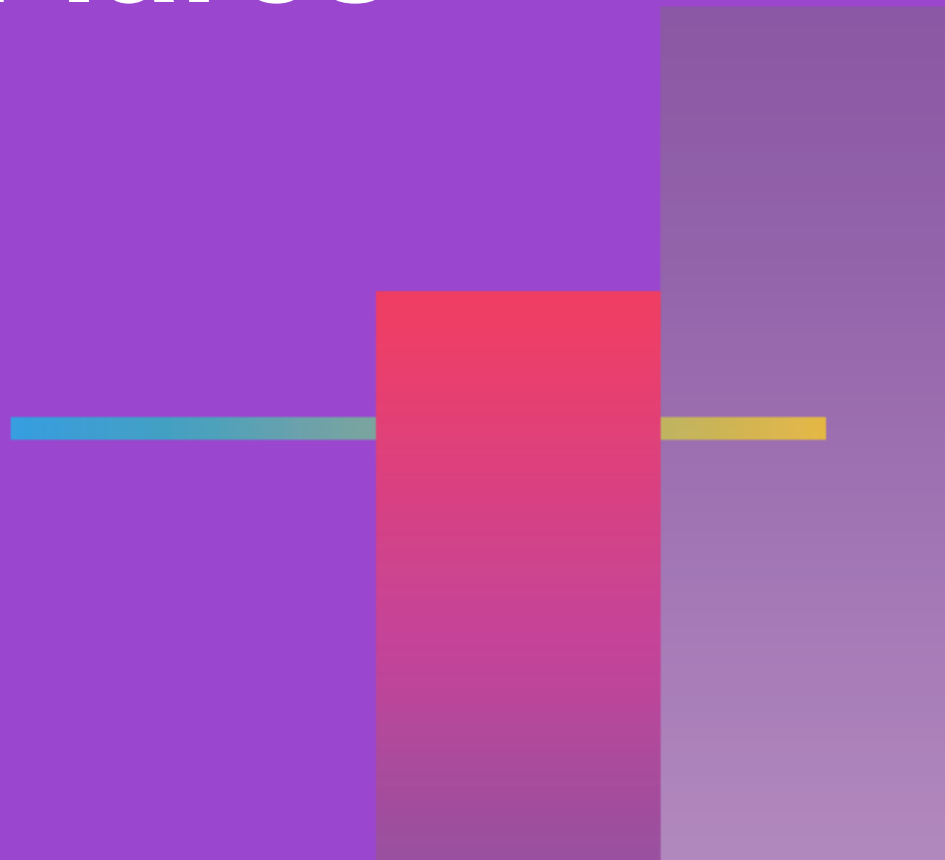
Synthetic Observables from Data-Driven Simulations of Solar Flares

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Alliance Meeting

CNR, 20th October 2026



University of Hertfordshire UH

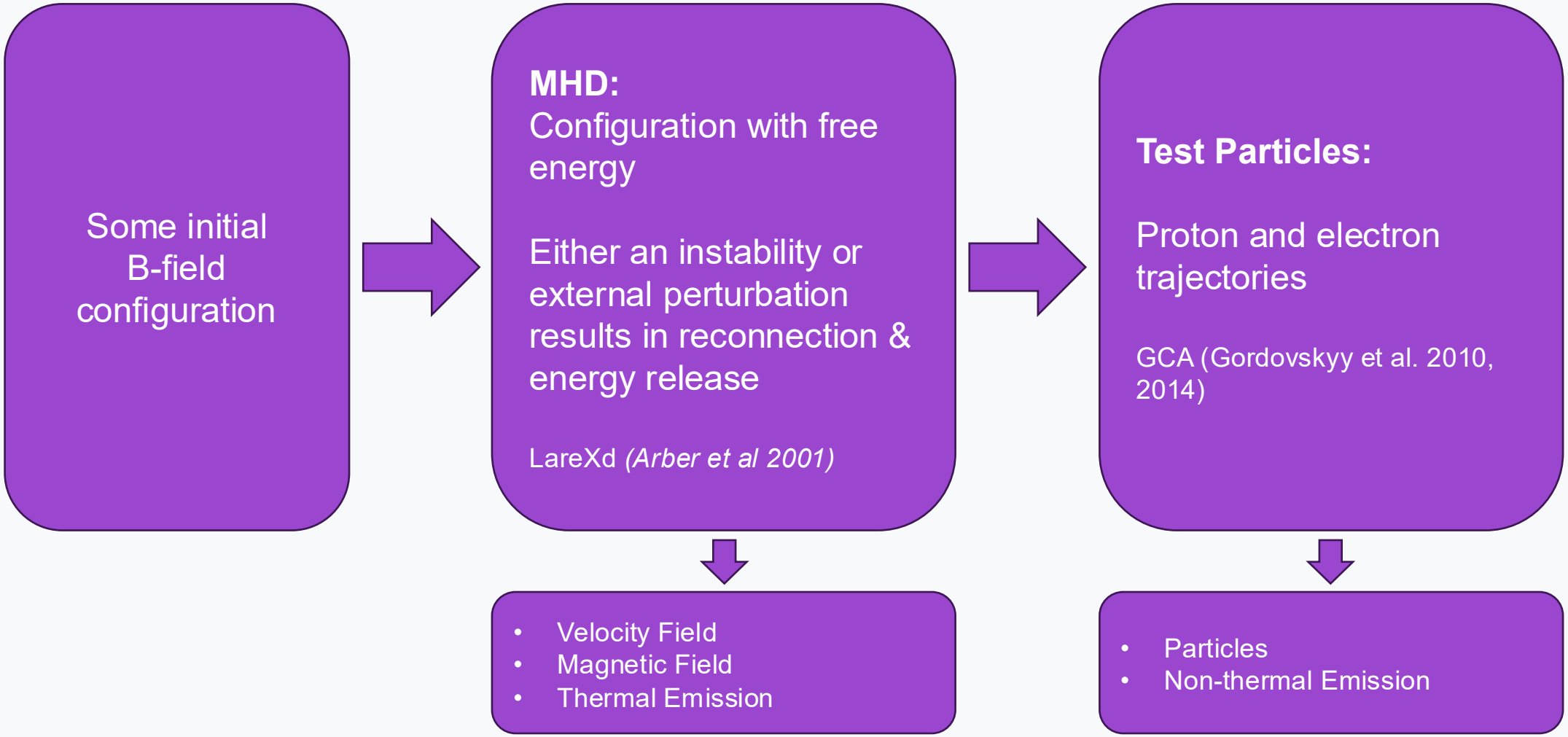
Introduction

- Scale separation is the main problem in large-scale modelling of non-thermal particle acceleration and transport

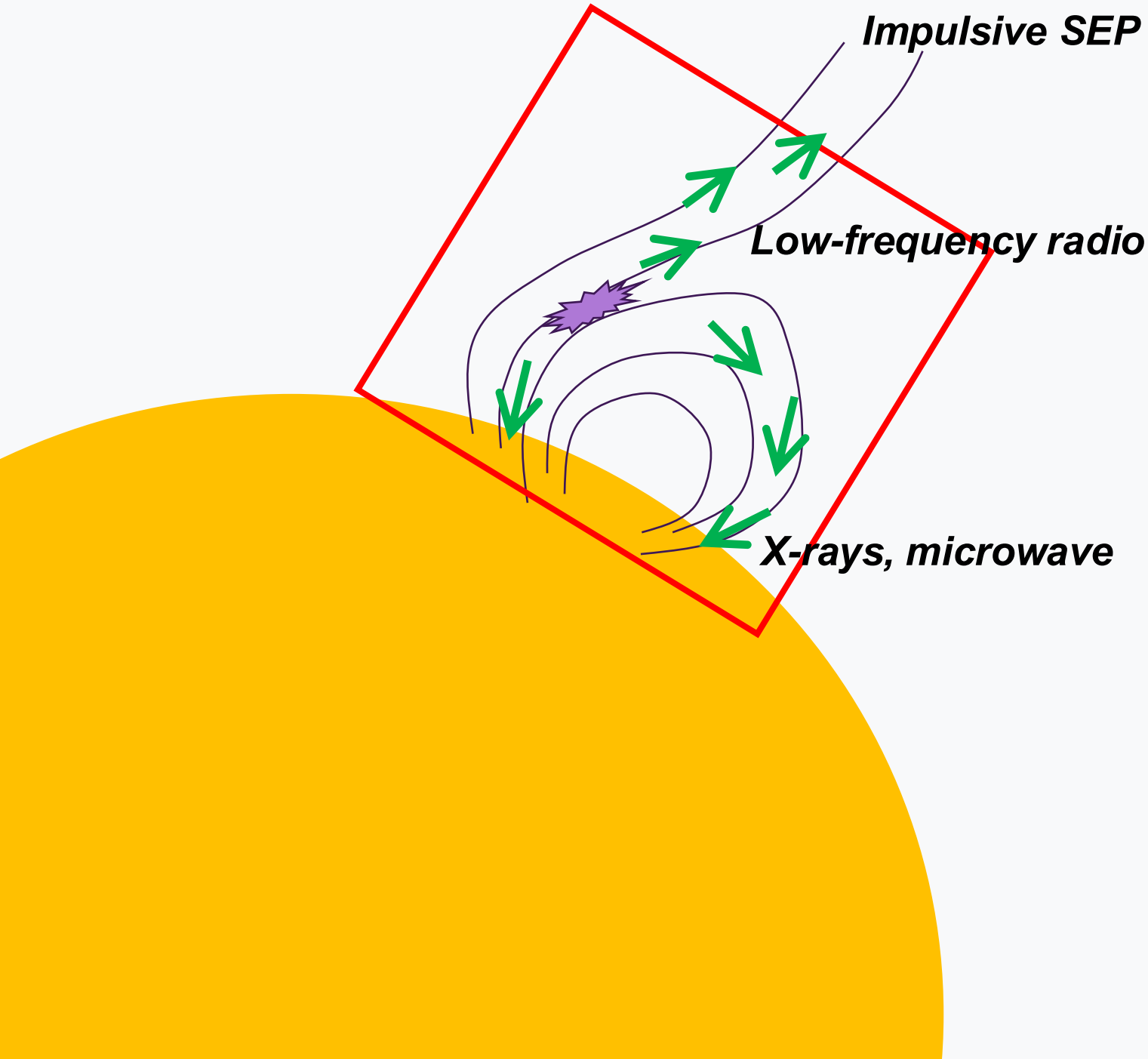
- Hybrid models (e.g. Sugiyama & Kusano 2007; Baumann et al. 2013; Makwana et al. 2017) can be used for some simpler configurations (see also review Gordovskyy et al. 2019 AdvSpRes)

- MHD+test-particles is a robust approach for studying complex large-scale configurations. However, because it is not self-consistent, it has limitations on acceleration efficiency

MHD + Test Particles

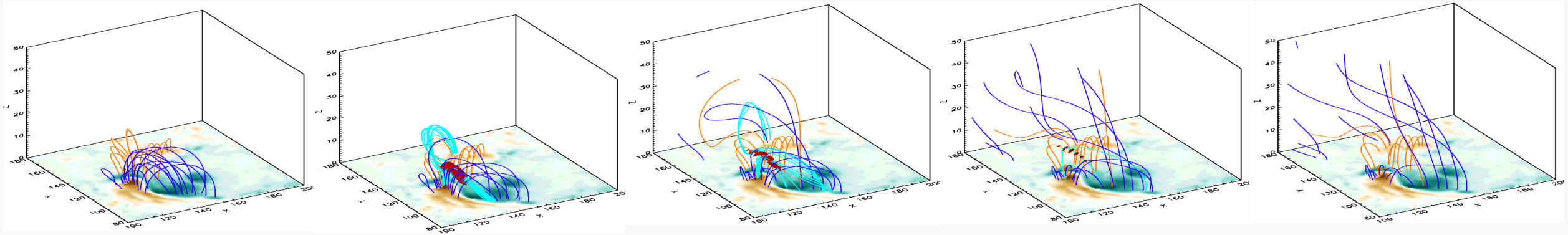


- Gordovskyy, Browning, Kontar & Bian 2014 (loop evolution, particles & HXR)
- Bareford, Gordovskyy, Browning & Hood 2016 (loop evolution)
- Pinto, Gordovskyy, Browning & Vilmer 2016 (thermal SXR, non-thermal HXR)
- Gordovskyy, Kontar & Browning 2016 (EUV lines – non-thermal broadening, shifts)
- Gordovskyy, Browning & Kontar 2016 (thermal and non-thermal microwave)


Impulsive SEP
Low-frequency radio
X-rays, microwave

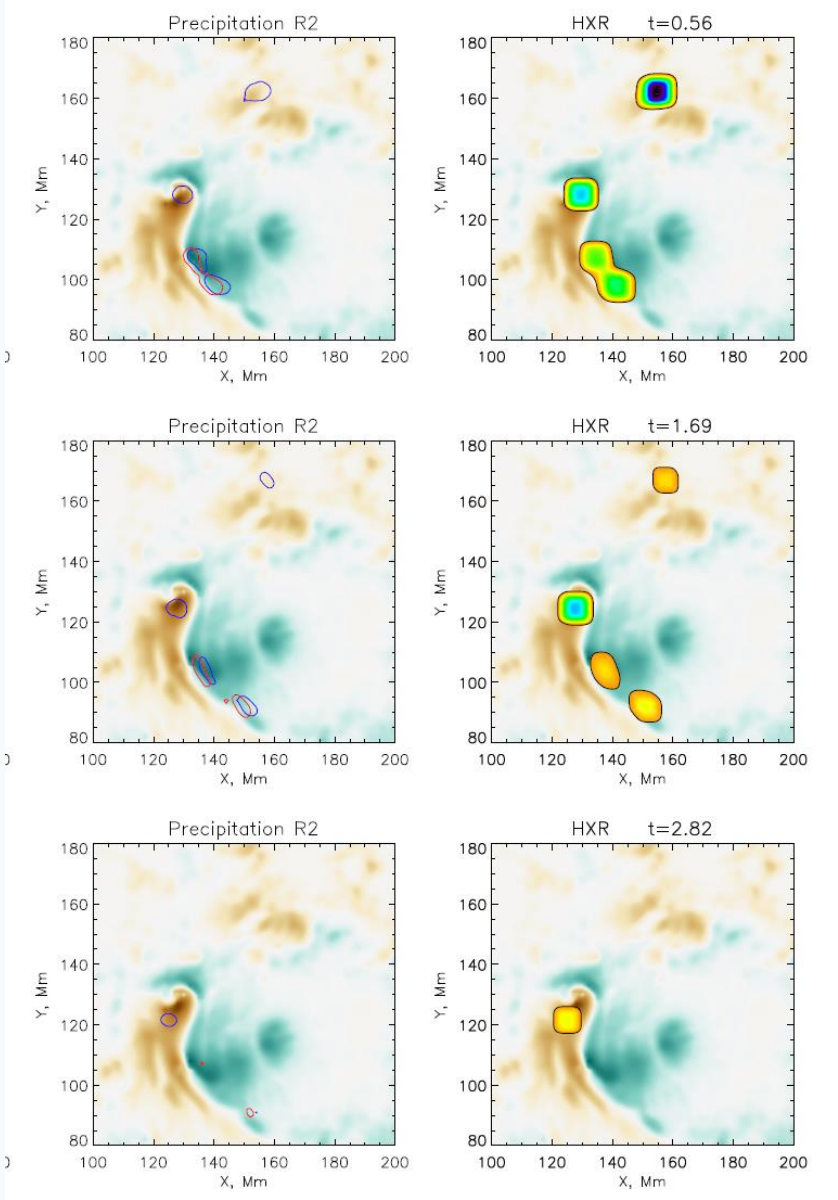
6-Sep-2017 flare

Magnetic Connectivity of the energy release region:



Gordovskyy + 2020

6-Sep-2017 flare

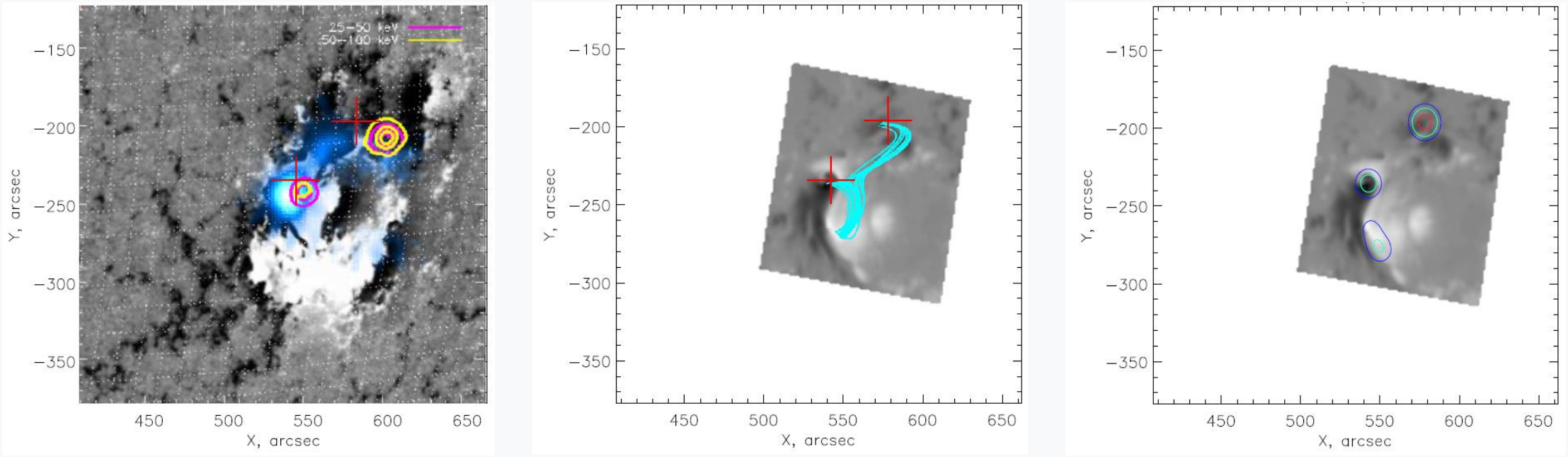


Locations of electron and proton precipitation sites and bremsstrahlung **HXR**

Gordovskyy + 2020

6-Sep-2017 flare

Comparison with observations:



Gordovskyy + 2020

Synthetic non-thermal bremsstrahlung HXR (model, 8 keV)

\+ Electron footpoints (model)

Bremsstrahlung HXR (RHESSI, 12, 25 and 60 keV)

Force-free models as initial conditions

- Force-free initial configurations need to be initiated/kicked
- This creates uncertainty for the onset time
- NLFF flare simulations also underestimate flare energy
- Solution? – Non-force-free initial configurations! (but how?)

Non-force-free extrapolations as initial conditions

This approach combines three linear force free fields as $\mathbf{B} = \mathbf{B_1} + \mathbf{B_2} + \mathbf{B_3}$; $\nabla \times \mathbf{B_i} = \alpha_i \mathbf{B_i}$,
with $i = 1,2,3$ and α_i the corresponding constant for each linear force free field.

$\mathbf{B_2}$ is chosen as a potential field, so $\alpha_2 = 0$, and we set $\alpha_1 \neq \alpha_3$.
An optimal set of α_1 and α_3 is found by minimising the difference between the observed and calculated transverse fields on the photospheric boundary.

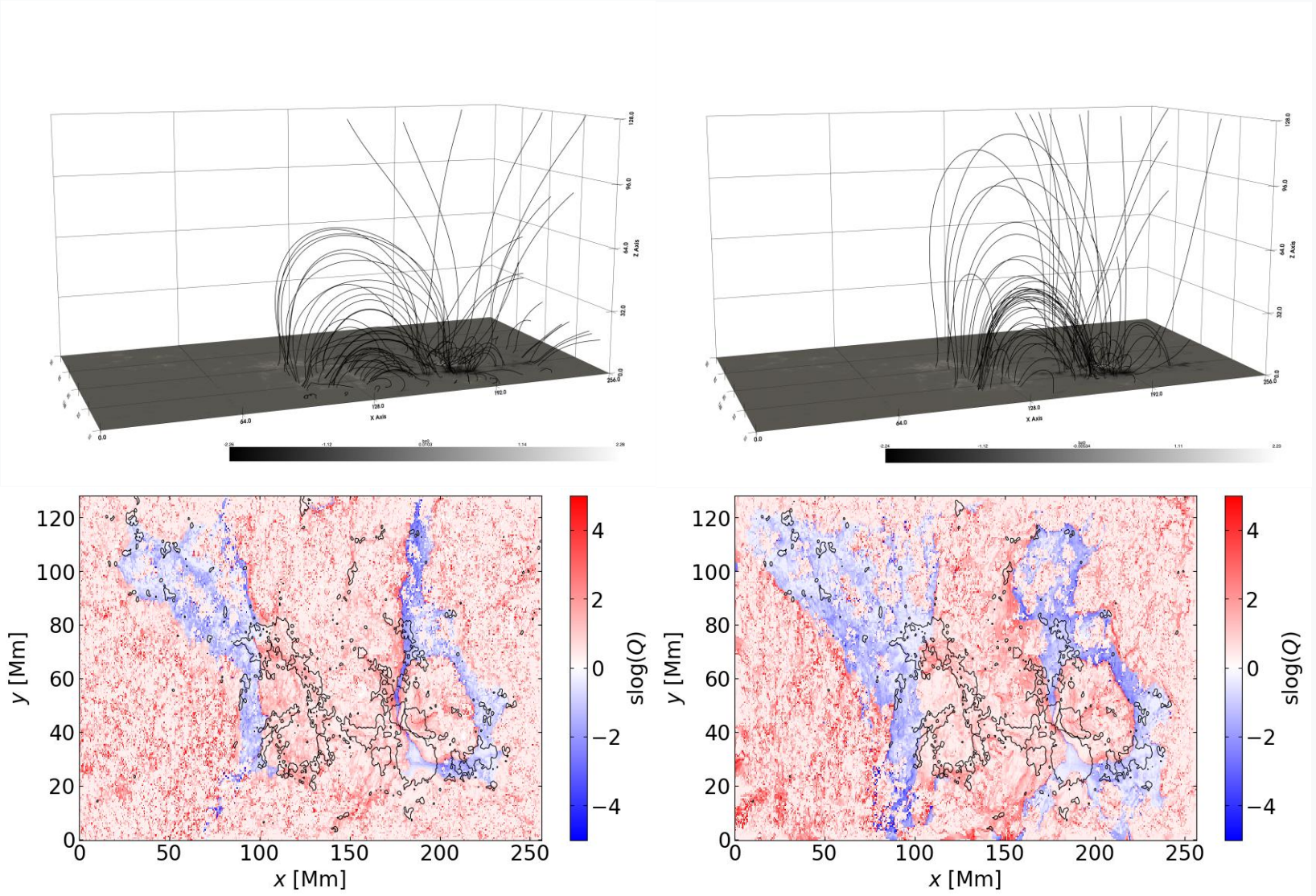
For more info: *Hu & Dasgupta (2008); Hu et al. (2008, 2010)*

Overview of our models

- Wish to compare NLFF and non-force free field extrapolations for flare modelling *Hu & Dasgupta (2008); Hu et al. (2008, 2010)*
- Examining the 6th September 2011 X-class flare for this
- MHD models with Lare3d – resistive MHD, thermal conduction OFF, anomalous resistivity ON, gravity ON
- 512 x 256 x 256 box (256 x 128 x 128Mm)
- Stratified Atmosphere
- Synthetic AIA emission as a diagnostic
- Lower boundary condition: HMI magnetogram

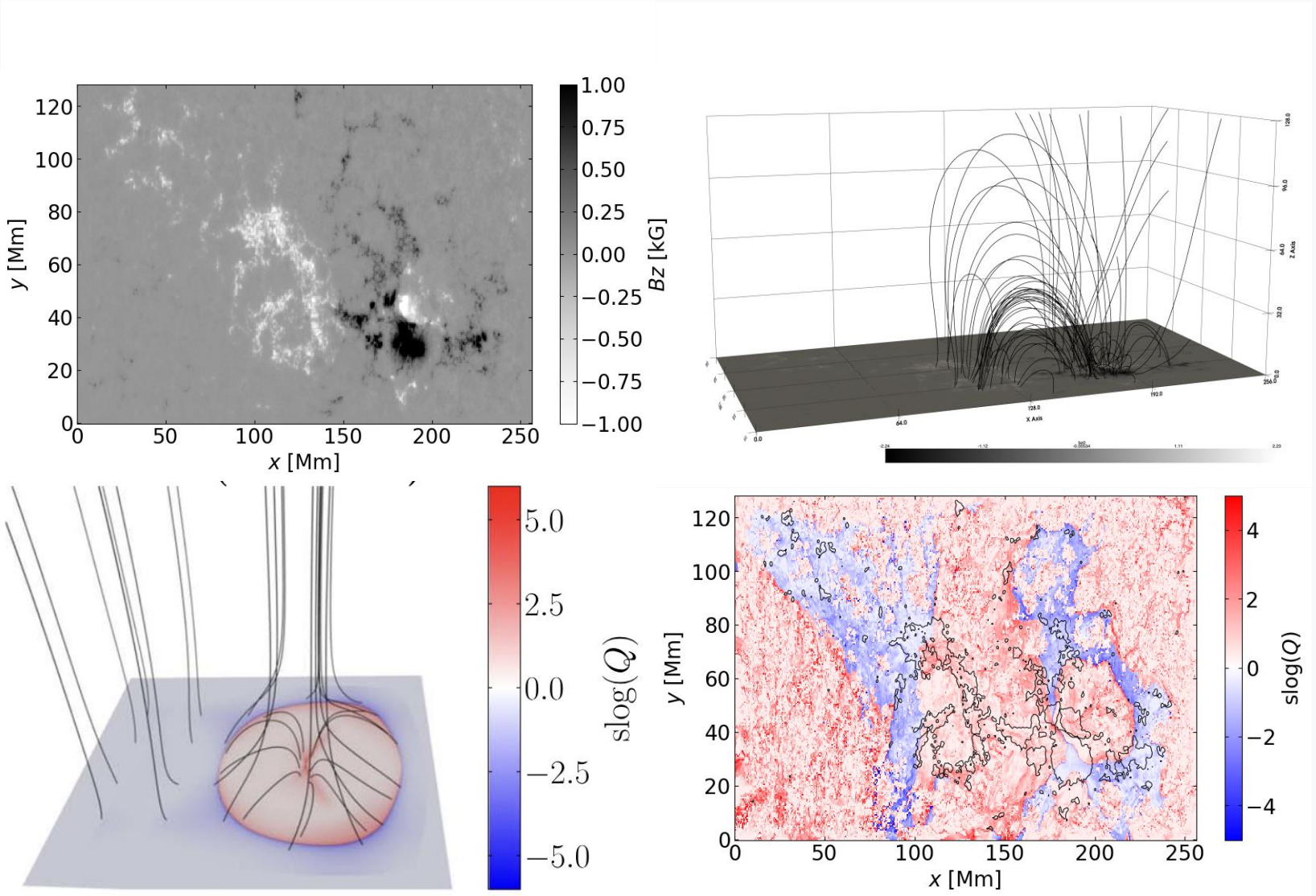
Initial Extrapolations

NLFF | **Non-force free**

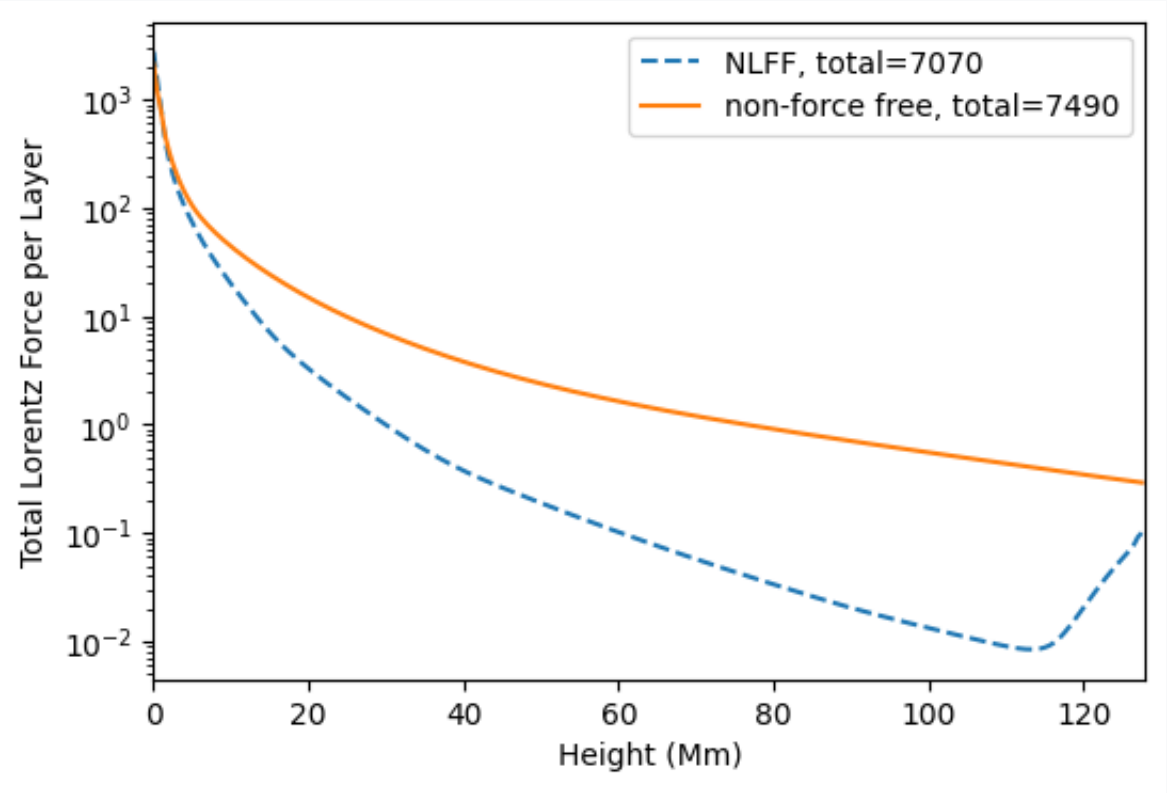


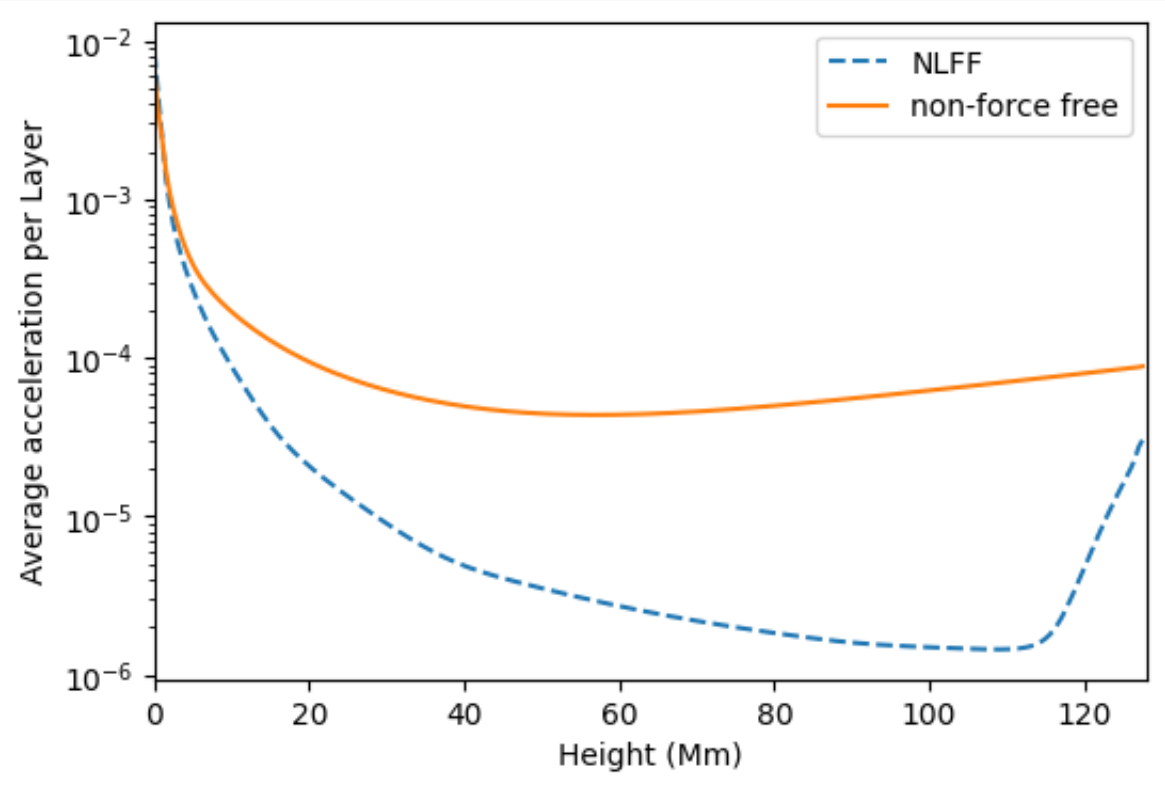
Initial Extrapolations

Non-force free



Initial Extrapolations





$$\rho = \rho_a e^{\frac{-z}{\Lambda}}, \qquad P = P_a e^{\frac{-z}{\Lambda}}, \qquad \epsilon = \frac{1}{100} = \frac{P}{\rho(\gamma - 1)}, \qquad \Lambda = 13.9\text{Mm}$$

Equations Solved in Lare3d

Lare3d is a Lagrangian remap code for solving the MHD equations:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho(\nabla \cdot \mathbf{v})$$

$$\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = \frac{1}{\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} - \frac{1}{\rho}\nabla P - g\hat{\mathbf{z}}$$

$$\frac{\mathrm{D}\mathbf{B}}{\mathrm{D}t} = (\mathbf{B} \cdot \nabla)\mathbf{v} - \mathbf{B}(\nabla \cdot \mathbf{v}) - \nabla \times (\eta \nabla \times \mathbf{B})$$

$$\frac{\mathrm{D}\epsilon}{\mathrm{D}t} = -\frac{P}{\rho}\nabla \cdot \mathbf{v} + \frac{\eta}{\rho}\mathrm{j}^2$$

Resistivity Model

- Size/shape/location of the energy release and particle acceleration regions are very sensitive to the resistivity function

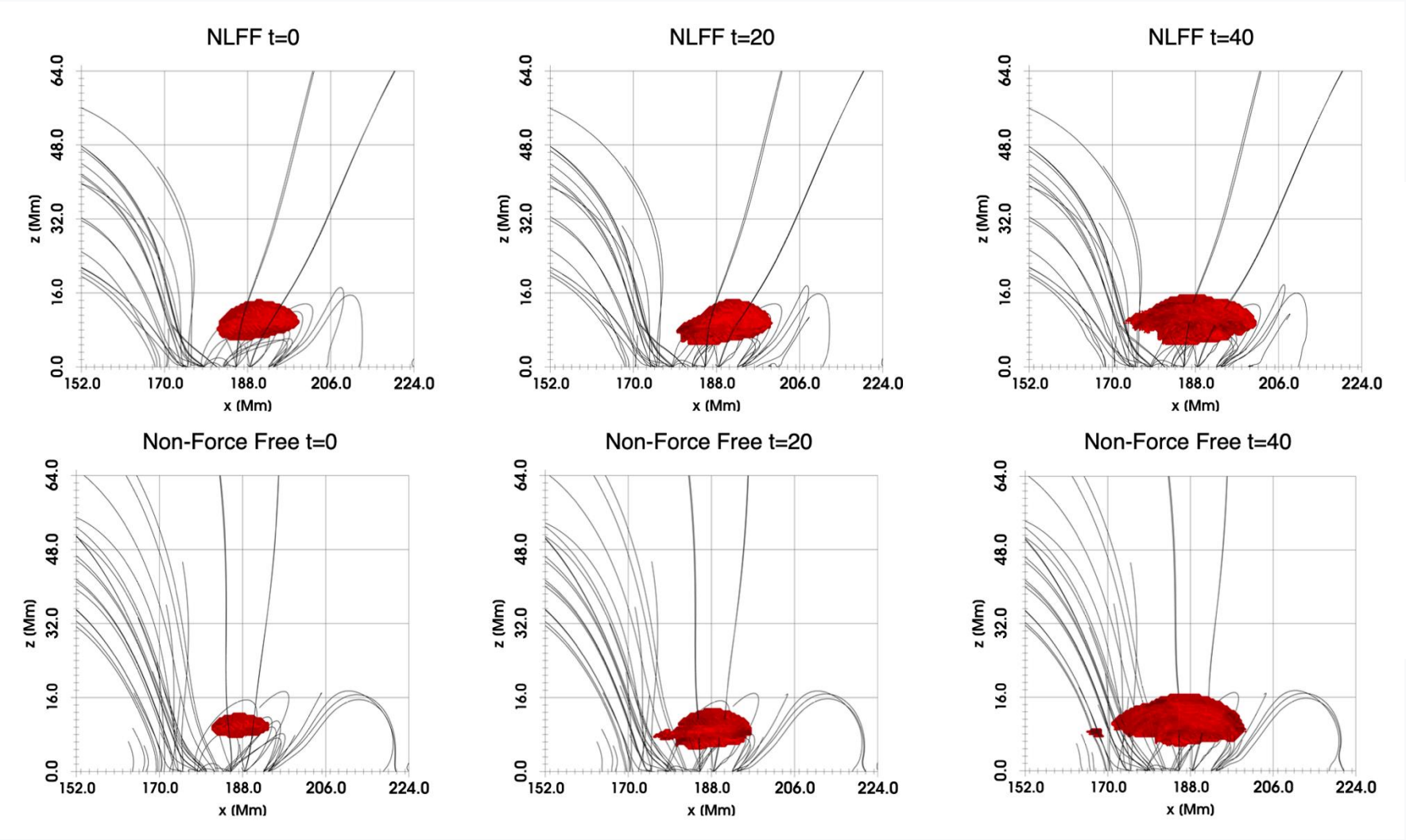
- Current-driven anomalous resistivity:

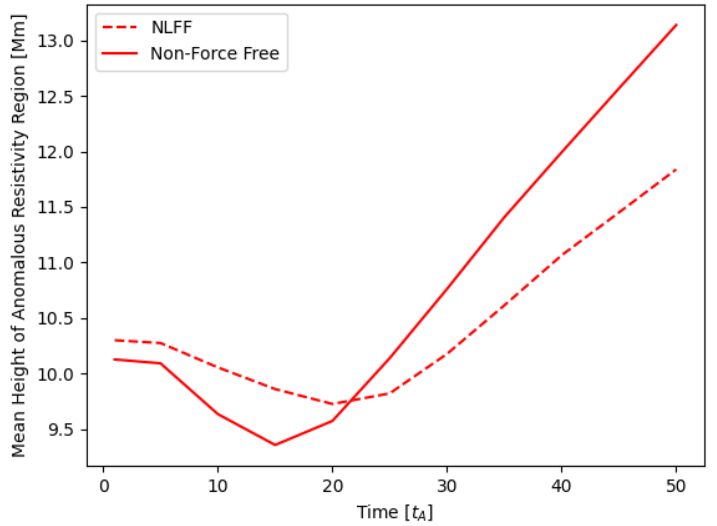
$$\eta = \begin{cases} \eta_0, \ IF \ \ j < \alpha \frac{\rho}{\sqrt{\epsilon}} \ OR \ z < 4Mm \\ \eta_1, \ IF \ \ j \geq \alpha \frac{\rho}{\sqrt{\epsilon}} \ AND \ z \geq 4Mm \end{cases}$$

where η_0 and η_1 are background and anomalous resistivities (10^{-5} and 10^{-3}, respectively), j is the current density, ρ is the density, and ϵ is the specific internal energy density

This mimics the anomalous resistivity triggered by the ion-cyclotron instability.

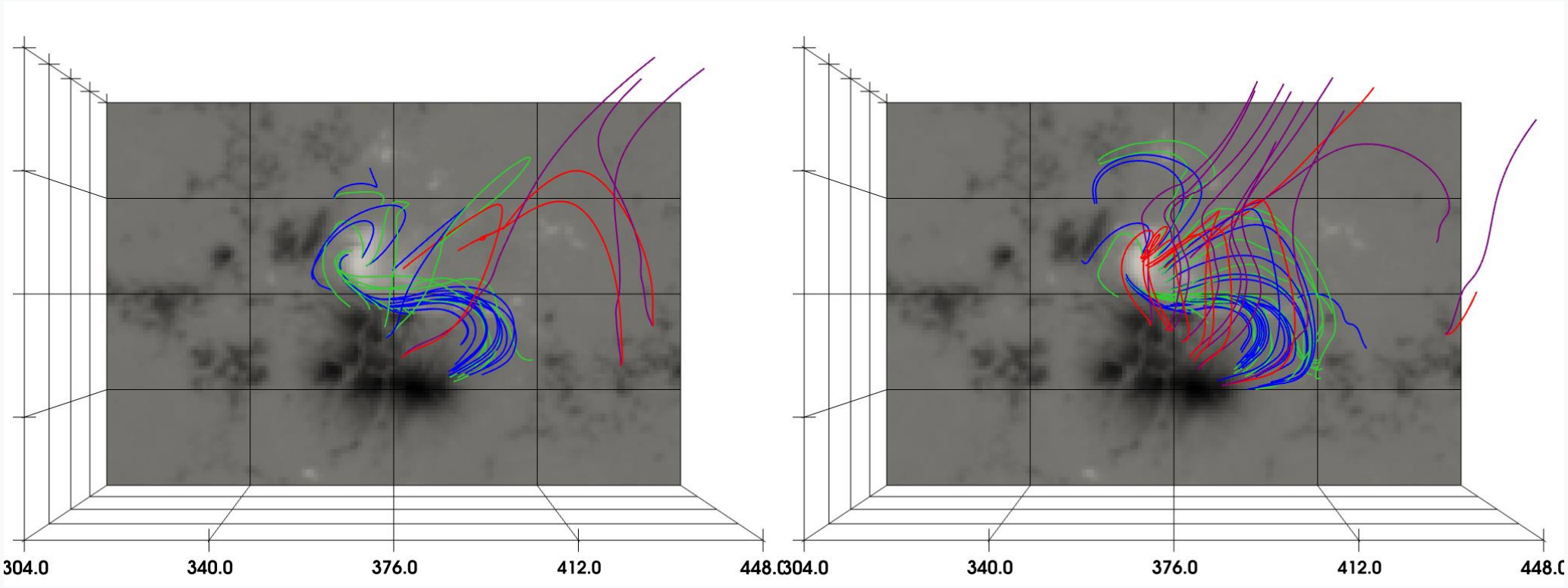
Anomalous Resistivity Region Evolution





Field Restructuring

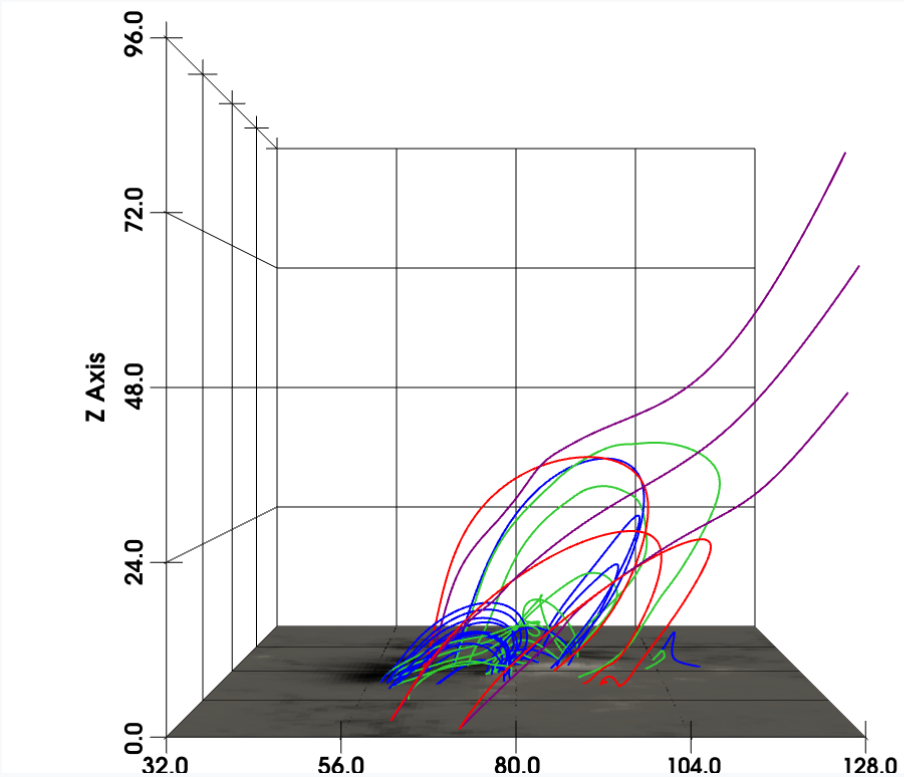
NLFF | **Non-force free**



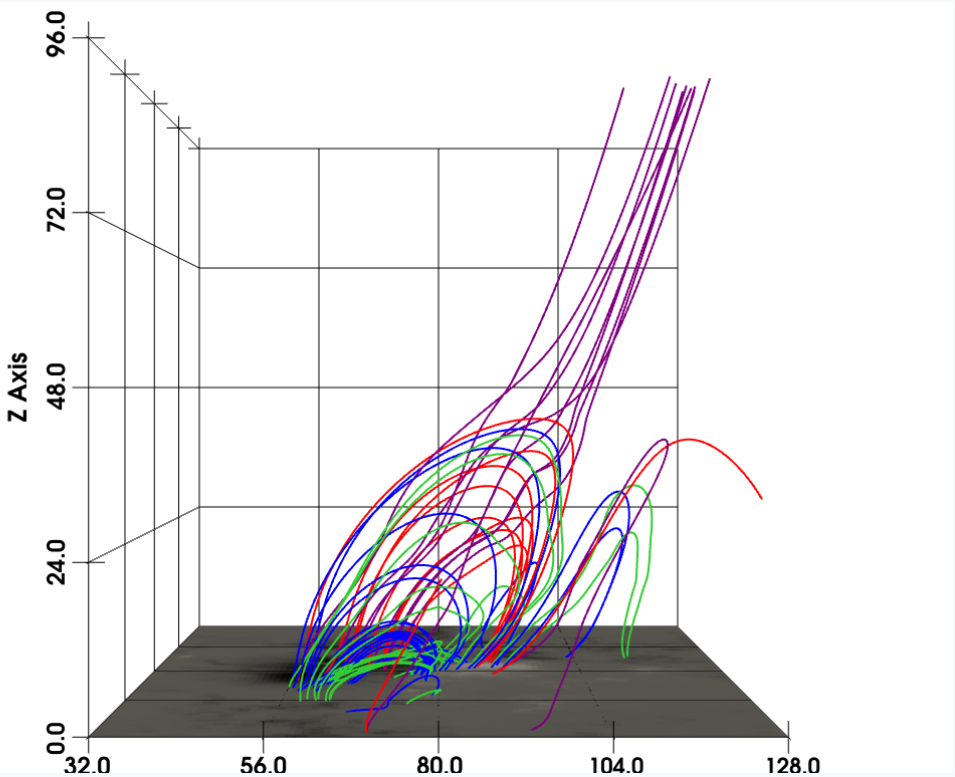
t=0	→	t=100
Red (closed)	→	Purple (open)
Blue (closed)	→	Green (closed, moved)

Field Restructuring

NLFF

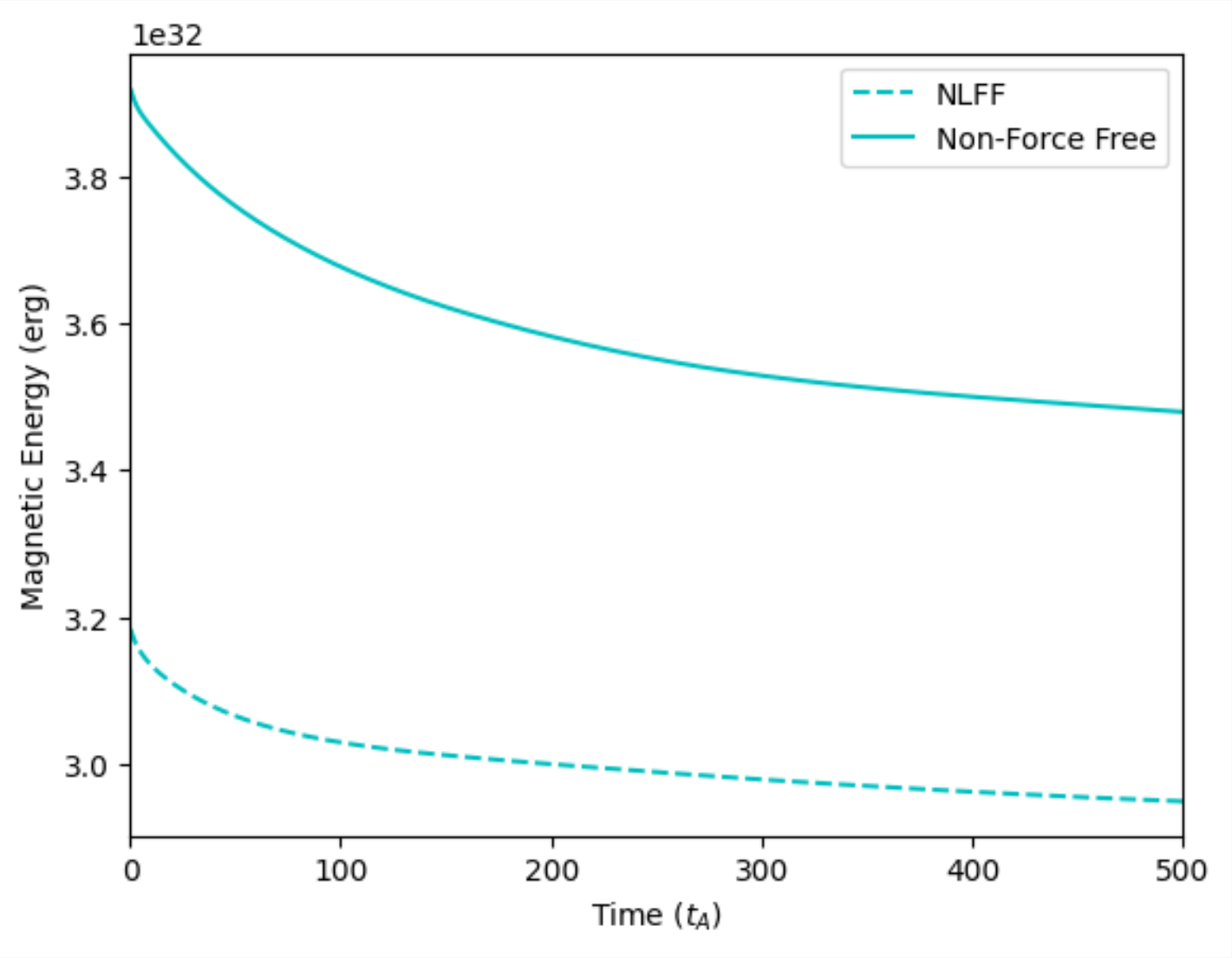


Non-force free



t=0	→	t=100
Red (closed)	→	Purple (open)
Blue (closed)	→	Green (closed, moved)

Magnetic Energy Evolution



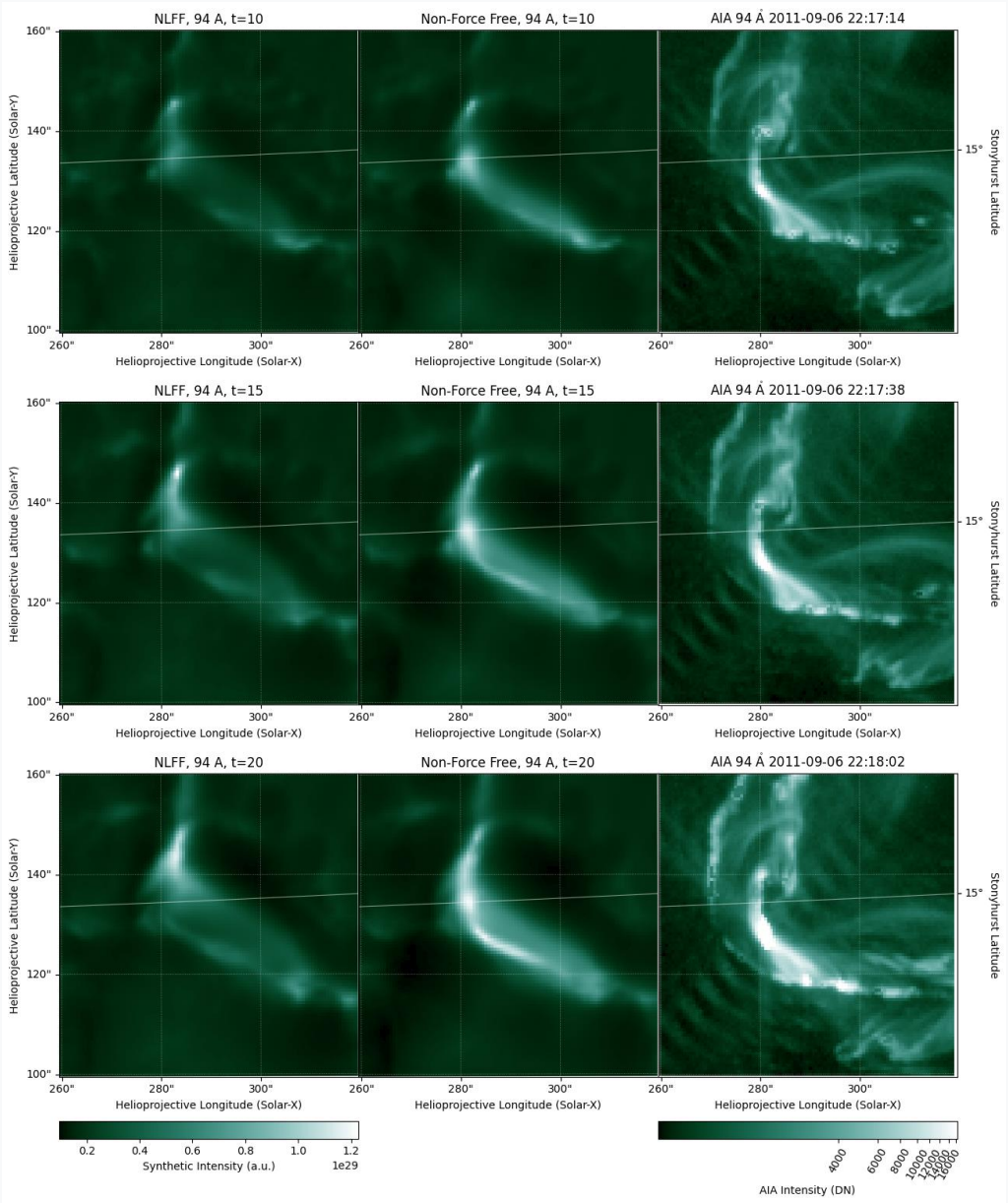
Initial energies:

NLFF	3.18×10^{32} erg
non-FF	3.92×10^{32} erg

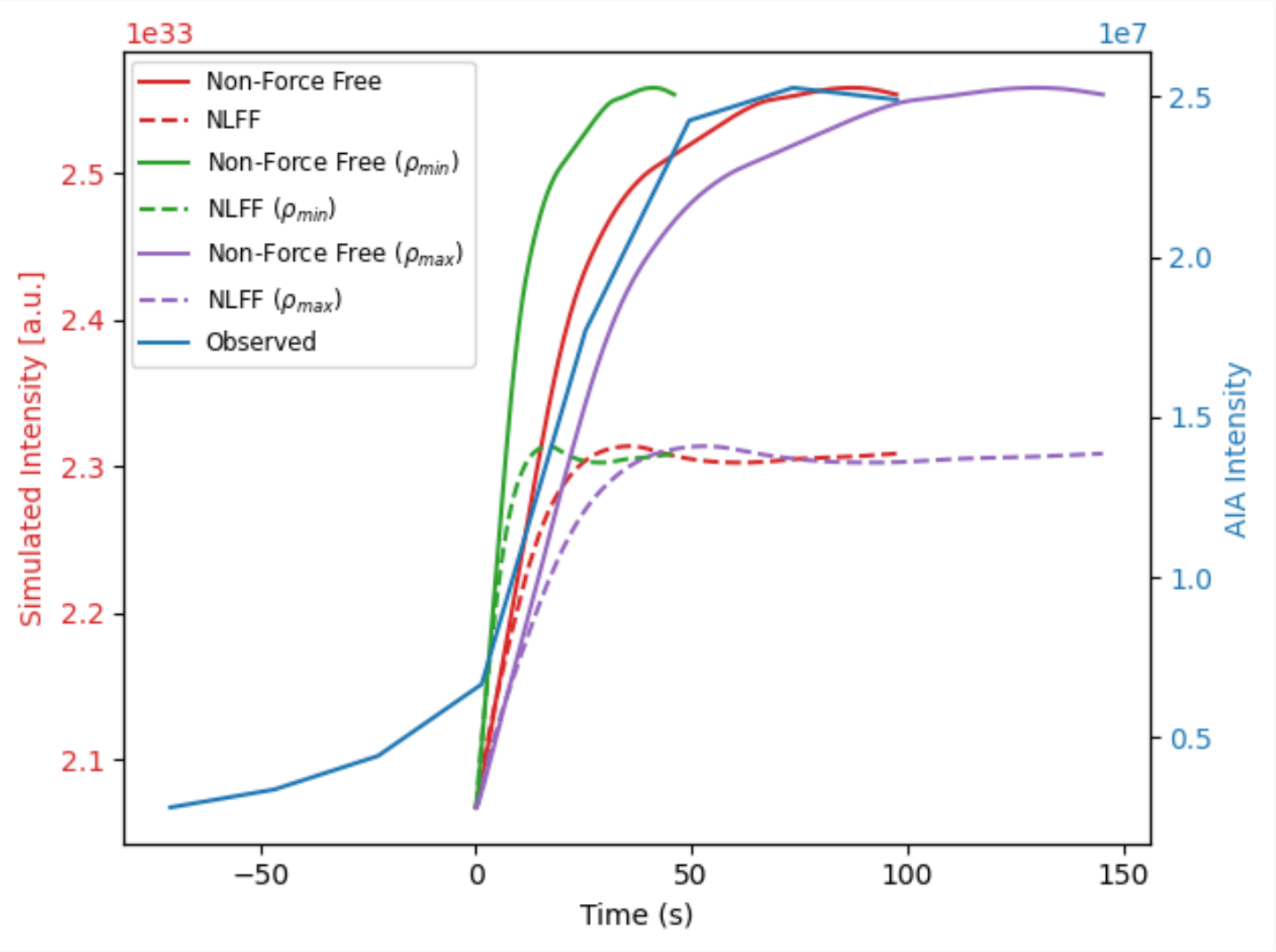
Energy loss:

NLFF	2.3×10^{31} erg
non-FF	4.4×10^{31} erg

AIA 94Å Synthetic Observables



Light Curves



Normalising magnetic field and length are fixed by our observed magnetogram:

$$B_0 = 0.1T; L_0 = 0.5\mathrm{Mm}$$

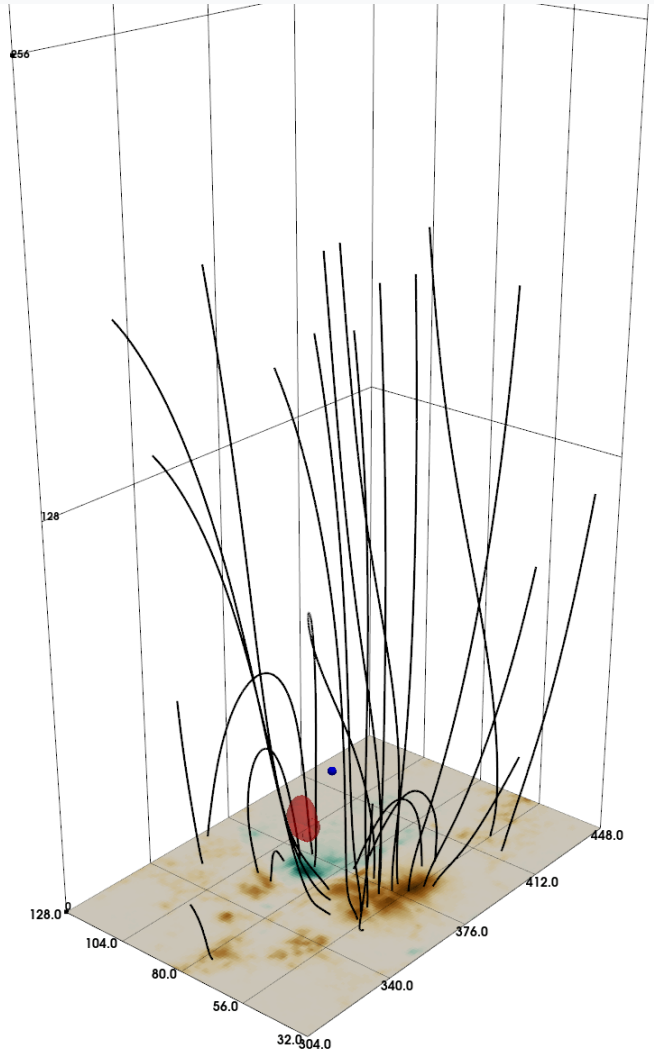
Normalising density is a free parameter as we do not measure this. For a range of physically plausible coronal densities, we can arrive at normalising times:

$$t_0 = [0.09,0.29]s$$

This allows a choice of normalising density which matches the observed flare timescale (red line)

*this is valid as all internal calculations are performed in normalised units

Particle Modelling (GCA)



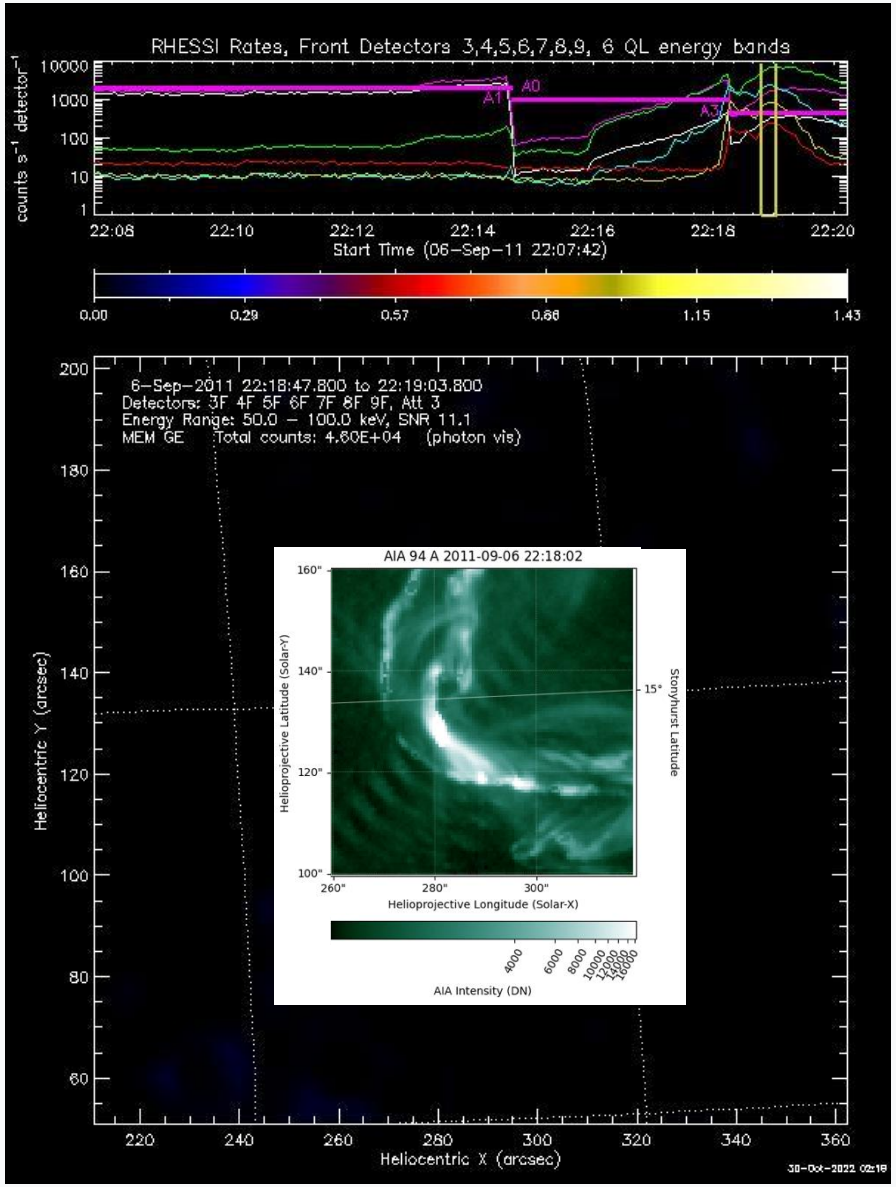
Reconnection Site vs Particle Acceleration Site

Particles (blue) are accelerated above the anomalous resistivity region (red)

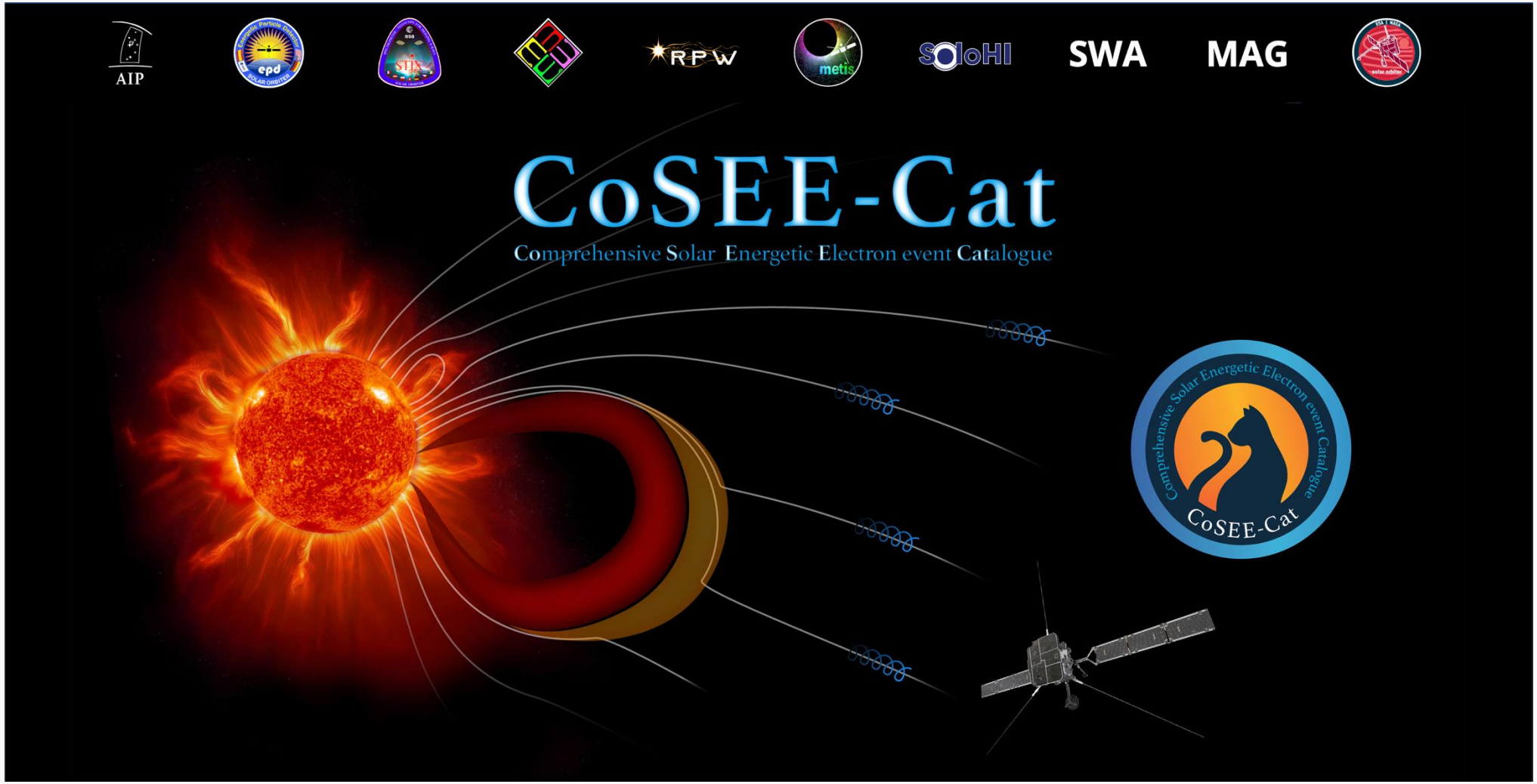
The intention is to be able to use this to create synthetic observables for footpoint x-ray emission

AND for in-situ particle detections.

AIA 94Å Synthetic Observables and RHESSI



Extention: Using a Catalogue



Warmuth+ 2025, A&A – an amazing resource!

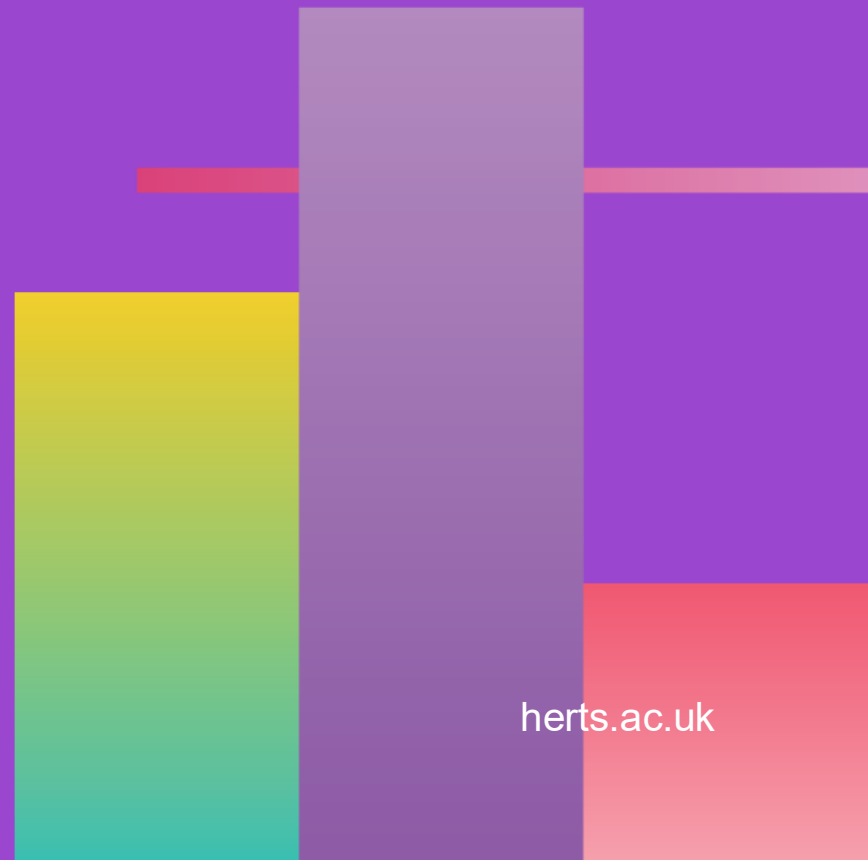
Conclusions

- Non-force free initialised simulation gives ‘more realistic’ flare
- Measured by brightness, emission distribution, and energy release
- Synthetic 94Å emission proved very useful as a diagnostic for this comparison
- Particle Simulations underway to provide x-ray and in-situ diagnostics
- Currently expanding to flares observed in-situ / from multiple angles

ApJ link:

Thank you

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