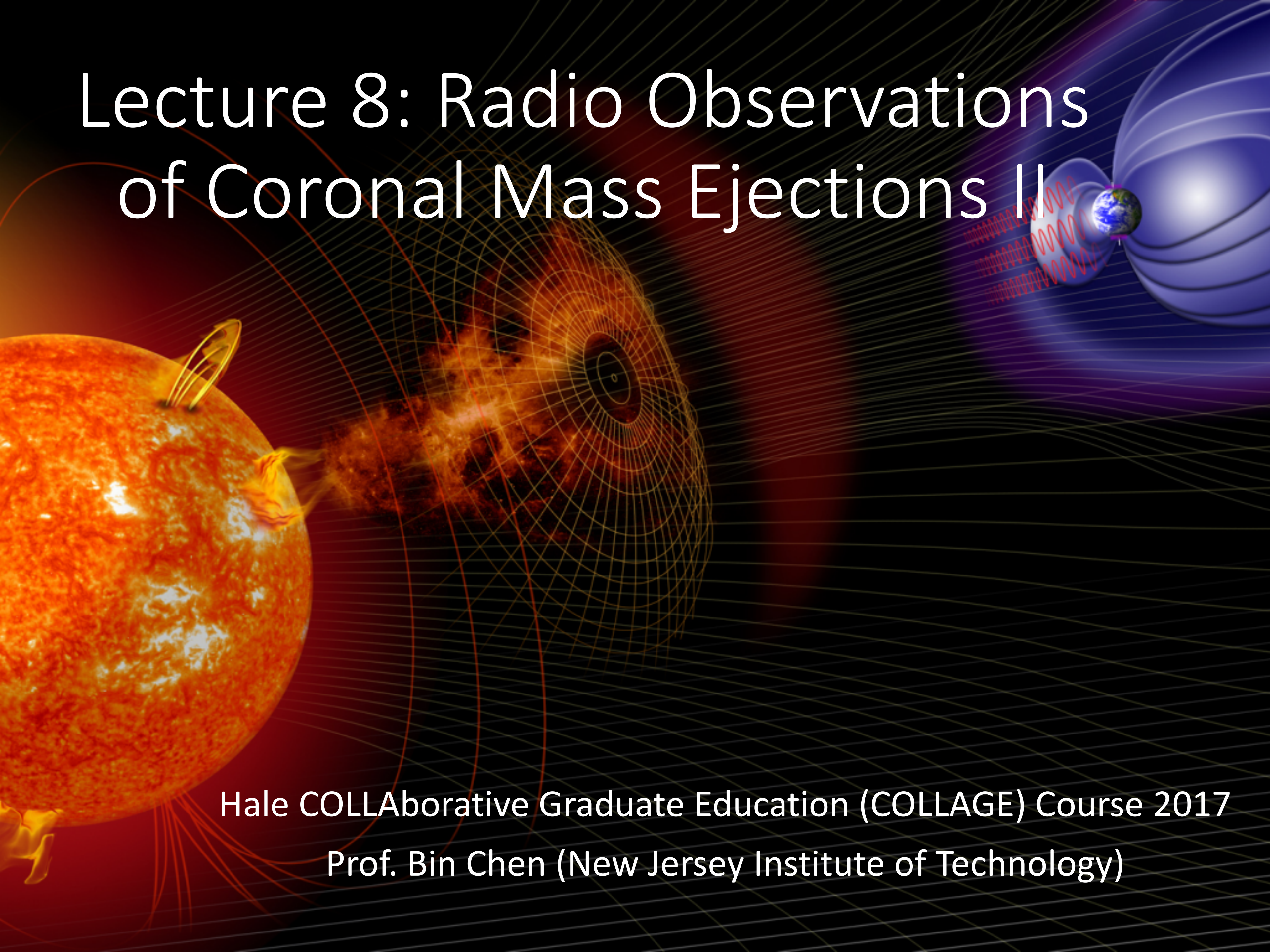
Lecture 8: Radio Observations of Coronal Mass Ejections II



Hale COLLAborative Graduate Education (COLLAGE) Course 2017

Prof. Bin Chen (New Jersey Institute of Technology)

Lectures 7-8 outline

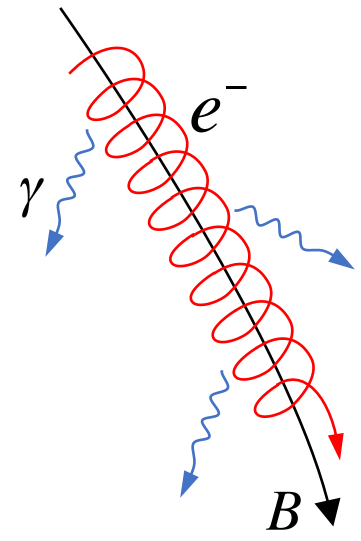
- Radio astronomy preliminaries
  - Radiative transfer
  - Relevant emission mechanisms
  - Types of solar radio bursts
- Radio observations of CMEs
  - CME body
    - Thermal CME
    - Gyrosynchrotron CME
    - Type IV radio bursts
  - CME-driven shocks
    - White light/EUV imaging, UV spectroscopy, and in situ signatures
    - type II radio bursts

This Lecture

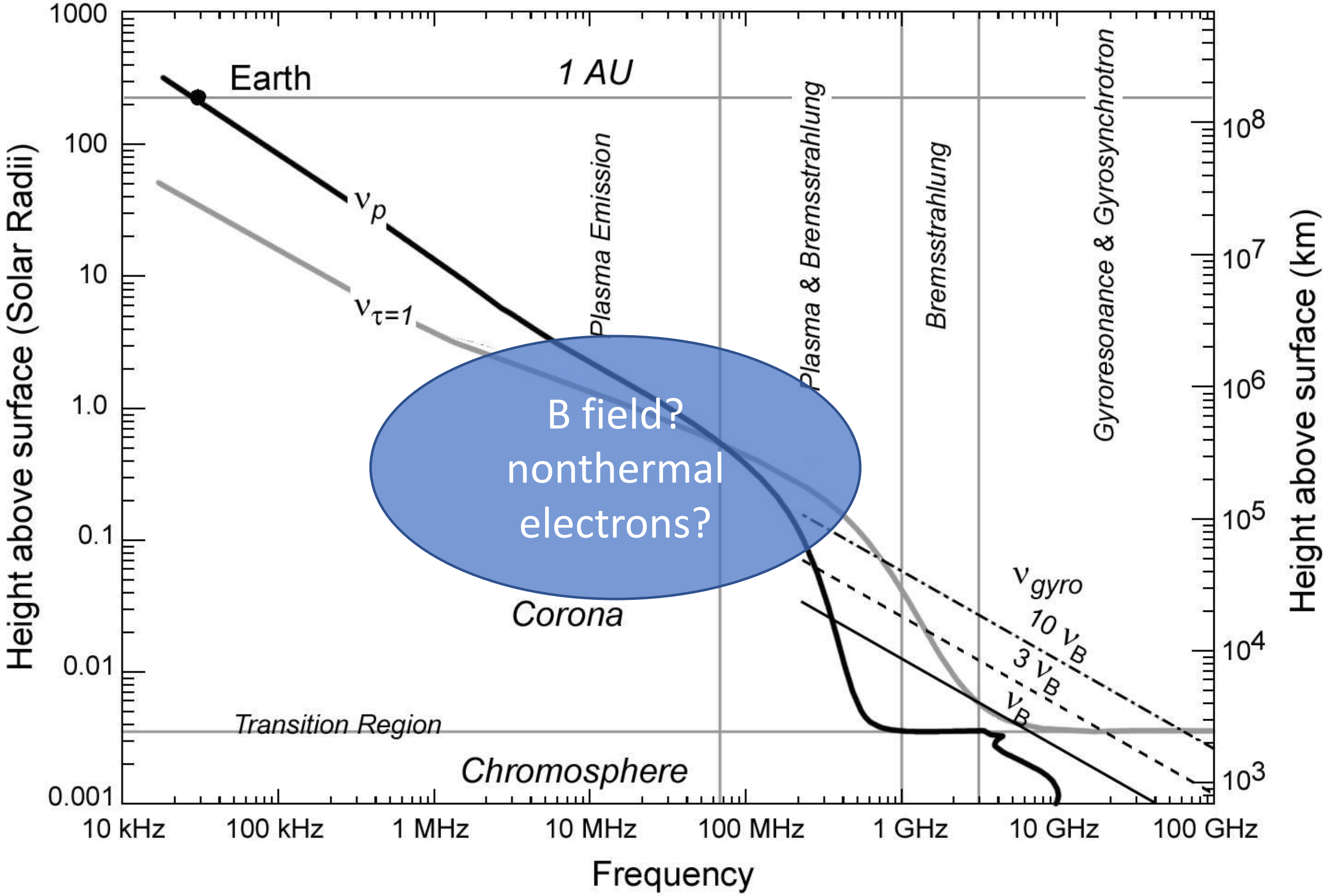
Gyromagnetic radiation

- Acceleration experienced in the magnetic field
- Gyroresonance radiation from thermal electrons. Relevant in places with strong B field: e.g., active regions
- Gyrosynchrotron radiation from relativistic electrons. Relevant when high energy electrons are present: e.g., flares and CMEs
- Electron gyrofrequency: one "natural frequency" of the solar corona

$$f_{ce} = \frac{eB}{2\pi m_e c} \approx 2.8B \text{ MHz}$$

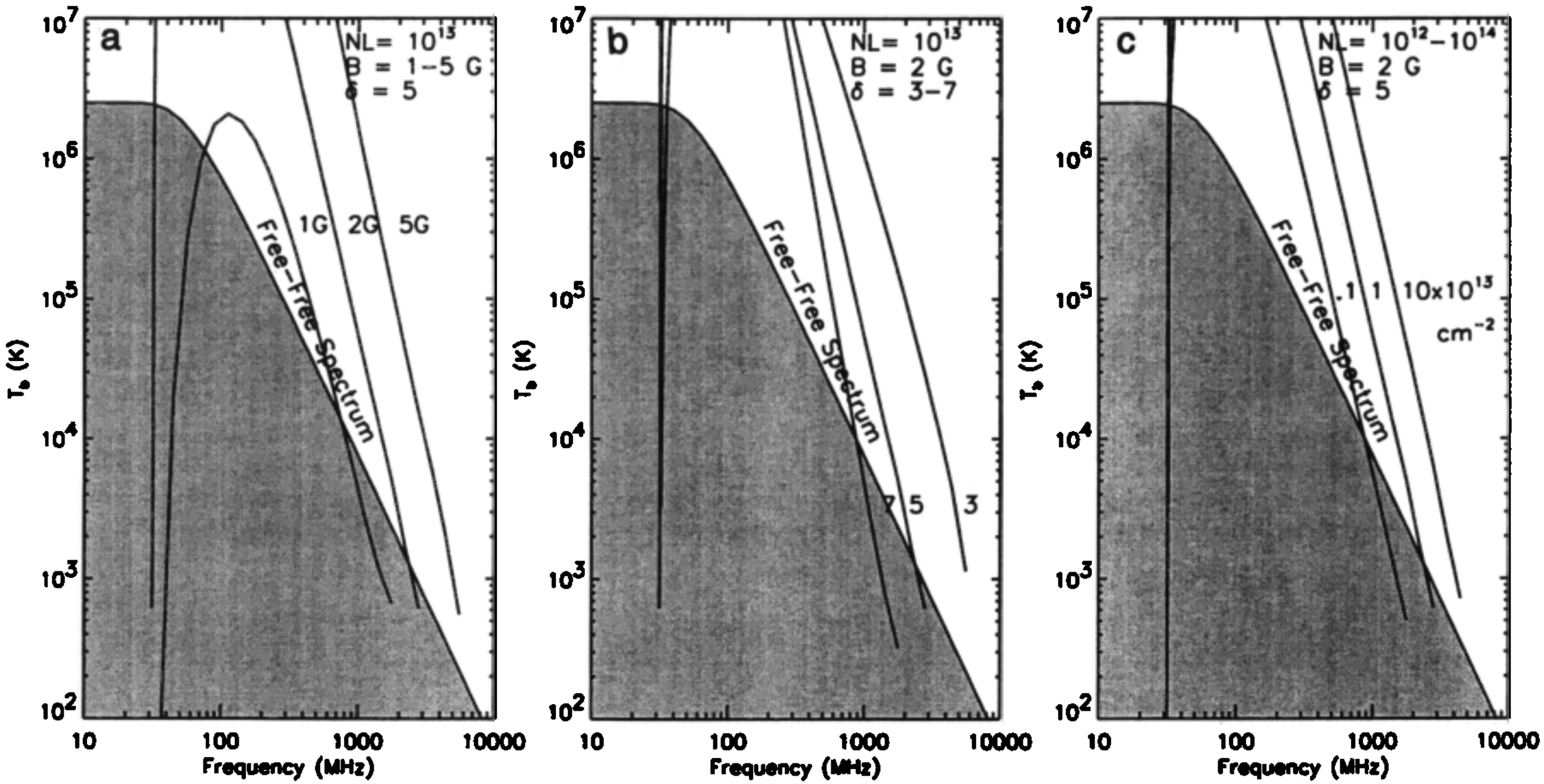


How about gyrosynchrotron emission?



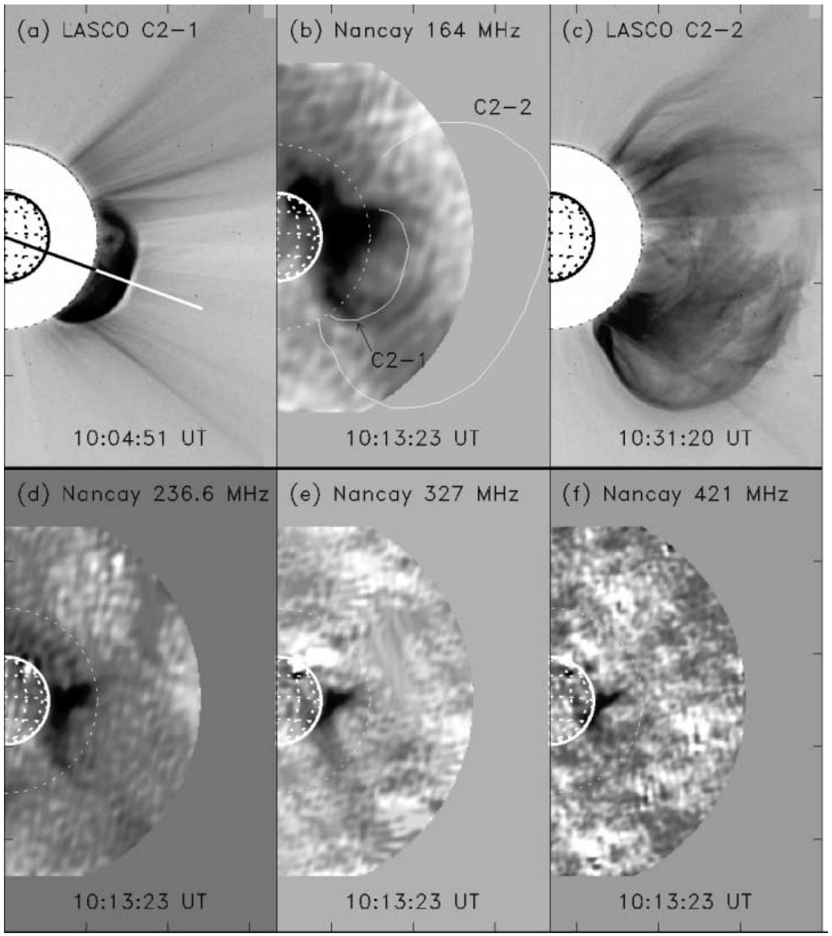
- CMEs/flares produce accelerate electrons
- CMEs are "magnetic clouds"

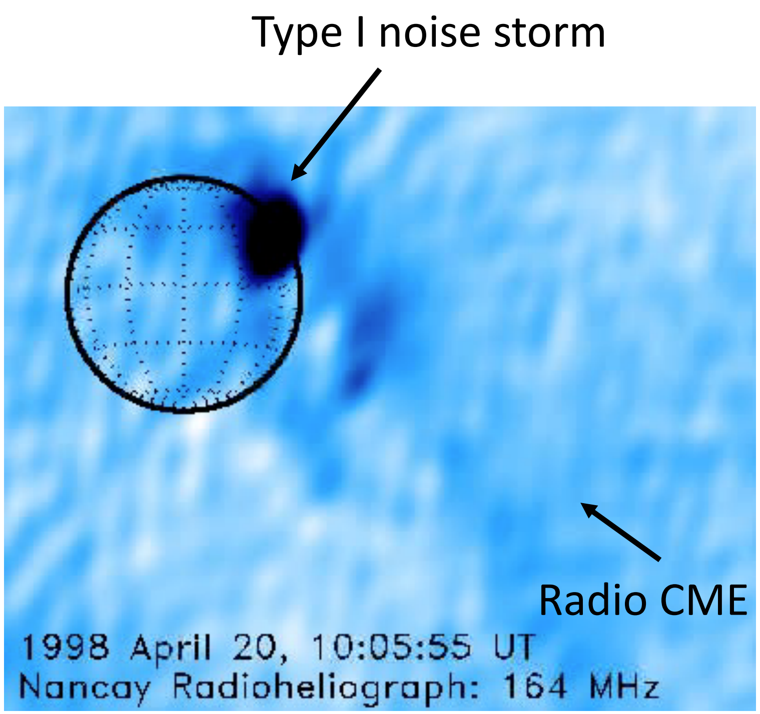
Gyrosynchrotron vs. thermal: from a toy model



From Bastian & Gary 1997

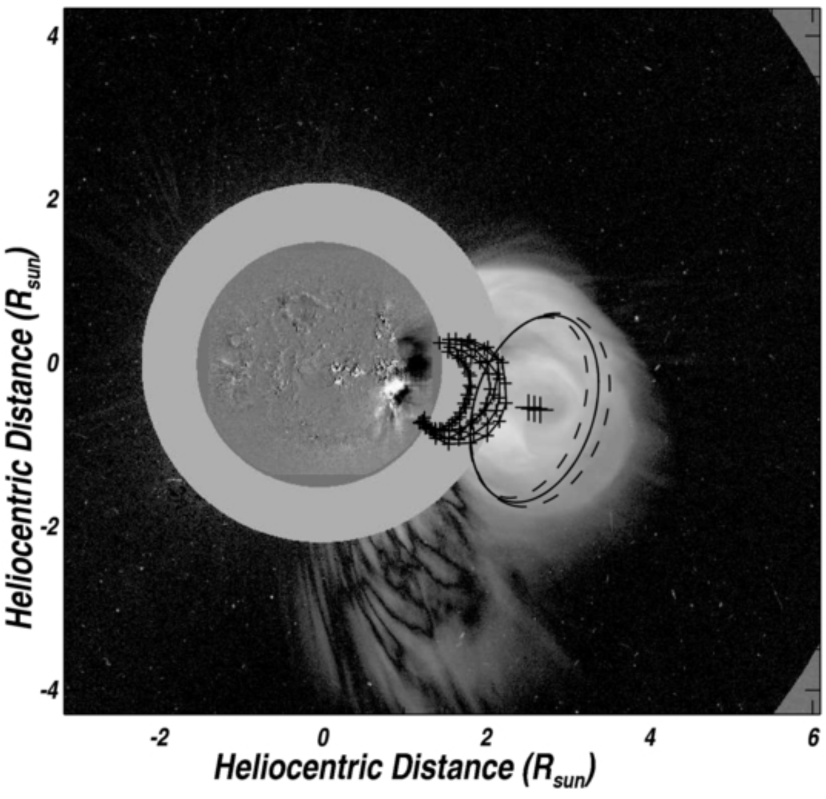
First observation of a gyrosynchrotron "radio CME"

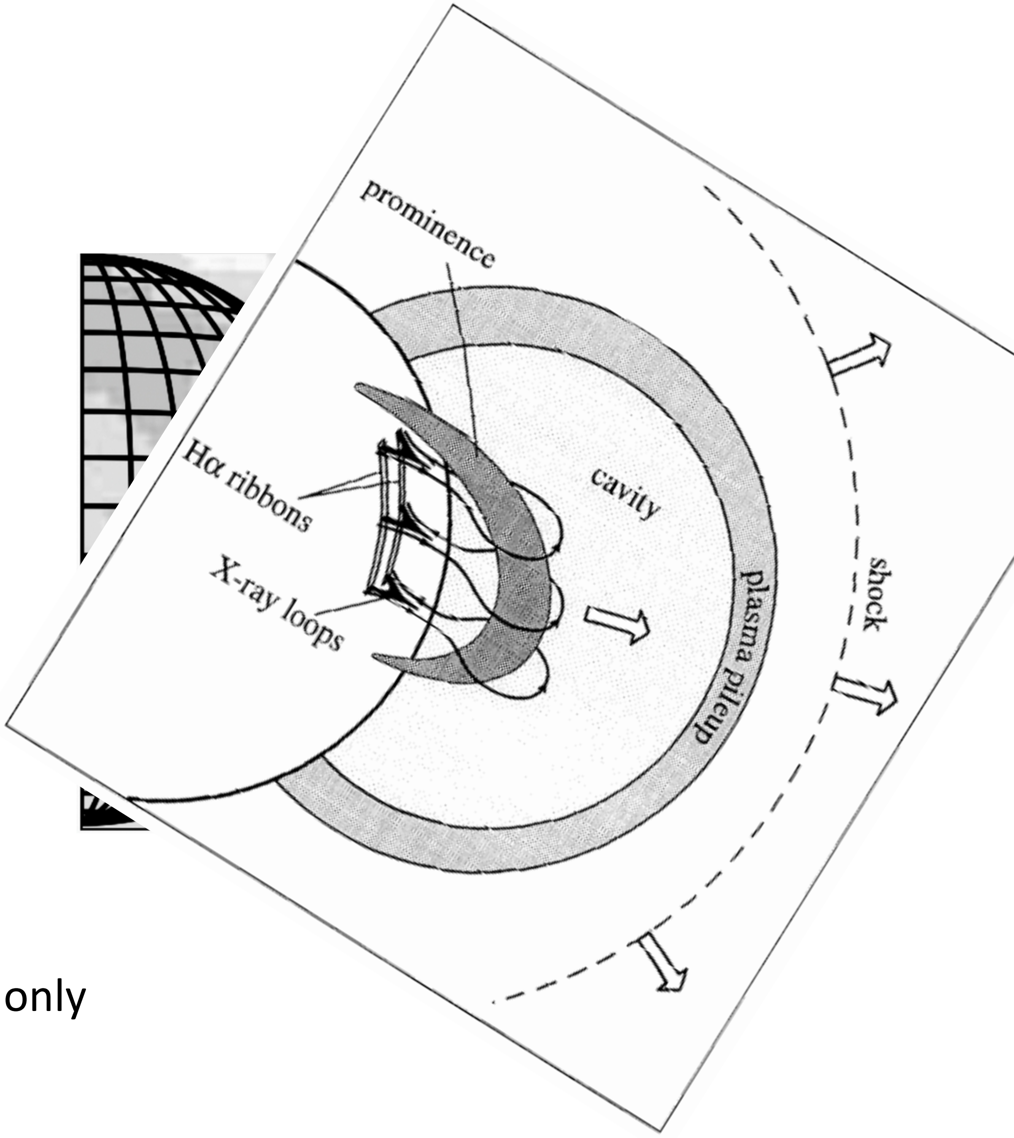




Bastian et al. 2001

Radio CME = CME cavity (flux rope)?



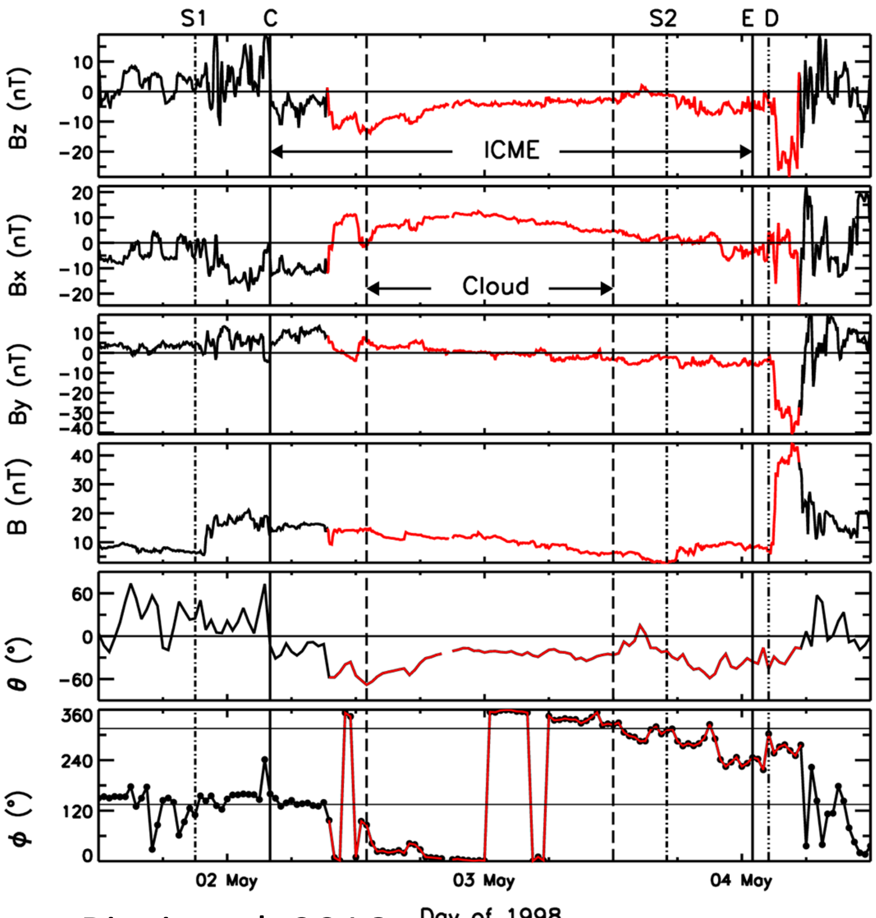


Demoulin et al. 2012, another (maybe the only other) radio CME event on 2001 April 15

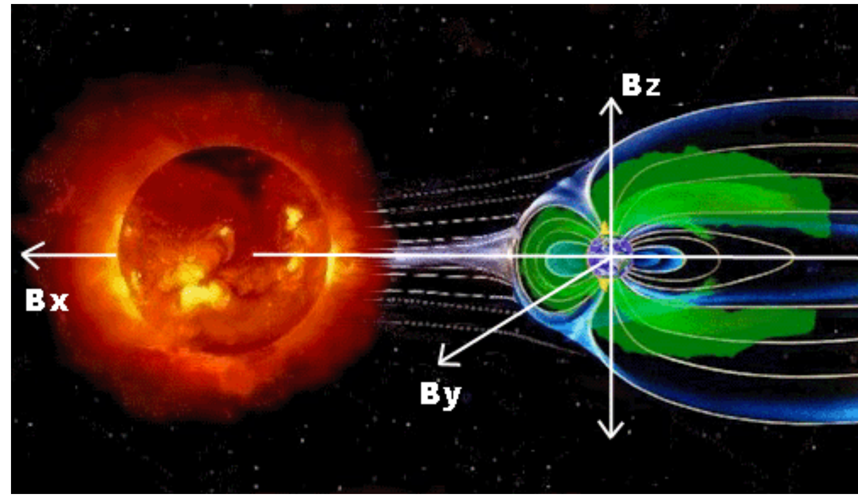
Why interested in gyrosynchrotron radio CMEs?

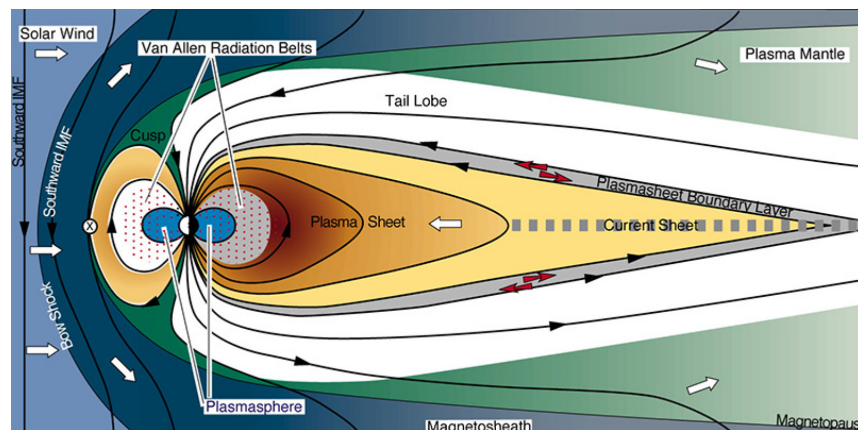
- Corona is
  - Optically thin
  - Low B field strength
  - High temperature -> large spectral line broadening
- Extremely difficult to measure B field in the corona
- Gyrosynchrotron radio measurement provides constraints on B and its direction
- CME is one of the most important drivers of space weather. Interplanetary magnetic field (IMF) B_z very important in space weather applications

Impacts of IMF B_Z

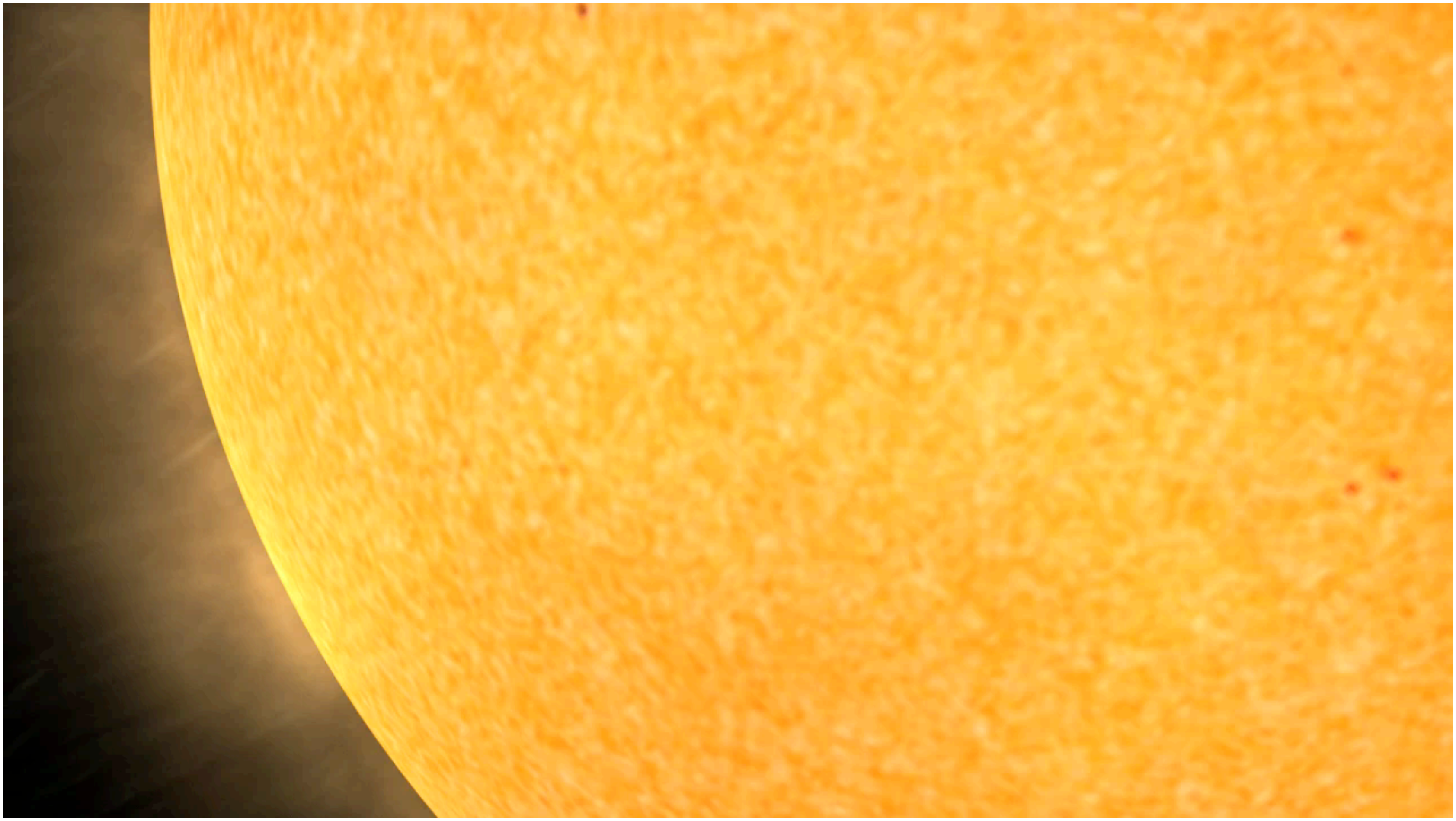


Bisoi et al. 2016



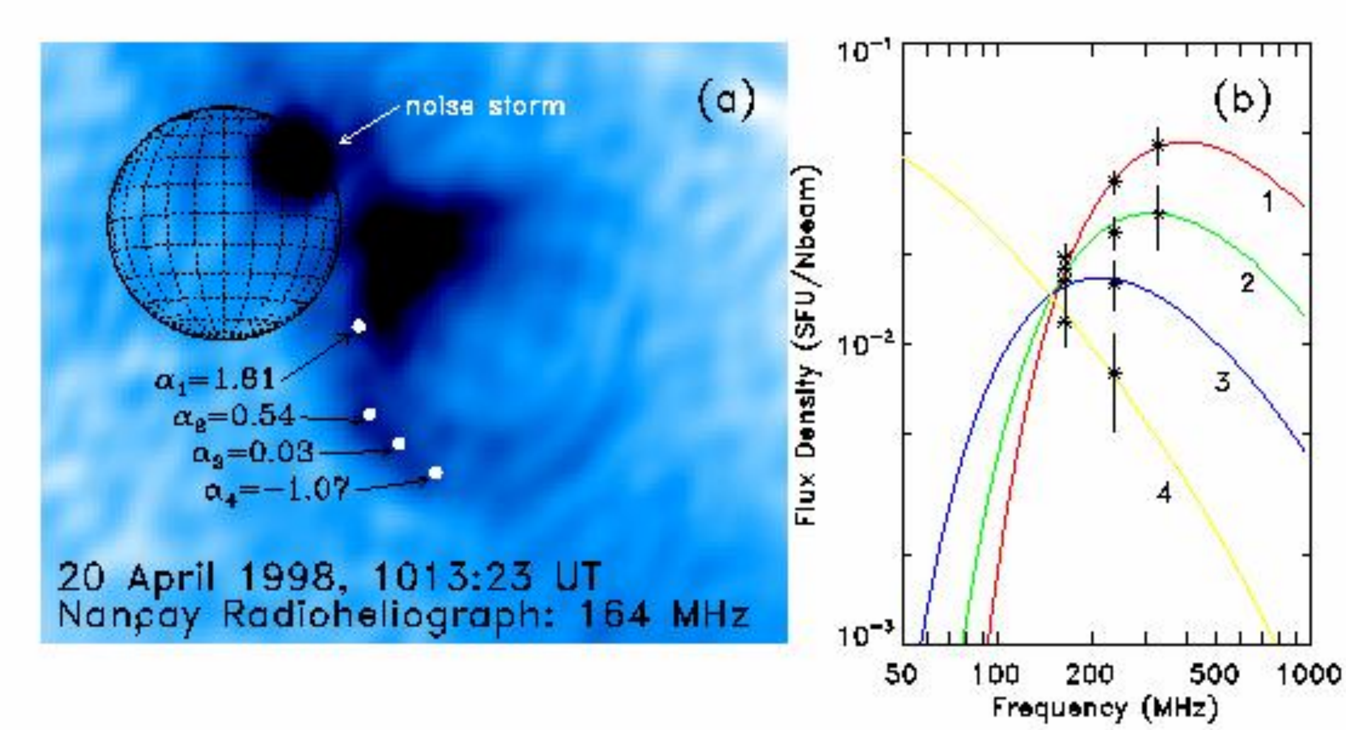


CME and magnetospheric substorm: an animation



Credit: NASA/THEMIS

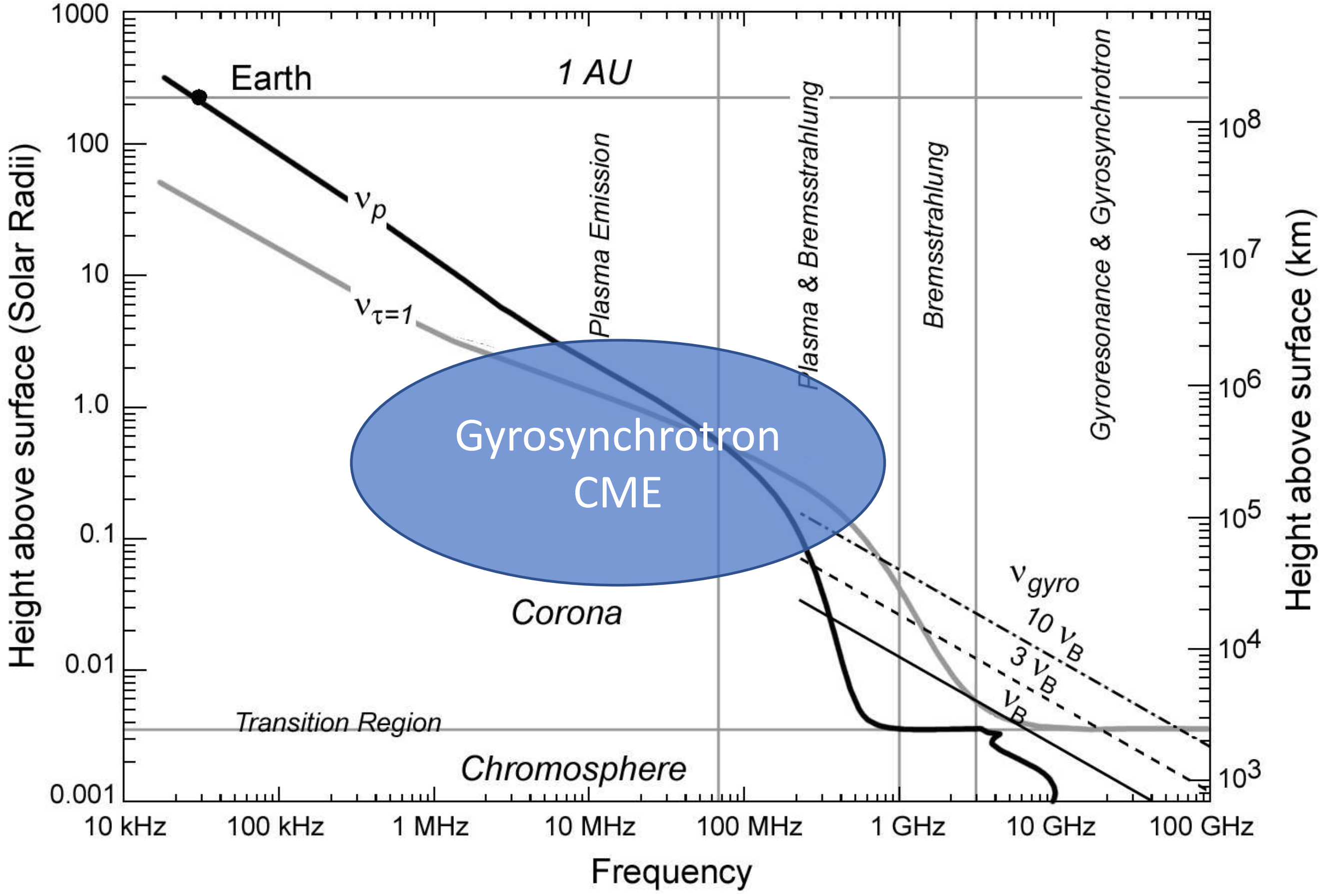
CME B field and thermal/nonthermal electron properties



- B_{CME} ~ 0.1 – few G
- n_{th} ~ few x 10^7 cm^{-3}
- E_e ~ 0.5 – 5 MeV

Bastian et al. 2001

Gyrosynchrotron or plasma radiation? How to tell?

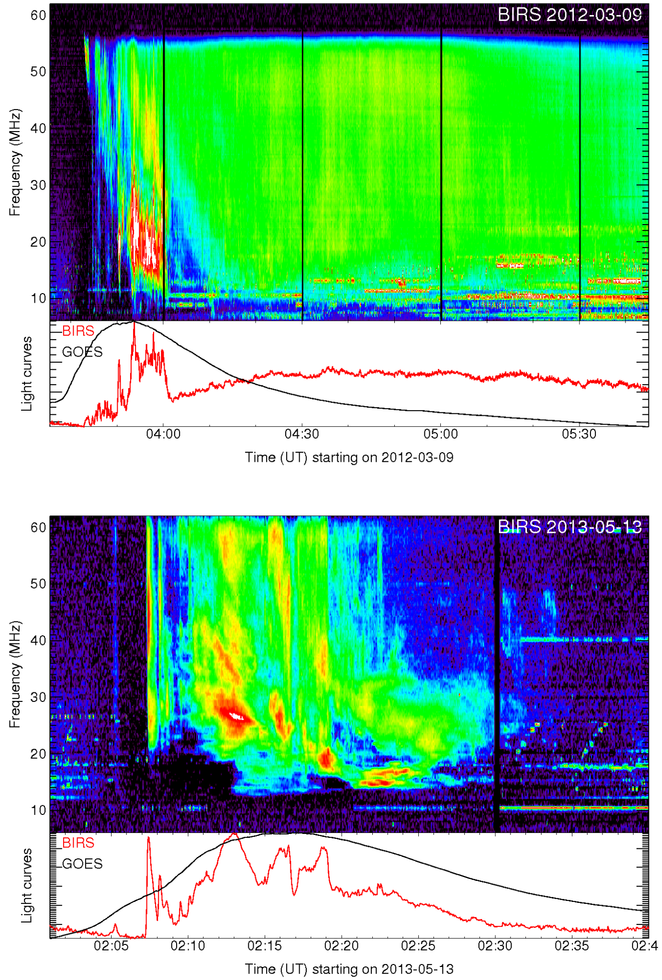


- Image features
- Spectral features
- Polarization

Solar Type IV Radio Bursts

Weiss 1963 categorized them in two subtypes:

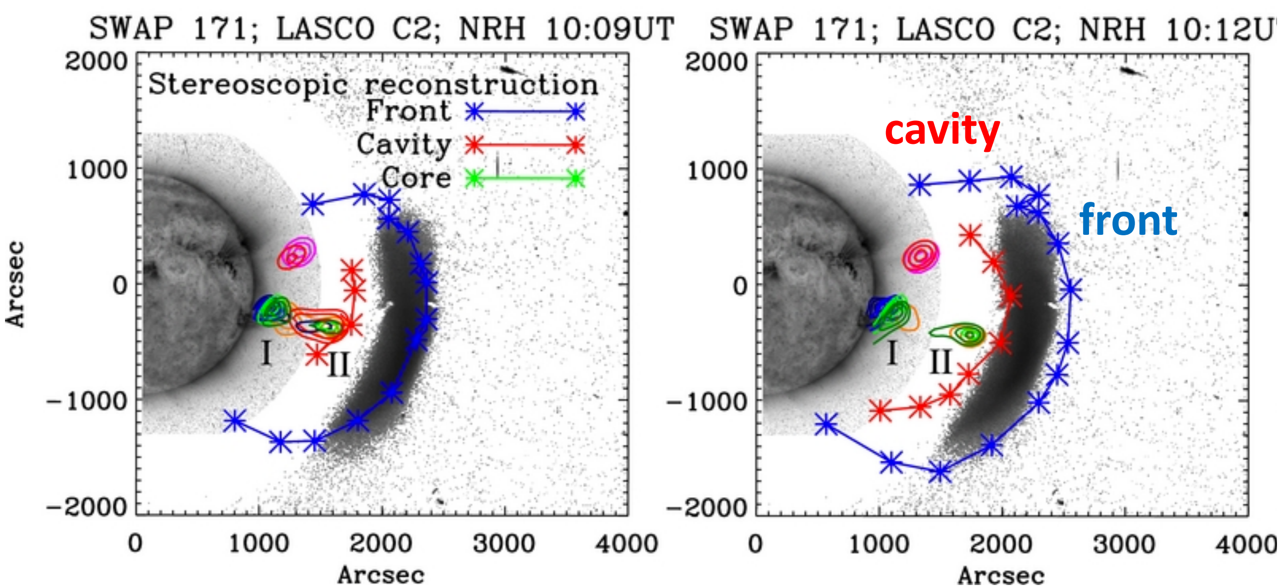
1. Stationary type IV (type IVs):
   - Relatively long-duration, broad continuous spectrum, little or no source movement, small source diameter, strong polarization (usually in o mode)
2. Moving type IV (type IVm):
   - Fairly short-duration, ill-defined spectral features, rapid outward movement through the corona (x100 km/s), sometimes polarized in x mode



From Stephen White

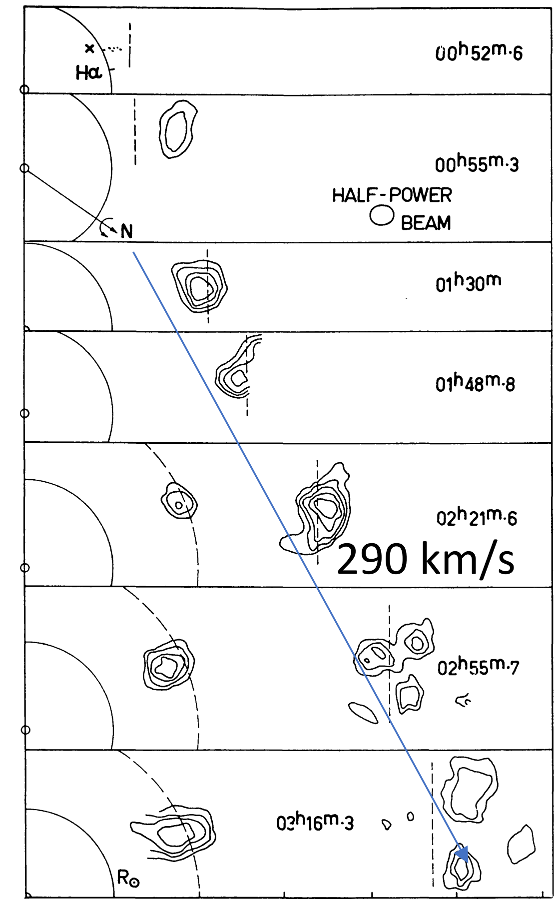
Moving Type IV Radio Bursts

- Ejecting radio blobs associated with CMEs, but usually slower
- Trailing CME front



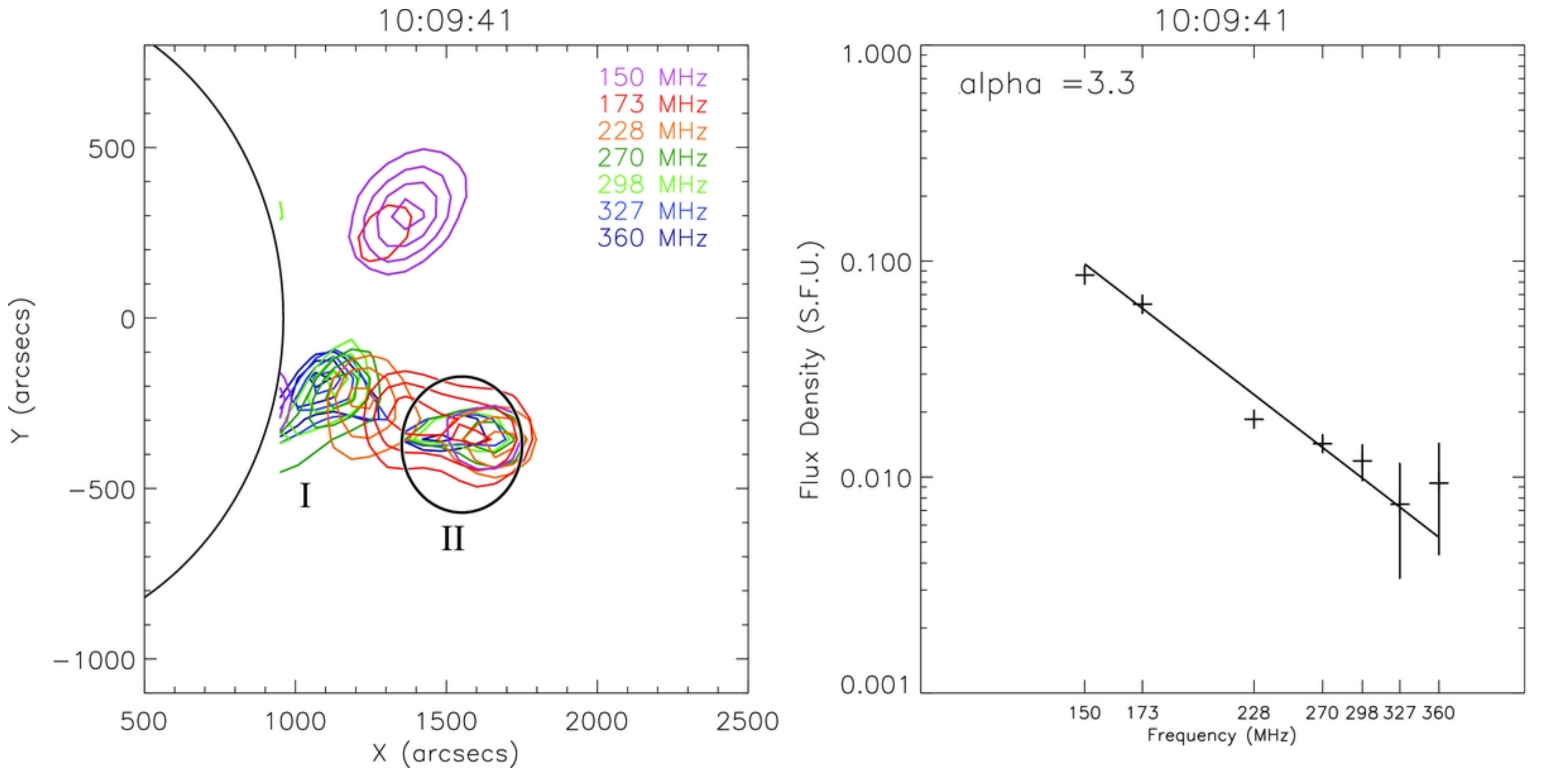
Bain et al. 2014

~250-500 km/s



Smerd & Dulk 1971

Spectral feature

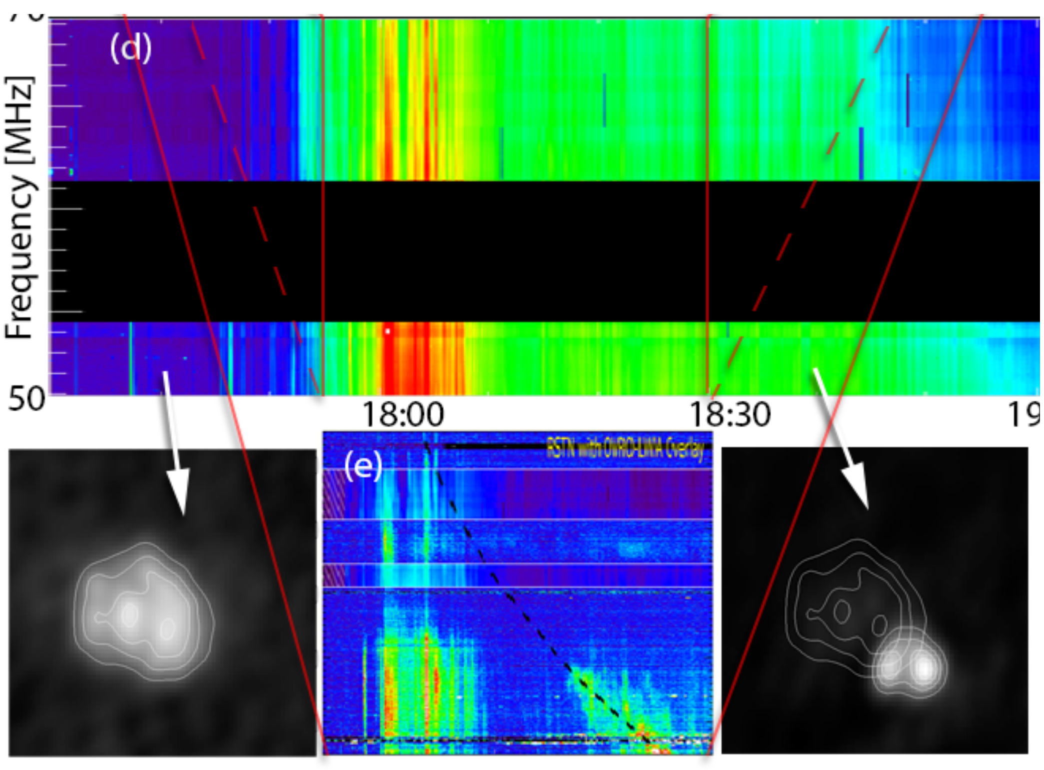


Indication of gyrosynchrotron emission

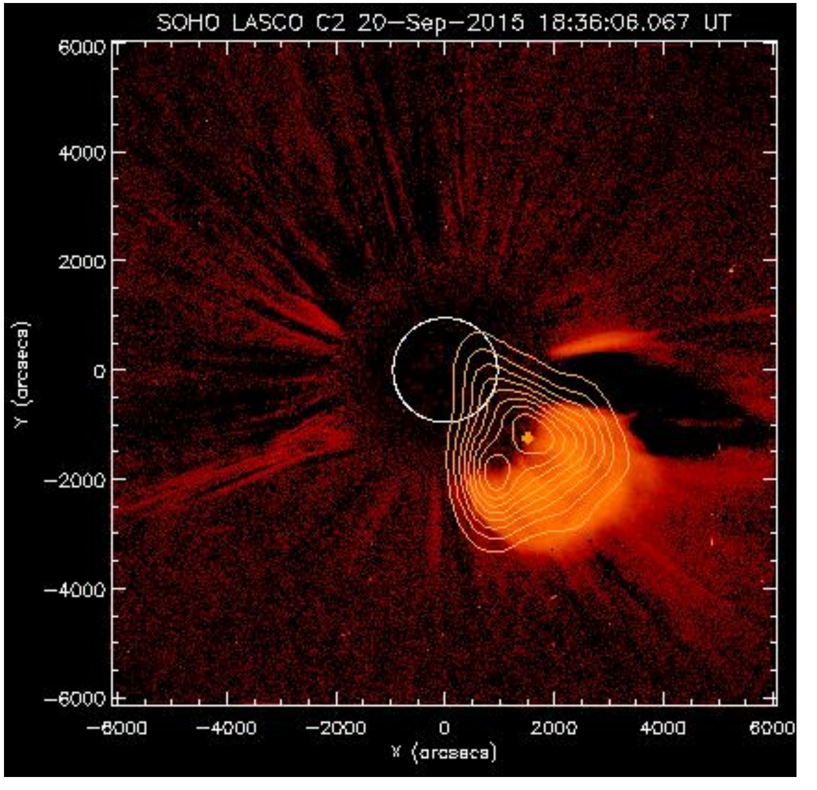
Bain et al. 2014

B ~ 4 G, $E_{nonthermal}$ ~ 0.001% - 0.1% $E_{thermal}$

Another example from a student in this class



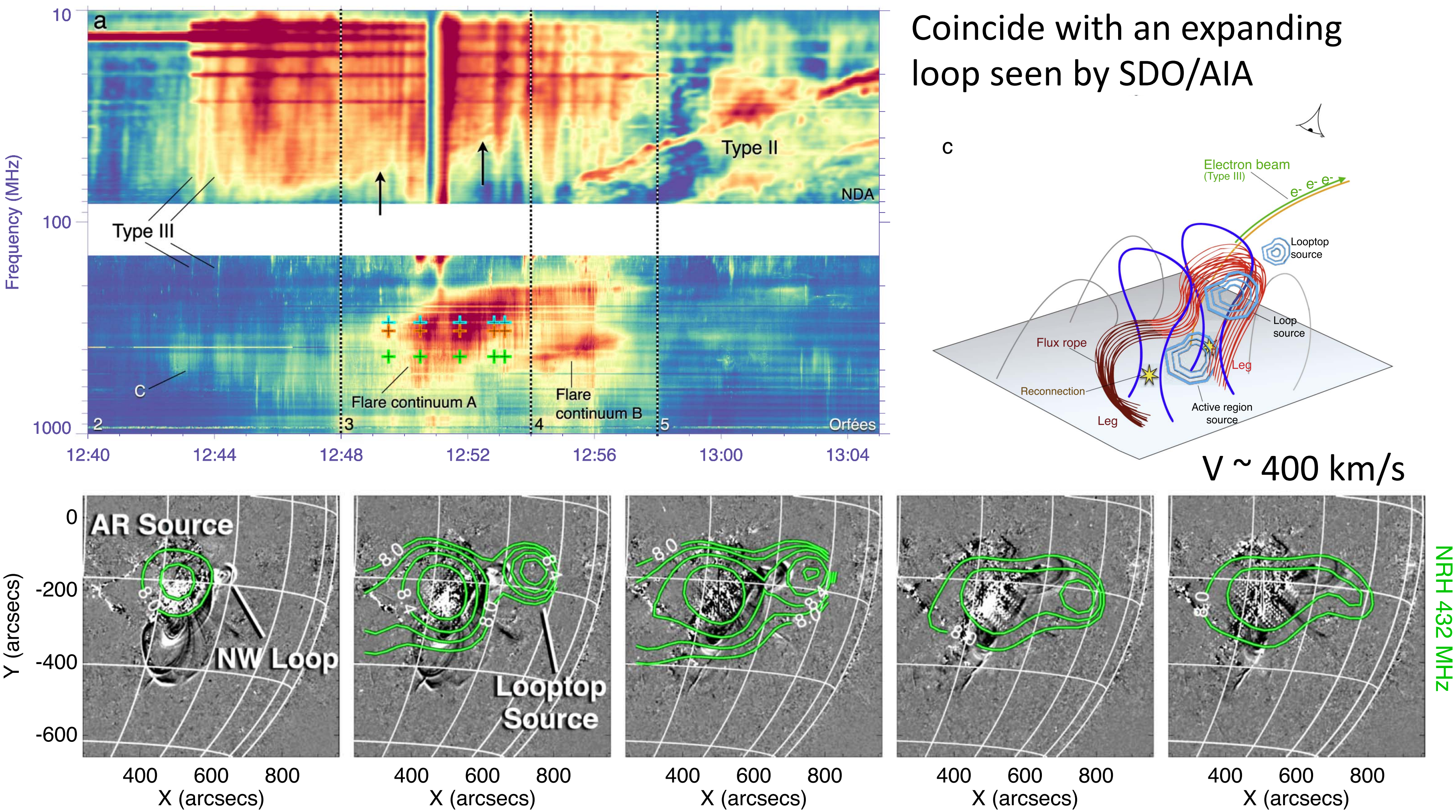
From Sherry Chhabra (NJIT)



Observed by Long Wavelength Array in Owens Valley at ~50 MHz. Optically thick part of the CME GS emission?

Type IVm from CME initialization stage

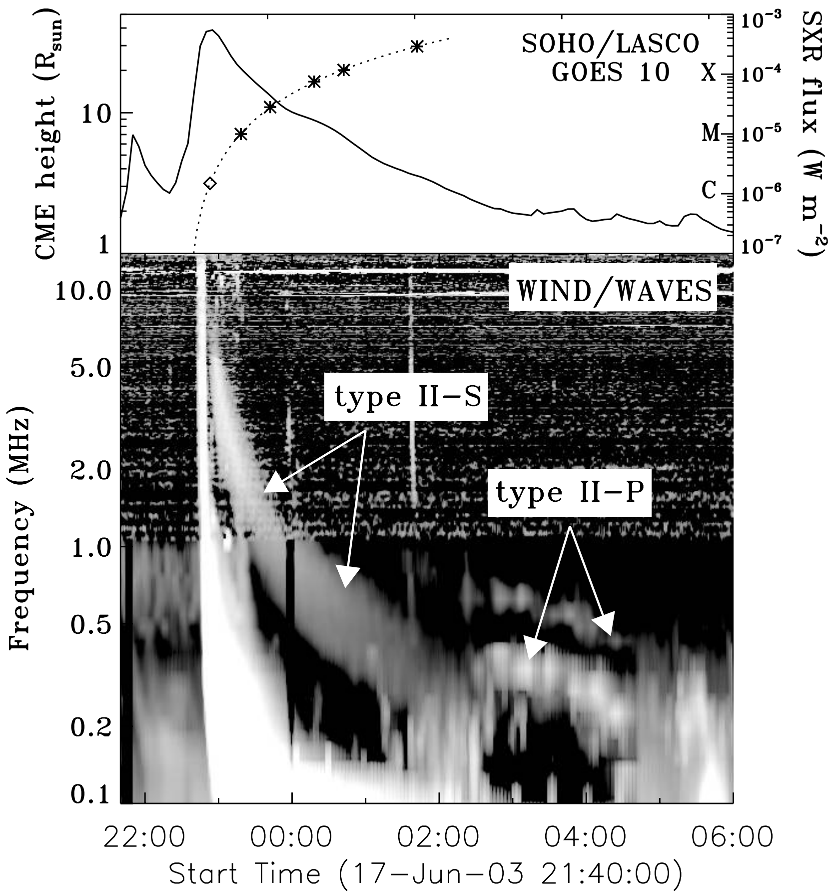
Coincide with an expanding loop seen by SDO/AIA



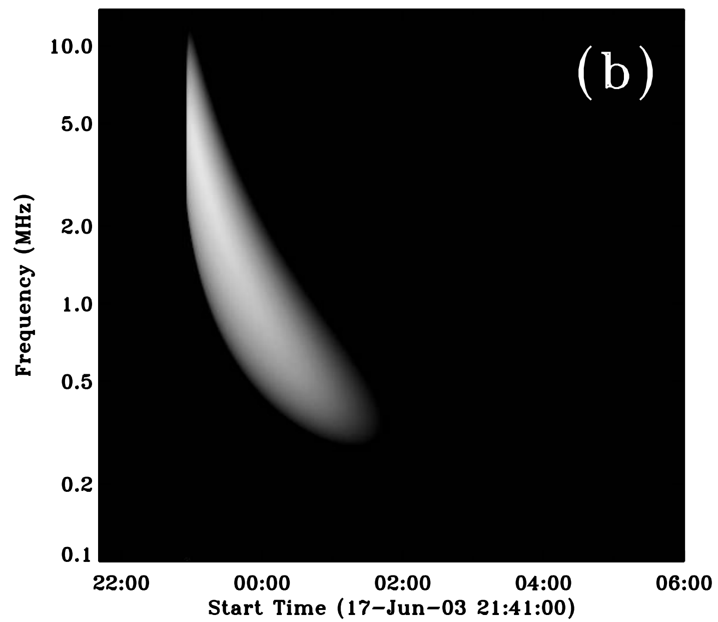
V ~ 400 km/s

Carley et al. 2016

Gyrosynchrotron emission from interplanetary CMEs?



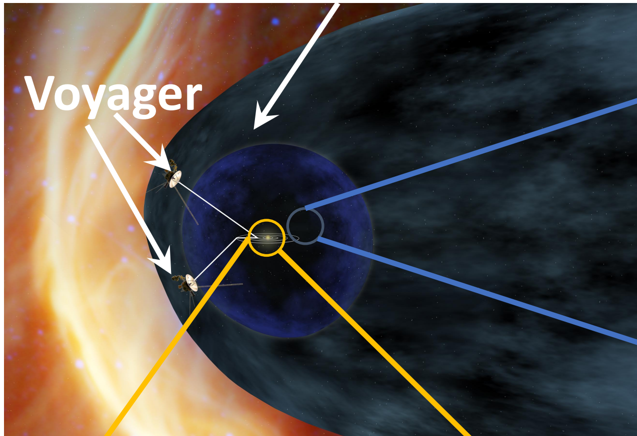
Modeled gyrosynchrotron emission:
B_{CME} ~ 0.5-0.001 G from 3 to 30 Rsun



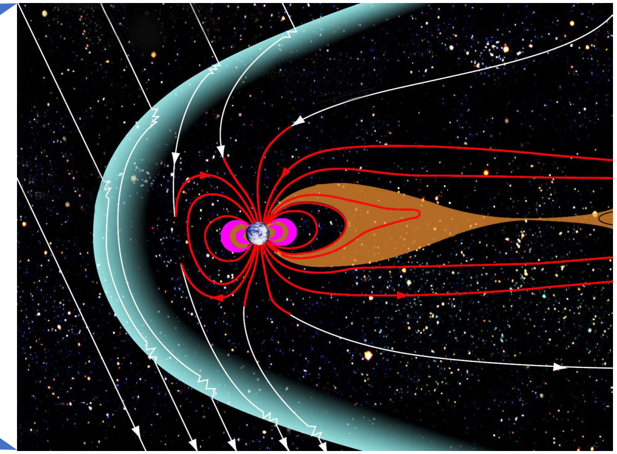
Bastian 2007, Pohjolainen et al. 2013

Shocks in the Heliosphere

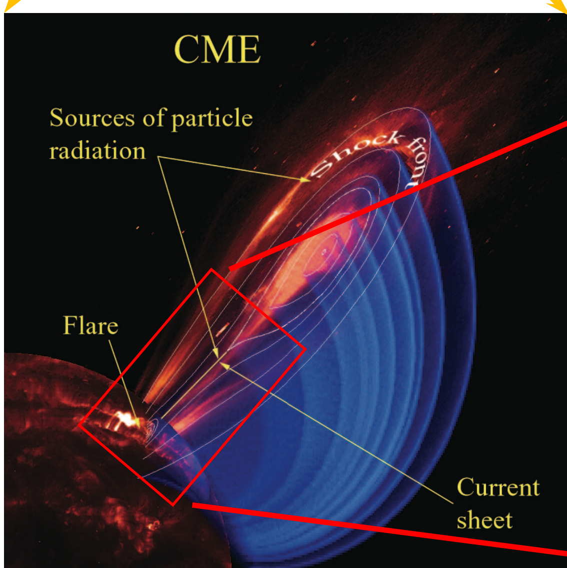
Heliospheric Termination Shock



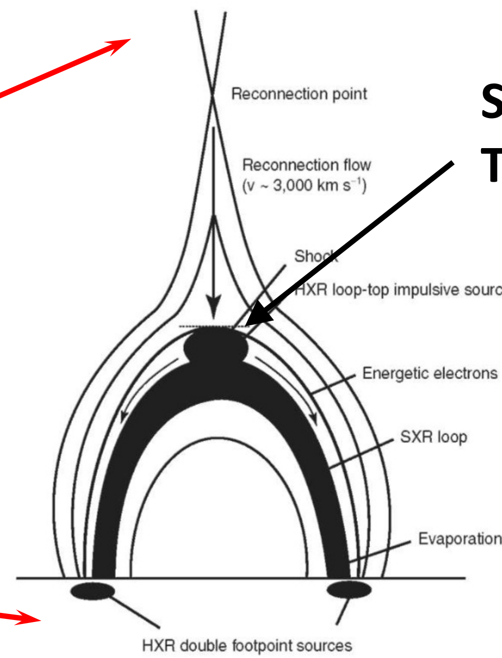
Planetary Bow Shock



CME-driven Shock



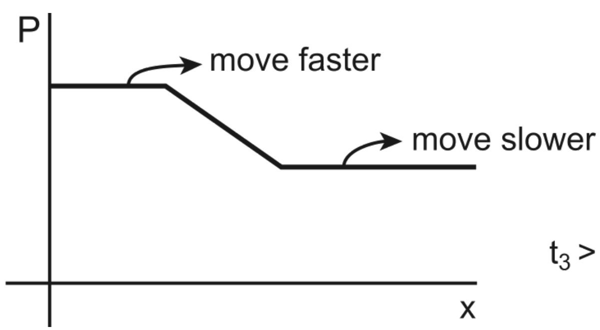
Solar Flare Termination Shock



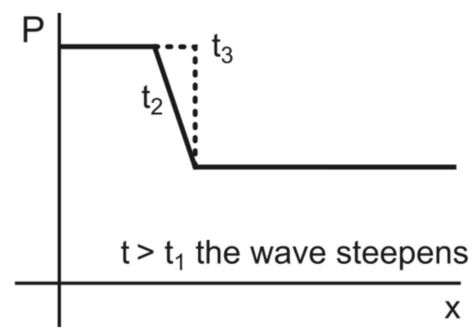
Why shocks happen?

- When the propagation speed gets faster than the "signal speed" of the medium
- Discontinuity (P, T, ρ, B)
- Example: propagation of a sound wave in an adiabatic medium

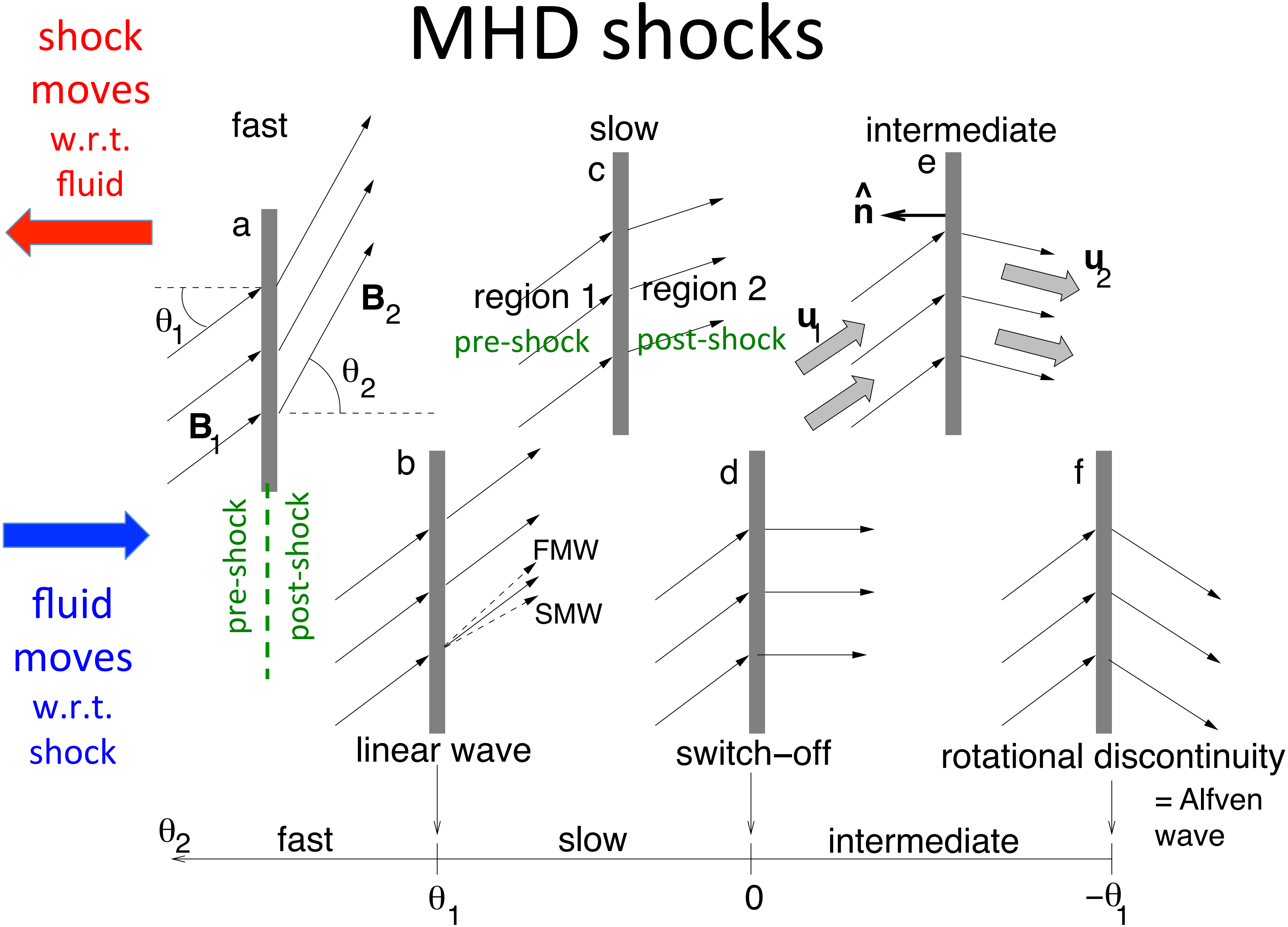
$$c_s = \sqrt{dP/d\rho} \qquad \frac{P}{\rho^\gamma} = constant \qquad c_s \propto P^\alpha\text{, where } \alpha = \frac{\gamma + 1}{2\gamma}$$



$t_3 > t_2 > t_1$



MHD shocks



From Lecture 3 (Prof. Longcope)

Shock Jump Conditions

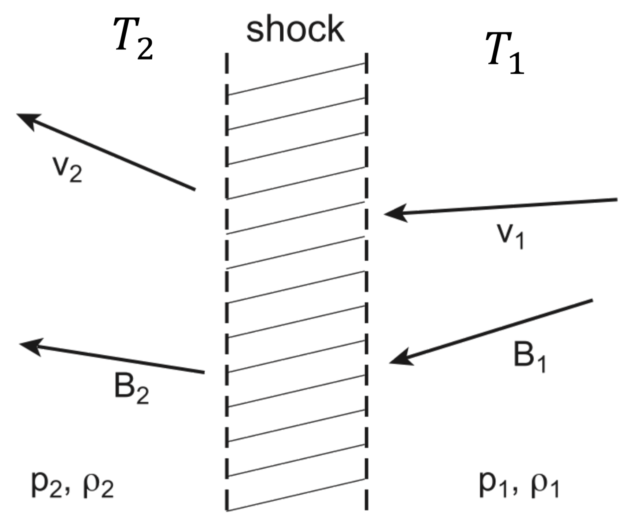
For plane-parallel shock (let's ignore B for now)

Mass

Momentum

$$\begin{aligned} \rho_1 u_1 &= \rho_2 u_2 \\ \rho_1 u_1^2 + P_1 &= \rho_2 u_2^2 + P_2 \\ \tfrac{1}{2}u_1^2 + \epsilon_1 + \frac{P_1}{\rho_1} &= \tfrac{1}{2}u_2^2 + \epsilon_2 + \frac{P_2}{\rho_2} \end{aligned}$$

Energy



Downstream Upstream

Reference frame of the shock

Shock Jump Conditions

- Mach number: $M_1 \equiv \frac{u_1}{c_1} = \left(\frac{\rho_1 u_1^2}{\gamma P_1}\right)^{1/2}$ (for a gas that has a polytropic equation of state)
- Rewrite jump conditions

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$$

$$\frac{P_2}{P_1} = \frac{\rho_2 k T_2/m}{\rho_1 k T_1/m} = \frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}$$

$$\frac{T_2}{T_1} = \frac{[(\gamma-1)M_1^2+2][2\gamma M_1^2-(\gamma-1)]}{(\gamma+1)^2 M_1^2}$$

- For strong shocks ($M_1 \gg 1$)

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} \approx \frac{\gamma+1}{\gamma-1} \qquad P_2 \approx \frac{2\gamma}{\gamma+1} M_1^2 P_1 \qquad T_2 \approx \frac{2\gamma(\gamma-1)}{(\gamma+1)^2} T_1 M_1^2$$

= 4 with $\gamma = 5/3$

Jump conditions for MHD Shocks

- More terms in momentum and energy conservation equation
- Additional equations from $\nabla \cdot B = 0$ and magnetic flux conservation

$$\rho_1 u_{\perp 1} = \rho_2 u_{\perp 2} \quad (1)$$

$$\rho_1 u_{\perp 1}^2 + P_1 + \frac{B_{\parallel 1}^2}{8\pi} = \rho_2 u_{\perp 2}^2 + P_2 + \frac{B_{\parallel 2}^2}{8\pi} \quad (2)$$

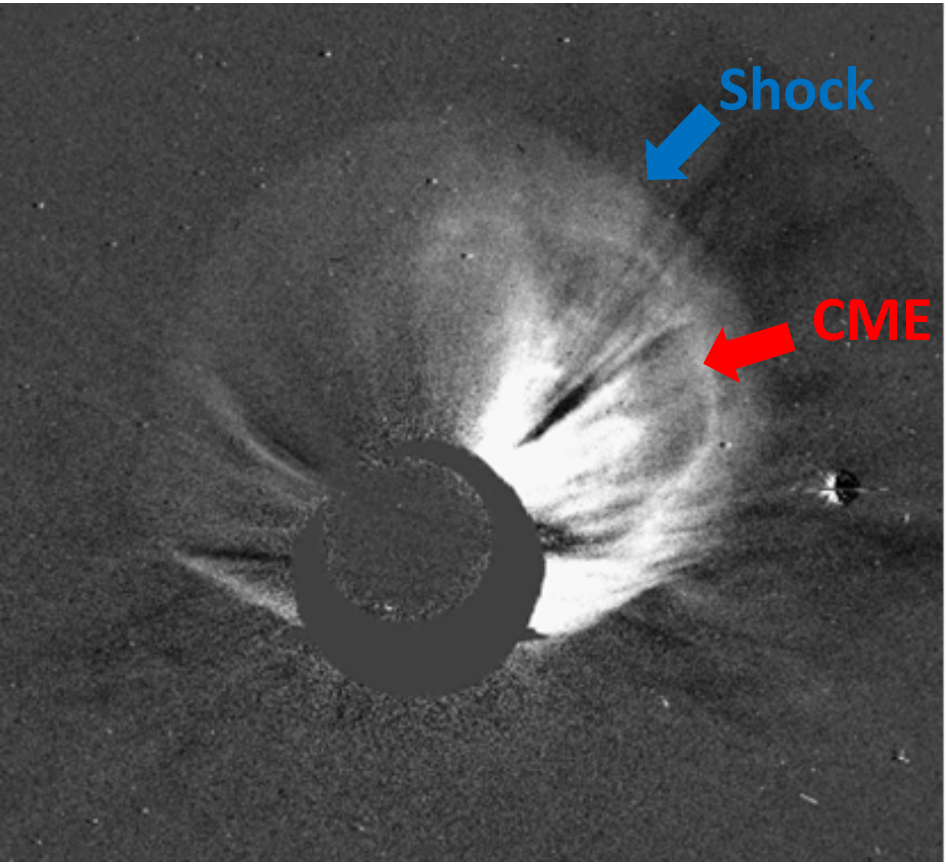
$$\rho_1 u_{\perp 1} u_{\parallel 1} - \frac{B_{\perp 1} B_{\parallel 1}}{4\pi} = \rho_2 u_{\perp 2} u_{\parallel 2} - \frac{B_{\perp 2} B_{\parallel 2}}{4\pi} \quad (3)$$

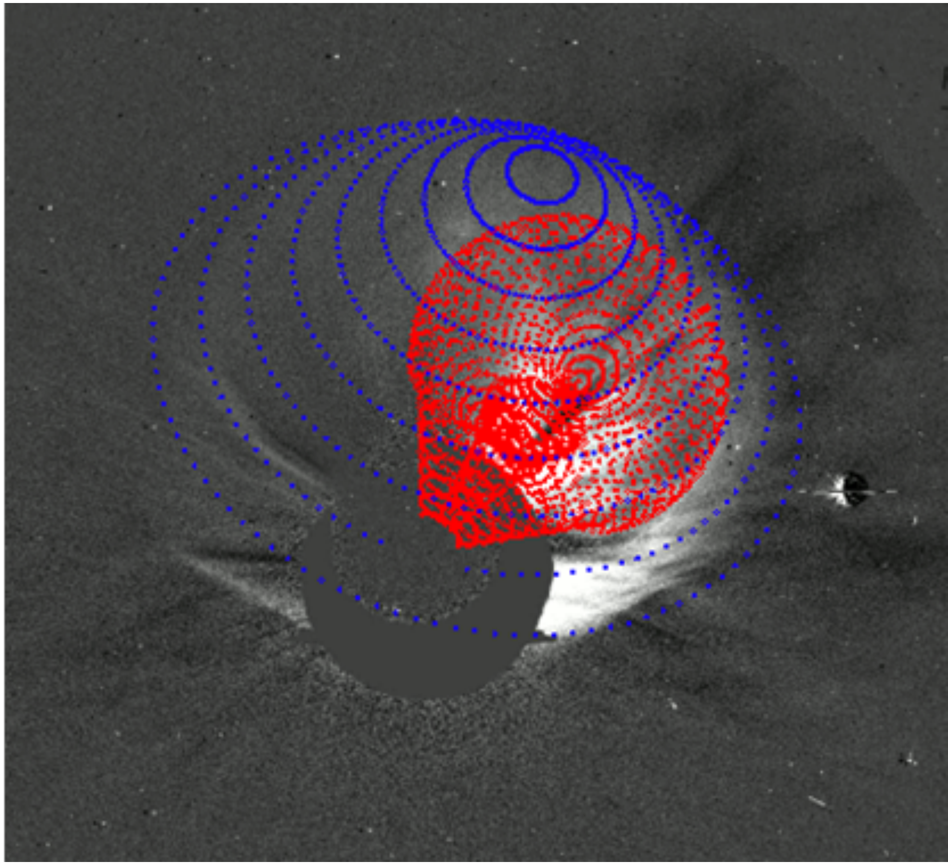
$$\rho_1 u_{\perp 1}\left(\frac{\gamma}{\gamma - 1}\frac{P_1}{\rho_1} + \frac{u_1^2}{2}\right) - \frac{B_{\parallel 1}}{4\pi}(B_{\perp 1} u_{\parallel 1} - B_{\parallel 1} u_{\perp 1}) = \rho_2 u_{\perp 2}\left(\frac{\gamma}{\gamma - 1}\frac{P_2}{\rho_2} + \frac{u_2^2}{2}\right) - \frac{B_{\parallel 2}}{4\pi}(B_{\perp 2} u_{\parallel 2} - B_{\parallel 2} u_{\perp 2}) \quad (4)$$

$$B_{\perp 1} u_{\parallel 1} - B_{\parallel 1} u_{\perp 1} = B_{\perp 2} u_{\parallel 2} - B_{\parallel 2} u_{\perp 2} \quad (5)$$

$$B_{\perp 1} = B_{\perp 2} \quad (6)$$

Shock signatures: white light and EUV imaging

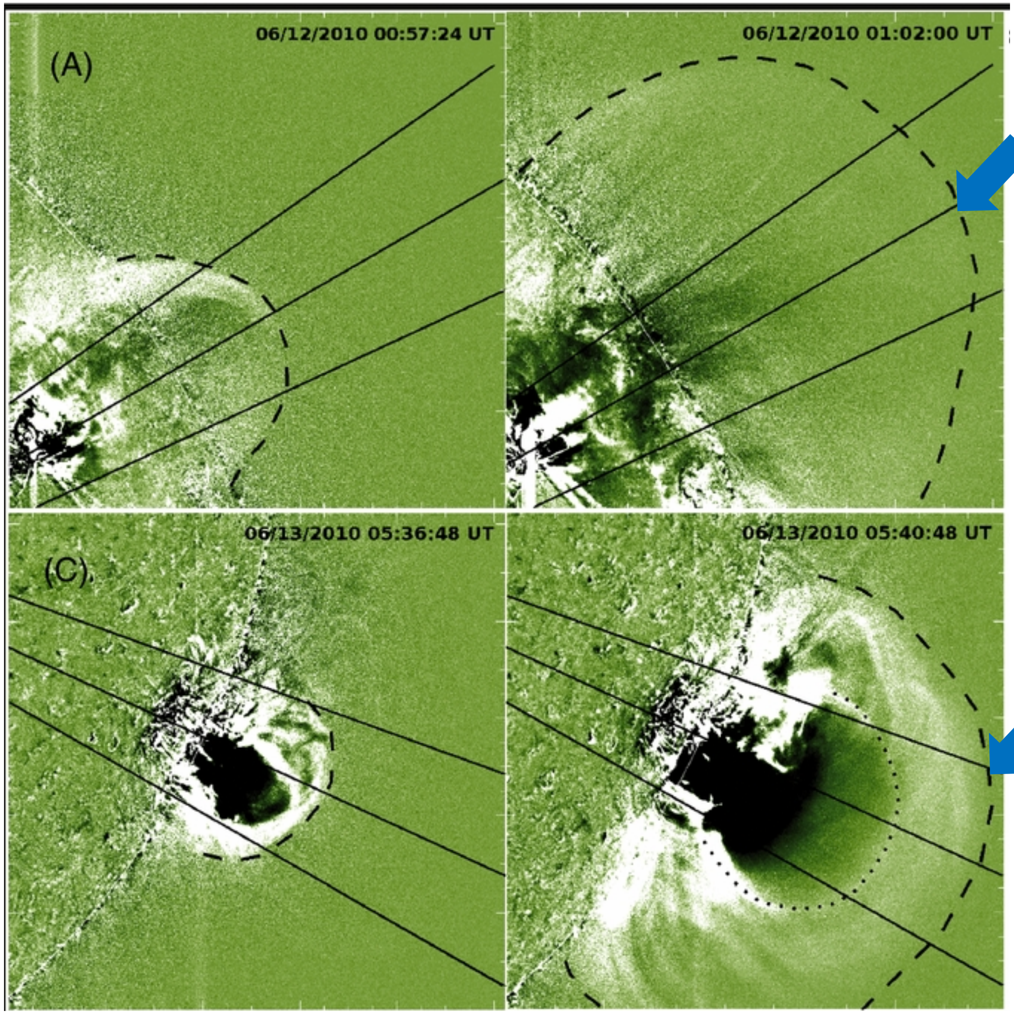




- Diffuse front in white light (LASCO/C2)
- Resulted from density compression: $I \propto n_e l$

From Angelos Vourlidas

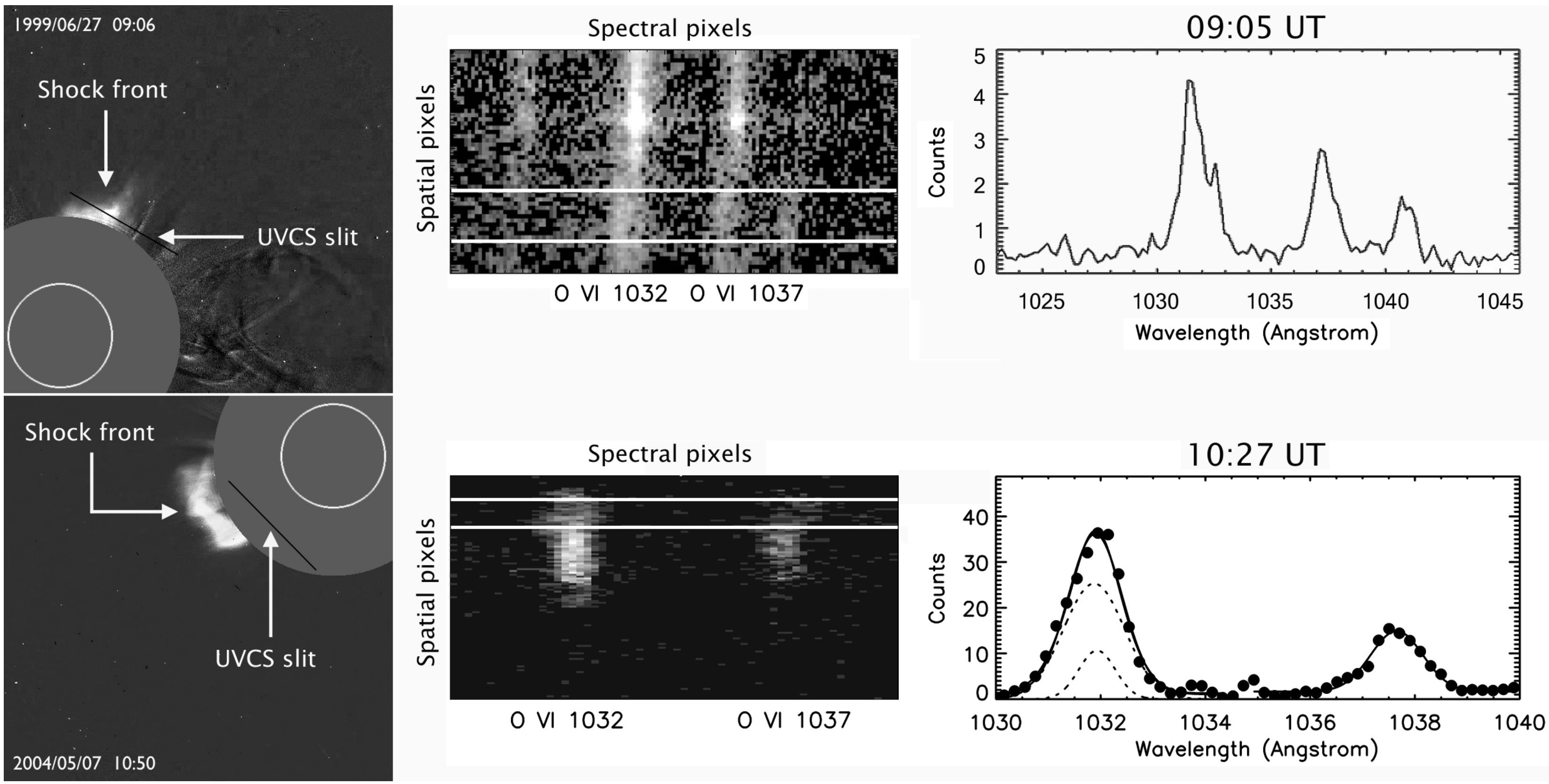
Shock signatures: white light and EUV imaging



- Diffuse front in EUV (SDO/AIA)
- Also resulted from density compression, but $I \propto n_e^2 l$
- Low corona

Kozarev et al. 2011, *ApJ*, 733, 25

Shock signatures: UV Spectroscopy



- UV Line broadening and Doppler shifts (SOHO/UVCS)
- Resulted from post-shock plasma heating, density enhancement, and bulk speeds

Constraining shock parameters

TABLE 1. CME-driven Shock Parameters Derived from UVCS data

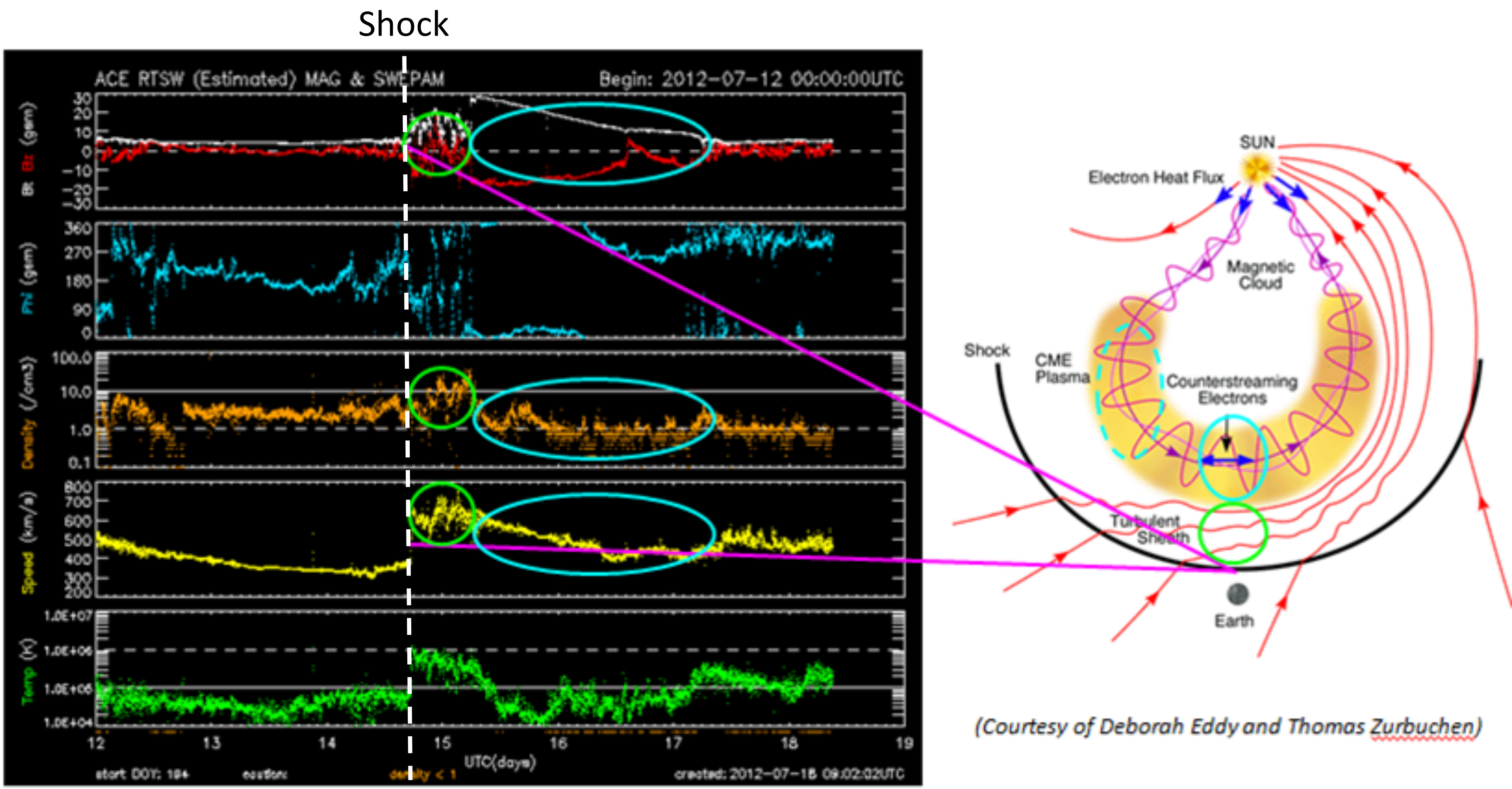
Date	Height ($R_\odot$)	Speed (km s^{-1})	Density (10^6 cm^{-3})	Compression Ratio Log(T_k)	X	Reference
06/11/98	1.75	1200	1	8.7	1.8	[20]
06/27/99	2.55	1200	—	<8.2	—	[19]
03/03/00	1.70	1100	10	8.2	1.8	[12]
06/28/00	2.32	1400	2	8.1	—	[3]
07/03/02	1.63	1700	5	8.0	2.2	[13]
22/03/02	4.30	1460	0.011	7.3	2.1	[2]
07/05/04	1.86	690	5	<7.0	—	[15]

TABLE 2. Physical Parameter at a CME-driven Shock derived by Bemporad & Mancuso (2010)

	T_e (10^6 K)	n_e (10^{-4} cm^{-3})	v (km s^{-1})	B (mG)
upstream	0.23	1.1	100	19
downstream	1.9	2.3	424	37

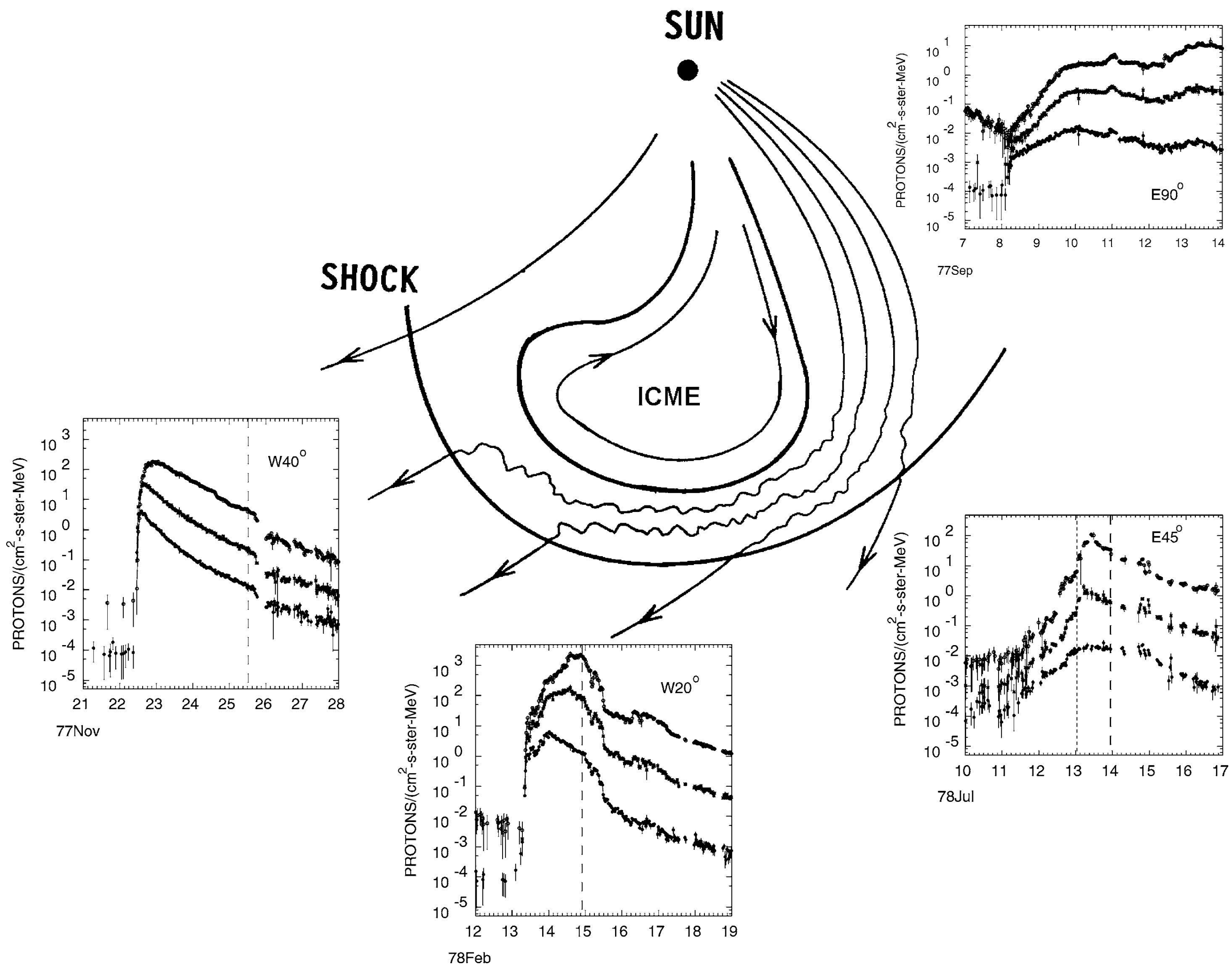
From Vourlidas & Bemporad 2012

CME-driven shocks: *in situ* signatures



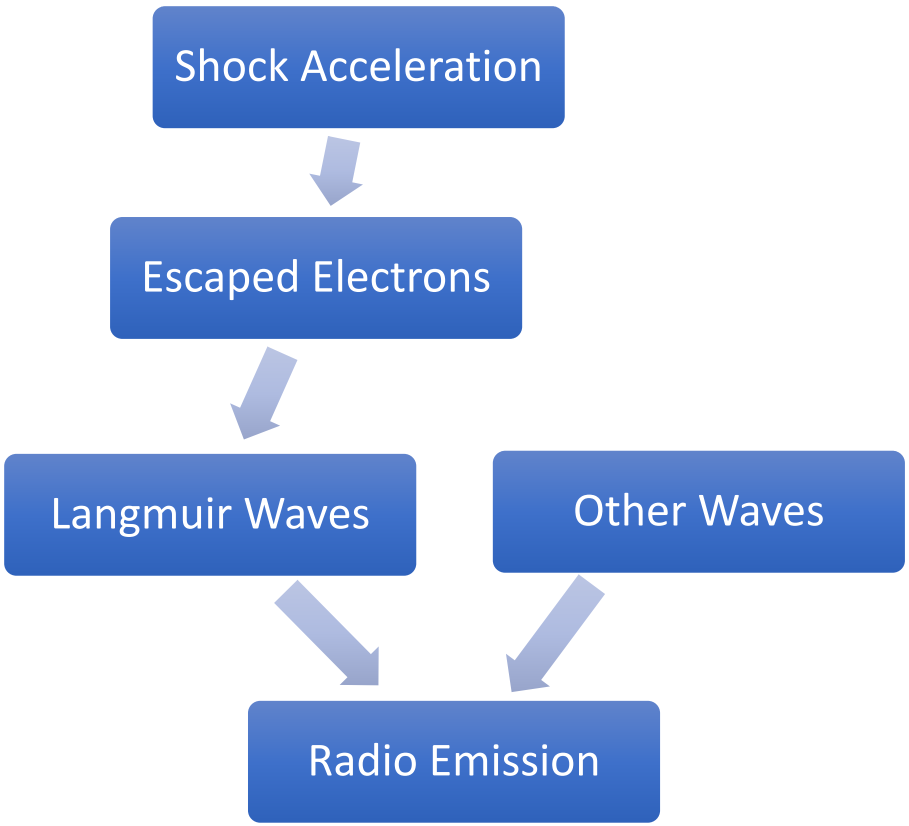
(Courtesy of Deborah Eddy and Thomas Zurbuchen)

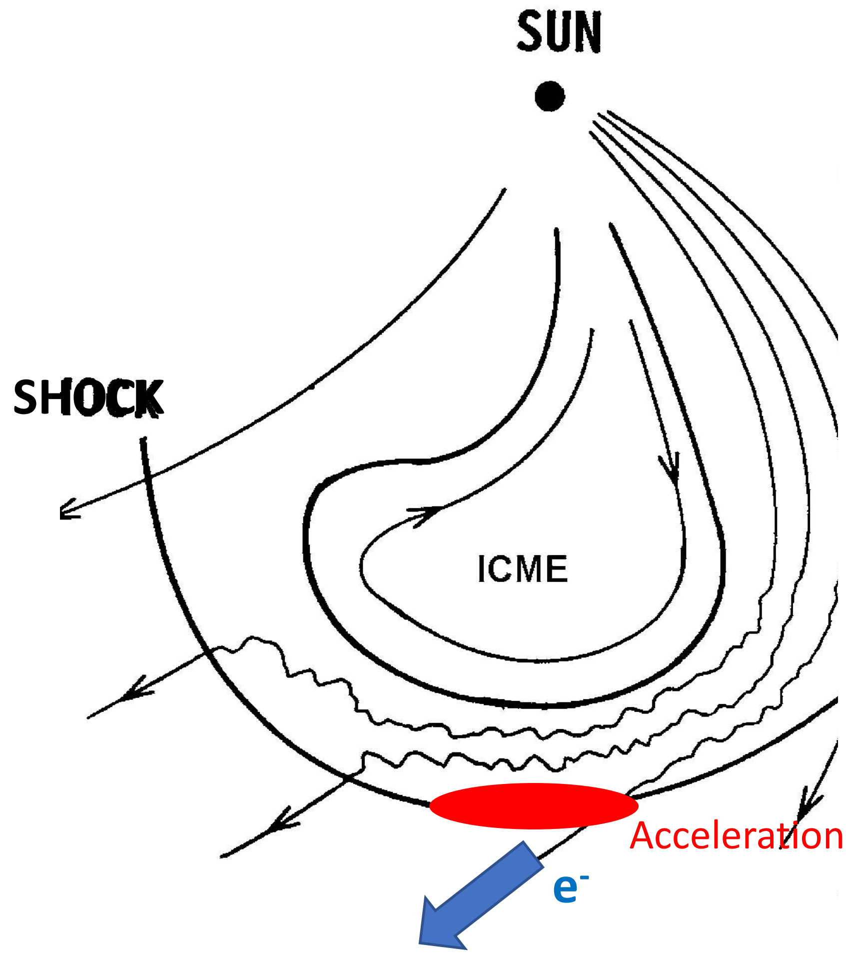
Shocks are good particle accelerators

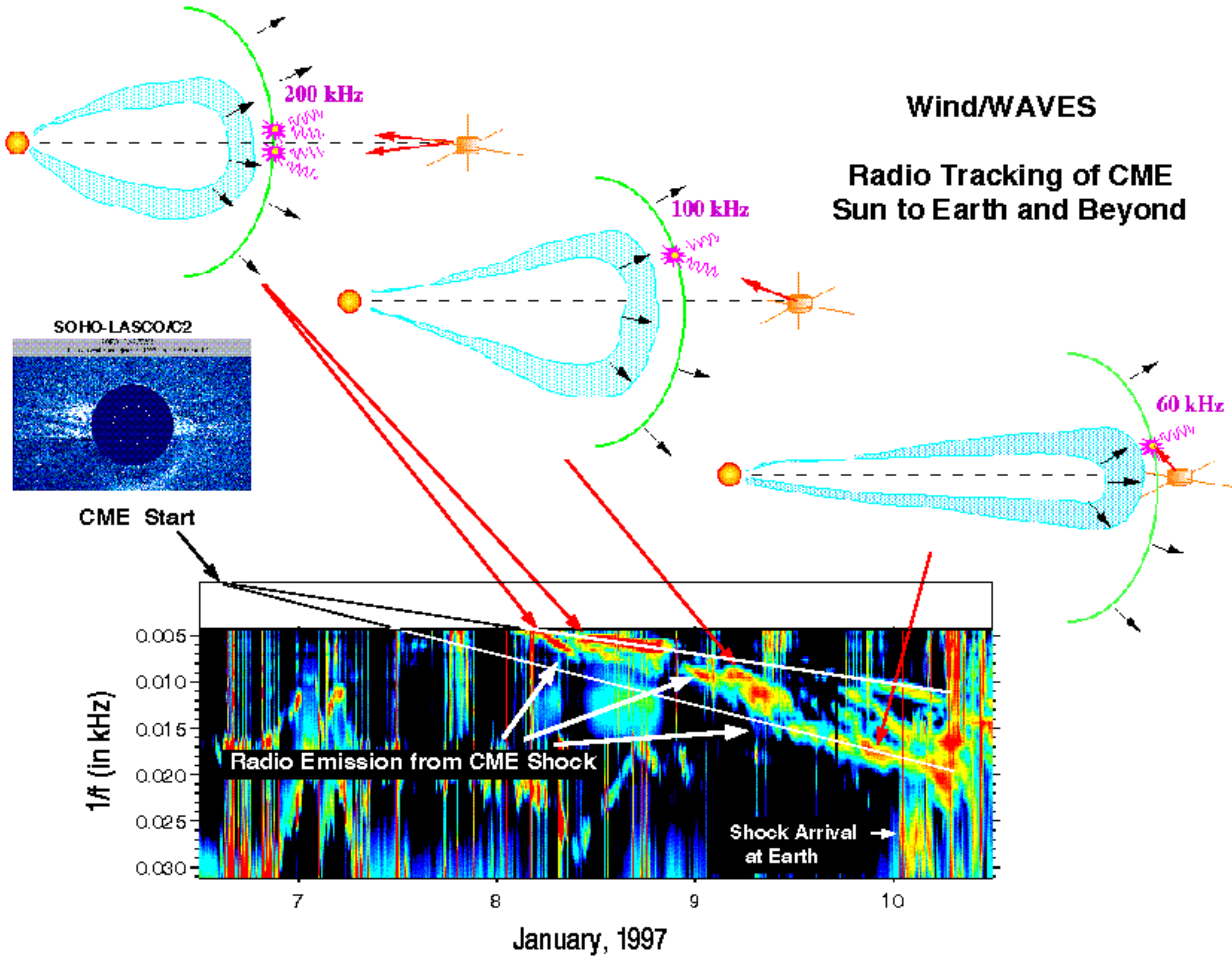


From Cane & Lario 2006

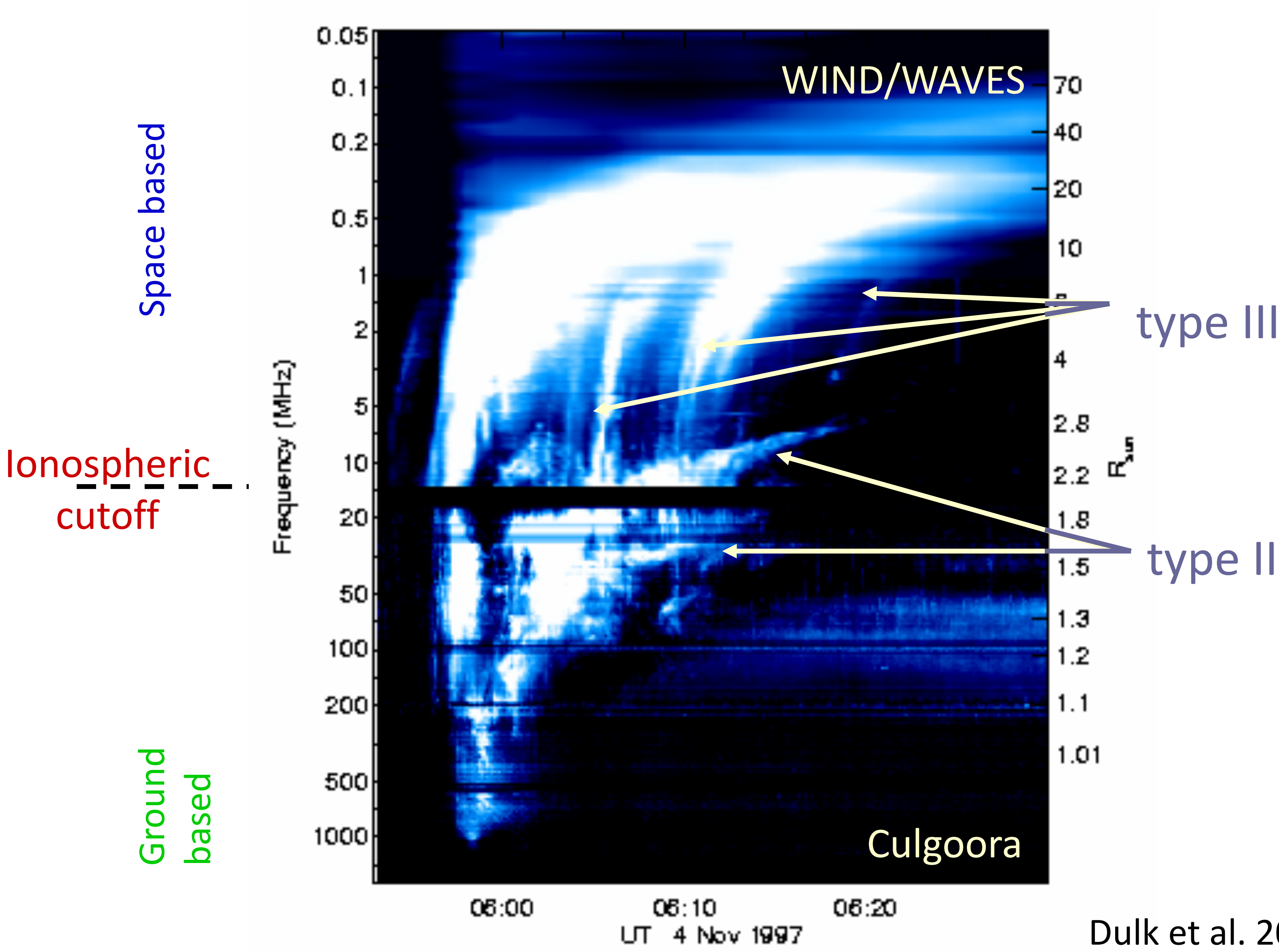
Type II radio bursts





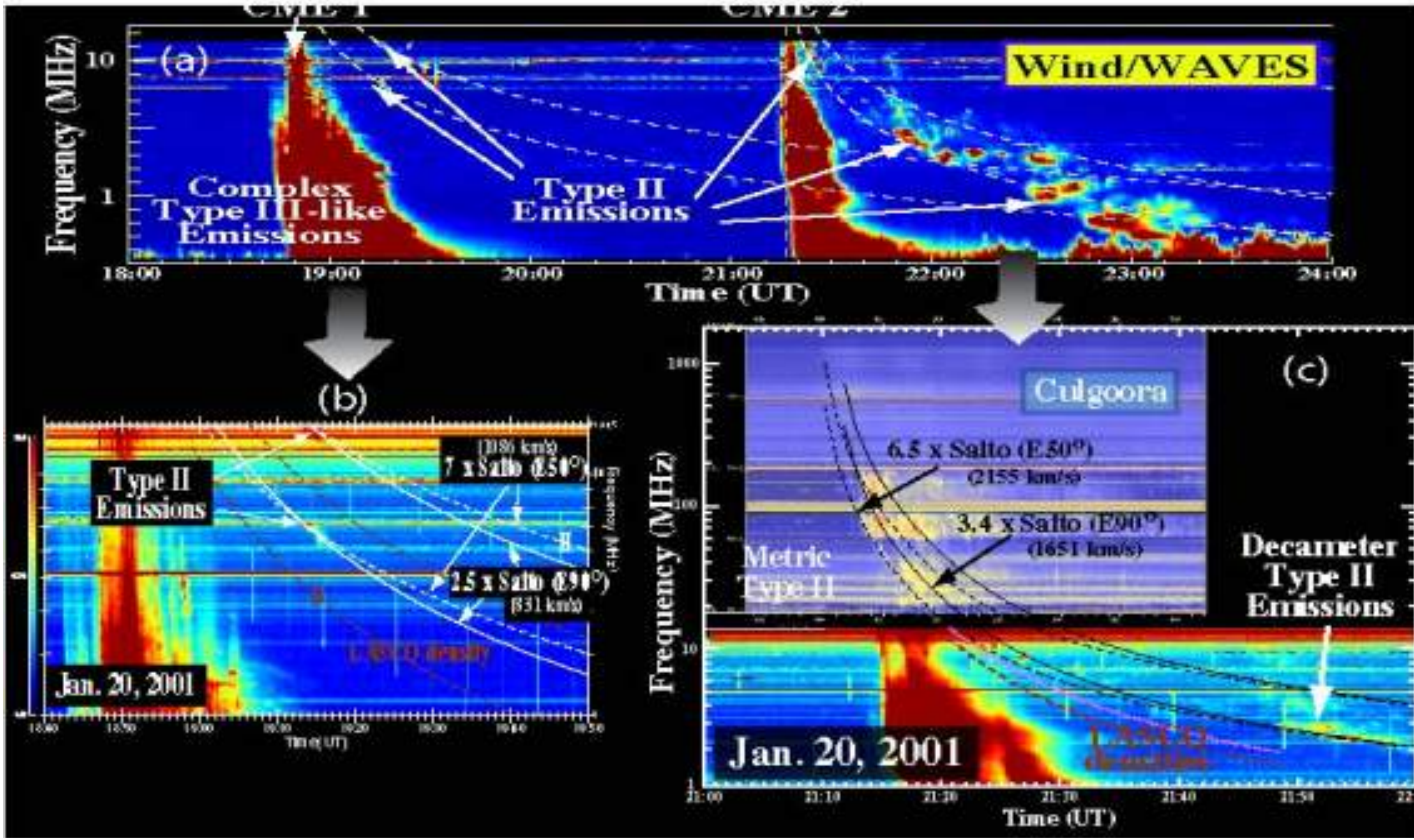

Wind/WAVES
Radio Tracking of CME
Sun to Earth and Beyond
200 kHz
100 kHz
60 kHz
SOHO-LASCO/C2
CME Start
Radio Emission from CME Shock
Shock Arrival
at Earth
1/f (in kHz)
0.005
0.010
0.015
0.020
0.025
0.030
7
8
9
10
January, 1997

Type II Observations: Spectrographs

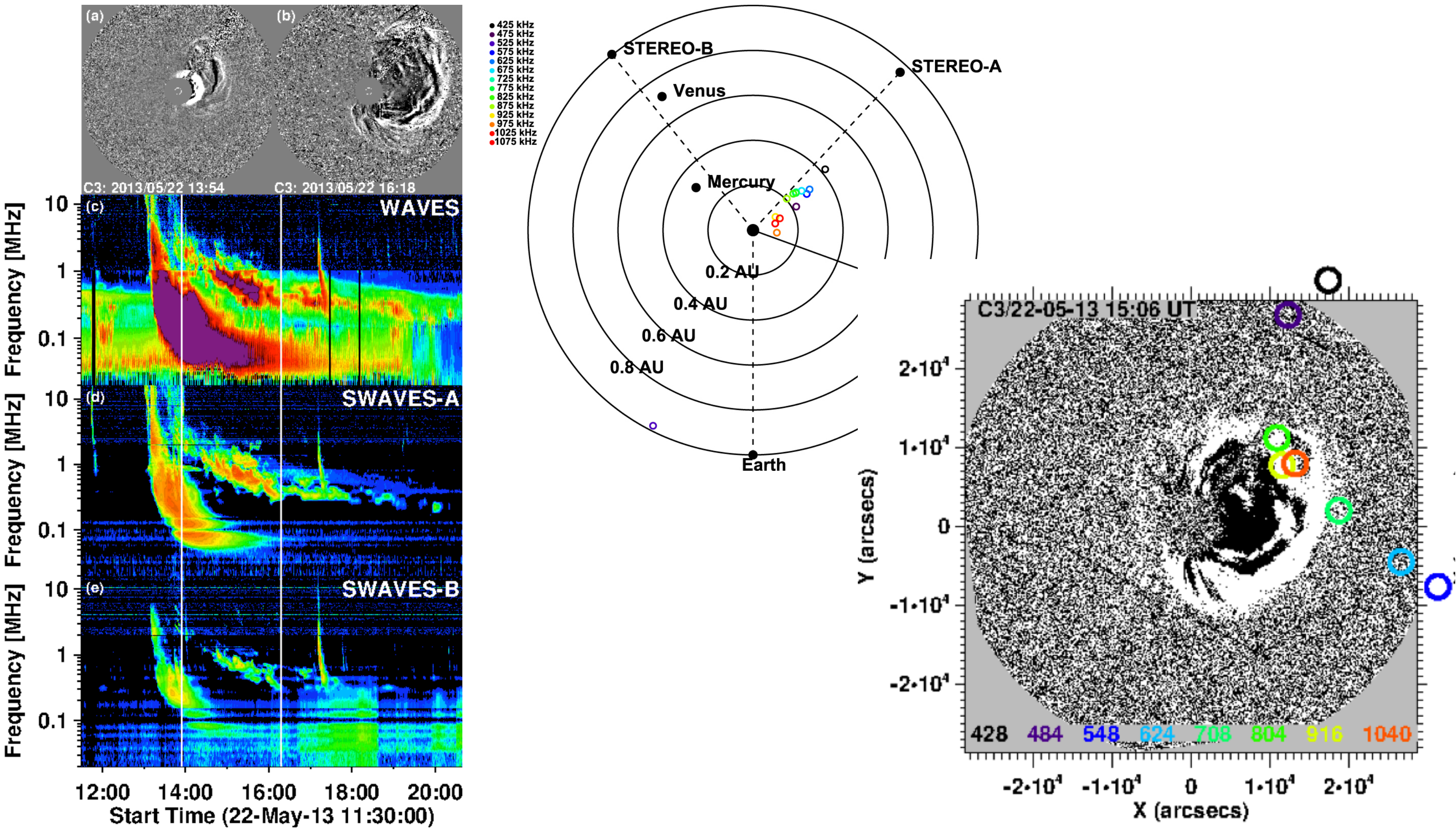


Dulk et al. 2001

Type II Observations: Spectrographs



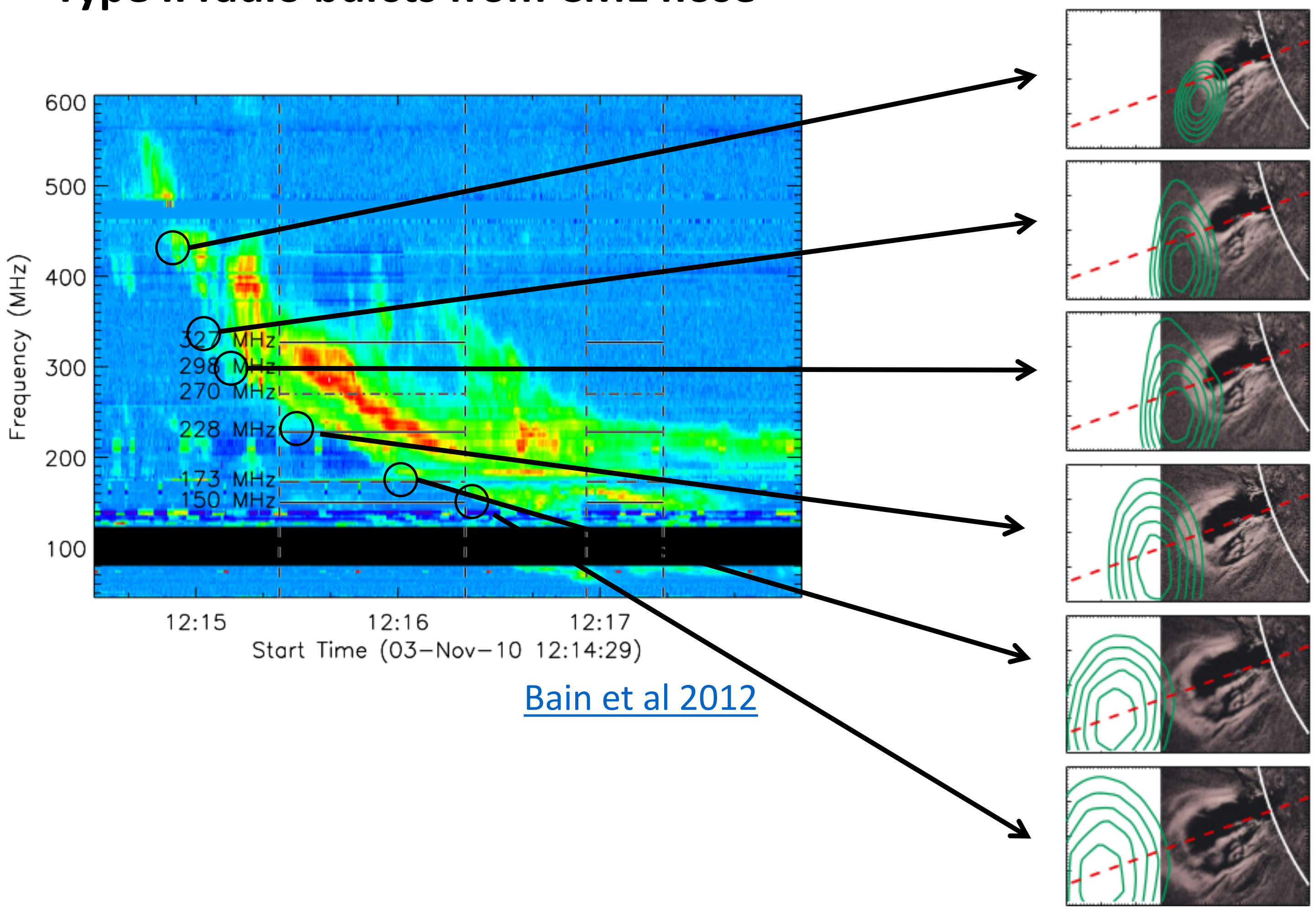
Type II observations: Goniopolarimetry and Triangulation



[Mäkelä et al. 2016]

Type II Observations: Imaging

Type II radio bursts from CME nose

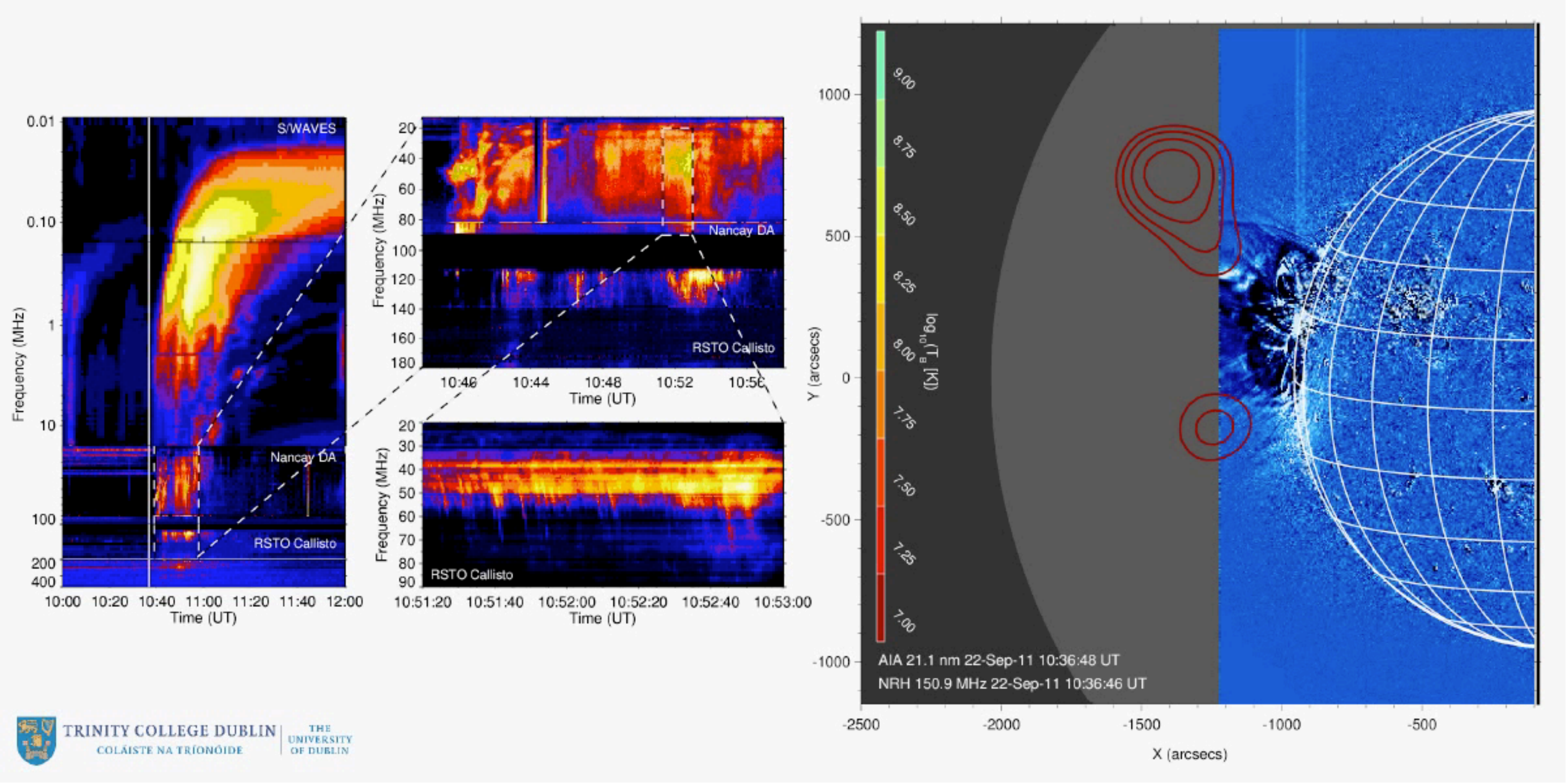


[Bain et al 2012]

[Zimovets et al 2012]

Type II Observations: Imaging

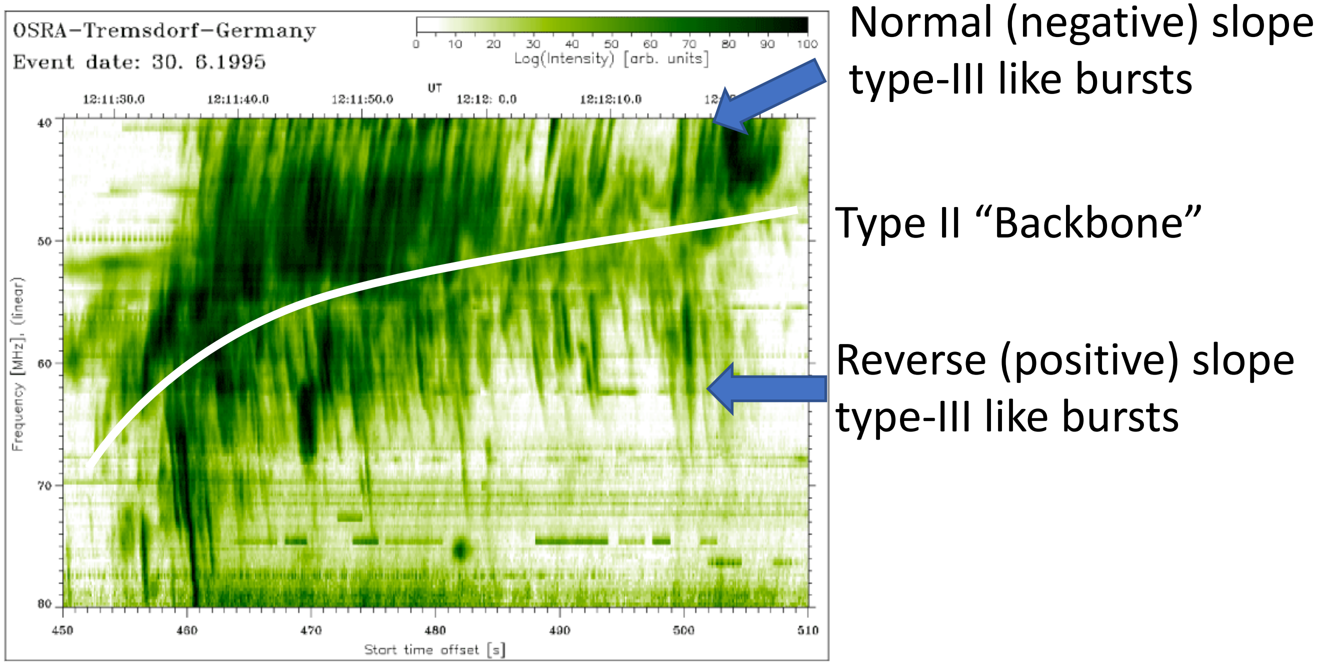
Type II radio bursts from CME flank



From Carley et al. 2013

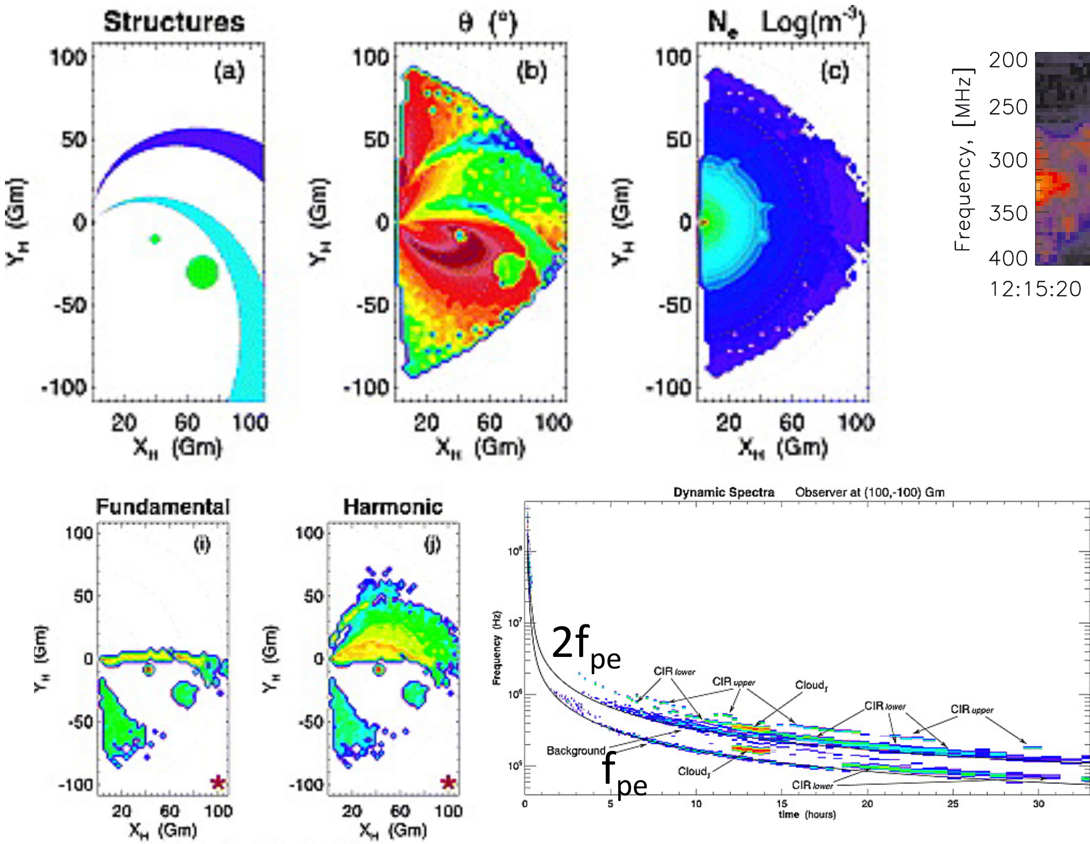
Fine structures of type II radio bursts: "Herringbone" structure

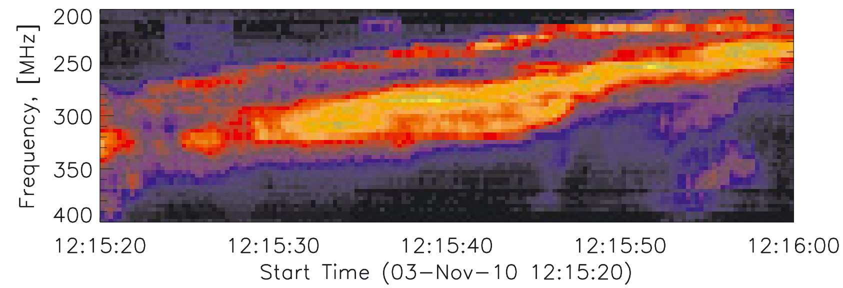
- Electron beams escaping both upstream and downstream

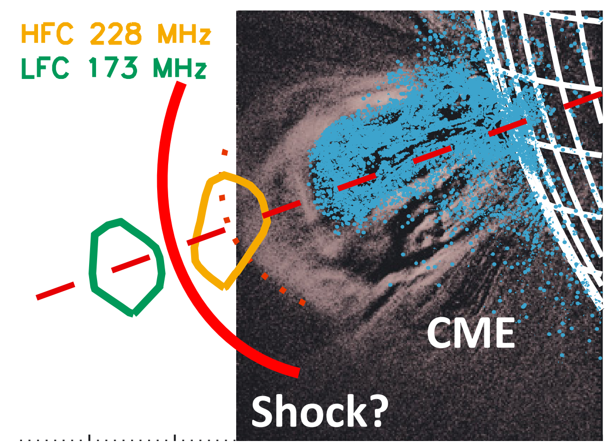


Fine structures of type II radio bursts: "Split-band" feature

- Plasma radiation from both shock upstream and downstream, or from different parts of the shock fronts



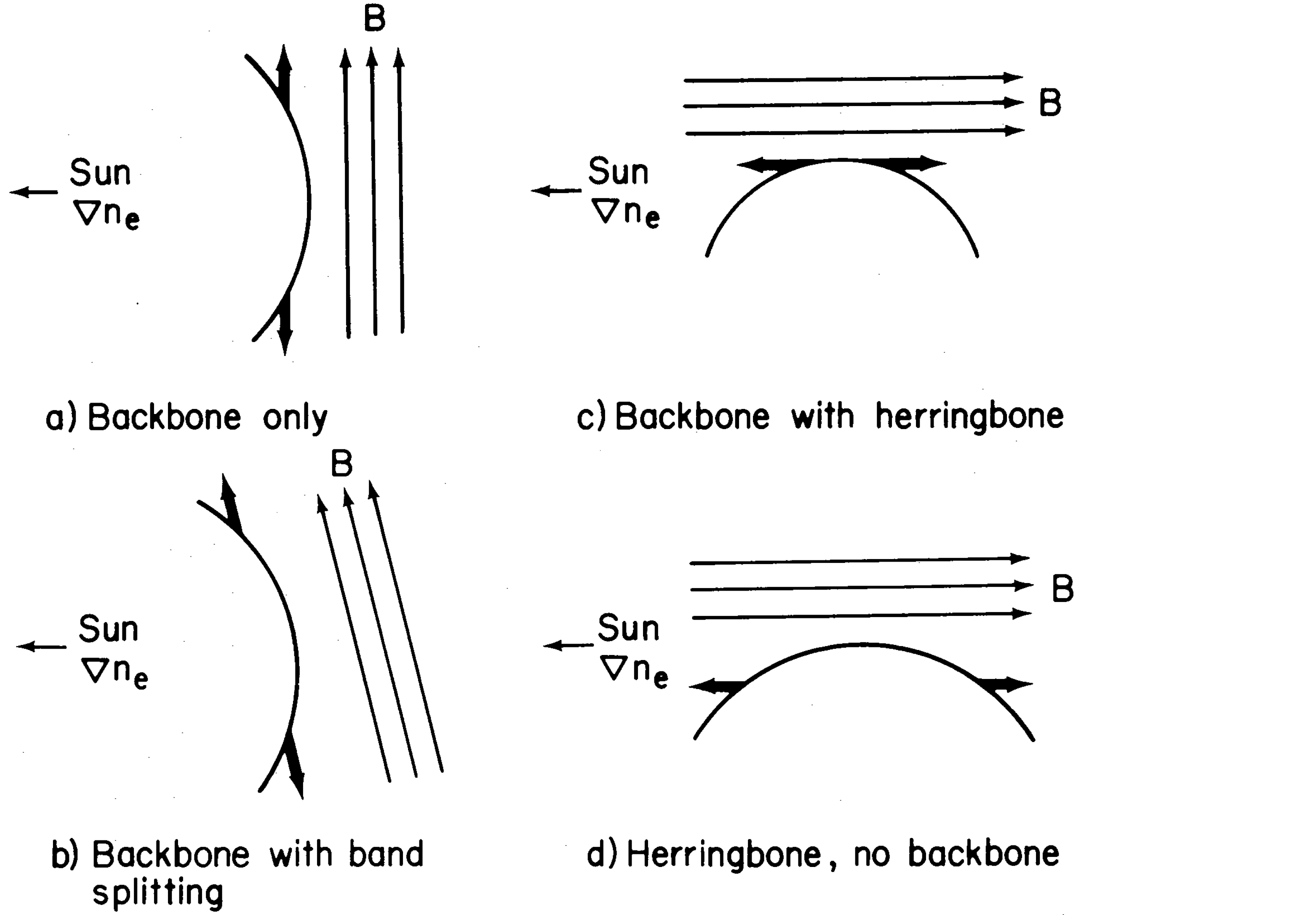




Zimovets et al 2012

Knock & Cairns 2005

Type II spectral features: a unified picture?



Holman & Pesses 1983

Summary

- Radio observations track CMEs from birth to Earth
- Sensitive to thermal (core, body), gyrosynchrotron (core, leading edge), and plasma radiation (core, body, shock)
- Provides means of measuring speed, acceleration, width (CME body and shock), and identification of electron acceleration site (type II)
- Can also measure B (CME), n_{th} (CME), $n_{nonthermal}$ (CME), n_{th} (core), T (core), X (shock)
- Complementary to white light and *in situ* observations