Solar activity related to SEP events: flares and coronal mass ejections (CMEs)

Karl-Ludwig Klein

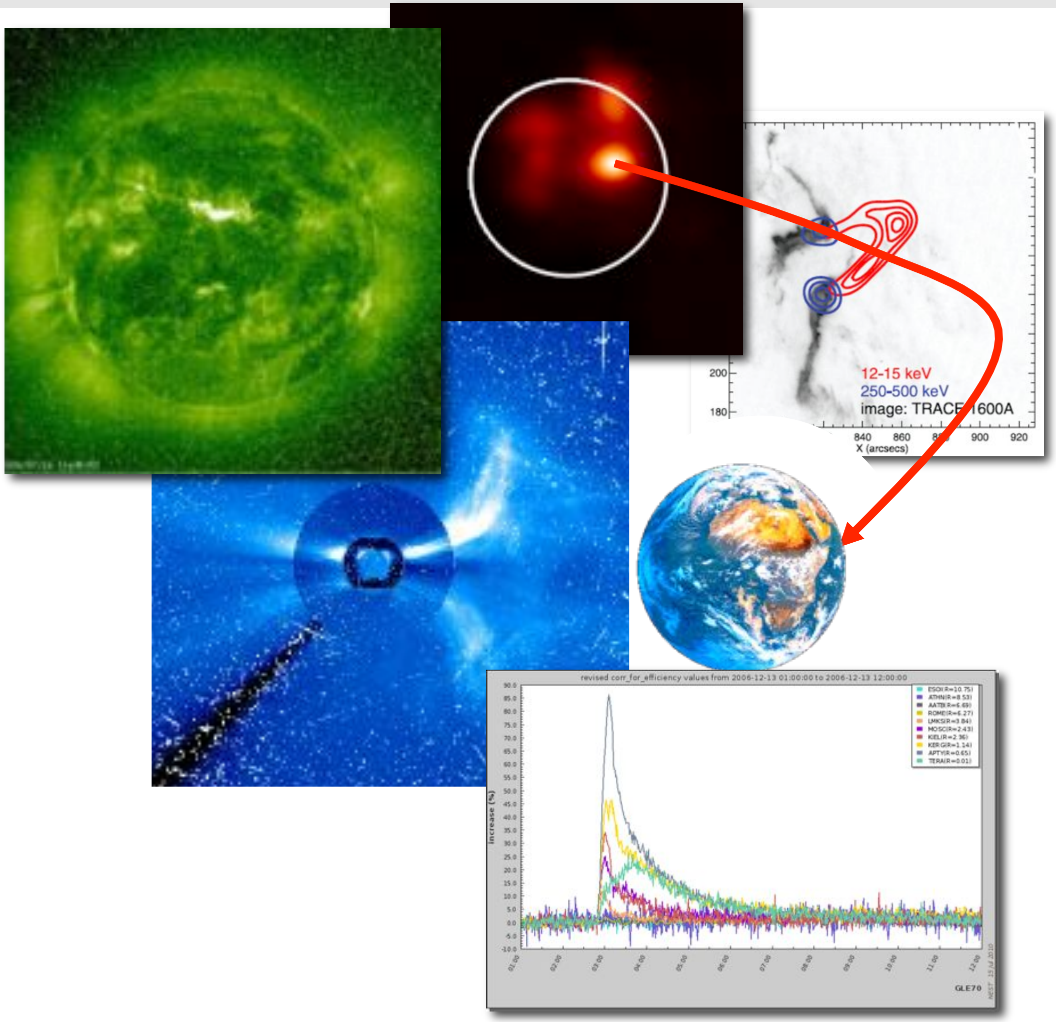
ludwig.klein@obspm.fr,

l'Observatoire de Paris — LESIA

(F-92195 Meudon)

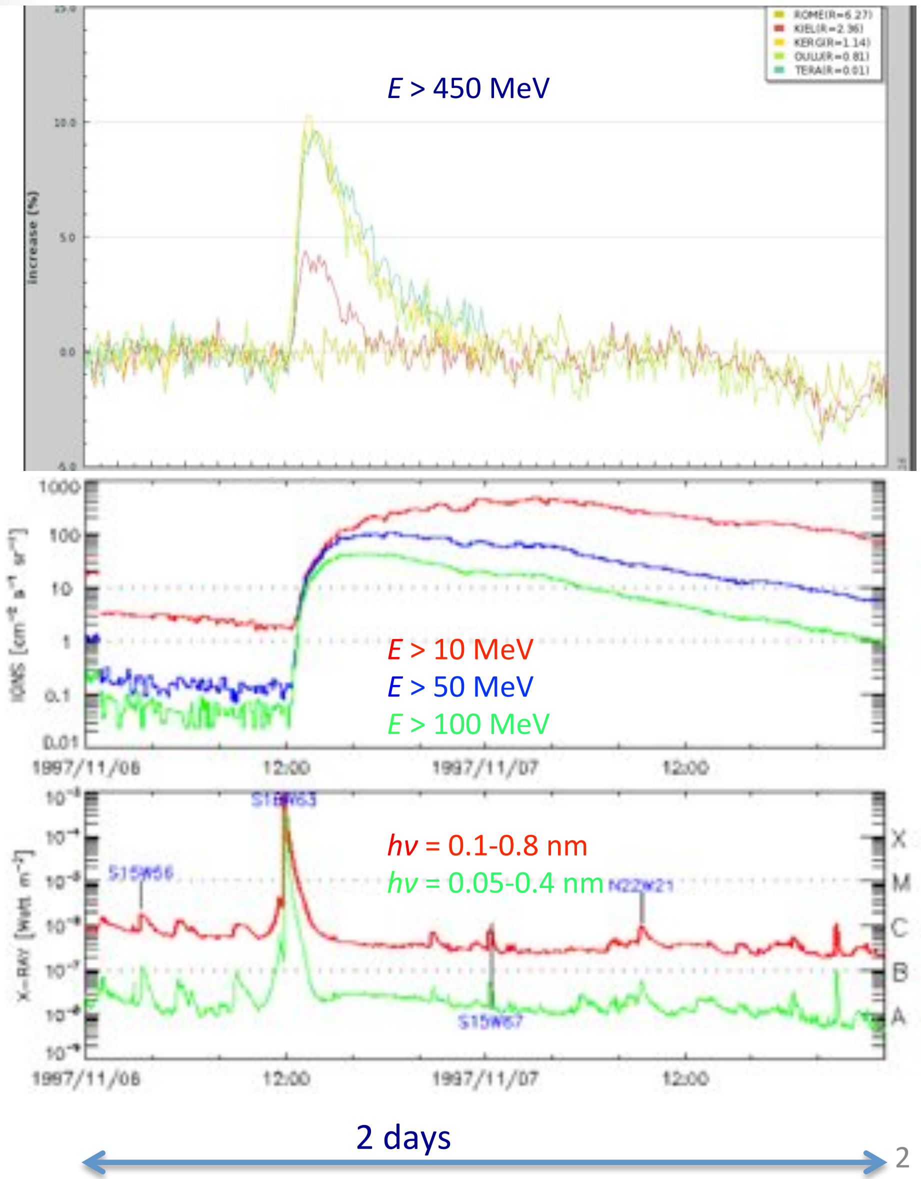
CNRS

Univ P&M Curie, Paris Diderot



Solar energetic particles
Time profiles, from 10 MeV to 1 GeV

- Solar energetic particles (SEPs): high-energy particles detected in space or by particle detectors on the Earth
- A large SEP event:
  - observations from space and ground
  - SXR time profile



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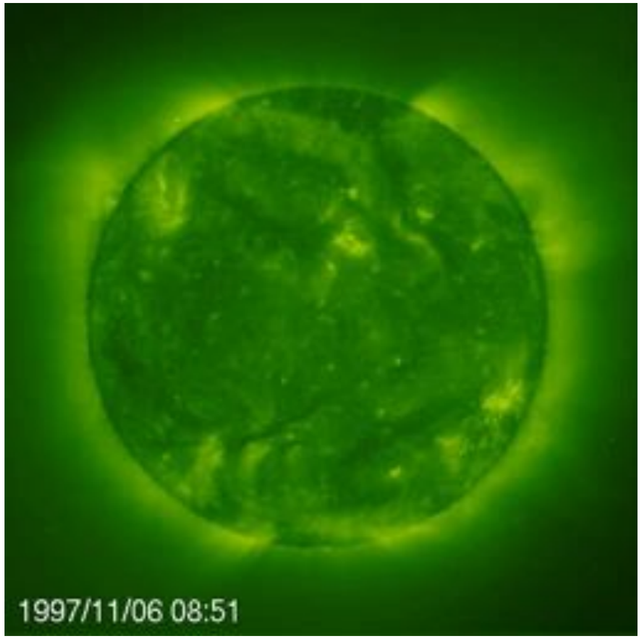
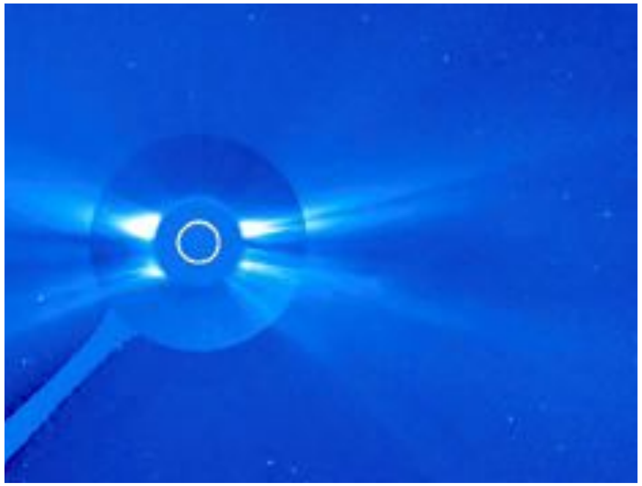
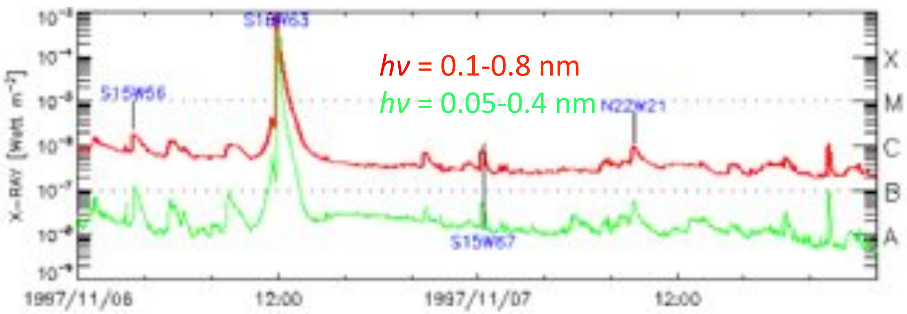
Solar energetic particles
Associated solar activity





- Solar flare (EUV, SXR): localised brightening, widespread dimmings & "EIT wave"
- Coronal mass ejection (CME; coronagraph): ejection of coronal plasma towards interplanetary space

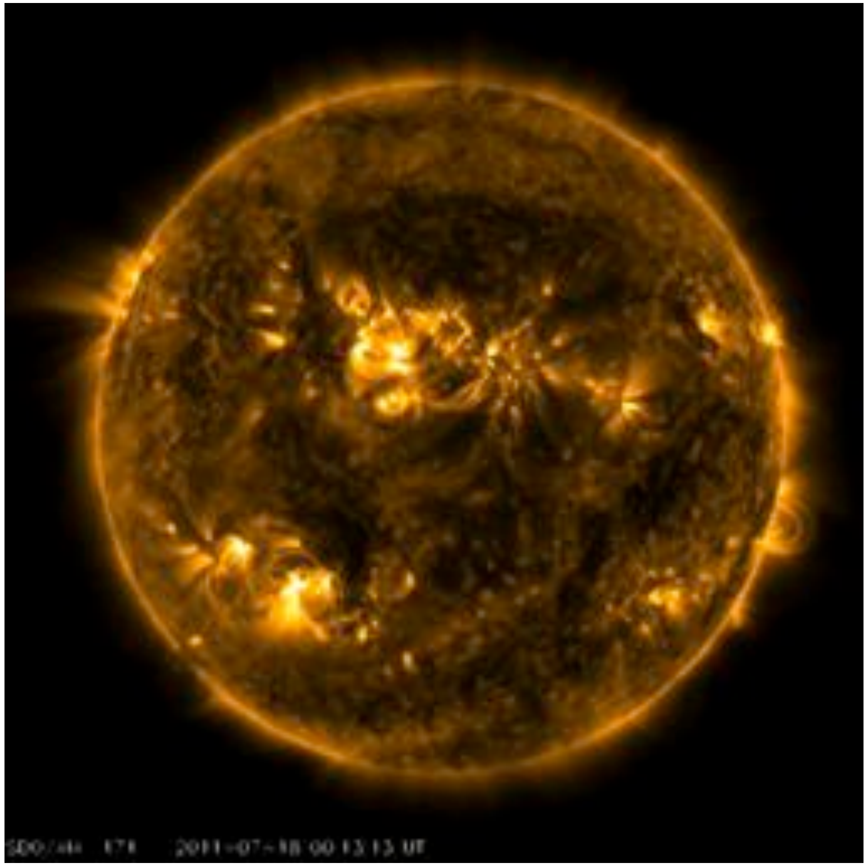


Outline
Flares, CMEs, and the acceleration of charged particles

- Introduction: solar energetic particle events and the related solar activity
- The scene: the magnetically structured solar atmosphere
- Solar flares: energy release and signatures of charged particle acceleration
  - What is a solar flare ?
  - Radiation from accelerated electrons in the solar atmosphere – hints to the acceleration region
  - Radiation from accelerated protons and ions
  - A qualitative view of acceleration processes
- Coronal mass ejections
  - What is a CME?
  - Shock waves
  - How does a coronal magnetic structure erupt ?
  - A qualitative view of acceleration processes
- Summary

Particle acceleration at the Sun

The scene - the magnetically structured solar corona

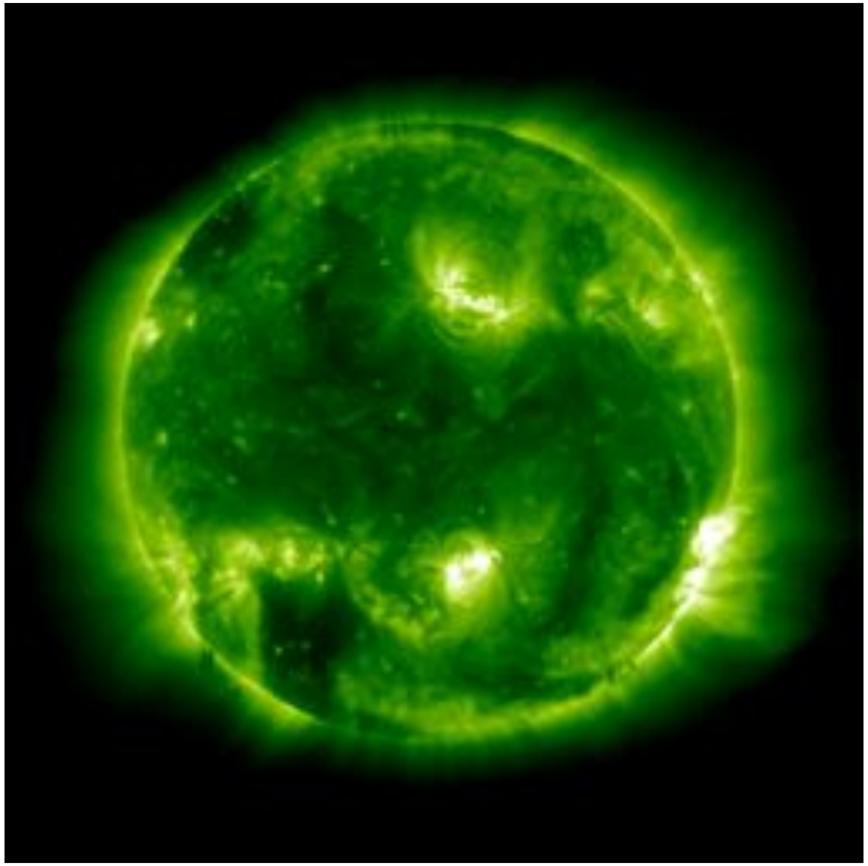


Solar Dynamics Observatory (NASA)

- Solar corona, $T \approx 10^6$ K, $kT \approx 100$ eV
- Magnetically structured
  - magnetic field rooted in/below photosphere
  - subject to mass motions (convection)
  - energy transport into & storage in the corona
- Result:
  - dynamical evolution: coronal heating to large eruptive events (flares, coronal mass ejections)
  - evolving magnetic fields, shocks, non thermal particle populations

Solar flares: an introduction

Solar flares
What is a solar flare ?

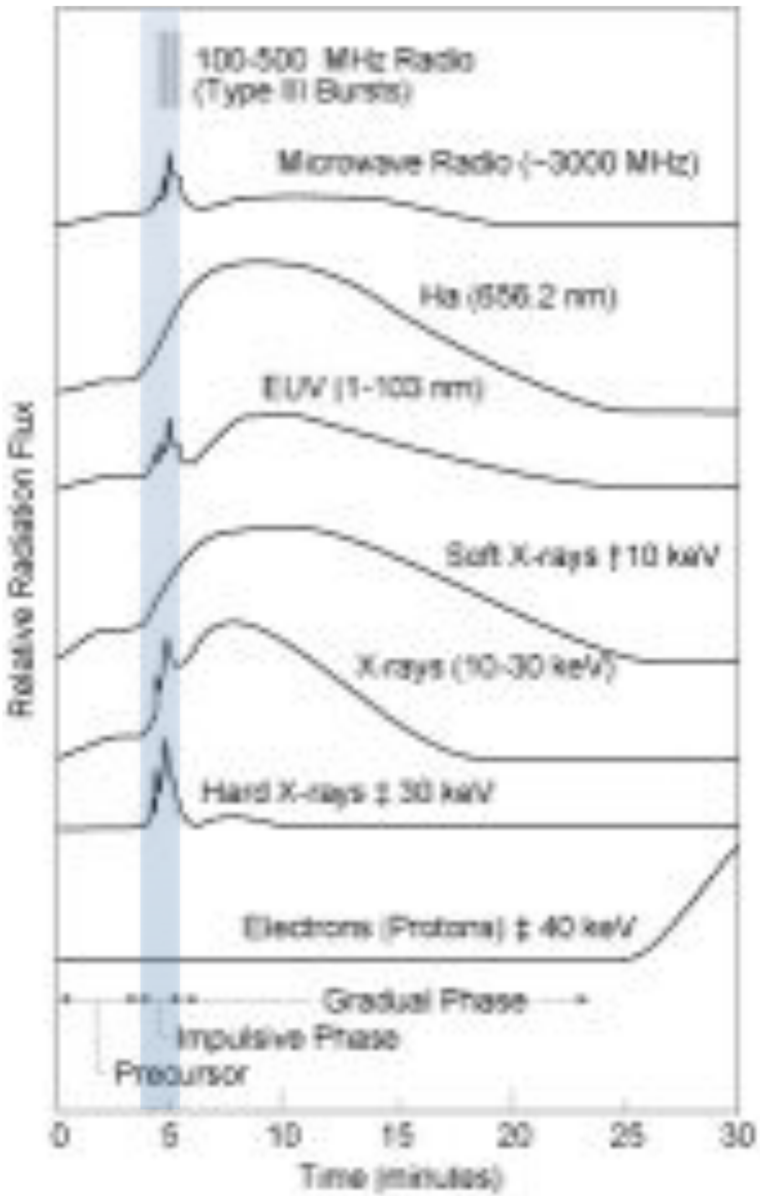


© SoHO/EIT (ESA/NASA)

- What is a solar flare ?
  - temporary brightening across the EM spectrum
  - limited volume of the corona and the underlying atmosphere
- No conclusive quantification, but: time scales seconds to a few hrs, volume within an active region
- Physical processes behind this phenomenology:
  - plasma heating to $T > 10^7$ K
  - acceleration of charged particles (electrons, protons, ions), sometimes to relativistic energies

Solar flares
Electromagnetic (EM) emissions

- Gross distinction:
  - short & spiky (radio, microwaves[1], HXR)
  - long-lasting, smoothly evolving (Hα, SXR)
- Phases of a flare:
  - precursor
  - impulsive phase
  - main phase/gradual phase
- Different decay times, different particle populations: thermal (long) vs non thermal (short & spiky)



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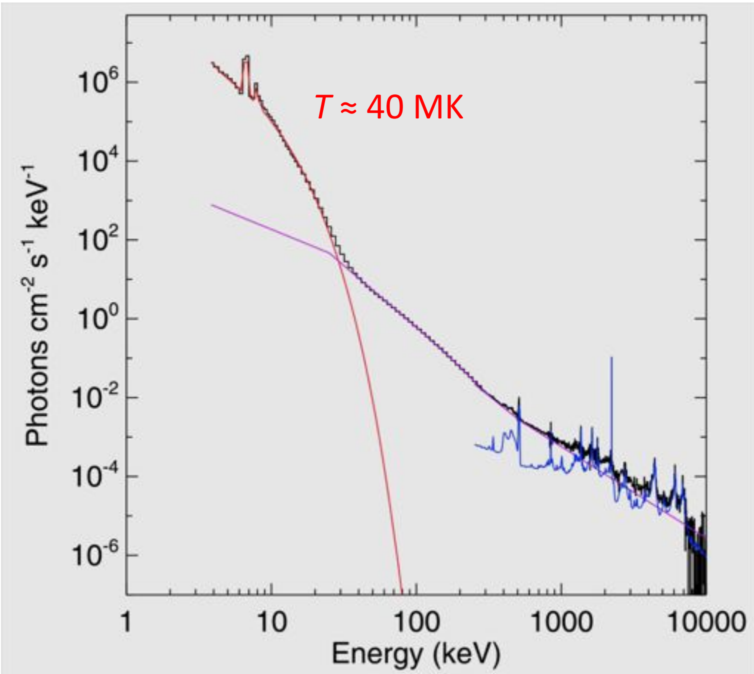
(1) ν ≥ 1 GHz

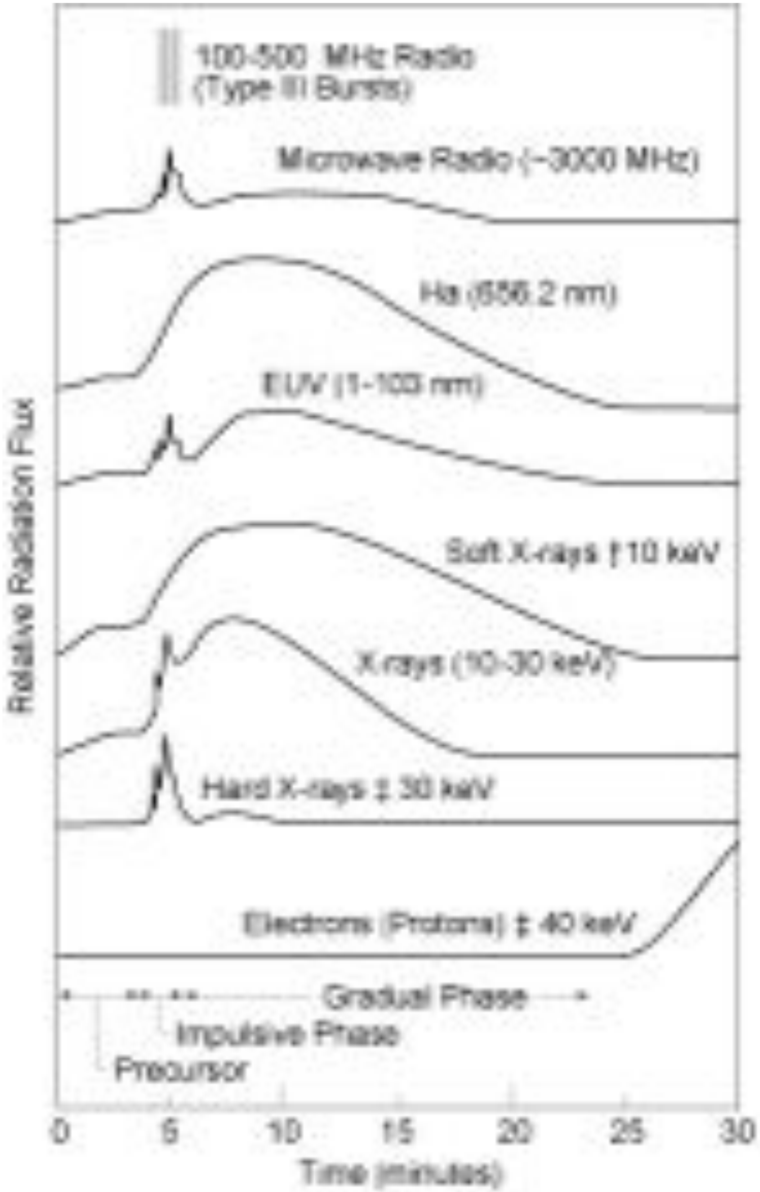
Solar flares
EM emission by the thermal plasma

- Photon spectrum (RHESSI/NASA) - thermal and non-thermal (power-law) parts



R.P. Lin 2011 Spa Sci Rev 159, 421

- Thermal: spectral lines and continuum (hν < 50 keV; maxwellian electron population in the corona)



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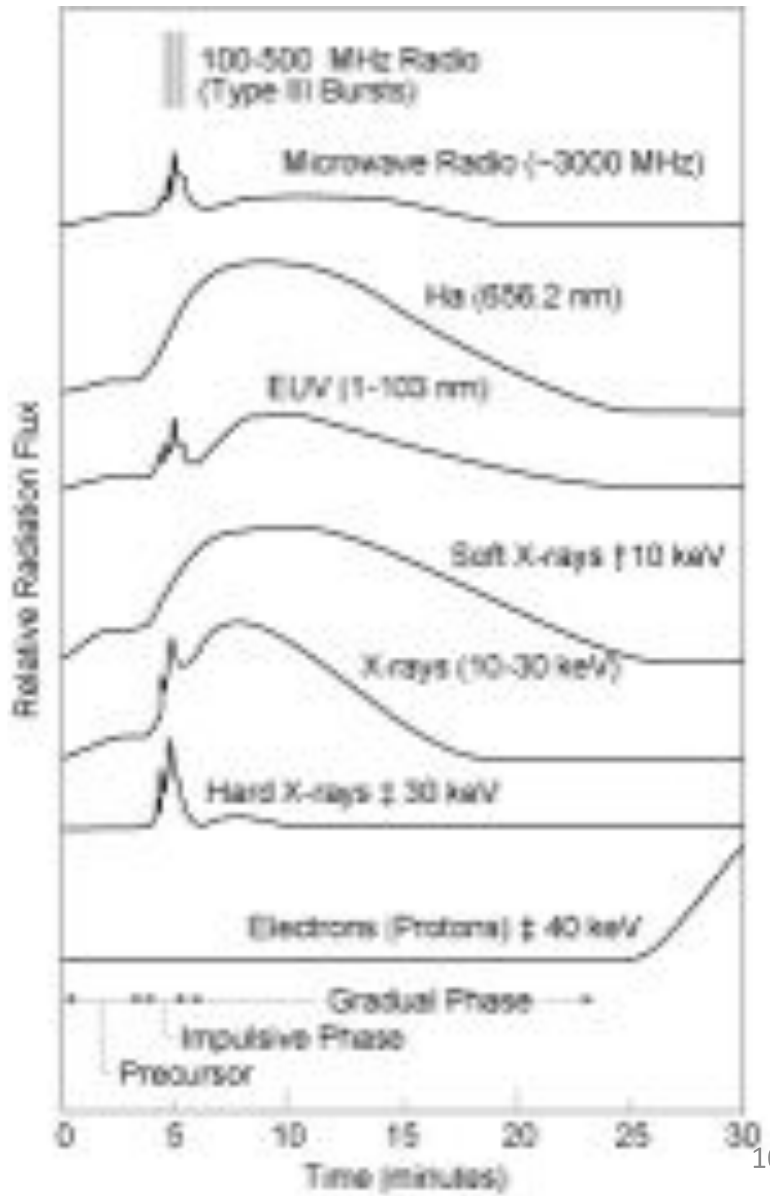
Solar flares
EM emission by the thermal plasma

- Slowly evolving emission (minute-time scales): thermal
- Different spectral ranges ⇔ different temperature domains, different regions of the atmosphere:
  - microwaves (1-some tens GHz) -> chromosphere-corona
  - Hα -> chromosphere
  - EUV, SXR -> corona



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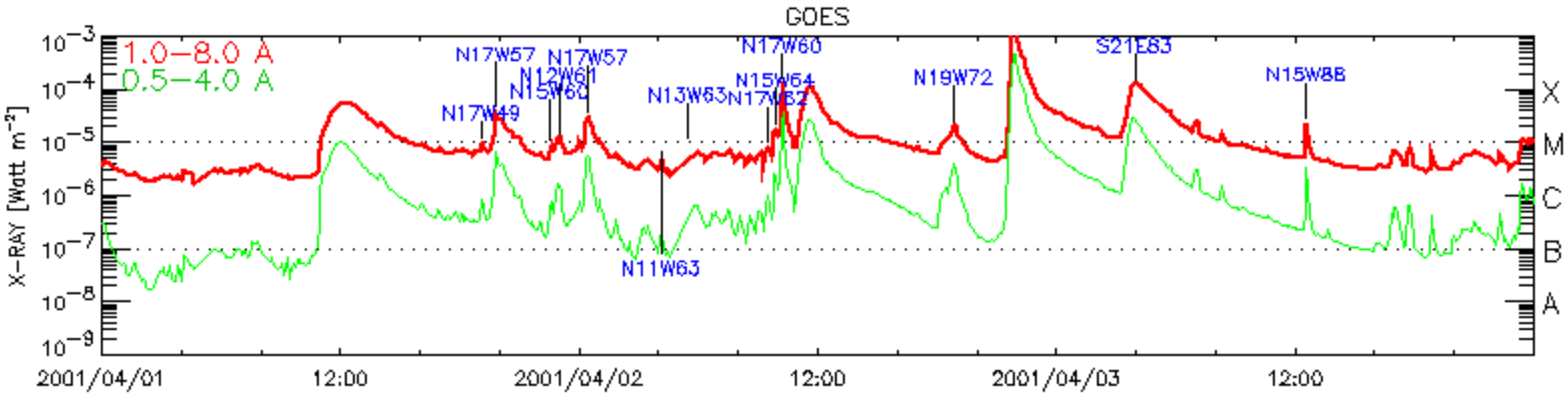
EM emission by the thermal plasma – flare classification

- Monitoring of the solar SXR emission by the GOES spacecraft (NOAA): 3 days in 2001

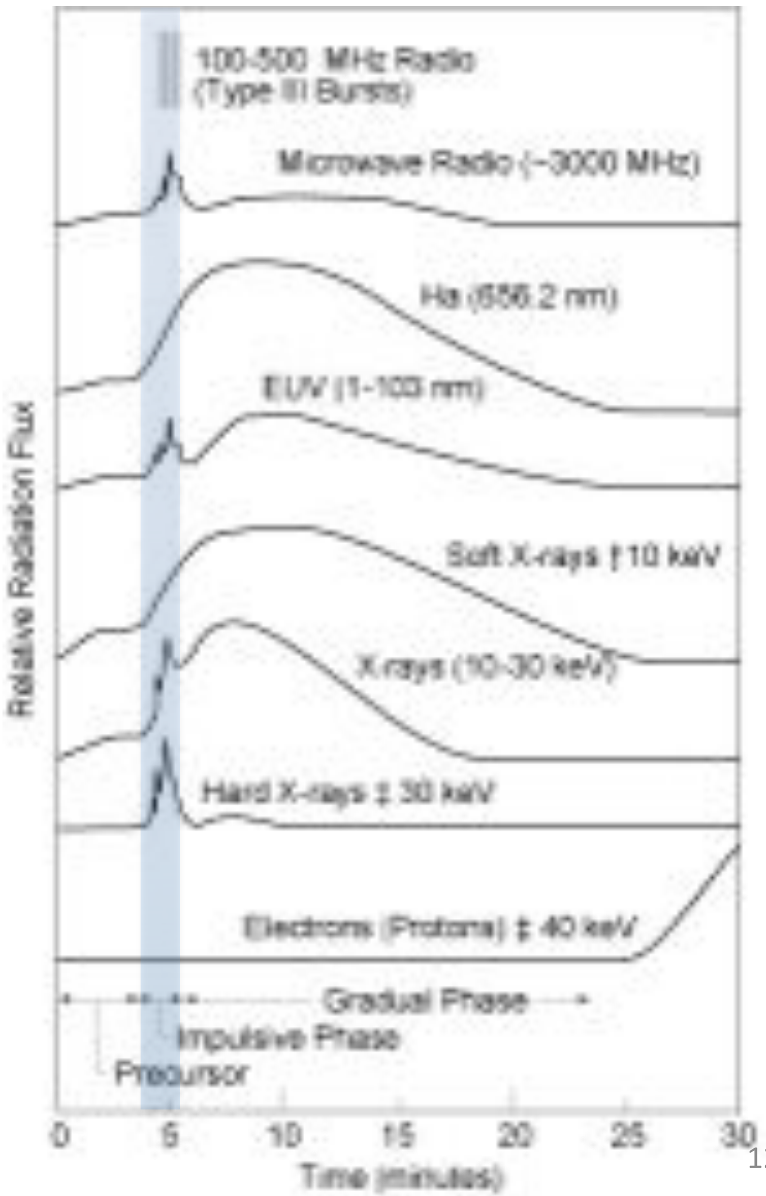


- Thermal emission (bremsstrahlung + spectral lines): plasma $T \geq 10^7$ K
- Classification by the peak flux in the 0.1-0.8 nm band:
  - X class: $\geq 10^{-4}$ W/m^2
  - M class: $\geq 10^{-5}$ W m^{-2} etc. for classes C, B, A
  - e.g., X3.5: peak flux = $3{,}5\times10^{-4}$ W m^{-2}

GOES SXR light curves: www.solarmonitor.org

Solar flares
EM emission by non-thermal electrons

- Spiky emission, particularly during the impulsive flare phase
- Different spectral ranges ⇔ different emission processes, different regions of the atmosphere:
  - microwaves (1 GHz - some tens GHz) -> gyrosynchrotron
  - HXR -> bremsstrahlung



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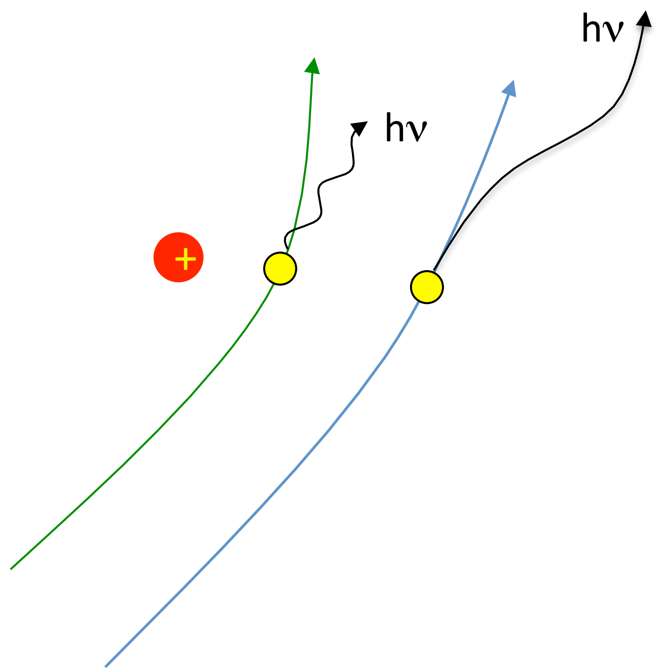
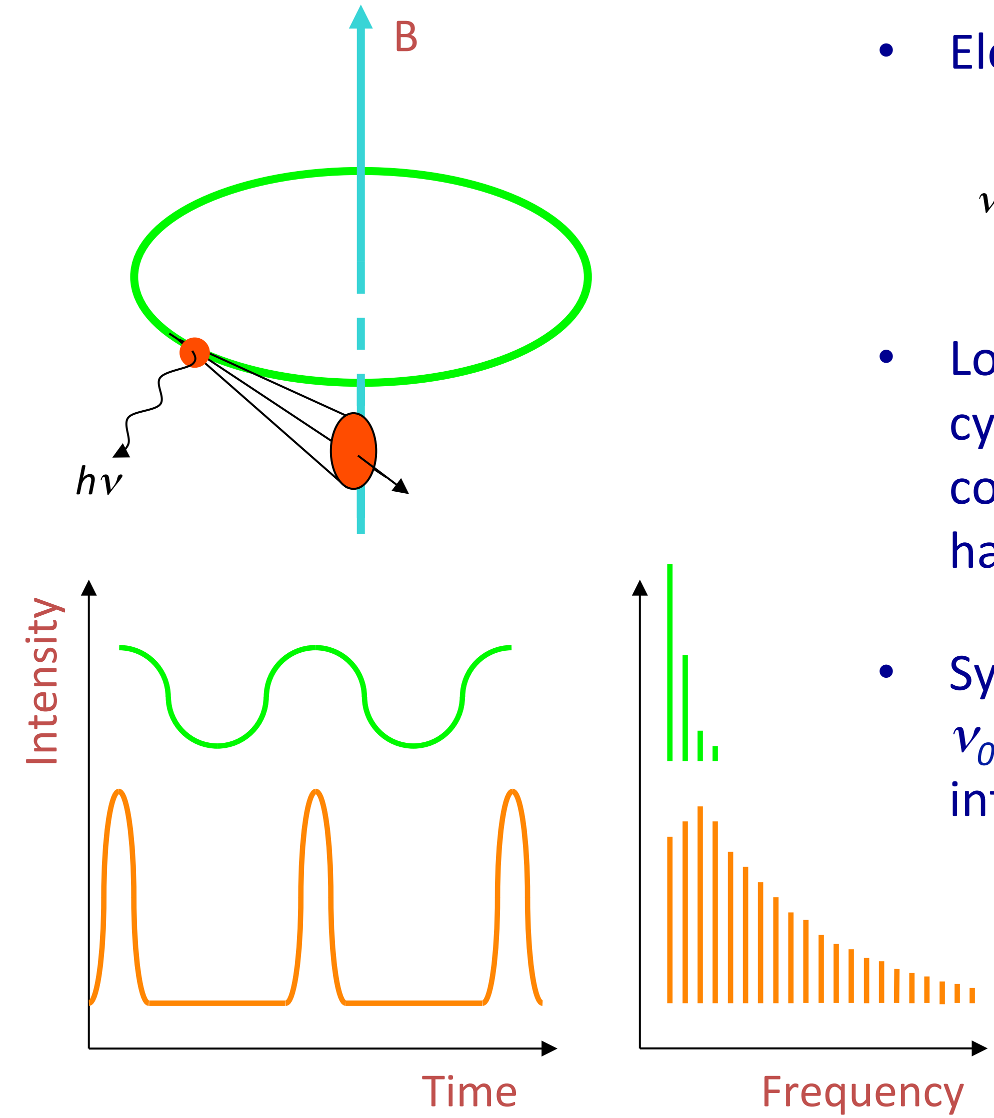
Non-thermal emission processes: bremsstrahlung

- Deflection of an electron in the electric field of a proton (ion) - bremsstrahlung:
  - close encounter - strong deviation / strong change of momentum - EM wave at high frequency (hard X-rays)
  - remote encounter - low frequency (radio)
  - emission – if optically thin (HXR) - preferably in a dense medium (numerous encounters): $\sim n_e n_i \sim n_e^2$
  - thermal (maxwellian) or non-thermal (high-energy excess above maxwellian)



Non-thermal emission processes: gyrosynchrotron



After Wild et al. 1963 Ann Rev Ast Ap 1, 291

- Electron cyclotron frequency

$$\nu_{ce} = \frac{1}{2\pi}\frac{eB}{m_e} \approx 2.8 \frac{B}{10^{-4}\ \mathrm{T}}\ [\mathrm{MHz}]$$

- Low speed electron ($T \approx 10^6$ K) : cyclotron line (unobservable in corona , since $\nu_{pe} > \nu_{ce}$) and low harmonics ($\nu = s\nu_0$, $\nu_0 = \nu_{ce}$, s=1,2,3)

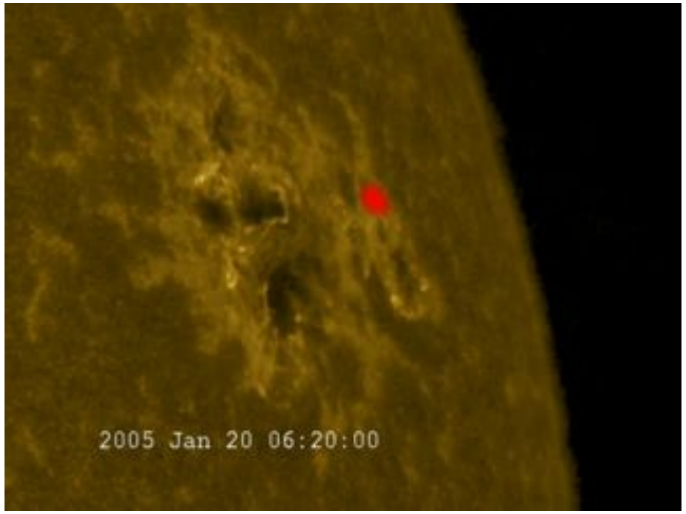
- Synchrotron rad., relativistic e: $\nu_0 = \nu_{ce}/\gamma$; beaming $\Rightarrow$ high s, max. intensity at

$$\nu_c = \frac{3}{2}\gamma^2 \nu_{ce}$$

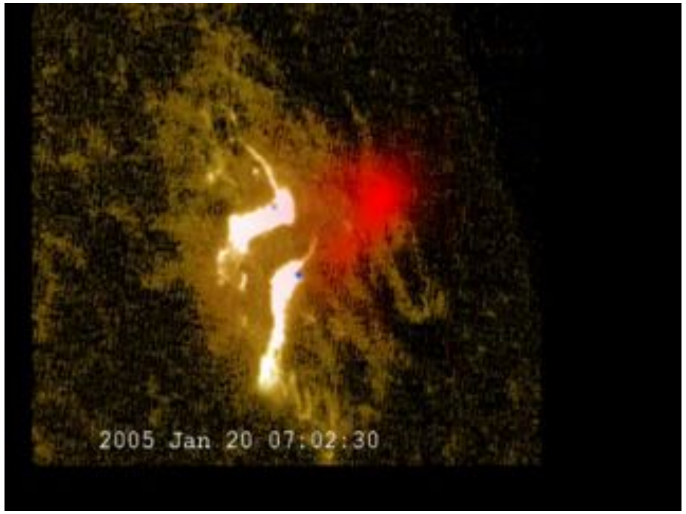
Solar flares: identification of the electron acceleration region (observations)

Solar flares – energy release and particle acceleration
Thermal and non-thermal emissions during a large solar flare

Krucker et al. 2008 ApJ 678, L63

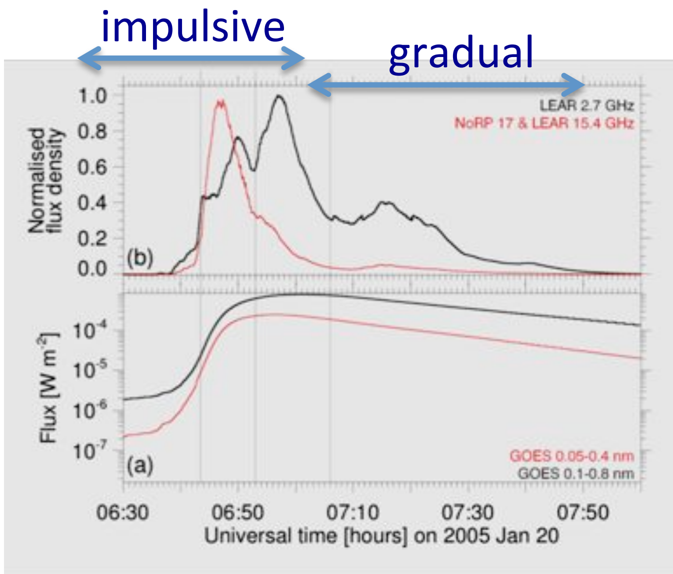


RHESSI & TRACE: impulsive phase



RHESSI & TRACE: gradual phase

- Impulsive phase: flare ribbons, SXR loop, irregular displacement of HXR footpoints



Klein, Masson et al. 2014 AA 572, A4

- Gradual phase: flare ribbons receding from PIL, SXR loop, rising EUV arcade, no/ weak HXR & microwaves

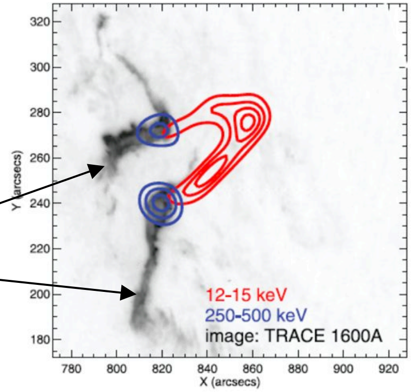
Solar flares – energy release and particle acceleration

A cartoon scenario

- X-ray emission during the flare - loop structure (thermal, T>10^7 K) & footpoints (impact of energetic electrons)

RHESSI + TRACE:

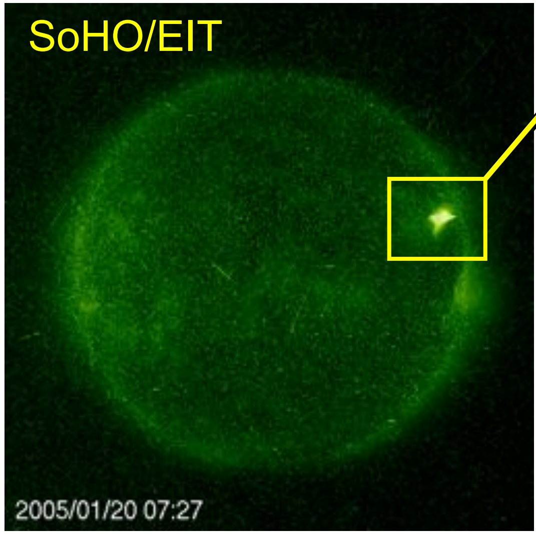
UV ribbons (chromosphere heated during flare)

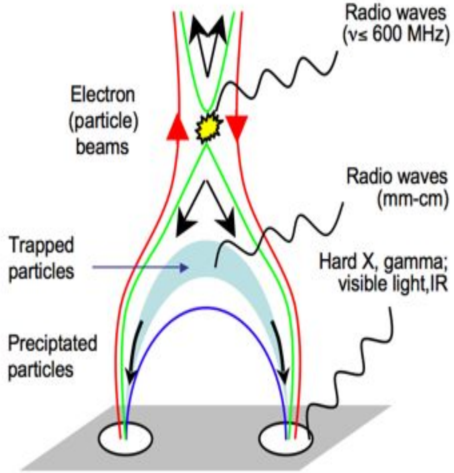


SXR loop (thermal)

HXR footpoints (non thermal)

Krucker et al. 2008 ApJ 678, L63



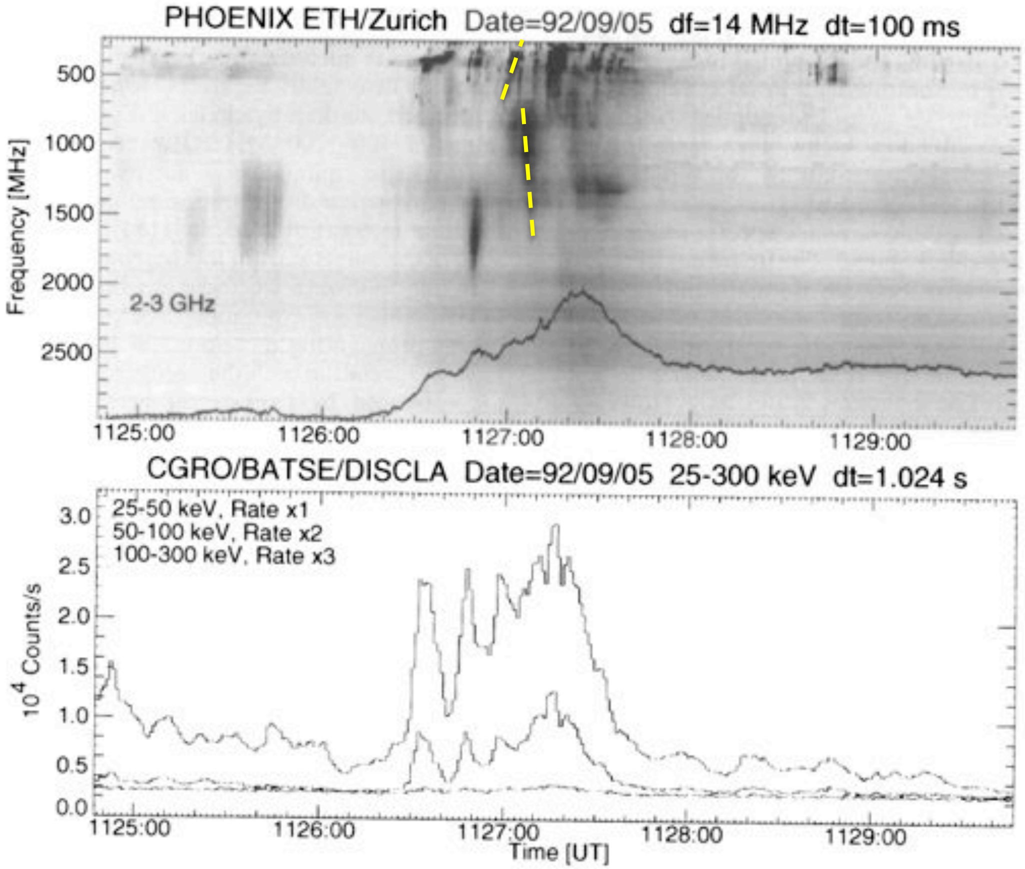


- A simple cartoon scenario: energy release and particle acceleration in the corona, loops underneath (magnetic reconnection)

Solar flares – energy release and particle acceleration

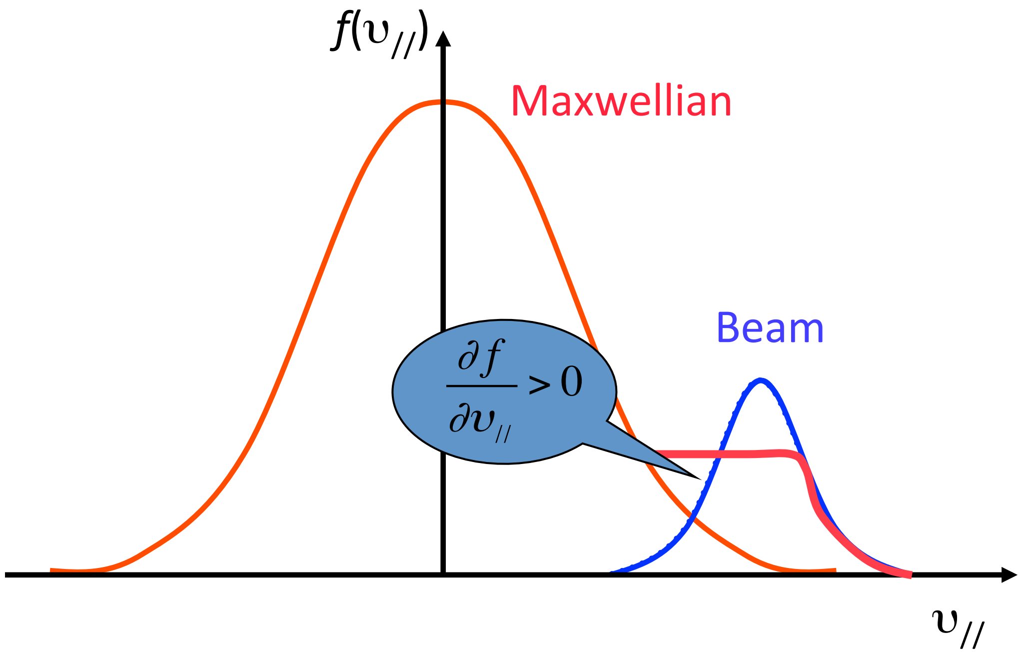
Evidence from radio observations

Aschwanden et al. 1993 ApJ 417, 790



- dm-m wave radio emission associated with HXR bursts
- Type III bursts: short bursts with a spectral drift
- Instantaneous bandwidth narrow ($\Delta\nu < \nu_0$) – unlike gyrosynchrotron emission !

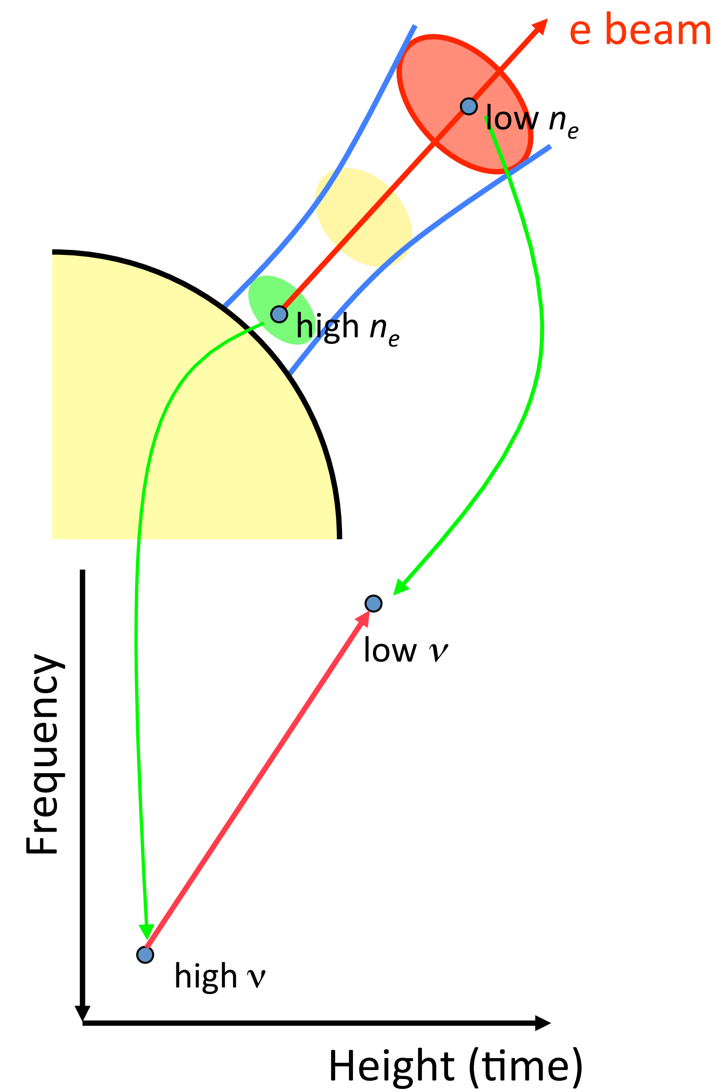
Solar flares – energy release and particle acceleration
Radio emission from electron beams



- Beam of suprathermal electrons injected upward from an active region.
- In the overlying corona: "bump on tail" distribution (maxwellian + e beam), $\partial f / \partial \upsilon_{//} > 0$
- Instability: transfer of energy from electrons to waves
  - growth of Langmuir waves, $\nu \approx \nu_{pe} \sim \sqrt{n_e}$
  - plateau distribution (lower energy than beam)

The Langmuir waves cannot escape from the corona, but can generate EM waves.

Solar flares – energy release and particle acceleration
Radio emission from electron beams

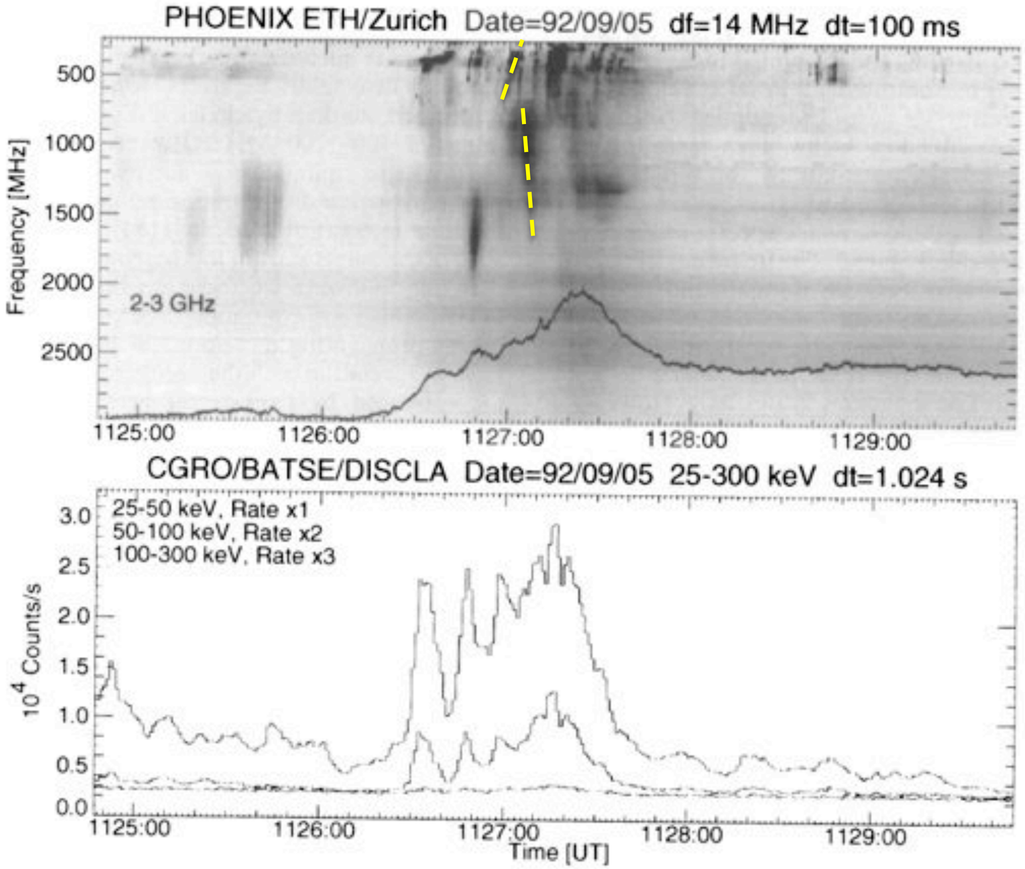


- e beam rising through corona → Langmuir waves at decreasing ν
- Coupling with ion sound waves ($\nu_S << \nu_L$) or Langmuir waves → EM waves (T=transverse) at
  - $\nu_T = \nu_L + \nu_S \approx \nu_L \approx \nu_{pe} \sim \sqrt{n_e}$ "fundamental"
  - $\nu_T = \nu_L + \nu_L = 2\nu_L \approx 2\nu_{pe}$ "harmonic"
- Short burst that drifts from high to low ν ("type III" burst); lower ν → greater height
- Radio image: ν-dependent height

Solar flares – energy release and particle acceleration

Evidence from radio observations

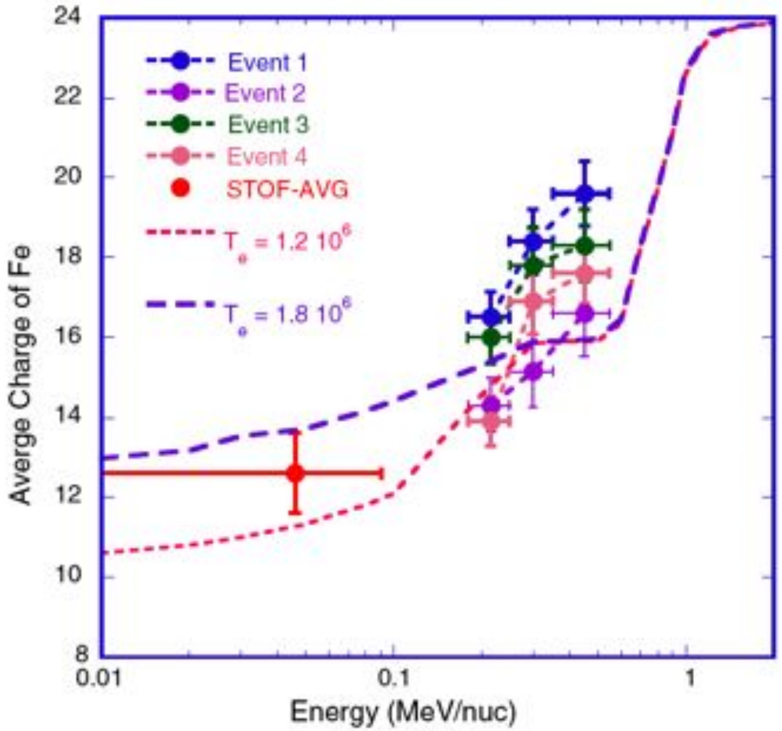
Aschwanden et al. 1993 ApJ 417, 790



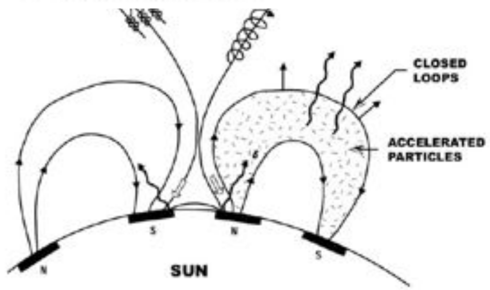
- Drift of type III-like bursts: towards
  - low frequencies at $\nu << 500$ MHz (upward propagating e-beams)
  - high frequencies at $\nu >> 500$ MHz (downward propagating e-beams)
- Simultaneous bursts with opposite drifts (bidirectional beams):
  - acceleration region near the start frequency
  - infer n_e from the start frequency
  - harmonic emission: $n_e=(10^9\text{-}10^{10})$ cm^{-3} (Aschwanden et al. 1995 ApJ 455, 347)

Solar flares – energy release and particle acceleration
Evidence from charge state measurements in SEP events

- ACE : Q of SEP ions (e.g., Fe) are energy-dependent
- inconsistent with ionisation in thermal equilibrium (dashed, dotted curves)
- Current interpretation: collisional stripping during the acceleration process (e.g., Dröge et al 2006, ApJ 645, 1516)
- Model-dependent constraint: $n_e \tau = (10^{10}\text{-}10^{11})\ \text{cm}^{-3}\ \text{s}$
- consistent with HXR/γR/radio signatures ?



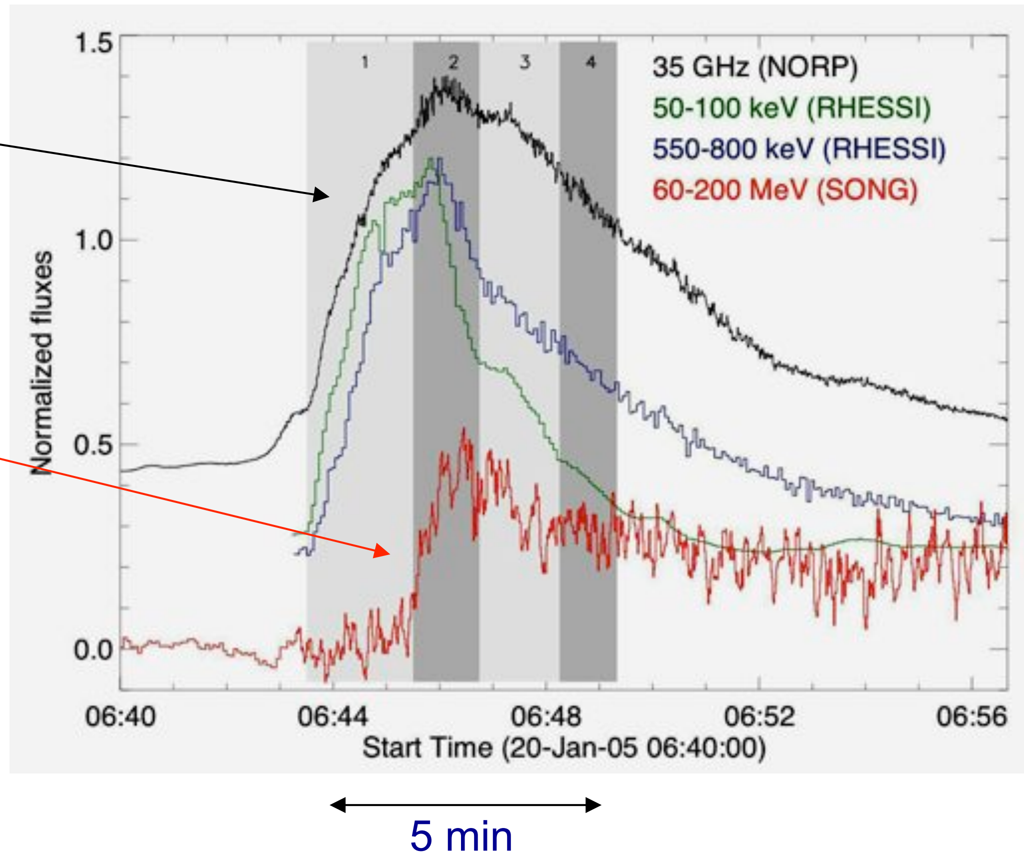
Klecker et al. 2006 Adv Space Res 38, 493



Solar flares: acceleration of protons and ions (observations)

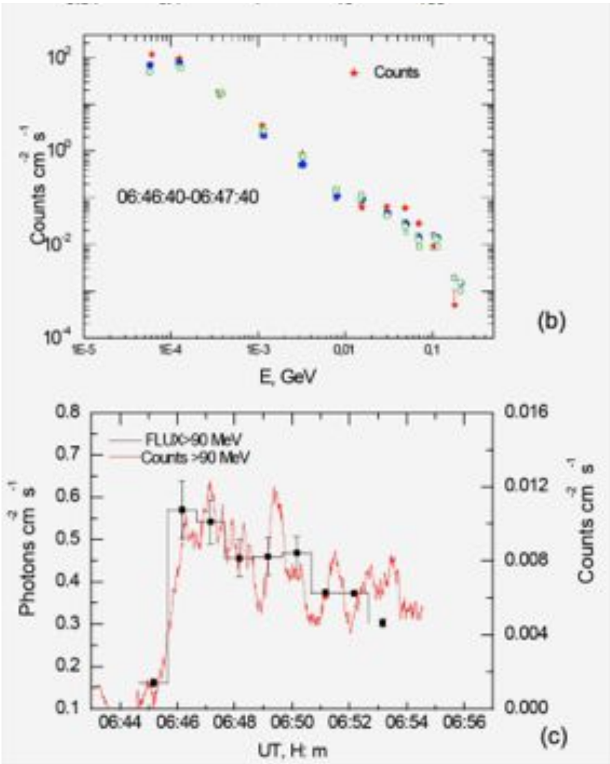
Solar flares – proton acceleration
Pion-decay gamma rays

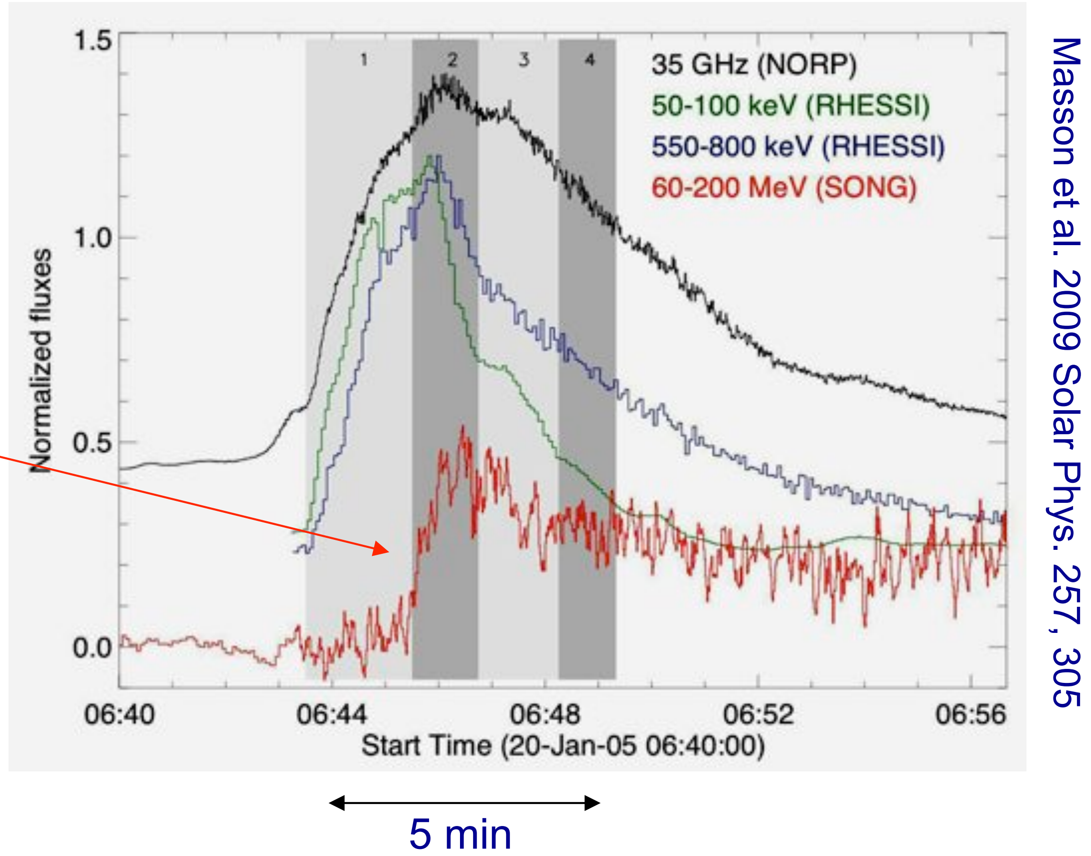
- Microwaves (Nobeyama, 35 GHz) & HXR (RHESSI): electrons up to some MeV
- Gamma rays $h\nu > 60$ MeV: π^0 decay from p>300 MeV
- Protons (ions) > 300 MeV/nuc ->
  - $\pi^{+/-}$ -> $\mu^{+/-}$ -> $e^{+/-}$
  - π^0 -> 2γ (67 MeV)



Masson et al. 2009 Solar Phys. 257, 305

Solar flares – proton acceleration
Pion-decay gamma rays

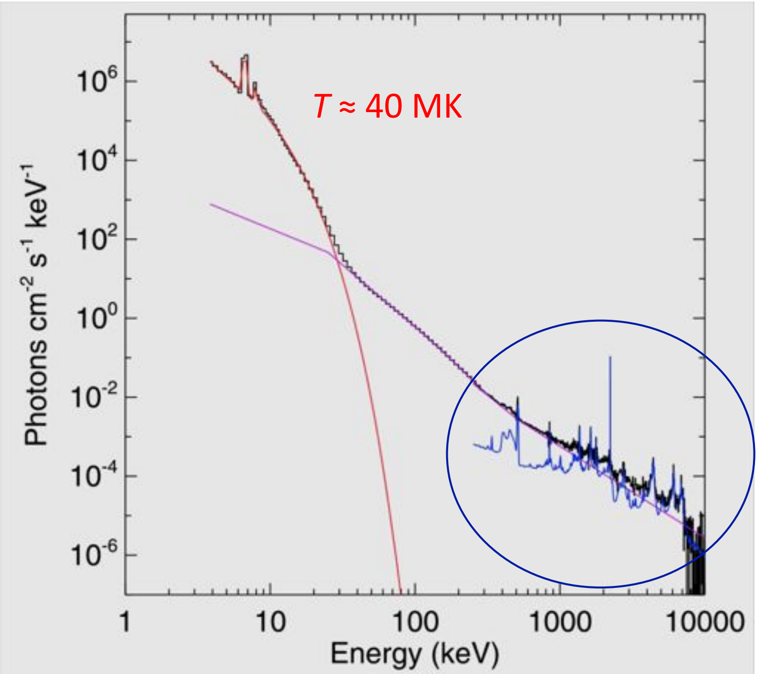




- Particle acceleration during impulsive flare phase strongly structured in time, sequence of acceleration episodes with varying e spectra and e/p ratio

Solar flares – proton acceleration
Nuclear gamma-ray lines

- Photon spectrum (RHESSI/NASA) - thermal and non-thermal (power-law) parts

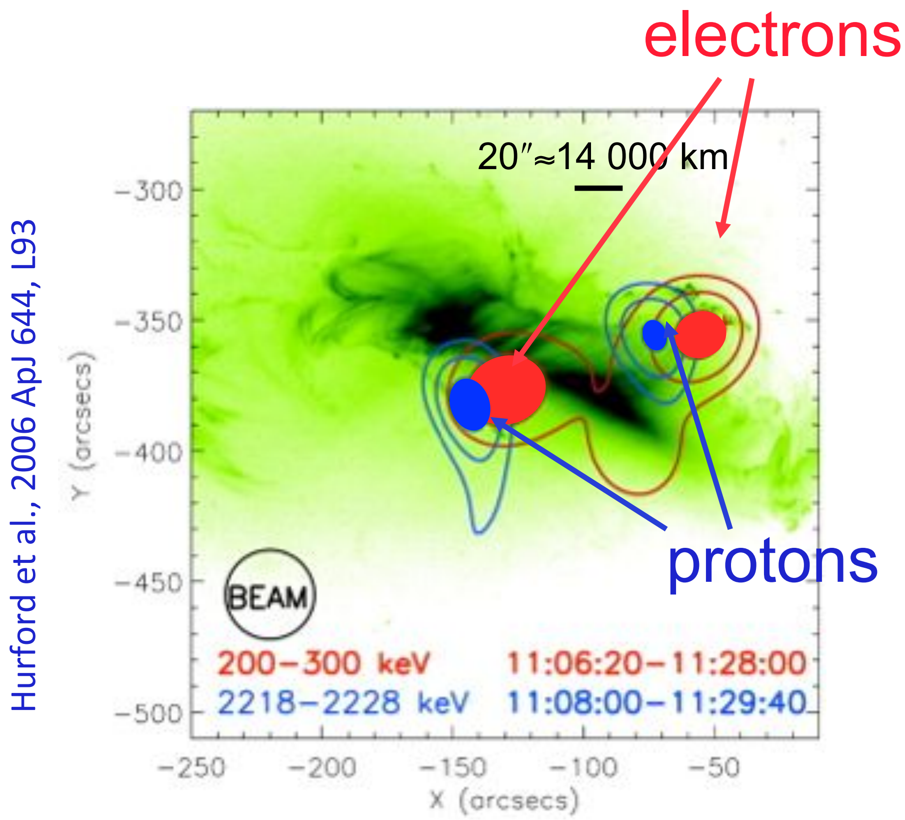


R.P. Lin 2011 Spa Sci Rev 159, 421

- hν ≈ 1-10 MeV: gamma-ray lines from nuclear reactions
- Recent review: Vilmer et al. 2011, Spa Sci Rev

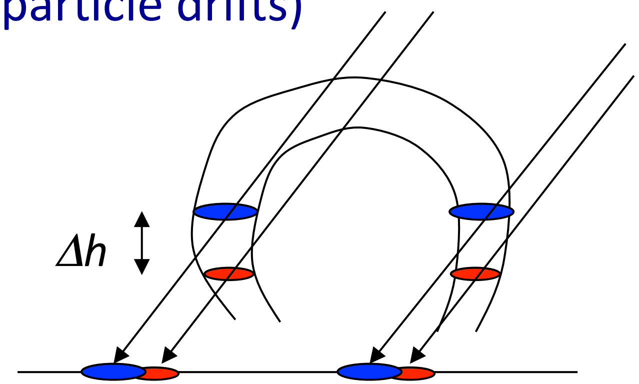
- Accelerated protons impinging on atmospheric ions: (narrow) de-excitation lines
- Accelerated ions impinging on atmospheric protons: broad de-excitation lines
- Neutron capture line:
- **???**
  - *p*(> 30 MeV)*+X* -> X'+*n*
  - *n (thermalised) + p* -> $^2H^*$ -> $^2H + \gamma$ (2.223 MeV)

Solar flares – proton acceleration
Imaging observations



- Imaging of the 2.223 MeV line (p≥30 MeV) and of HXR bremsstrahlung (e^- ≥200 keV): consistently (4/5 cases) different sources (see Vilmer et al. 2011, Spa Sci Rev).

- Simple explanations do not work (instrumental artefact, projection effects, particle drifts)



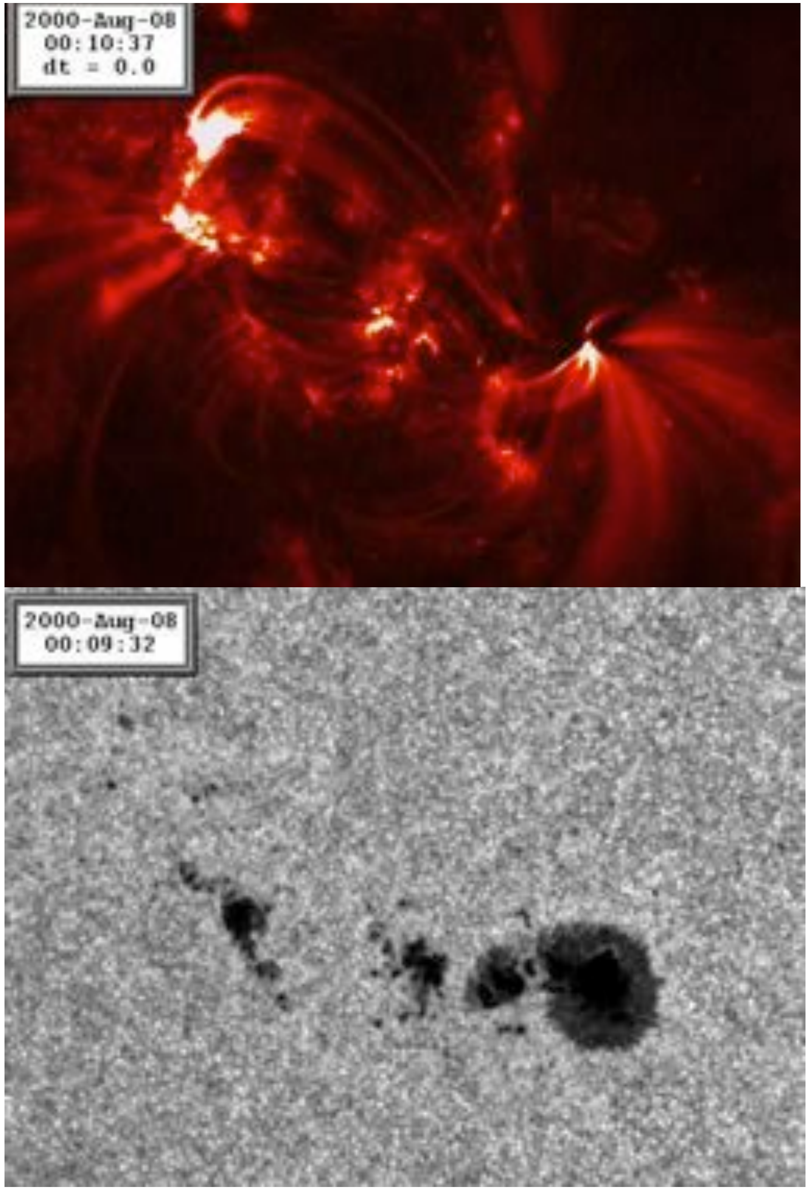
- Different acceleration regions ?

Solar flares: a qualitative view on the acceleration processes

Particle acceleration in solar flares
Electrodynamic coupling in the solar atmosphere

- Transport of energy from the photosphere (gaz motion) to the corona by field-aligned electric currents: electrodynamic coupling; storage in the corona

- Illustration (obs. SoHO, ESA/NASA):
  - active region in the photosphere, including a rotating sunspot
  - magnetic connection to the corona outlined by some bright loops (EUV)
  - the loops seem to follow the rotation of the sunspot – reconfiguration of the coronal magnetic field



Brown 2003 Solar Phys. 216,79

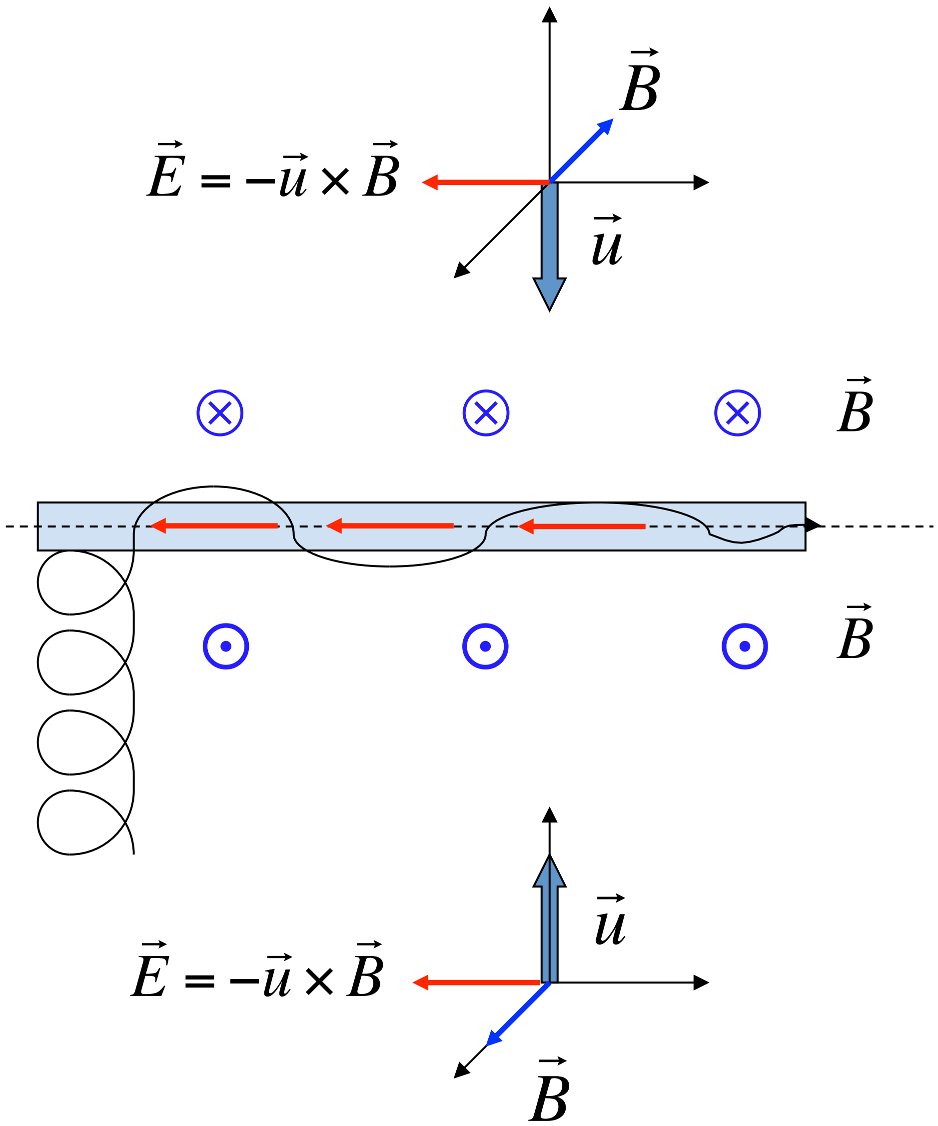
Particle acceleration in solar flares
Electric fields in the solar corona ?

- To accelerate a charged particle: need electric field along the magnetic field $\vec{F} = q(\vec{E} + \vec{v} \wedge \vec{B})$
- Solar corona: highly conducting medium in most parts (≈ Cu), no static electric field can be maintained along the ambient magnetic field

$$\text{Ohm: } \vec{E} + \vec{u} \times \vec{B} = \eta \vec{j} = 0$$

- Peculiar configurations where *B*-aligned electric fields can exist: current sheets and transient configurations (magnetic reconnection, shock waves)
- We cannot measure electric fields in the corona, only infer them from the analysis of plasma motions.

Particle acceleration in solar flares
« Direct » electric field acceleration in a current sheet



- A simple scenario of charged particle motions in a current sheet (CS).
- Direct electric field (stationary situation)

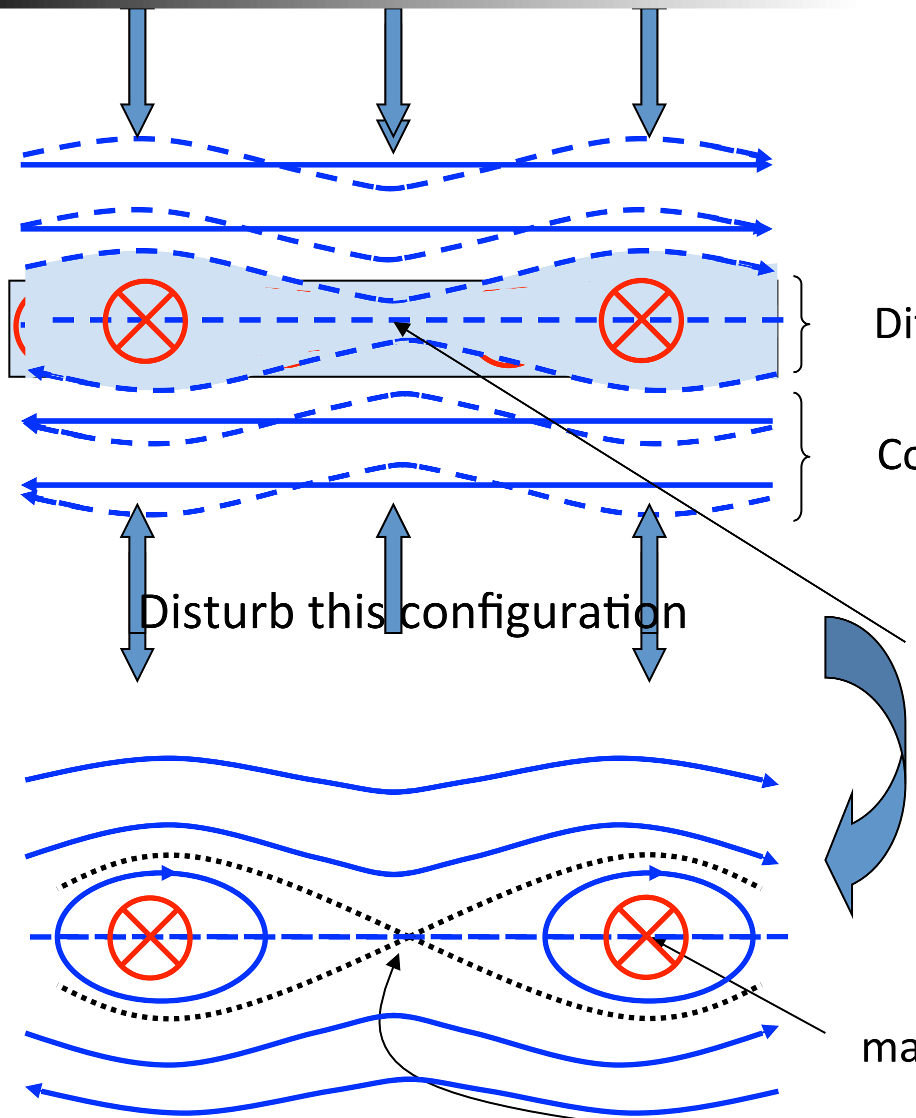
$$0 = \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \Rightarrow \vec{E} = const.$$

- Charged particles (here : electron) **E**×**B** - drift into the CS. Those crossing *B*=0 are accelerated by the **E** field ("meander orbit").

Particle acceleration in solar flares
Instability of a current sheet

$$E + \vec{u} \times \vec{B} = \eta \vec{j} = \frac{\eta}{\mu_0} \nabla \times \vec{B}$$

$$\Rightarrow \frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} \right) - \frac{\eta}{\mu_0} \nabla^2 \vec{B}$$



Diffusion $$\frac{\partial \vec{B}}{\partial t} = -\frac{\eta}{\mu_0} \nabla^2 \vec{B} \approx -\frac{\eta \vec{B}}{\mu_0 L^2}$$

Convection $$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} \right)$$

Smaller scale, enhanced diffusion, magnetic field reconnection

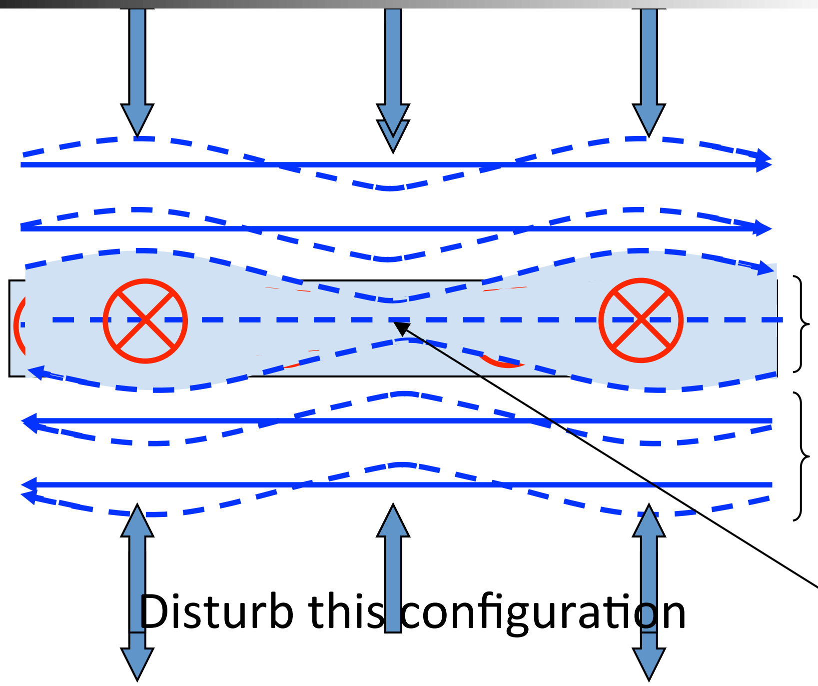
Tearing mode instability, magnetic island formation

magnetic O-line

magnetic X-line

Particle acceleration in solar flares

Instability of a current sheet



$$E + \vec{u} \times \vec{B} = \eta \vec{j} = \frac{\eta}{\mu_0} \nabla \times \vec{B}$$

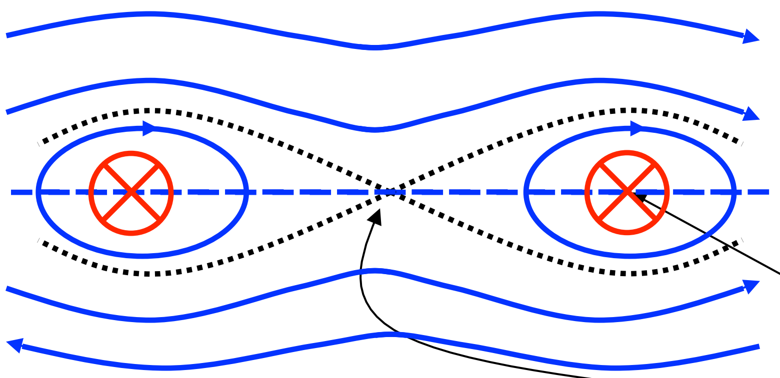
$$\Rightarrow \frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} \right) - \frac{\eta}{\mu_0} \nabla^2 \vec{B}$$

Diffusion $$\frac{\partial \vec{B}}{\partial t} = -\frac{\eta}{\mu_0} \nabla^2 \vec{B} \approx -\frac{\eta \vec{B}}{\mu_0 L^2}$$

Convection $$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} \right)$$

Smaller scale, enhanced diffusion, magnetic field reconnection

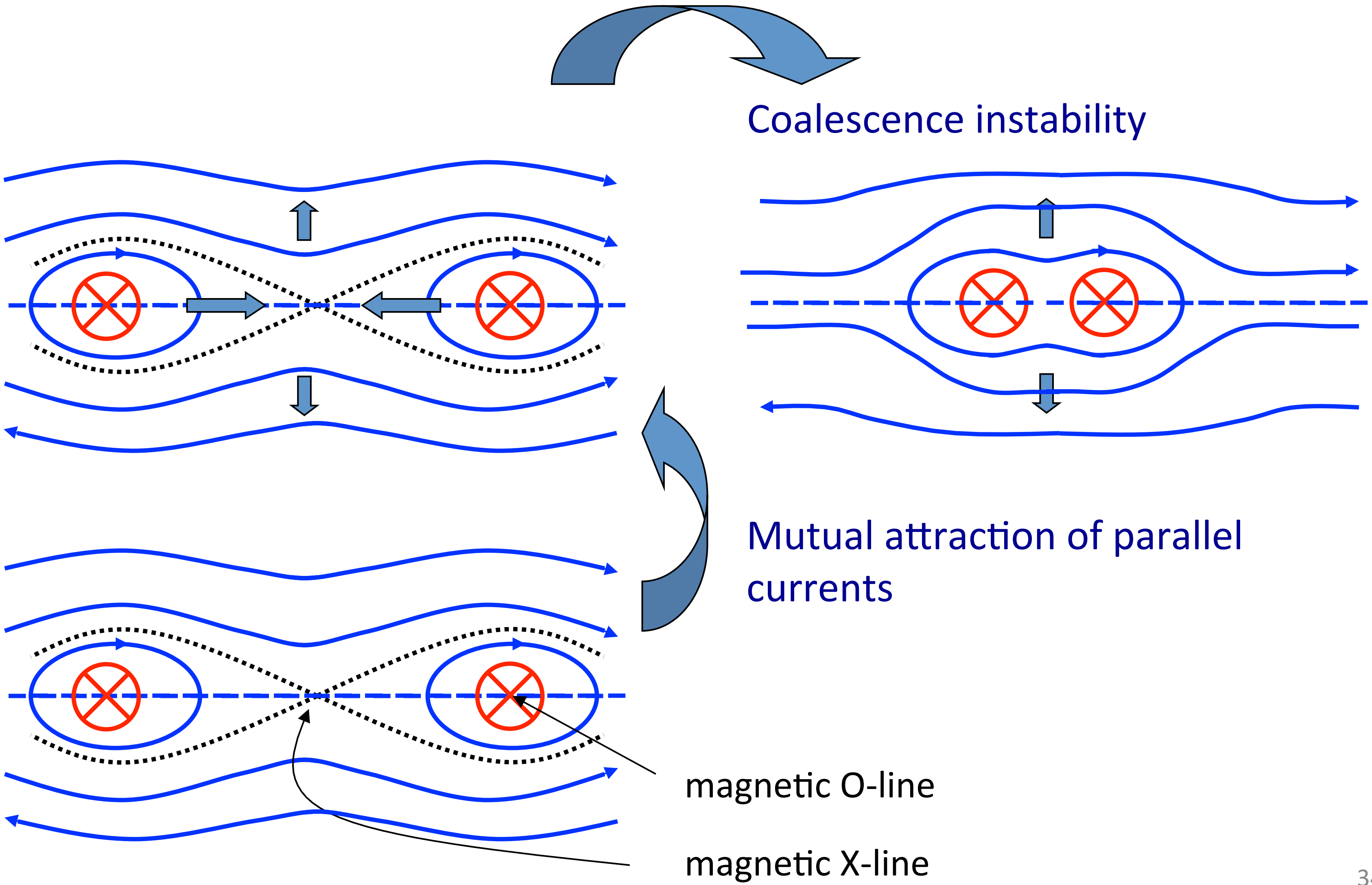
Tearing mode instability, magnetic island formation



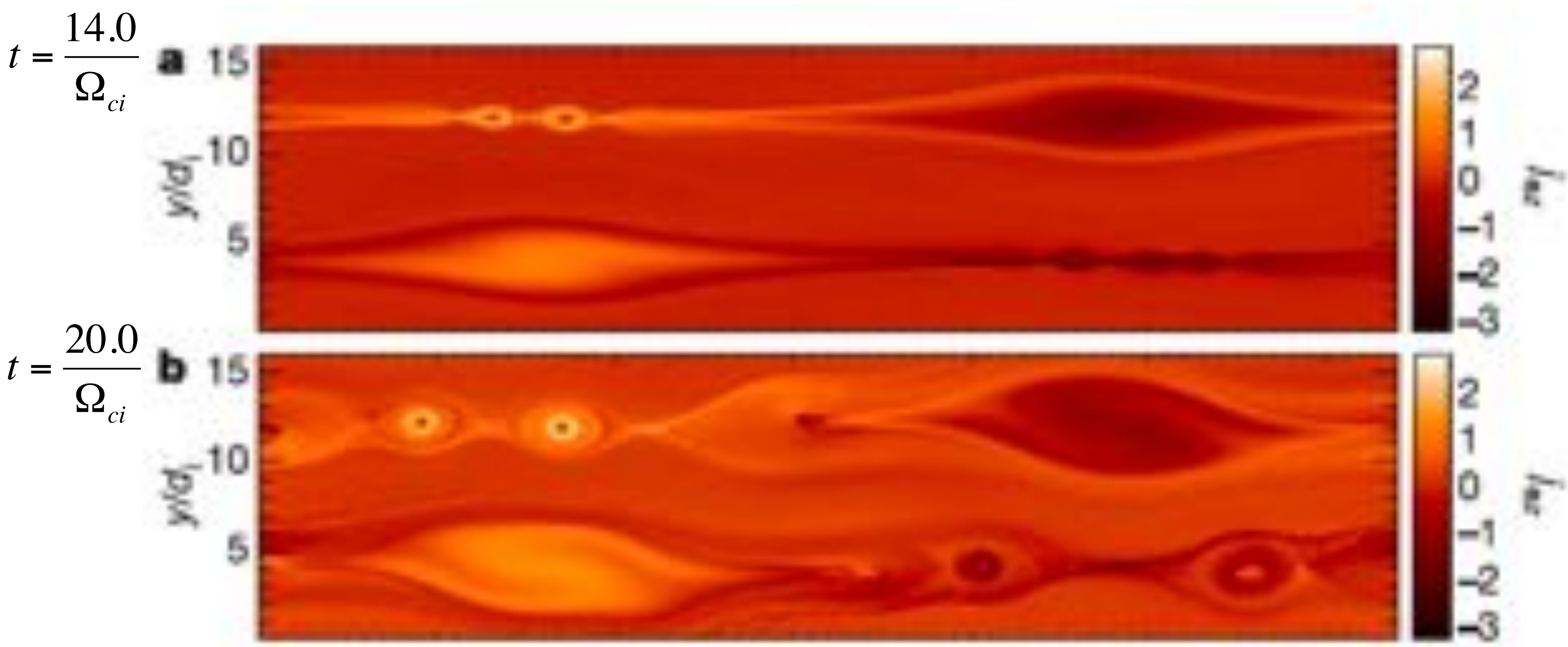
magnetic O-line

magnetic X-line

Particle acceleration in solar flares
Instability of a current sheet



Particle acceleration in solar flares
« Direct » electric field acceleration in a current sheet

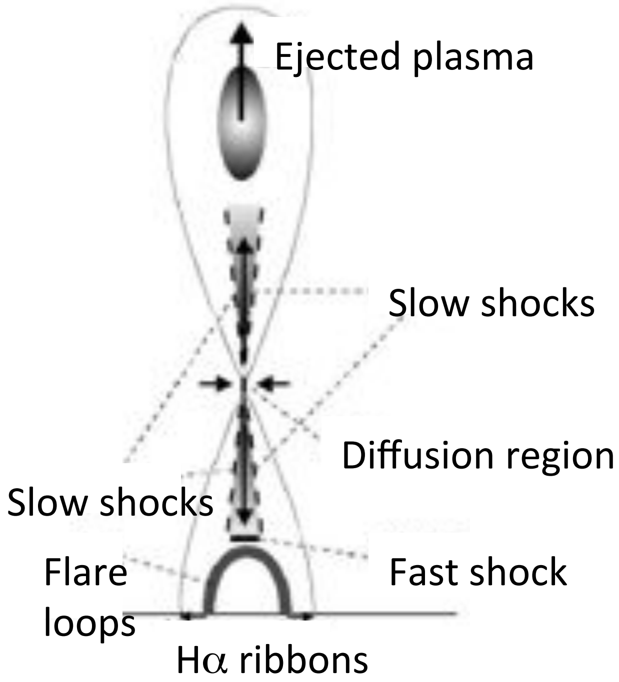


- Numerical simulation of island formation starting with two parallel current sheets (Drake et al. 2006 Nature 443, 553): sequence tearing-coalescence; fragmentation of the current sheet

- Trapping of particles between coalescing magnetic islands: particles collide with approaching islands to gain more energy (Fermi)

Particle acceleration in solar flares
Other acceleration mechanisms in a reconnecting CS

Mann et al. 2006 A&A 454, 969



- Reconnection jets generate
  - shock waves when impinging on the underlying magnetic structures
  - waves (turbulence) in the ambient plasma - acceleration when particle resonates with Doppler-shifted wave frequency
- Reconnected magnetic field lines retract (magnetic tension) => trapped particles are accelerated by
  - reflection between "approaching" magnetic mirrors (Fermi 1)
  - electric fields induced by the compression of the magnetic field (betatron acceleration)

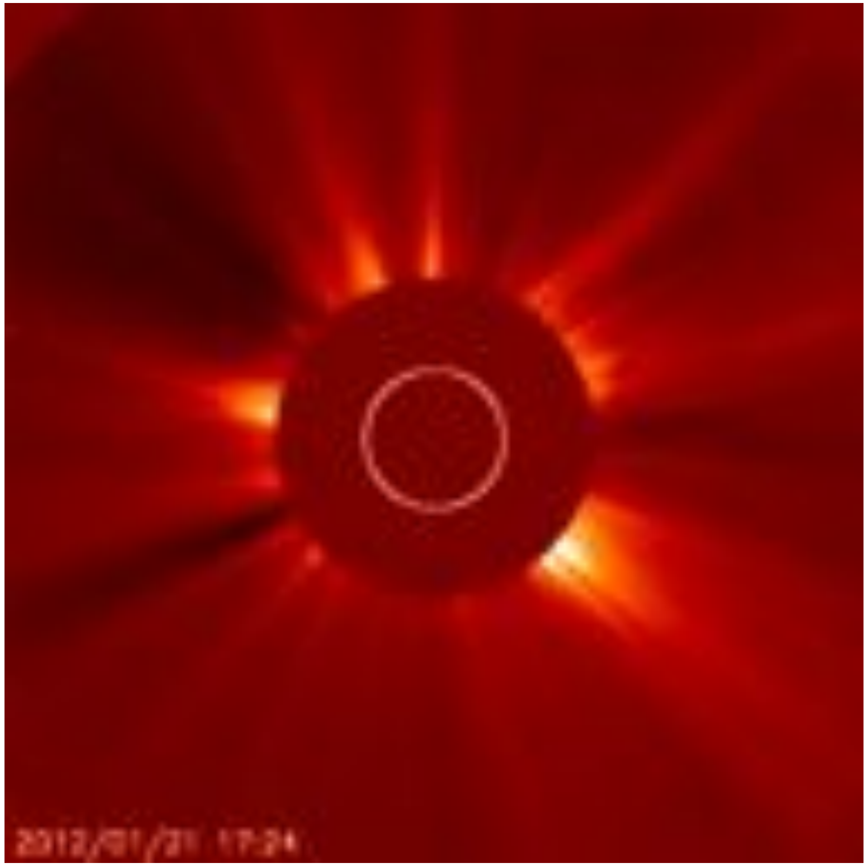
See R. Vainio's lecture

Coronal mass ejections: an introduction

Coronal mass ejections

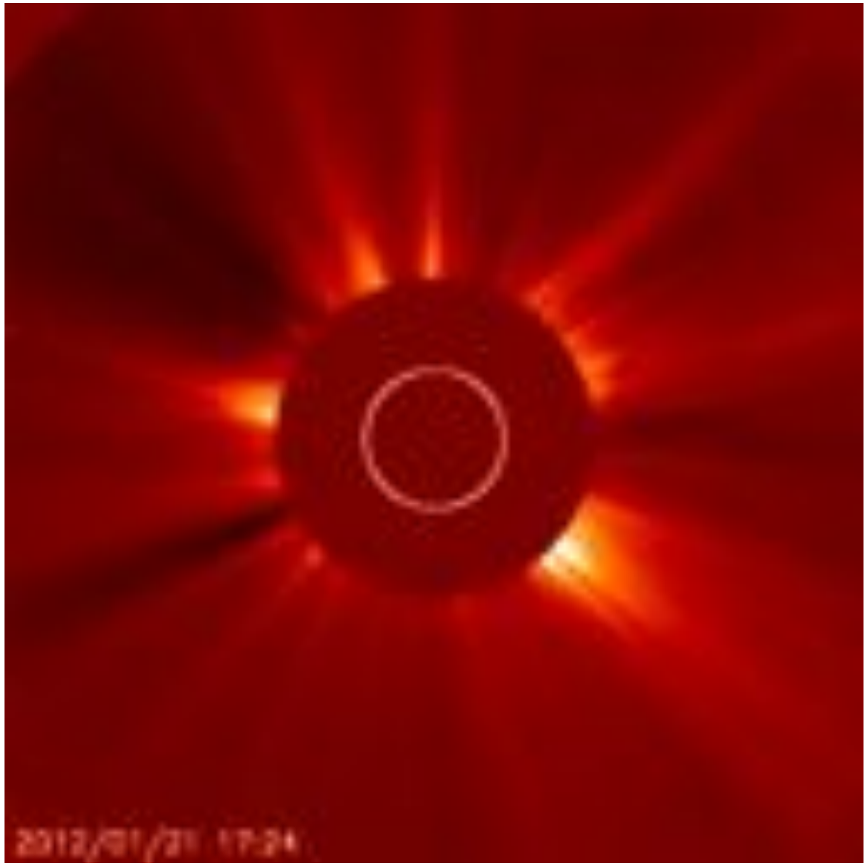
What is a CME ?

© SoHO/LASCO (ESA/NASA)



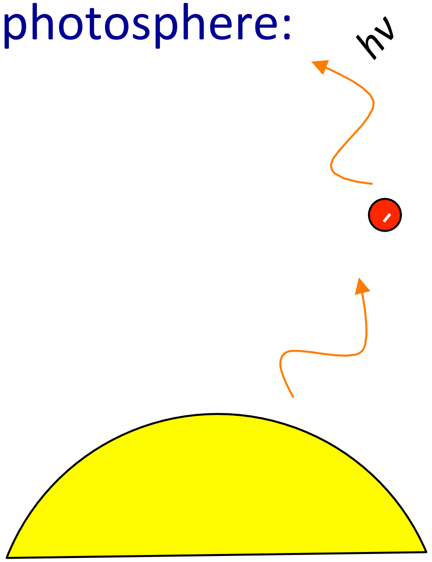
2012 Jan 21 - 25

- What is a CME ?
  - standard observations: coronagraph (white light)
  - structures ejected from the corona into IP space
- Physical processes behind this phenomenology:
  - large-scale instability of coronal magnetic structures
  - possible formation of shock waves (corona, IP medium)



2012 Jan 21 - 25

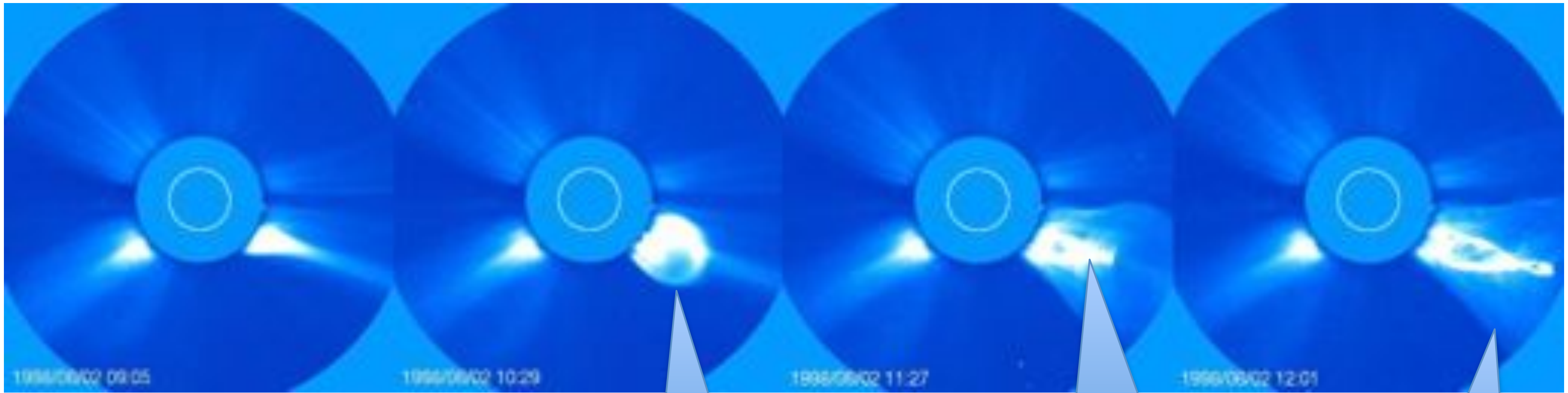
- Coronographic observations
- Thomson-scattered light emitted by the photosphere:



$$I = \int_{LOS} n_e \, ds$$

- Morphology of a large CME: 3-part structure (coronagraphic images, plane of the sky)

© SoHO/LASCO (ESA/NASA)

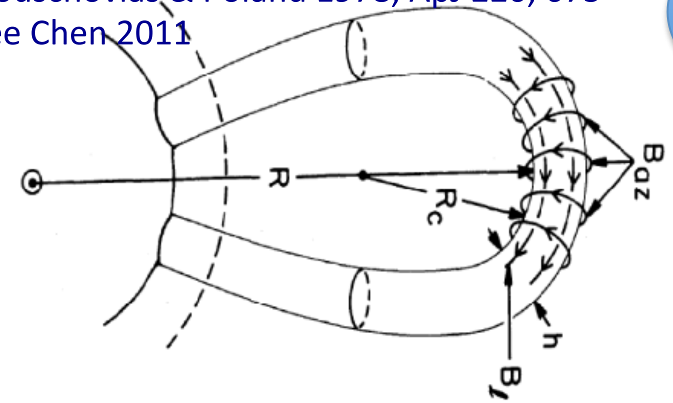


Outer loop

Core (prominence)

Cavity

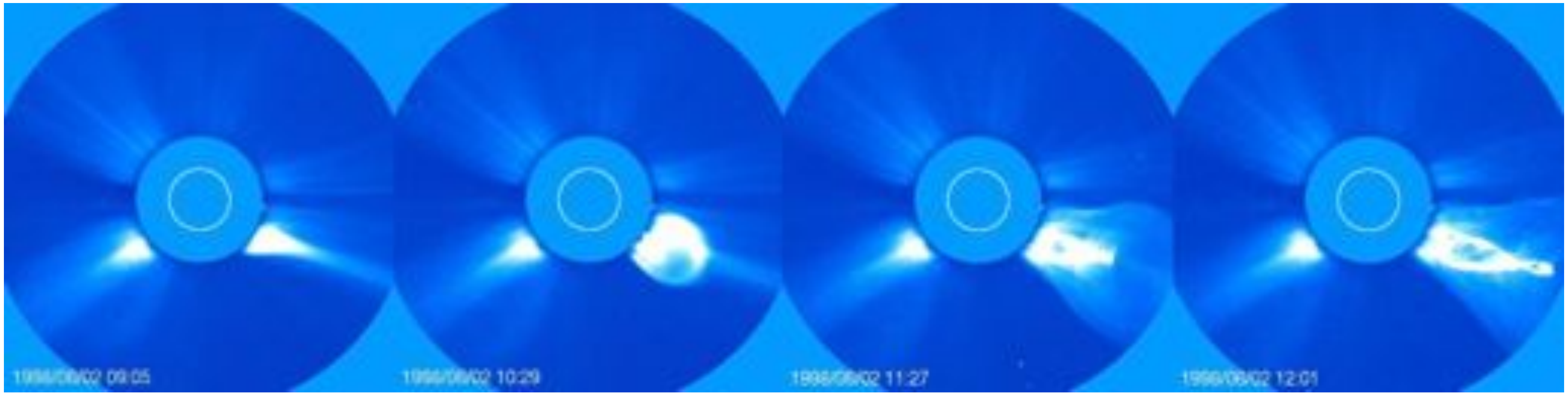
Mouschovias & Poland 1978, ApJ 220, 675 – see Chen 2011

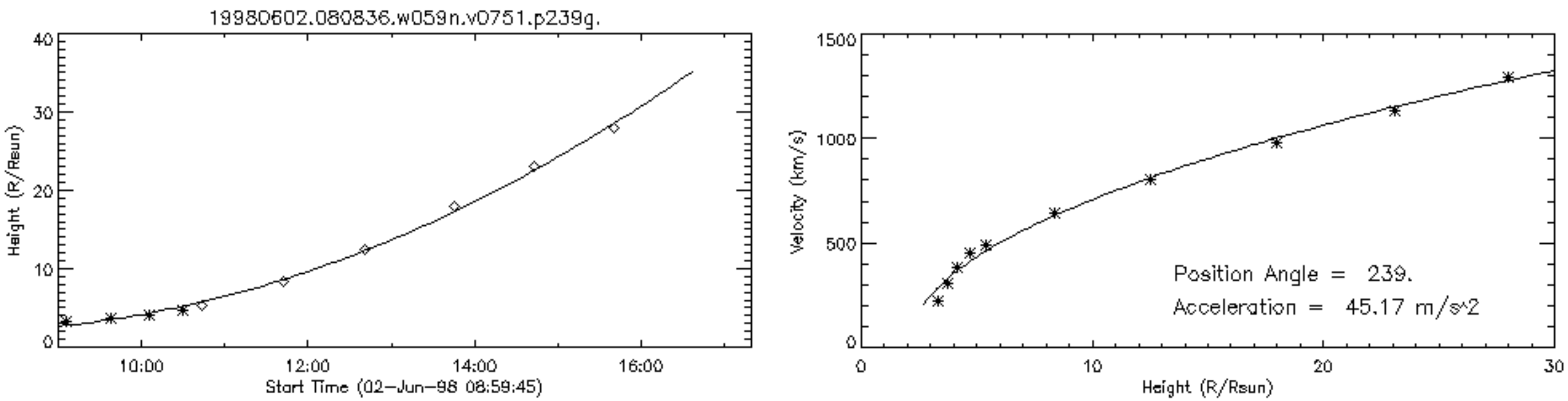


- Suggestive of a magnetic flux rope – prominence material (dense/cold) supported by the Lorentz force

Coronal mass ejections
Kinematics

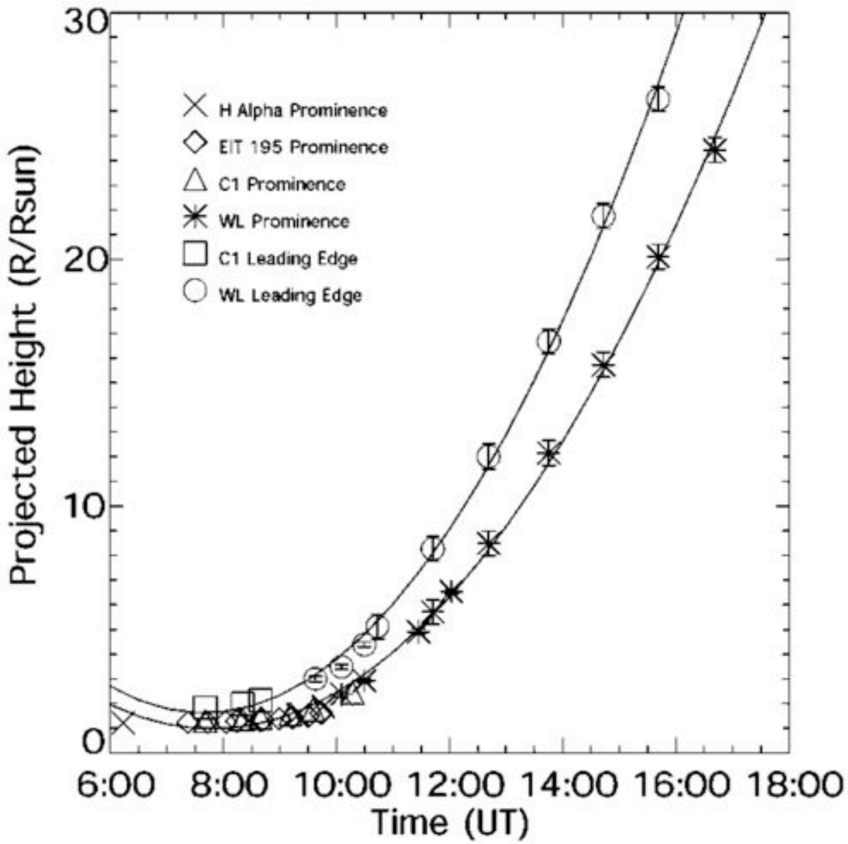
- Time-height trajectory of the top of a CME (coronagraphic images, plane of the sky)



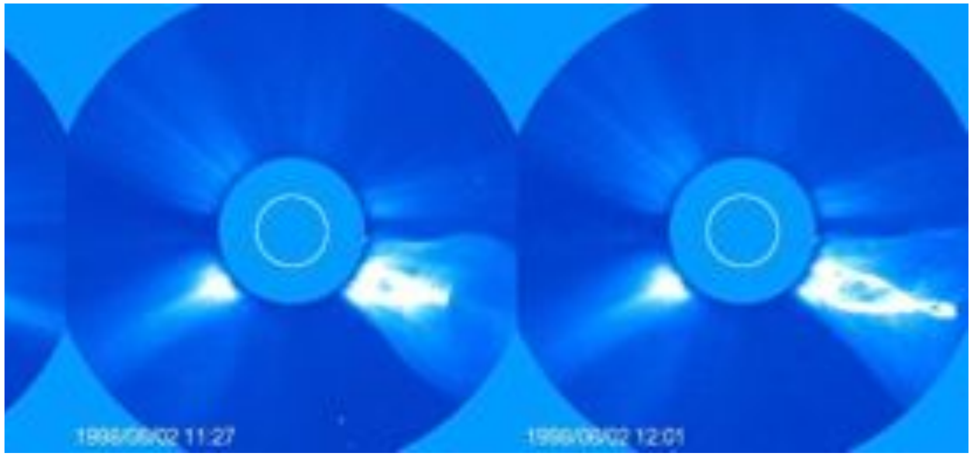


http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/1998_06/htpng/19980602.025951.p117g.htp.html

- Time-height trajectory of the top of a CME (coronagraphic images, plane of the sky)



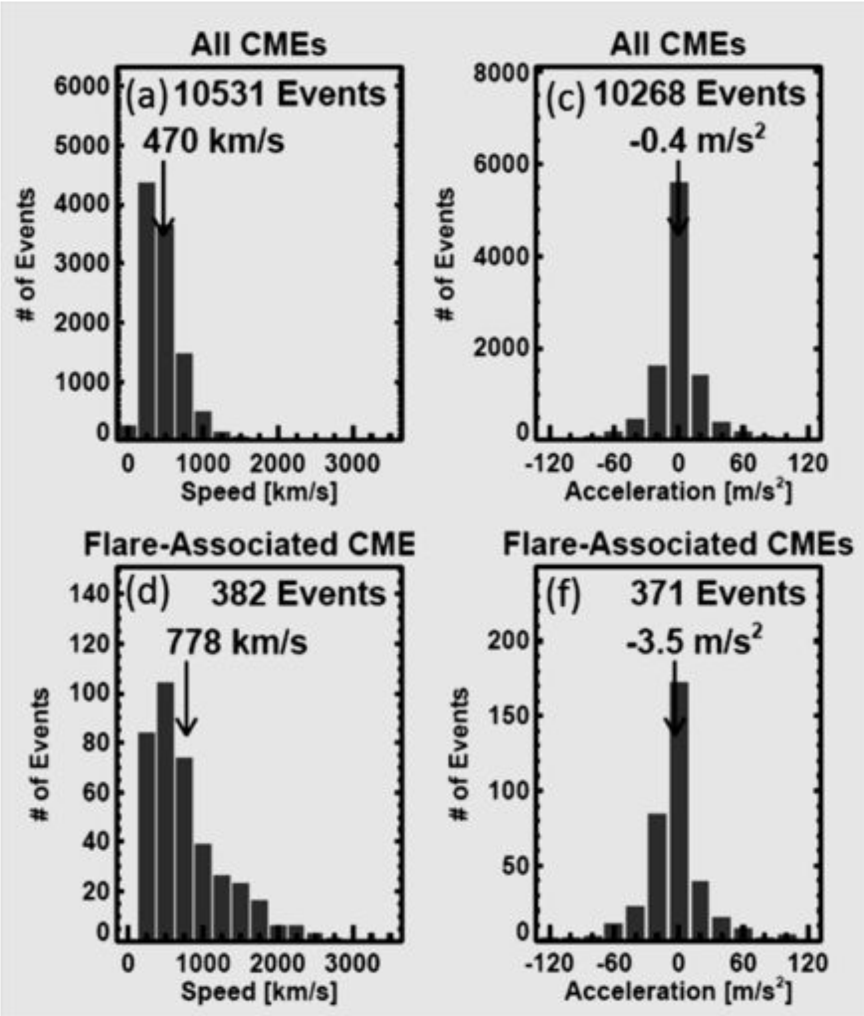
Plunkett et al. 2000 Solar Phys. 194, 371



- Continuous acceleration out of the corona
- highest speed at CME front, subsequent structures (cavity, core) are slower

Coronal mass ejections
Kinematics

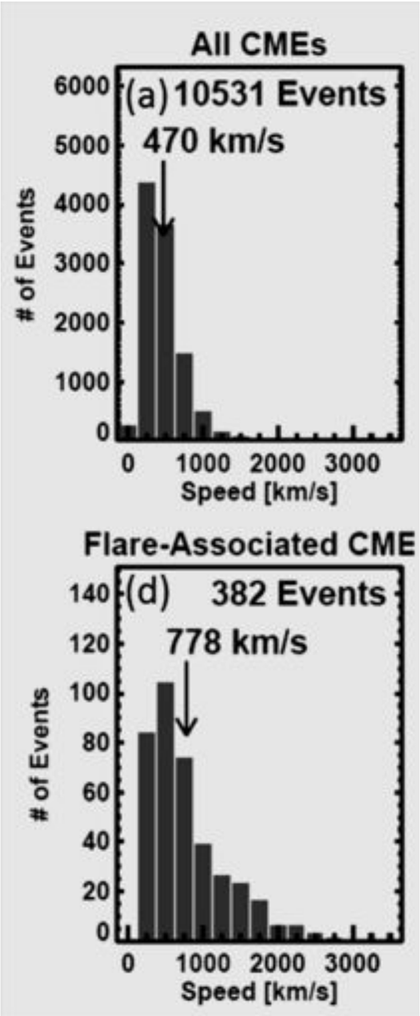
Gopalswamy 2009, CAWSES Symp Kyoto 2007, p. 77



- Distributions of CME velocities (left) and acceleration (right) in the plane of the sky, 1996-2005
  - top panels: all CMEs
  - bottom panels: CMEs associated with flares within 30° of the solar limb
- Kinematics:
  - acceleration or deceleration, depending on events
  - speeds up to > 3000 km s^{-1}

Coronal mass ejections
Shock waves

Gopalswamy 2009, CAWSES Symp yoto 2007, p. 77

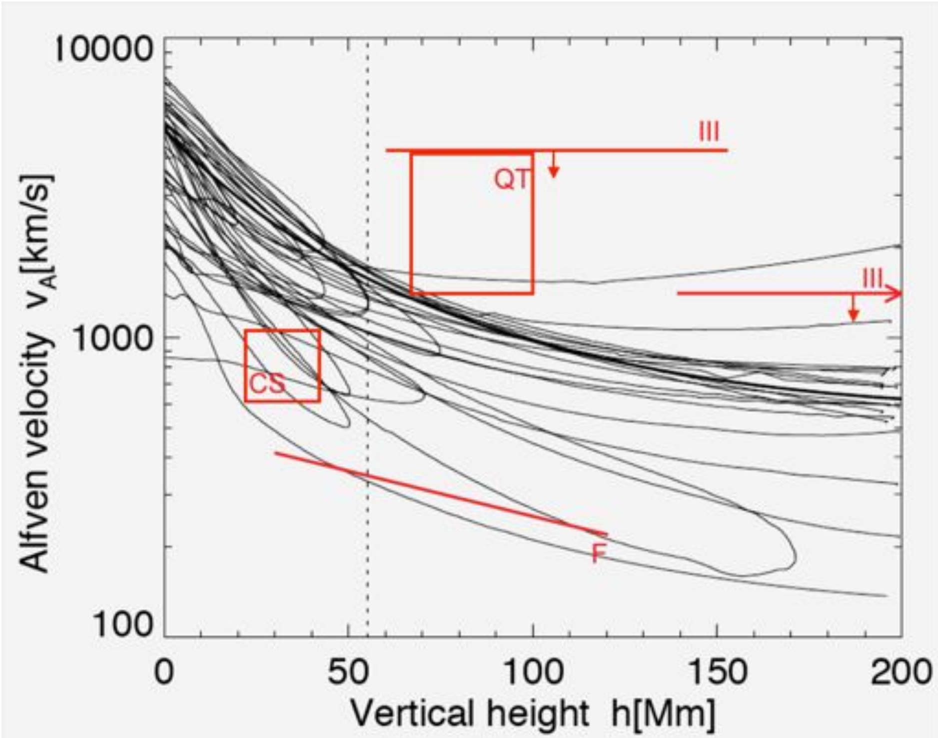


- Characteristic speeds in the corona
- Sound speed $c_s = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma K T}{\mu m_p}} \approx 151 \sqrt{\frac{T}{10^6\ \mathrm{K}}}\ [\mathrm{km\ s^{-1}}]$
- Alfvén speed $c_A = \frac{B}{\sqrt{\mu_0 \rho}} = \ ???\ [\mathrm{km\ s^{-1}}]$
- For reference: plasma beta $\beta = \frac{2\mu_0 P}{B^2} = \frac{2}{\gamma}\frac{\mu_0 \rho}{B^2} c_s^2 = \frac{2}{\gamma}\left(\frac{c_s}{c_A}\right)^2$
- Conclusion:
  - most CMEs are supersonic in the corona
  - many may become super-alfvenic in the high corona (β≥1)

Coronal mass ejections
CME speeds vs Alfven speed in the corona

- Magnetic field in the corona:
  - extrapolation of the measured photospheric magnetic field
  - Zeeman effect of IR lines
  - radio observations (model-dependent)

- Illustration: magnetic field intensity and Alfvén speed above an active region
  - extrapolation (Aschwanden et al. 1999)
  - in red: other tools
    - Z Zeeman IR lines
    - CS coronal seismology
    - QT, III, F radio bursts



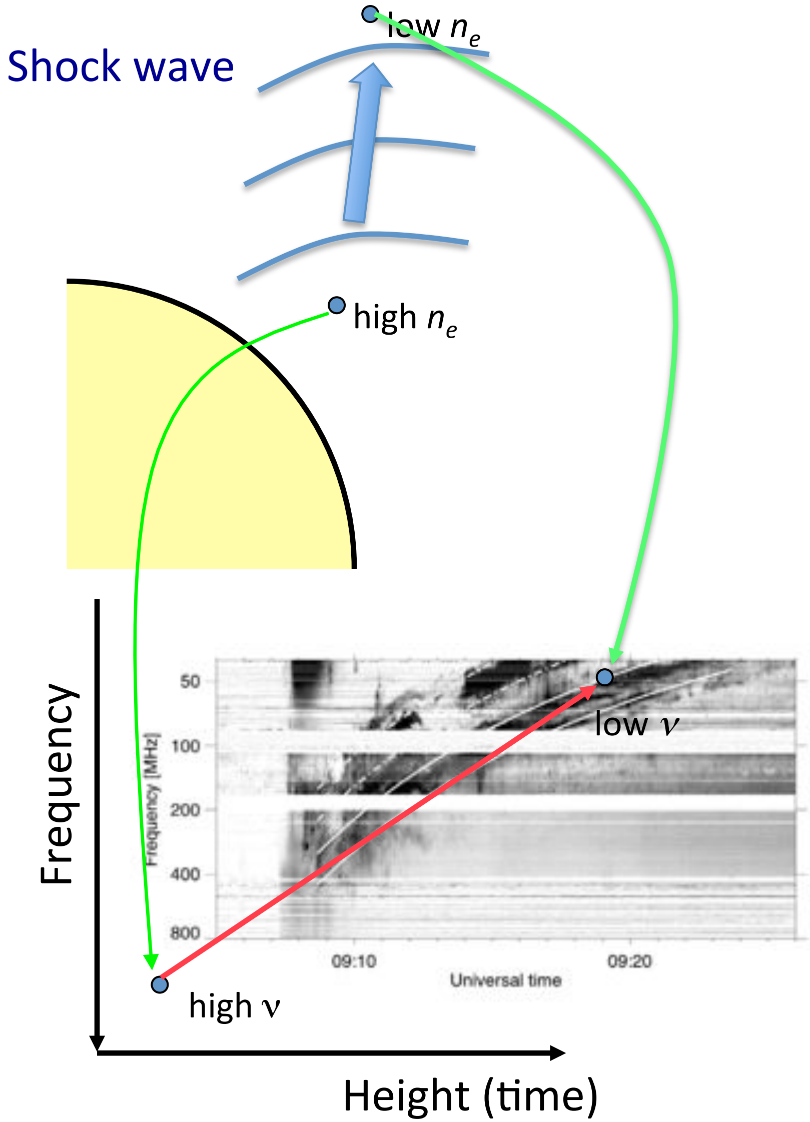
Coronal mass ejections
Shock parameters in the corona

- Measurements for type II burst associated shocks near 1 AU (Pulupa & Bale 2008 ApJ 1676, 1330): M_A=2.6-3.2
- An alternative technique: derive the Mach number from the density compression ratio

$$X := \frac{n(\text{downstream})}{n(\text{upstream})}$$

- For a perpendicular shock: $M_A = \sqrt{\frac{X}{2}\frac{5+5\beta+X}{4-X}}$
- Fast magnetosonic Mach number: $M_f = \frac{M_A}{\sqrt{1+\frac{1}{2}\beta\gamma}}$
- Density compression ratio from
  - Coronographic density measurements (SoHO/LASCO)
  - UV spectroscopic diagnostics (SoHO/UVCS)
  - Radio spectrographic diagnostics

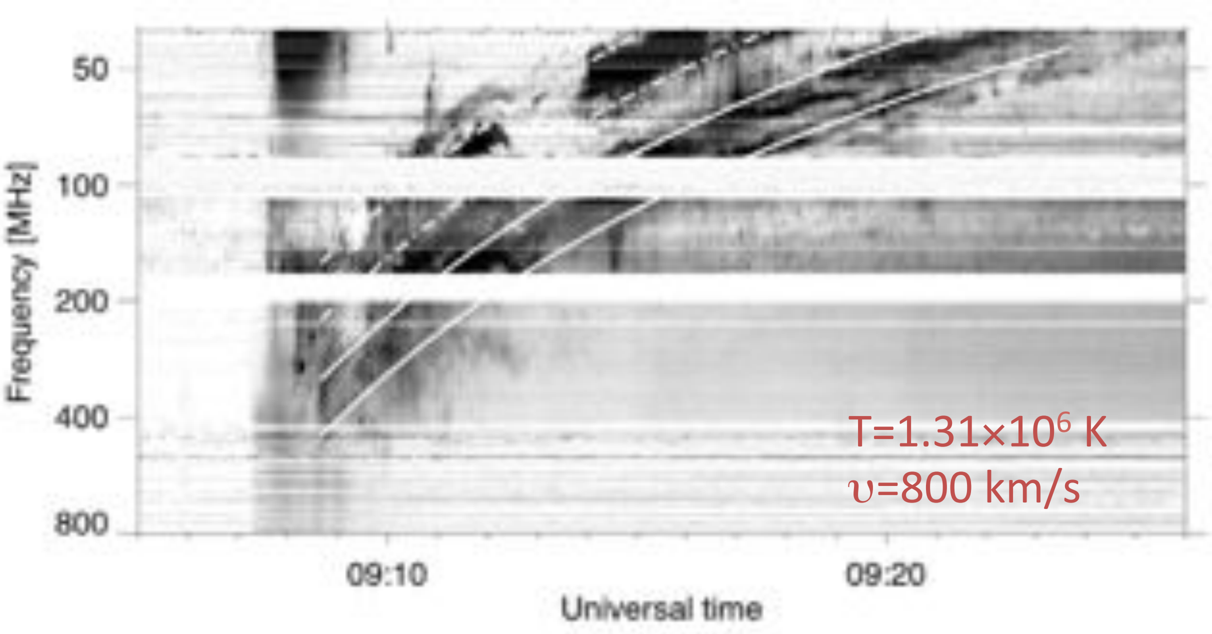
Radio emission from a shock wave



- Shock wave rising through corona → e-reflection → Langmuir waves at decreasing ν
- Coupling with ion sound waves ($\nu_S << \nu_L$) or Langmuir waves → EM waves (T=transverse) at
  - $\nu_T = \nu_L + \nu_S \approx \nu_L \approx \nu_{pe} \sim \sqrt{n_e}$ "fundamental"
  - $\nu_T = \nu_L + \nu_L = 2\nu_L \approx 2\nu_{pe}$ "harmonic"
- Burst that drifts from high to low ν more slowly than type III ("type II" burst); lower ν → greater height

- Compression ratio from type II burst spectra: split bands (interpretation: upstream/downstream emission)

Khan & Aurass 2002 A&A 383, 1018

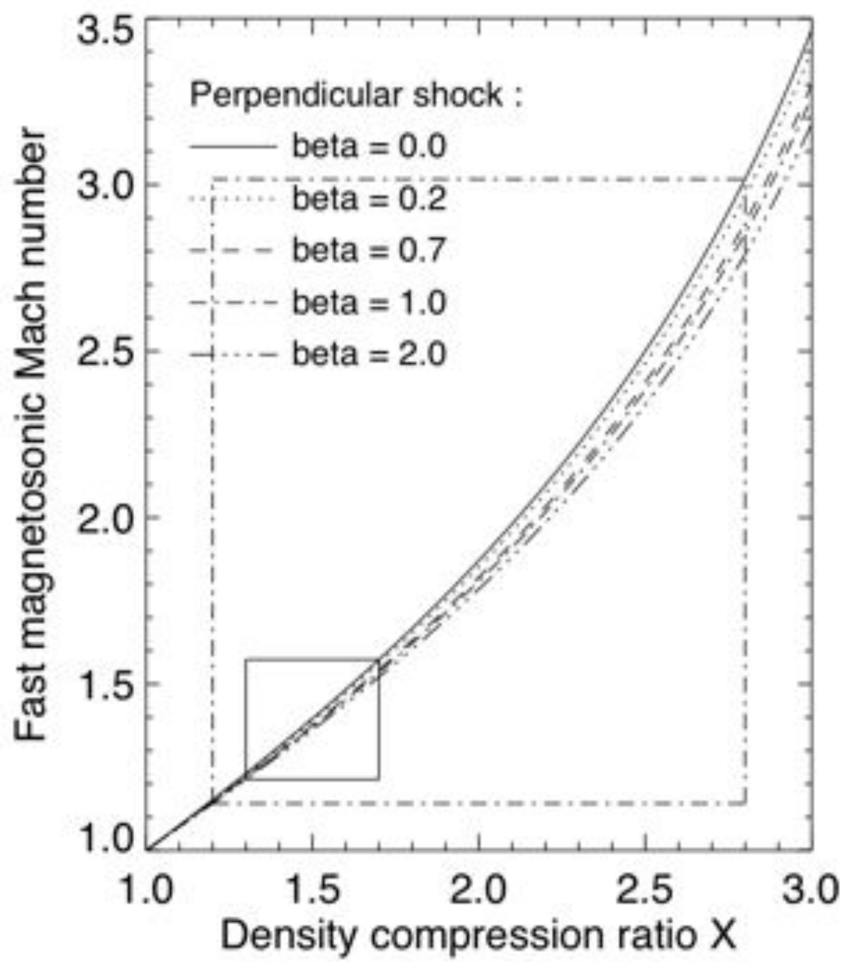


- Observation: extrapolated upstream/downstream densities correspond to measured values as shock passed 1 AU (Vrsnak et al. 2001 A&A 377, 321)

Coronal mass ejections
Shock parameters in the corona

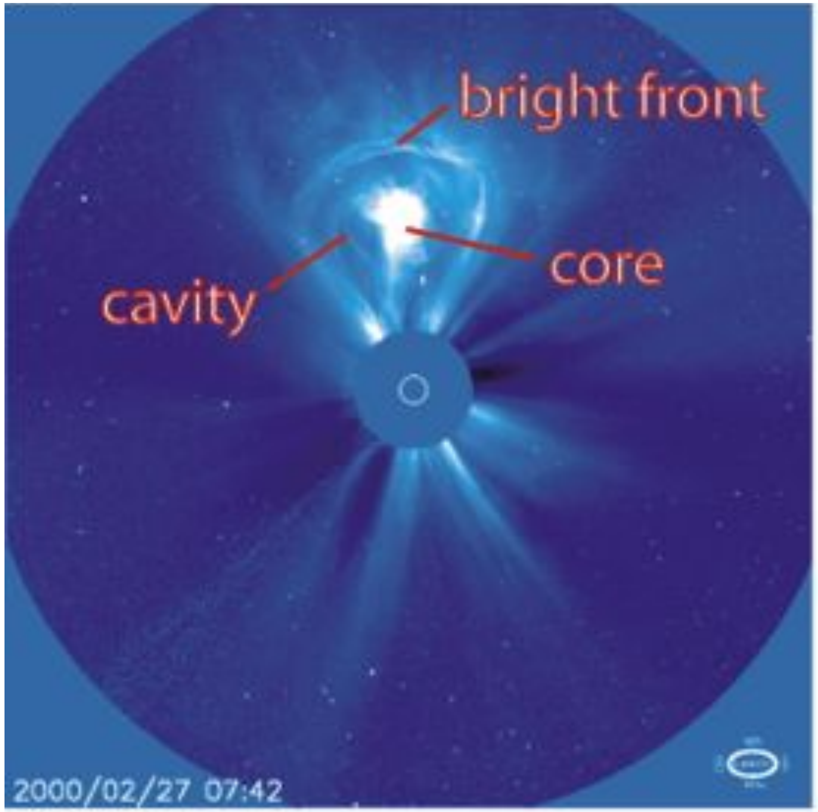
- Fast MS Mach numbers from white light (dashed rectangle, Ontiveros & Vourlidas 2008) and average radio type II bursts (solid rectangle; Vrsnak et al. 2004 A&A 413, 753) analyses

- Consistent with SoHO/UVCS analyses: X=1.8-2.2



Coronal mass ejections
Once more: what is a CME ?

Riley 2008 ApJ 672, 1221

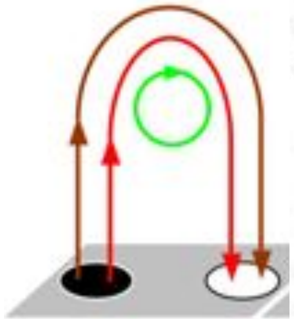


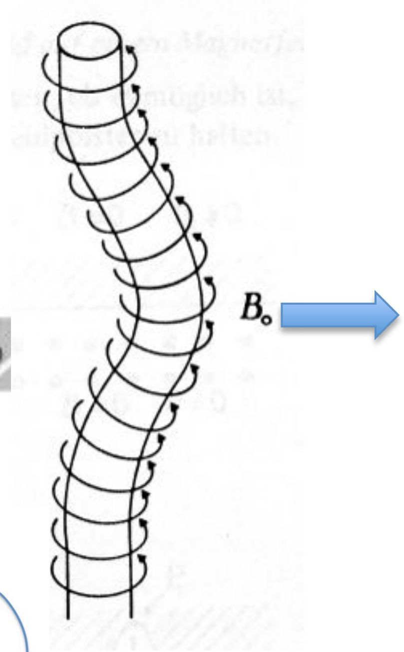
- Core = flux rope (prominence material)
- Cavity: low-density material embedded in the flux rope
- What do we see as the "bright front" ?
  - outer magnetic loop
  - swept-up material from the ambient corona
  - compressed plasma in the upstream medium of a shock wave (sheath)
- More detailed discussion: Chen, Liv Rev SP 8 (2011) http://solarphysics.livingreviews.org/Articles/lrsp-2011-1/ - Sevt. 4)

Coronal mass ejections

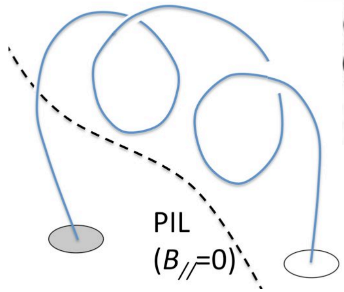
How does a coronal magnetic structure erupt ?

- Pre-eruptive equilibrium configuration of a flux rope:
  - Downward: Lorentz force of the surrounding magnetic field
  - Upward: Lorentz force of the flux rope (upward magnetic pressure = “hoop force” and magnetic tension)





- Instability or loss of equilibrium
  - Change of the surrounding magnetic field (magnetic reconnection): flux emergence underneath the flux rope (“tether cutting”), reconnection of the overlying magnetic field (“breakout”)



  - enhancement of the twist of the flux rope magnetic field by motions of the photospheric footpoints (hoop force)
  - kink instability

Coronal mass ejections

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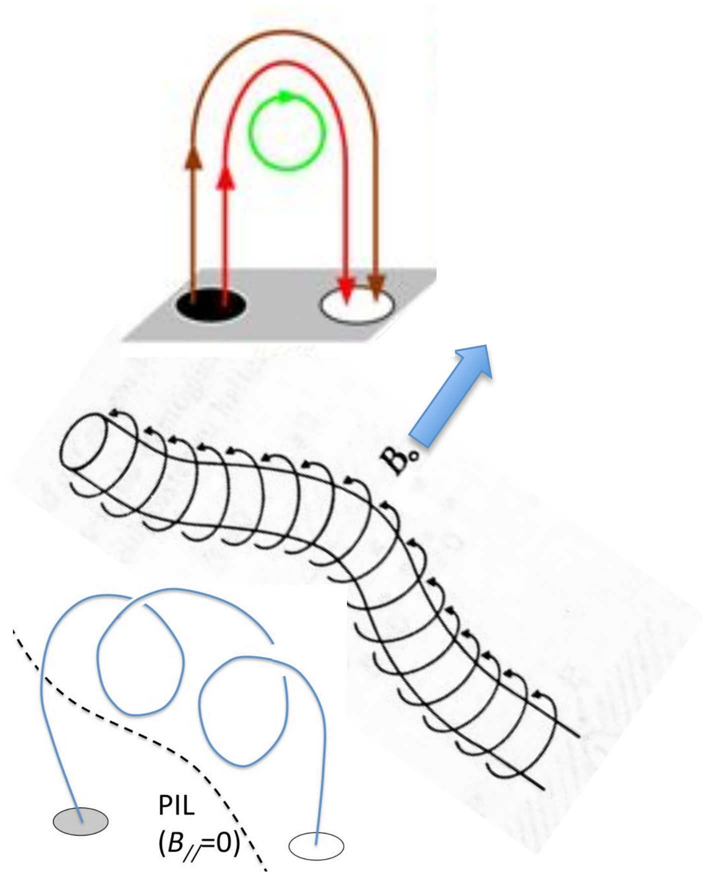
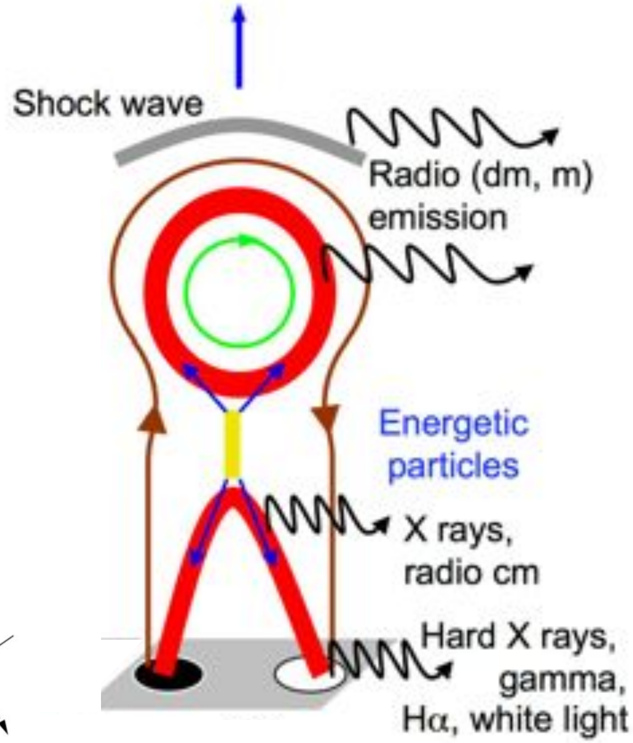
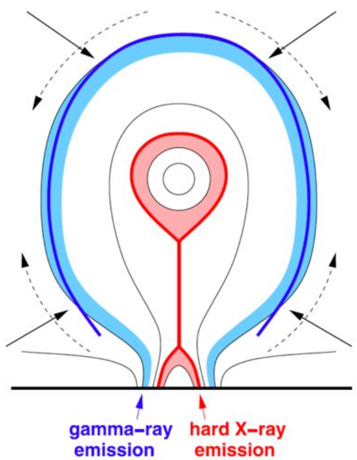


Coronal mass ejections
Particle acceleration mechanisms

- Particle acceleration related to CMEs:
  - magnetic reconnection related to "post flare loop" formation
  - turbulence in the post-eruptive corona
  - shock wave driven by the outward motion of the CME
  - shock wave driven by the lateral expansion of the CME (possible signature: EIT wave)





Pomoell et al. 2008
Solar Phys 253, 249

Summary
Flares, CMEs, and the acceleration of charged particles

- Flares and CMEs related to a variety of radiative signatures of energetic charged particles
  - Observational bias towards electrons (HXR, radio)
  - HXR and gamma-ray modelling suggest comparable overall energy contents in accelerated electrons and protons/ions, with variations from event to event and within individual events (see review Vilmer et al. 2011, Spa Sci Rev 159, 167)
  - Evidence from HXR and gamma-rays that electrons may be accelerated to 10s of MeV, ions to several GeV in extreme solar events.

- Acceleration related to magnetic reconnection and/or turbulence in complex magnetic configurations (impulsive phase and afterwards) and large-scale shock waves. May be naïve to search for a single process that explains all non-thermal particle populations during a given event.

- Difficult (but not impossible !) comparison between the time histories of interacting particles and SEPs at 1 AU: transport modelling (see N. Agueda) and SEP measurements close to the Sun (Solar Orbiter, Solar Probe +).