Solar energetic particles : Observations & modelling

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Observatoire Radioastronomique de Nançay

Outline

1 - A quick introduction of solar eruptions

2 - Observational diagnostics

-observations

-multi-wavelength & multi-messenger analysis

3 - Modelling particle acceleration in solar eruptions

- kinetic models for particle acceleration
- MHD models for solar eruptions

4 - Coupling MHD and PIC simulations

Introduction

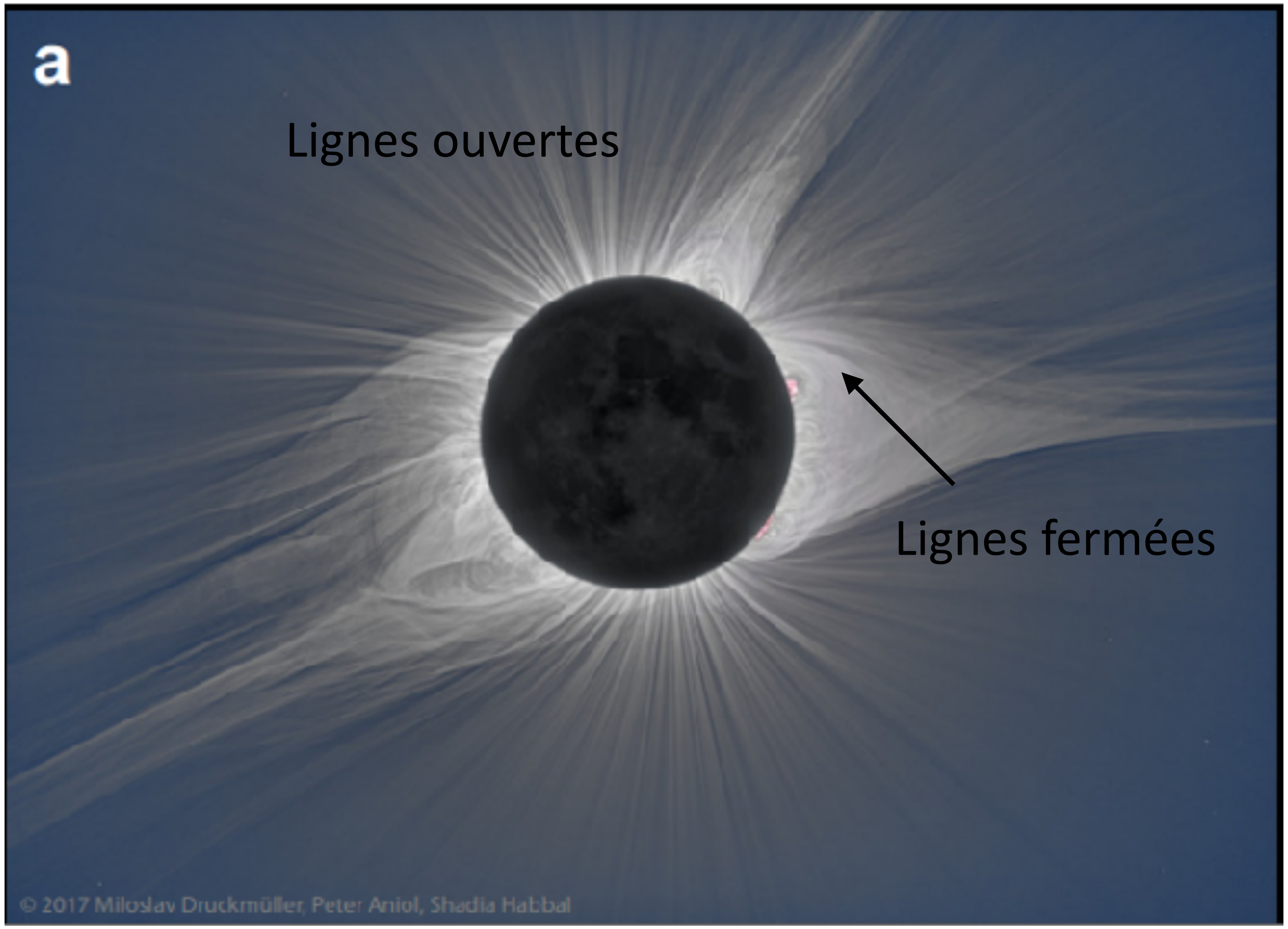
The Solar Corona

- ionized plasma $n \sim 10^{14\text{-}16}\ m^{-3}$ (Hydrogen, Helium & heavy ions)

- Magnetized plasma with strong B-field in active region ~ 1000 G $\rightarrow \beta << 1$

- flares/ eruptions spatial scales > particle characteristic lengths => Ideal MHD

- Small electric resistivity : $R_m >> 1$ - magnetic reconnection develops at small scales

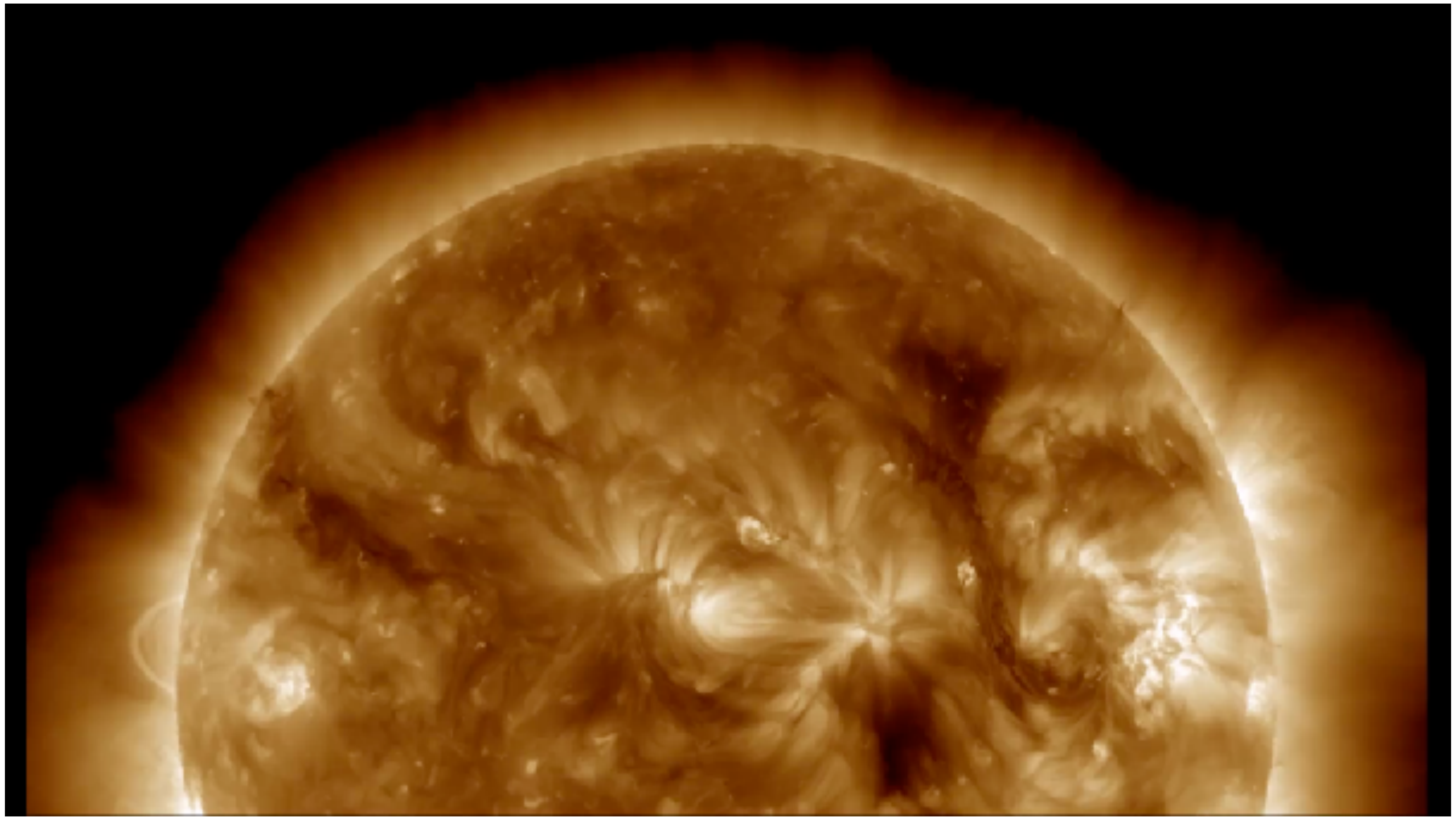


Natural Eclipse

3D reconstruction of **B**

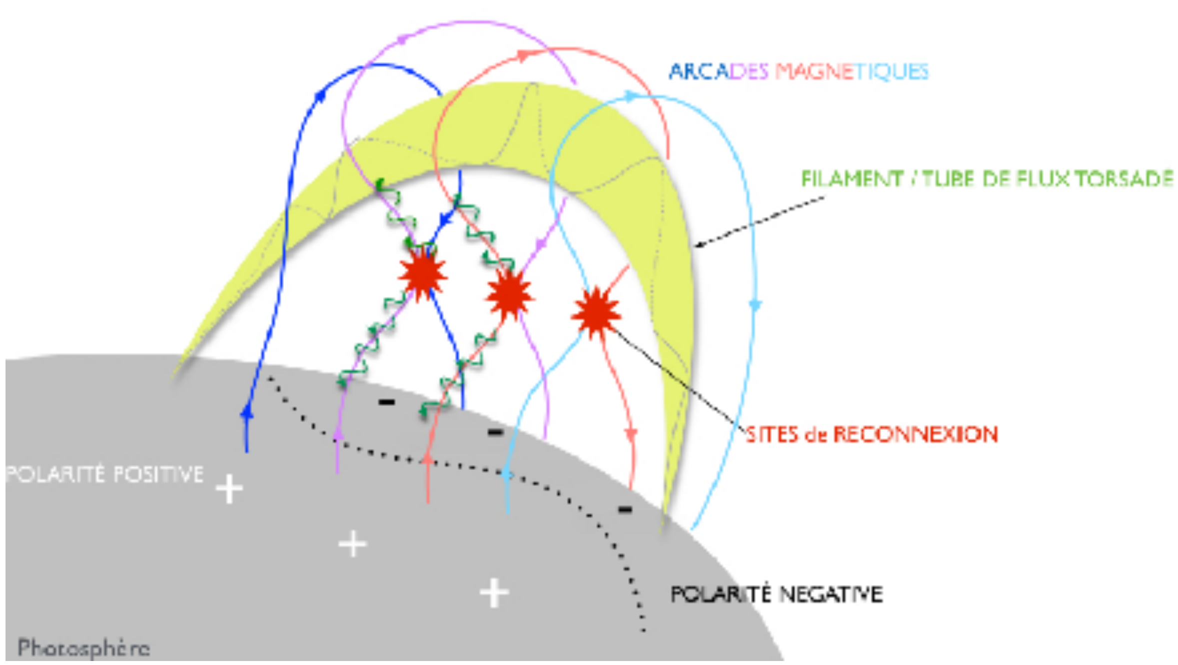
Introduction

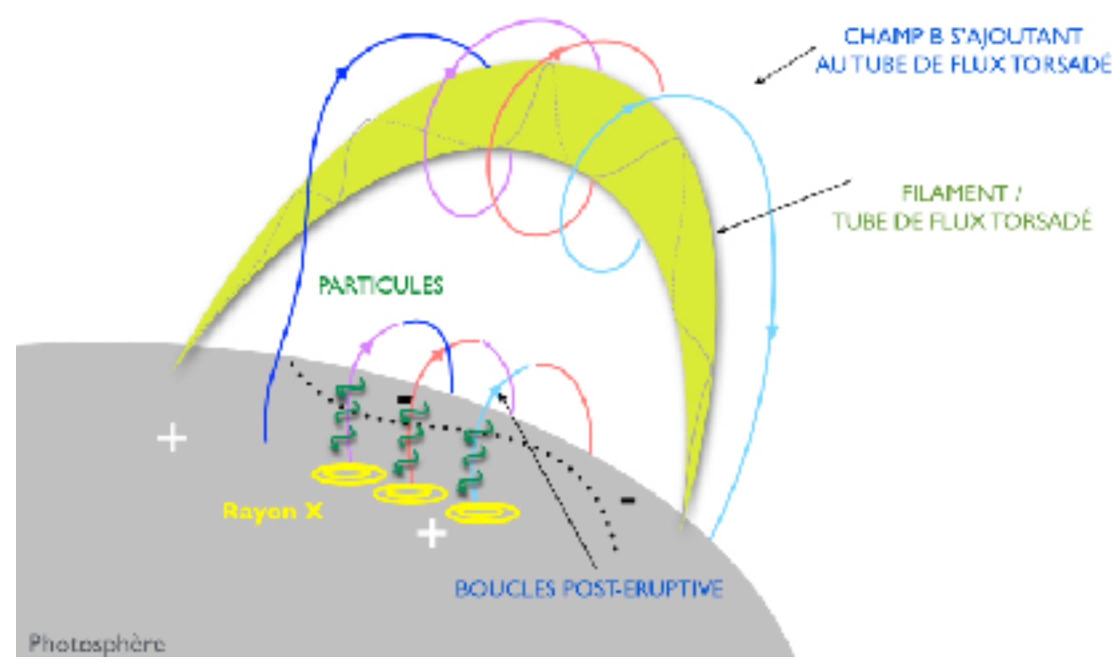
Solar eruption



Magnetic reconnection

=> Explosive release of magnetic energy
=> plasma heating, particles acceleration (GeV)
=> **B** reconfiguration





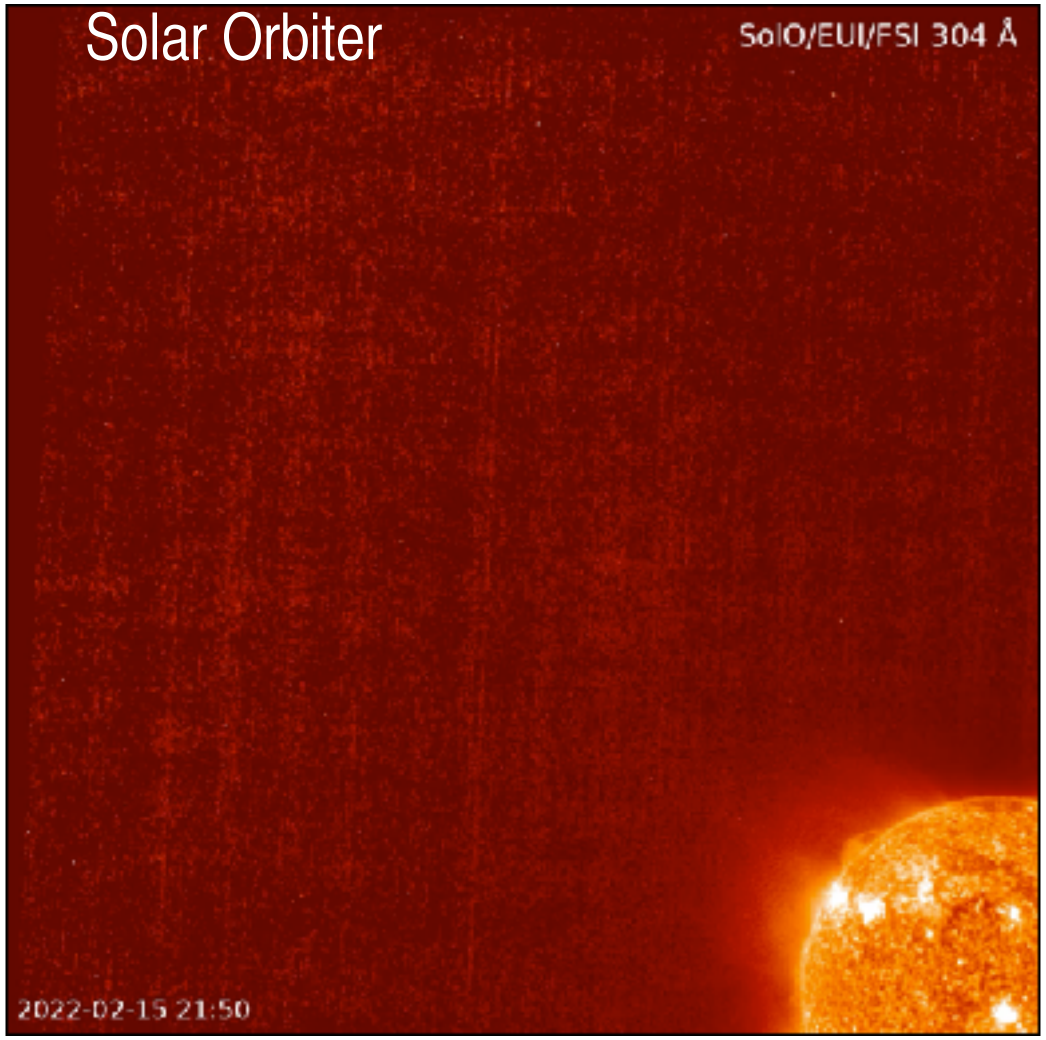
Introduction

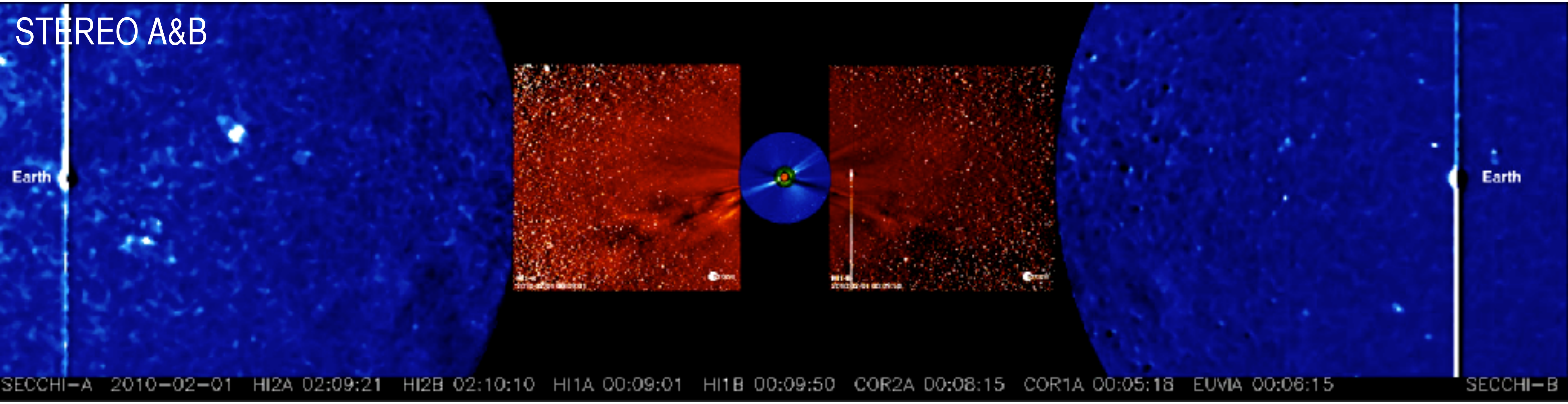
Coronal mass ejection

- Magnetised coronal plasma ~ 10^{13} - 10^{14} g
- Speed of ejection ~ 400 - 3000 km.s-1
- Interplanetary propagation (~2-4 jrs)

CME-driven shock = > Particle acceleration

t_{acc} ~ few minutes - few hours



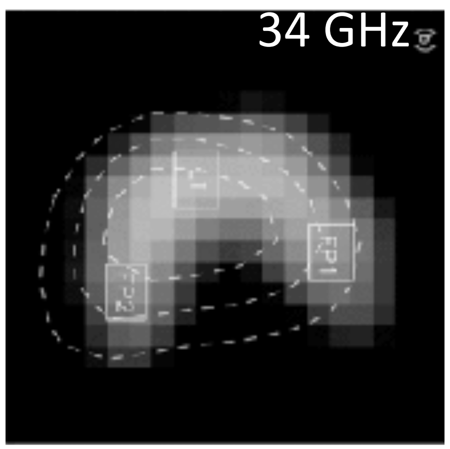


Solar eruption radiative signatures

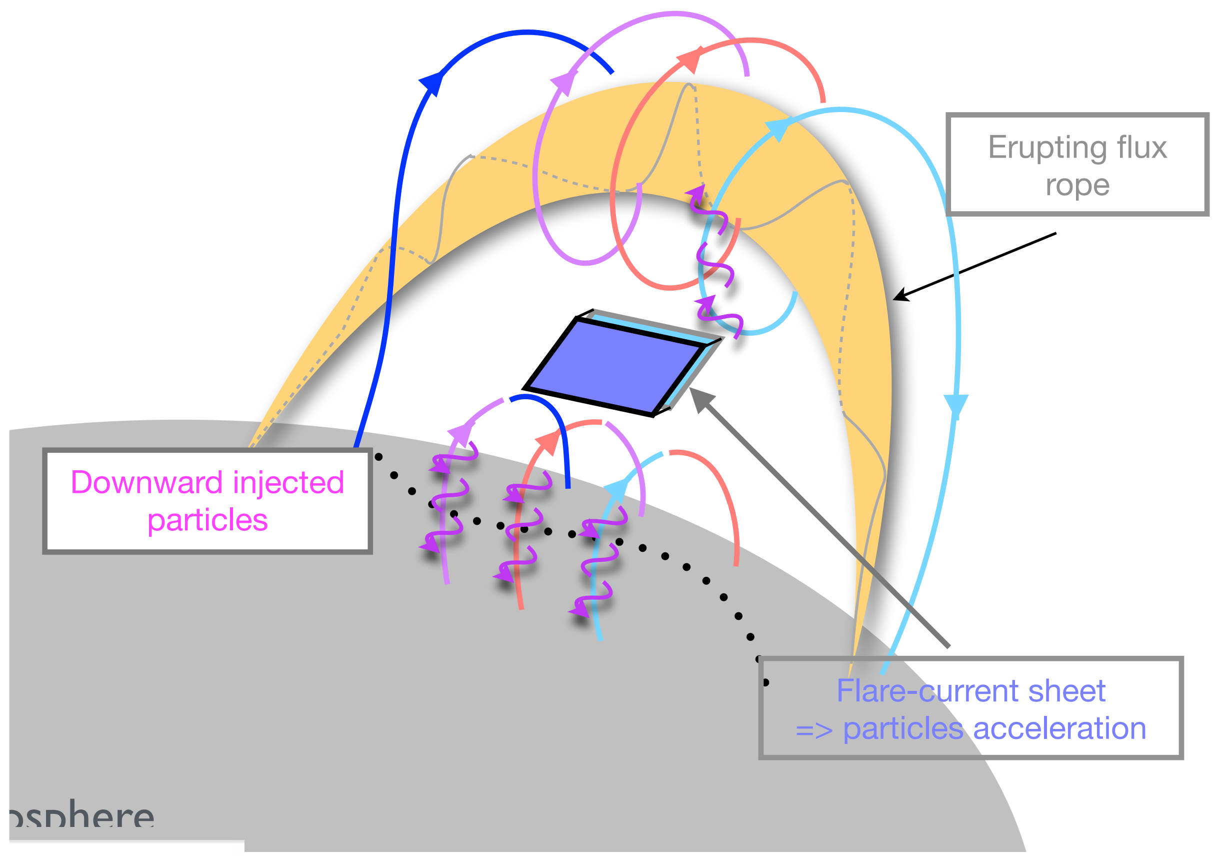
Magnetic reconnection
=> particle acceleration

t_{acc} ~ few seconds - few minutes

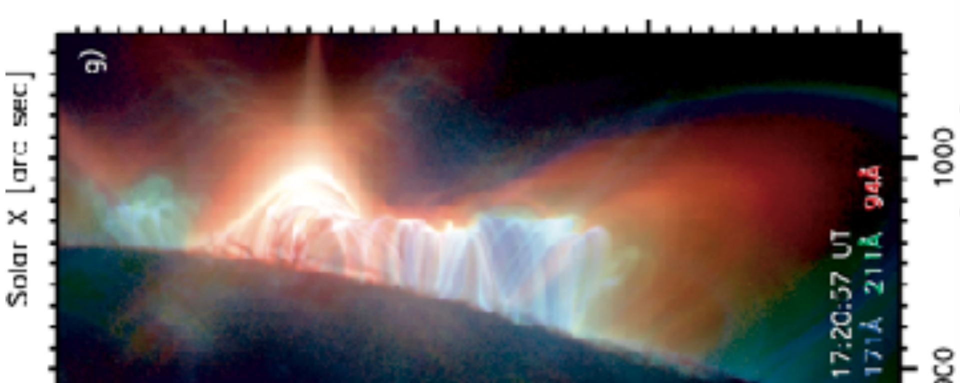
Nobeyama RadioHéliographe



Microwave emission



EUV coronal loops



Lorincik, Dudik, Aulanier 2021

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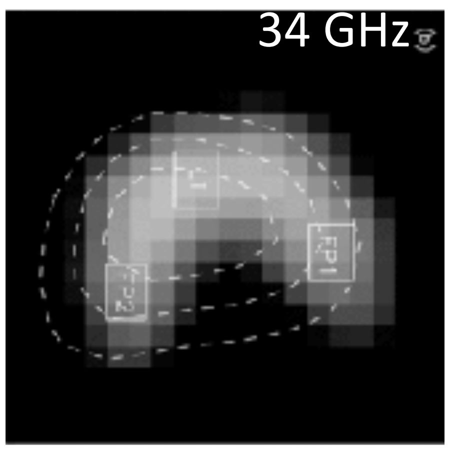

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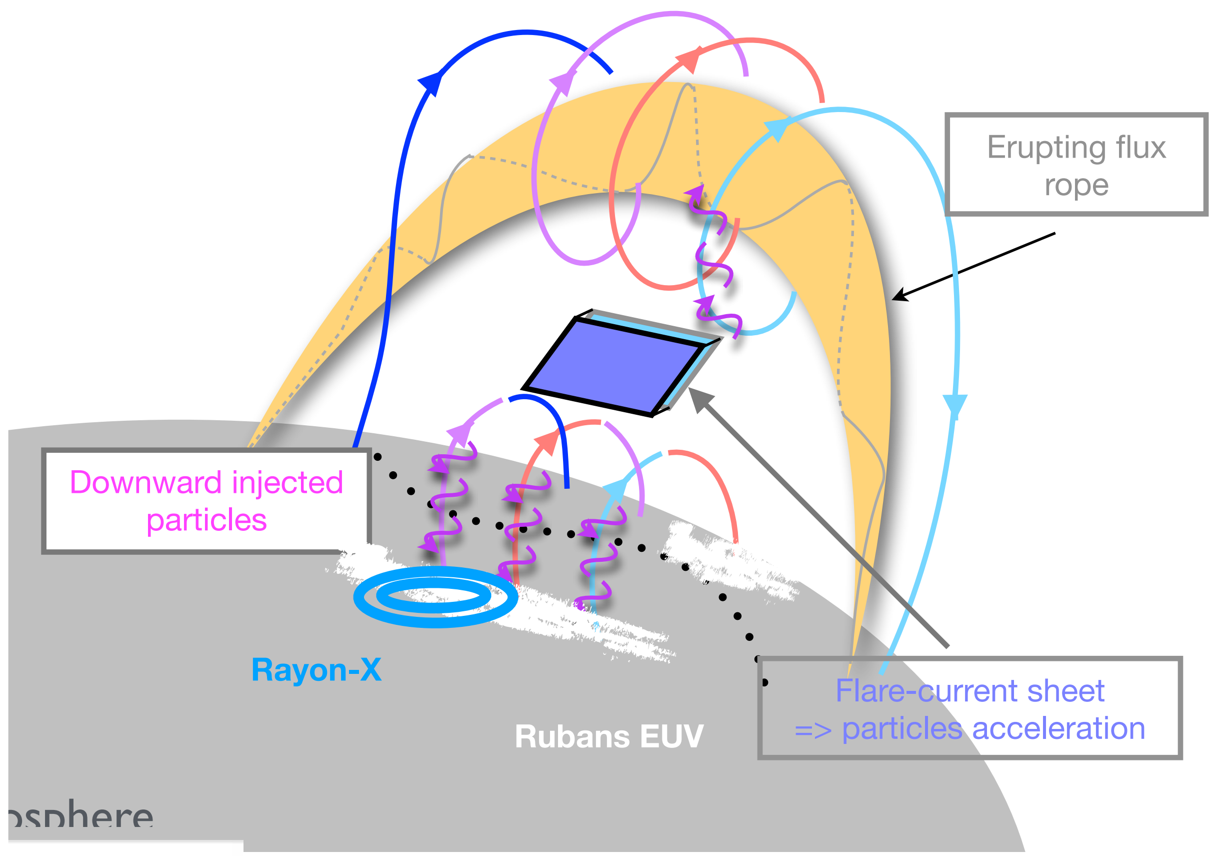

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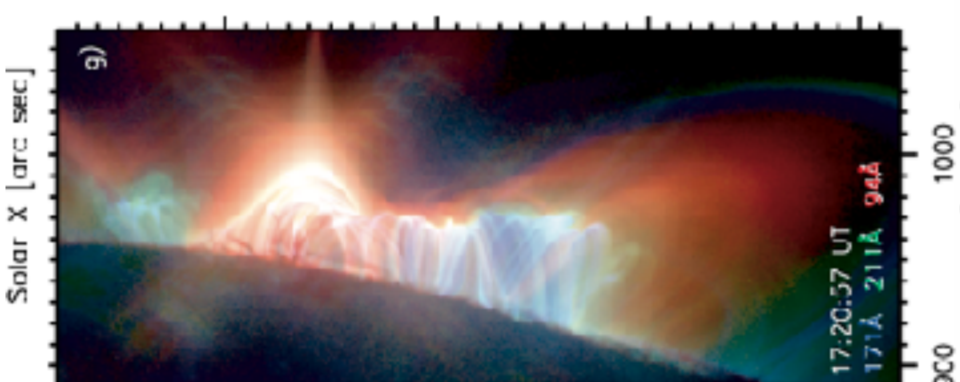

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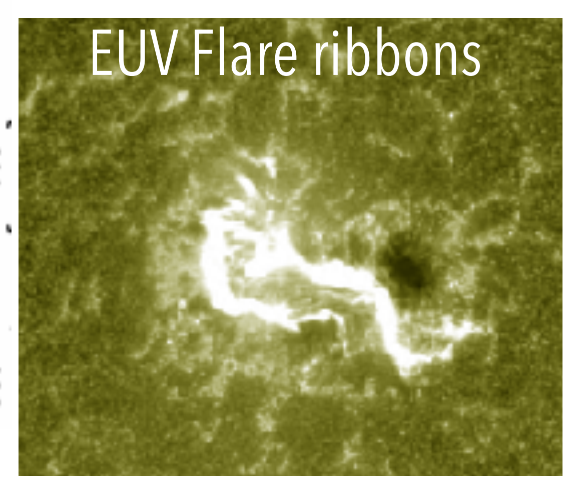
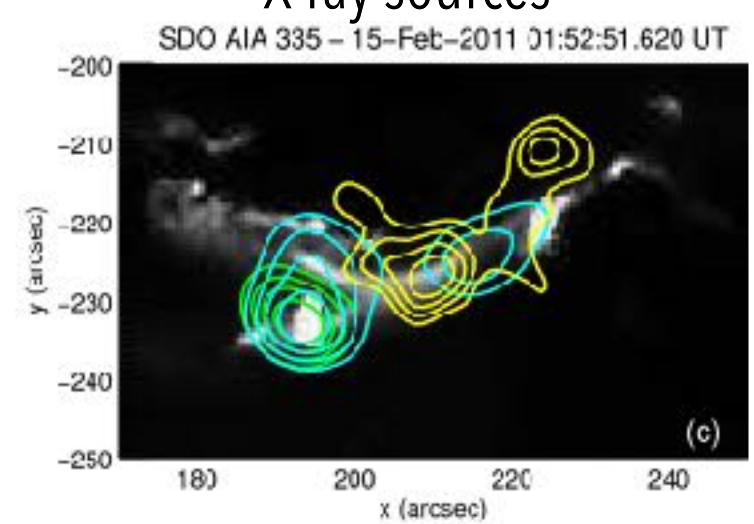


X-ray sources



Musset et al., 2015

Solar eruption radiative signatures

Magnetic reconnection
=> particle acceleration

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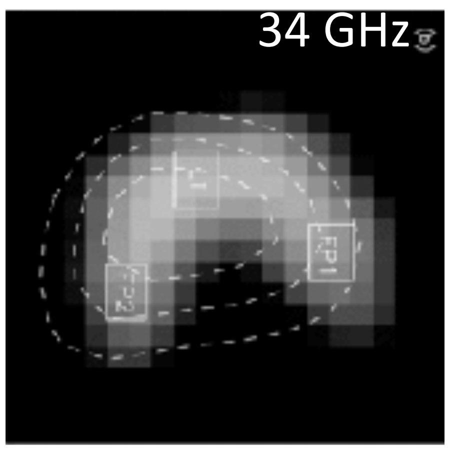

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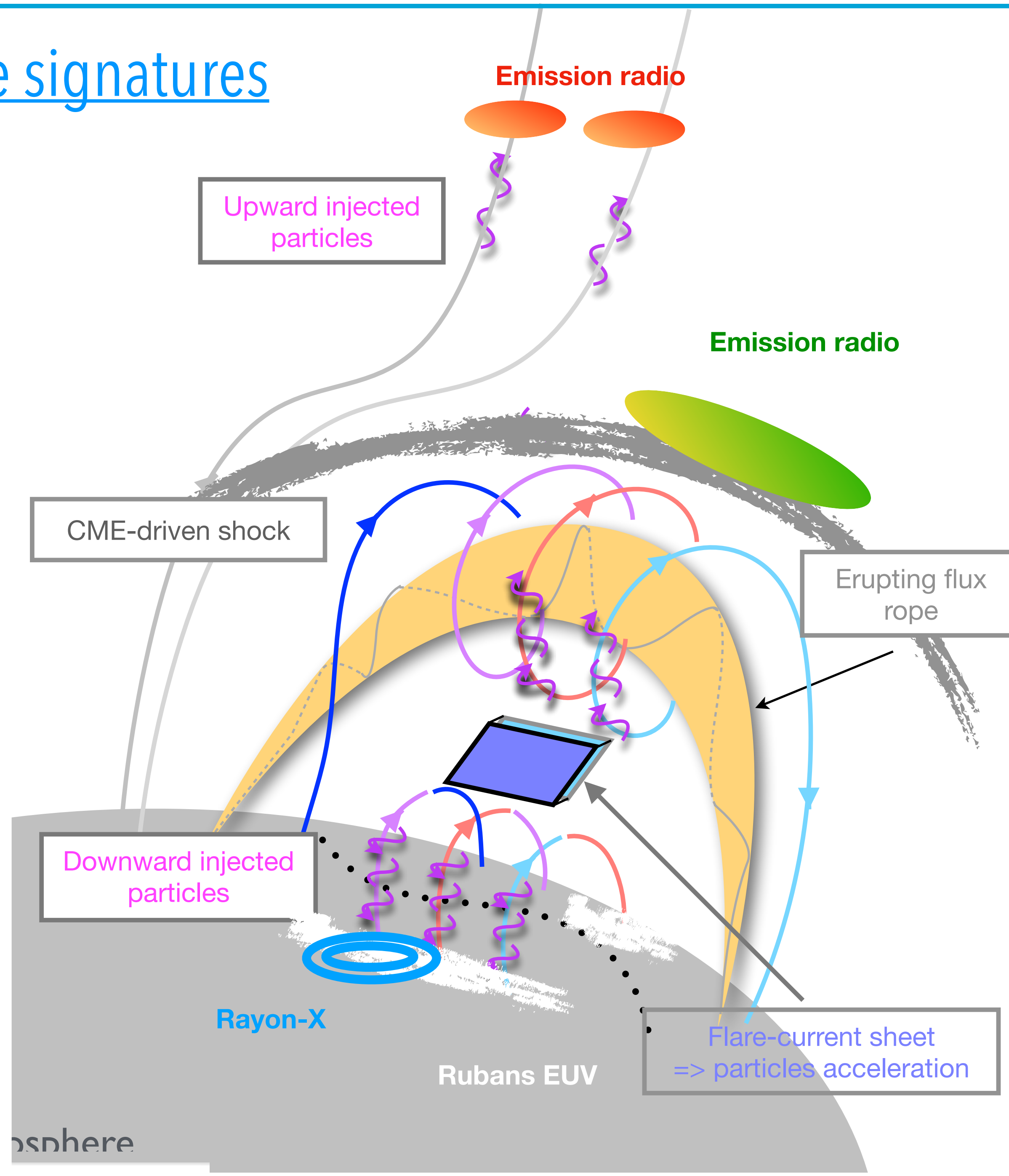
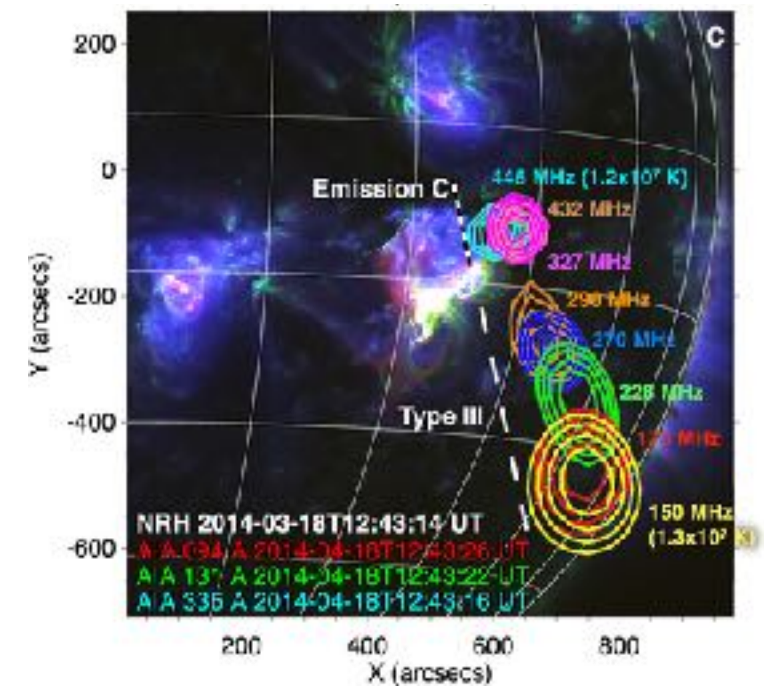
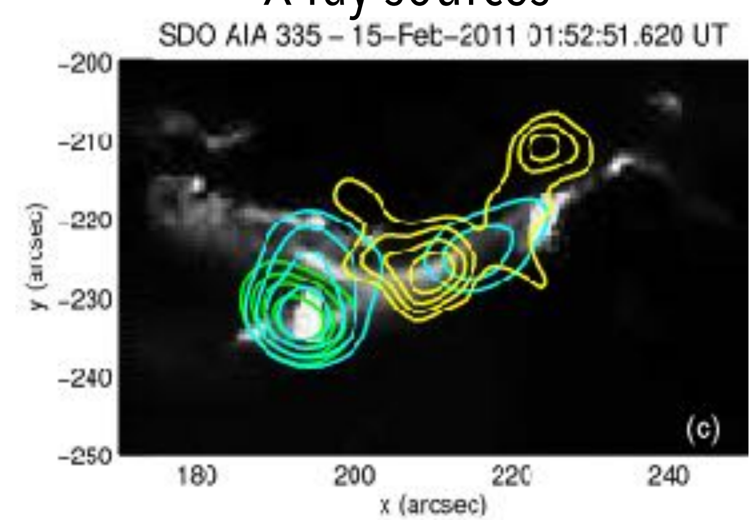


Radio emission



Carley et al., 2015

X-ray sources



Musset et al., 2015

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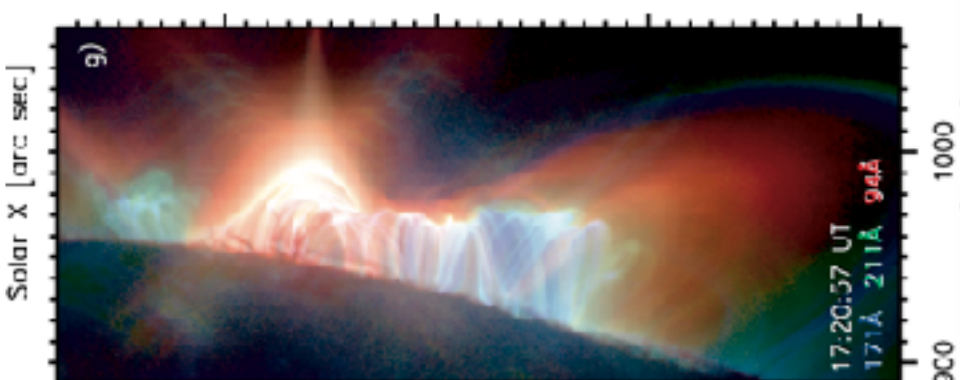

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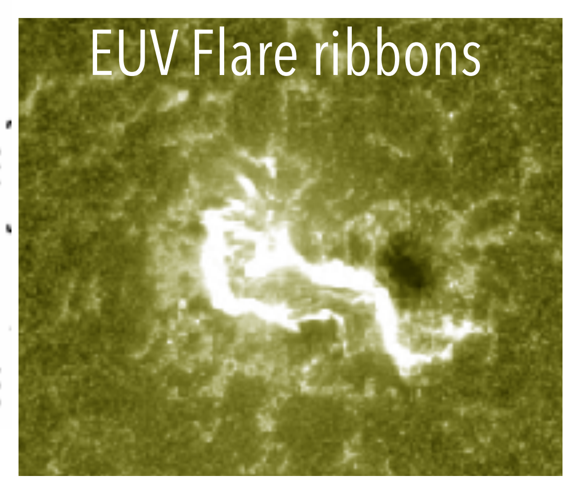

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Observational diagnostics

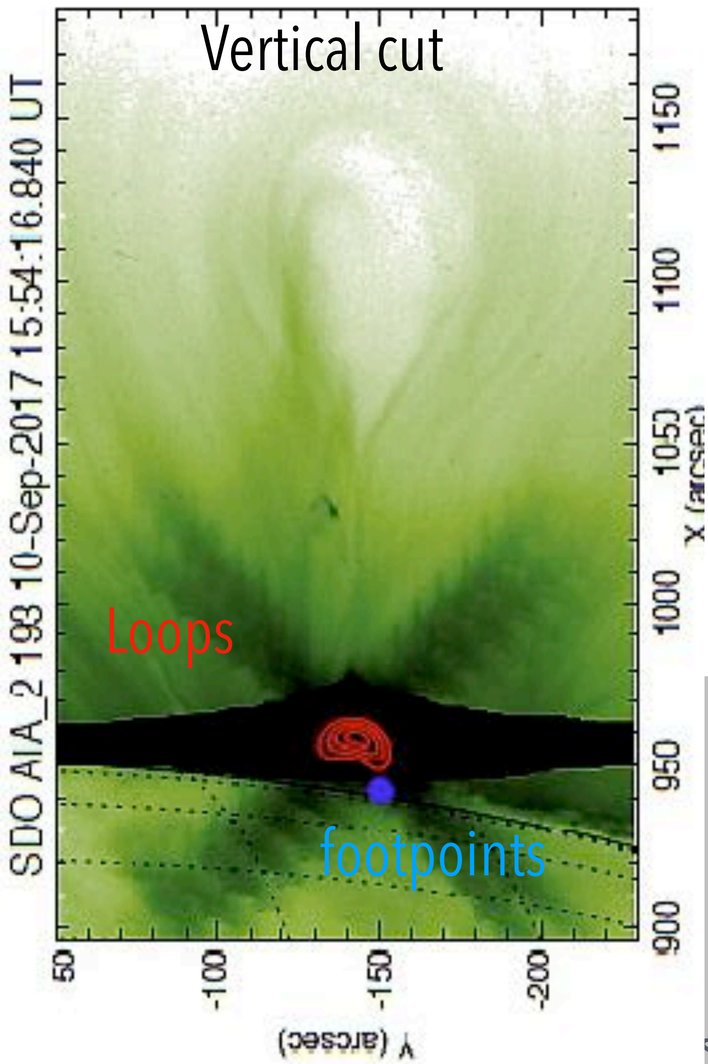
X-rays observations

Bremsstrahlung emission with ions from the very low corona :

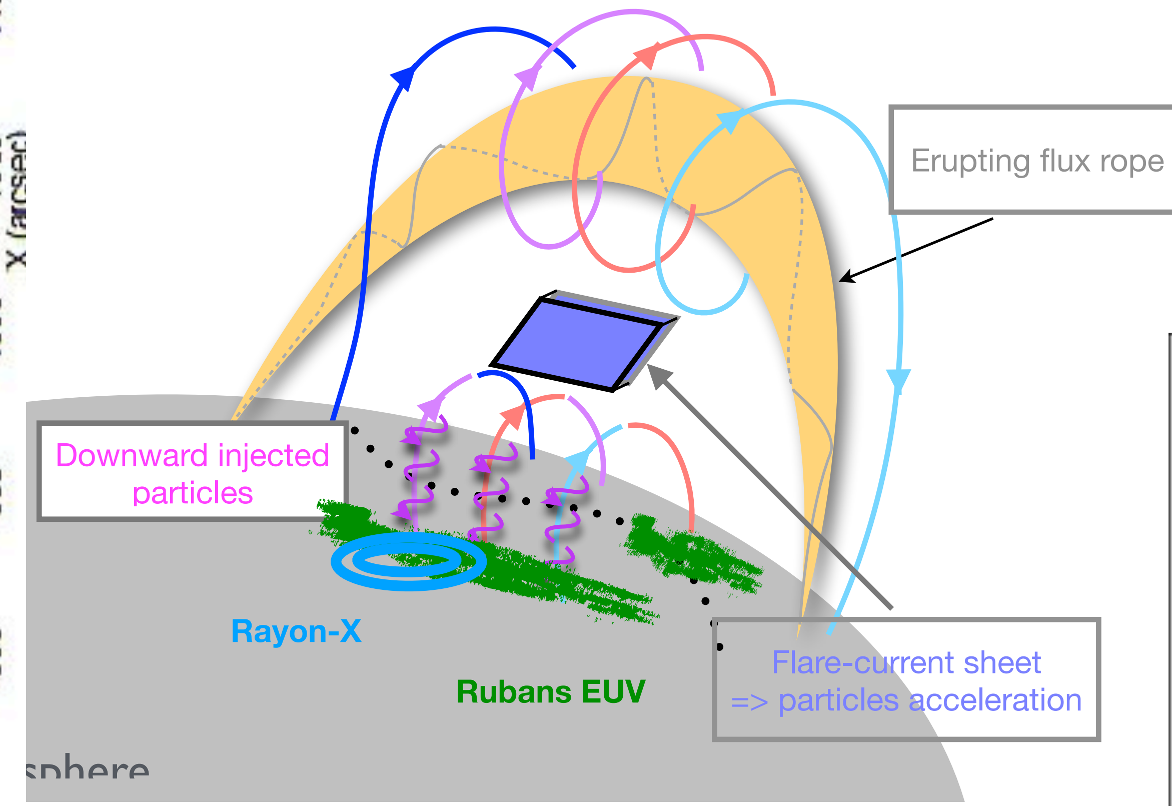
Soft X rays : E(e-) ~ 0,1 - 5 keV , thermal brem. Emission

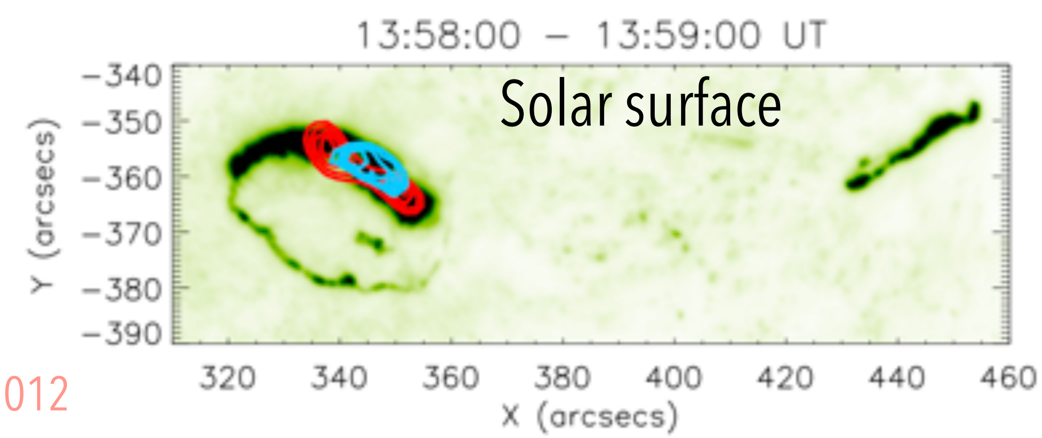
Hard X-rays : E(e-) ~ 10-100 keV

Photons and electrons spectrum, numbers of e-
Location of the X-ray sources / flare signatures (EUV ribbons)

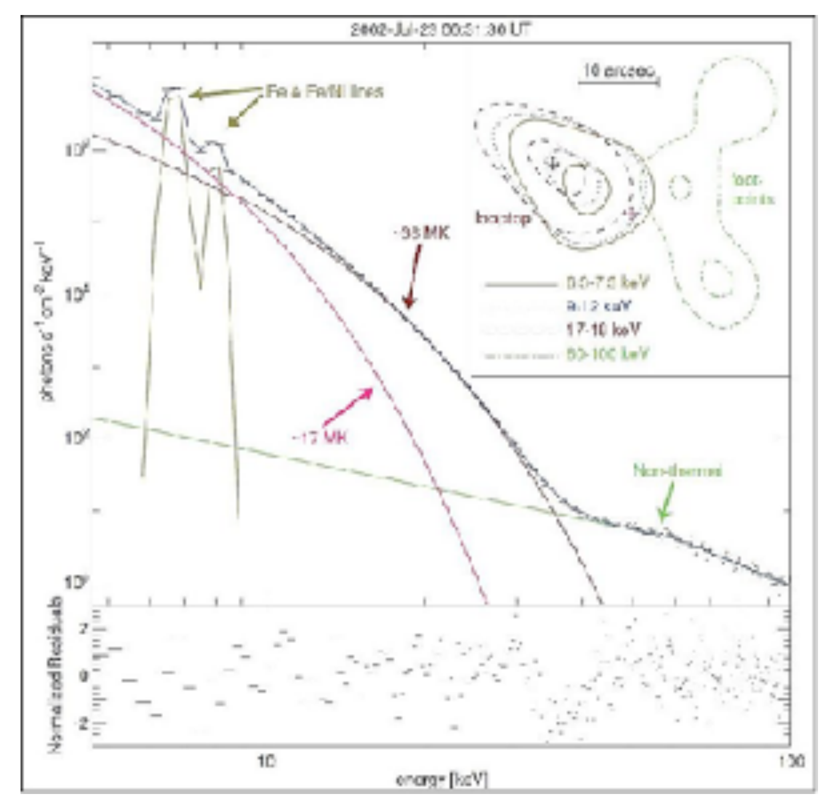


Dennis et al., 2017





Reid et al., 2012



Dennis et al., 2017

Observational diagnostics

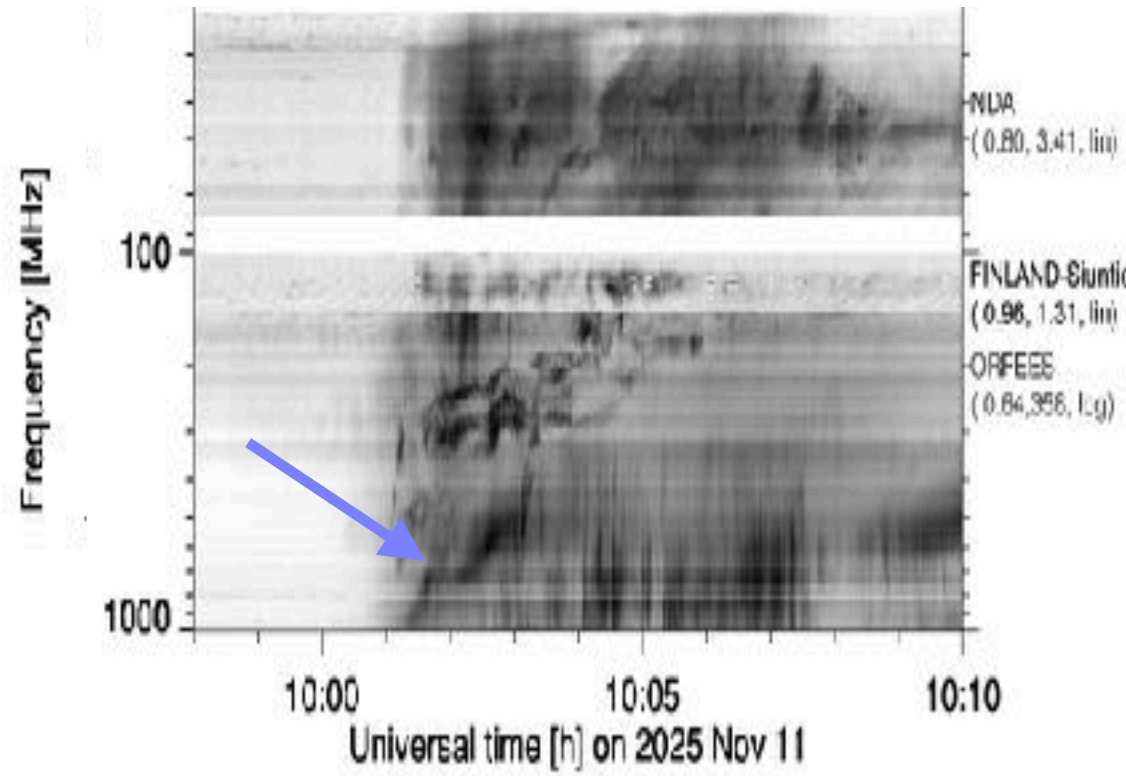
Radio emissions

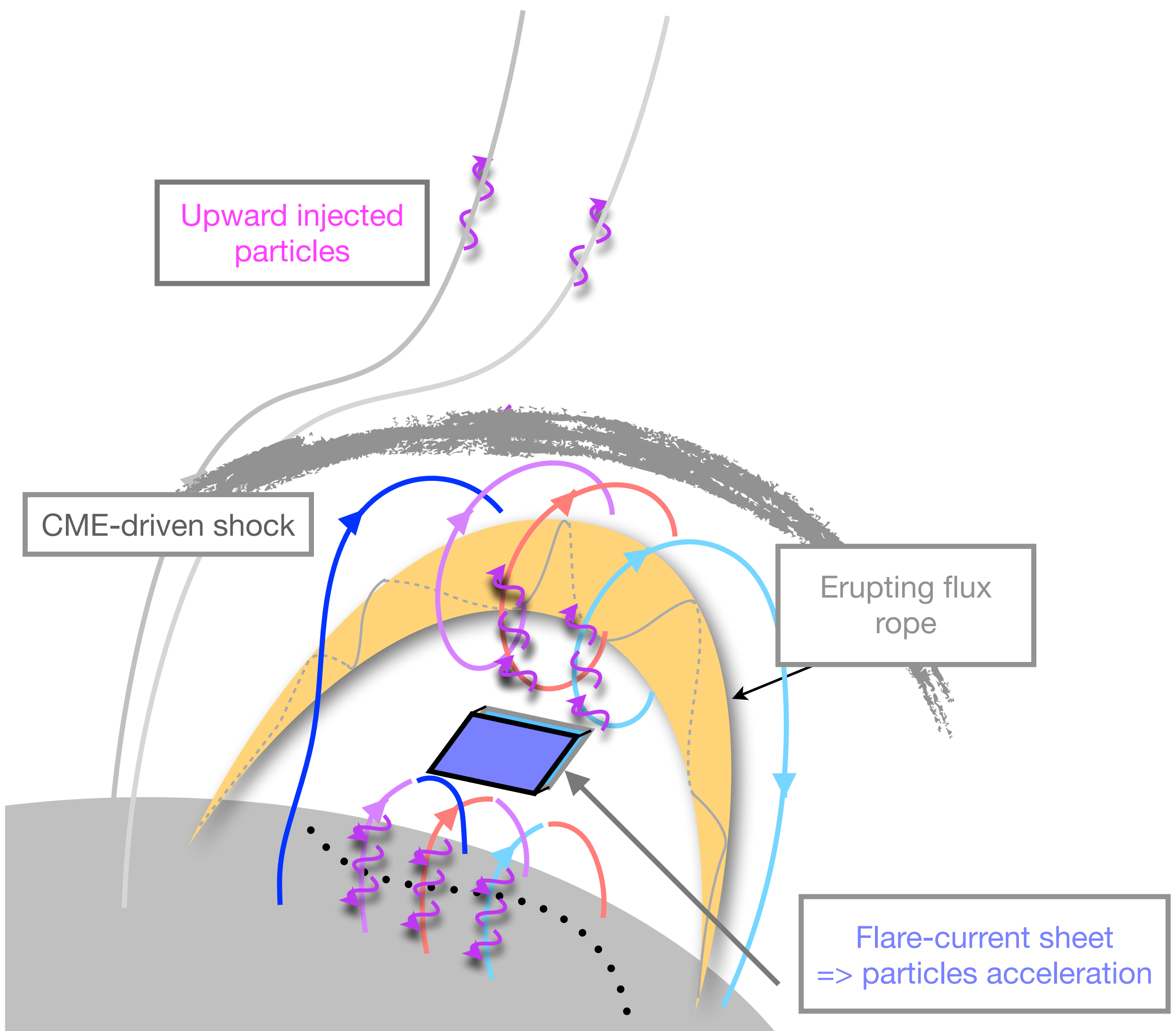
Synchrotron $\nu_B = \dfrac{eB}{2\pi m_e^- c} \simeq 2.8 \times 10^6 B\ [Hz]$ => depends on B

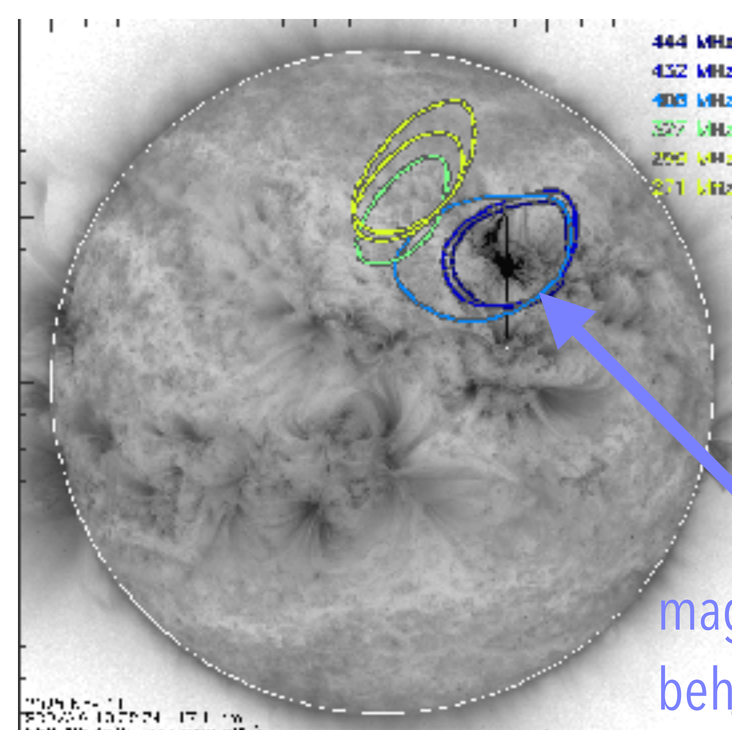
Plasma instability : $\nu_{pl} \propto \sqrt{n_e^-}$ => frequency decrease with solar distance

Radio interferometer : Location of the emissions
Dynamical spectrum : type of the emission

Dynamical spectrum







magnetic reconnection behind the CME (type IV)

Mishev et al., 2026

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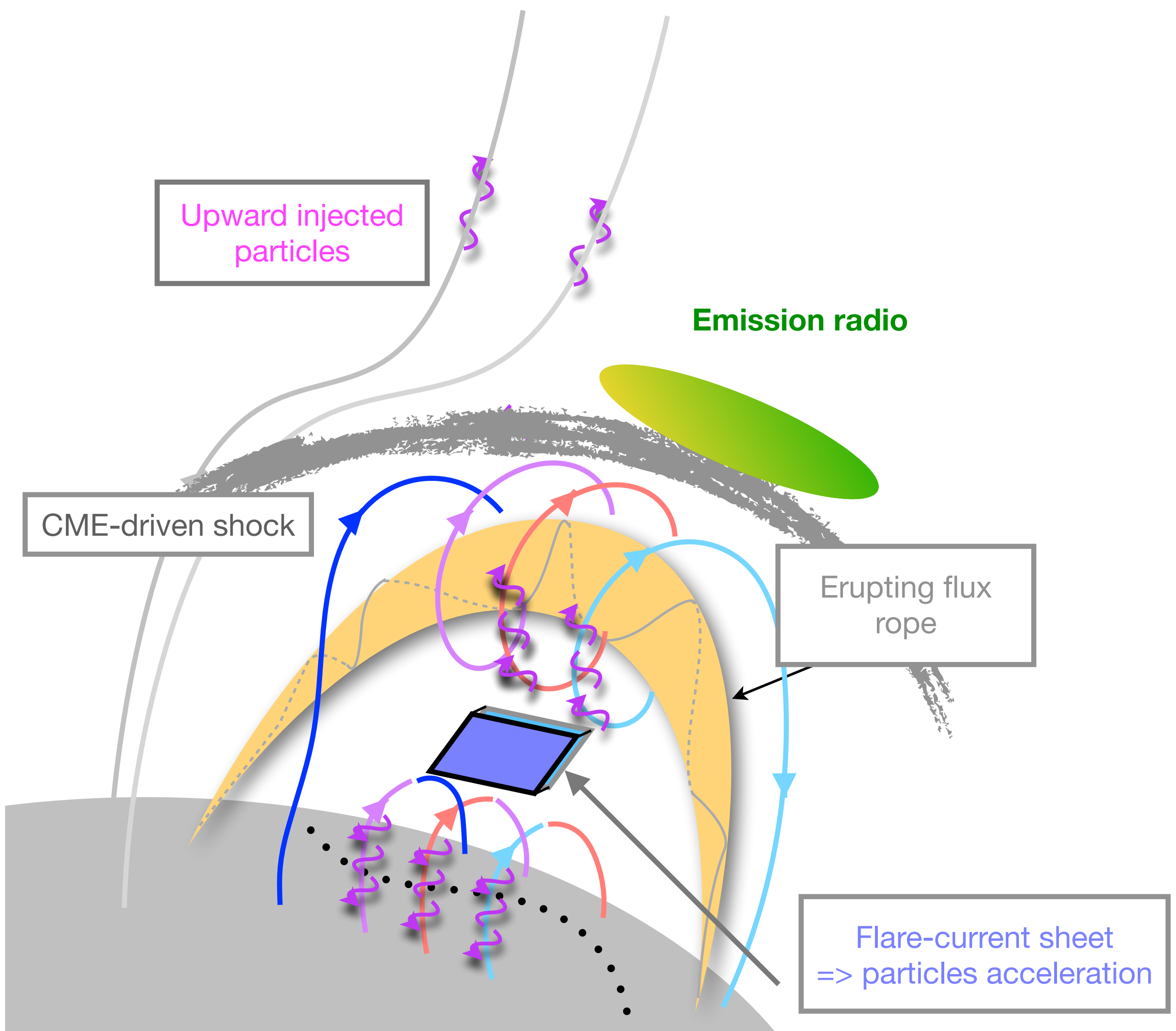
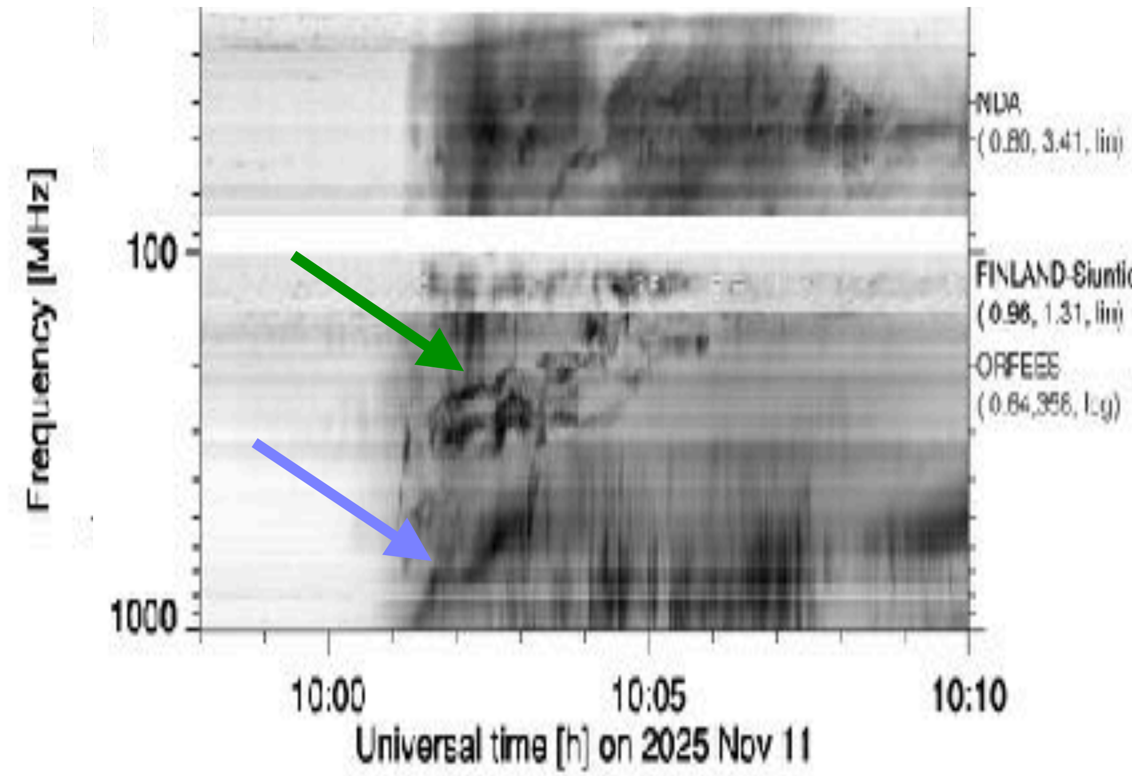
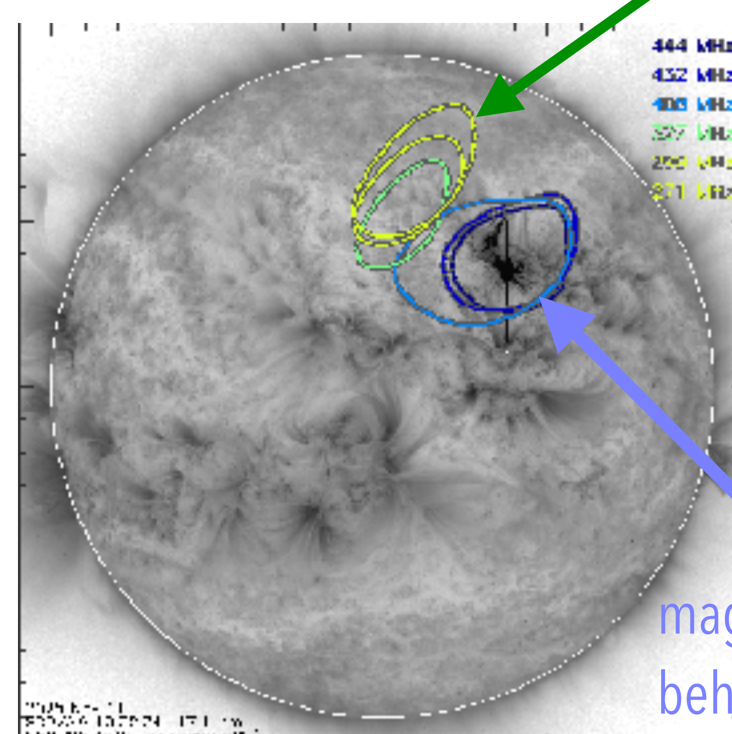


Dynamical spectrum



coronal shock : shock



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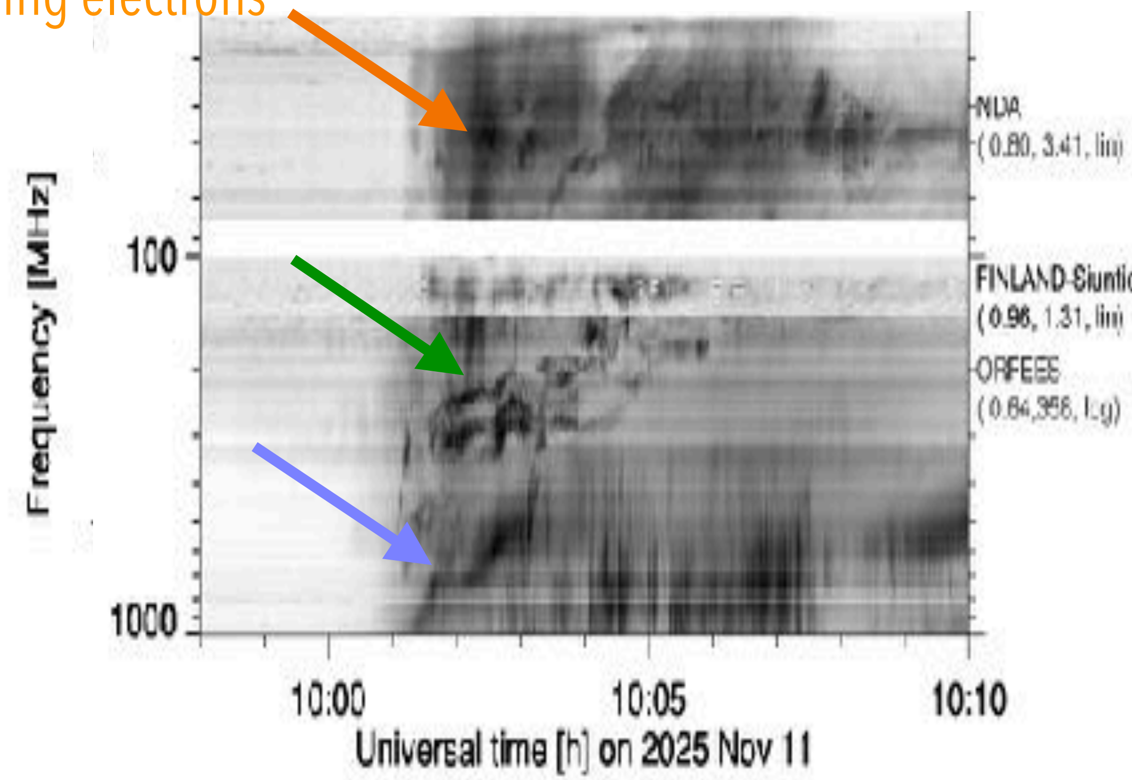
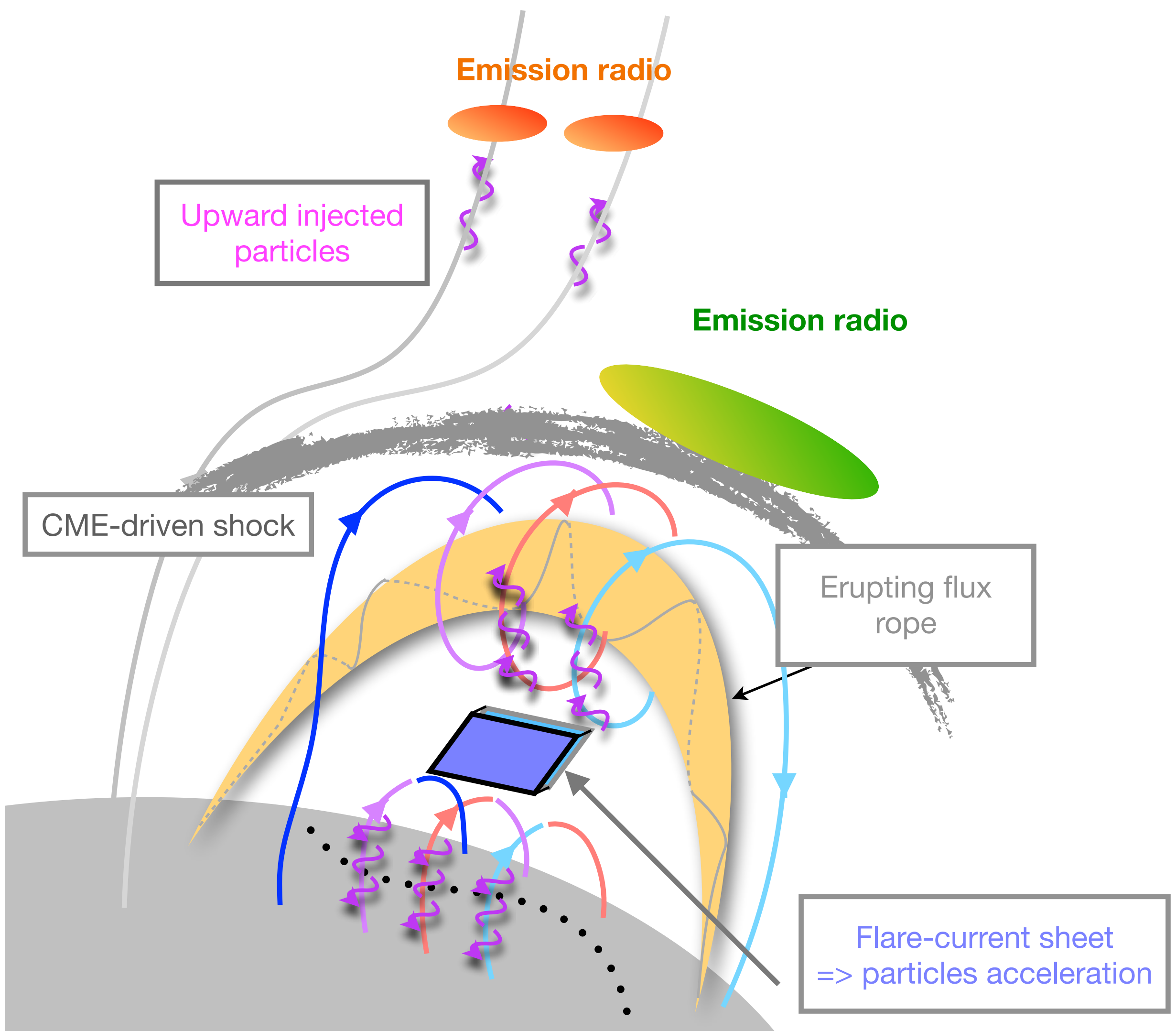
Dynamical spectrum

Escaping electrons





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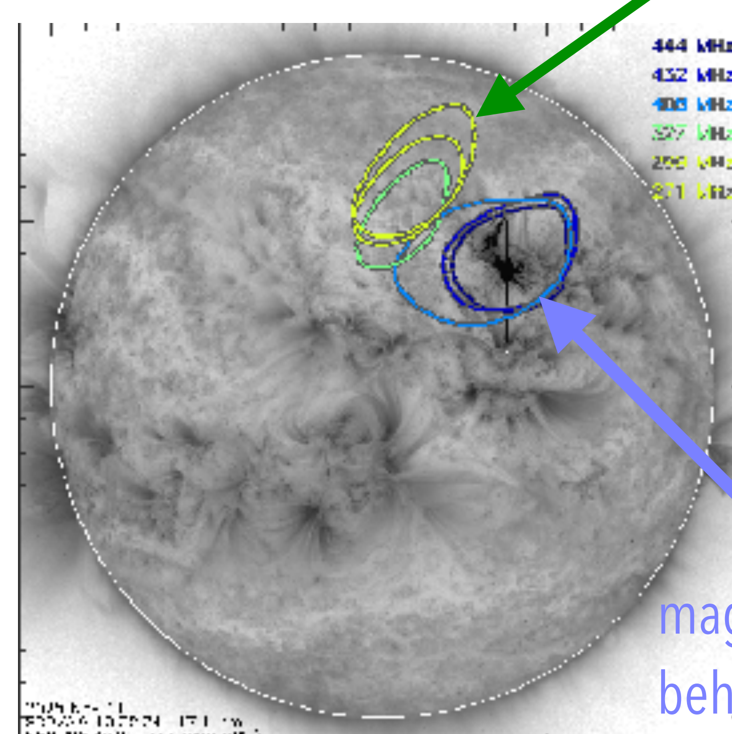
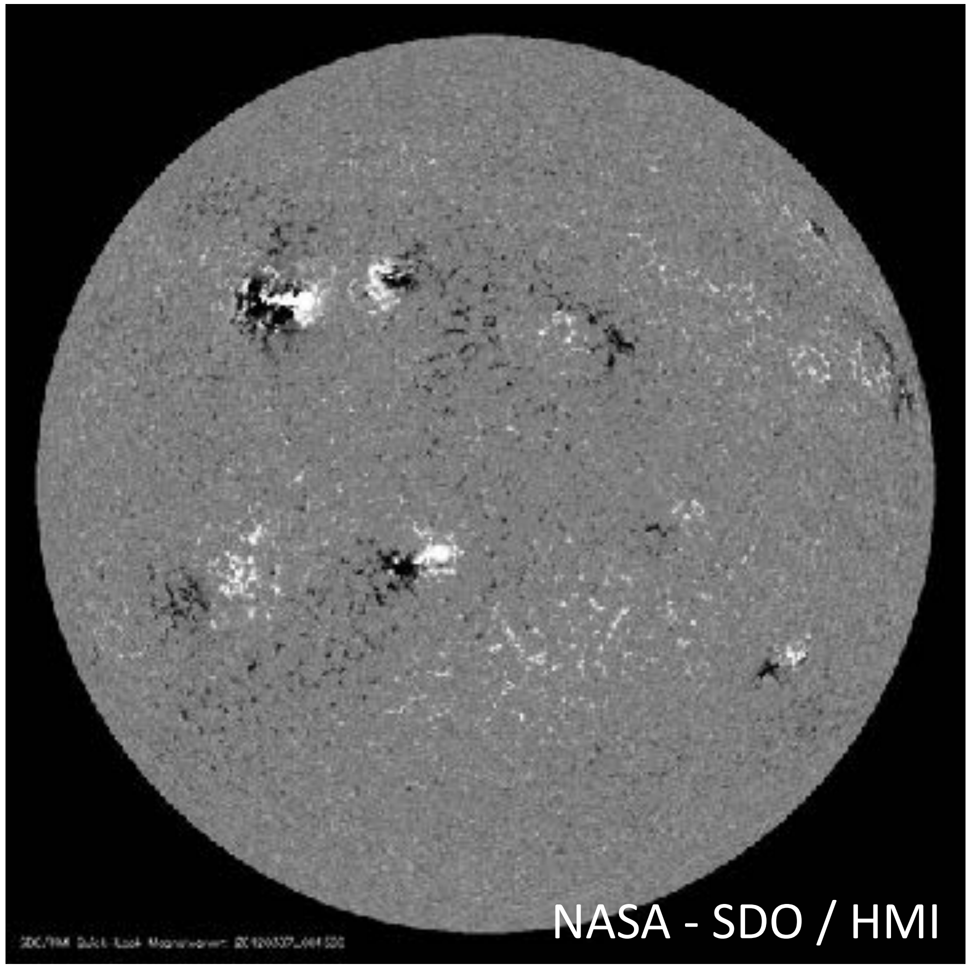


magnetic reconnection
behind the CME (type IV)

Mishev et al., 2026

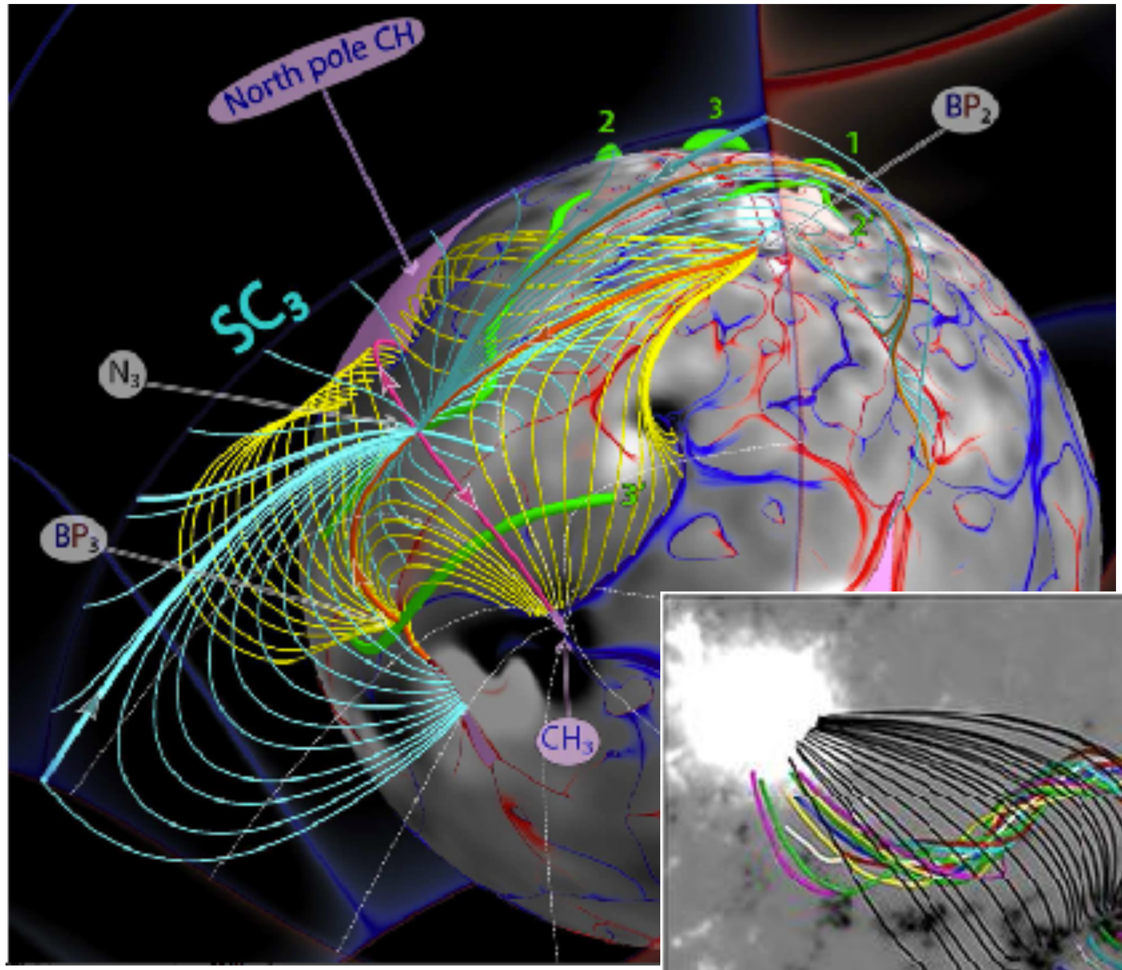
Magnetic field topology

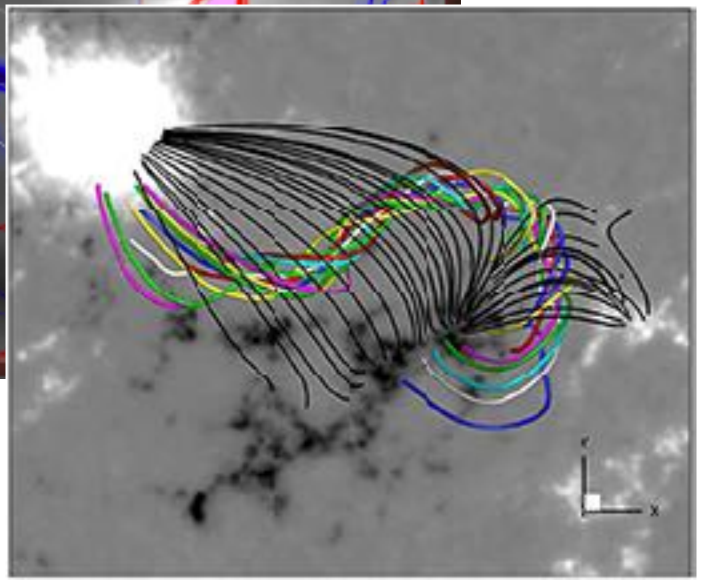
Magnetic field measurement at the solar surface



3D reconstruction of B-field

Titov et al, 2012



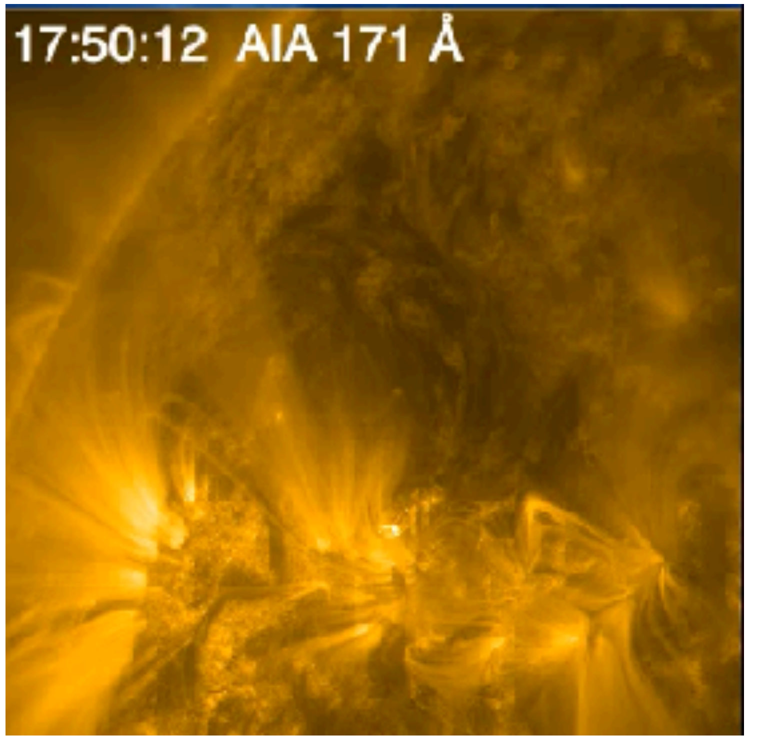


B-field topology :
Geometrical structures of magnetic connectivity

Discontinuity & gradient of B field connectivity

Magnetic reconnection sites

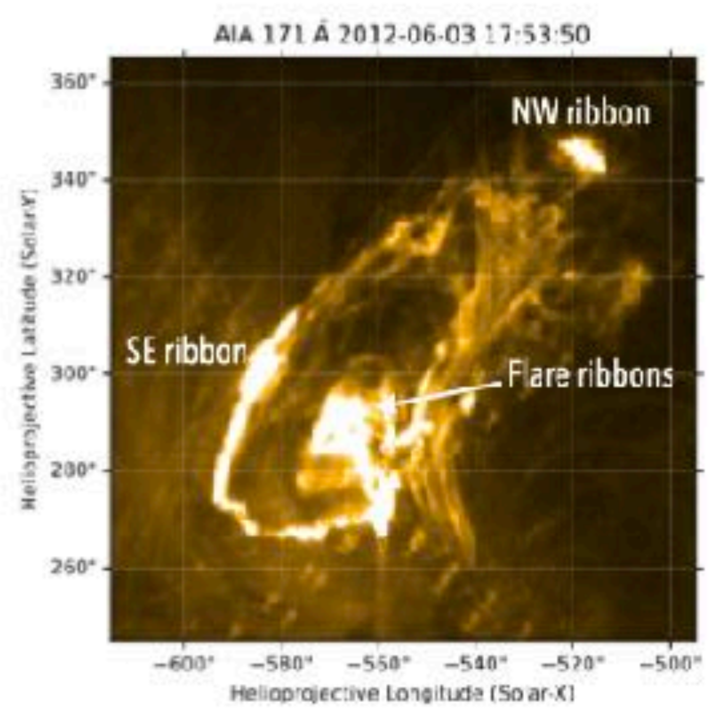
Identifying the acceleration process for 2 peaks γ-ray events



Identifying the acceleration process for 2 peaks γ-ray events

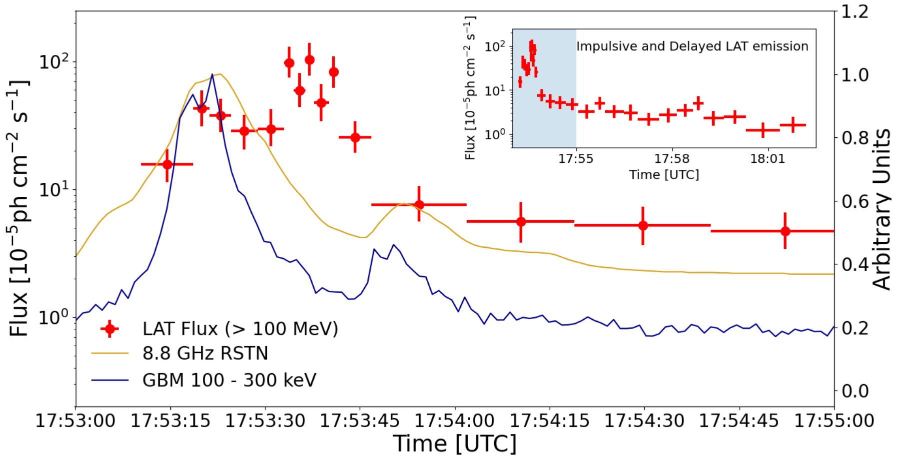
EUV ribbons :

footprints of reconnected magnetic field



Identifying the acceleration process for 2 peaks γ-ray events

FERMI/LAT : protons > 300 MeV



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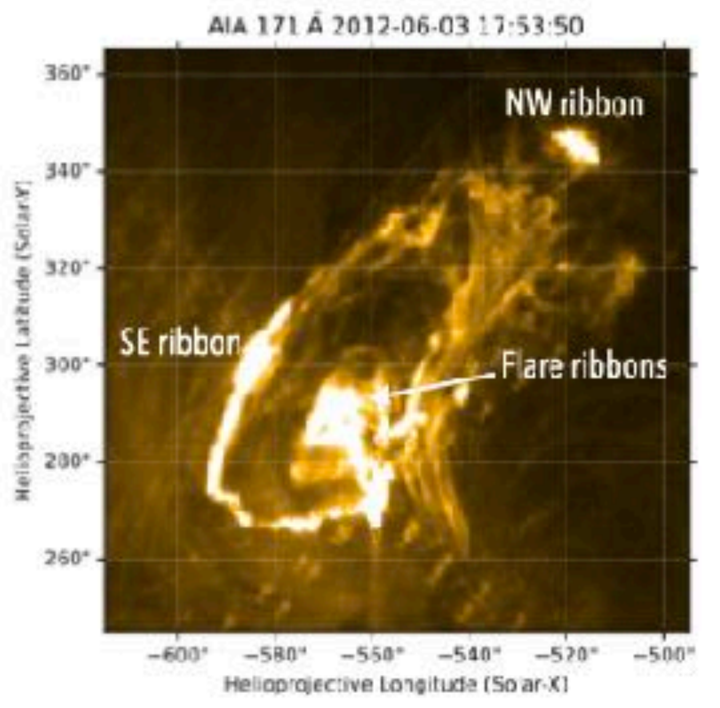
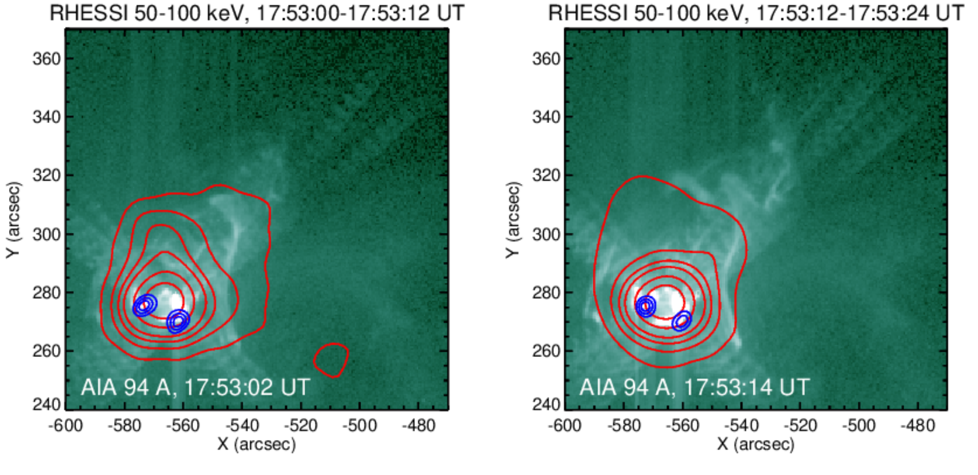


X-rays sources : energetic electrons impact



Pesce-Rollins et al., 2025

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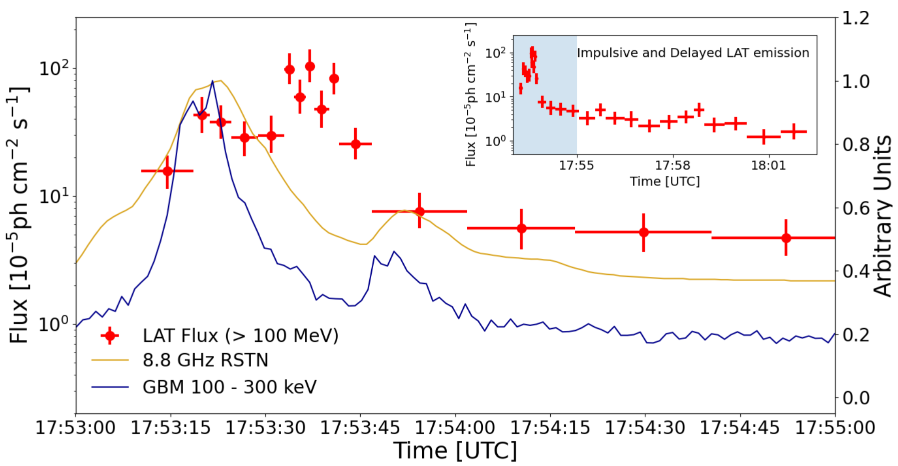

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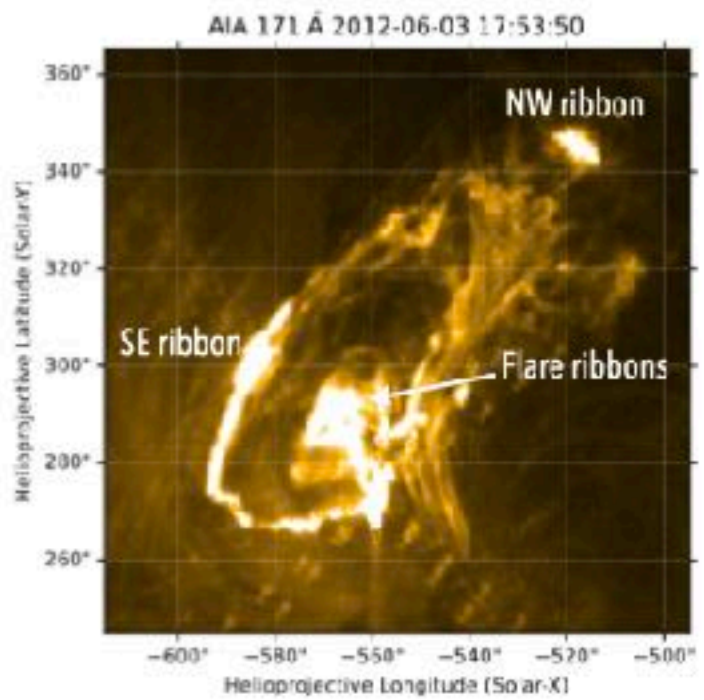

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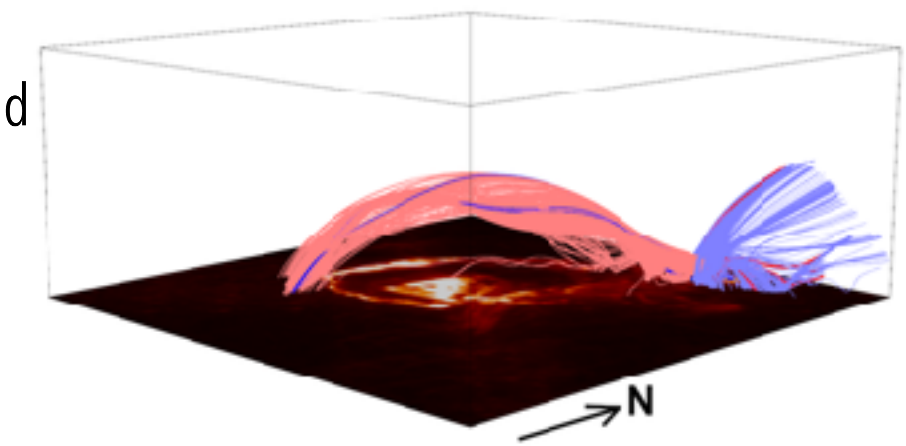

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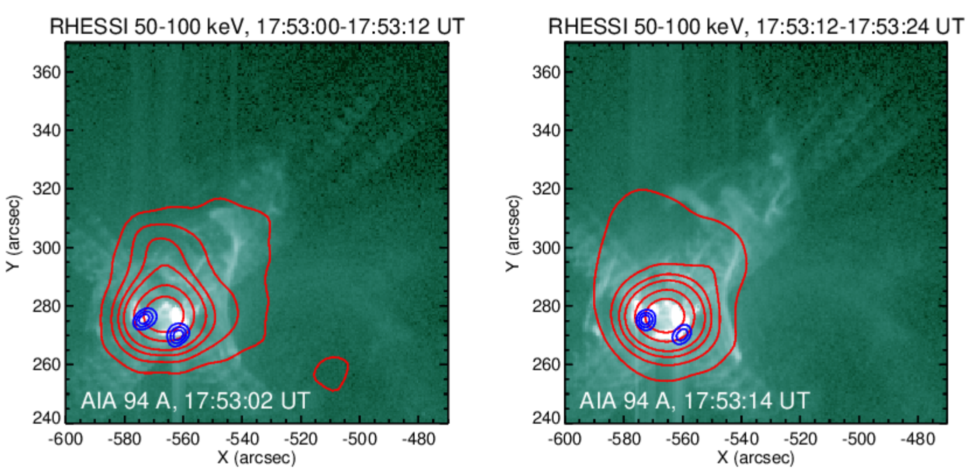

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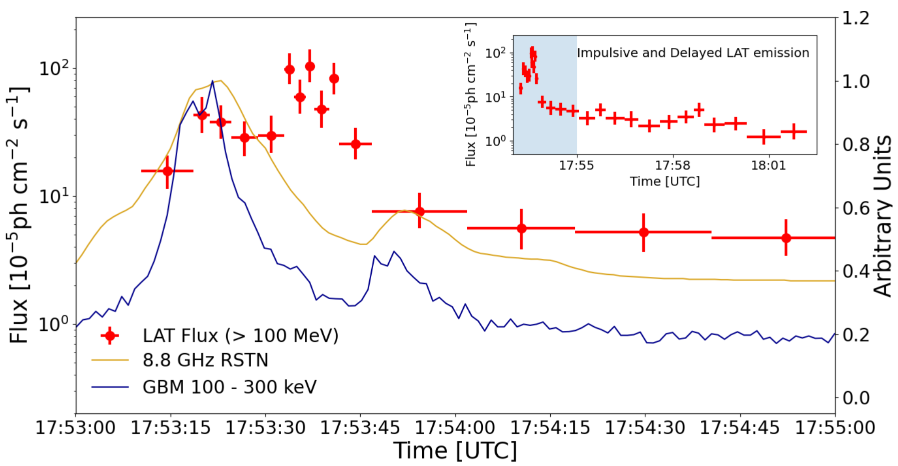

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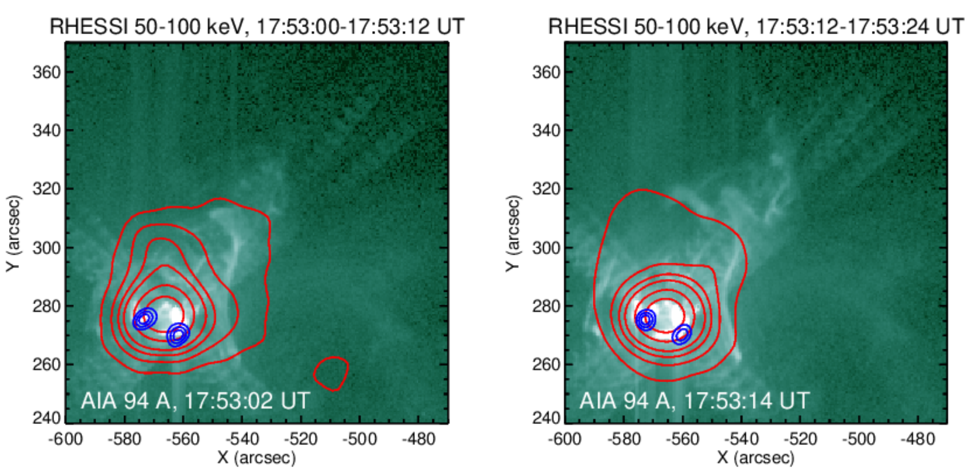

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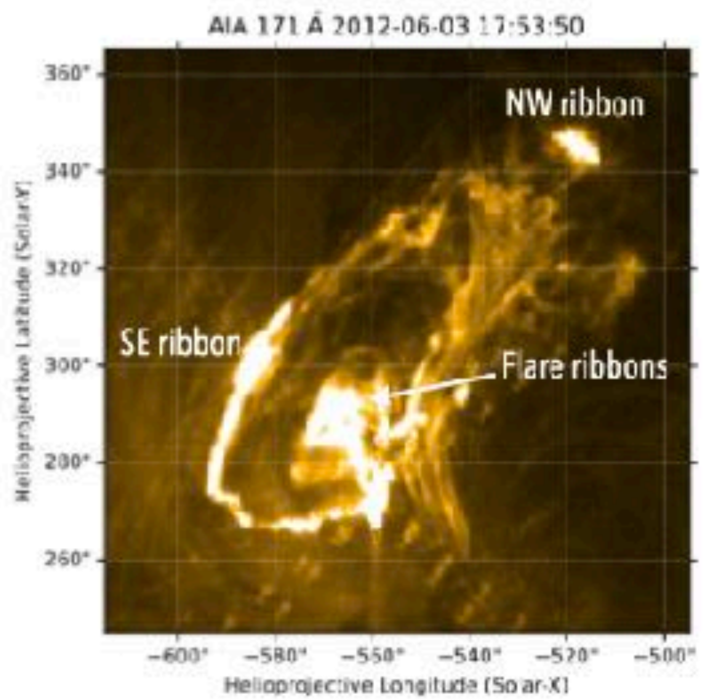

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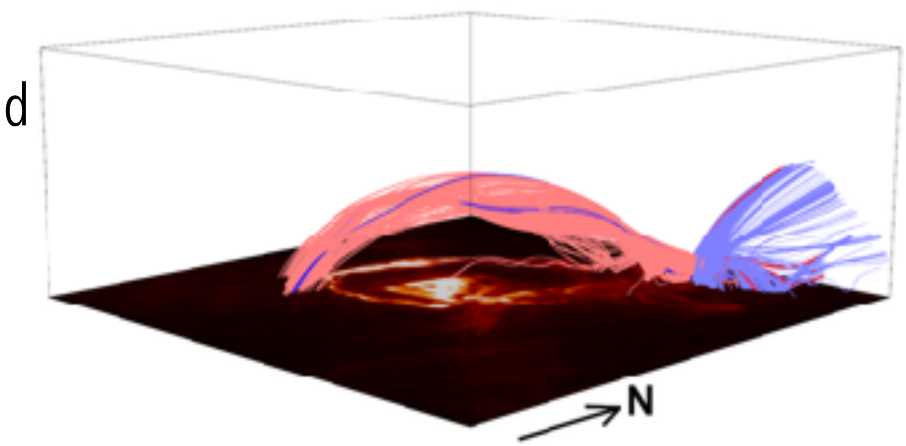
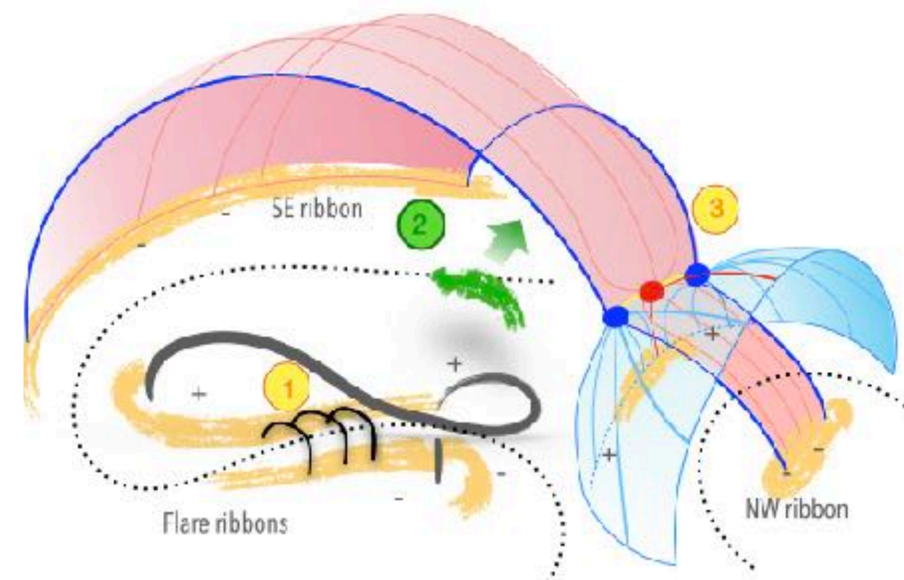
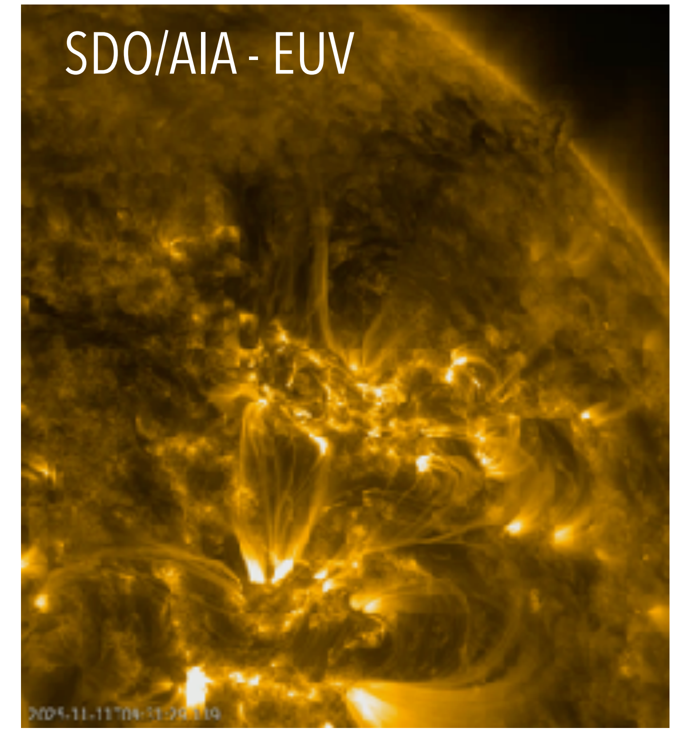




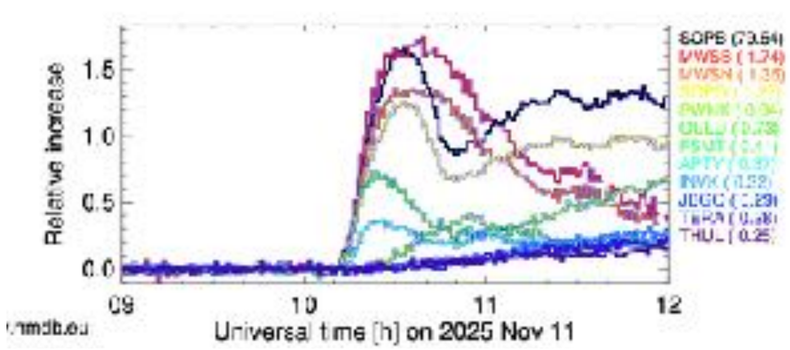
First acceleration related to **magnetic reconnection** during the main phase of the flare => protons & electrons
Second acceleration simultaneous with the erupting structures : **shock** or new **reconnection** episodes at the nulls

Solar relativistic particle event



Temporally associating radiative signatures

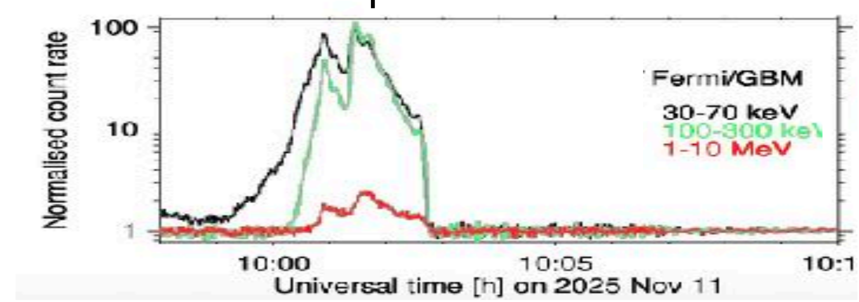
Solar relativistic @ Earth
Neutron monitors

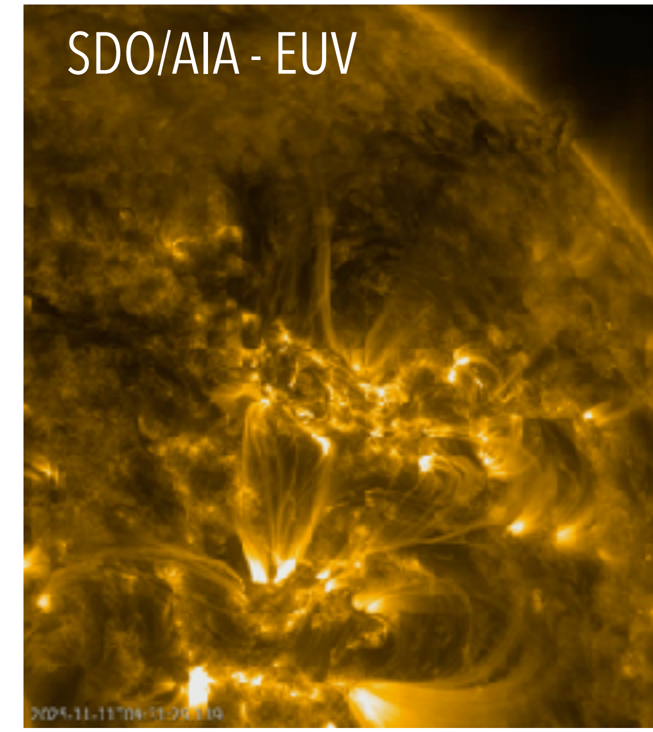


Solar relativistic particle event

X-rays/gramma rays

=> particles acceleration





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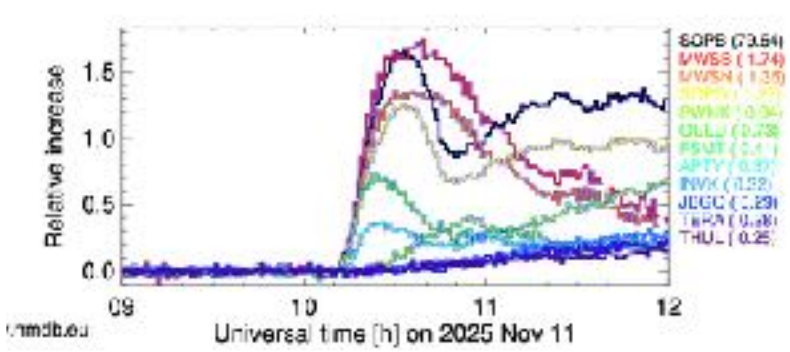


$$\mathrm{Lenght}(B_{\mathrm{helio}}) \simeq 1.2\ \mathrm{UA}$$

$$\Delta t = 1 - 2\mathrm{min}$$

Multi-wavelengths & Multi-messenger

Solar relativistic particle event

Temporally associating radiative signatures

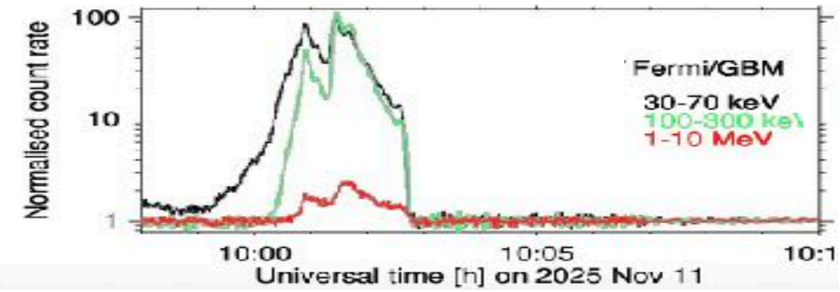
CME-driven shock and/or magnetic reconnection

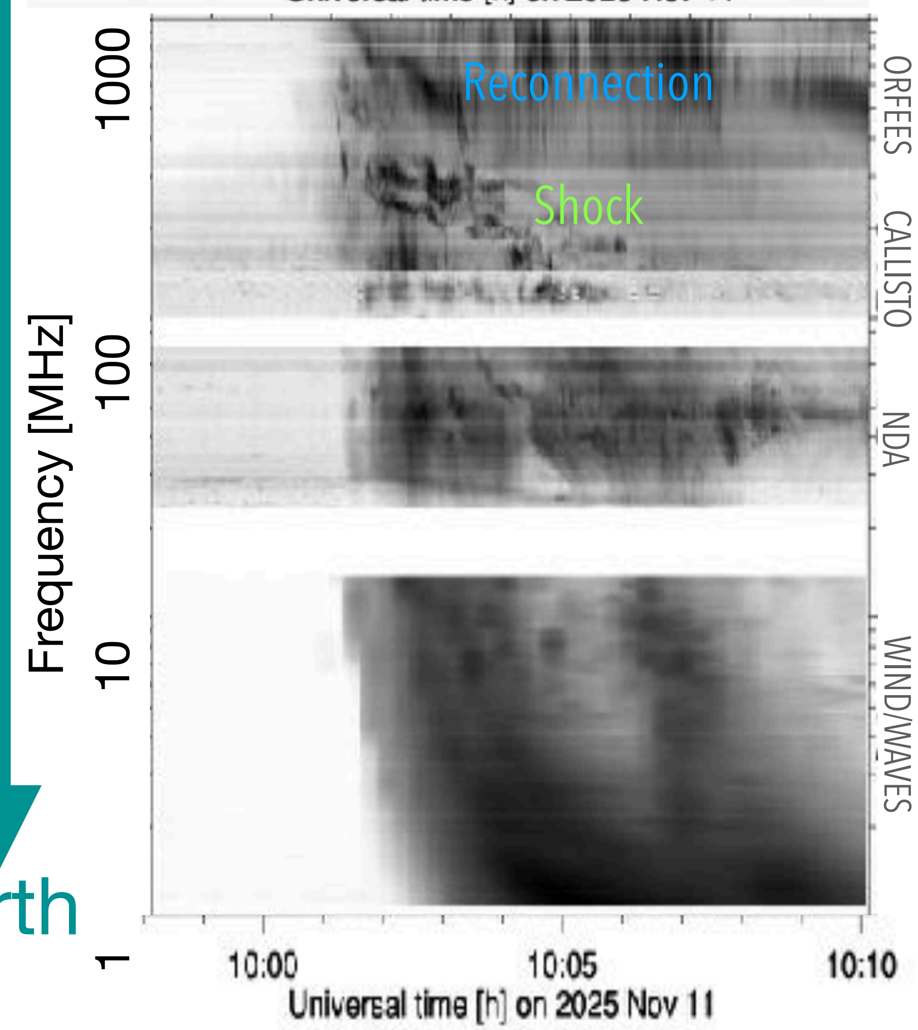
Mishev et al., 2026

Sun

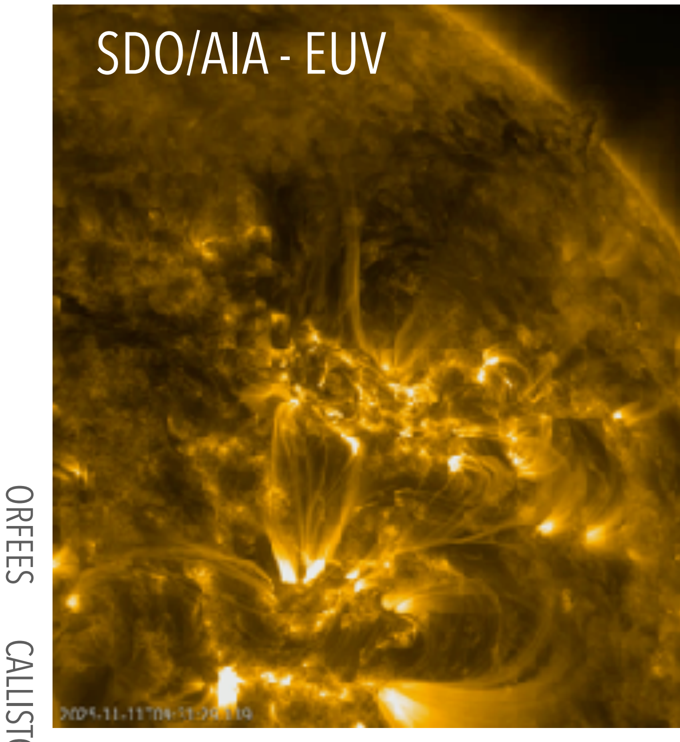
X-rays/gramma rays

=> particles acceleration





Earth



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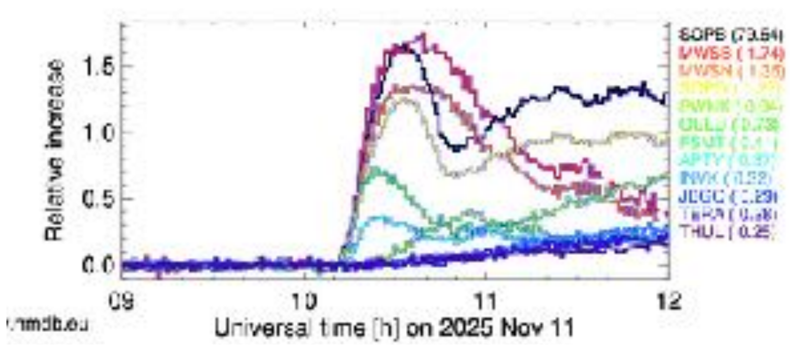

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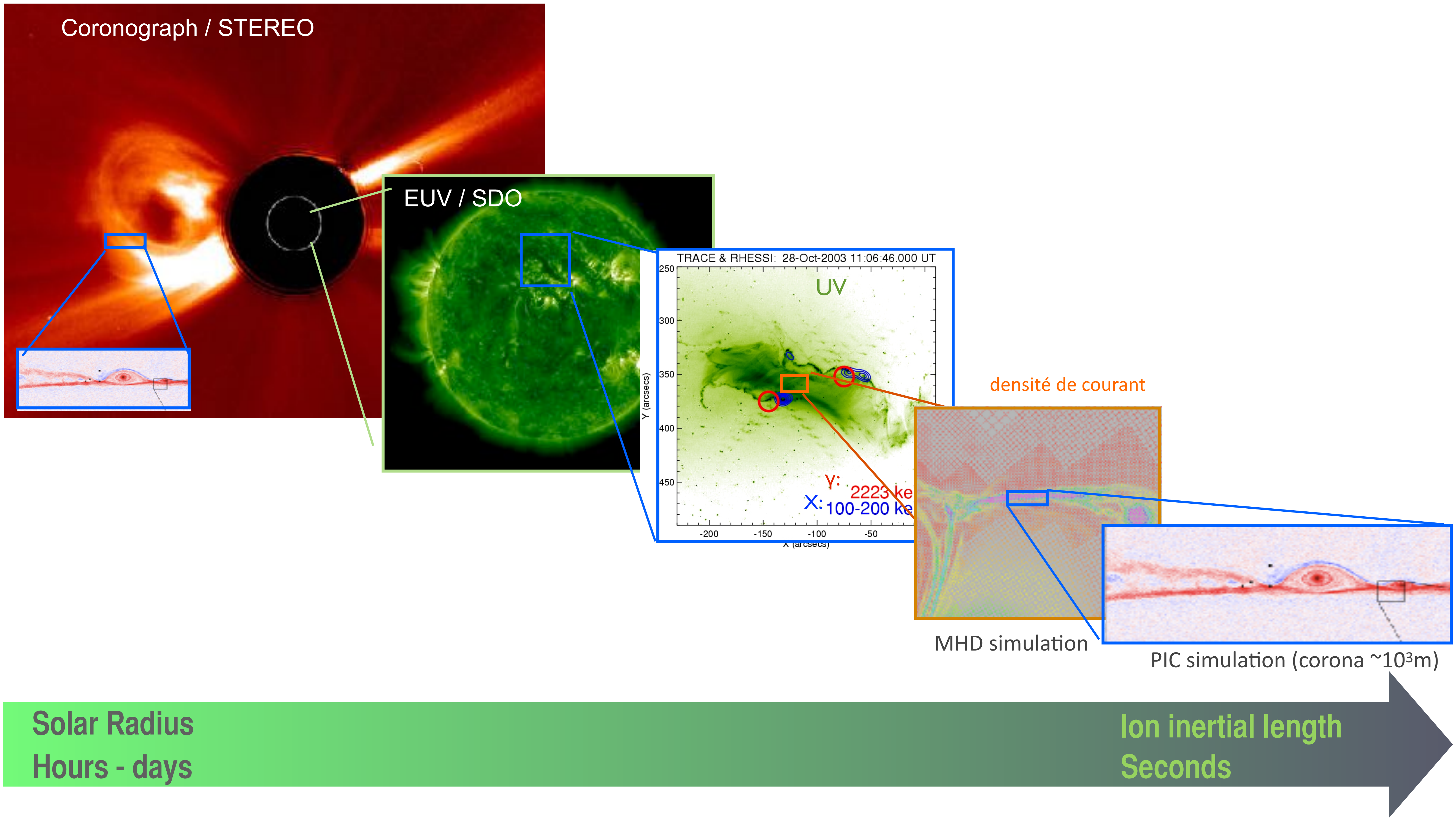
Scaling challenge



Modelling particle acceleration

Possible acceleration processes during solar eruption

Magnetic reconnection

Turbulence acceleration Petrosian et al., 2021, Stores et al., 2026

Magnetic island contraction / merging Arnold et al., 2021; Drake et al., 2019 Guidoni et al, 2016;2022;2024; Li et al., 2018

Electric field Gordovskyy et al., 2018; Gordovskyy et al., 2014

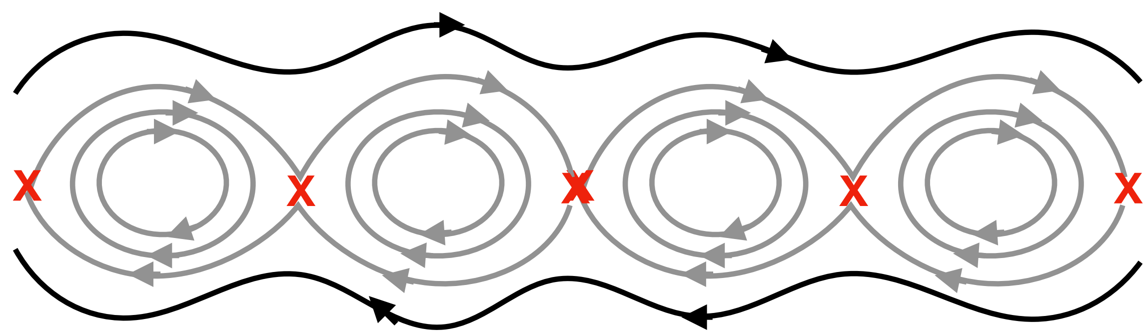
Fermi acceleration between islands Che &Zank, 2019

CME driven shock

Drift shock acceleration, Fermi acceleration Petrosian et al., 2021, Stores et al., 2026
Vainio et al.,2004, 2018

Current sheet fragmentation : Tearing instability

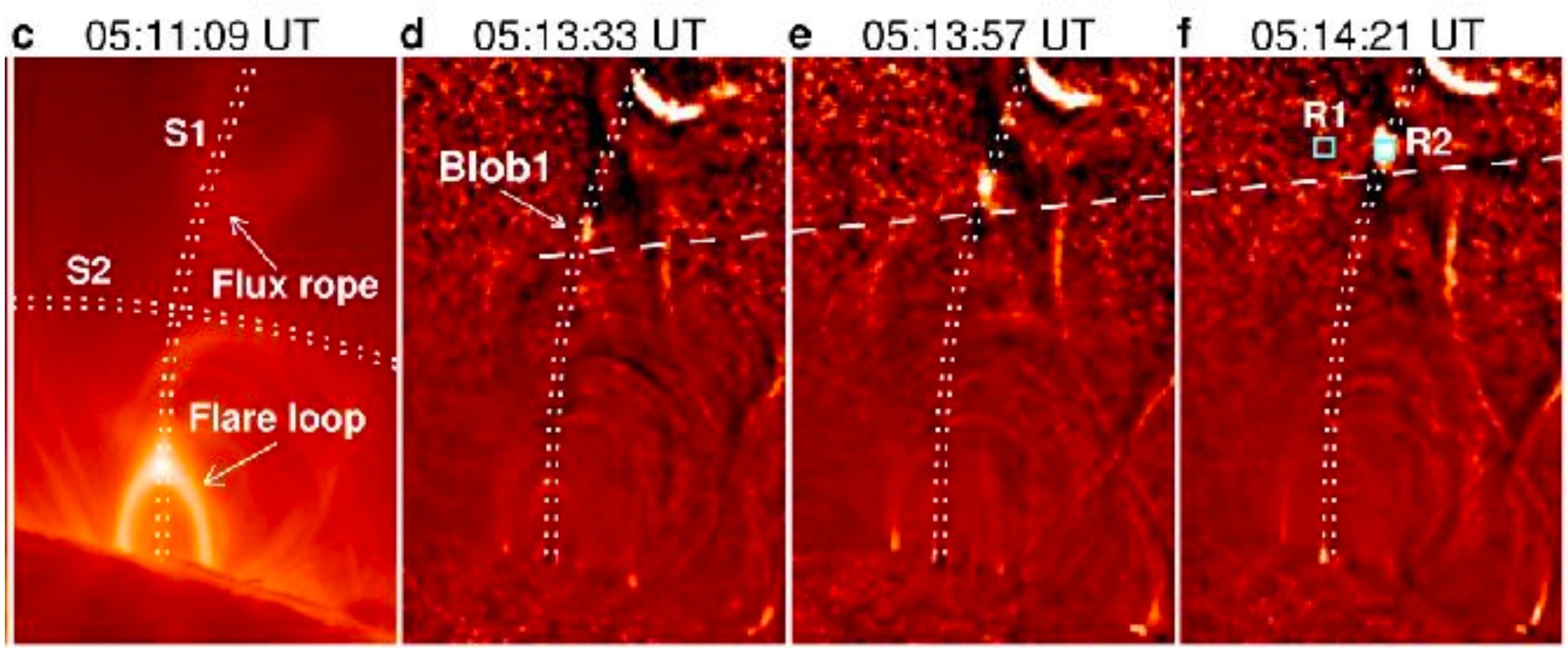
Furth 1963



Current sheet

2D magnetic islands

Observations



Plasma EUV **blobs** (not islands) in the flare-current sheet behind the CME (flux rope)

Lu et al, 2022

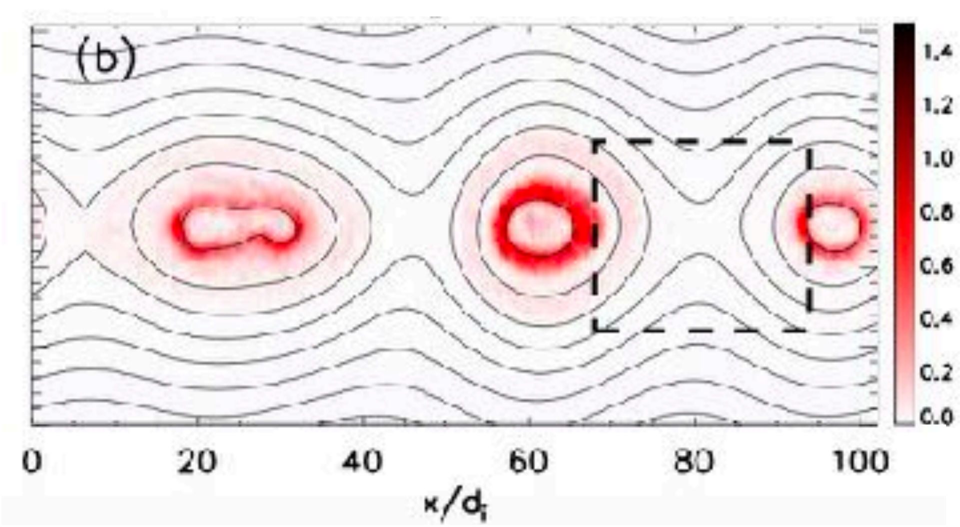
Modelling particle acceleration

- Particles acceleration Drake et al., 2006; Guidoni et al., 2016; 2022; Arnold et al., 2021
- Explosive nature of the flares = increasing the reconnection rate Kliem et al., 2000; Karpen et al., 2012
- EUV ribbons small-scale structures Wyper & Pontin 2022; Dahlin et al., 2025

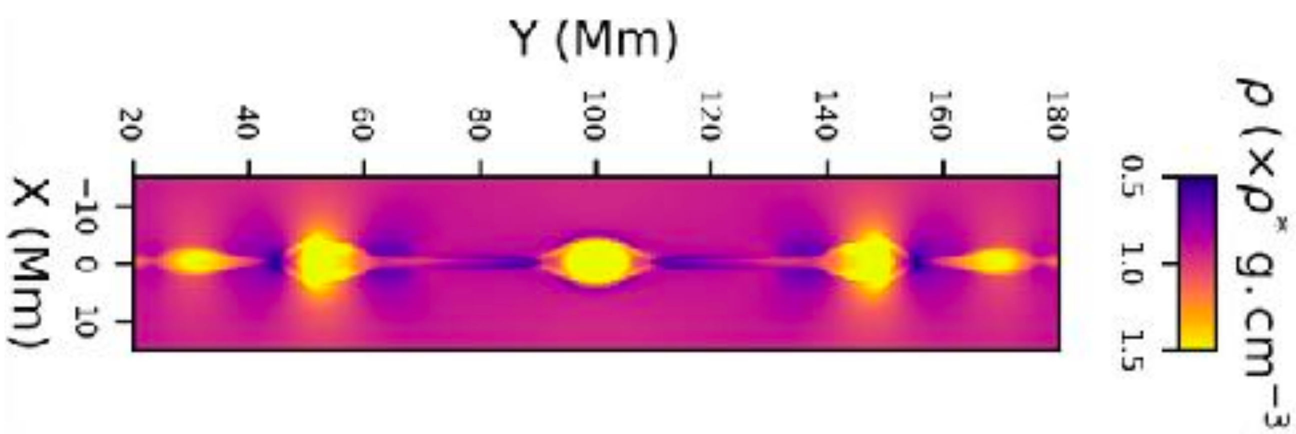
Tearing instability simulations

- PIC simulations Dahlin et al., 2017

Parallel energy density e-



- MHD simulations Mondal et al., 2024



Magnetic island contraction & merging

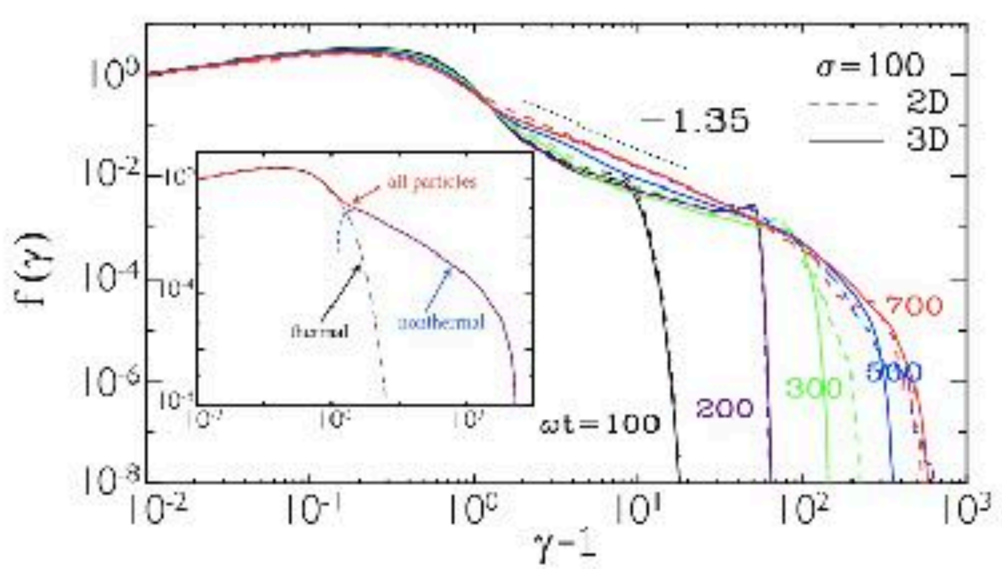
Drake et al., 2006;Guidoni et al., 2016

Efficient acceleration for μ (magnetic momentum) & J (angular momentum) conserved
=> B length decrease : increase of particle speed

Numerical domain ~ 10^4 km & 1 cell : 10^3m

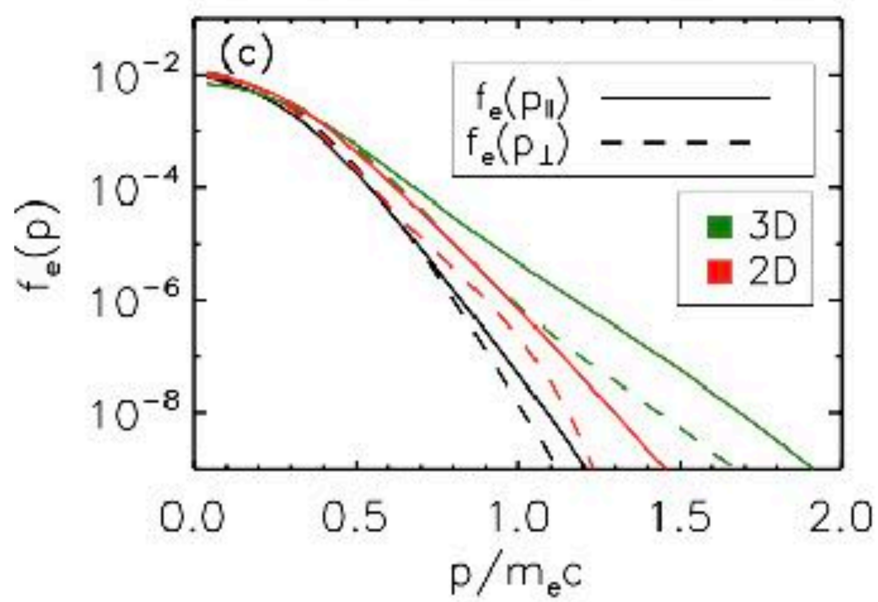
- **2.5D full PIC**

Power-law Distribution



relativistic PIC Guo et al.,2018

Non-power-law Distribution



Mildy relativistic PIC Dahlin et al., 2014

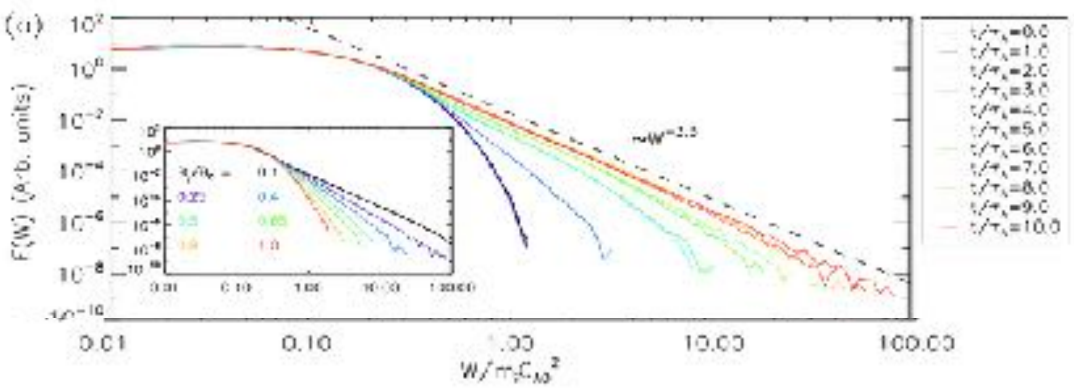
Solar conditions

=> limited acceleration & no power law

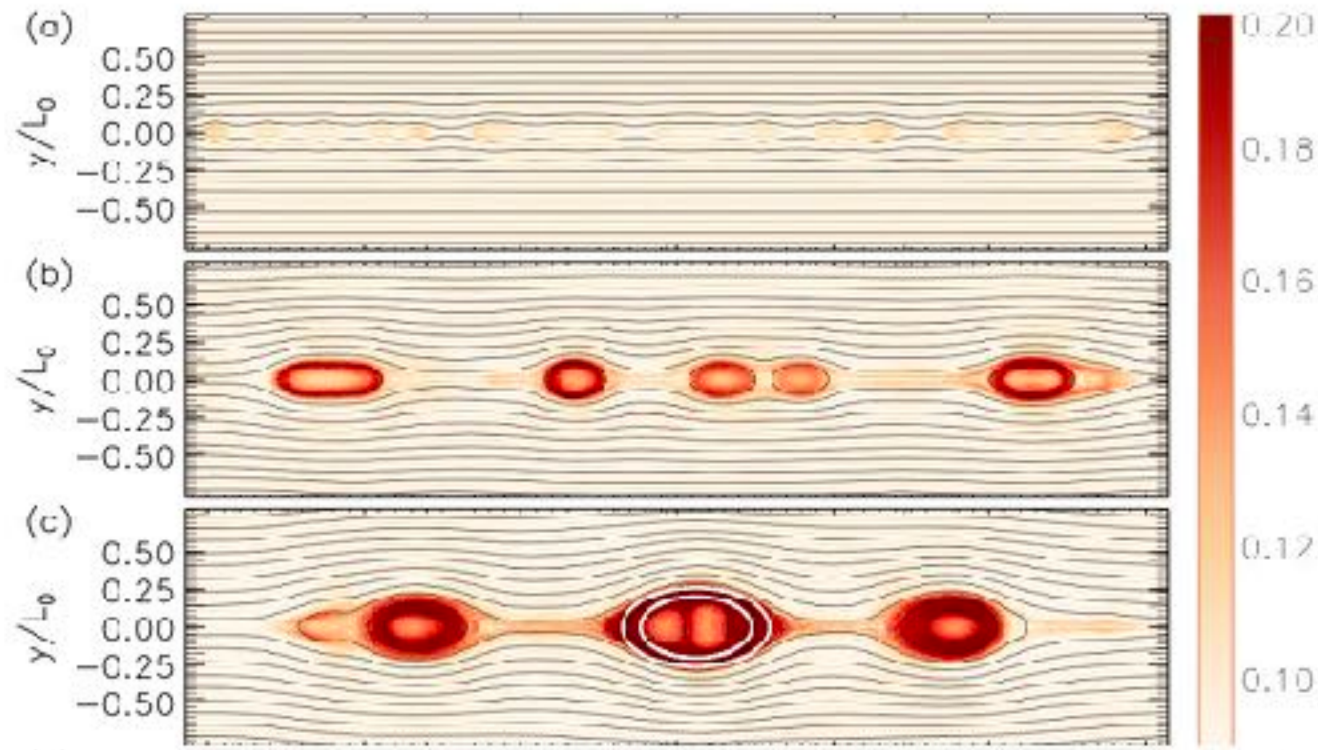
Magnetic island contraction & merging

2.5D MHD current sheet + **kinetic** electrons as macro-particles

+ hyper resistivity to speed up reconnection

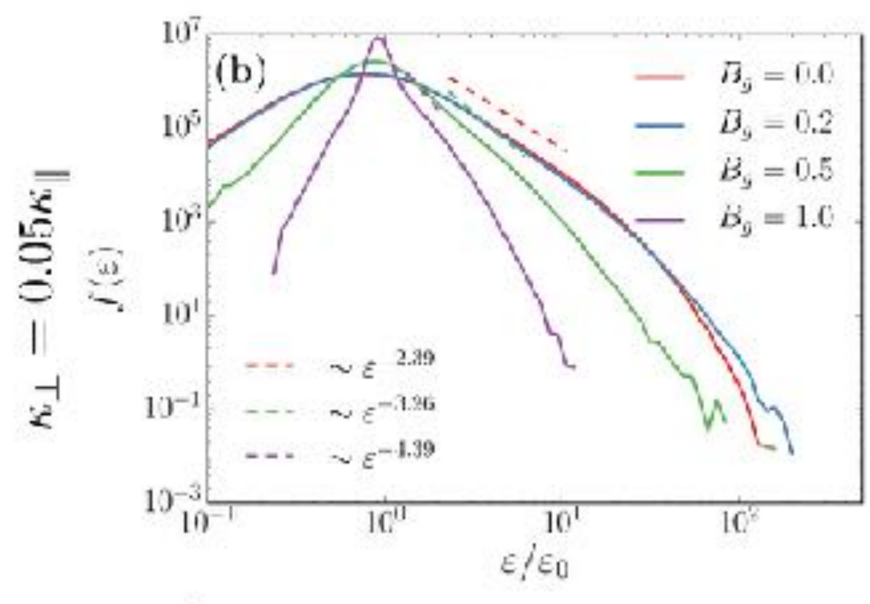


Electron spectrum extends over 2 decades



Drake et al., 2019; Arnold et al., 2021

Some limits

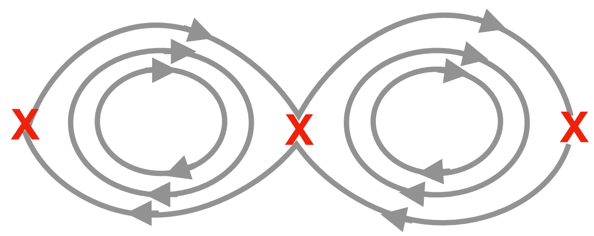


Strong guide field decrease the acceleration efficiency

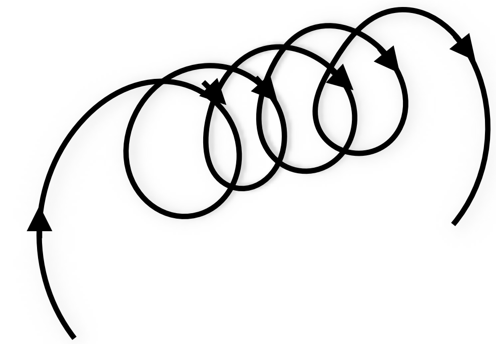
Li et al., 2018

What happens for tearing instability in 3D then ?

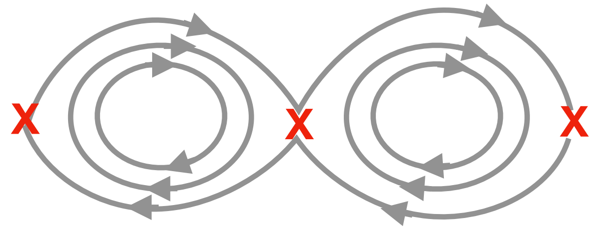
Current sheet fragmentation in 3D …



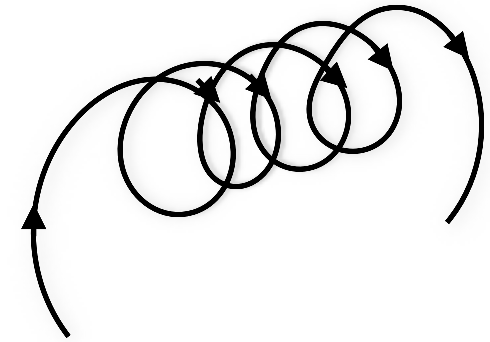
2D magnetic islands ≠ 3D plasmoids



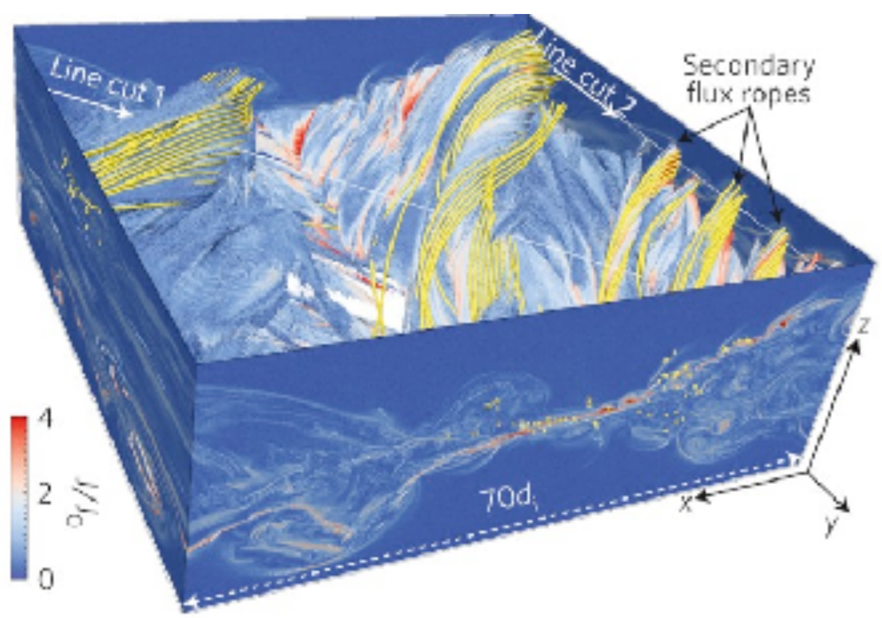
Current sheet fragmentation in 3D …



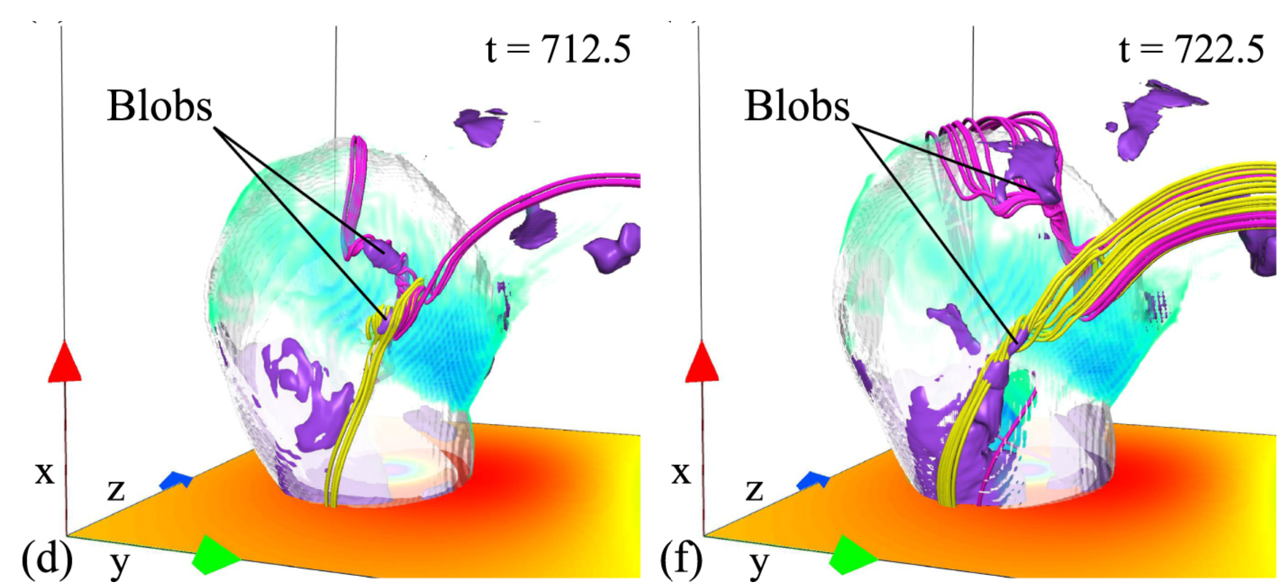
2D magnetic islands ≠ 3D plasmoids



3D full PIC simulation Daughton et al., 2006



3D MHD simulation of solar eruption Wyper & Pontin, 2016



Plasmoids do no merge or contract

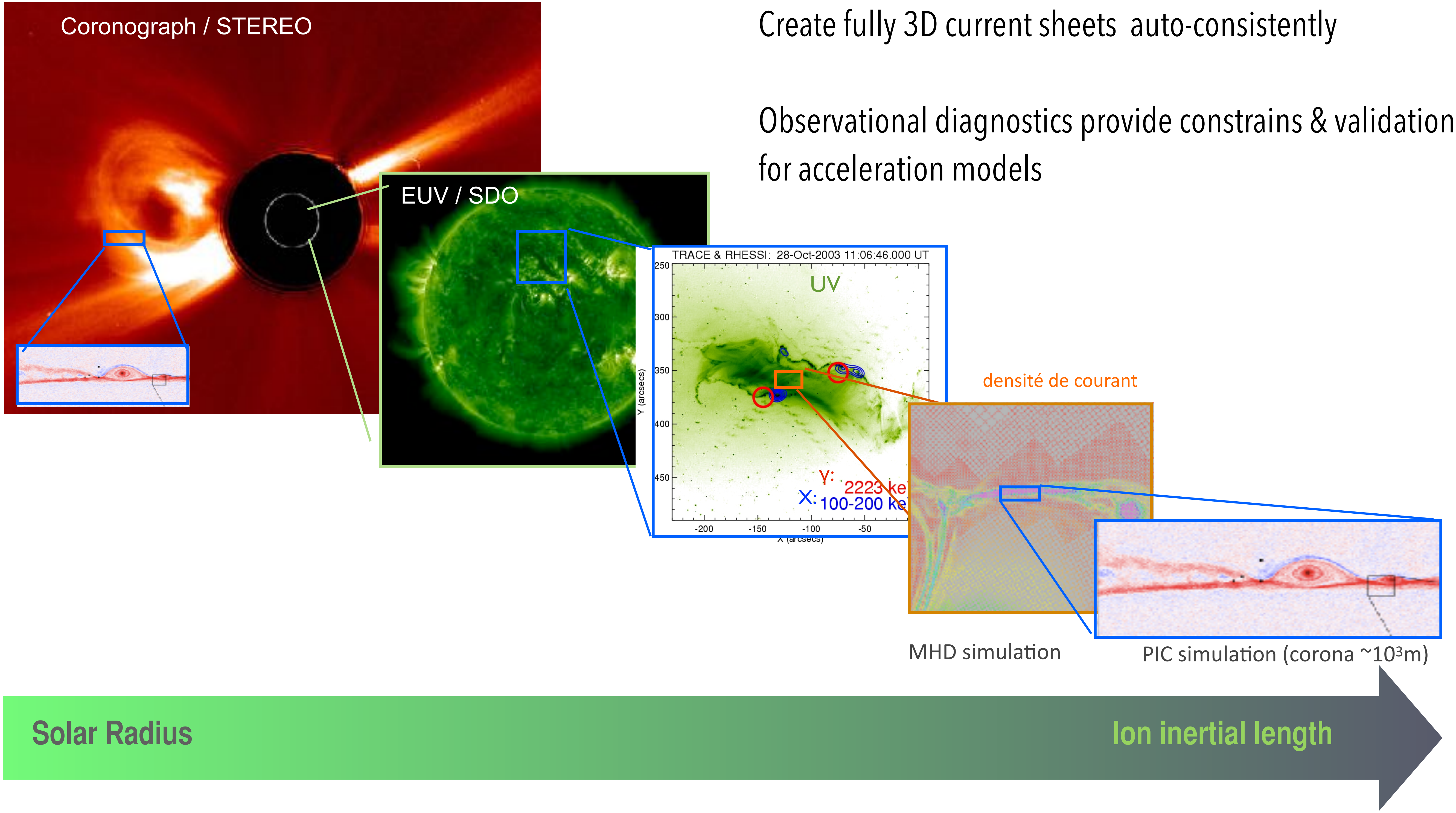
Scaling challenge

Modelling particle acceleration at small scales will not be enough !

Model solar eruptions => MHD simulations

Create fully 3D current sheets auto-consistently

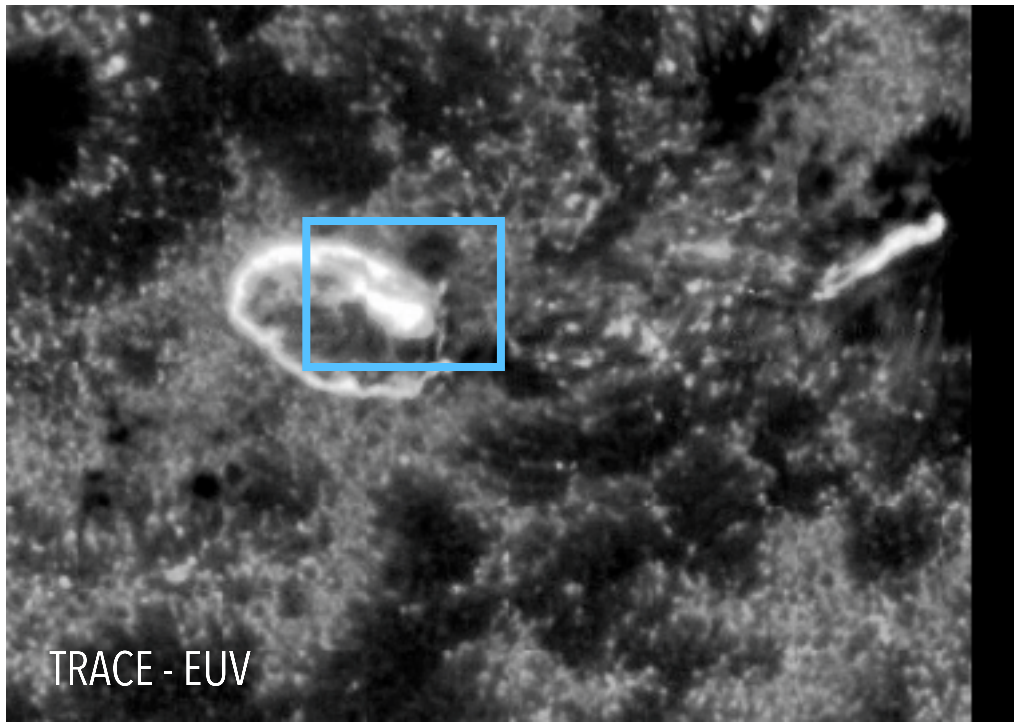
Observational diagnostics provide constrains & validation for acceleration models



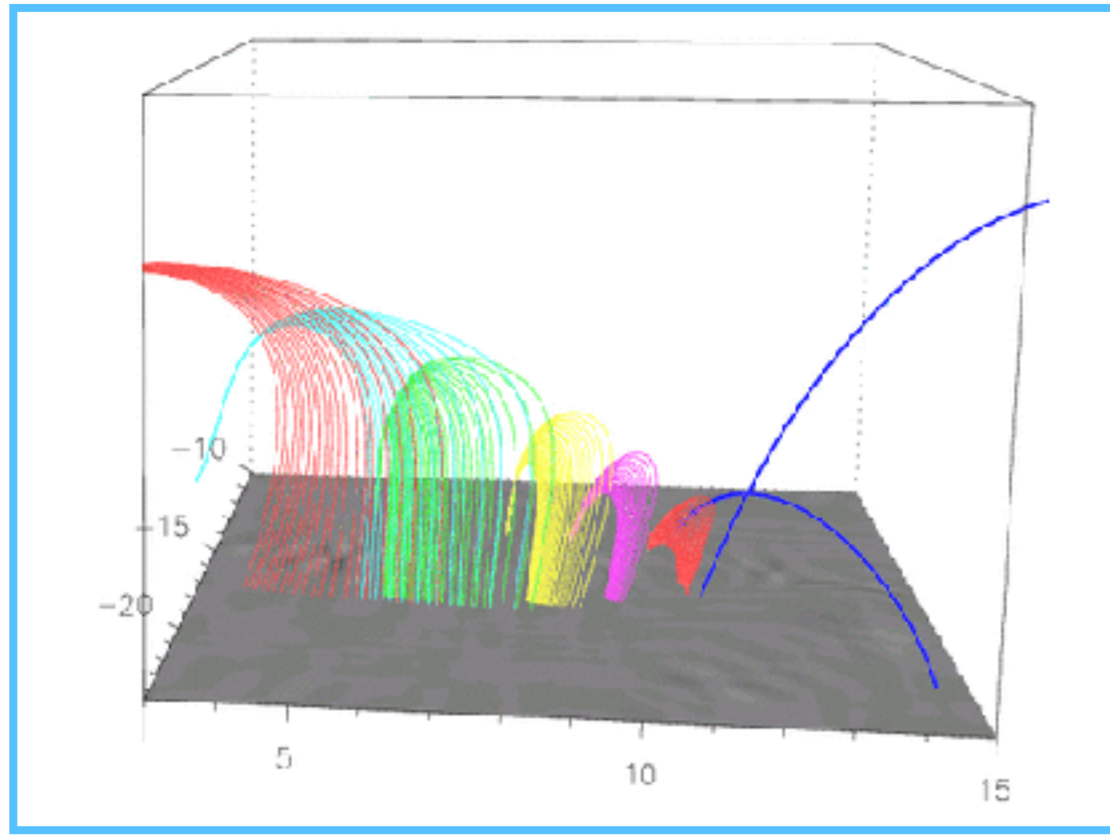
MHD simulation of solar eruptions

Modelling an observed solar flare

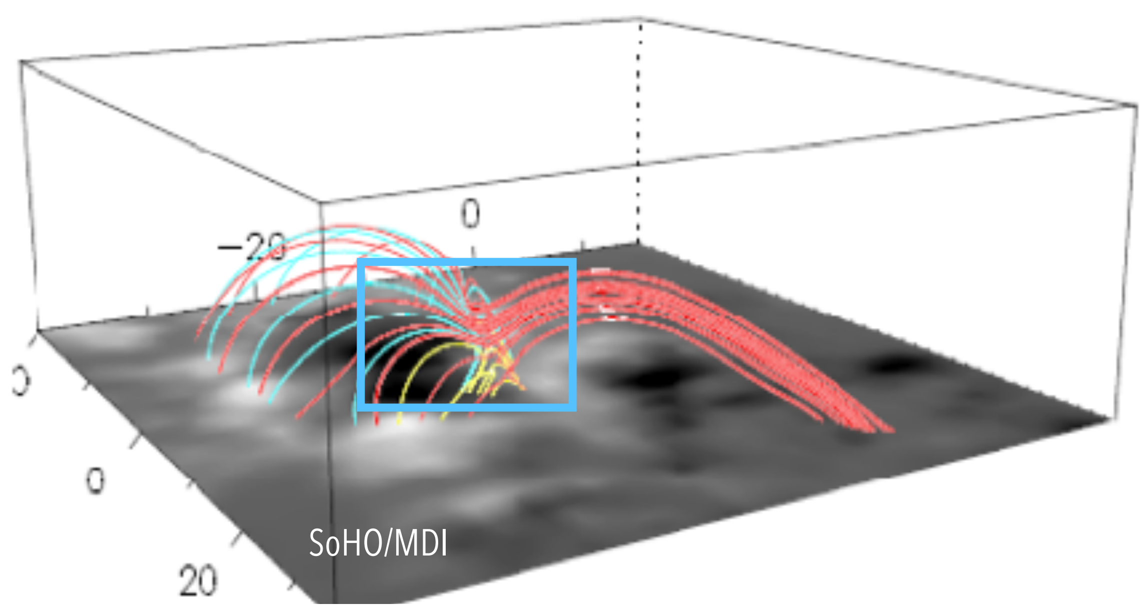
EUV Flare ribbons



3D MHD data -driven simulation



3D reconstruction of B-field prior to magnetic reconnection



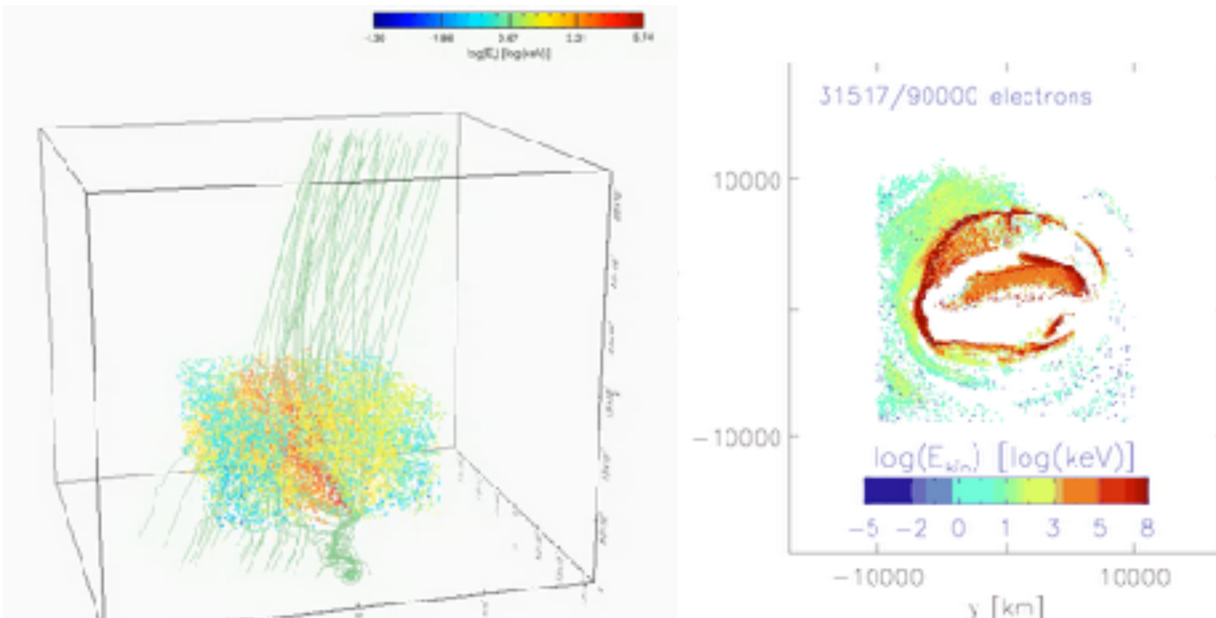
Reconnection => B-field dynamics

Dynamic of the impact site of energetic particles

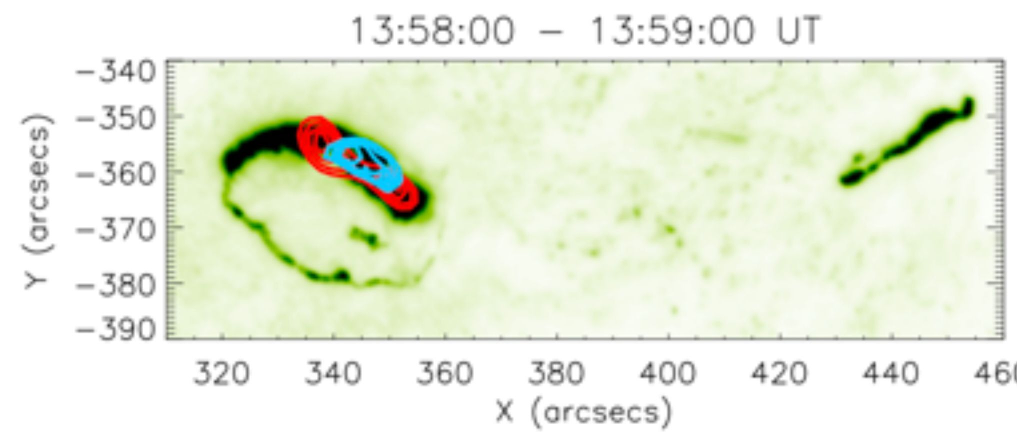
Masson et al., 2009

Including test particules in MHD simulations

- Static MHD computed B-field



Rosdahl & Galsgaard, 2010



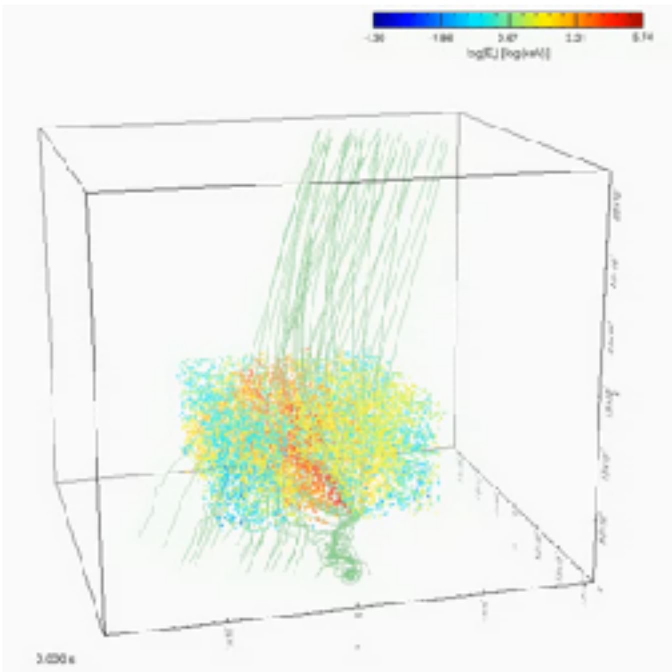
Reid et al., 2012

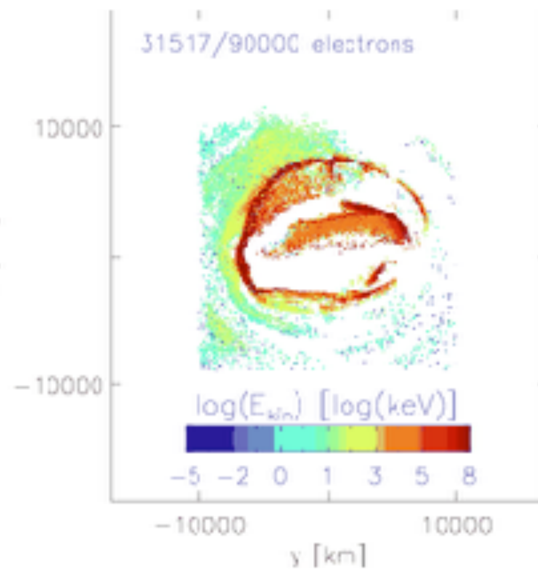
Particles acceleration + propagation
→ particles impact sites ~ EUV ribbons

MHD simulation of solar eruptions

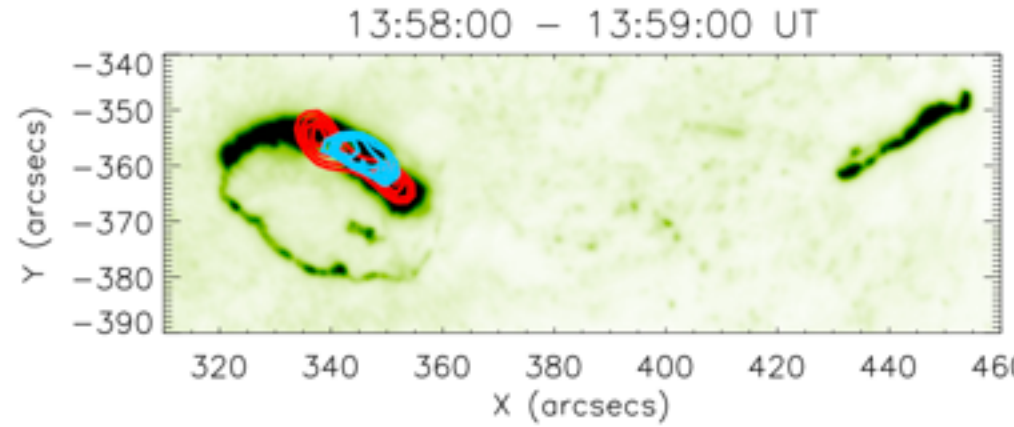
Including test particules in MHD simulations

- Static MHD computed B-field





Rosdahl & Galsgaard, 2010

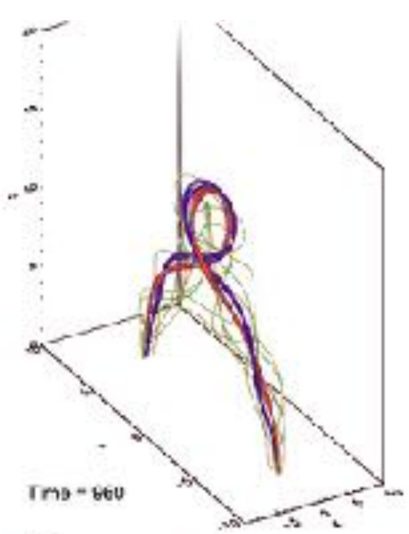


Reid et al., 2012

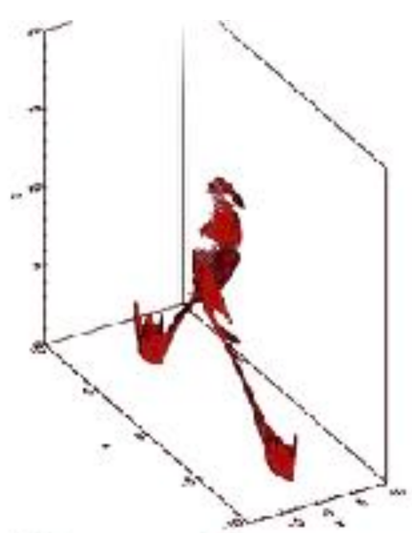
Particles acceleration + propagation
→ particles impact sites ~ EUV ribbons

- Evolving MHD B-field

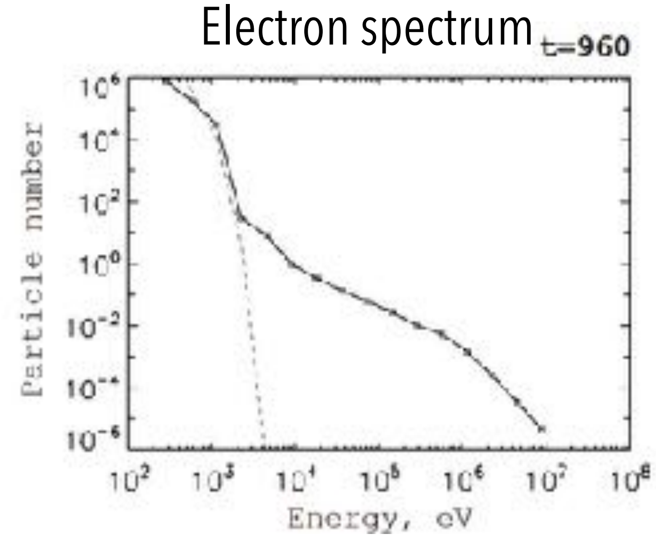
3D B field lines



Electric current density



Electron spectrum

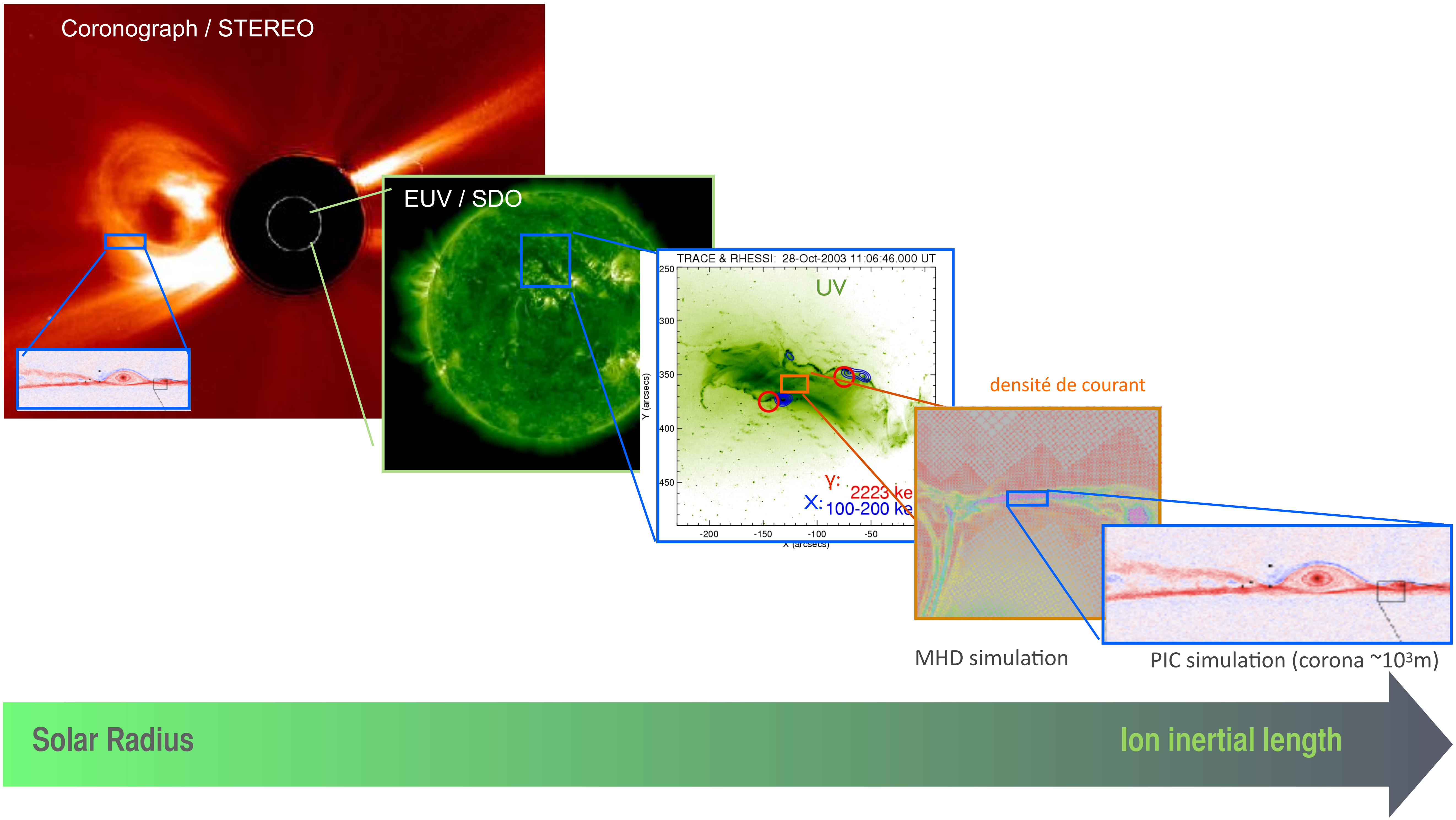


→ Stochastic process to gain sufficient energy
→ Takes too long (several minutes)
→ No reconnection

Gordovskyy et al., 2014

Scaling challenge

Coupling MHD & PIC



Outline

1 - A quick introduction of solar eruptions

2 - Observational diagnostics

-observations

-multi-wavelength & multi-messenger analysis

3 - Modelling particle acceleration in solar eruptions

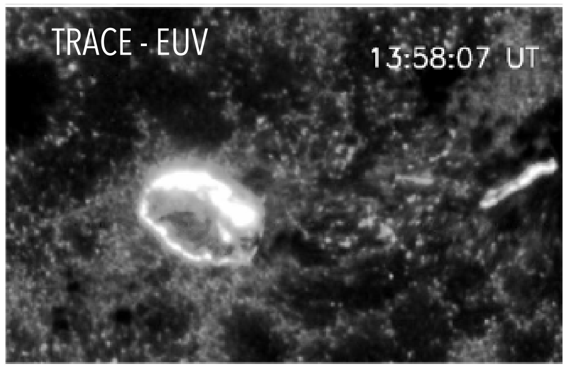
- kinetic models for particle acceleration
- MHD models for solar eruptions

4 - Coupling MHD and PIC simulations

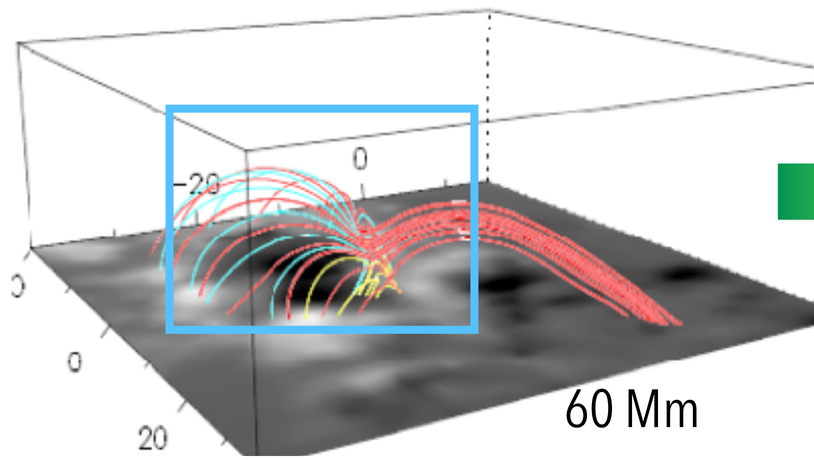
Coupling PIC & MHD simulations

A first attempt

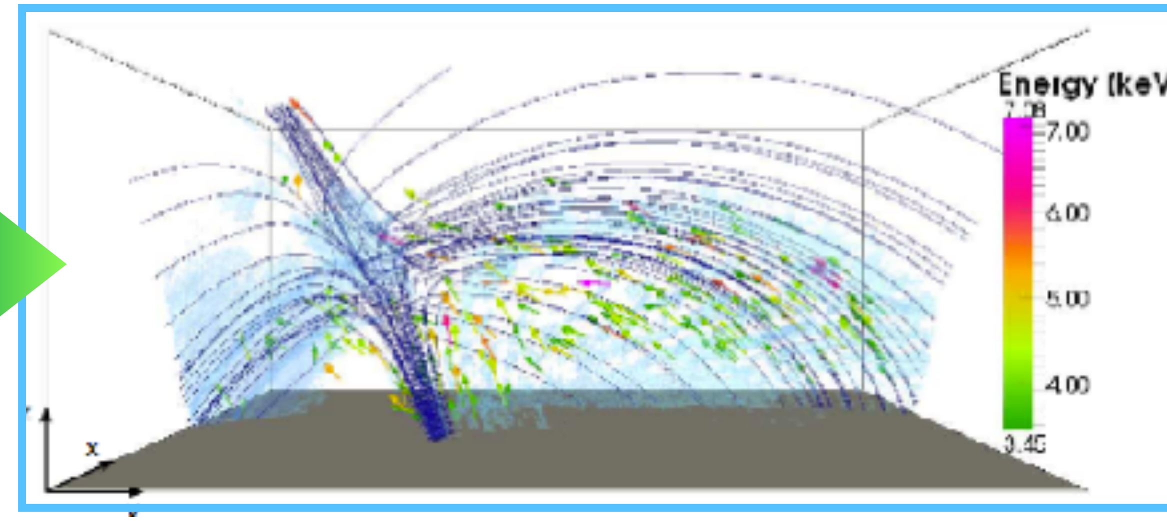
Data-driven MHD simulation Masson et al., 2009



Rubans d'éruption



Full PIC (constant adjustments) Baumann et al, 2013

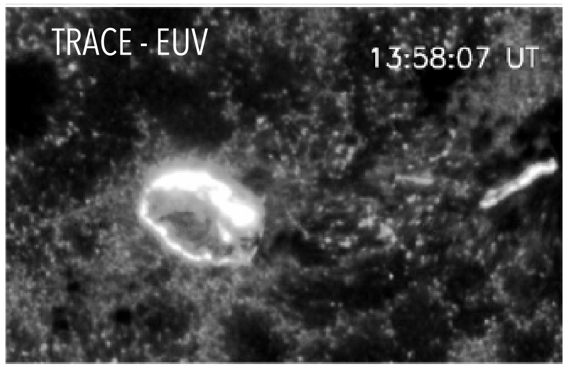


Only a fraction of a small active region
Not much energy

Coupling PIC & MHD simulations

A first attempt

Data-driven MHD simulation Masson et al., 2009



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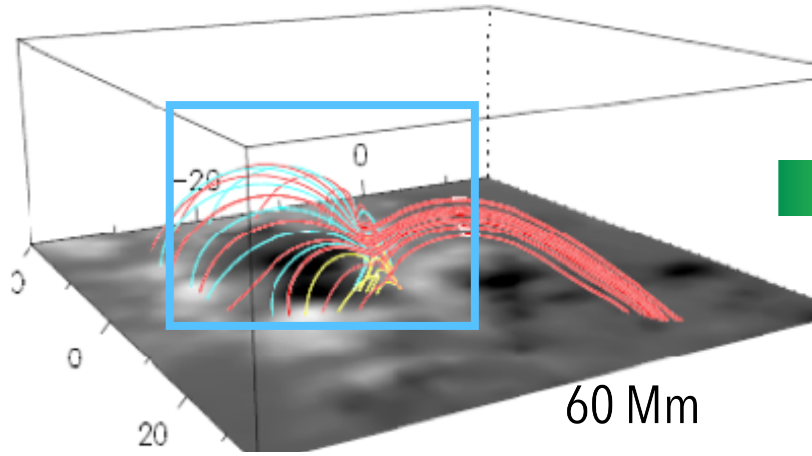

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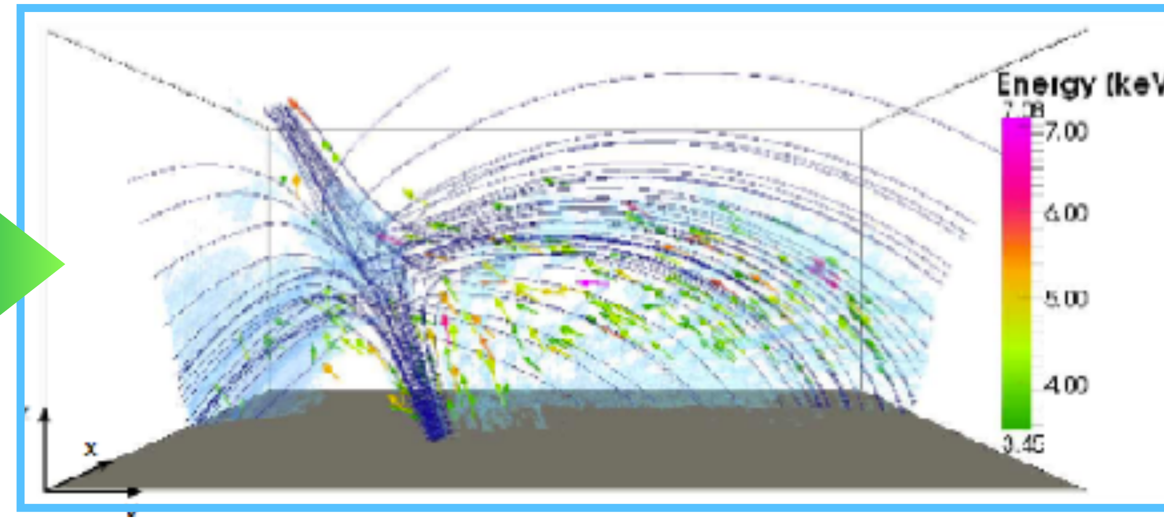


Only a fraction of a small active region
Not much energy

Going further

Mutli-scale models for solar eruption

Code MHD 3D **ARMS** (ideal, non relativistic MHD equations)
DeVore 1991;

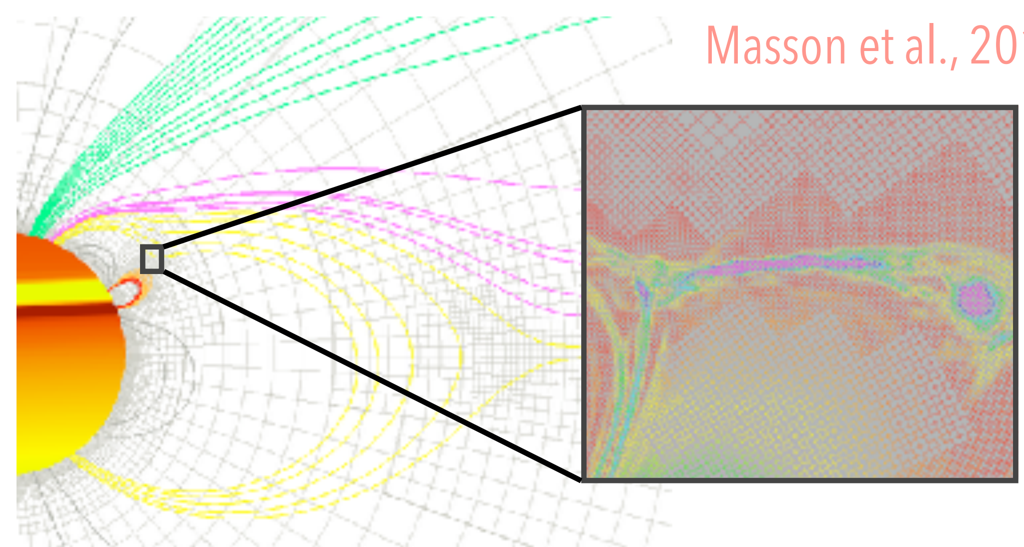
Adaptive Mesh refinement Mac Neice et al., 2000

=> multi-scale simulations

$$50\ R_\odot = 3{,}5 \times 10^{10}\ \mathrm{m}\ \text{to}\ L_{min} < 10^6\ \mathrm{m}$$

+ solar boundary conditions

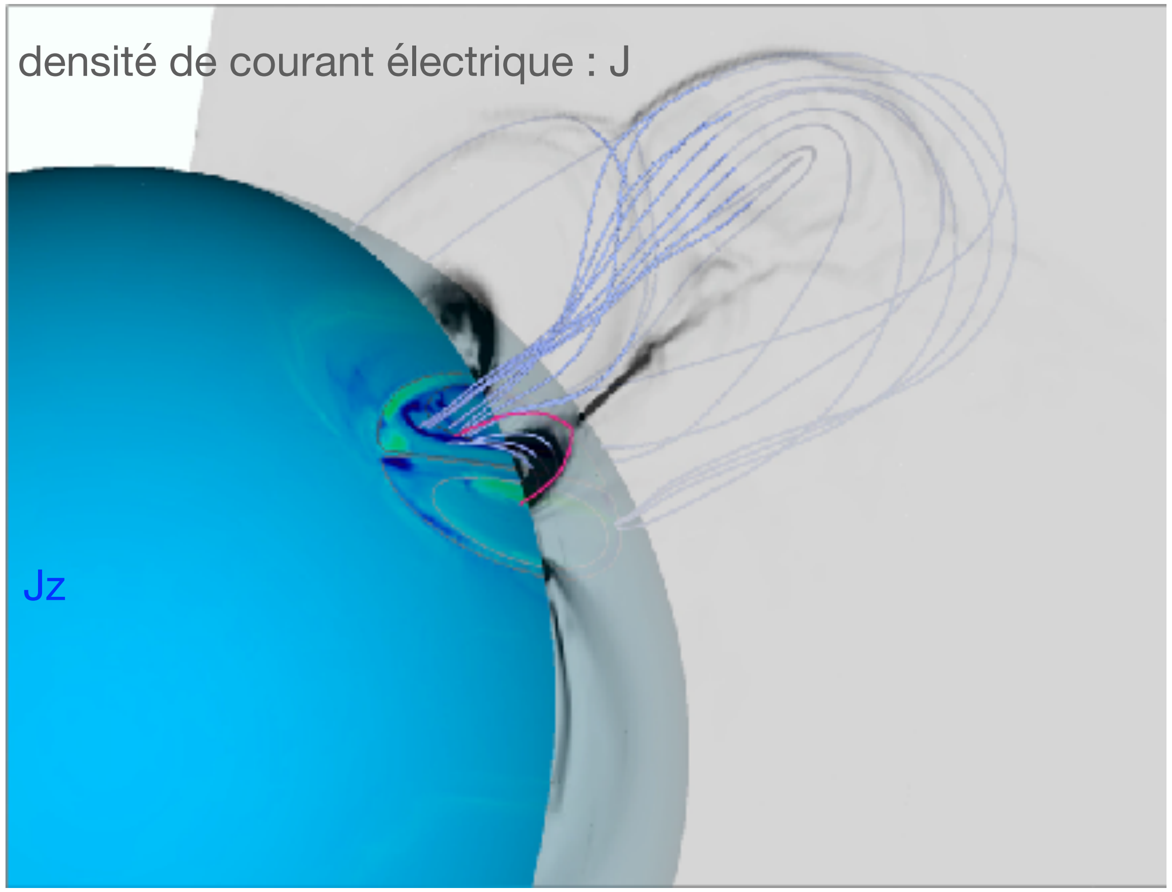
Masson et al., 2013



designed to study MHD magnetic reconnection in solar eruptions

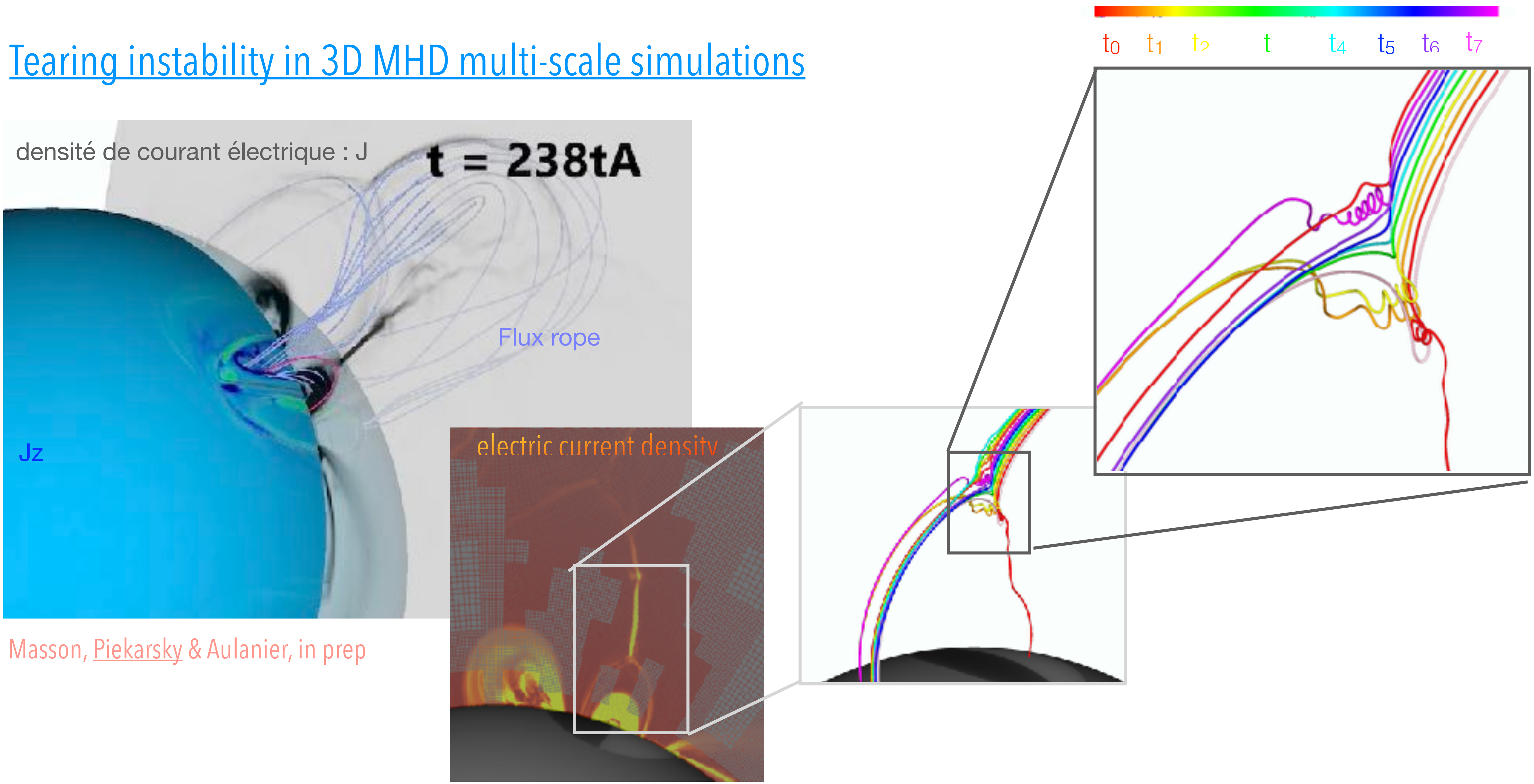
Coupling PIC & MHD simulations

Tearing instability in 3D MHD multi-scale simulations



Coupling PIC & MHD simulations

Tearing instability in 3D MHD multi-scale simulations



Masson, Piekarsky & Aulanier, in prep

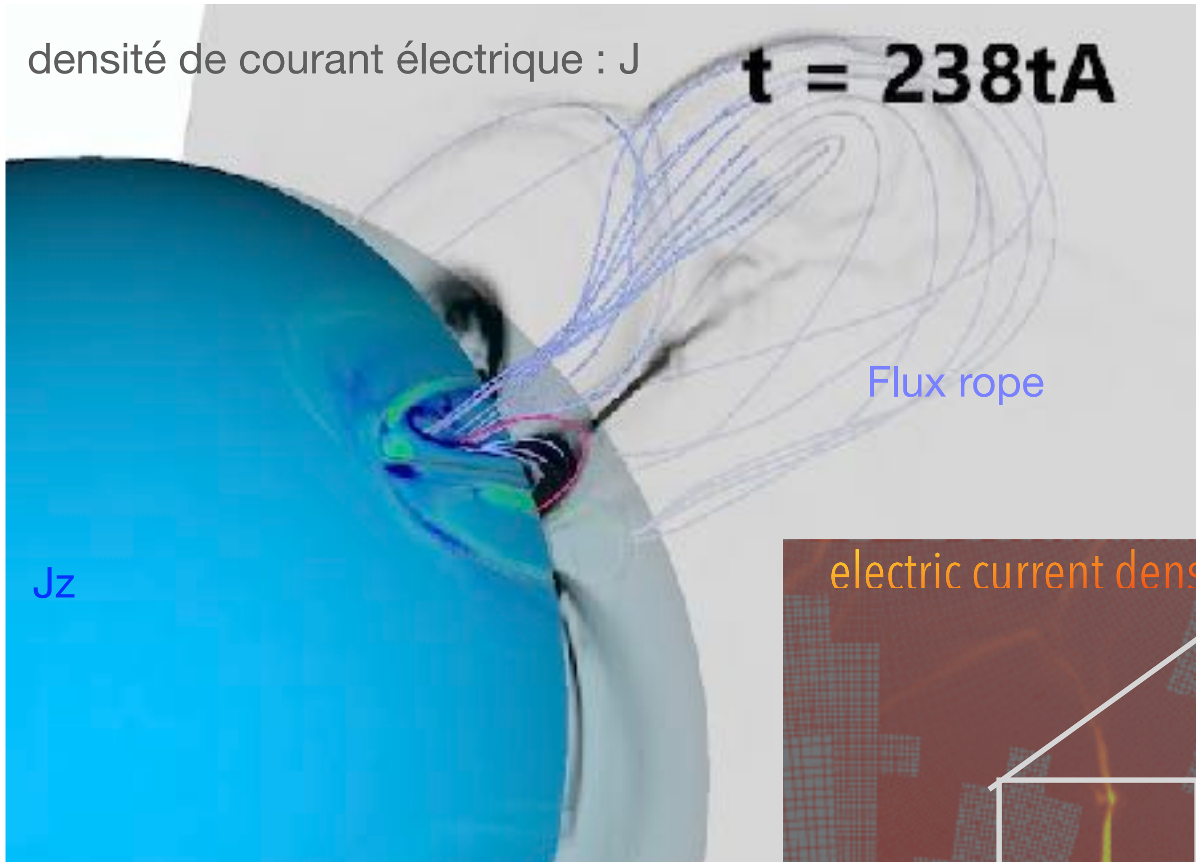
Weak guide field : B_{gf} ~ 6% of B_{local}

Plasmoids reconnects with the ambiant field

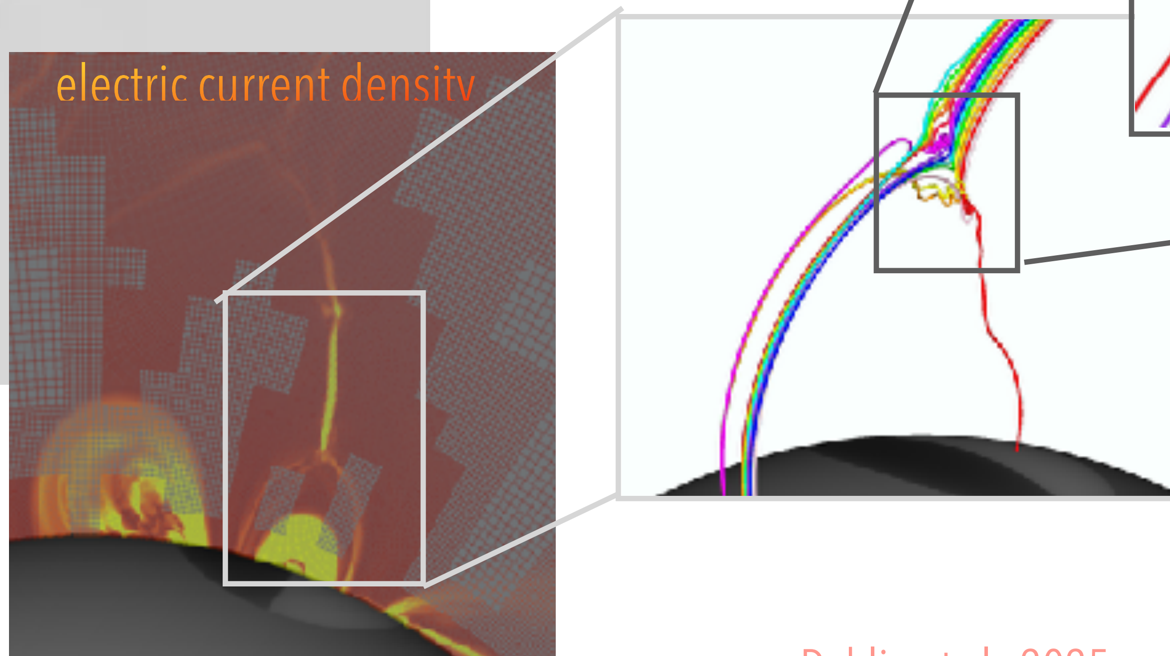
- Twist exchange and transfer
- Current sheet fragmentation

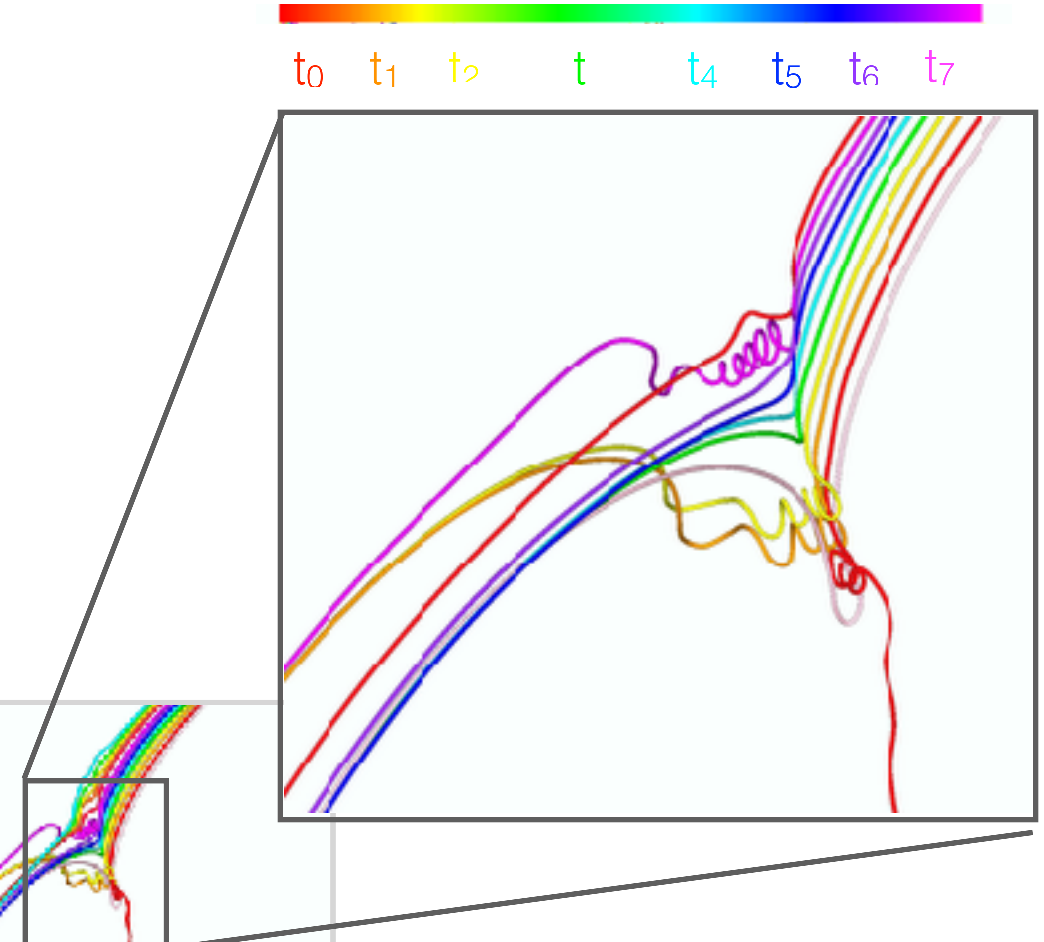
Coupling PIC & MHD simulations

Tearing instability in 3D MHD multi-scale simulations



Masson, Piekarsky & Aulanier, in prep





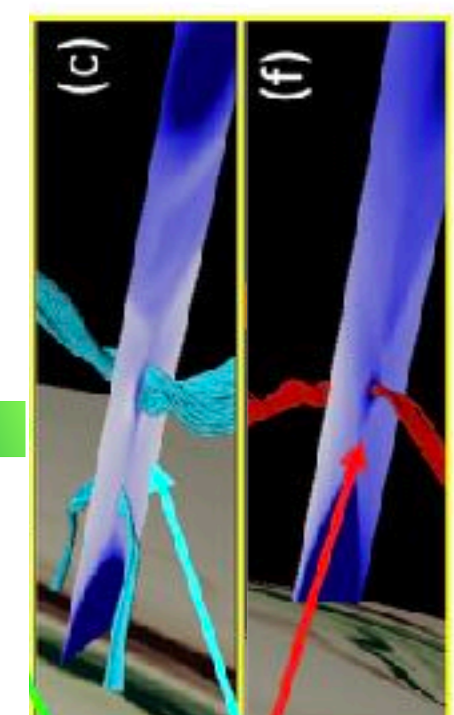
Weak guide field : B_{gf} ~ 6% of B_{local}

Plasmoids reconnects with the ambiant field

- Twist exchange and transfer
- Current sheet fragmentation

Dahlin et al., 2025

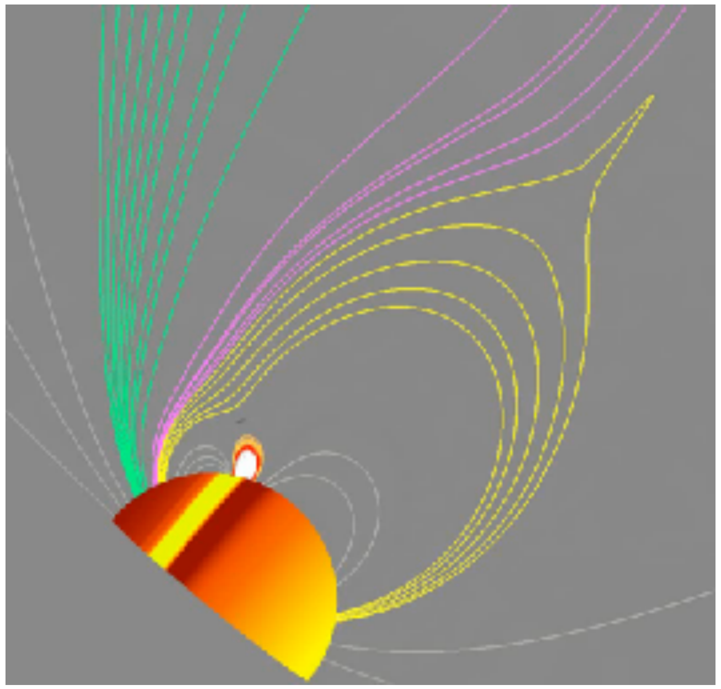
Strong guide field
Less twisted plasmoids

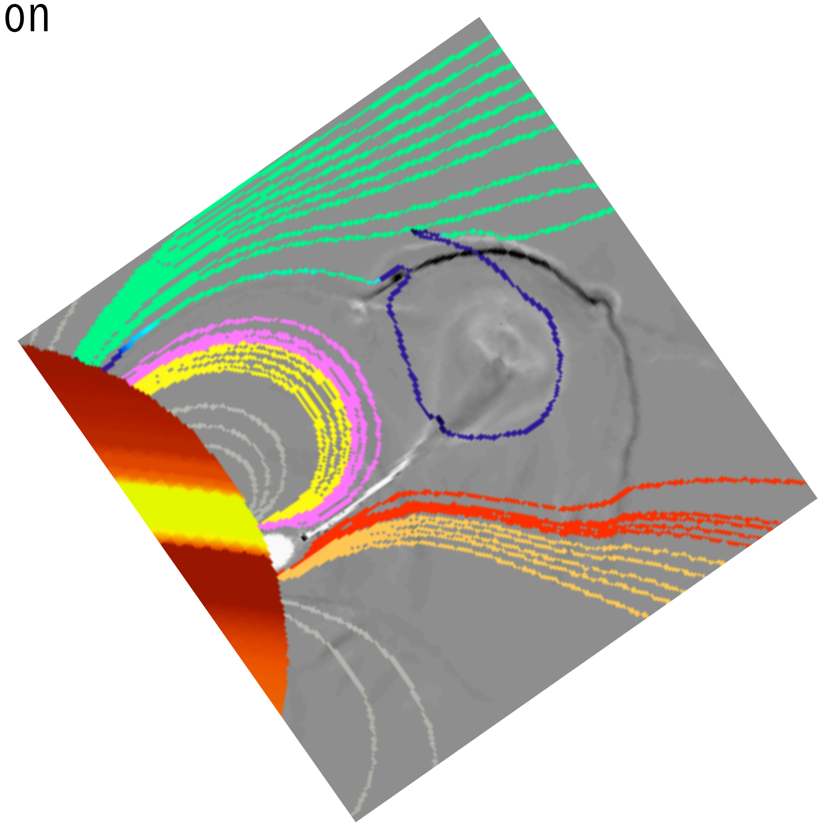


Present & future modelling efforts

Coupling MHD & kinetic

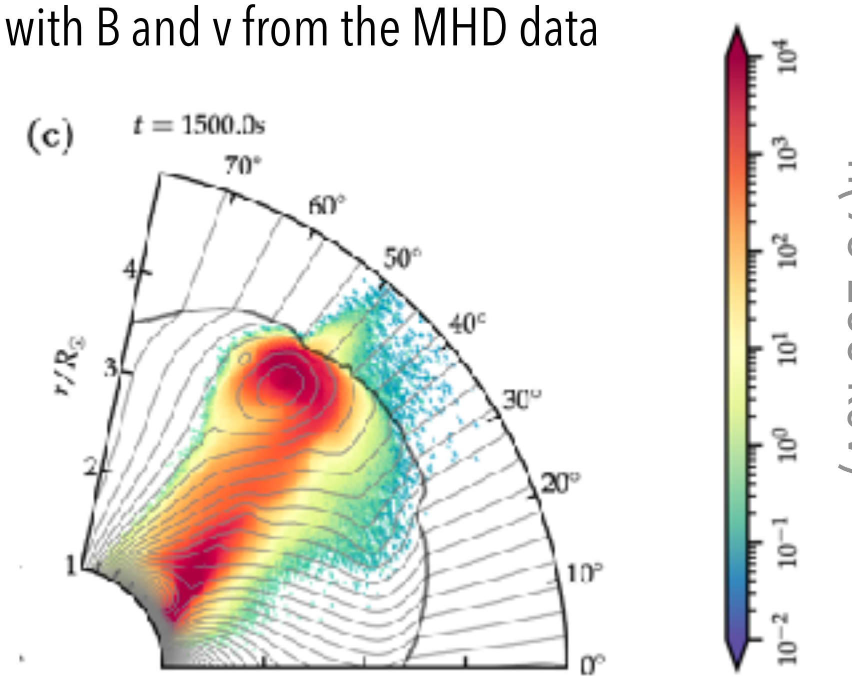
- 2.5D MHD simulation + focused transport equation





AMR : large scale dynamic results from the refined the current sheets Masson et al., 2013

Solve the focused transport equation with B and v from the MHD data



Li et al., 2025

Particles 'acceleration' & escape

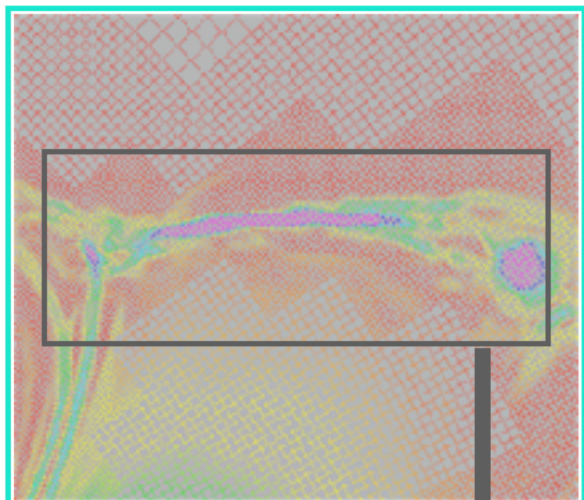
- MHD-PIC coupling framework designed for Bifrost and Rieman (RAMSES) solver Haahr et al., 2025

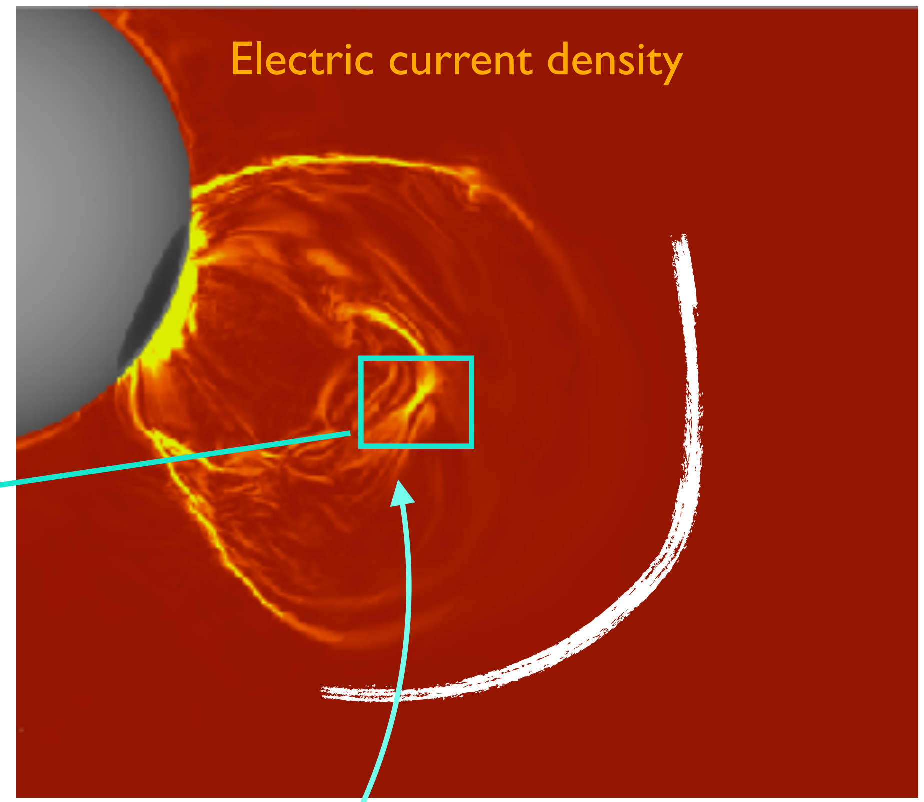
Present & future modelling efforts

Developping dedicated PIC-MHD code for particles acceleration in solar eruptions

3D MHD models with ARMS

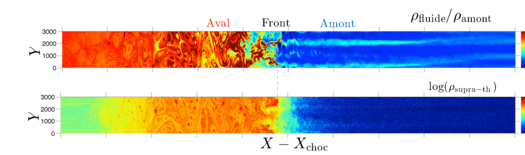
AMR : small scale current sheet



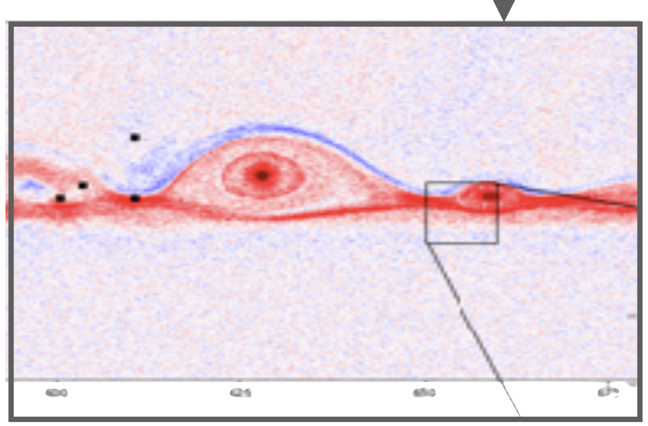


Particles acceleration at the CME-driven shock

MHDPIC



Accelerated particles in the large scale B-field



PIC in refined =current sheet

Localised acceleration & propagation in the B-field of the eruption

=> Determine the acceleration processes at small scales created by the large scale dynamics

=> Synthetic observables (X-rays & radio) & Comparison with the observations

Summary

Observations & modelling of energetic solar particles

- Multi-wavelength and multi-messenger analyses
  => strong constrains on energetic particle properties (spectrum, location, acceleration site)
- Kinetic models to study particle acceleration
  => BUT limited because of 2D geometry & the assumption on the electric current sheet
- Need to consider the full 3D dynamics of the acceleration region

Moving toward multi-scale models : coupling MHD and kinetic (PIC) codes