Theory of Solar Eruptions and Its Applications to the Magnetic Eruption in the Other Astrophysical Environments

Lin, Jun

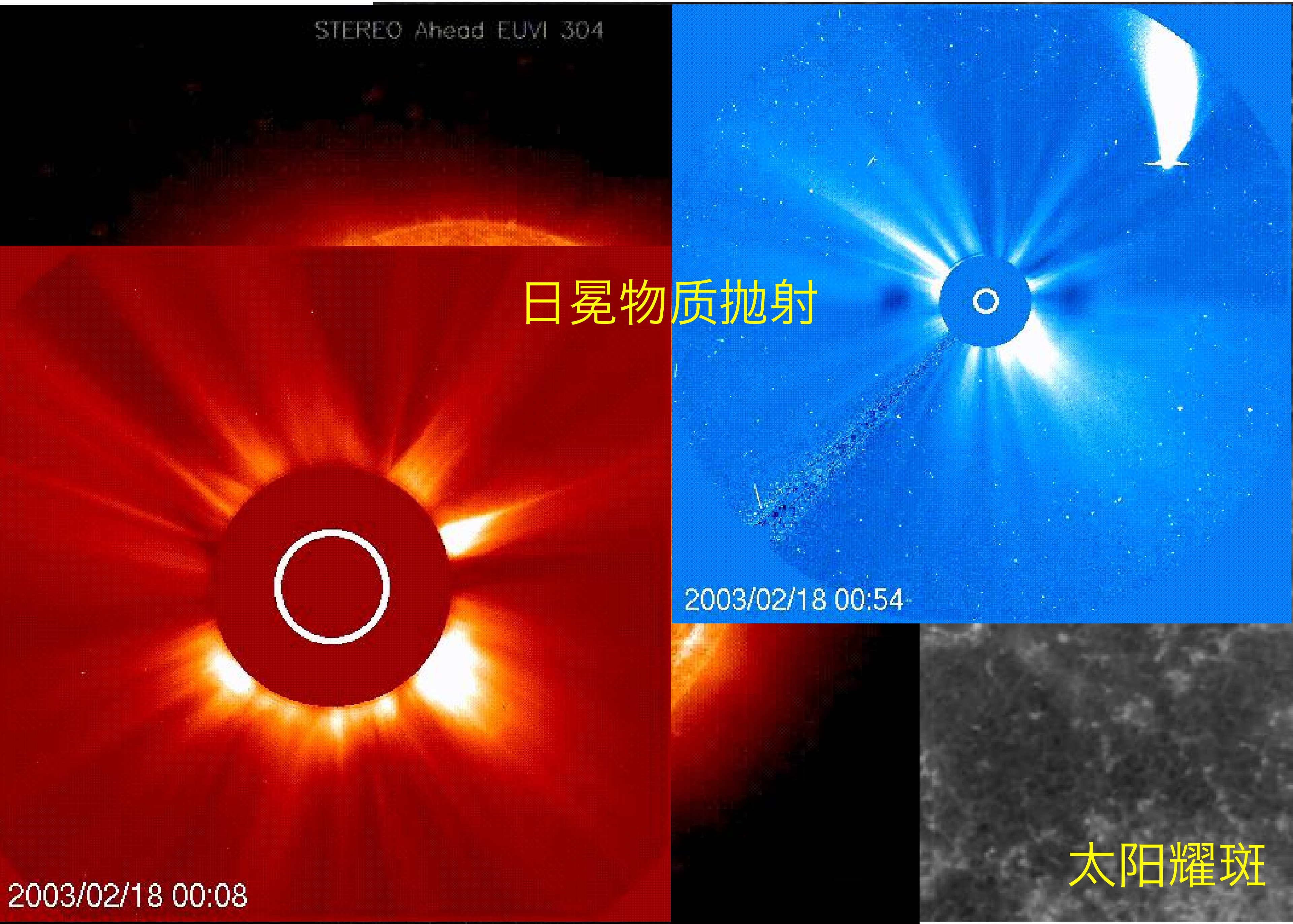
林 隽

中国科学院云南天文台
YUNNAN ASTRONOMICAL OBSERVATORY CHINESE ACADEMY OF SCIENCES

Yunnan Astronomical Observatories

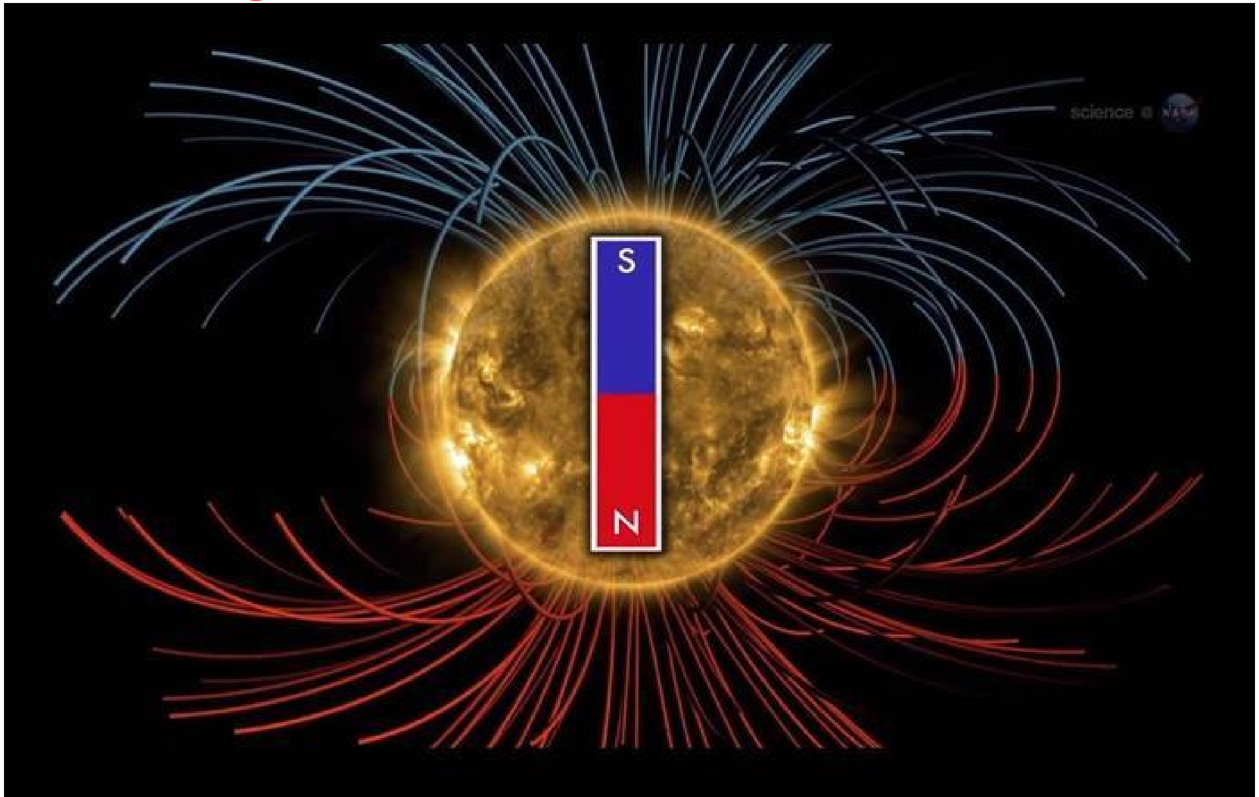
Content

- Brief introductions of solar eruptions
- Magnetic field and magnetic eruptions in the universe
- Applications of Lin-Forbes model to the magnetic eruption at the other places in the universe
- Summary

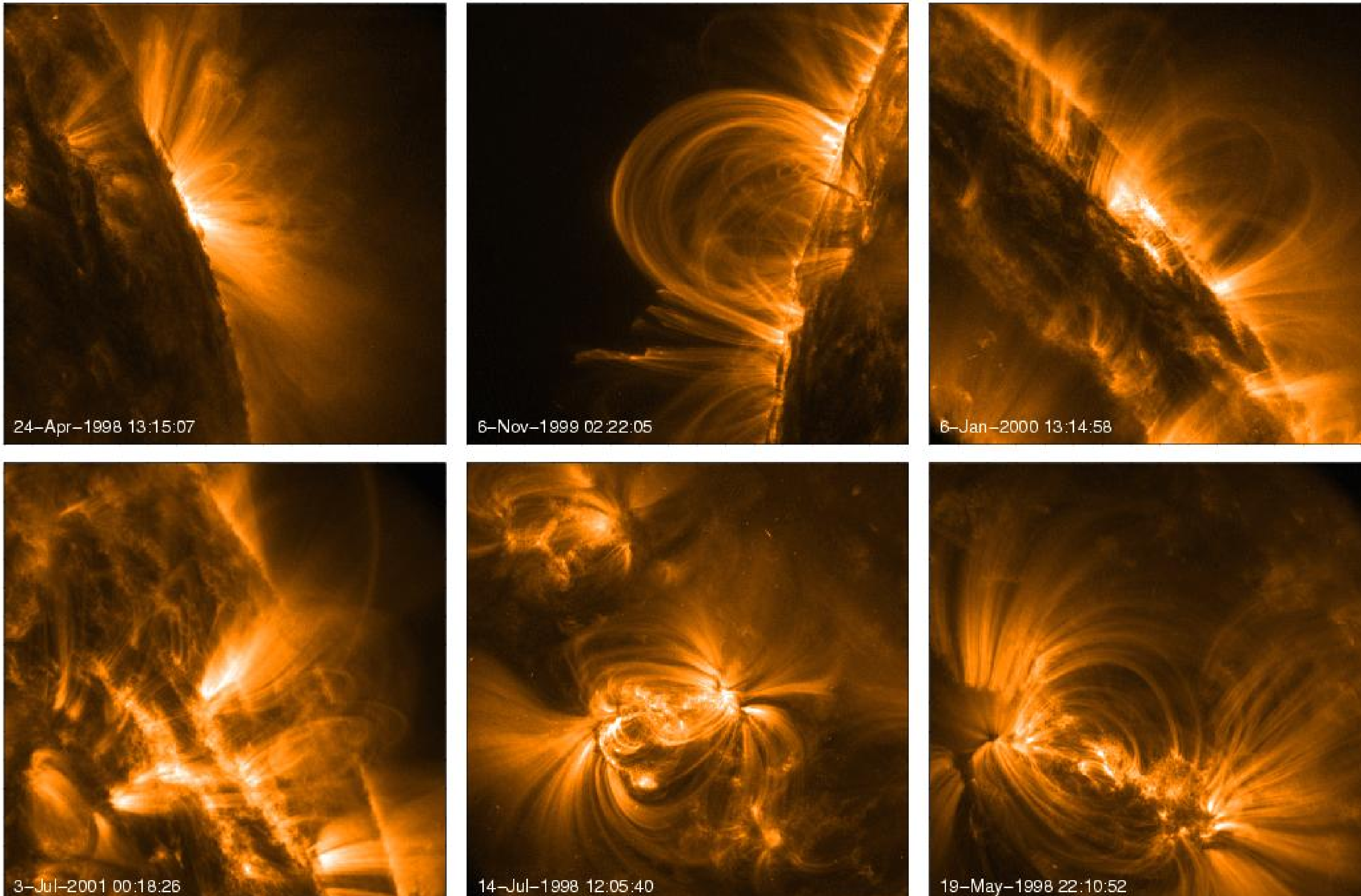

STEREO Ahead EUVI 304
日冕物质抛射
2003/02/18 00:54
2003/02/18 00:08
太阳耀斑

Solar Eruptions

- Solar flares, eruptive prominences, and coronal mass ejections;
- The energy driving the eruption is stored in the coronal magnetic field beforehand;

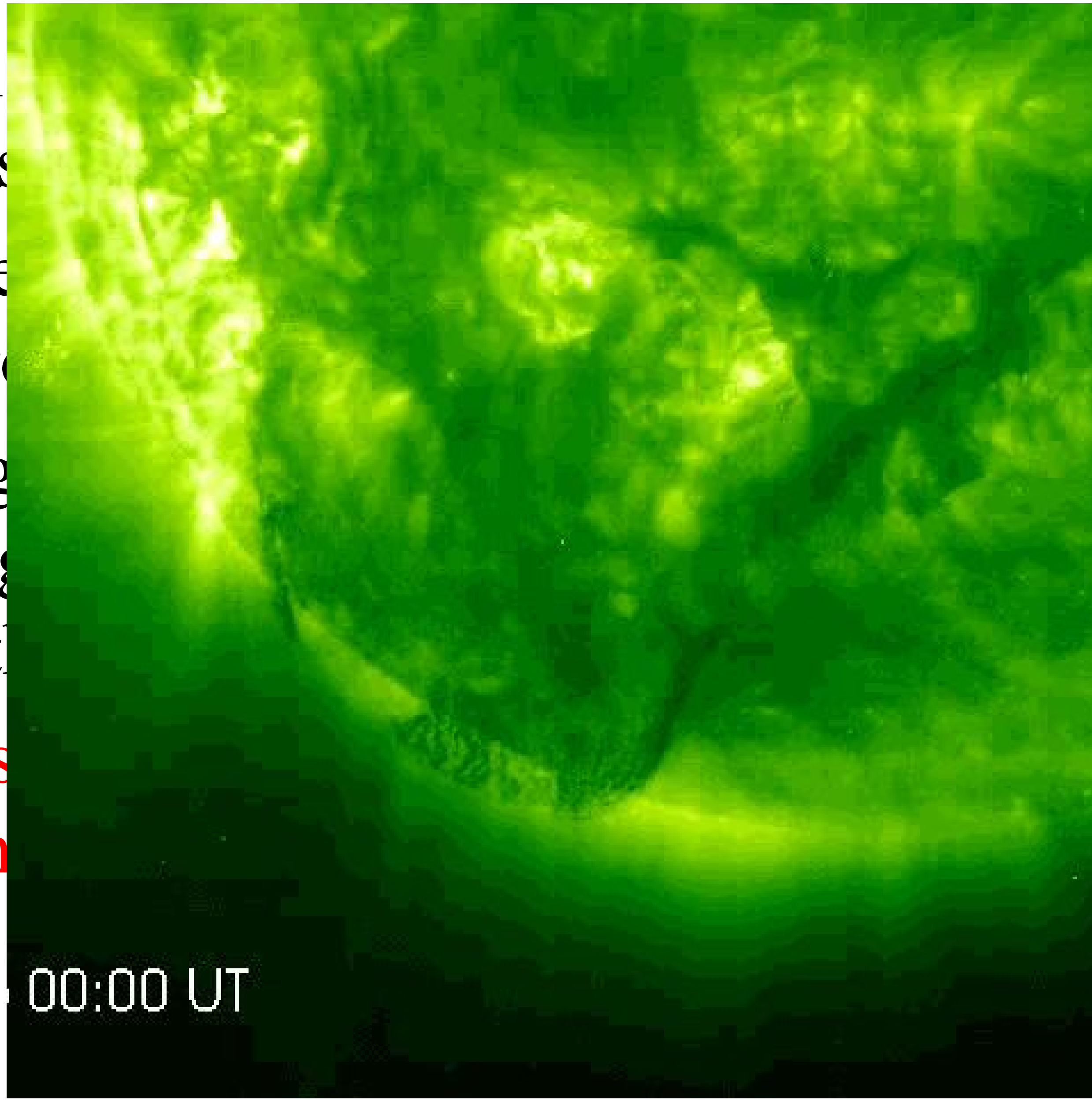


Solar Eruptions

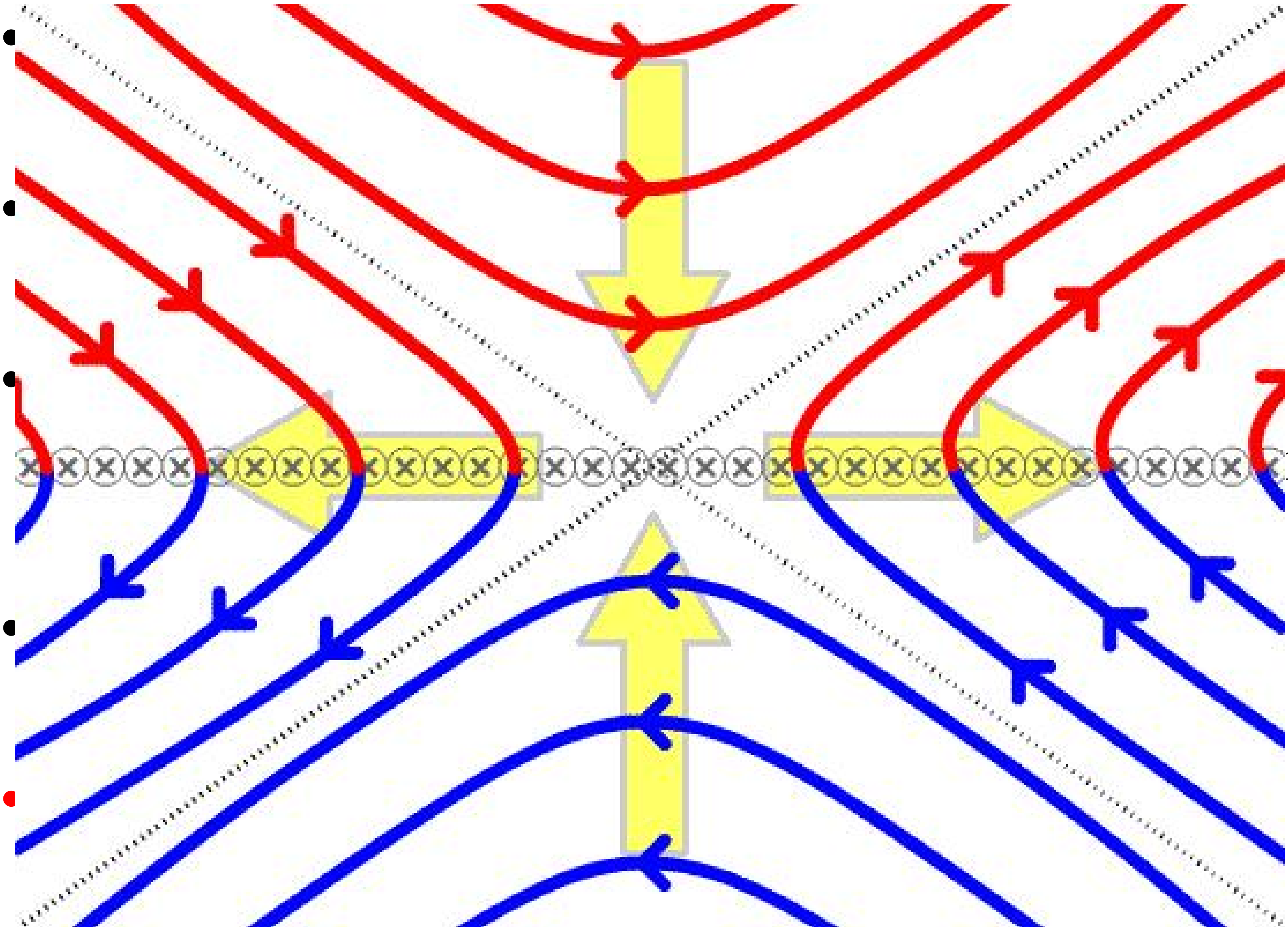


Solar Eruptions

- Sol … coronal
  mas …
- The … d in the
  cor …
- Hig … al
  mag … stored
  in t …
- Los … netic
  con …



Solar Eruptions



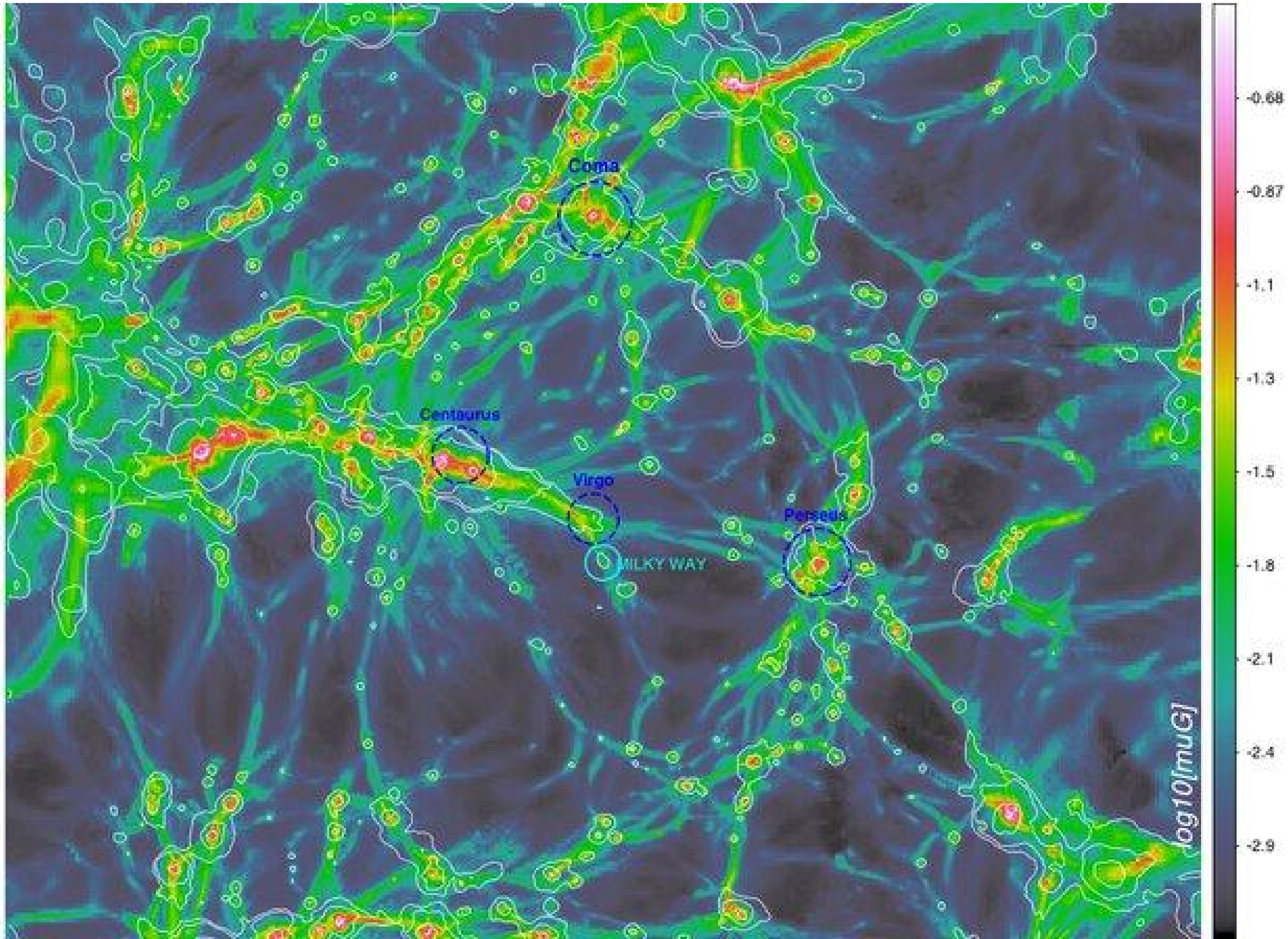
in

Content

- Brief introductions of solar eruptions
- Magnetic field and magnetic eruptions in the universe
- Applications of Lin-Forbes model to the magnetic eruption at the other places in the universe
- Summary

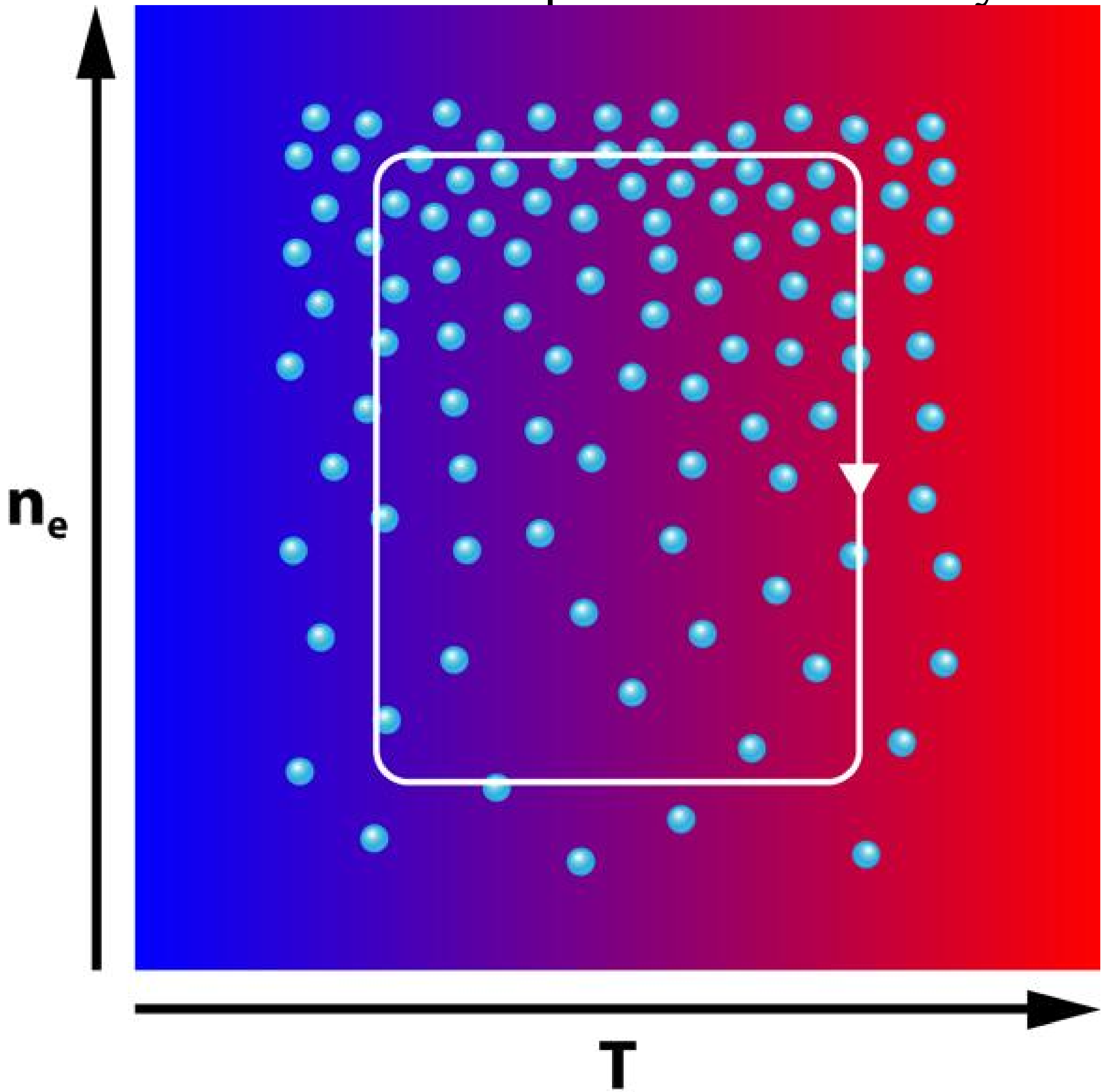
Magnetic Field in the Universe

- Most of the universe is in the form of a plasma threaded by a magnetic field.



Magnetic Field in the Universe

- Most of the universe is in the form of a plasma threaded by a magnetic field.



➢ Magnetic
in the plas

➢ The magn
known as t

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times$$

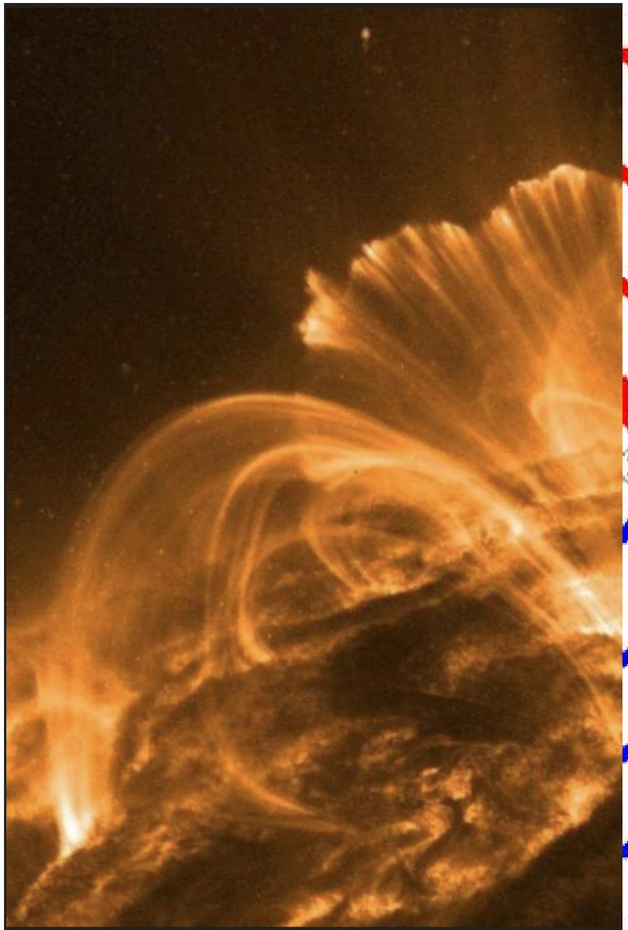
Magnetic Field in the Universe

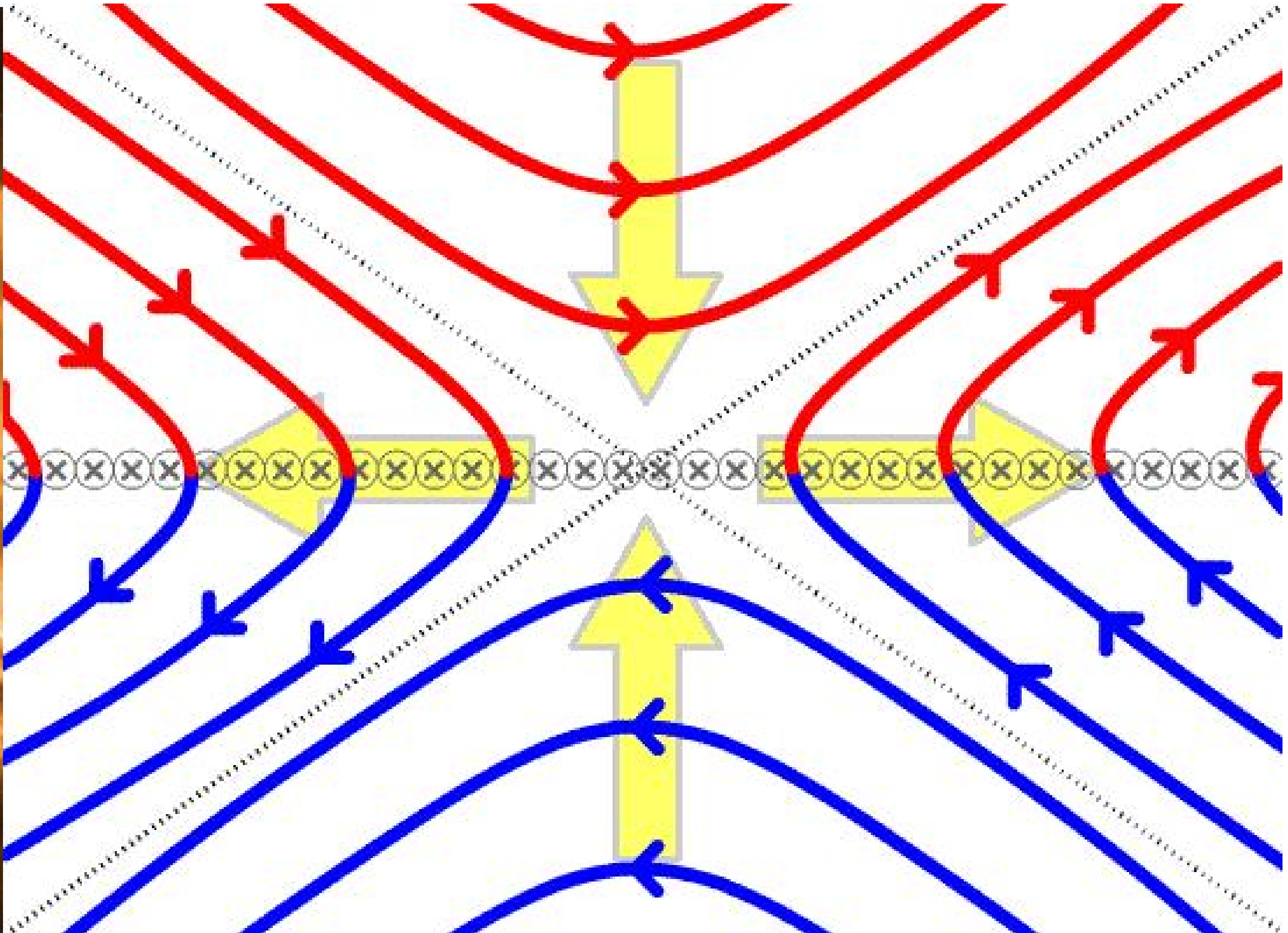
- Most of the universe is in the form of a plasma threaded by a magnetic field.

- ➢ Strength of seed field: $10^{-21} \sim 10^{-19}$ G, undetectable;
- ➢ Dynamo process in interstellar space amplifies the seed field to the strength of $10^{-7} \sim 10^{-6}$ G, detectable;
- ➢ Dynamo process inside the star further amplifies the magnetic field up to $\sim 10^{3}$ G.

Magnetic Reconnection

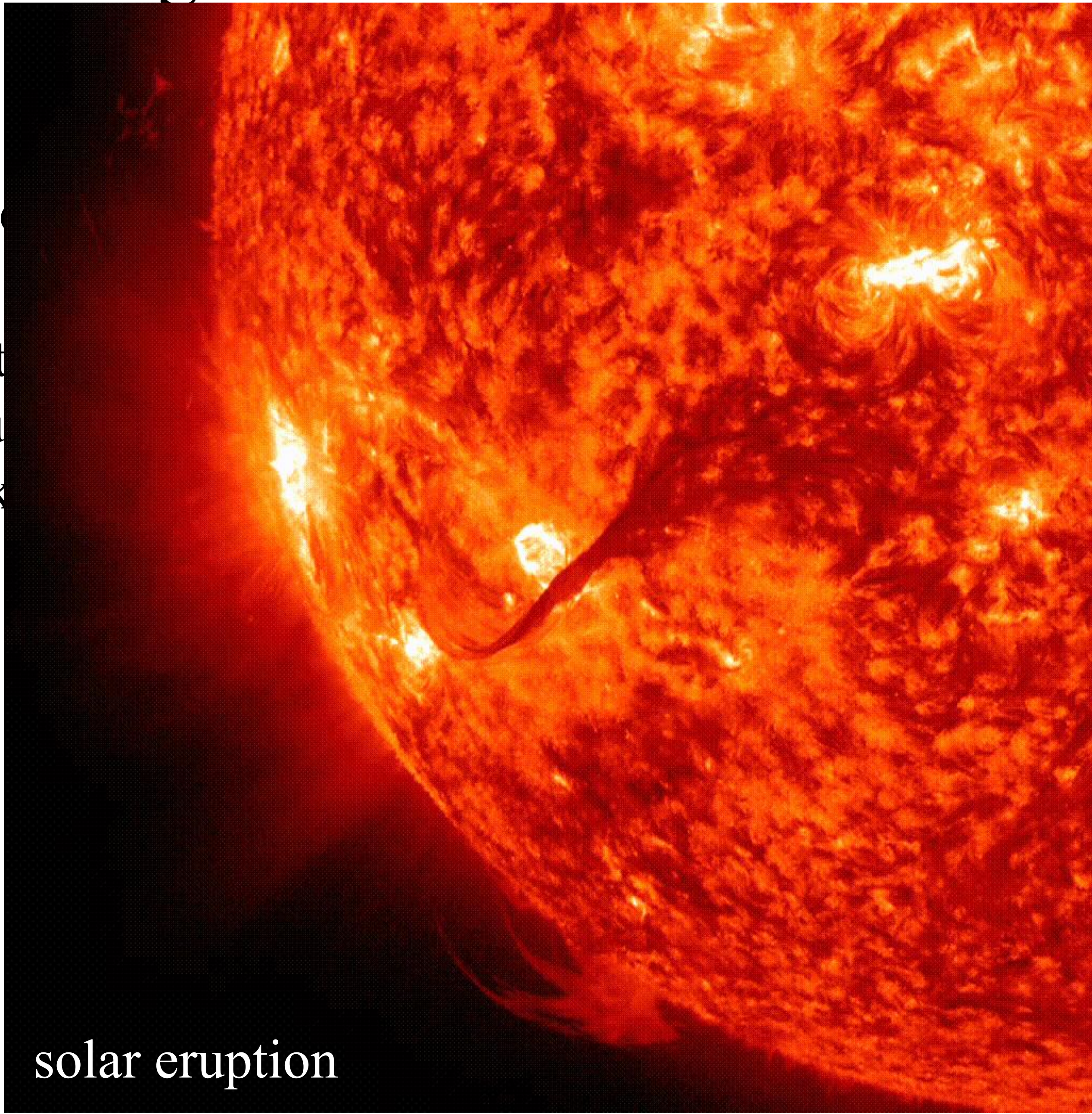
- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect rapidly, converting magnetic energy into heat and kinetic energy.





Results of Magnetic Reconnection

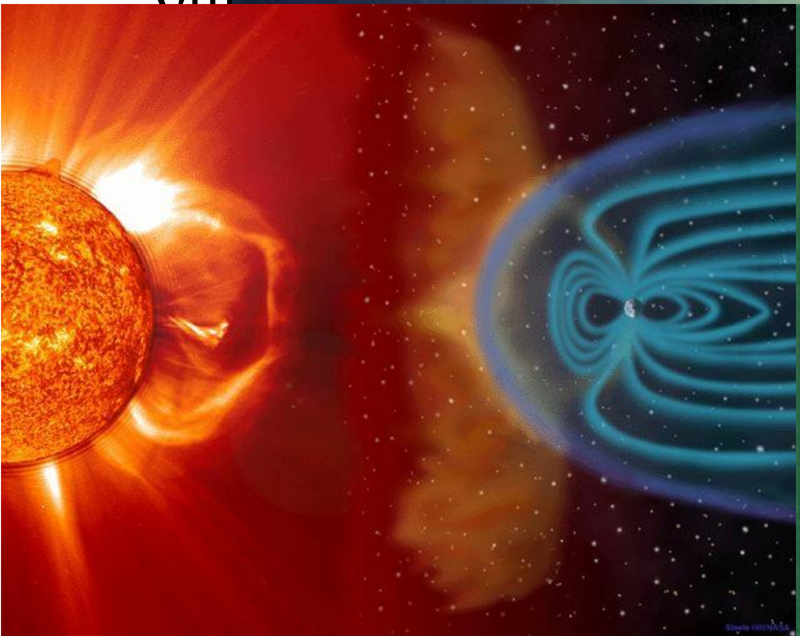
- Most of the univers
  magnetic field.
- When twisted or sh
  rapidly, converting
- Magnetic reconnect
  phenomena in the u
  substorms, tokamak
  other astrophysical

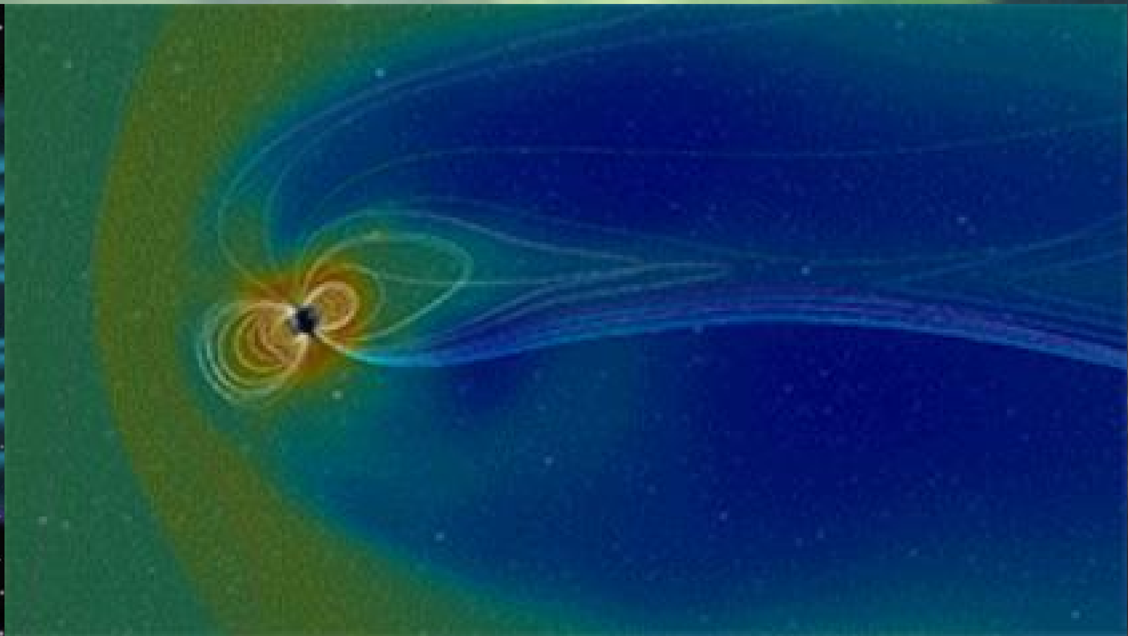


solar eruption

Results of Magnetic Reconnection

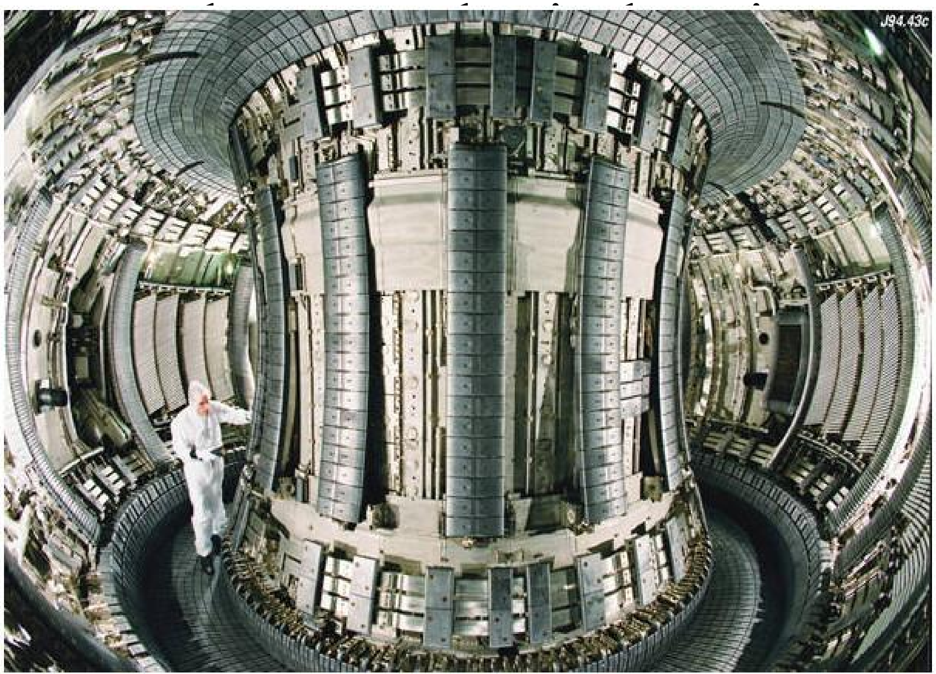
- Mo
  ma
- Wh
  rap
- Ma
  phe
  sub
  oth





Results of Magnetic Reconnection

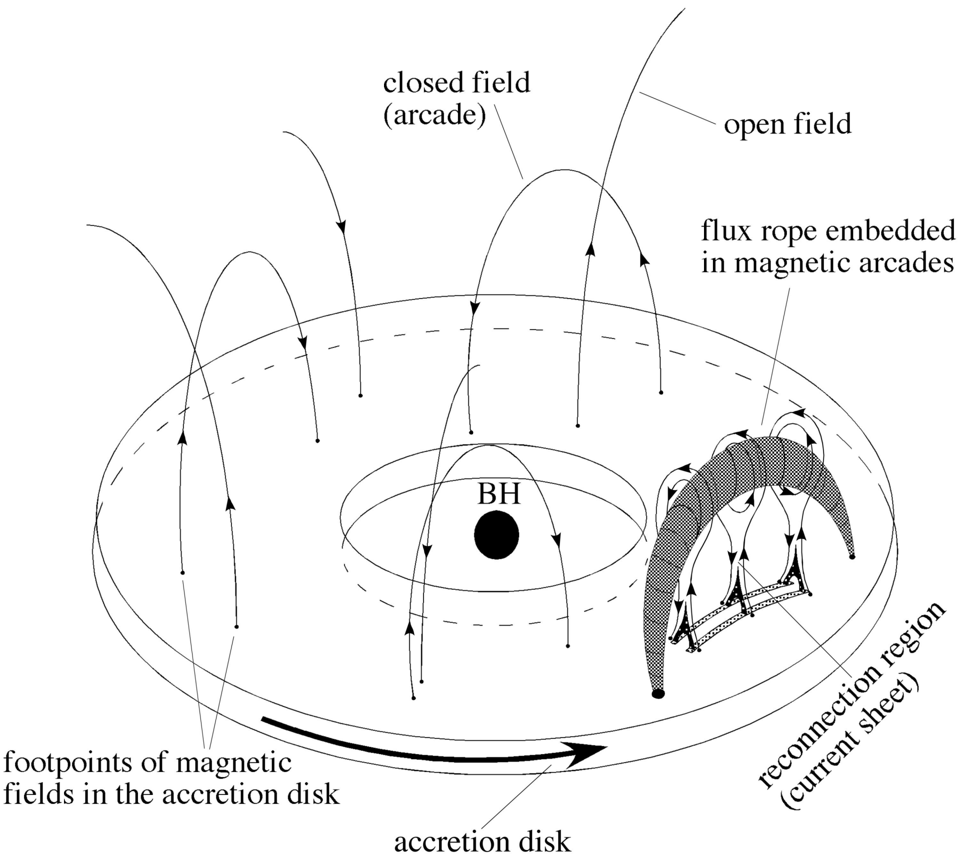
- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect rapidly, converting magnetic energy into heat and kinetic energy.
- Magnetic reconnection is at the core of many dynamic phenomena in the universe, such as solar eruptions, geomagnetic substorms, tokamak disruptions, and disruptive processes in the



tokamak disruption

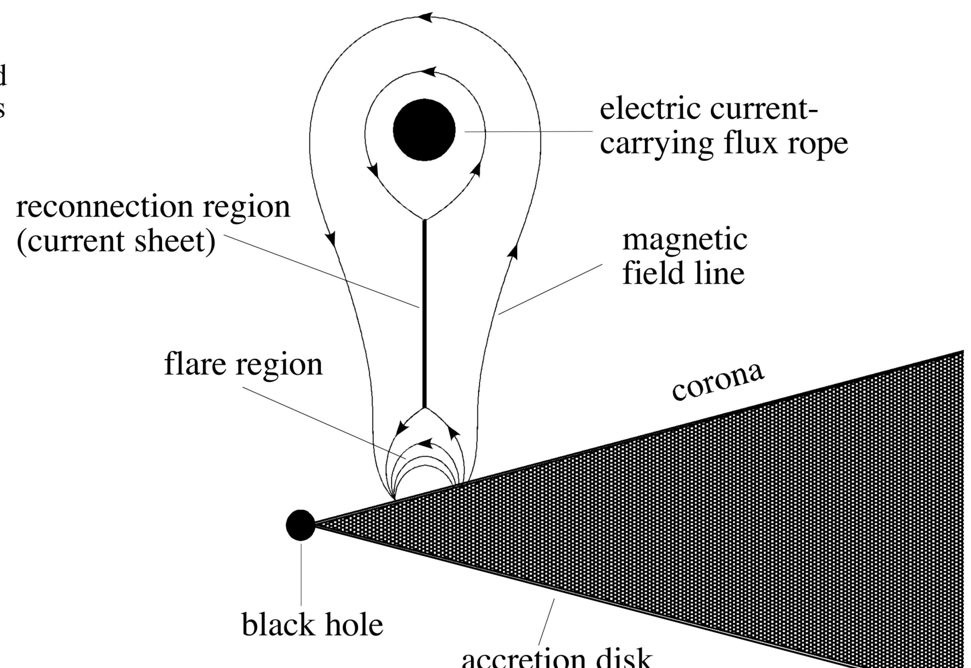
Results of Magnetic Reconnection

- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect



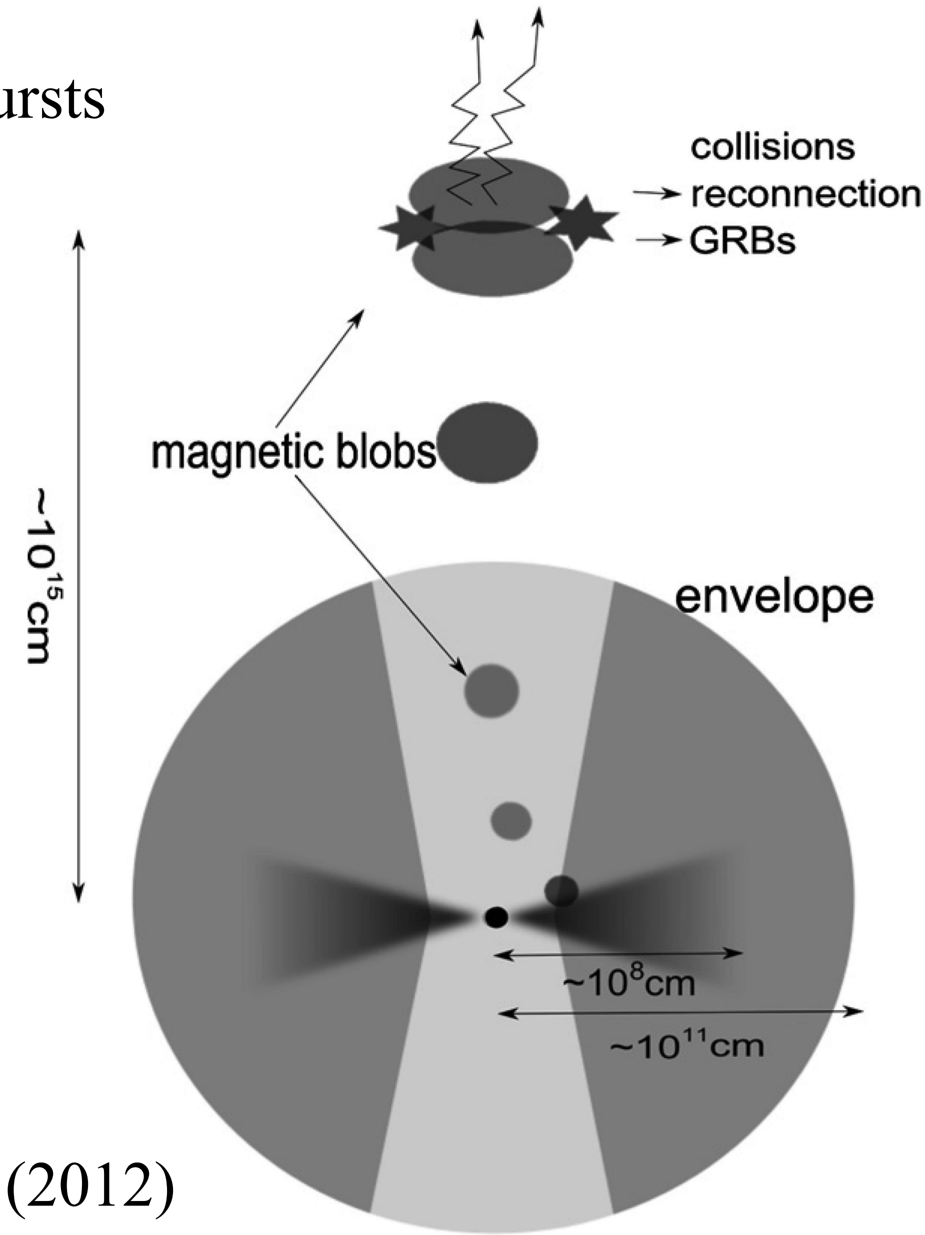
(b)

Episodic jets (Yuan et al. 2009)



Results of Magnetic Reconnection

Gamma ray bursts



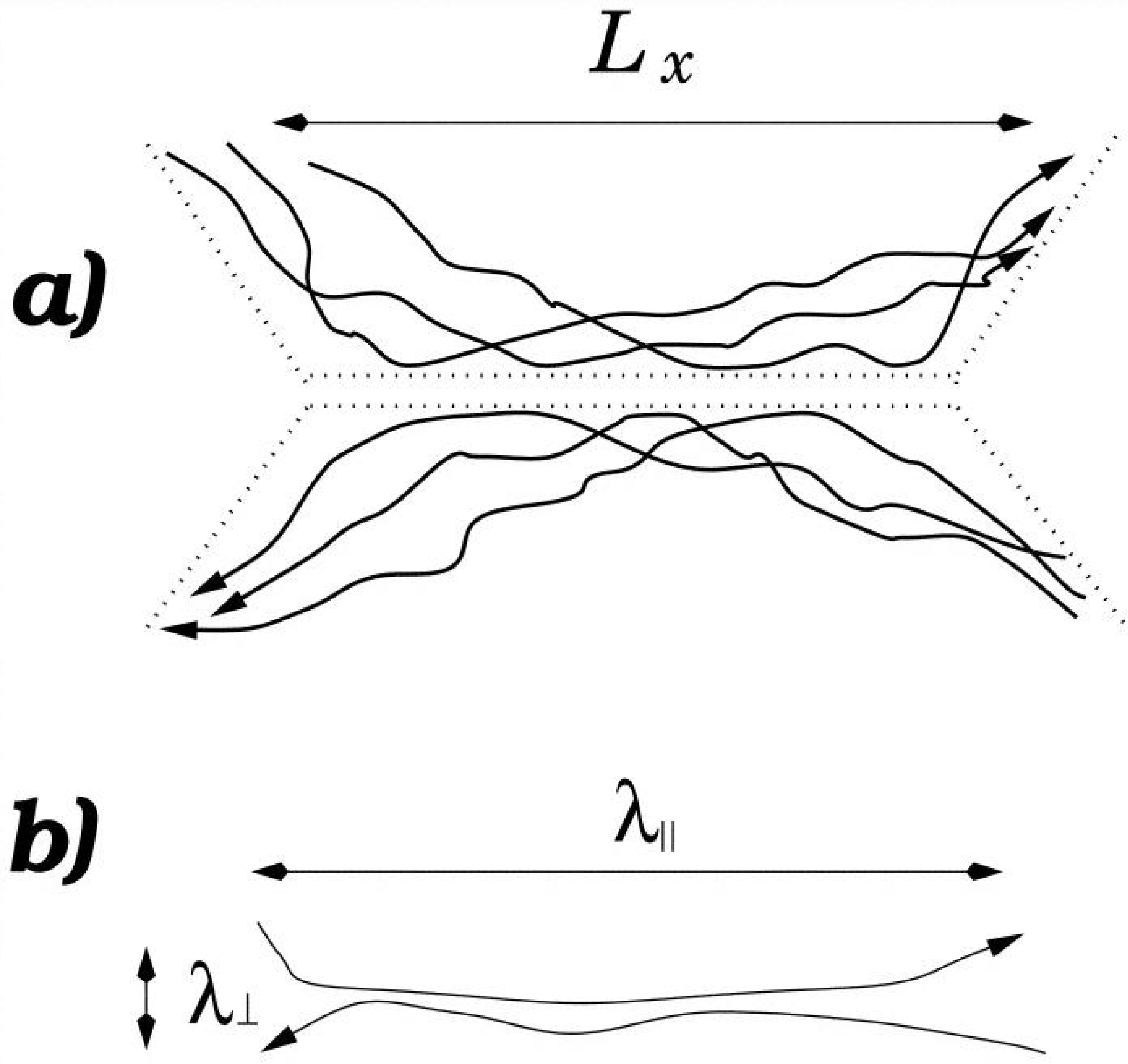
Yuan & Zhang (2012)

Results of Magnetic Reconnection

- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect rapidly, converting magnetic energy into heat and kinetic energy.
- Magnetic reconnection is at the core of many dynamic
  p … etic
  s … he
  o

Giant flare from magnetars (Meng et al. 2014, 2025)

- Mo
  ma
- Wh ... ct
  rap ... y.
- Ma
  phe ... ic



Modes of Magnetic Reconnection

- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect rapidly, converting magnetic energy into heat and kinetic energy.
- Magnetic reconnection is at the core of many dynamic phenomena in the universe, such as solar eruptions, geomagnetic substorms, tokamak disruptions, and disruptive processes in the other astrophysical environments of the magnetized plasma.
- Fashions of magnetic reconnection extensively studied include Sweet-Parker ($M_A \sim R_m^{-1/2}$), Petschek ($M_A \sim 1/\ln R_m$), Hall ($M_A \sim d_i/L$, Malyshkin 2009), and turbulence ($M_A \sim R_m^{-3/16}$, Lazarian & Vishniac 1999; $M_A \sim 0.01$, Bhattacharjee et al. 2009).

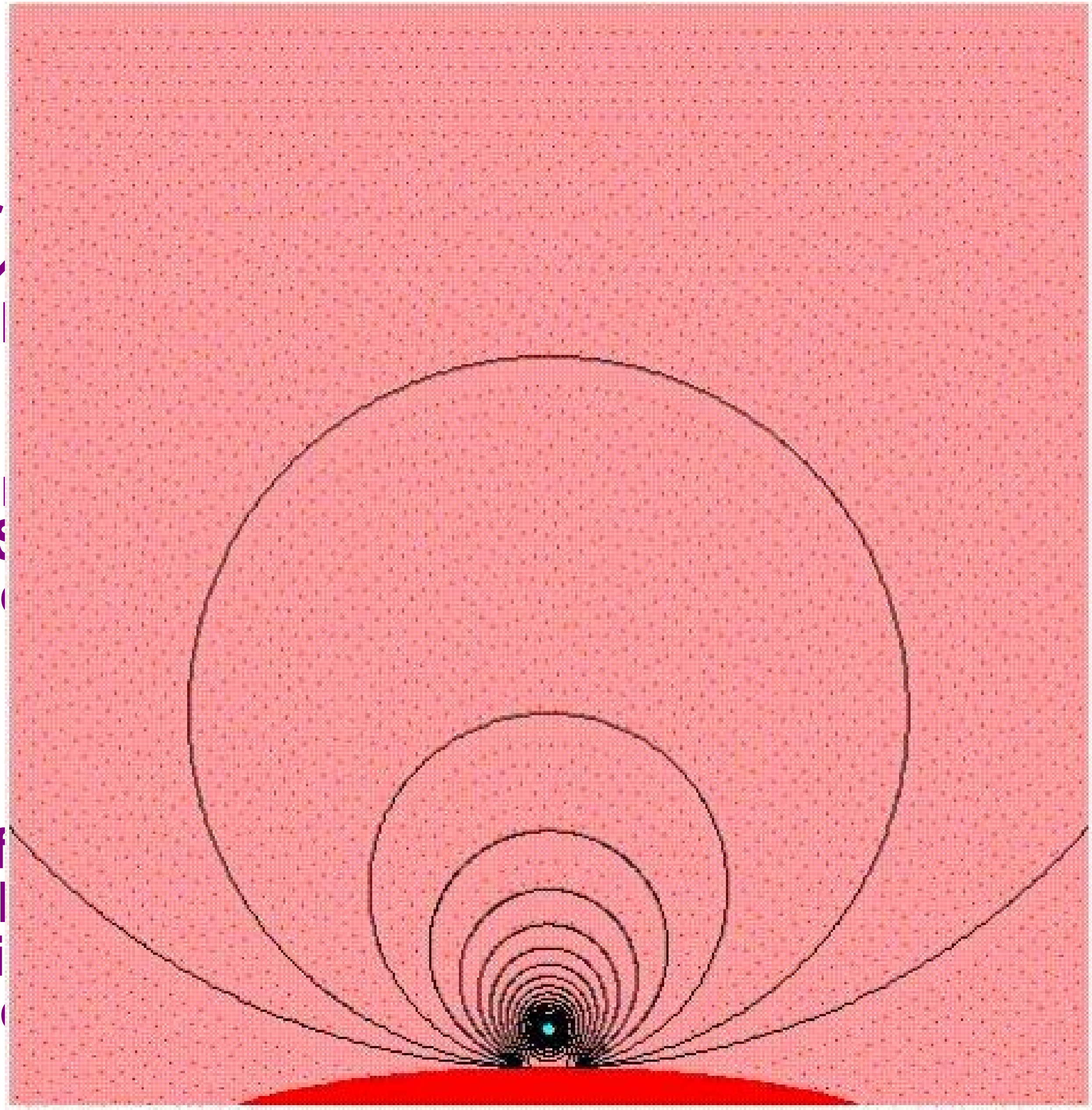
Theories/Models of CME/Flare Current Sheets

- **Since** … **d that the**
  two-ri … **nection**
  occur … **s of**
  (CSHK … **6 and**
  Švestk

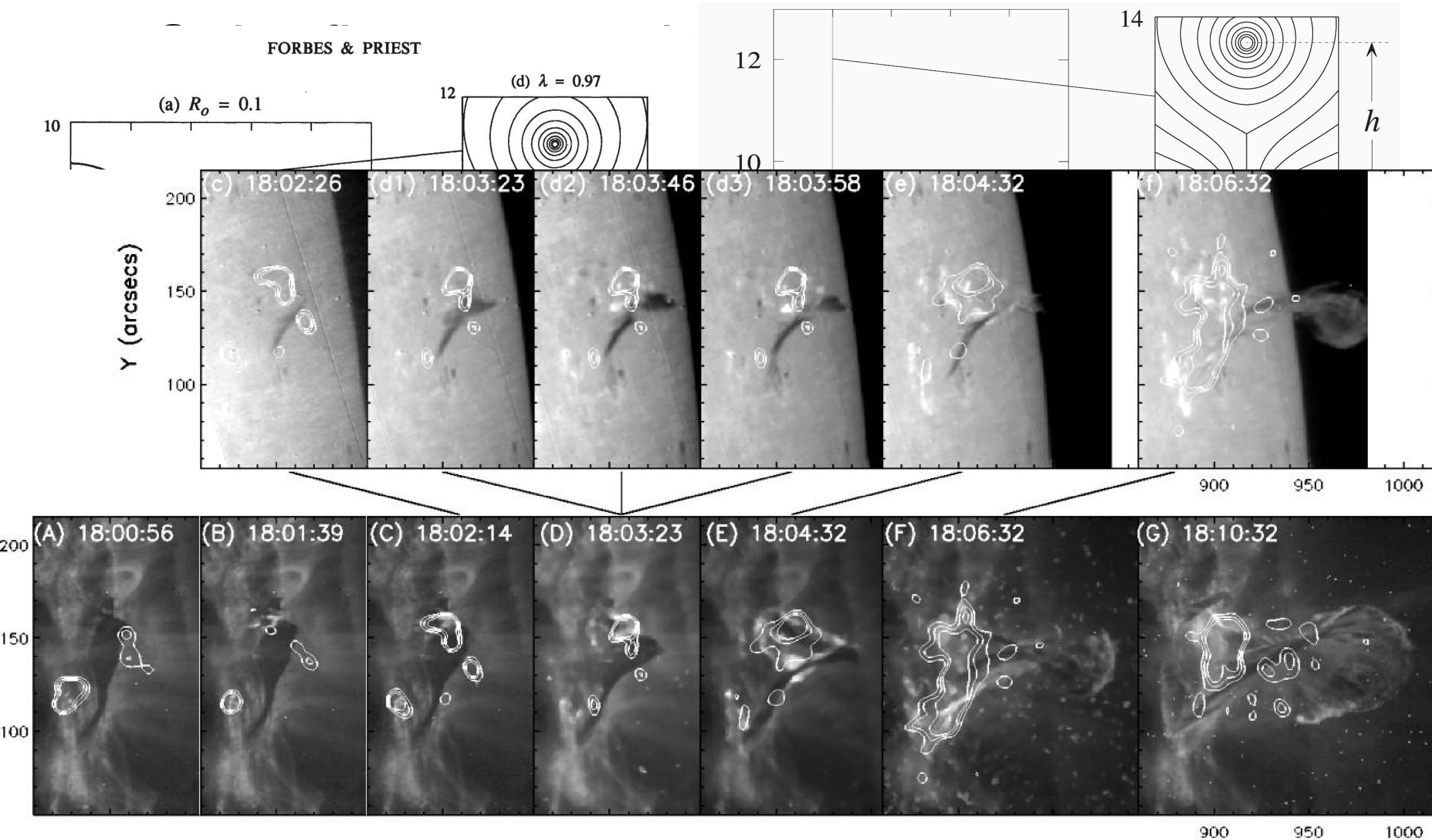
(a)

- **Marte** … **time that**
  the CS … **g**
  magn … **e and a**
  short … oint

- **Lin &** … **f**
  CME/f … **n**
  actual … **ng the**
  erupti … **%**
  magn … **nt sheet.**



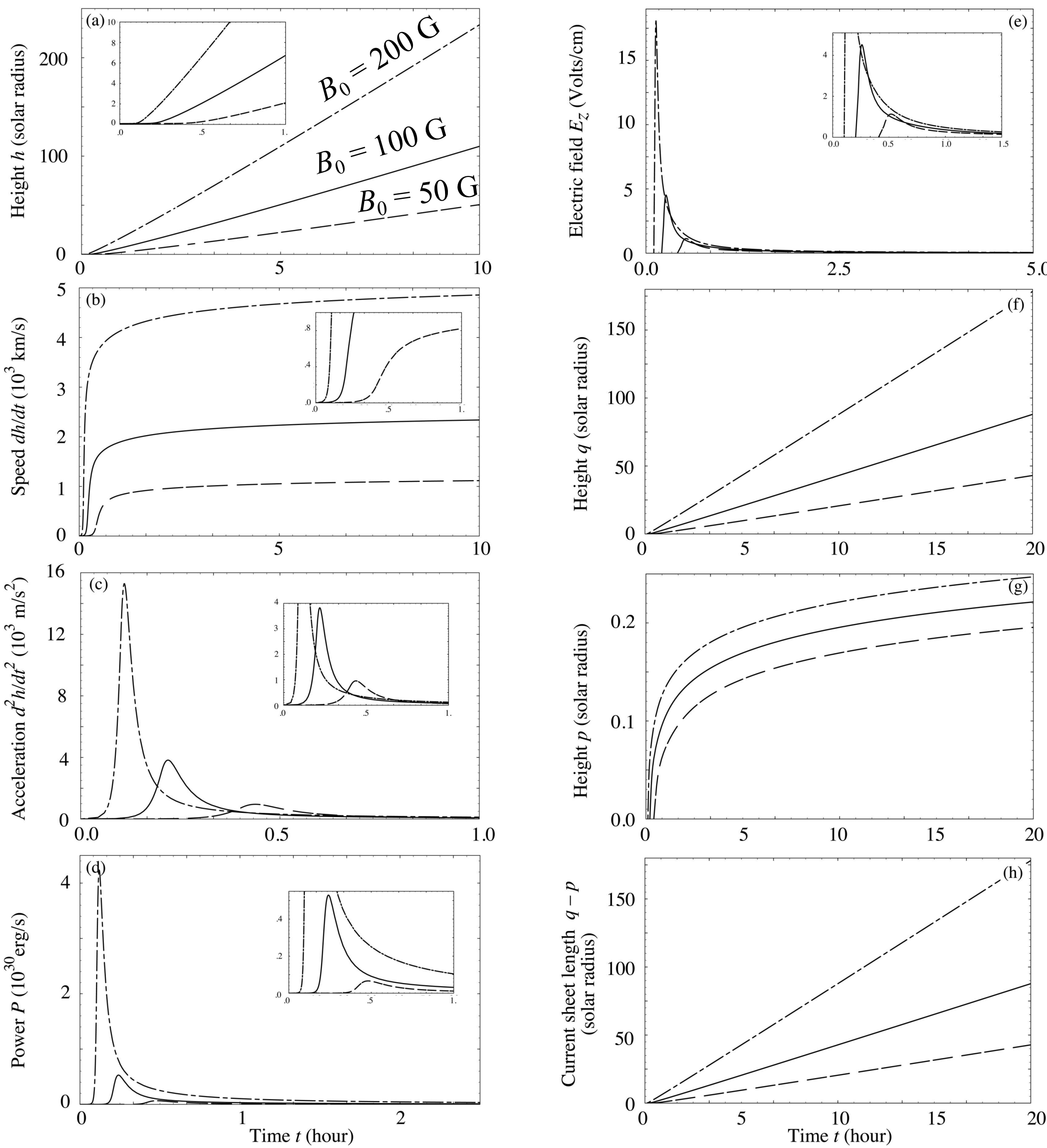
Role of Reconnection in Eruptions

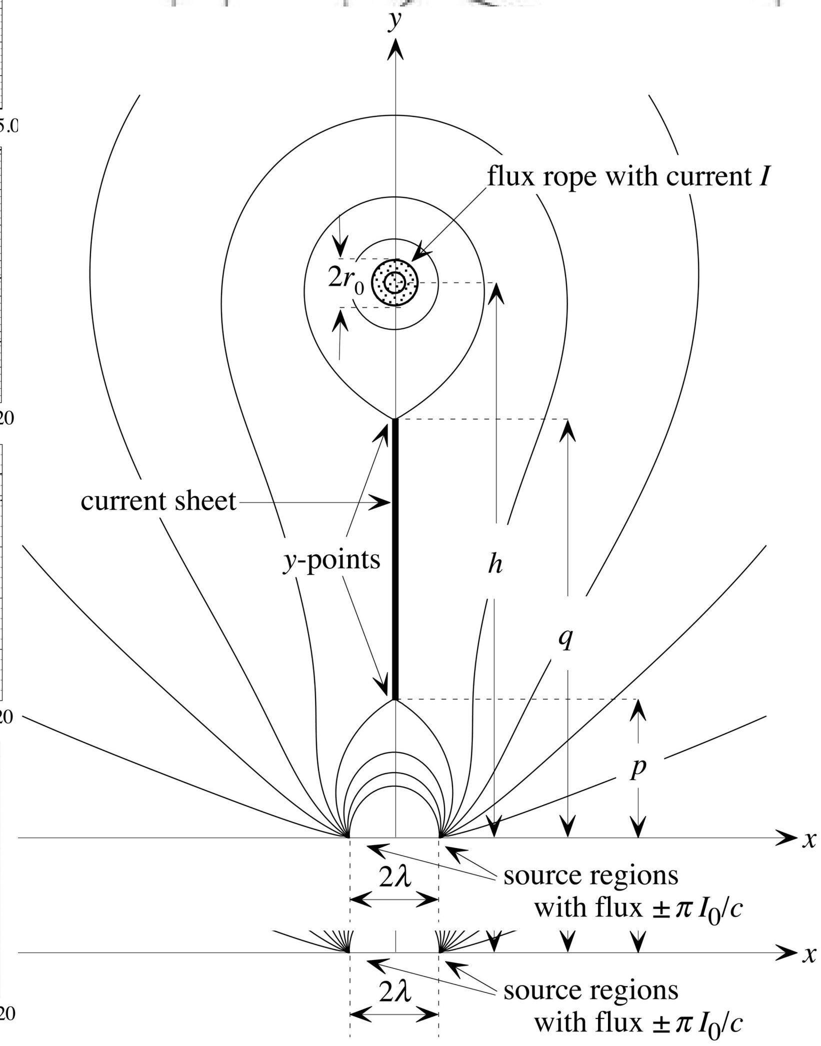


Ji et al. (2003)

Dynamical Properties of CMEs: Theory and Observations

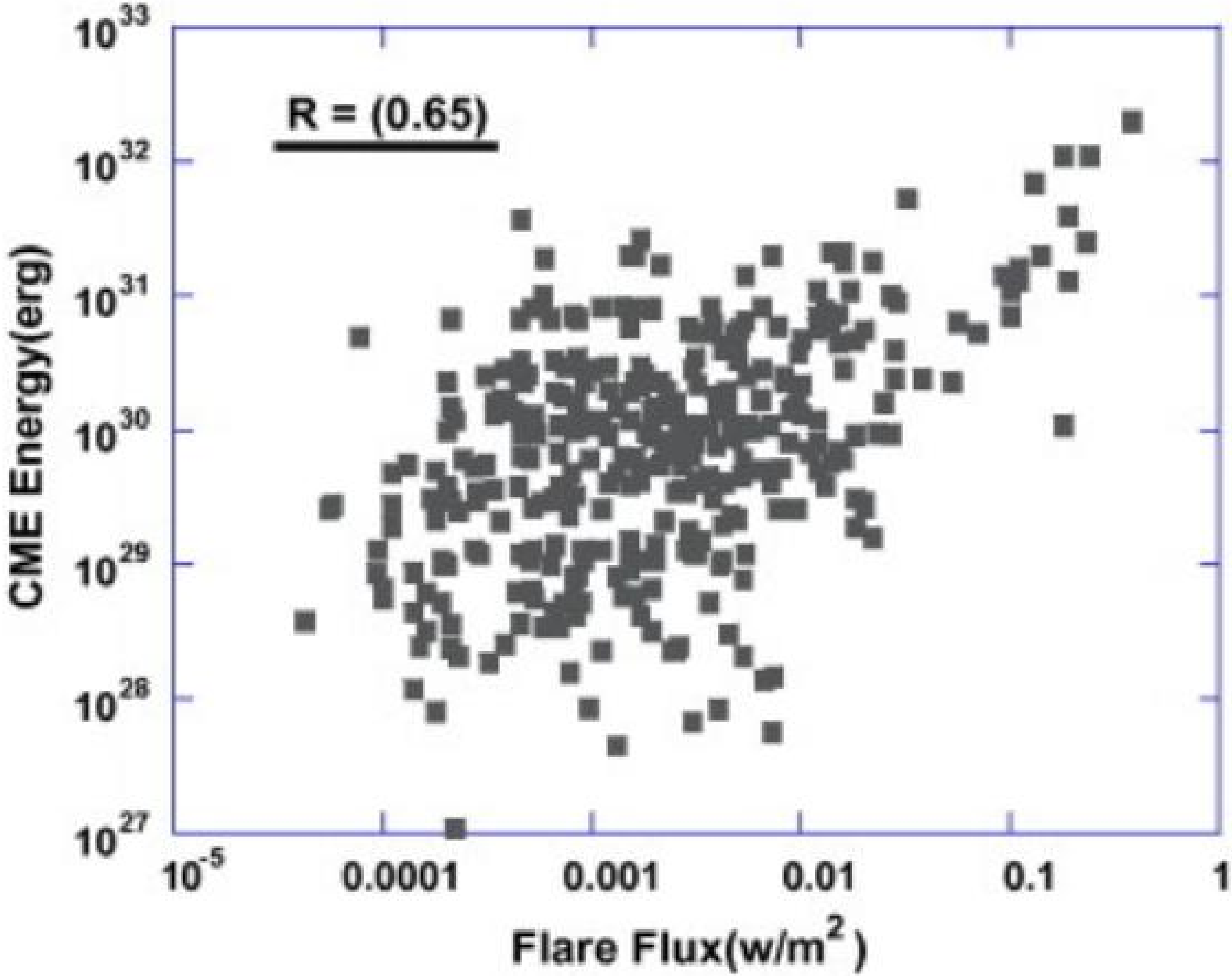
($M_A = 0.1$)



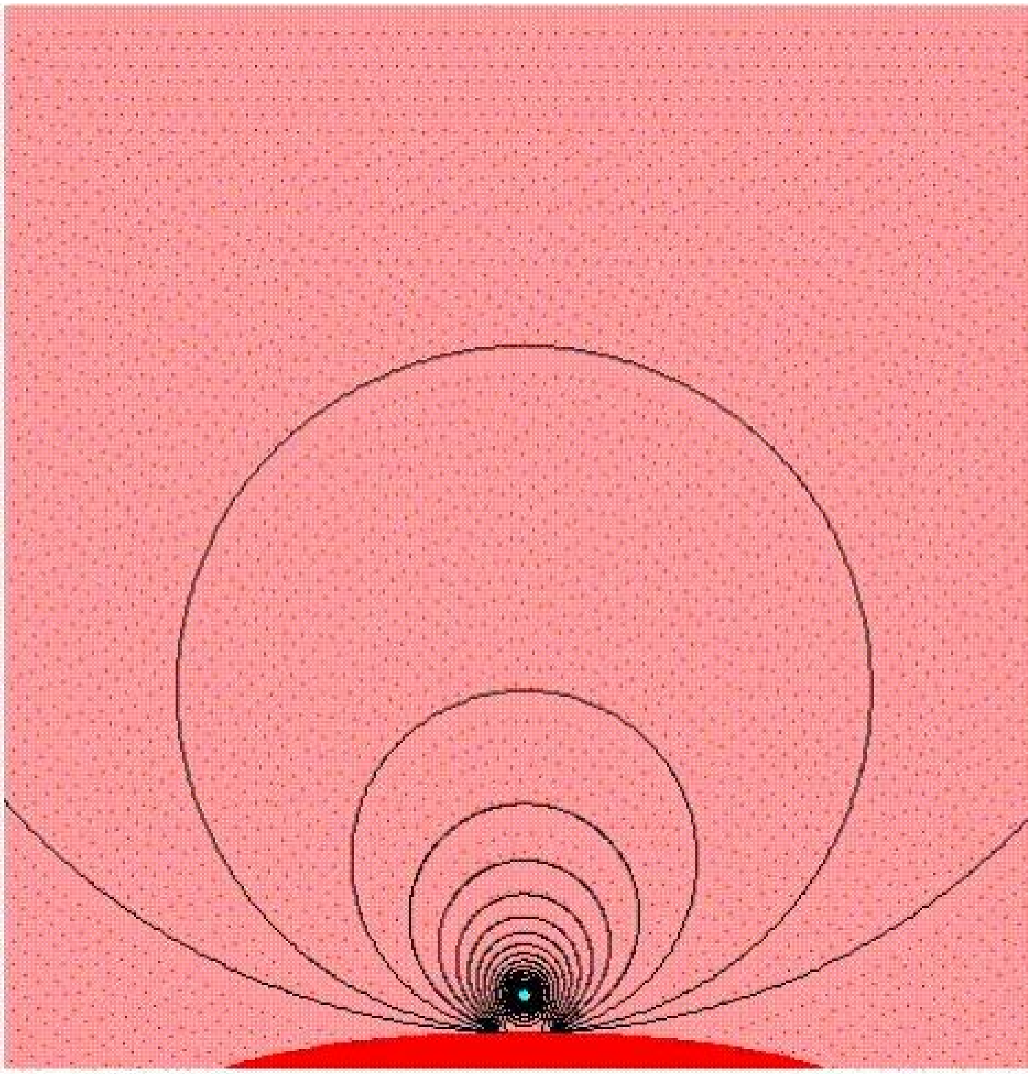


Correlations of CMEs to Flares

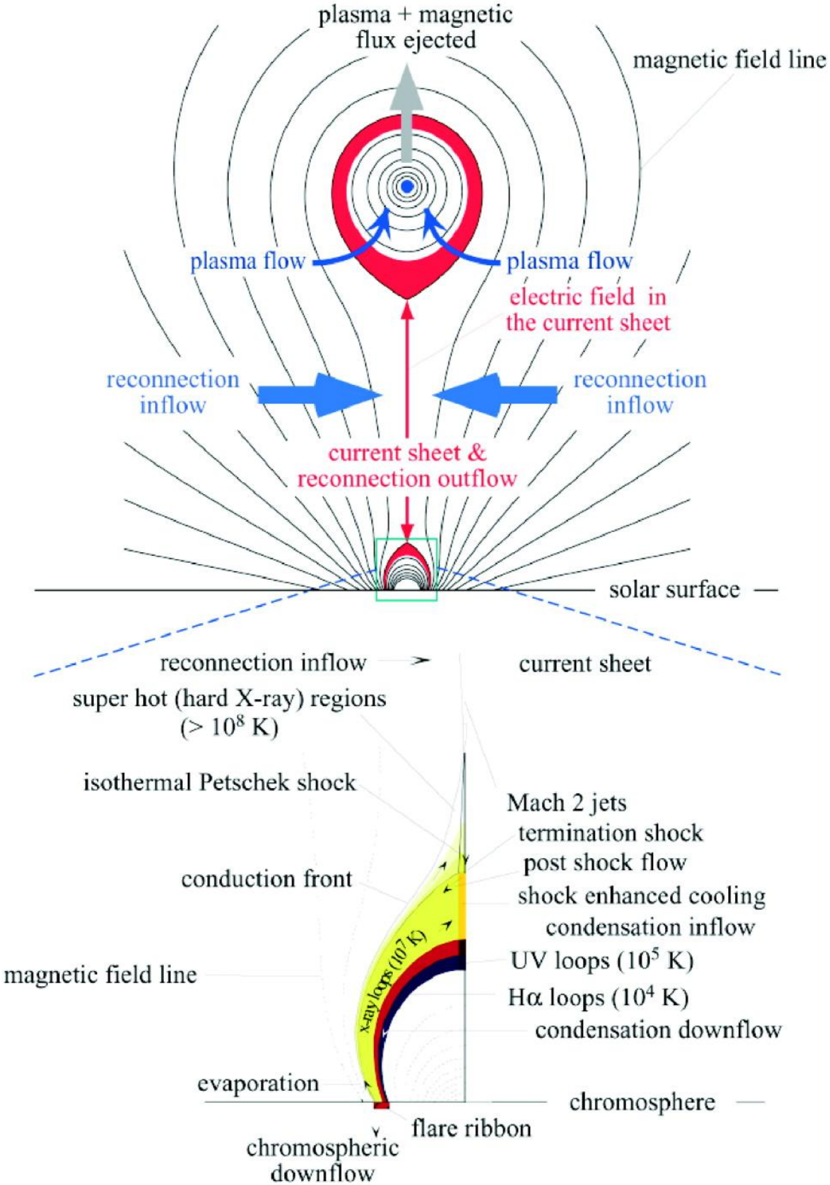
(Zhang *et al.* 2002; Zhou *et al.* 2003; Lin 2004; Youssef 2012)



Multiple Scale Features & Complex Structures of the Current Sheet



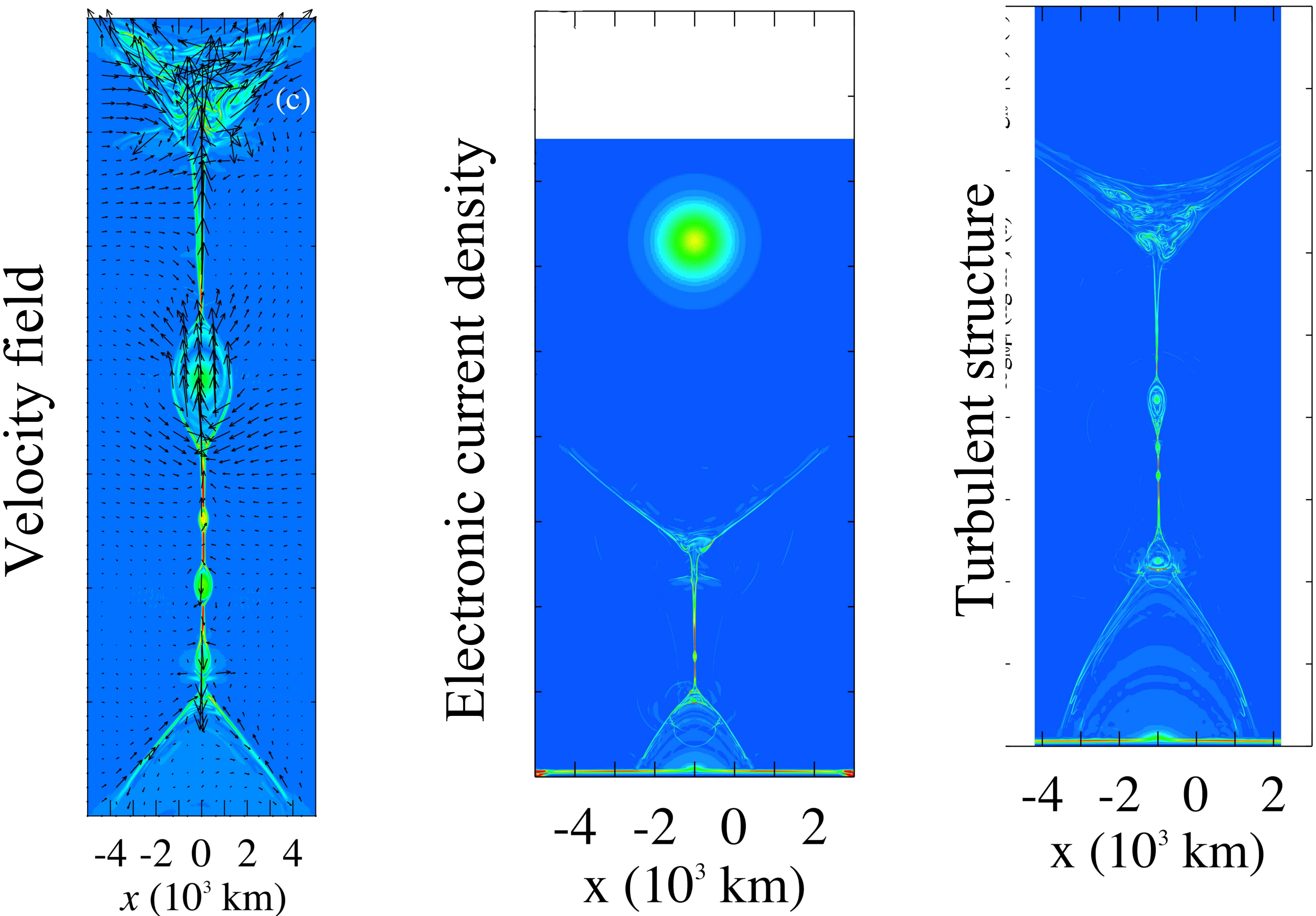
Lin & Forbes (2000), Lin (2002)



Lin et al. (2004, 2005, 2015)

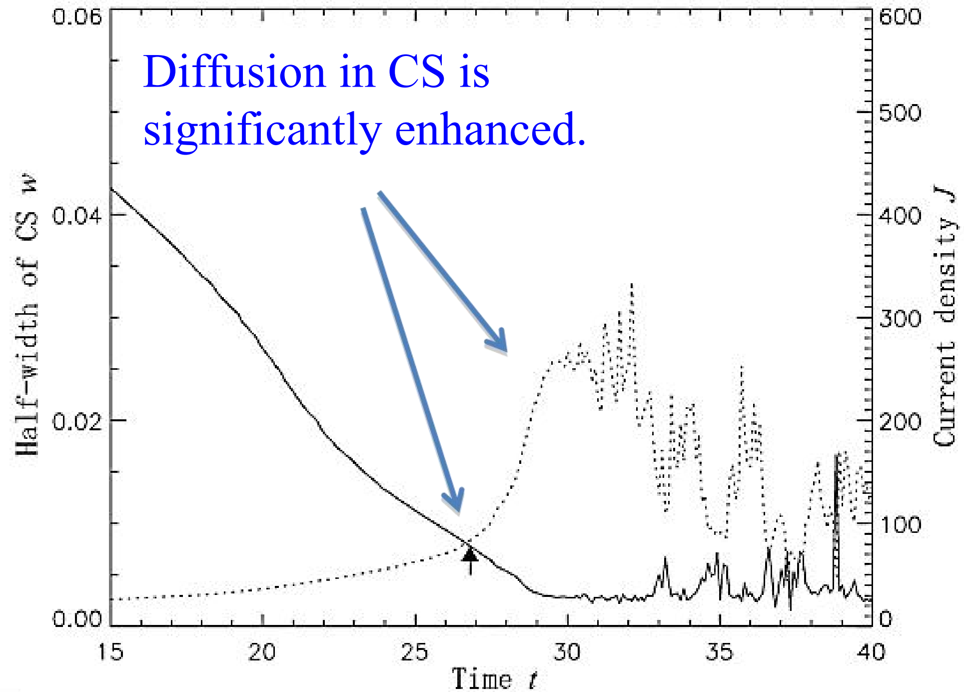
Multiple Scale Features & Complex Structures of the Current Sheet

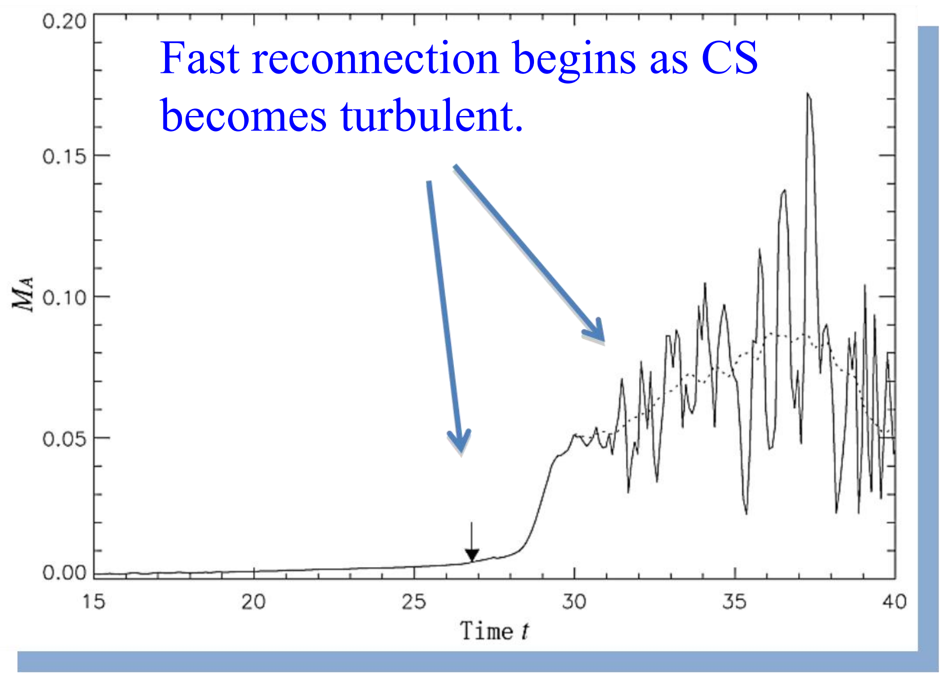
Mei et al. (2012, 2017), Ni et al. (2015), Ye et al. (2019, 2023)



- **Fine structures of CS and the dynamic feature of magnetic reconnection**

The half-width w (solid line) near the PX-point, decrease to about 7.5×10^{-3} at time $t = 26.8\tau_A$ when the first island appearing. Then w gradually decreases to the minimum value 2.5×10^{-3} and it subsequently fluctuates around this minimum value.





- **The Rate of magnetic reconnection M_A**

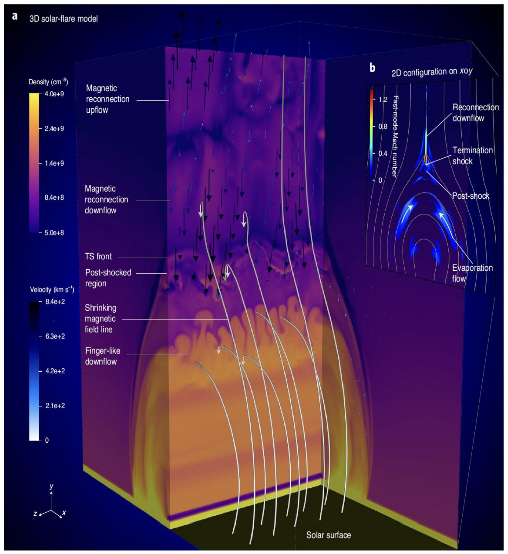
$$M_A = \frac{v_i}{v_A}$$

The solid line shows the instant value and the dotted line is for the corresponding average value. The arrow indicates time $t = 26.8\ \tau_A$ when the first magnetic island forms

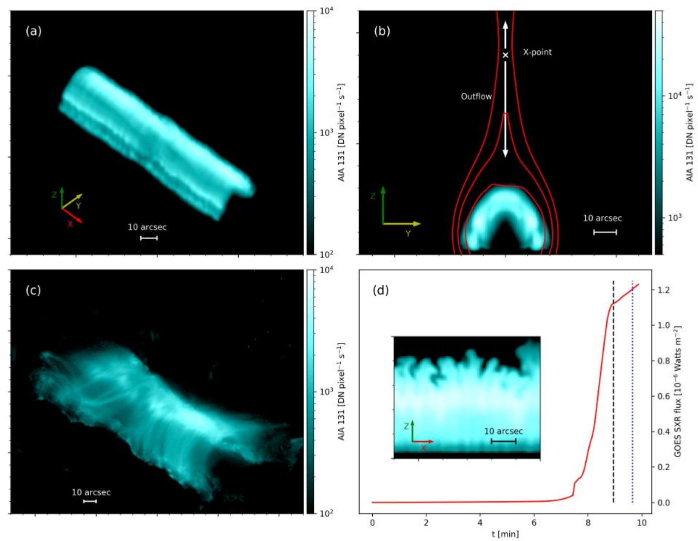
Shen et al. (2011)

Current Sheet and Reconnection in 3D

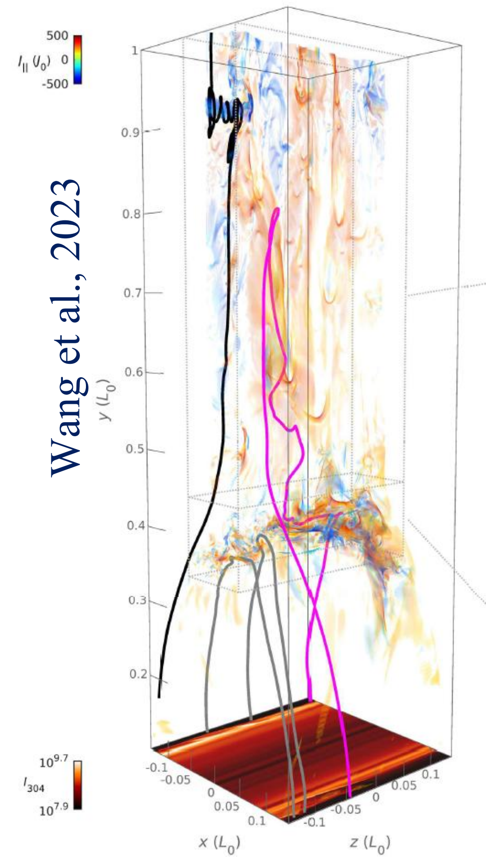
Shen et al., 2022



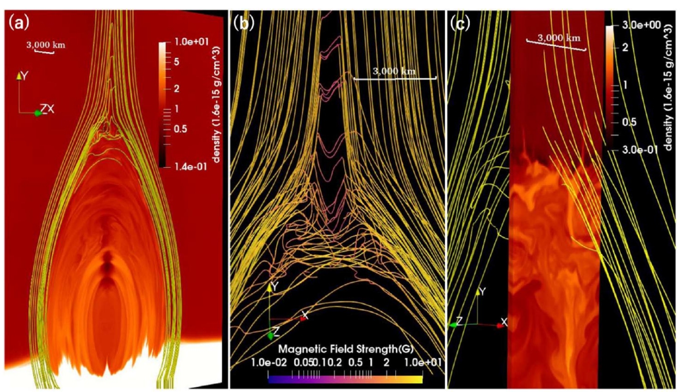
Ruan et al., 2023



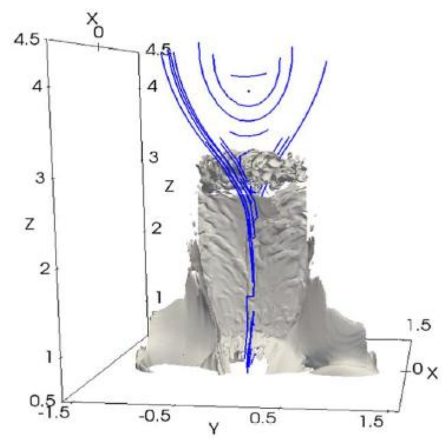
Wang et al., 2023



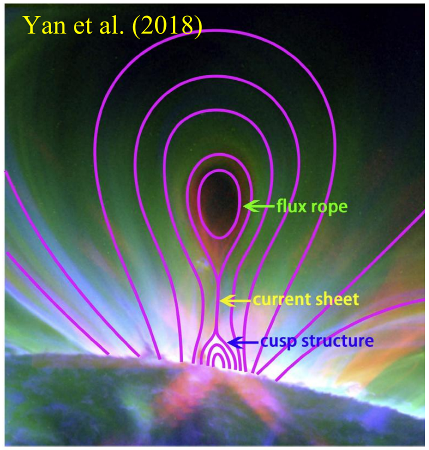
Shibata et al., 2023

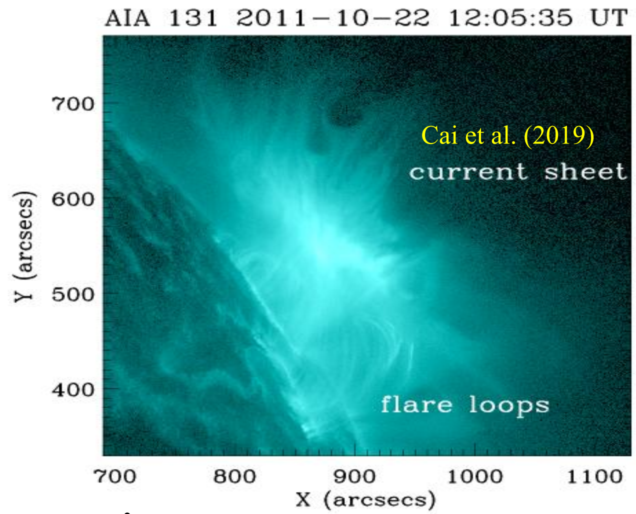


Ye et al., 2023

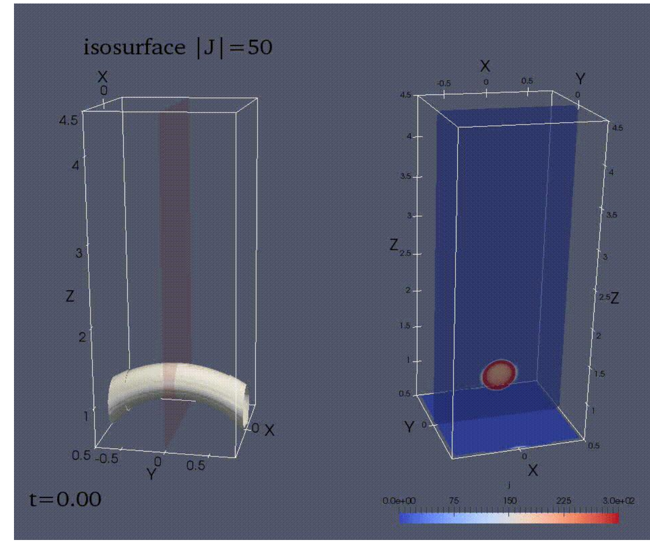


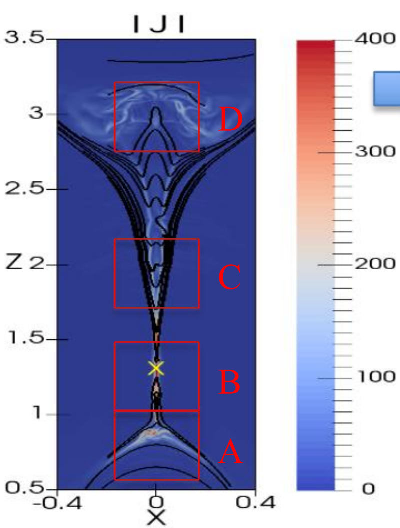
Current Sheet and Reconnection in 3D





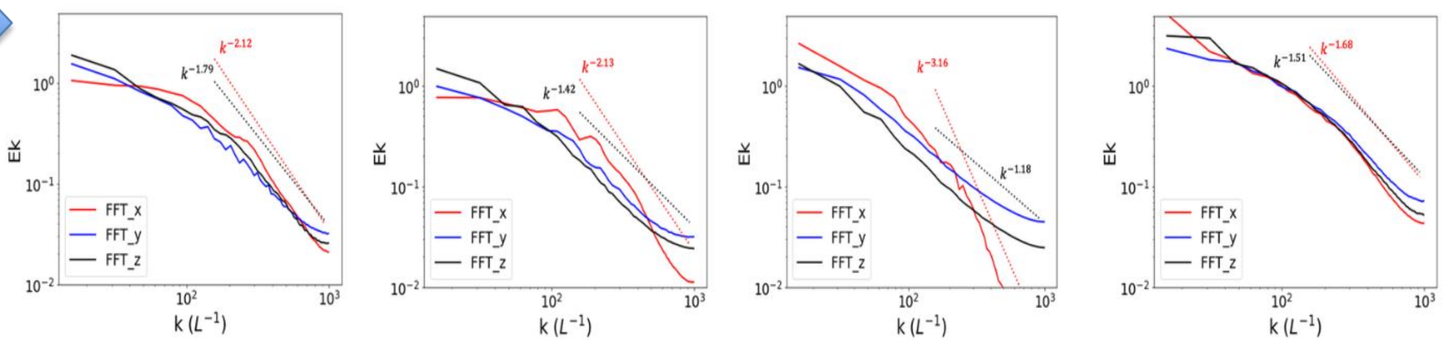
Observations





Ye et al. (2023)

Numerical experiments



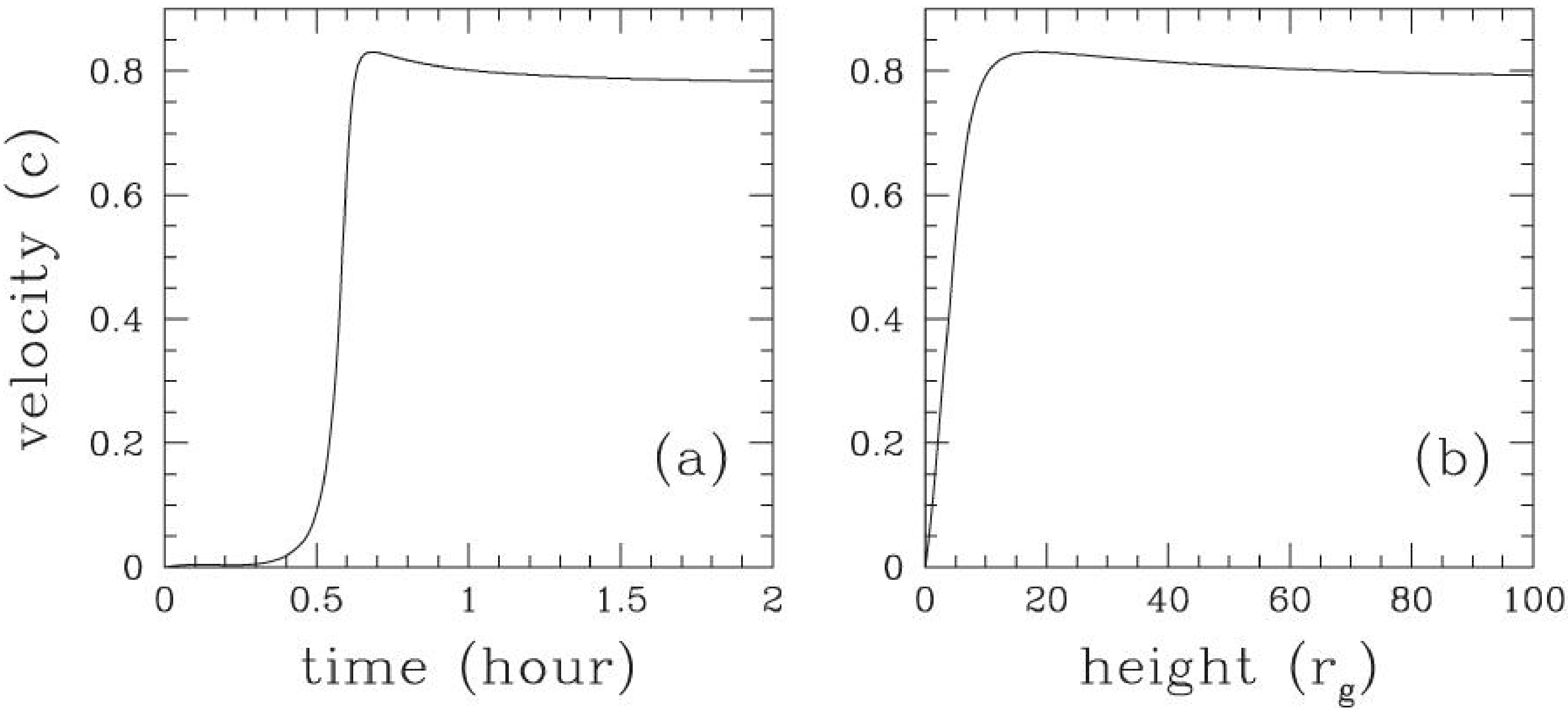
A: In the flare loops B: close to the PX C: far above the PX D: under the CME

3D Fourier spectra of the kinetic energy in x-, y-, and z-directions

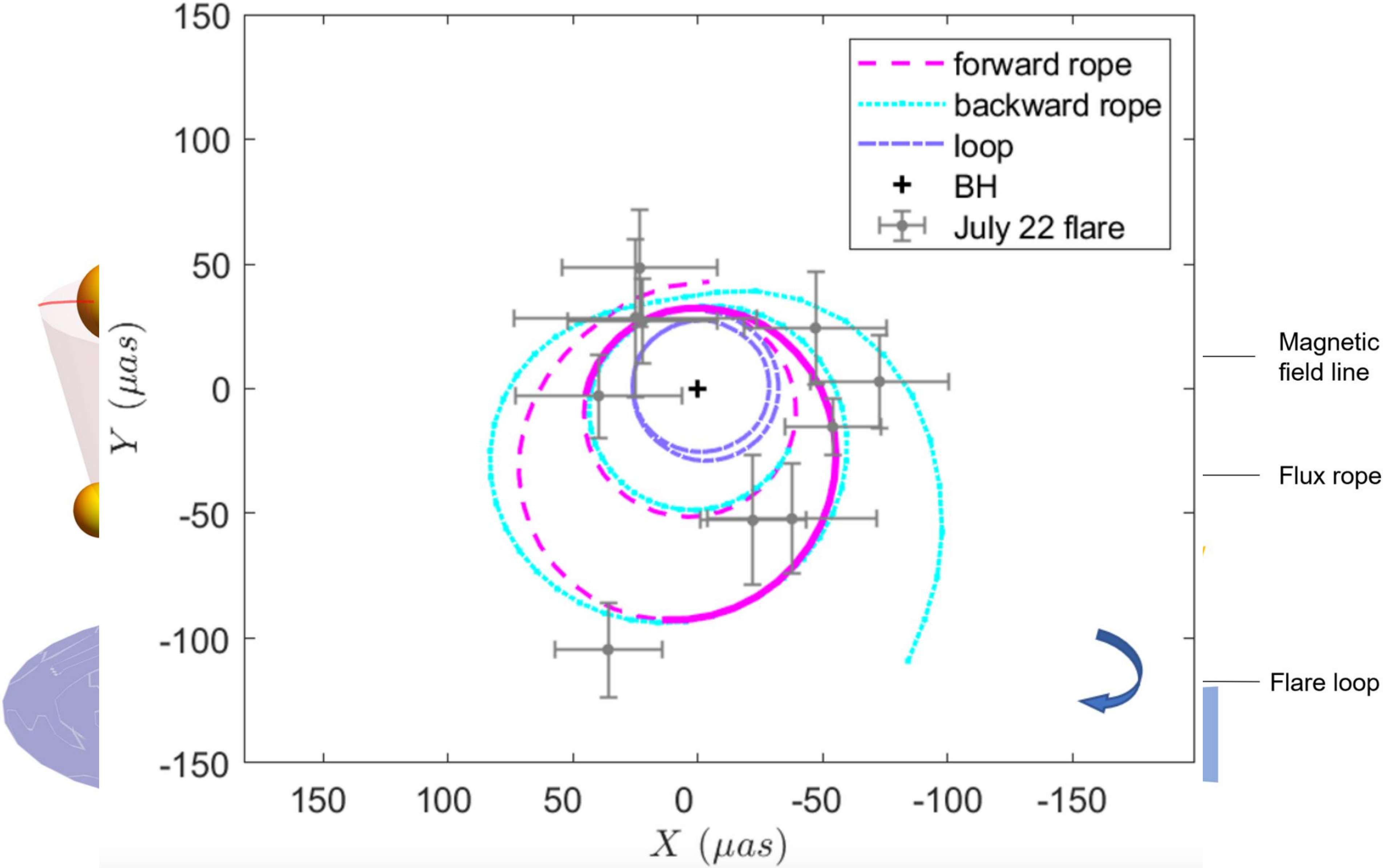
Content

- Brief introductions of solar eruptions
- Magnetic field and magnetic eruptions in the universe
- Applications of Lin-Forbes model to the magnetic eruption at the other places in the universe
- Summary

Episodic Jets from BH-AD

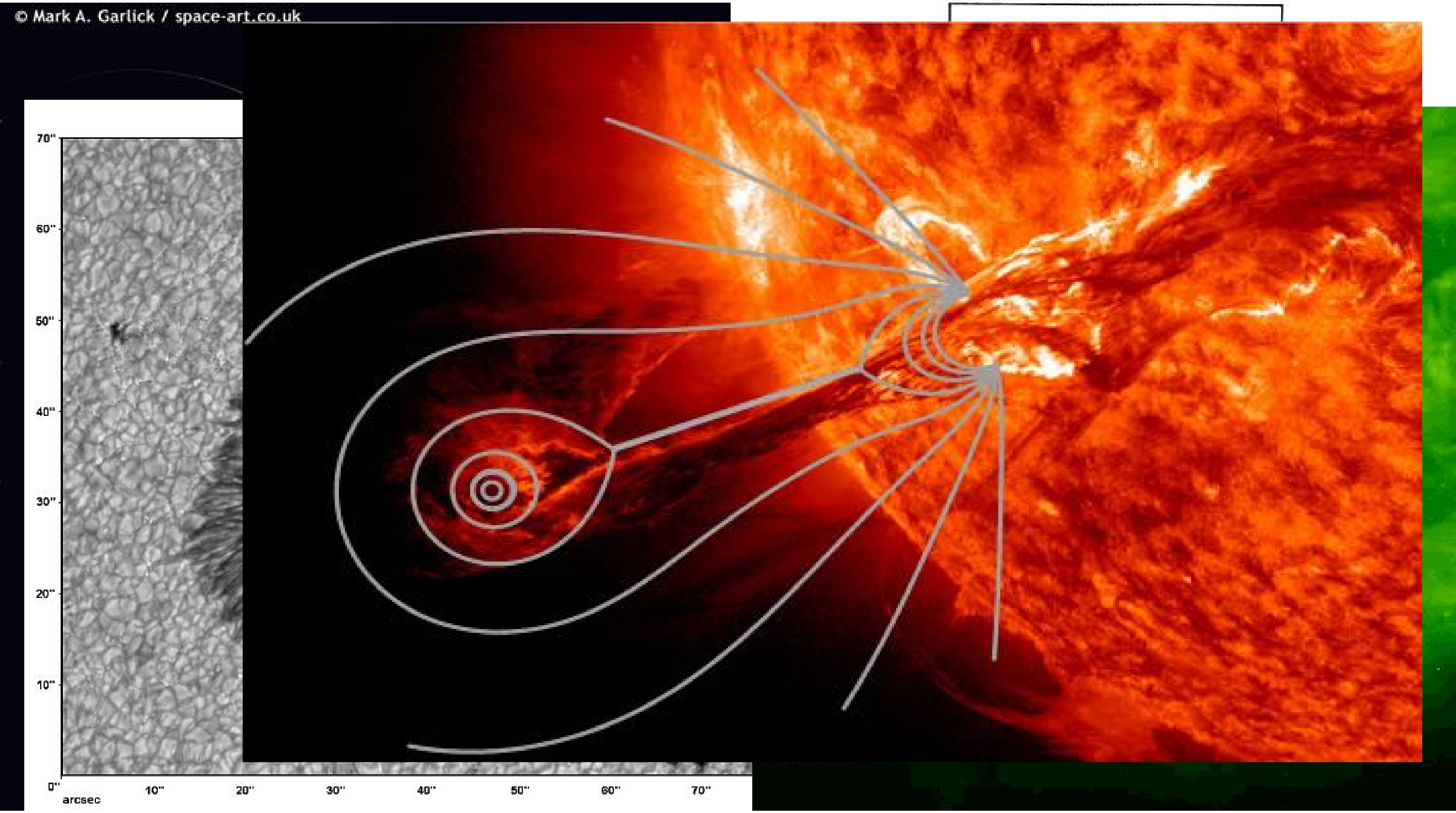


Yuan et al. (2009)

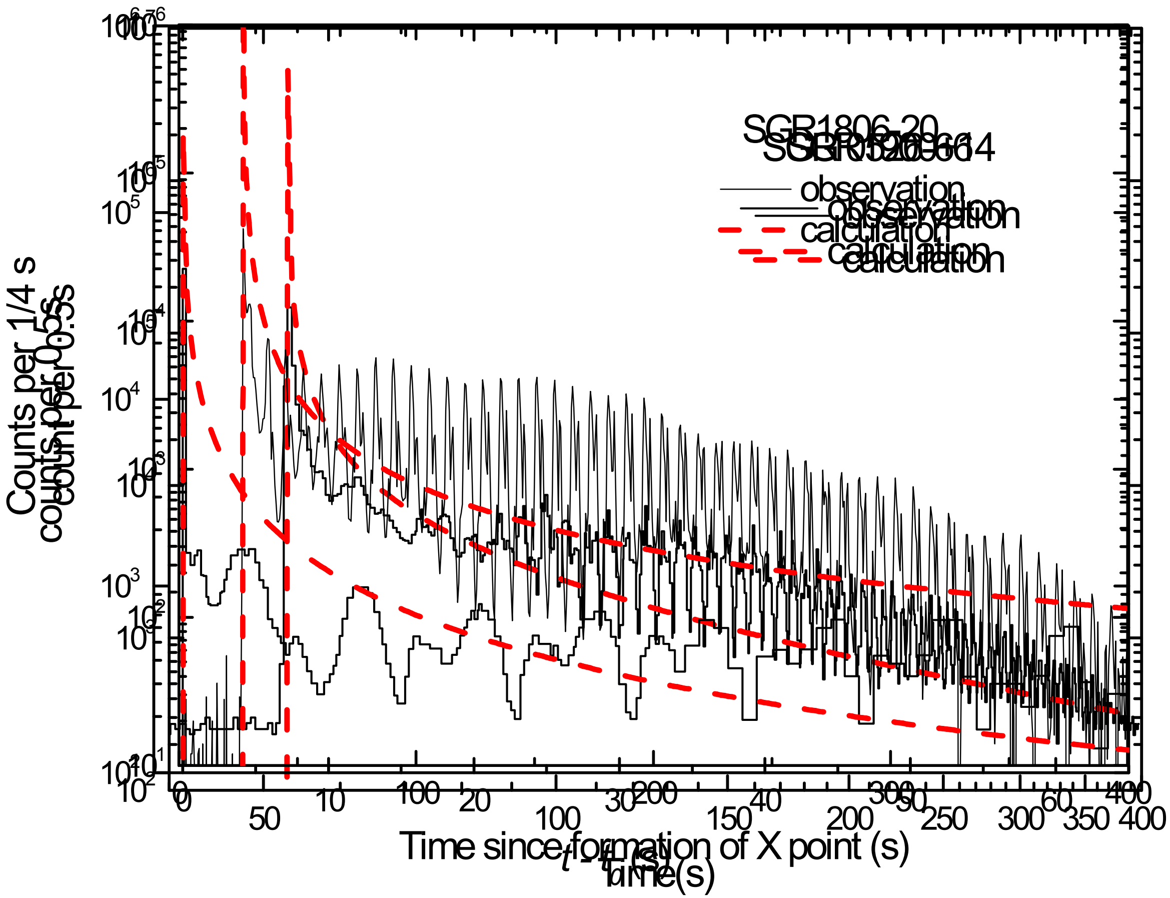


Lin et al. (2023)

Giant Flares from Magnetar

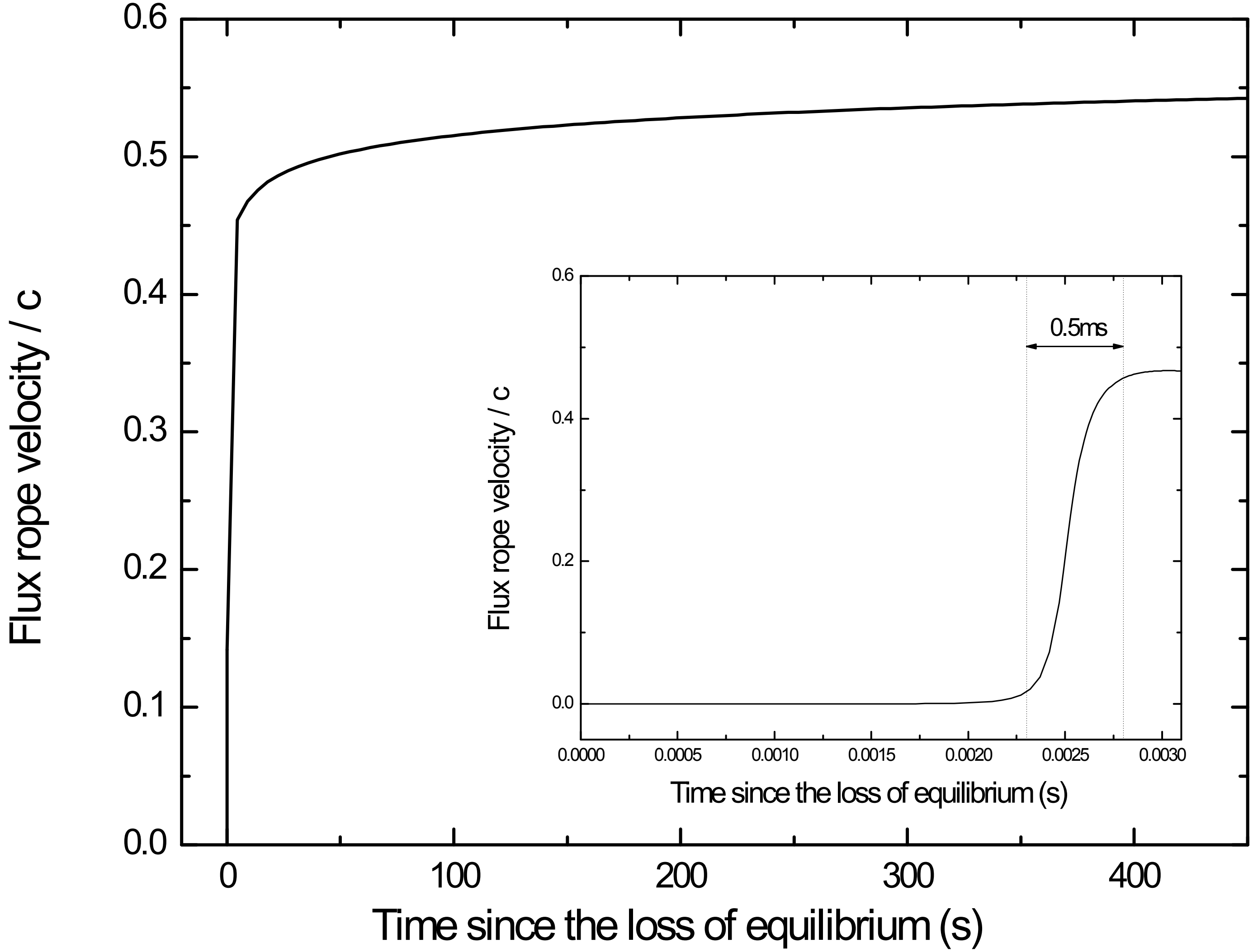


Giant Flares from Magnetar



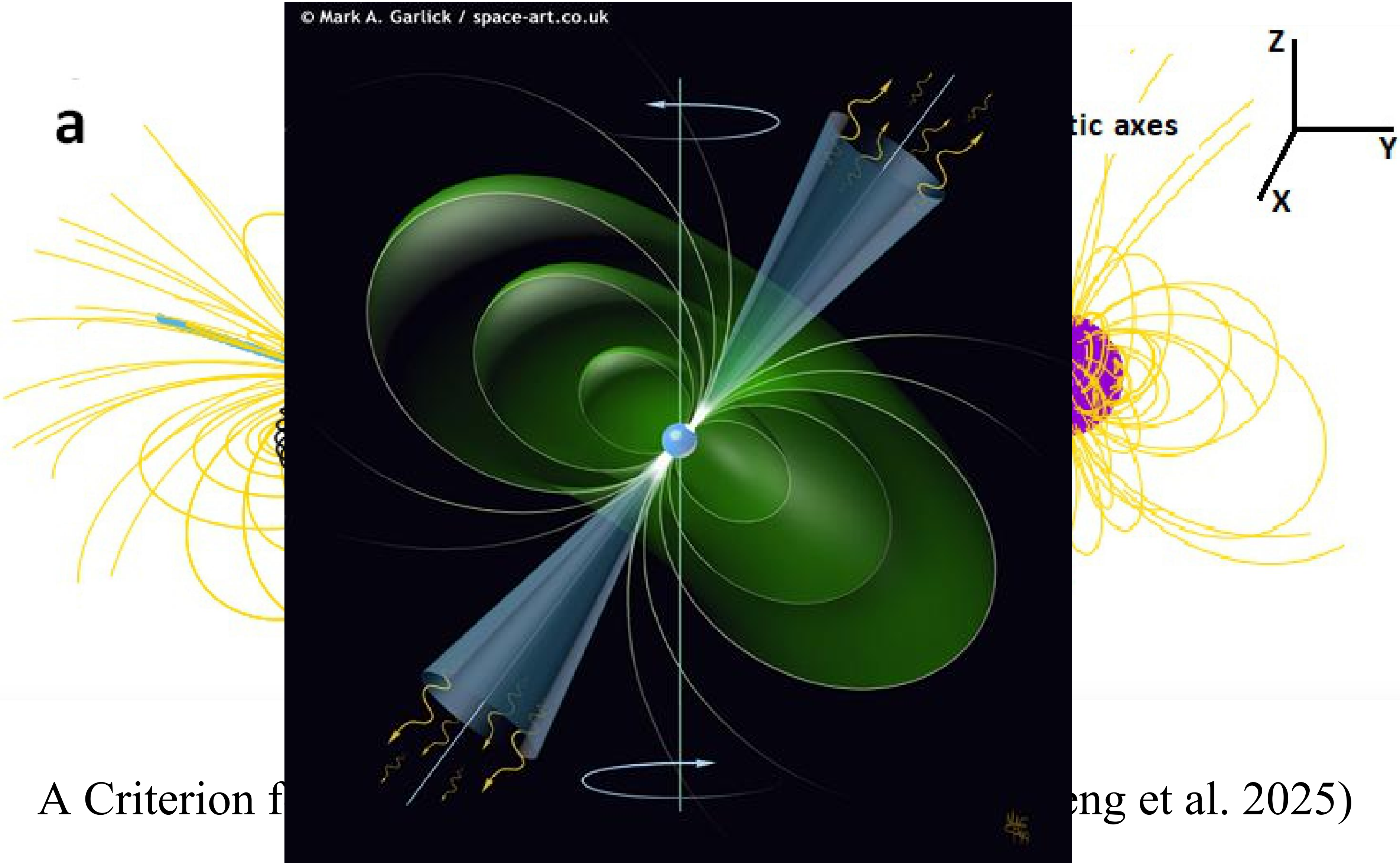
Meng et al., 2014, ApJ, 785, 62

Giant Flares from Magnetar



Meng et al., 2014, ApJ, 785, 62

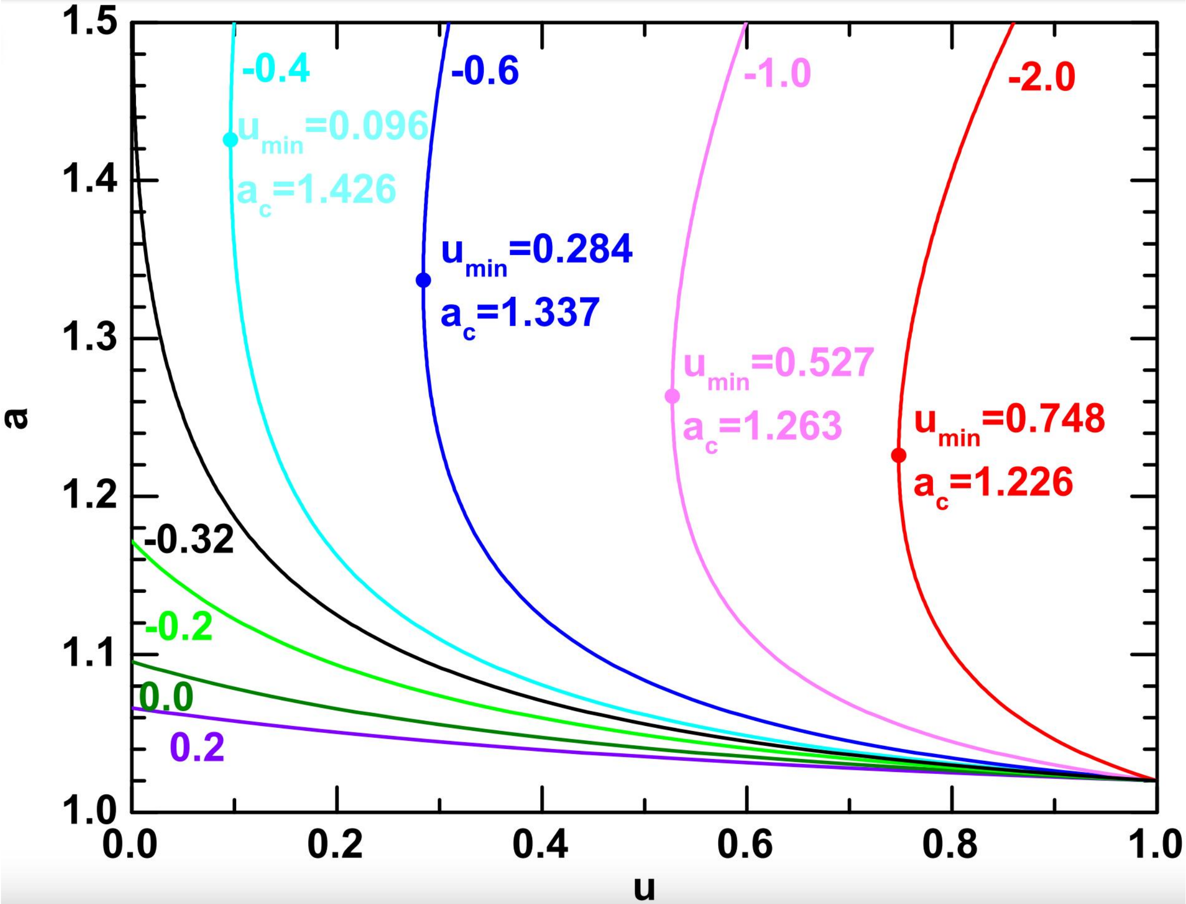
Giant Flares from Magnetar



A Criterion f eng et al. 2025)

Giant Flares from Magnetar

- Whether a magnetar could produce giant flare is governed by many issues, including the magnetic field on the star surface and the total mass that could be ejected.

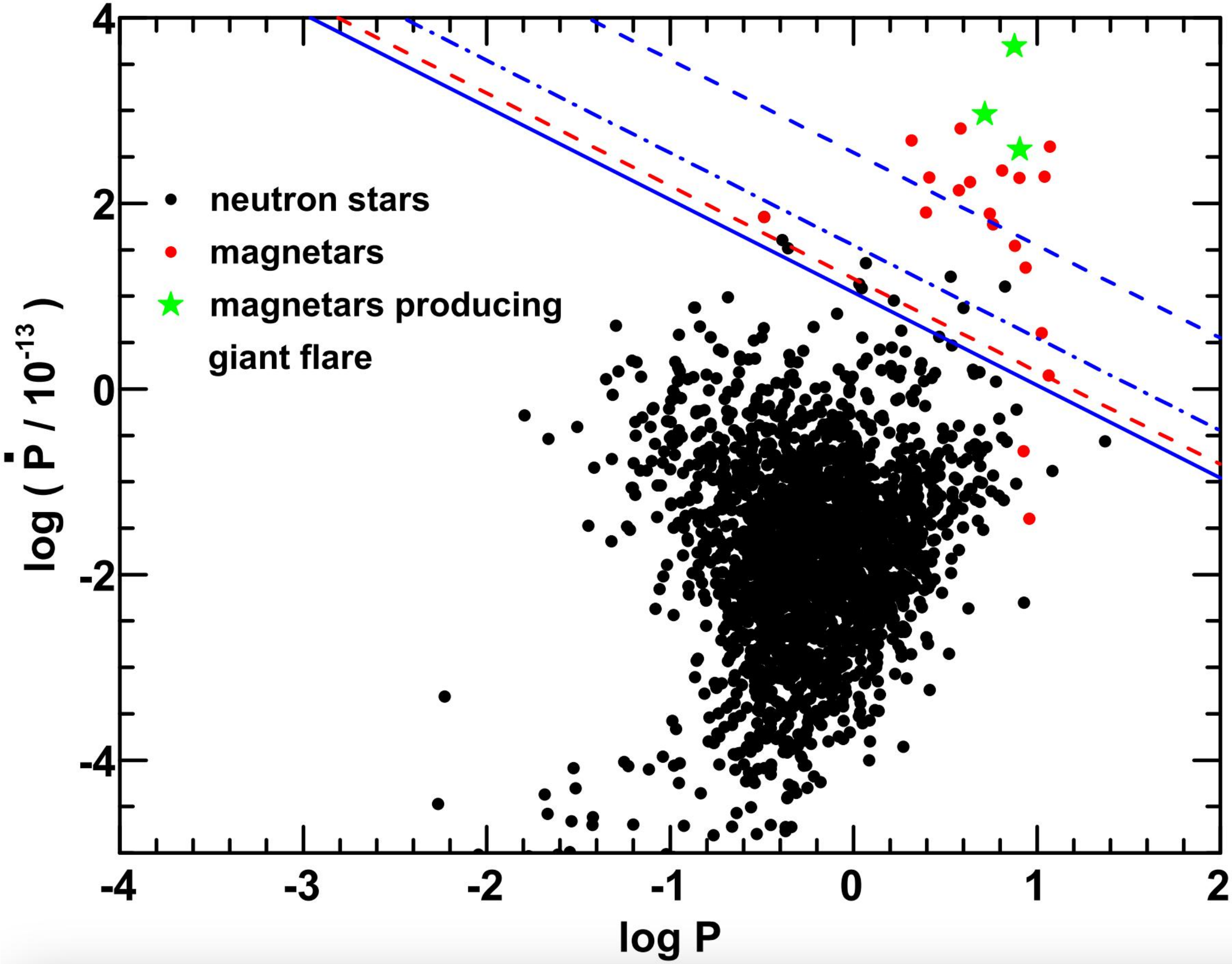


a: Equil. height of the ejecta
u: Relative stregnth of BG-field

Different colors are for the logarithm of $\eta = GMm/(R^2B_0)^2$ with G the gravity constant, m the mass of ejecta, and B_0 the initial BG-field.

Evolution of a vs. u continues monotonously until $\log(\eta) < -0.32$. This indicates the loss of equilibrium occurring for a certain range of η.

Giant Flares from Magnetar



For $R = 10$ km, and $M = 3 \times 10^{33}$ g, $\log(\eta) < -0.32$ leads to B_0^2 (G) > 417 m (g).

From $B_0^2 = \dfrac{3Mc^3 P\dot{P}}{20\pi^2 R^4}$,

we have

$$P\dot{P} > 3.3 \times 10^{-33} m$$

B-S line: $B_0 = 3.6 \times 10^{13}$ G, $m = 10^{24.5}$ g, the lower limit to the ejecta mass deduced from observations

B-D-D line: $B_0 = 6.5 \times 10^{13}$ G, $m = 10^{25}$ g

B-D line: $B_0 = 2 \times 10^{14}$ G, $m = 10^{26}$ g

---------- B_{crit}, quantum electron critical B-field

Content

- Brief introductions of solar eruptions
- Magnetic field and magnetic eruptions in the universe
- Applications of Lin-Forbes model to the magnetic eruption at the other places in the universe
- Summary

Summary

- The solar eruption results from the conversion of magnetic energy into heating, bulk motion of the flaring plasma, and energetic particles;
- Magnetic reconnection is the key in the second stage for energy conversion to drive the evolution;
- The universe fills with magnetic field and plasma, interactions of magnetic field and plasma may result in similar energy conversion fashion;
- The way constructing the solar eruption model has been successfully used for the episodic jet from the BH-accretion disk system, and the giant flare from magnetars;
- More applications are expected.

中国科学院云南天文台诚邀海内外优秀青年人才加入

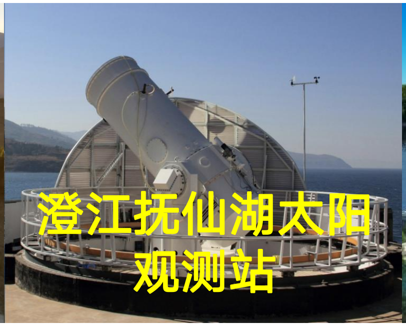
基金委海外优青/中国科学院人才计划

- 事业编制内高级专业技术岗位
- 科研启动经费：100 - 300 万
- 生活补贴：> 100万
- 有竞争力的薪酬福利待遇
- 3H人才公寓（过渡）

全年招聘

- 引进人才（全职引进、柔性引进）
- 青年科技人才（中级在编岗位）
- 特别研究助理（在编待遇项目聘用）
- 博士后

联系人：林老师； Email: linguifang@ynao.ac.cn; Tel: +86-871-63920899, 13658816712



https://www.ynao.ac.cn/zhaopin