Shocks in the ICM and the IPM

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Outline

Setting the stage for following talks

- The Interplanetary and Intracluster Media as Collisionless Plasmas
- Basic Introduction to IPM Shocks & (Some) Issues
- Basic Introduction to ICM Shocks & (Some) Issues

Some Representative IPM & ICM Plasma Properties:

Measure:	Solar Wind (IPM): R ~ 1 AU	ICM: Outside cluster cores
kT_e (keV)	~0.01	~1 - 10
n_e (cm^{-3})	~ 1 - 10	~ $10^{-4} - 10^{-2}$
$\omega_{pe}/(2\pi)$ (Hz)*	~ 10^4	~ 10^2 - 10^3
$P_e \sim nkT$ (dyne/cm^2)	~ $10^{-11} - 10^{-10}$	$10^{-13} - 10^{-10}$
B (μG)** B $\propto n_e^{(1/2)}$(roughly)	~ 10 - 100	~ 0.1 – 5

* $\omega_{pi} \sim 0.02\omega_{pe}$

**1 μG = 0.1 nT

Some Characteristic "Micro-Physics" Lengths: I

Both plasmas are collisionless!

Length:	IPM:	ICM:
Coulomb scattering length $\lambda_{coulomb}$~0.2 pc $T_{keV}{}^2/n_e$	~ 0.4 -4 AU	~.02 – 200 kpc
electron thermal gyro radius: $r_{ge}=\rho_e$ ~ 1300 km $T_{keV}{}^{(1/2)}$ /$B_{\mu G}$	~ 1 – 10 km	~ 300 - 4x10^4 km
proton thermal gyro radius: $r_{gp}=\rho_I$ ~ 5.6x10^4 km $T_{keV}{}^{(1/2)}$ /$B_{\mu G}$	~ 50 - 500 km	~ 10^4 – 2x10^6 km

1 AU ≈ 1.5x10^8 km
r_{sun} ~ 10^6 km
1 kpc ≈ 3x10^{16} km ≈ 2x10^8 AU

IPM and ICM thermal gyroradii are very much smaller than $\lambda_{coulomb}$

Some Characteristic "Micro-Physics" Lengths: II

Length:	IPM:	ICM:
electron skin depth*: $\lambda_e = c/\omega_{pe} \sim 5\text{km}\ n_e^{(-1/2)}$	~ 1 - 5 km	~ 50 – 500 km
Ion inertial length**: $\lambda_i = c/\omega_{pi} \sim 200\text{km}\ n_i^{(-1/2)}$	~60 – 200km	~2000 – 20,000 km
Debye length: $\lambda_D \sim 0.24\ \text{km}\ (T_{keV}/n_e)^{1/2}$	~ .01 km (~ 10 m)	~ 2 – 100 km

*EM field penetration length

**Ions decouple from electrons

IPM λ_i is comparable to r_{gp}

ICM λ_i is smaller than r_{gp}

Some Dimensionless IPM/ICM Plasma Measures

Measure:	Solar Wind:	ICM:
$\beta = P/(B^2/8\pi) = (6/5)\ c_s^2/v_A^2$ $\sim 8\text{x}10^4\ \ n_e\ T_{keV}/B_{\mu G}^2$	$\sim 0.1 - 80$	$\sim 50 - 10^3$
Ion gyro/inertial length $r_{gi}/\lambda_i = \rho_i/\lambda_I \sim \sqrt{\beta}$	~ 0.3 - 10	~ 7 - 30
$N_d = n_e \lambda_D^3 \sim 10^{13}\ T_{keV}^{(3/2)}\ /n_e^{(1/2)}$	$\sim 10^{10}$	$\sim 10^{14}$

ICM is generally High β;
IPM can be "High" β (border-line?)

Both media are "good plasmas" $N_d >> 1$
(support collective plasma wave families)
In effect both become "weakly collisional"

Some Characteristic IPM/ICM Velocities

Velocity:	IPM:	ICM:
Ion acoustic (sound) speed: $c_s = \sqrt{(5P/3\rho)} \sim 500\ T_{keV}^{(1/2)}$ km/s	~ 50 km/s	~ 500 – 1500 km/s
Alfven speed: $v_A = B/\sqrt{(4\pi\rho)} \sim 2\ B_{\mu G}/n_e^{(1/2)}$ km/s	~20 – 100 km/s	~ 20 – 100 km/s
Turbulent velocities: δv	~ 10 - 50 km/s	~ 300 km/s *
Bulk flows:	~ 300 – 600 km/s	Up to ~ 2000 km/s

*Assuming $P_{turb} \sim 0.1\ c_s$
Not measured directly

Turbulence in both IPM and ICM should be compressional ($\delta v/c_s$ can be ~ 1)

IPM turbulence should be "MHD" ($\delta v < v_A$)
ICM turbulence (on large scales) should be "HD" ($\delta v > v_A$)
but, MHD for $l < l_A \sim L\ (v_A/\delta v)^3$; $l_A \sim 1\%$ L (very crude)

Some IPM/ICM Shock Parameters

IPM and ICM shocks are both collisionless, magnetized shocks

Parameter:	Solar Wind (IPM):	ICM:
$M_s = M_f = V_s/c_s$	< a few	< a few
$M_A/M_s \sim \beta^{1/2}$	~ 1	~ 10
Density compression	~ 2 - 3	~ 2 - 3

IPM and ICM shocks have similar sonic (fast mode) Mach numbers

ICM shocks (mostly) have higher Alfvenic Mach numbers than IPM shocks

Quick Recap So Far

IPM and ICM plasmas both:

- ✓ are collisionless – Coulomb collision lengths can approach system size
- ✓ have much smaller particle kinetic scales (e.g., gyro radii, inertial lengths)
- ✓ are "good plasmas" (e.g., carry plasma waves, collective behaviors dominate)
- ✓ host compressible turbulence
- ✓ contain shocks with sonic Mach numbers of a few

$\beta = P_g/P_B \sim (c_s/v_A)^2$ generally smaller in the IPM than the ICM, so:

--Usually--

- ✓ IPM turbulence is MHD on largest scales, while
- ✓ ICM turbulence is HD on largest scales, but probably MHD on smaller scales
- ✓ ICM shocks are less magnetized than IPM shocks, with larger Alfvenic Mach numbers

Some Features of Collisionless, Magnetized Plasma Shocks (Fast, "Magnetosonic" Mode)

Shock Characterization Parameters:

Quasi parallel $(B_{||} > B_{\perp})_{incident}$ (relative to shock normal)

Quasi perpendicular $(B_{\perp} > B_{||})_{incident}$ (relative to shock normal)

Subcritical Shocks, $M_f < M_{crit}$
(Nonlinear wave steepening/resistive dissipation may be enough)
Postshock flow speed less than c_s

Supercritical Shocks, $M_f > M_{crit}$
Viscous dissipation needed
Ion reflection important

Shock "foot" is a (diagnostic) feature

The Subcritical/Supercritical Shock Domains

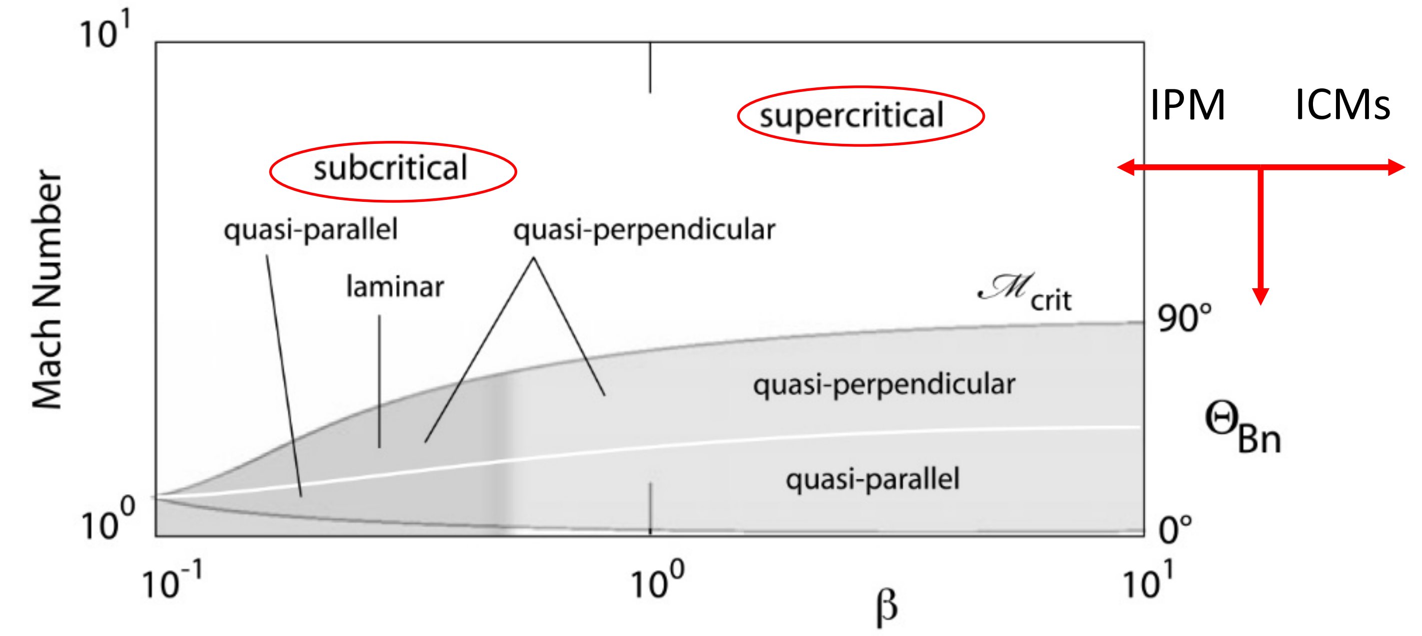


Figure 4.2: The range of supercritical and subcritical shocks in the $(\mathcal{M}_{ms}, \beta)$-plane. The critical Mach number range is shown in shading varying between perpendicular and parallel shocks. The *white line* is the demarcation line between quasi-perpendicular and quasi-parallel shocks. The *lower dark* line belongs to strictly parallel shocks. At low β the parameter range of laminar shocks is shown in fuzzy shading. The transition to higher beta is blurred as it is not sharply defined. For a given shock normal angle Θ_{Bn} the *region below the curve* is subcritical. Quasi-parallel shocks can be subcritical only below the *white line*, depending on their shock normal angle.

Balogh & Treumann 2013

Example Subcritical Shock Transitions

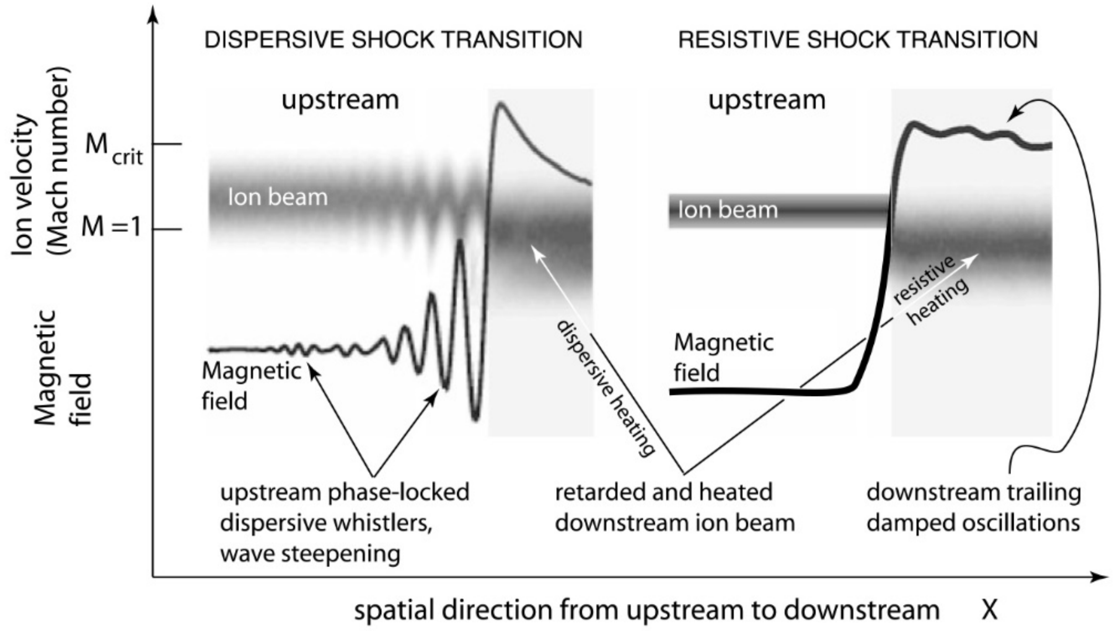
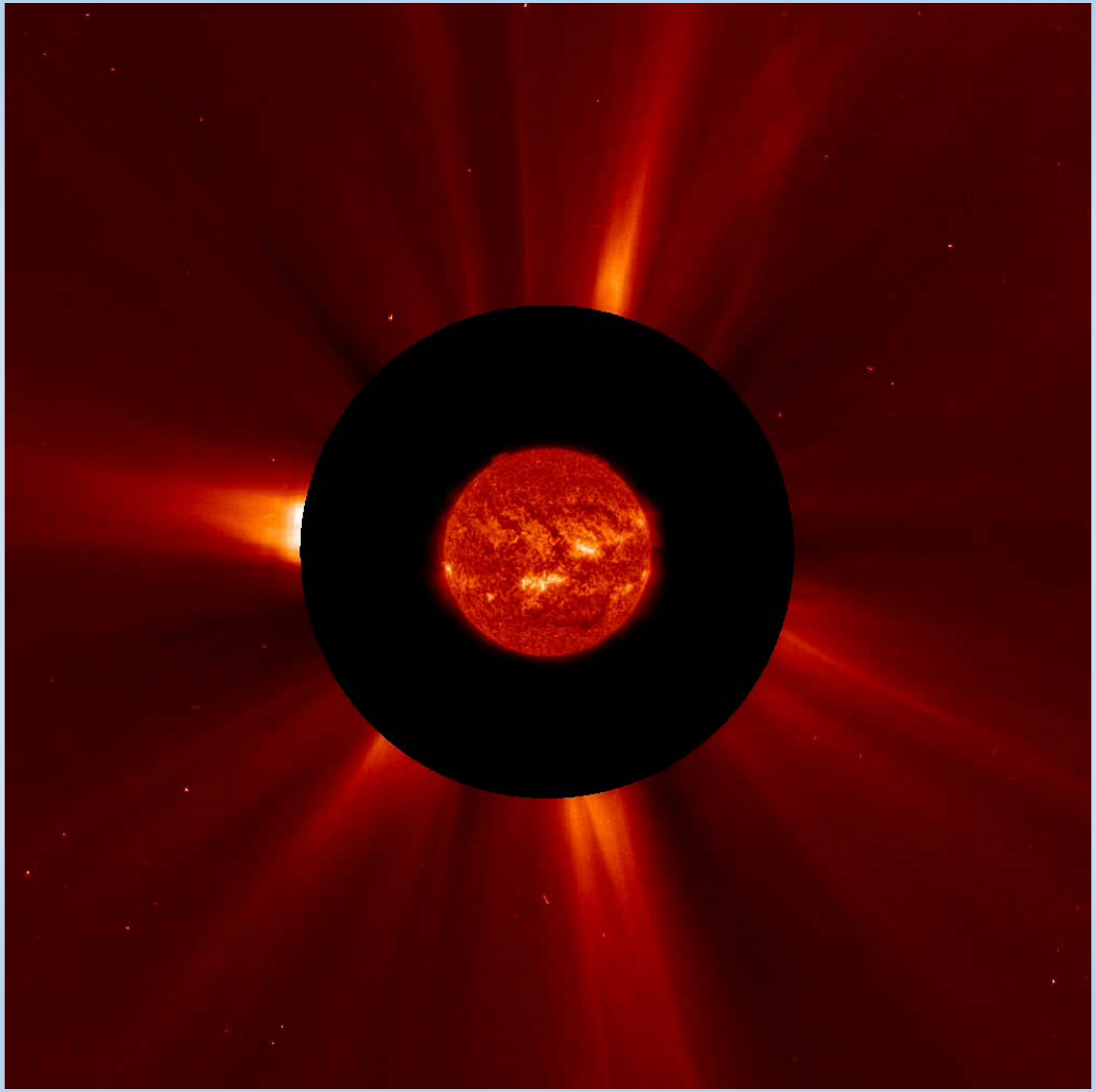


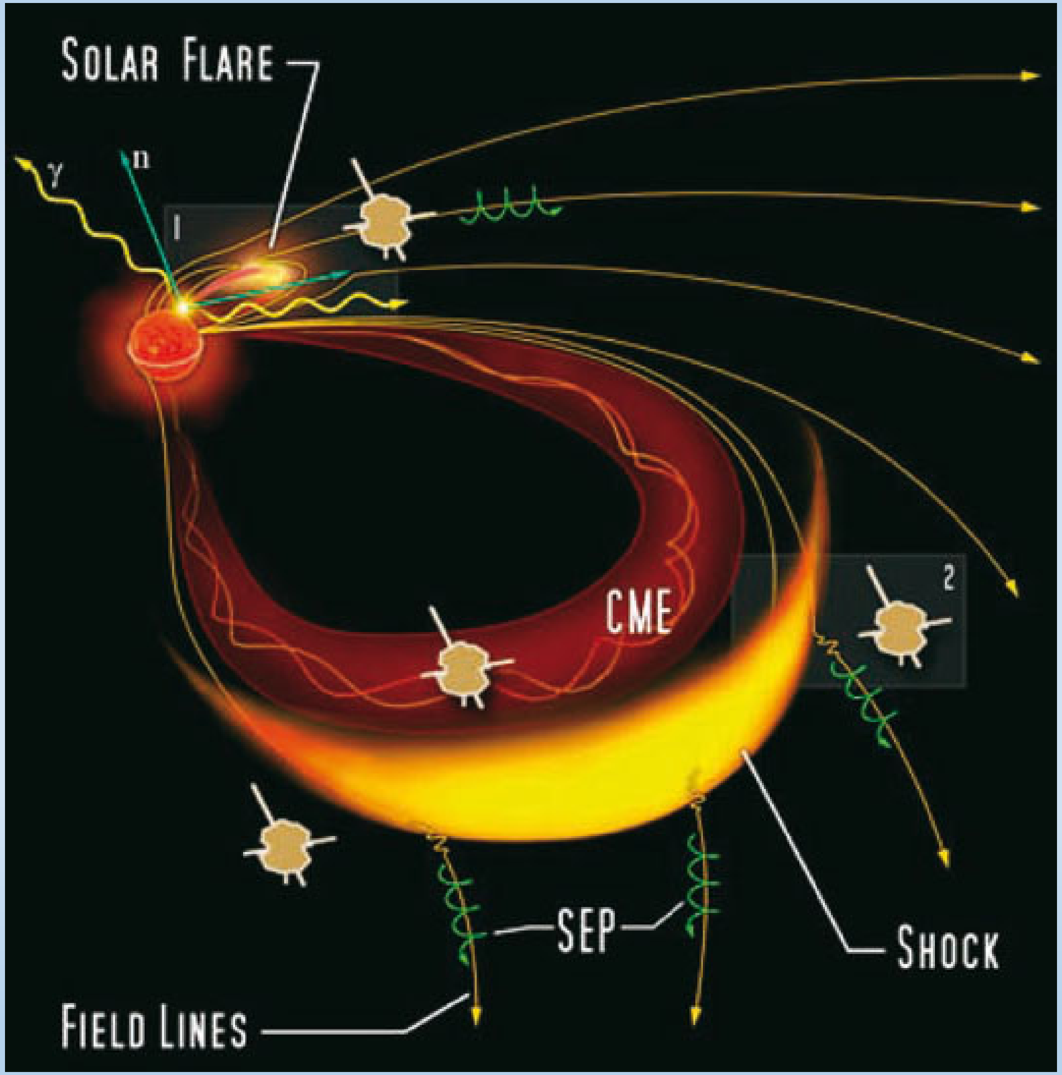
Figure 4.1: Schematic of the two types of subcritical shocks in ion phase space and magnetic field profile. In the dispersive shock transition the upstream whistler steepens nonlinearly while being phase-locked to the shock and causing coherent oscillations in the upstream ion beam. The upstream ion beam is subcritical. Heating and retarding in the shock is caused by dispersive effects. In resistive shock transition the shock forms a steep ramp lacking upstream oscillations. Heating and retarding is due to resistive Joule heating. Downstream the magnetic field may evolve trailing oscillations. Other shock transitions based on the Korteweg-deVries and related equations are also possible.

Balogh & Treumann 2013

IPM Shocks: CMEs $\Rightarrow$ Interplanetary Shocks



Resulting Interplanetary Shock



Some Example IPM, Solar Wind Shocks
(Solar Wind Shocks measured by "Wind")

subcritical

Quasi Parallel

Note "loud" upstream foot

Quasi Perpendicular

supercritical

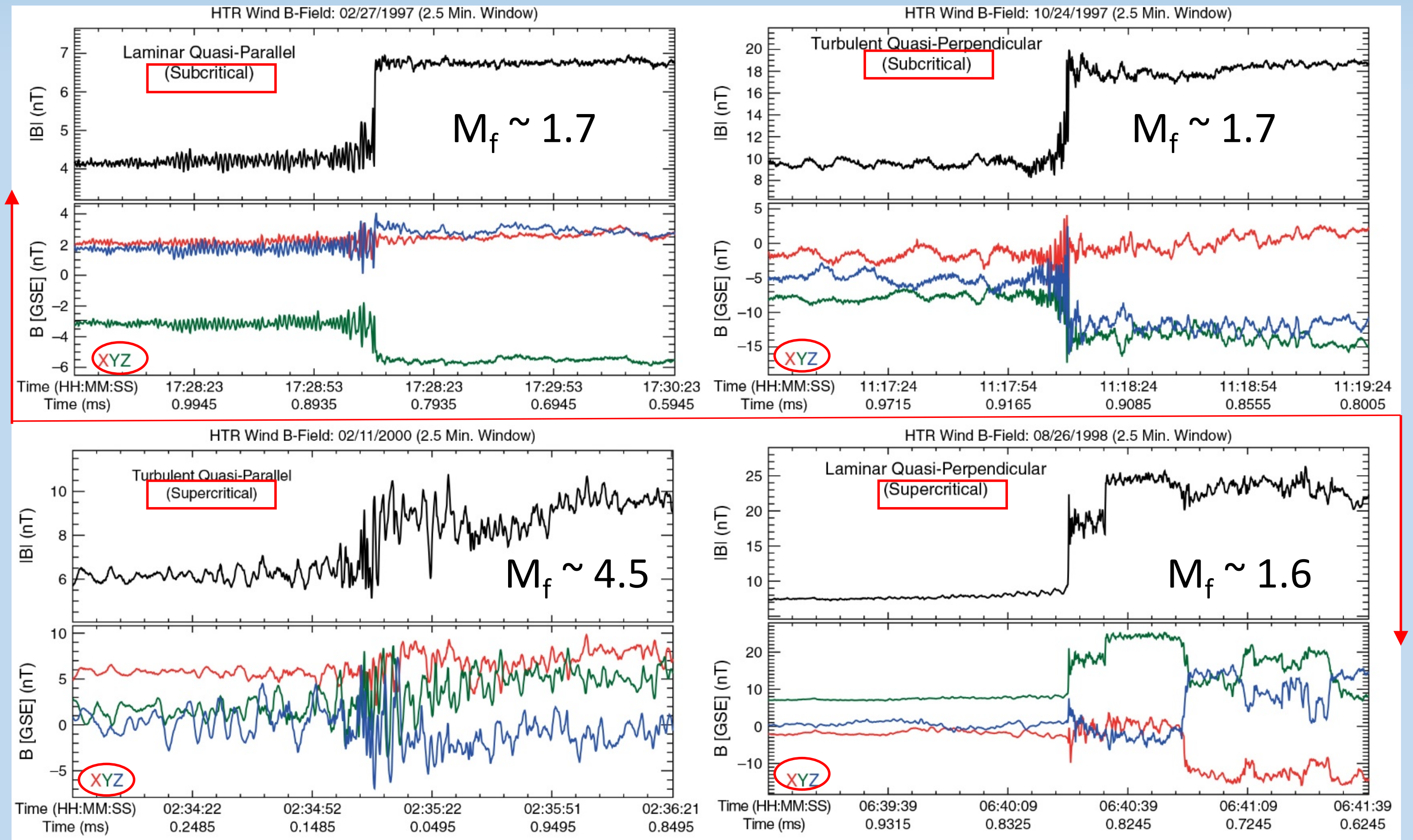


Figure 16.2 Four examples of interplanetary shocks observed by the *Wind* spacecraft. Each example shows 2.5 min of magnetic field data versus time (B_o in top and GSE $\mathbf{B}_o$ in bottom panel). The shock parameters are, in clockwise order starting from the upper left-hand panel, as follows: $\theta_{Bn} \sim 42°, 68°, 12°, 80°$; and $M_f \sim 1.7, 1.7, 1.6, 4.5$. The upper left-hand, upper right-hand, and lower left-hand panels all show examples of whistler precursors. The lower right-hand event had whistler precursors as well, but they were not resolved with the fluxgate magnetometer data shown here [e.g., *Wilson III et al.*, 2012]. Reprinted from Figure 1.4 in *Wilson III* [2010].

Wilson 2013

The Most Familiar IPM Shocks:

Planetary Bow Shocks

Cartoon of Earth's Bow Shock: Note both Quasi-parallel & Quasi-Perpendicular Forms

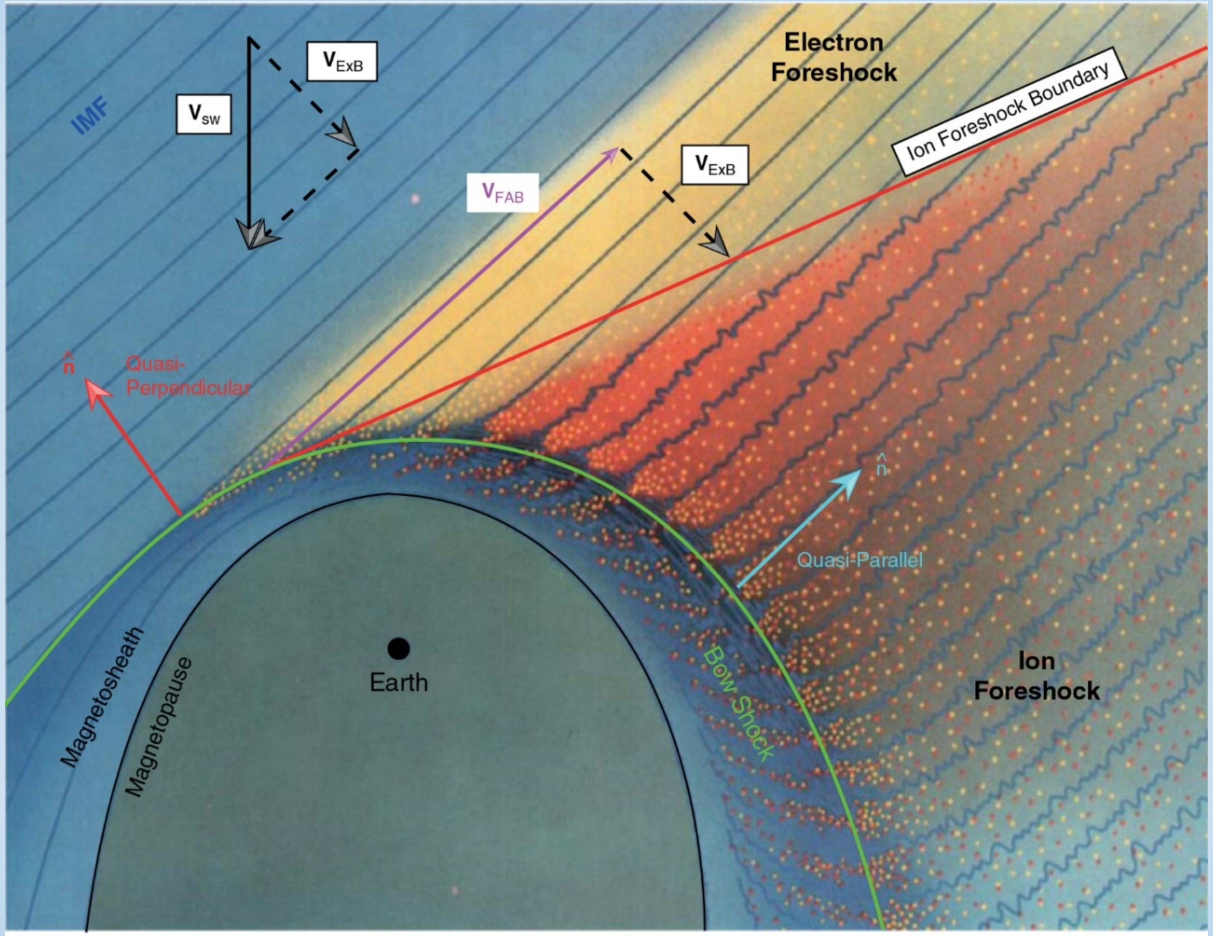
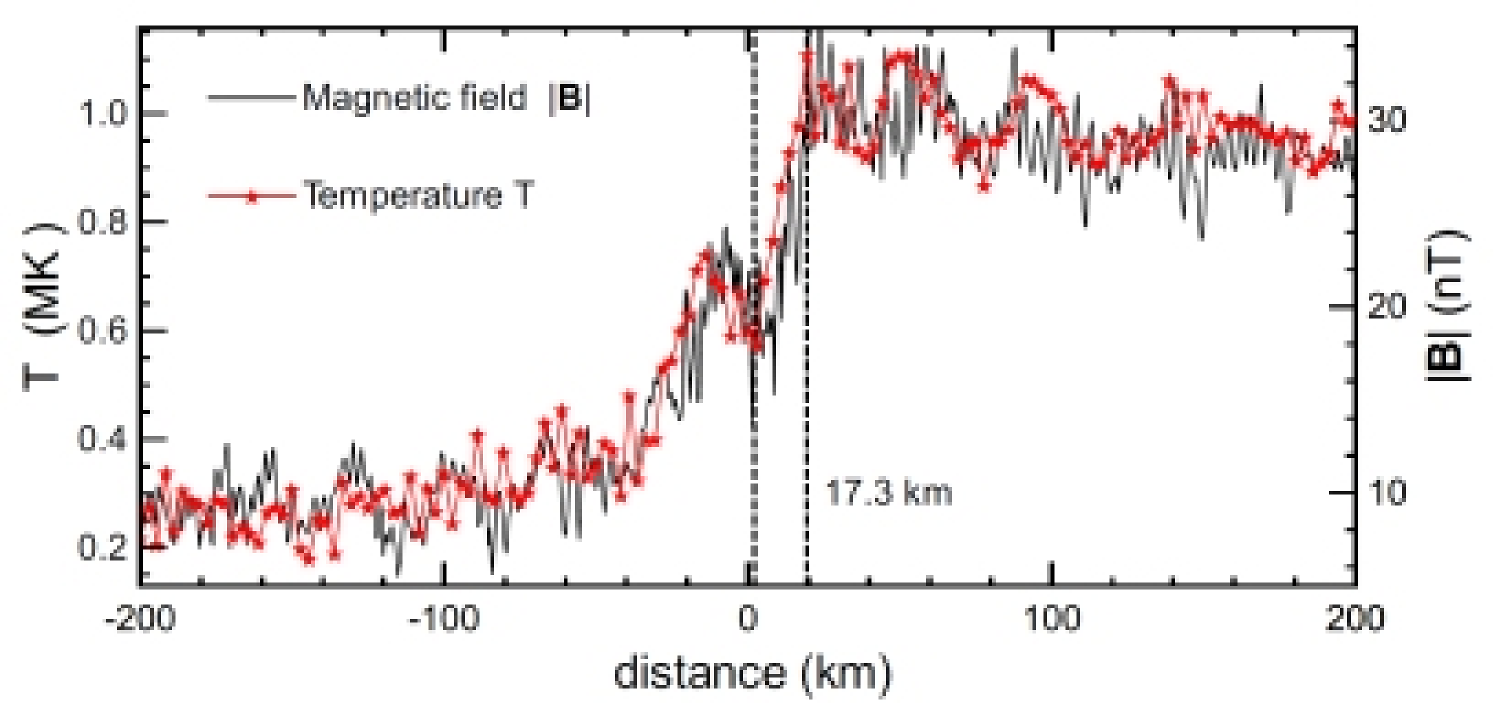


Figure 16.1 Cartoon example of a possible terrestrial foreshock configuration. The interplanetary magnetic field (IMF) is represented by the dark blue lines, $\mathbf{V}_{sw}$ represents the bulk solar wind velocity, $\mathbf{V}_{ExB}$ is the $(E \times B)$-drift velocity due to the solar wind convection electric field, and $\mathbf{V}_{FAB}$ is the reflected field-aligned ion beam (FAB) velocity Adapted from Plate 1 of *Tsurutani and Rodriguez* [1981].

Earth's Bow Shock Profile (Quasi-Perpendicular)



$M_s \sim 3.5$

Thickness "a few" ion inertial lengths

Schwartz + 11

Collisionless Plasma, so Commonly Not Isotropic, Maxwellian Distributions

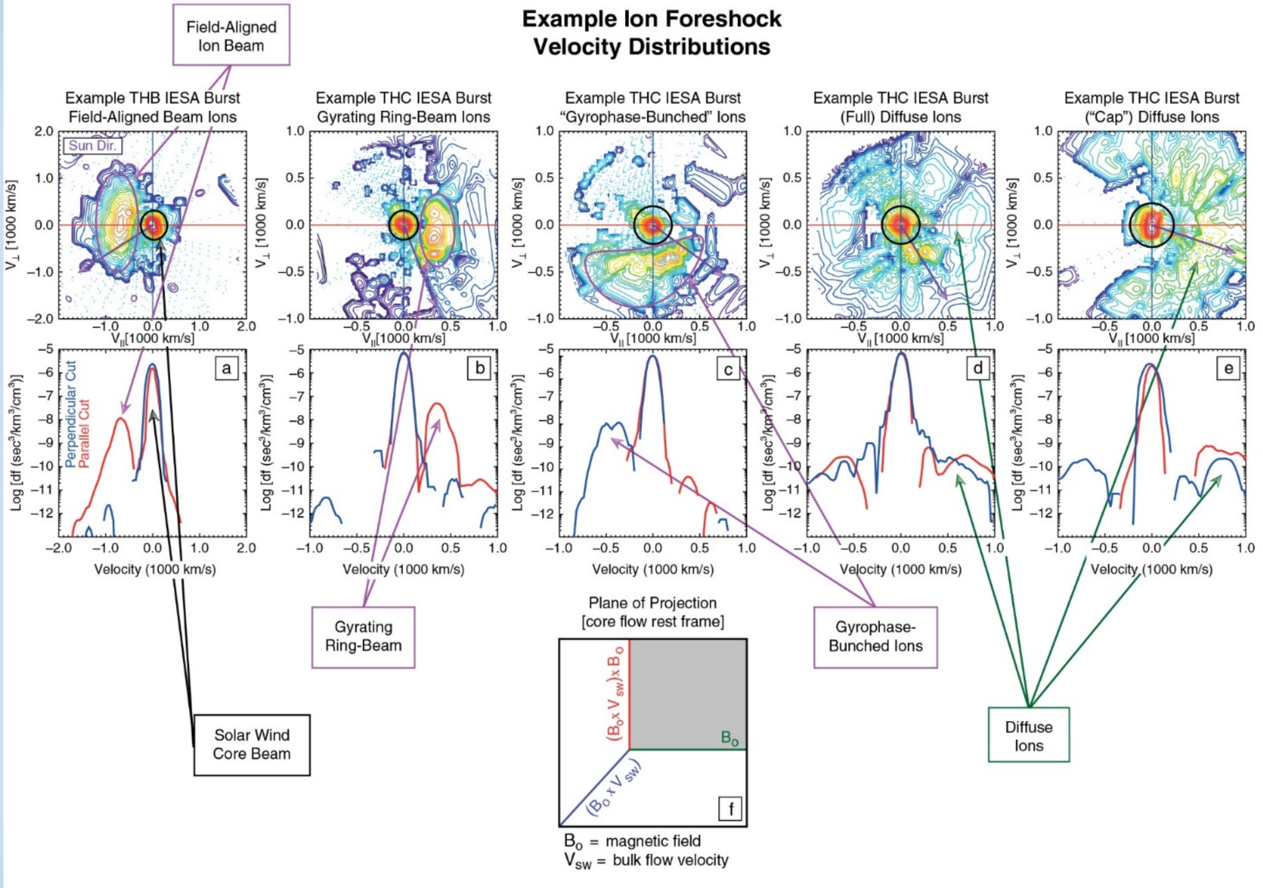
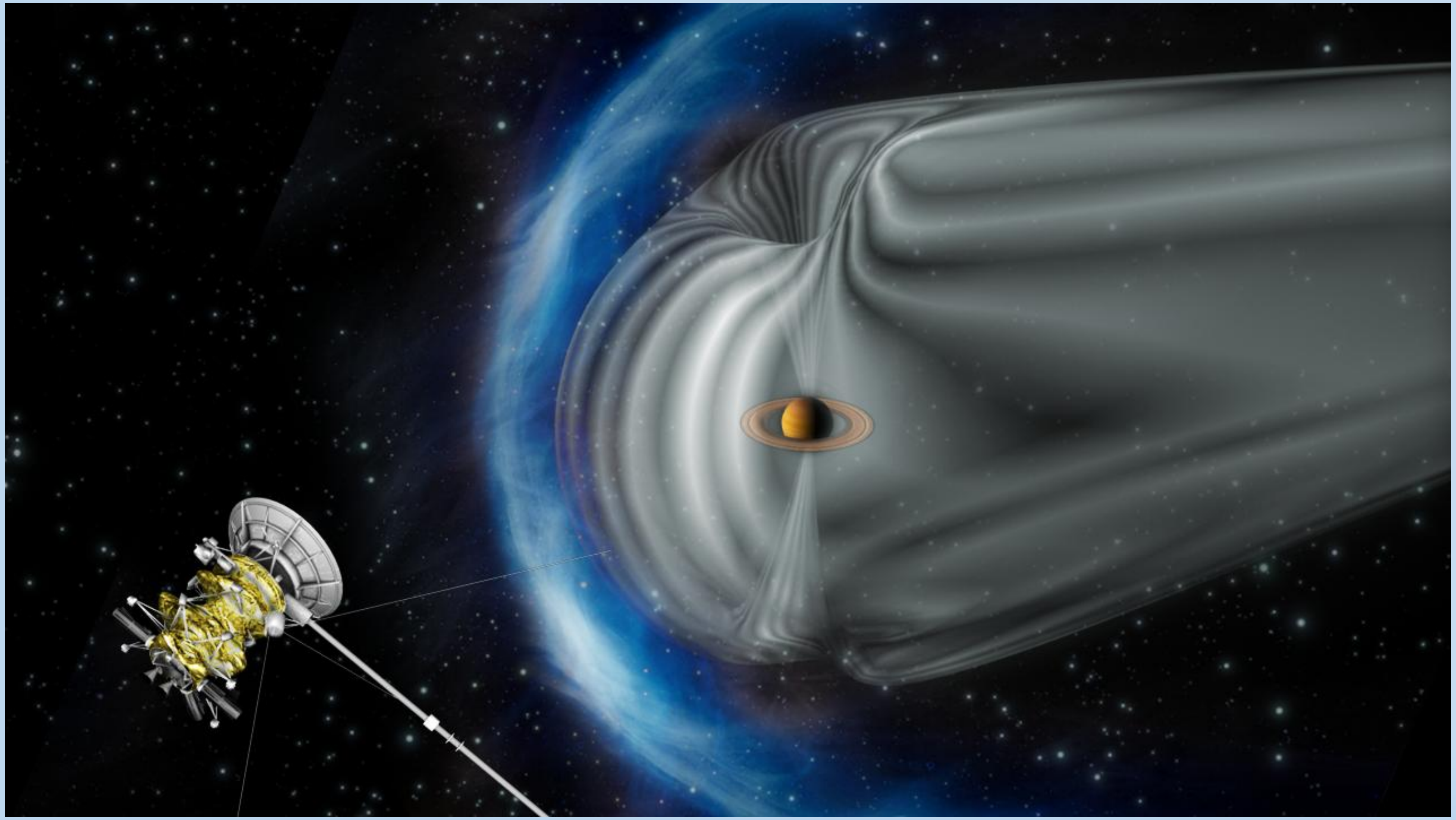


Figure 16.4 Examples of five commonly observed ion velocity distributions (a–e) in the terrestrial foreshock measured by the THEMIS IESA instrument [*McFadden et al.*, 2008a, b]. In each panel, the top plot shows contours of constant phase space density ($s^3 km^{-3} cm^{-3}$) versus velocity in the bulk flow rest frame (coordinate basis and plane of projection shown as gray-shaded region in panel f), while the bottom plot shows cuts along the parallel (red line) and perpendicular (blue line) velocity directions. In a–e, the solar wind beam is encompassed by a black circle, the sun direction is shown as a purple arrow, and the relevant features are marked by arrows and/or a magenta outline. The "cap" diffuse ion distribution shown in panel e was recently described by *Kempf et al.* [2015].

Wilson 2013

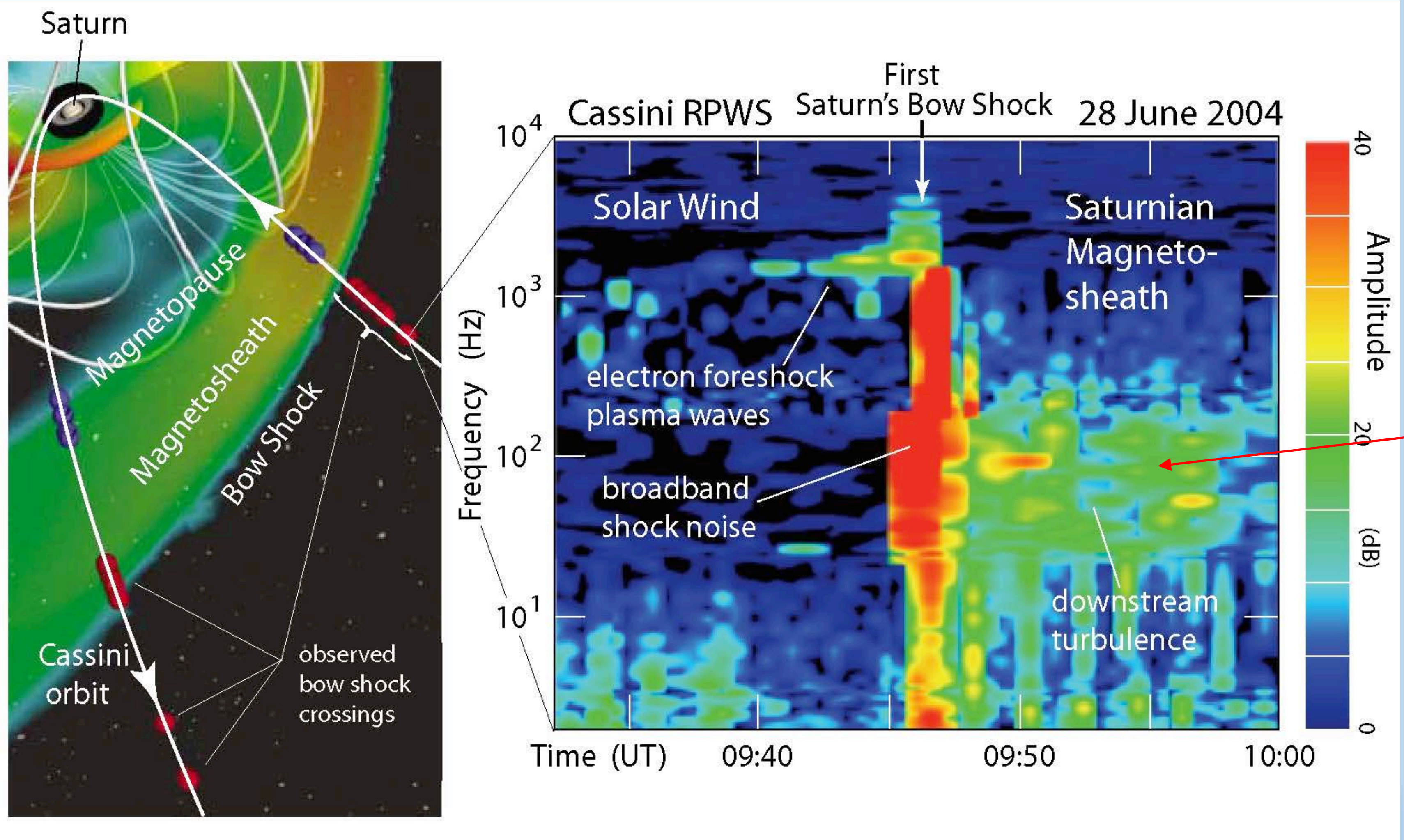
Saturn’s Bow Shock
(Cartoon with Cassini)



Saturn is special:

Large Solar wind Mach #
High β
Mostly quasi perpendicular

What Does Cassini See?



Plasma waves

Sulaiman et al 2016

Some Saturn Bow Shock Crossings by Cassini

P_{dyn} is ram pressure

SULAIMAN ET AL.: SATURN'S BOW SHOCK

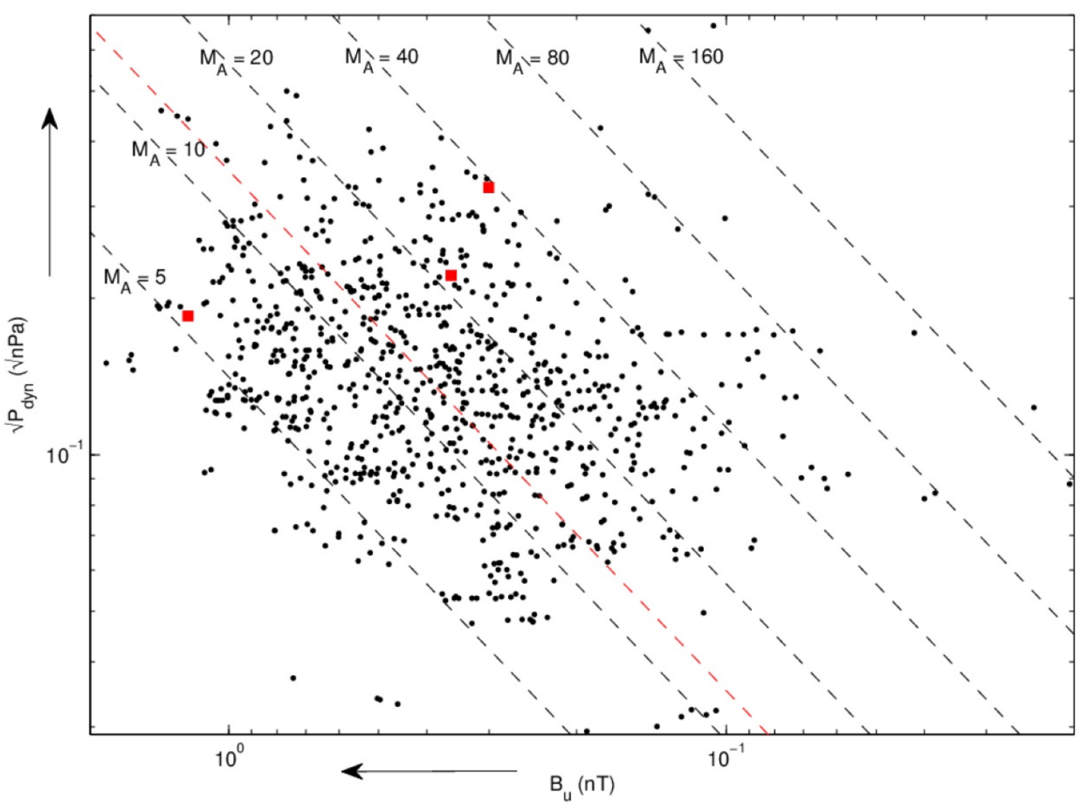


Figure 2.: M_A parameter space of $\sqrt{P_{dyn}}$ vs B_u on a log-log scale. Note abscissa is increasing from right to left. Each marker represents a shock crossing. The three red markers are examples in Figure 3. Contours are overlaid as black dashed lines satisfying Equation 3 and represent lines of constant M_A. The red dashed line is the median M_A of 14.

IPM Field Strength
& Alfven Mach number

$5 < M_A < 40$
(most)

Sulaiman et al 2016

Saturn Quasi Perpendicular Bow Shock Structures

M_A ~ 5
θ_{Bn} = 65°

M_A ~ 25
θ_{Bn} = 81°

M_A ~ 33
θ_{Bn} = 77°

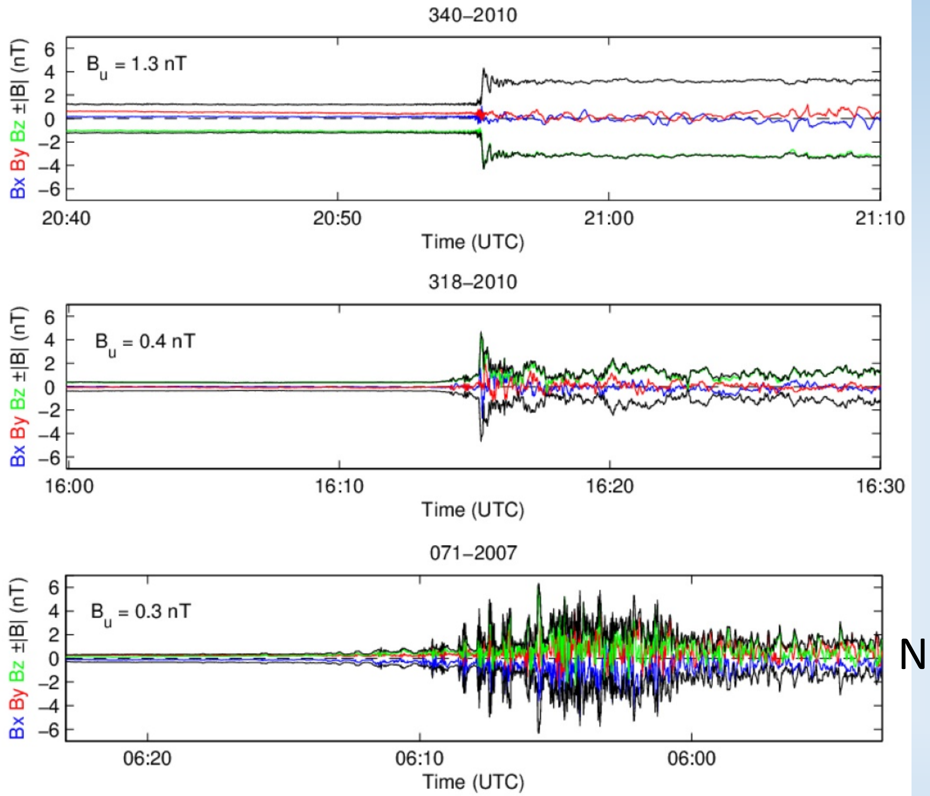


Figure 3.: Three magnetic field time series of quasi-perpendicular shock crossings of increasing M_A corresponding to the three red markers on Figure 4.6. From top to bottom: $M_A \sim 5$ & $\theta_{Bn} = 65°$, $M_A \sim 22$ & $\theta_{Bn} = 81°$ and $M_A \sim 33$ & $\theta_{Bn} = 77°$. The top two panels are inbound crossings. The bottom panel is an outbound panel with the time series reversed.

M_A

Note significant "magnetic overshoot"

Sulaiman et al 2016

ICM Shocks:
Focus on Cluster Formation Shocks

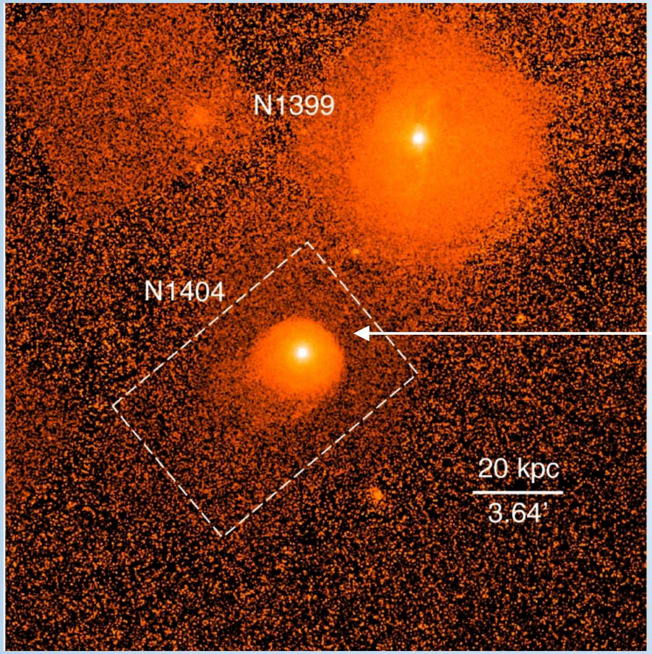
e.g., Accretion & Mergers

But, there are others, including bow shocks

ICM Shock (X-ray) Examples:

Bow Shock of Galaxy NGC1404 moving in the Fornax Cluster ICM

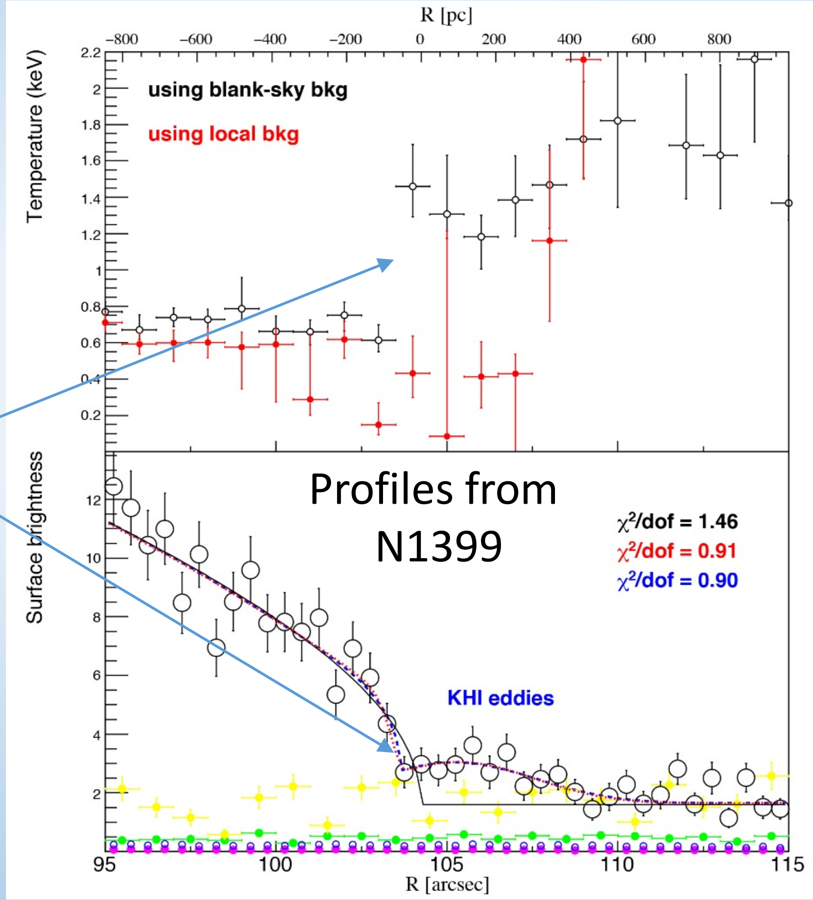
Chandra X-ray Image



Bow Shock

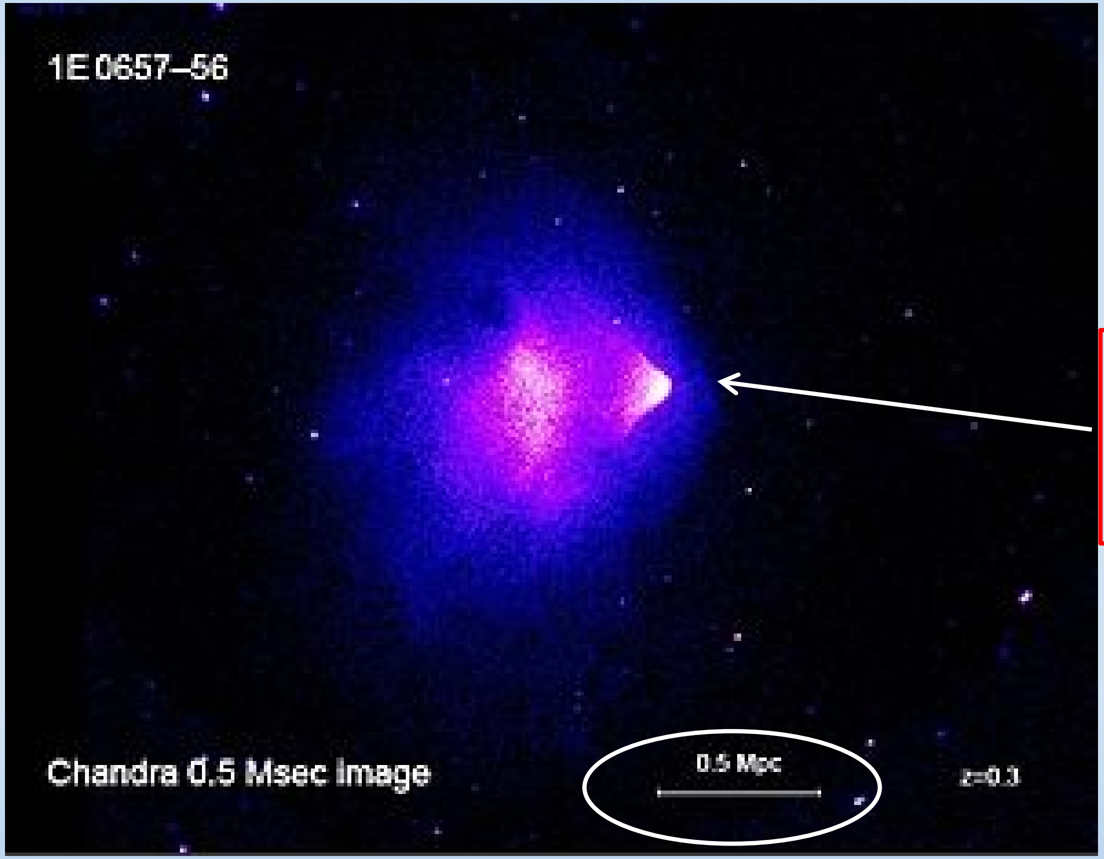
λ_{Coul} ~ 700 pc

δ_{shock} < 50 pc



Su + 2016

Cluster Scale Shock Examples:
"Bullet" Cluster X-ray Merger Shock

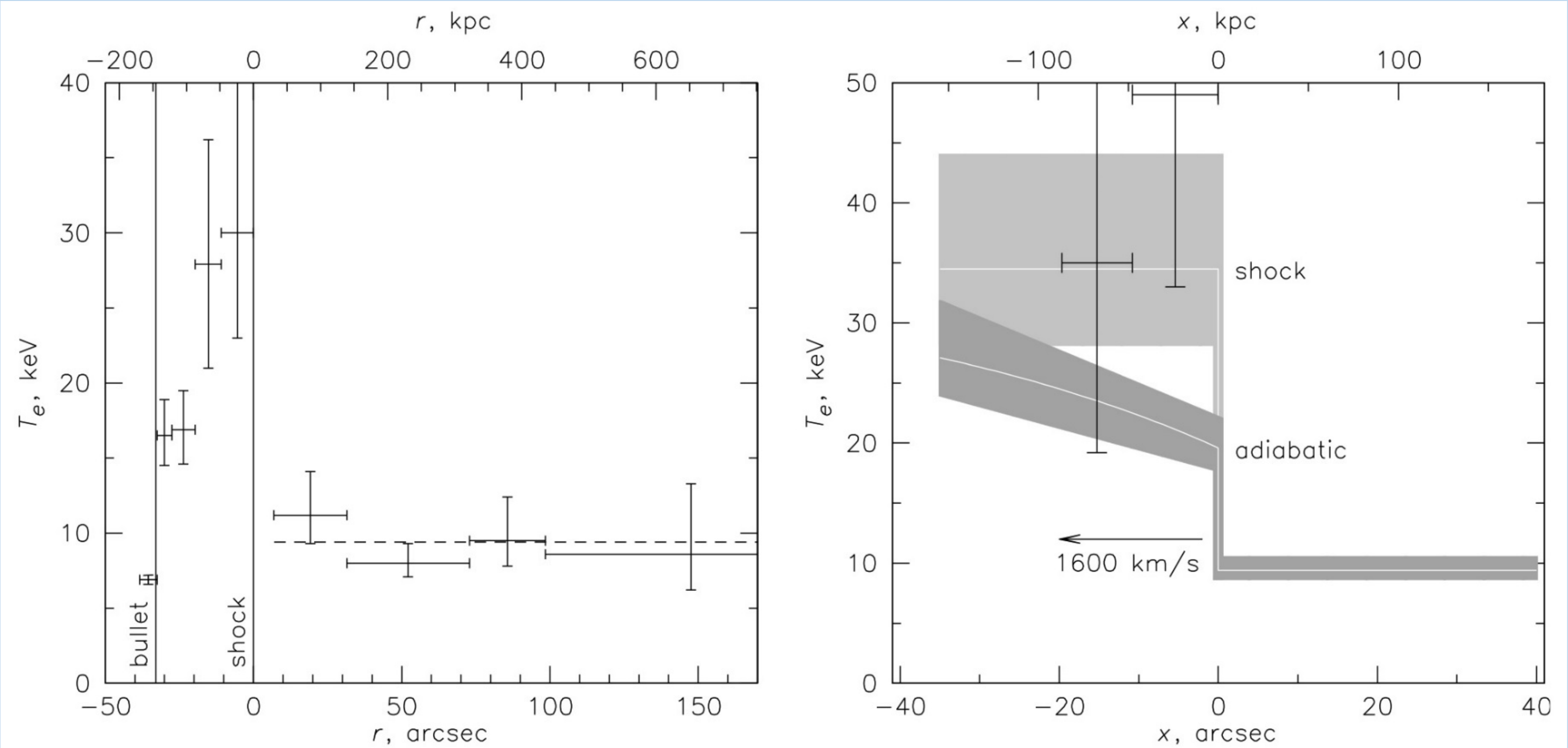


Merger Shock
M ~ 3
X-ray thickness, δ_{shock} < 2 kpc

$\lambda_{coulomb}$ ~ 10 kpc

Markevitch 05

Bullet Cluster X-ray Shock Profile



$M_s \sim 3$

Markevitch 05

Shocks in Cluster Formation Simulation

ICM Density volume rendering

(Major Merger
~ 2/3 through the
Movie)

6.3 Mpc subvolume
Δx = 20 kpc

Movie spans
~ 10 Gyr

Vazza + (TJ) 2017

Shocks in Cluster Formation Simulation

ICM Velocity
volume rendering
Colored by speed
Dark (< 100 km/sec)
“White” > 300 km/sec

(Major Merger
~ 2/3 through the
Movie)

6.3 Mpc subvolume
Δx = 20 kpc

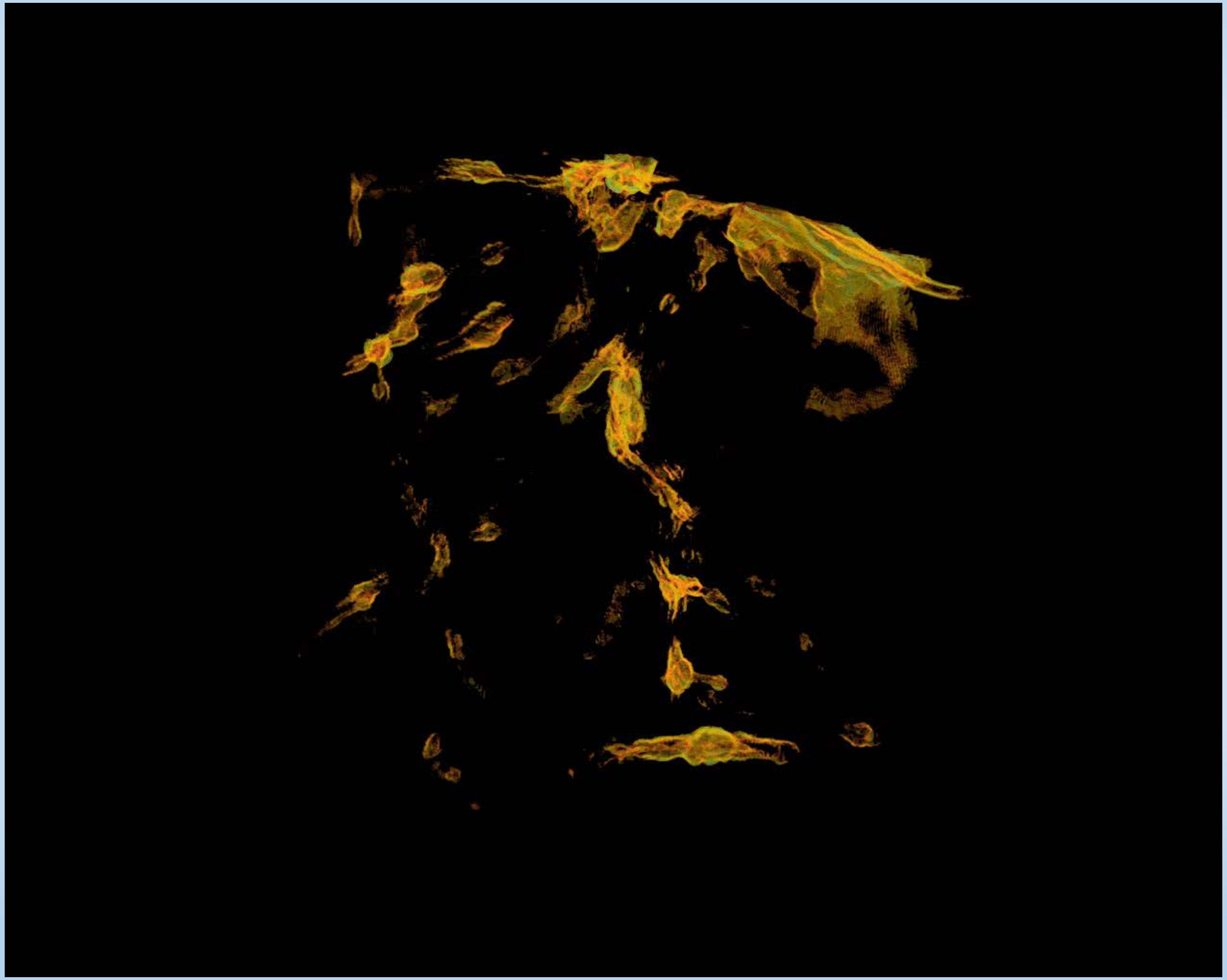
Movie spans
~ 10 Gyr

Vazza + (TJ) 2017

Shocks in Cluster Formation Simulation

ICM Shocks volume rendering
Colored by sonic Mach number
(red M~ 1.5)
(blue M ~ 20)

(Major Merger ~ 2/3 through the Movie)



6.3 Mpc subvolume
Δx = 20 kpc

Movie spans ~ 10 Gyr

Vazza + (TJ) 2016

Shocks in Cluster Formation Simulation

ICM Turbulence
“Intensity”
(vorticity)
Volume rendering

(Major Merger
~ 2/3 through the
Movie)

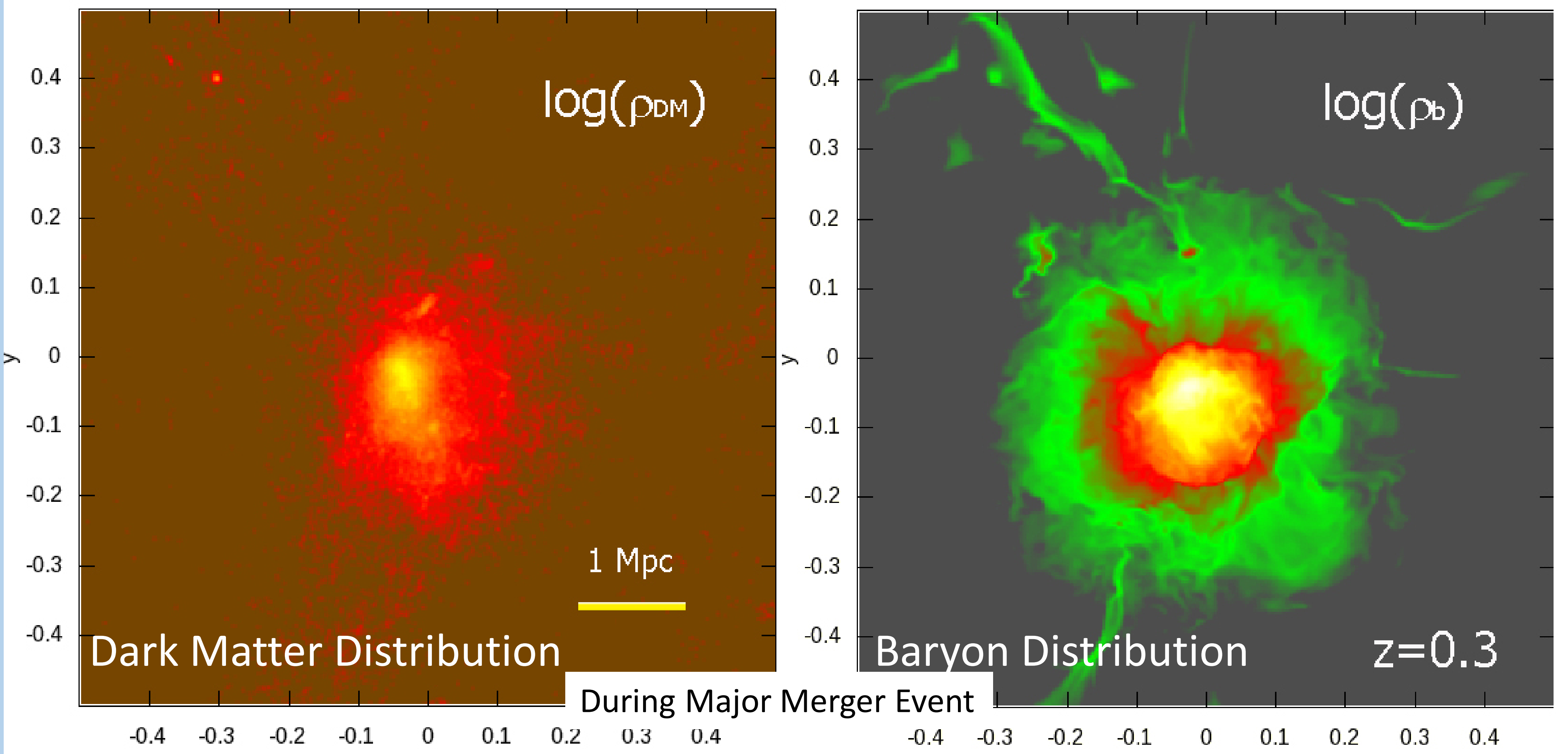
6.3 Mpc subvolume
Δx = 20 kpc

Movie spans
~ 10 Gyr

Vazza + (TJ) 2017

2D Snapshots

Slice Through Cluster Center

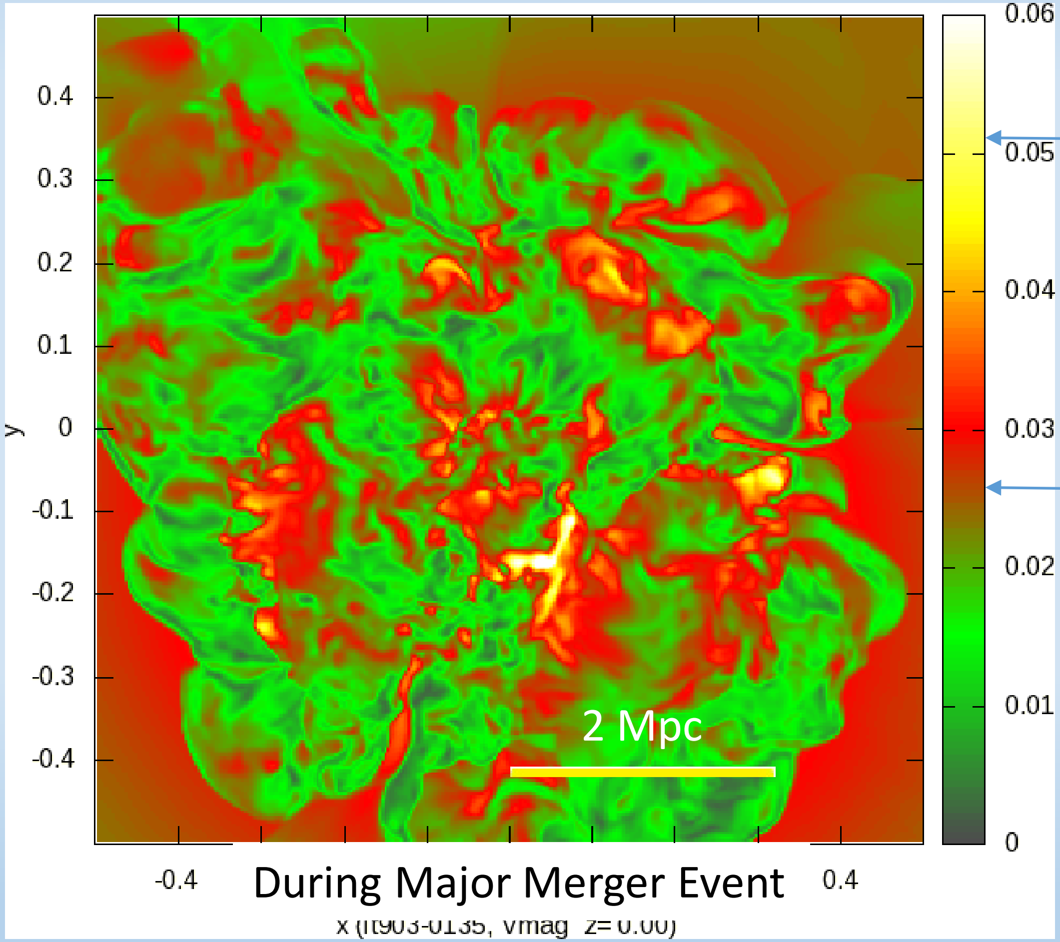


During Major Merger Event

2D Snapshots

Slice Through Cluster Center

ICM Flow Velocity
(code units)



During Major Merger Event

800 km/sec

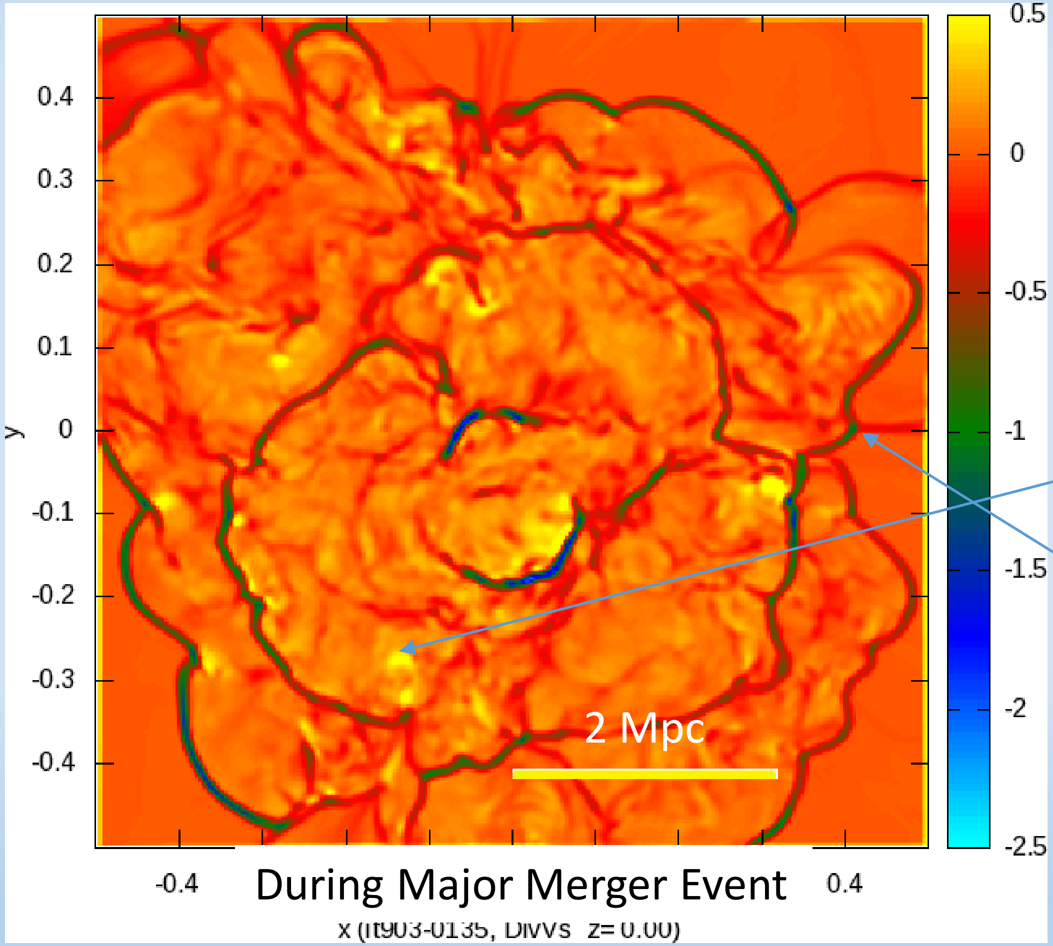
400 km/sec

z = 0.3

2D Snapshots

Slice Through Cluster Center

Div V_{ICM}
(rate of expansion)



During Major Merger Event

rarefaction

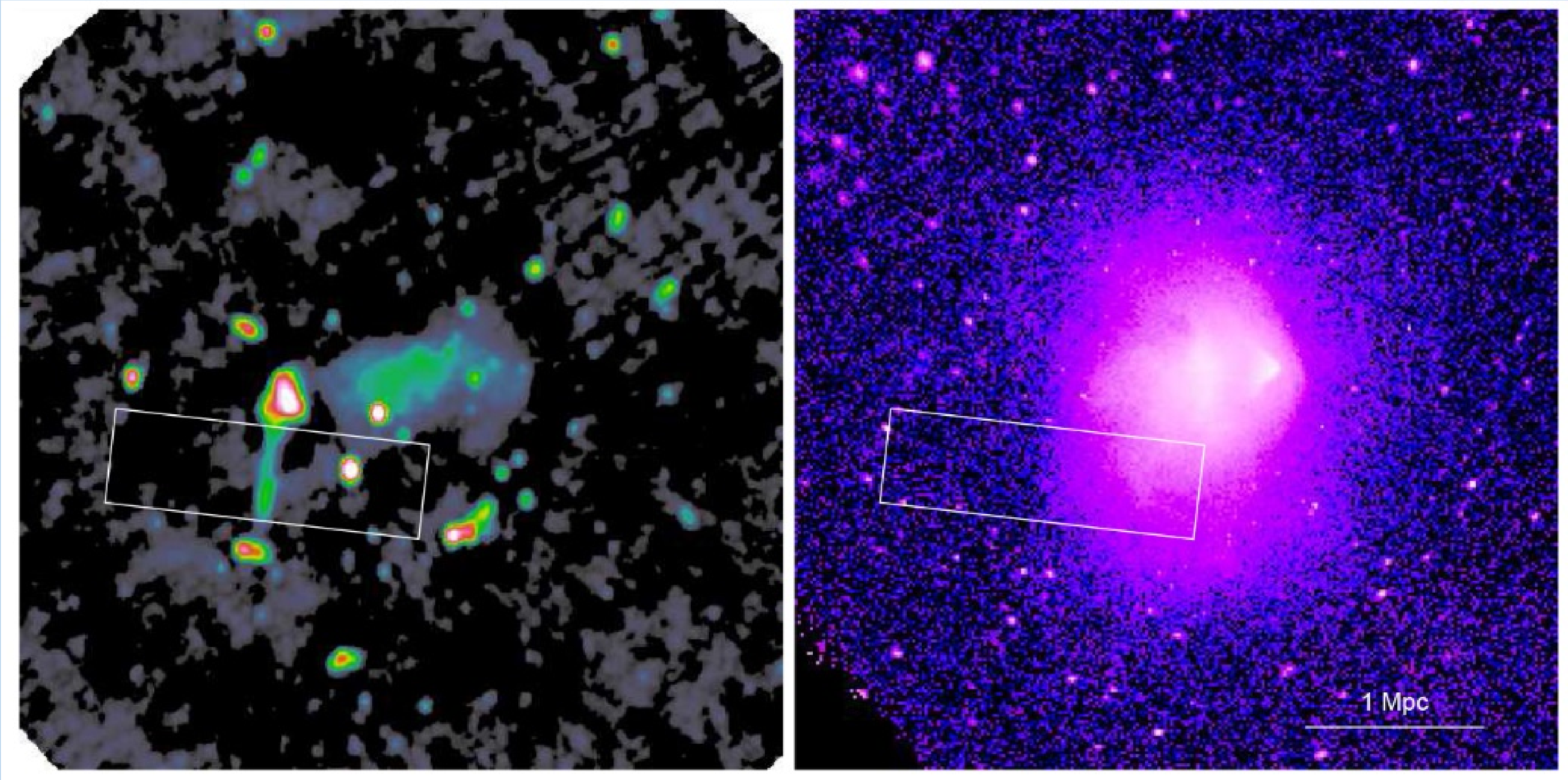
compression

rarefaction

shock

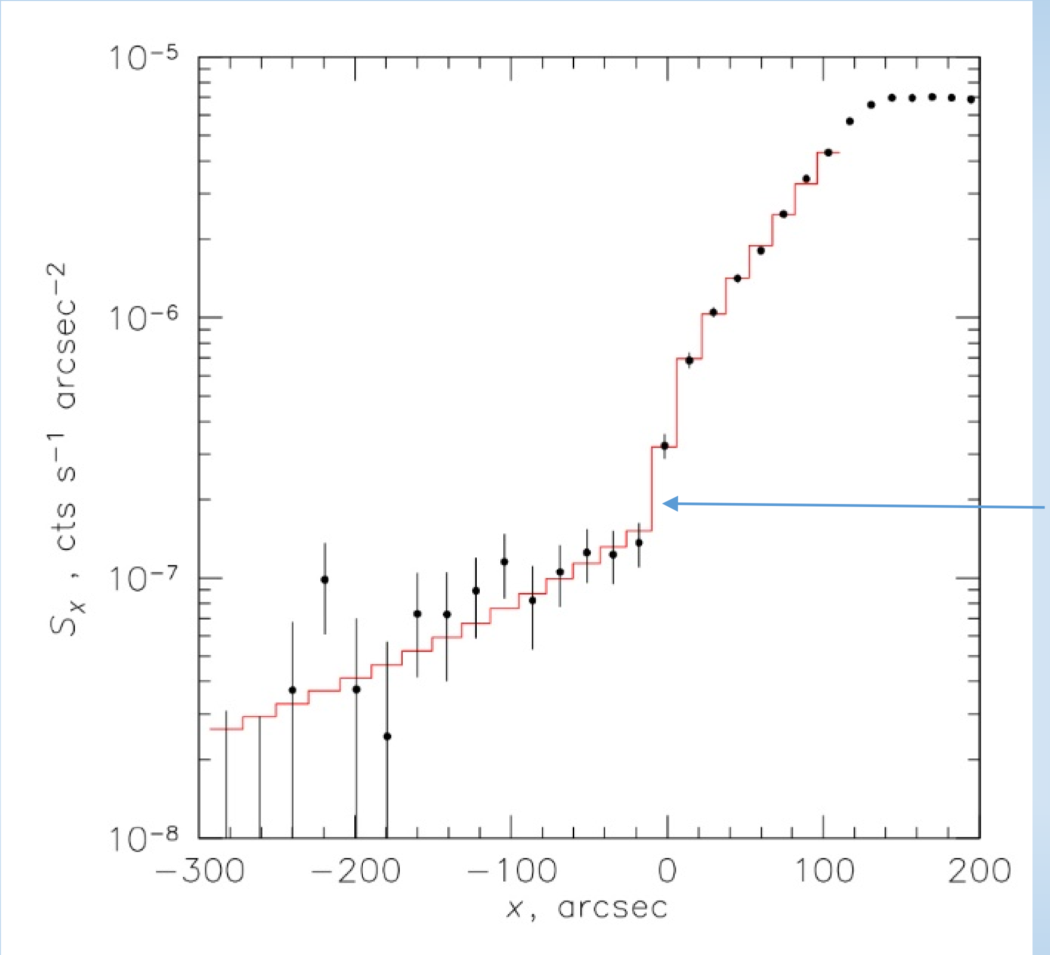
z = 0.3

Merging Cluster Shocks Sometimes Illuminated as Synchrotron "Radio Relics": Example: Eastern Merger Shock in Bullet Cluster



Shimwell et al 2014

X-ray Profile Across Bullet Relic (East)

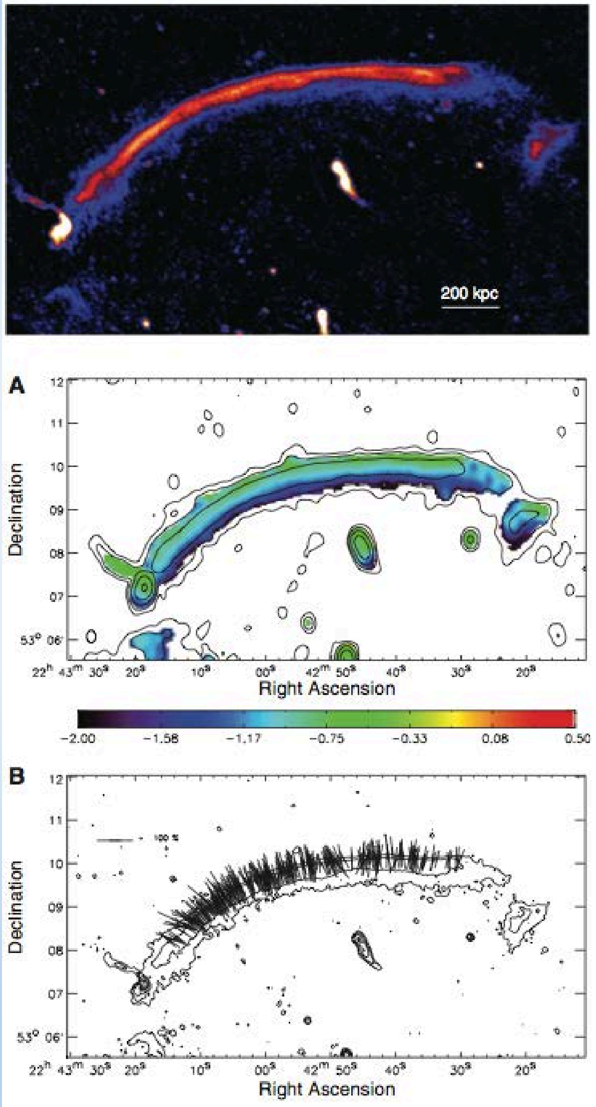


M_s ~ 2.5
Shock

Shimwell et al 2014

Other "Famous" Examples: "Sausage Cluster" (CIZA J2242.8+5301)

GMRT 610 MHz



X-ray and radio "shock estimates"
$M_s \sim 3 - 4$

Van Weeren etal 2010

Other “Famous” Examples:
“Toothbrush Cluster” (IRXS J0603.3+4214)

THE ASTROPHYSICAL JOURNAL, 818:204 (19pp), 2016 February 20 VAN WEEREN ET AL.

LOFAR 120-181 MHz

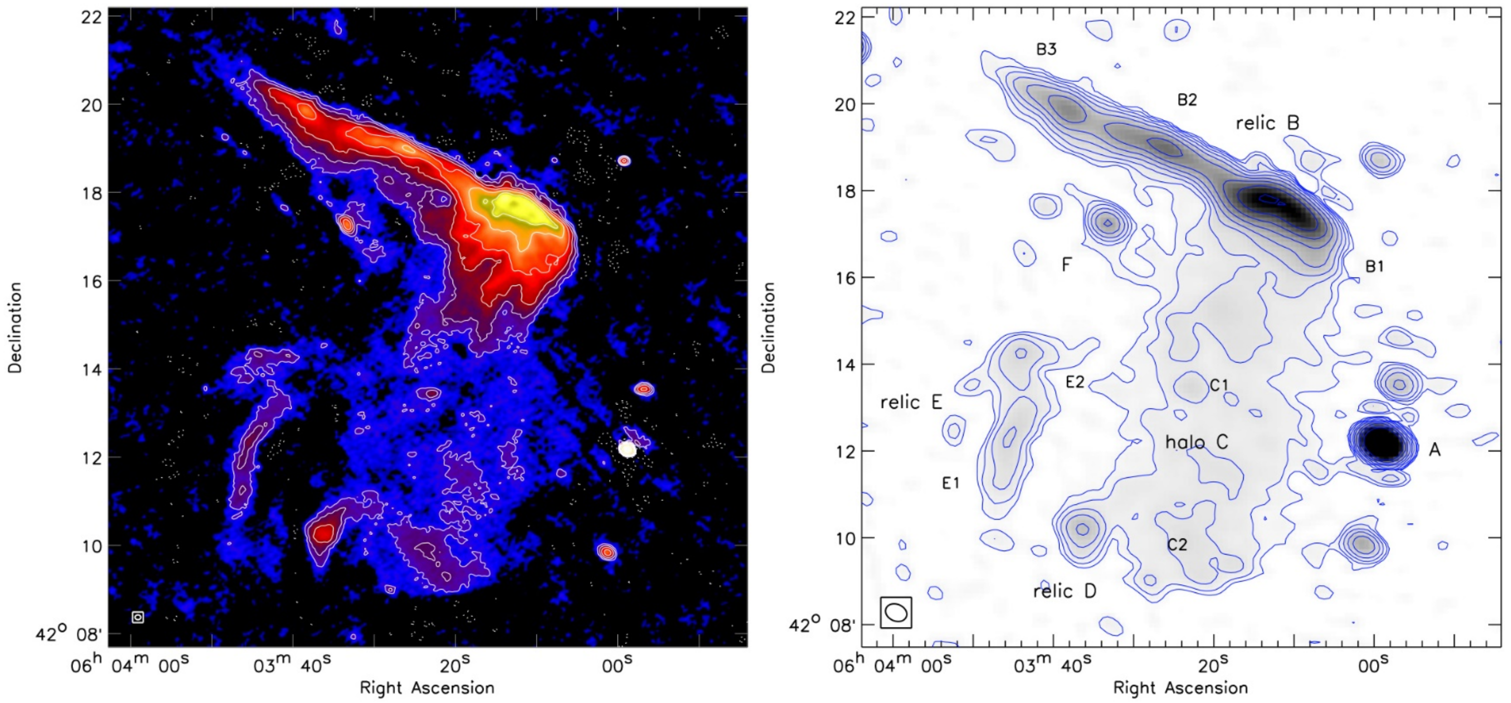
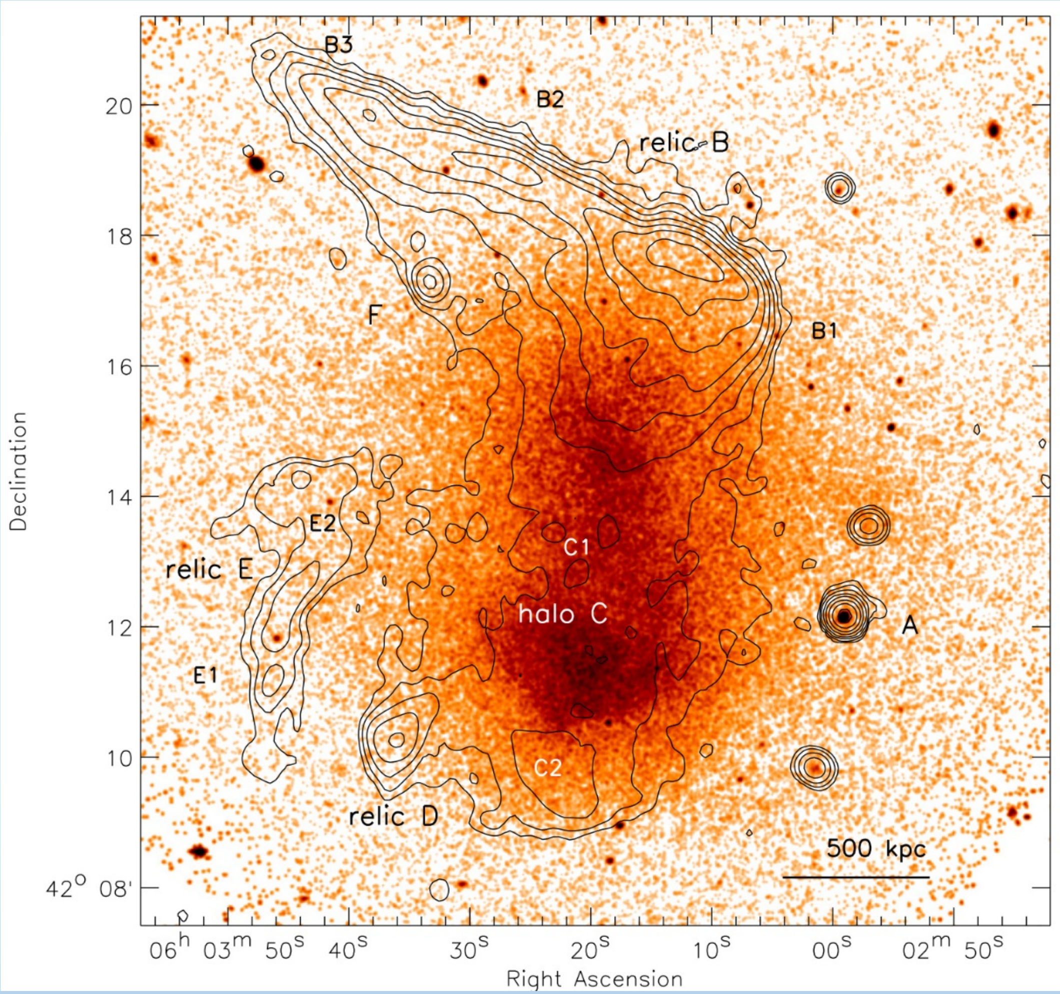


Figure 1. Left: LOFAR HBA 120–181 MHz image. The beam size is 8.″0 × 6.″5 as indicated in the bottom left corner. Contour levels are drawn at [1, 2, 4, 8, …] × $4\sigma_{\rm rms}$, with $\sigma_{\rm rms} = 93\ \mu$Jy beam^{-1}. Negative $-3\sigma_{\rm rms}$ contours are shown with dotted lines. Right: D-array VLA 1–2 GHz image with various sources labelled, following van Weeren et al. (2012a). Some of the sources are further subdivided into numbered components, e.g., relic E is divided into E1 and E2. The beam size is 31″ × 24″. Contour levels are drawn at the same levels as in the left panel, but with $\sigma_{\rm rms} = 35\ \mu$Jy beam^{-1}.

Van Weeren etal 2016

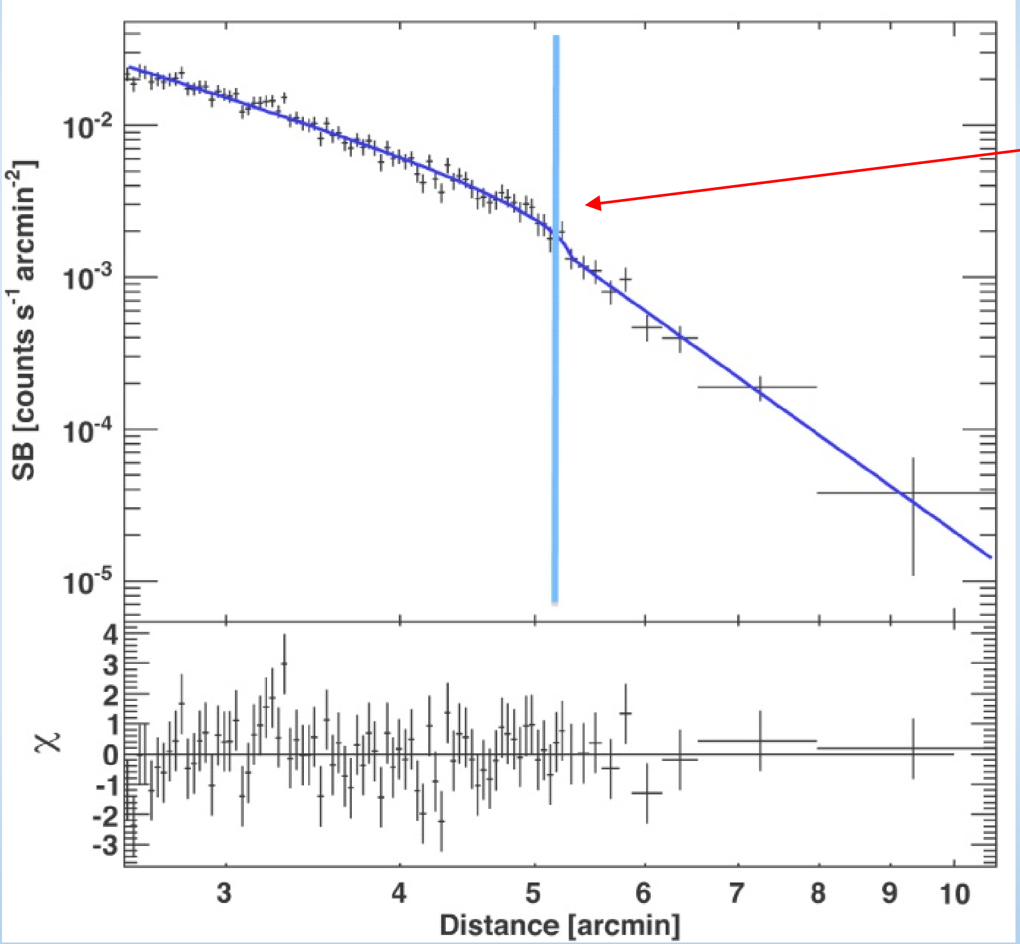
Toothbrush: Radio & X-ray

Contours: radio
Color: X-ray (Chandra)



Van Weeren etal 2016

X-ray Profile Across Toothbrush "Head"

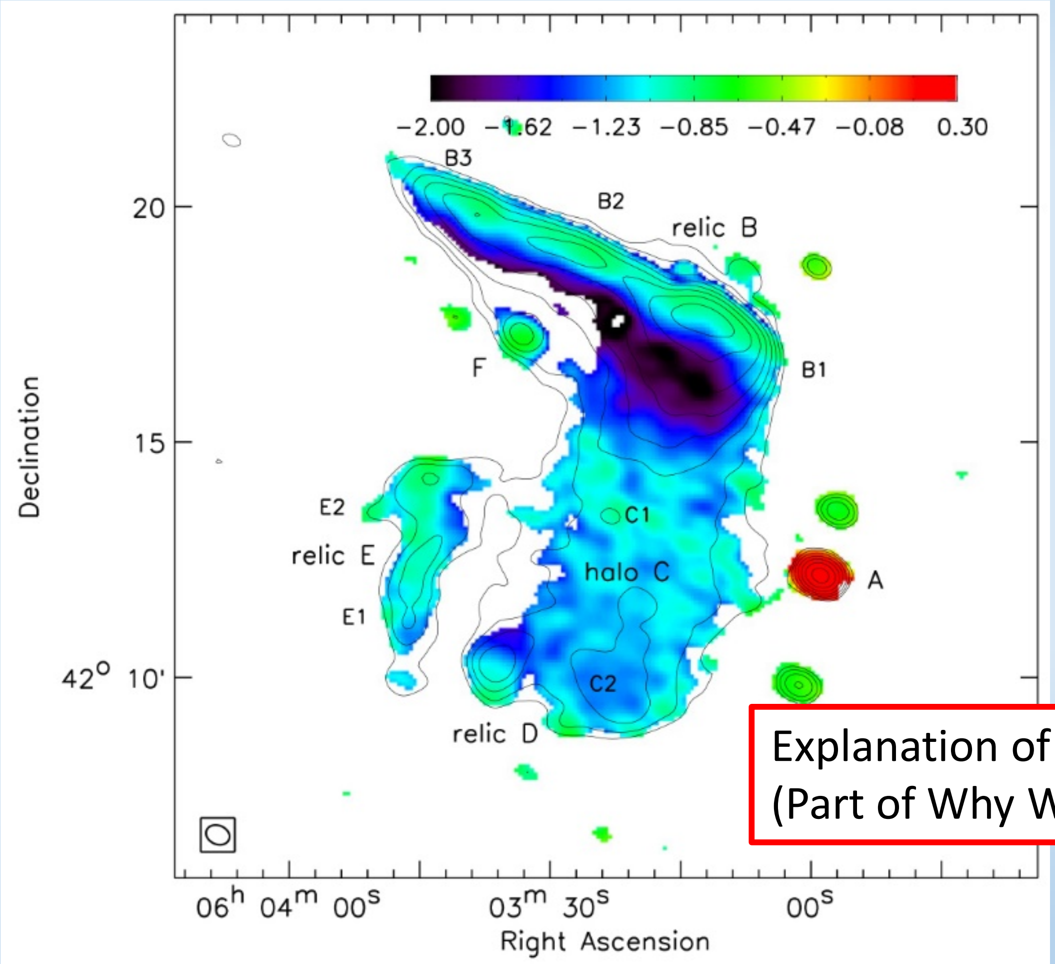


Relic "Leading Edge"

Evidently a Very Weak Shock
σ~ 1.26
M_s < 1.5

Van Weeren etal 2016

Radio Spectral Map Not Consistent with Simple "DSA" Model in this Shock



$N(E) \propto E^{s}$

$s = 2\alpha - 1$

Implying
$s \sim (-2, -3)$

"Standard" DSA

$M_s \sim 3$

Explanation of Relic is More Complex (Part of Why We are Here in Ulsan!)

Van Weeren etal 2016

Summary

- The IPM and ICMs are both collisionless plasmas with microphysics dominated by fast, collective interactions ($\Rightarrow$ "weakly collisional")

- Each is weakly to moderately magnetized:
  -In the IPM $\beta = P_g/P_B \sim (c_s/v_A)^2 \sim 1$ (within an order of magnitude), so $v_A \sim c_s$
  -In ICMs $\beta = P_g/P_B \sim (c_s/v_A)^2 >> 1$, so $v_A < c_s$

- Both media develop shocks up to sonic Mach numbers of a few (ignoring external)
  -In the IPM we can measure the shock (& plasma) properties directly
  -In ICMs we depend on "remote sensing" (X-rays, radio emission & γ-rays)
  We are greatly constrained by both the data and our limited understanding of very complex phenomena

감사합니다!