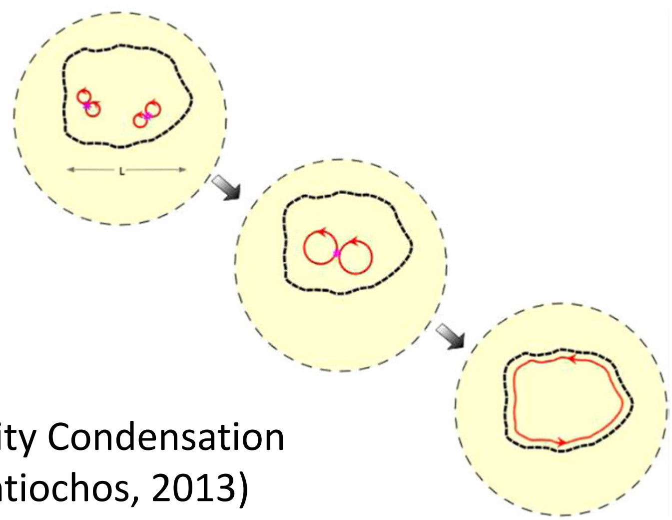


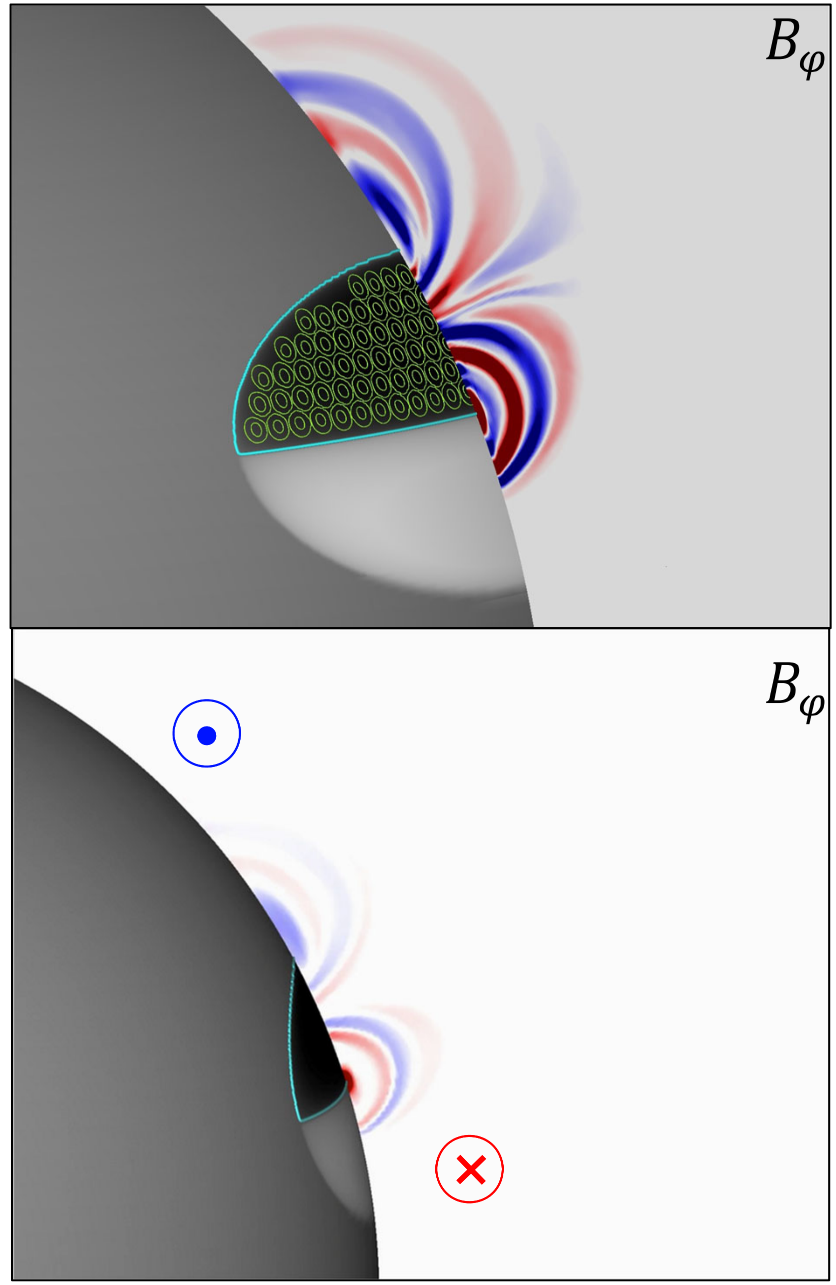
Consistent with Zhao et al., 2015; Knizhnik et al., 2015, 2017

Filament Channel Formation

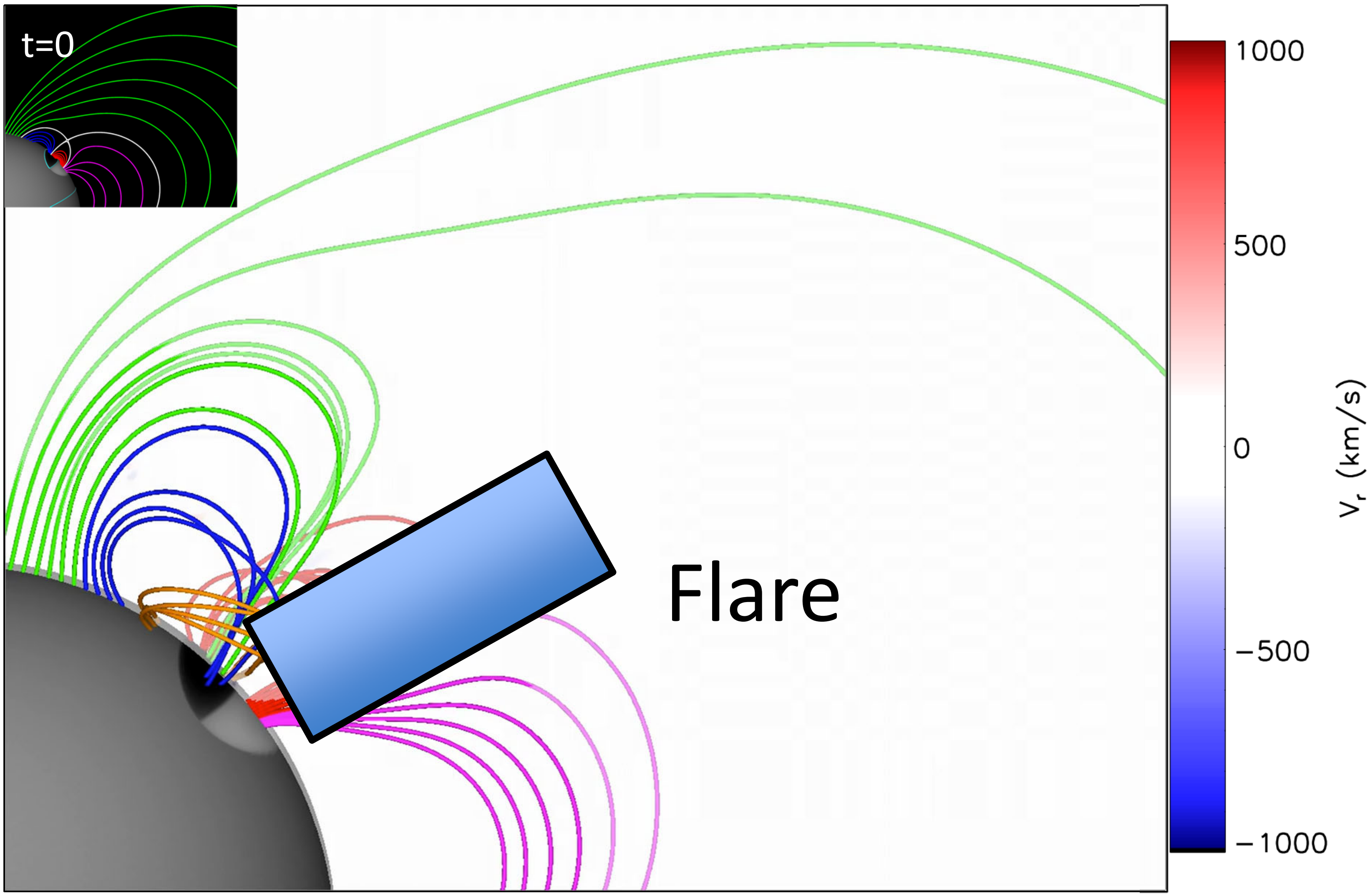
- Rotational flows twist bundles of field lines
- Inverse helicity cascade **mediated by reconnection** “condenses” magnetic shear at PIL



Helicity Condensation
(Antiochos, 2013)

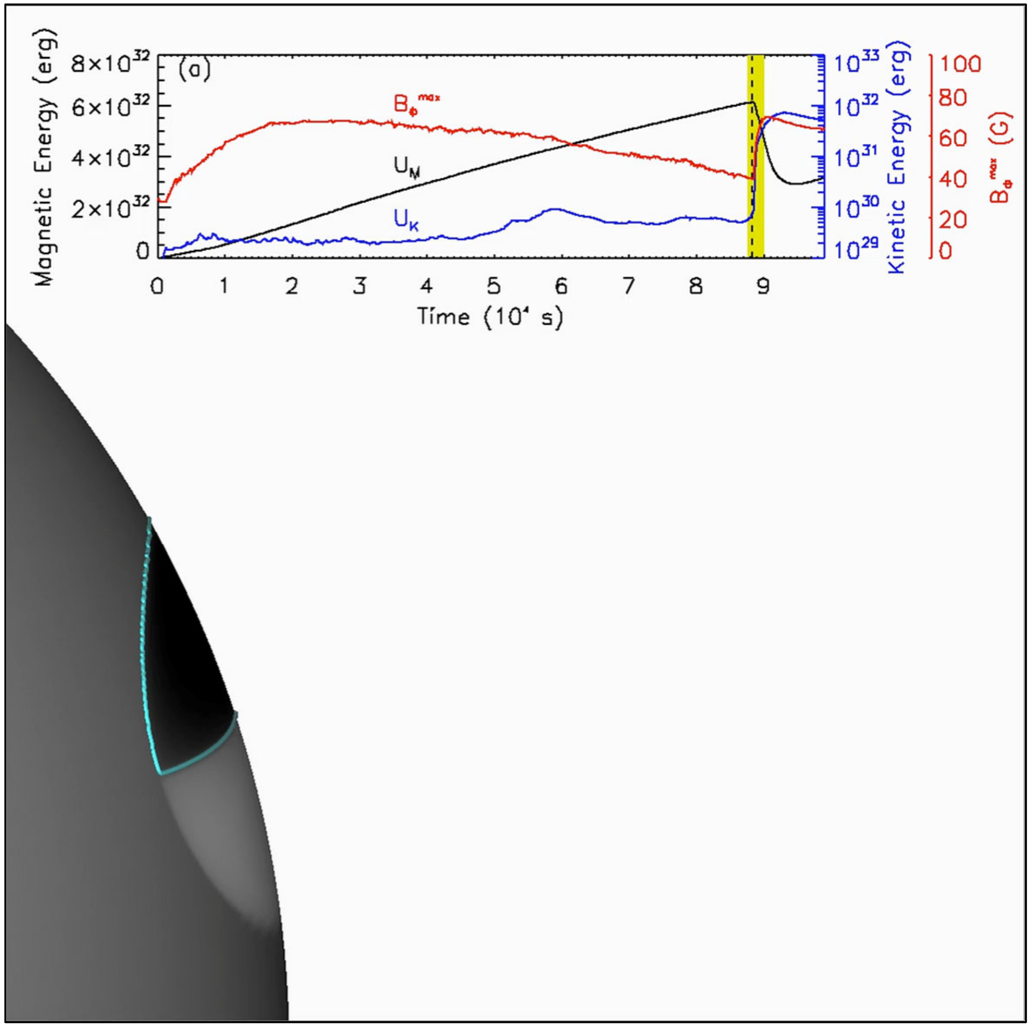


Coronal Mass Ejection & Flare



Global Energetics & Shear Evolution

- Extended energy build up (~90000s)
- Rapid release of ~50% of **free energy** during eruption
- Three-stage evolution of **max B_ϕ** (shear field) at the surface
    1. Buildup: helicity condensation builds up magnetic shear
    2. Expansion: dome expands upward in response to increasing magnetic pressure
    3. Eruption: ejection of shear in CME, flare reconnection jets compress field



Breakout Reconnection

- Challenge to identify & quantify reconnection in 3D
- Magnetic mappings track topological evolution due to reconnection in the corona
- Positive flux maps to two regions
  - "Closed" field into minority polarity
  - "Open" to southern hemisphere
- Breakout reconnection swaps open/closed footpoints
- "External" reconnection

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Closed

Newly Closed

Newly Open

Open

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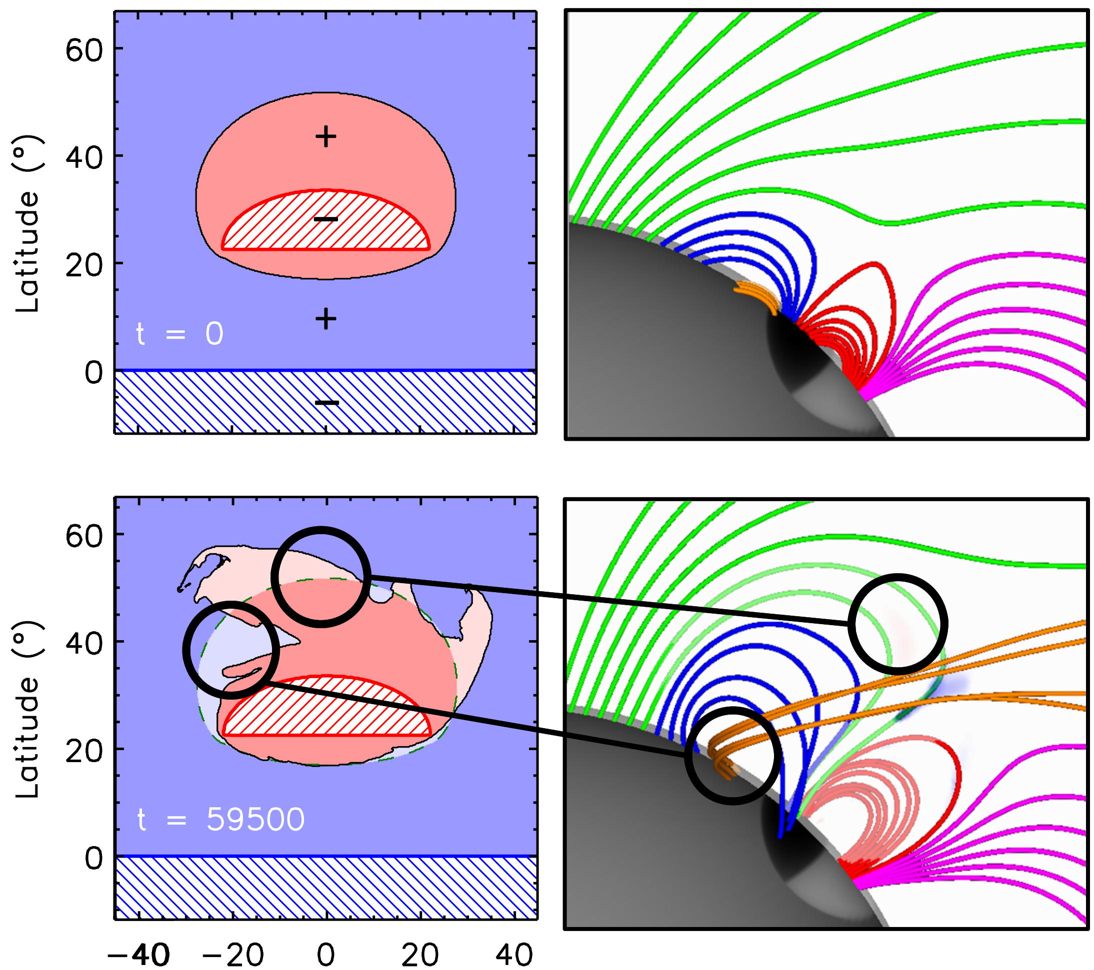
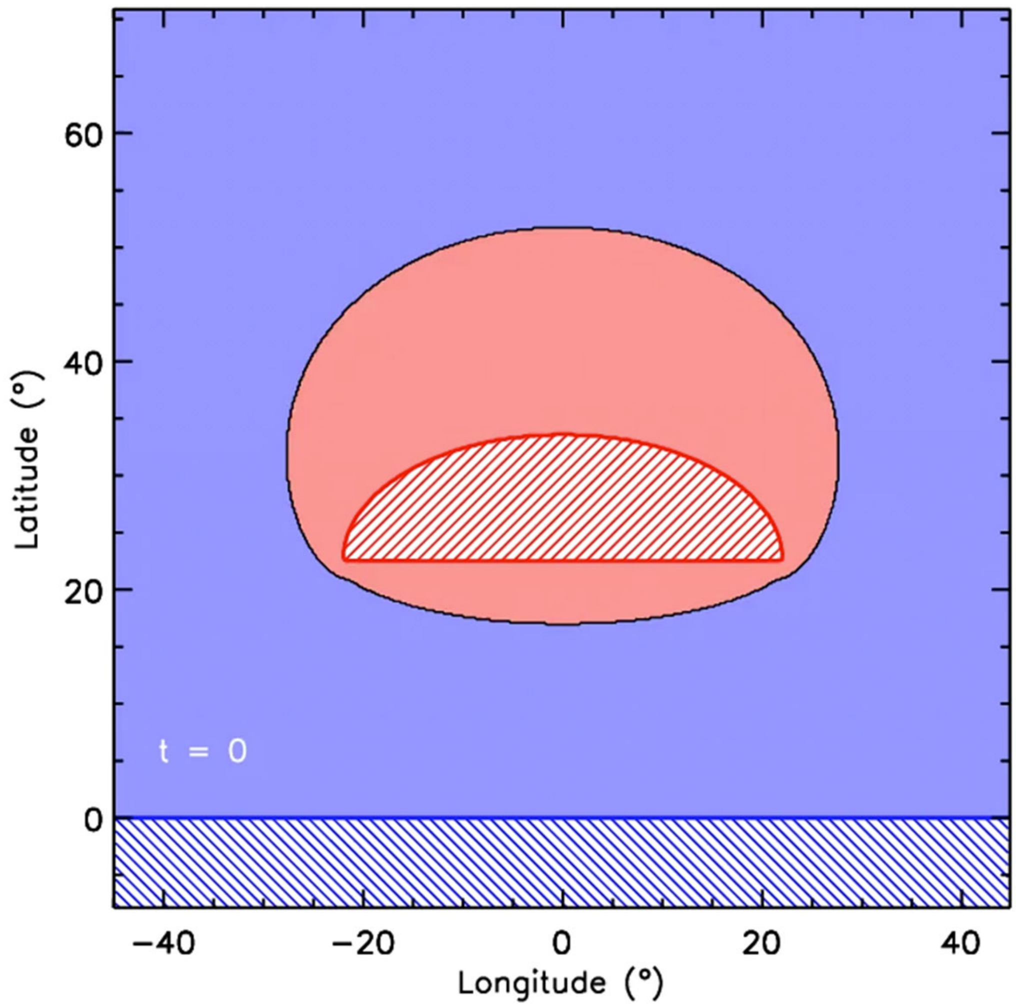
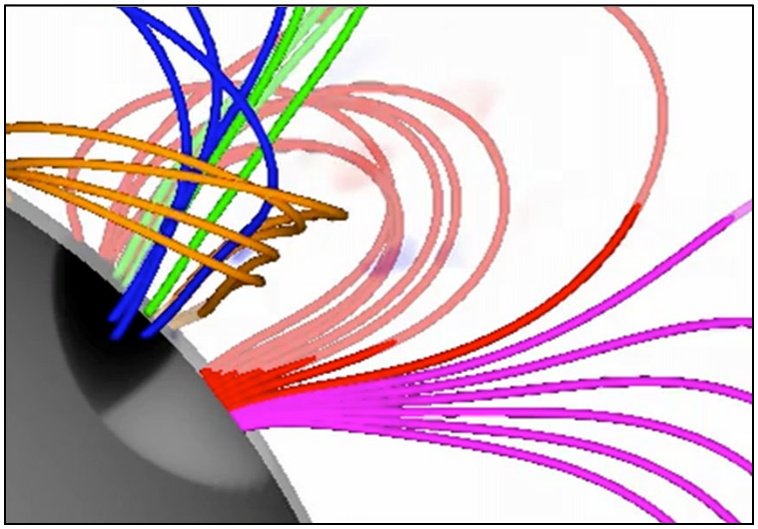


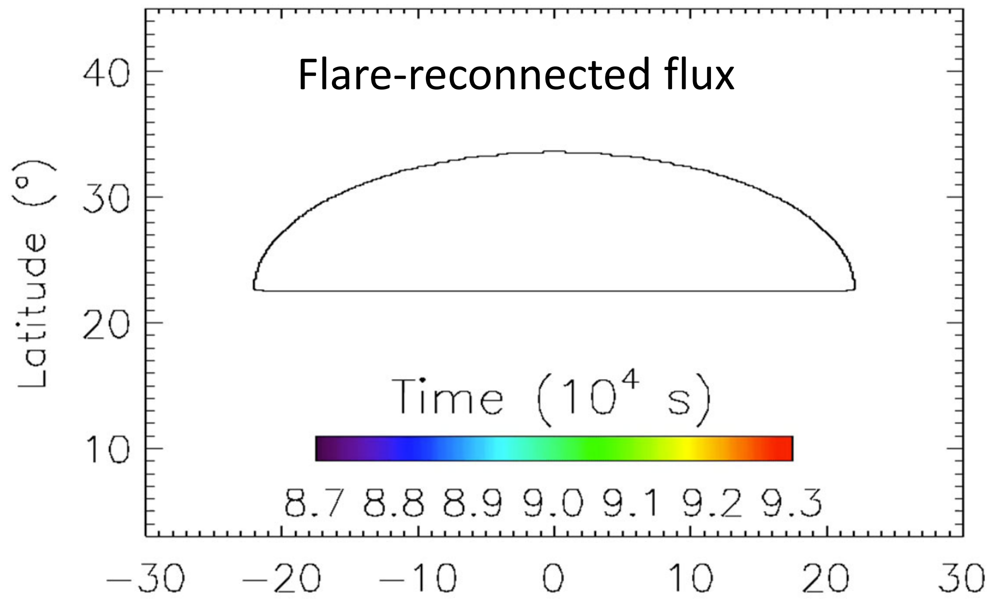
Breakout Reconnection

- Topology slowly evolves in response to shear/energy buildup
- Fast reconnection onsets, fractal mapping traces chaotic structure
- Ejection of sheared flux returns system to near pre-eruptive topology



Flare Reconnection

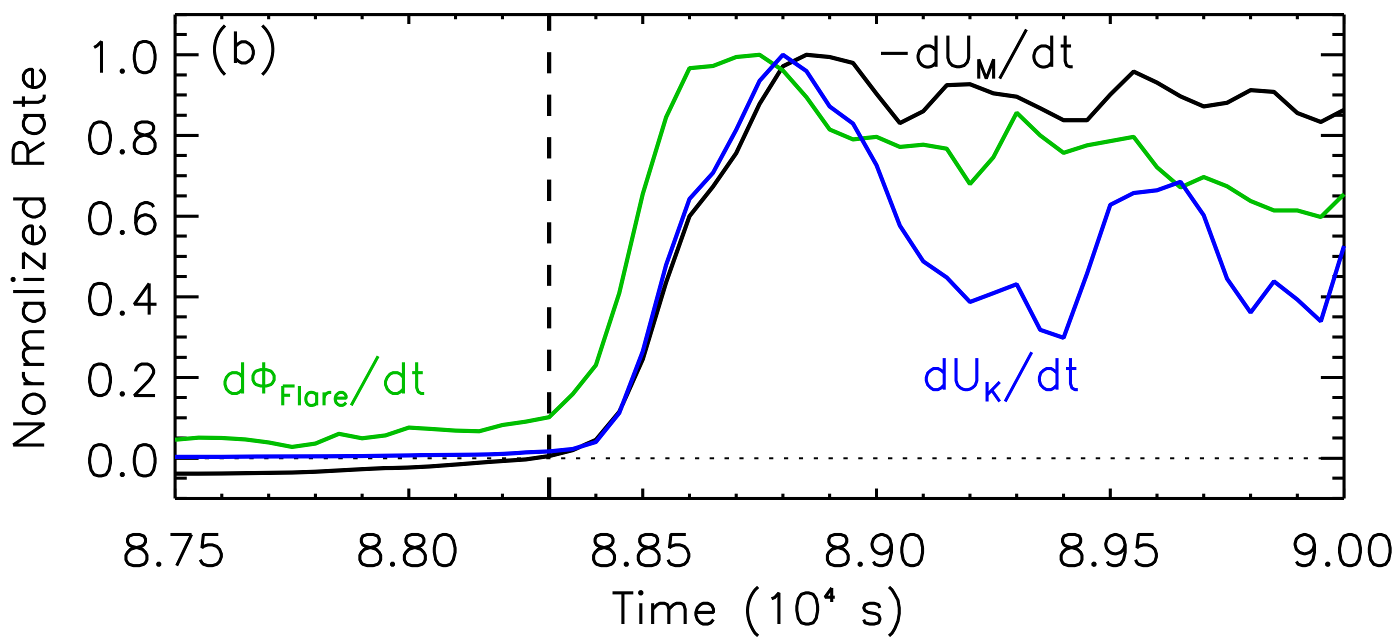




- Field lines stretch as shear field expands outward
- Flare reconnection abruptly shortens stretched field lines, indicates what field lines have reconnected
- Reconnection spreads in 3D from initial location on southern half of PIL
- All flux in PIL is reconnected

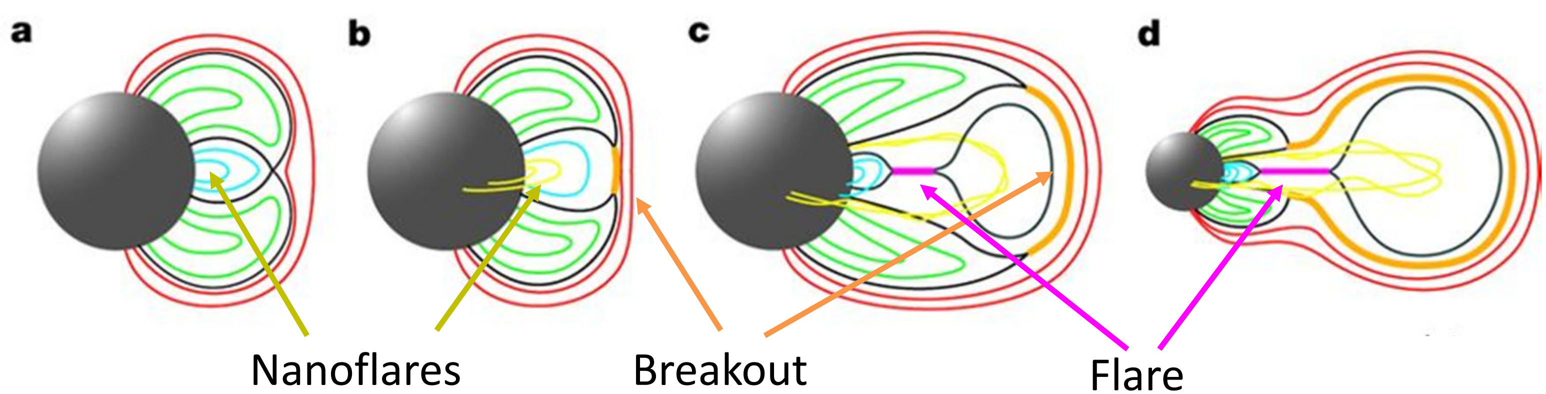
Reconnection Timing

- Timing for CME onset:
  - **1. Flare reconnection**
  - **2. Kinetic energy rise** & **magnetic energy release**
- Flare initiates prior to fast eruption as in 2.5D simulations (Karpen et al., 2012)
- Suggests flare reconnection drives fast ejection (rather than e.g. ideal instability driving reconnection)



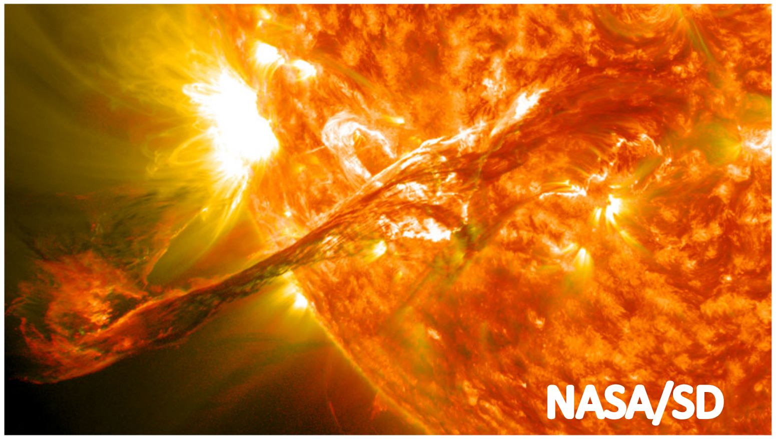
Partial Summary

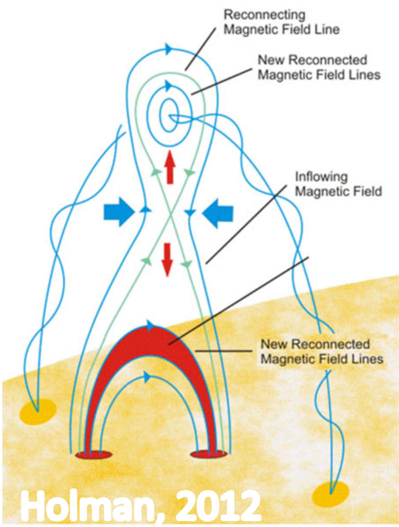
- Three types of reconnection
  - Nanoflares mediate helicity cascade
  - Breakout destabilizes filament channel
  - Flares
- What manifestations of reconnection accelerate particles?



Particle Acceleration in Flares

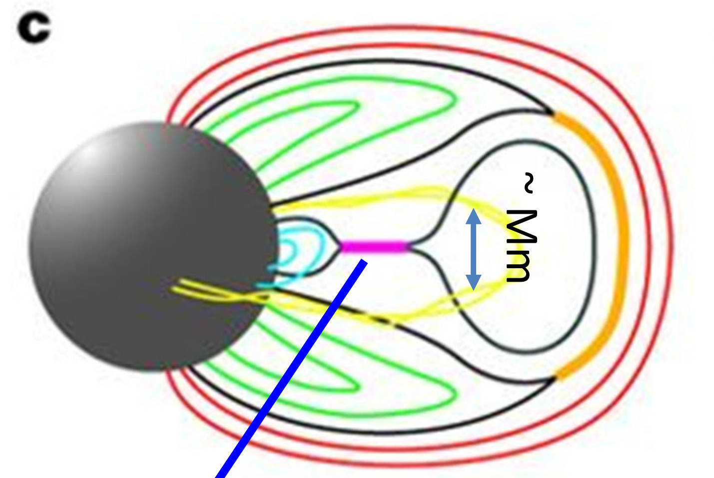
- Hard X-ray and microwave emissions in flares indicate efficient particle acceleration
  - In some observations, nonthermal energy reaches equipartition with magnetic energy
- Why is flare reconnection an efficient accelerator?
  - Microscale kinetic physics are important (MHD ‘sub-grid’)
  - How does the magnetic configuration (guide field) impact the acceleration?

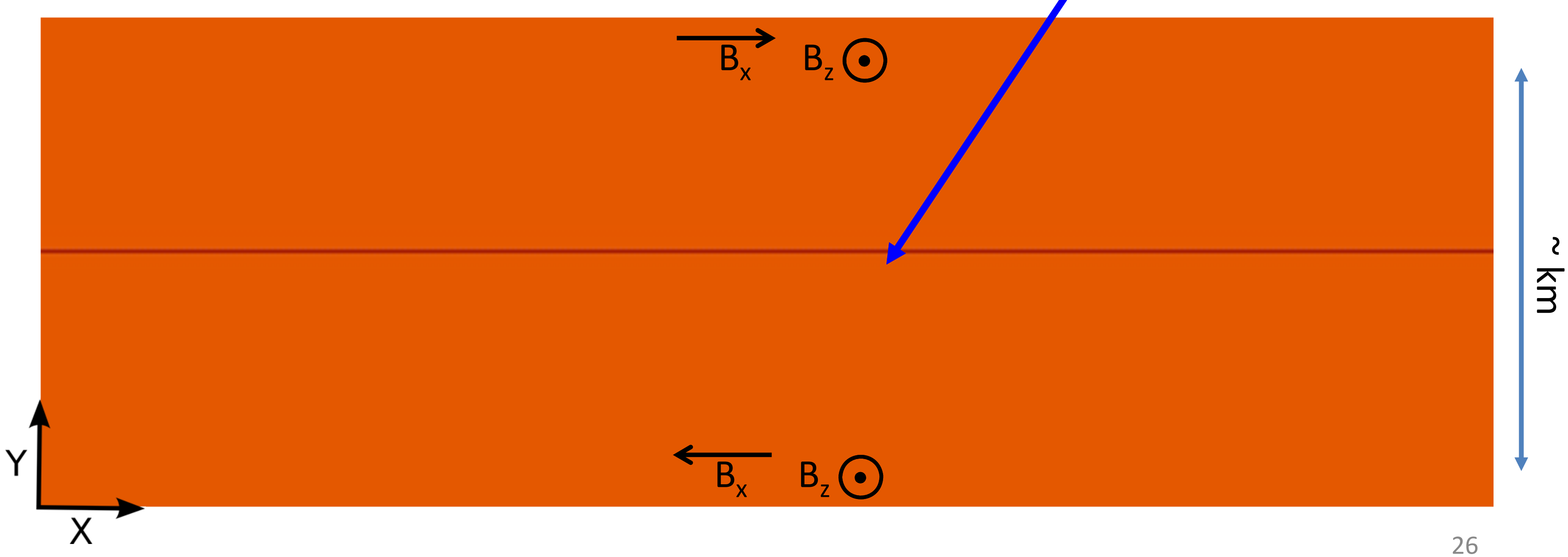




Kinetic Particle Acceleration

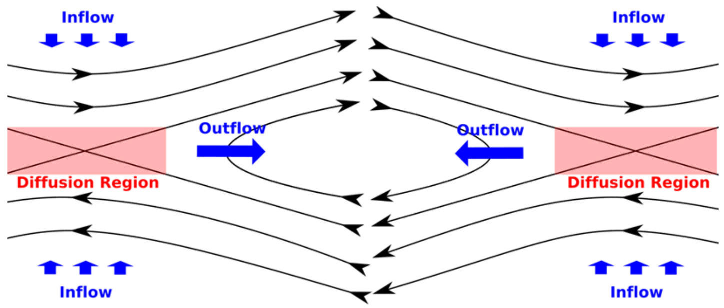
- PIC simulations (microscale physics)
- **How does the macro-scale reconnection configuration impact particle acceleration efficiency?**
- **Key parameter: out-of-plane field B_z**
  - Shear field in MHD simulation
  - Guide field $b_g = B_z/B_x$

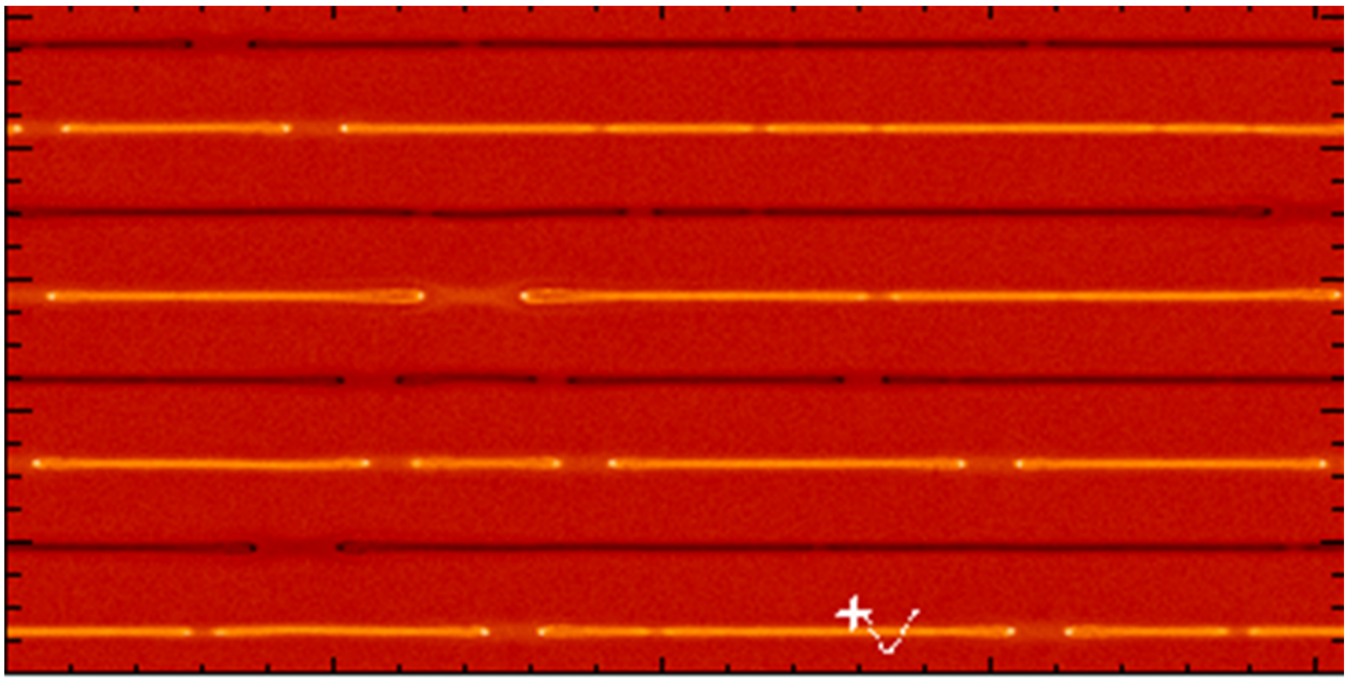




Acceleration in Magnetic Islands

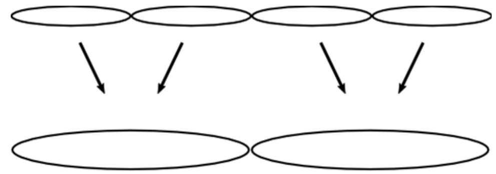
- Fermi mechanism of Drake et al., 2006
- Reconnecting current sheets break up into many islands
- Particles trapped in islands reflect from contracting field lines

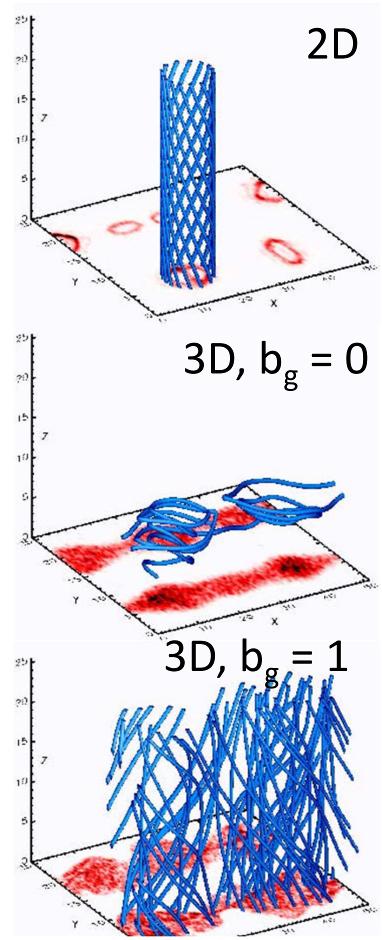


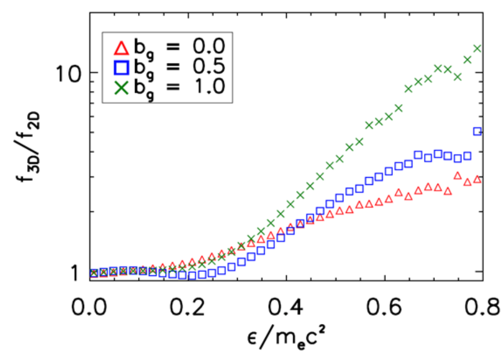


Courtesy of K. Schoeffler

A Guide Field Enhances Acceleration



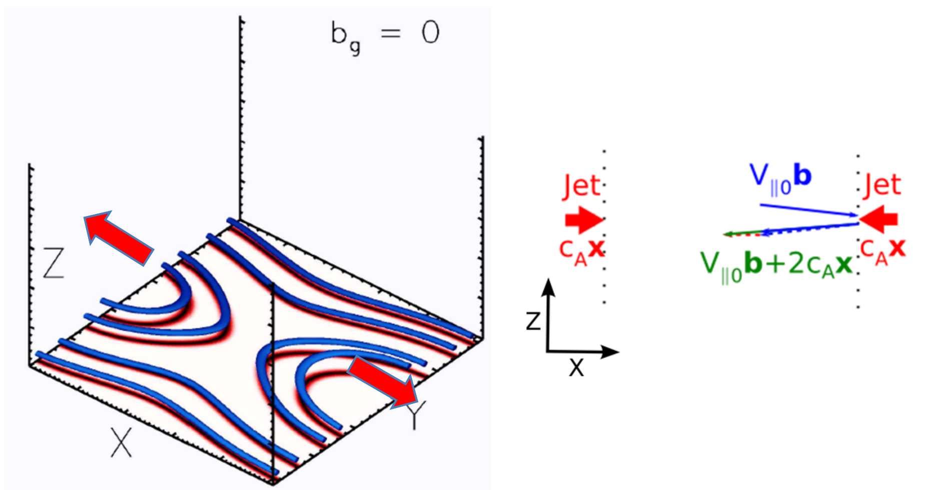




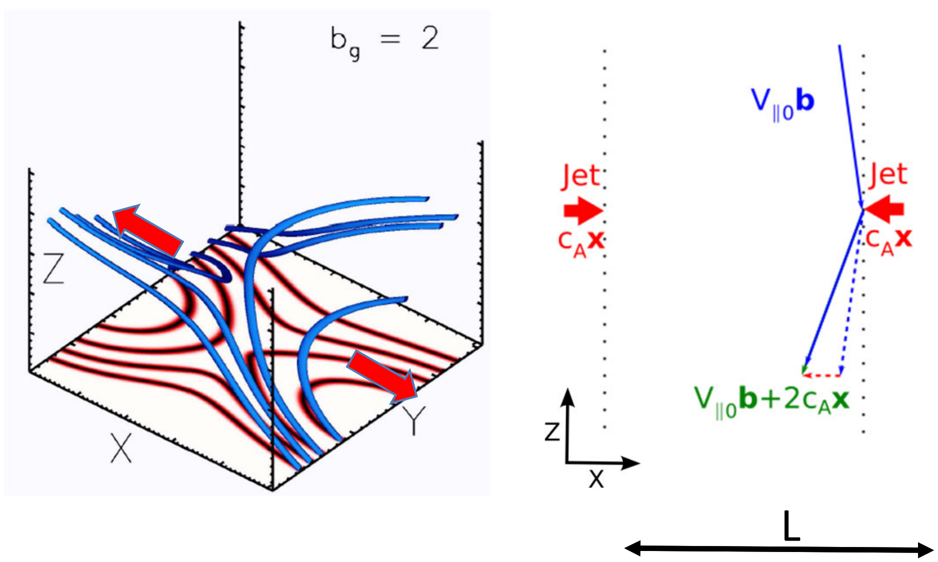
- Particles accelerate via island contraction *and* island mergers
- As islands merge and grow, acceleration slows as acceleration time scale rate L/c_A increases
- In 2D, new islands continue to be generated, but energetic particles cannot access them
- In turbulent 3D guide field reconnection, electrons escape islands & sample newly generated secondary islands
- **Enhancement increases with guide field**

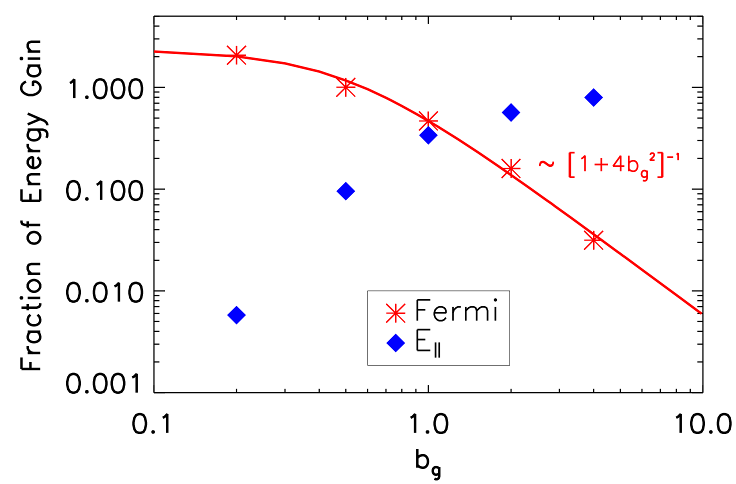
Dahlin et al., 2015, 2017 (Phys. Plasmas)

A Strong Guide Field Suppresses Acceleration

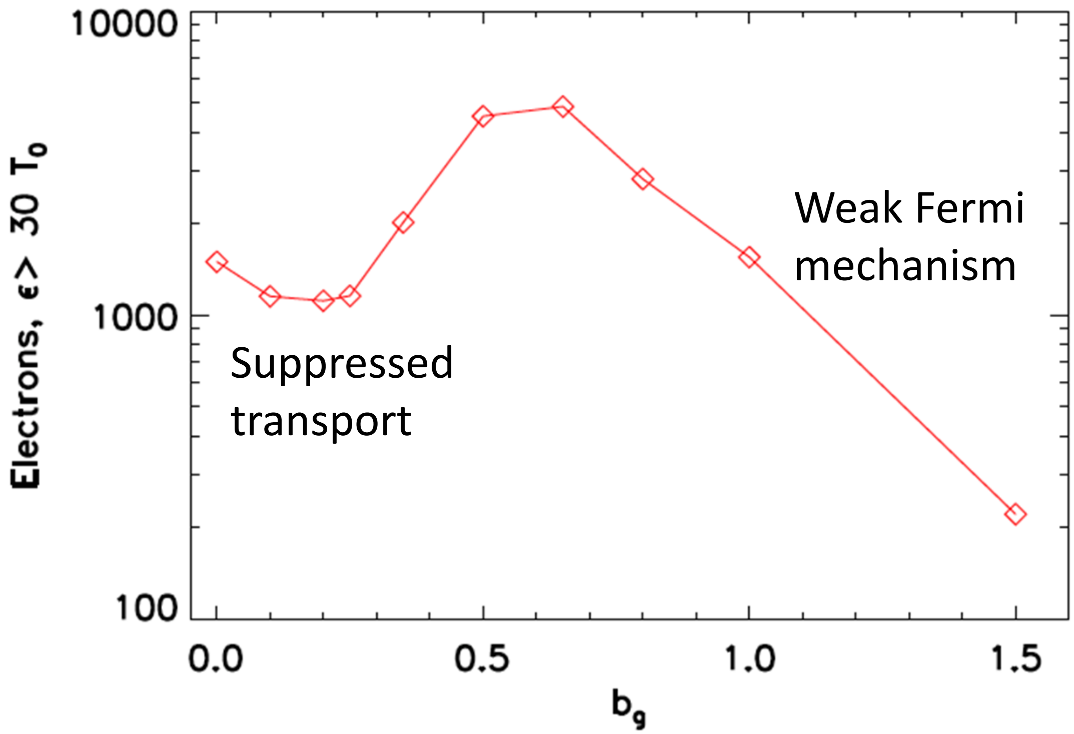


- Fermi acceleration is driven by collisions with reconnection outflows
- Weak guide field ($b_g < 1$): head-on collision with outflow
- Strong guide field ($b_g \gg 1$): glancing collision with outflow





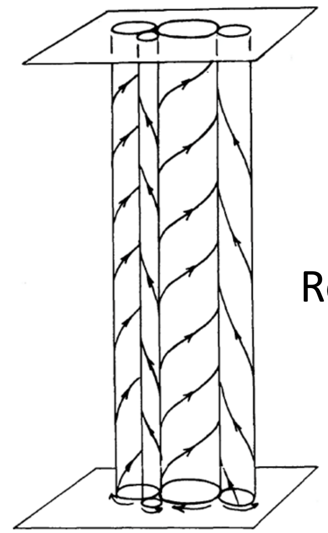
The Moderate Guide Field Regime



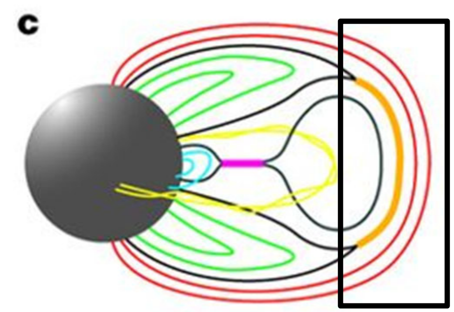
- **Reconnection with a moderate guide field (b_g~ 1) generates the greatest number of energetic electrons**
- Dahlin et al., 2016, 2017
- Consistent with strongest magnetosphere reconnection observations up to 300 keV with guide field present (Øieroset et al., 2002)

Implications for Reconnection-driven Particle Acceleration in Solar Eruptions

- Nanoflare reconnection:
  - Strong guide field
  - Observations most consistent with heating
- Breakout reconnection: guide field likely to be weak
  - Current sheet formed via deformation of null point
  - Antiparallel ($b_g \sim 0$)
  - Some evidence of (weak) particle acceleration in microwave emission



Nanoflare Reconnection



Breakout Reconnection

Flare Guide Field Observations

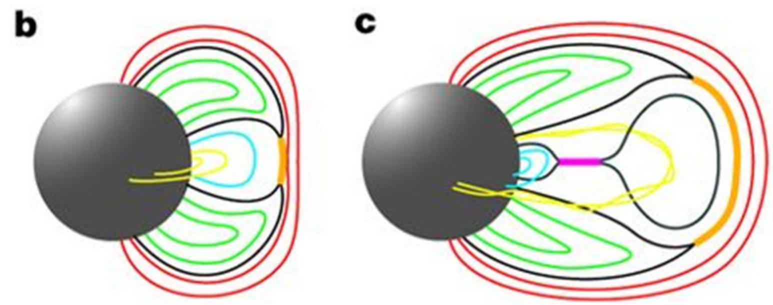
- Qiu et al., 2017 observations of two-ribbon flares
  - Study of 3D spread of reconnection
  - Theory predicts spreading velocity proportional to guide field (e.g. Shepherd & Cassak, 2012)
  - Guide field can also be estimated from the angle between reconnected loops & PIL (proxy for current sheet direction)
- More than half of flare events are consistent with guide field ~ 1

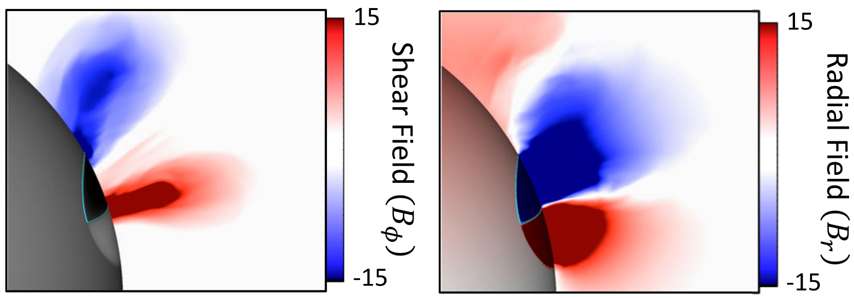
	Date, Magnitude[a,b]	B_g/B_o
1	2011 Sep 13 C2	0.7
2	2011 Dec 26 C3.7	0.9
		…
3	2005 May 13 M8.0	5.1
		…
4	2000 Jul 14 X5.7	1.0
		0.8
5	2004 Nov 07 X2.0	>3
		…
		…
6	2005 Jan 15 X2.6	1.2
		0.3

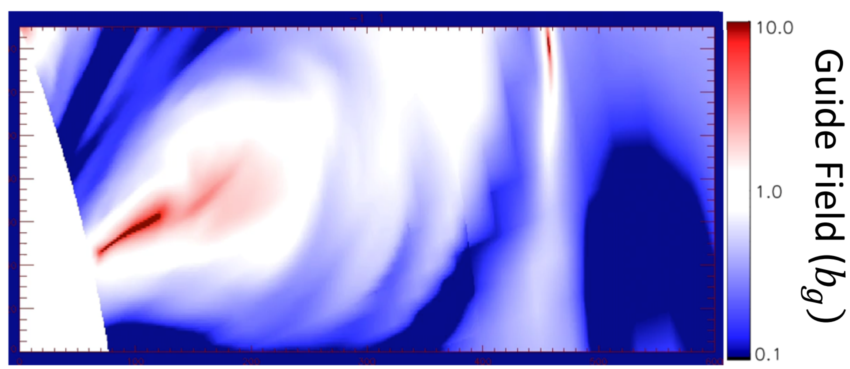
Modified from Qiu et al., 2017

Guide Field Temporal Evolution

- Flare reconnection associated with electron acceleration (Hard X-rays, microwave emission)
- In standard flare model, reconnection processes/ejects shear field (guide field)
- Guide field must initially be ~1
  - Force balance between tension (reconnecting field) and magnetic pressure (guide field)
- Guide field weakens as flare reconnection proceeds & magnetic shear is ejected

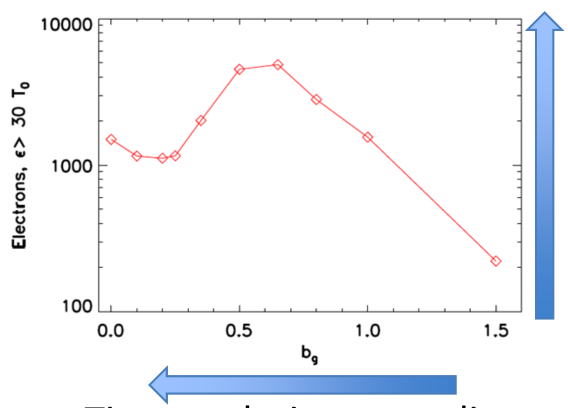






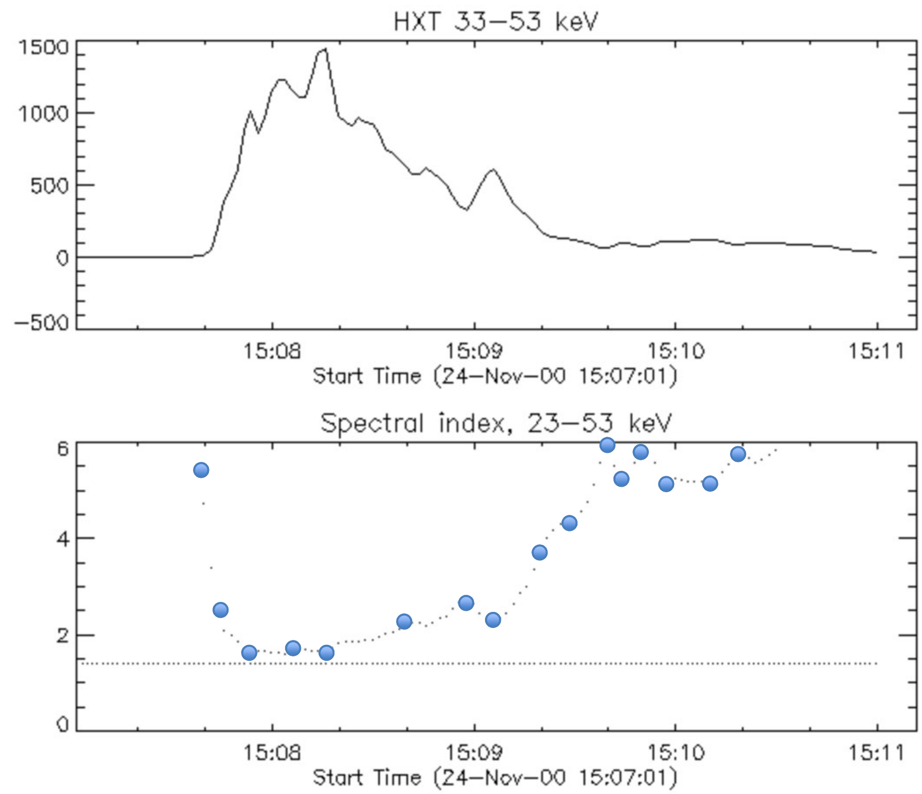
Solar Flare Spectral Evolution

- MHD simulation: guide field evolves from strong to weak
- PIC simulation: acceleration efficiency (~ spectral hardness) peaks for b_g~ 1
- Consistent with typical soft-hard-soft spectral evolution in hard X-rays



Accel. Efficiency according to PIC

Time evolution according to MHD model



Counts

Spectral Index

Soft-Hard-Soft Spectra (RHESSI Hard X-Rays)

Conclusions

- MHD simulation demonstrates 3 reconnection roles
  - Energy buildup: “nanoflare” reconnection mediates helicity cascade
  - Destabilization: “breakout” reconnection disrupts force balance
  - Explosive release: “flare” reconnection ejects accumulated shear
- Kinetic studies show the guide field controls efficiency of energetic particle production
  - Strong guide field $b_g >> 1$ in nanoflares (coronal heating)
  - Weak-moderate guide field/overall magnetic field in breakout reconnection (weak acceleration
  - Many flares have a moderate guide field ~1
    - Guide field weakens as flare evolves, spectral evolution consistent with b_g prediction

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