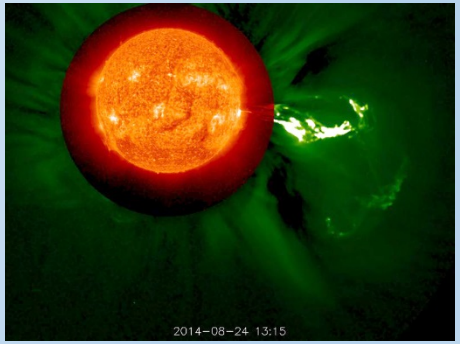
ICMs and the IPM: Birds of a Feather?

Tom Jones

University of Minnesota



Outline:

- ICM plasma is the dominant baryon component in the biggest gravitationally bound structures in the universe

- ICMs are basic barometers of cosmic large scale structure formation dynamics and physics

- ICMs are difficult to study (remote, faint and have cosmological evolutionary timescales)

- The Solar Wind plasma - interplanetary medium (IPM)
  – surrounds us and is available for in-situ study
  – dynamical times are accessible

Plan: Lay out in general terms similarities and contrasts of these two environments

- What insights can the IPM provide to the study of ICMs?

- What common questions of mutual interest can we identify?

ICMs are Very Hot, Very Dilute and Fully Ionized Plasmas

ICMs are Dynamic:

- ✓ Exhibit large scale, structured flows
- ✓ Frequented by shocks
- ✓ Turbulent

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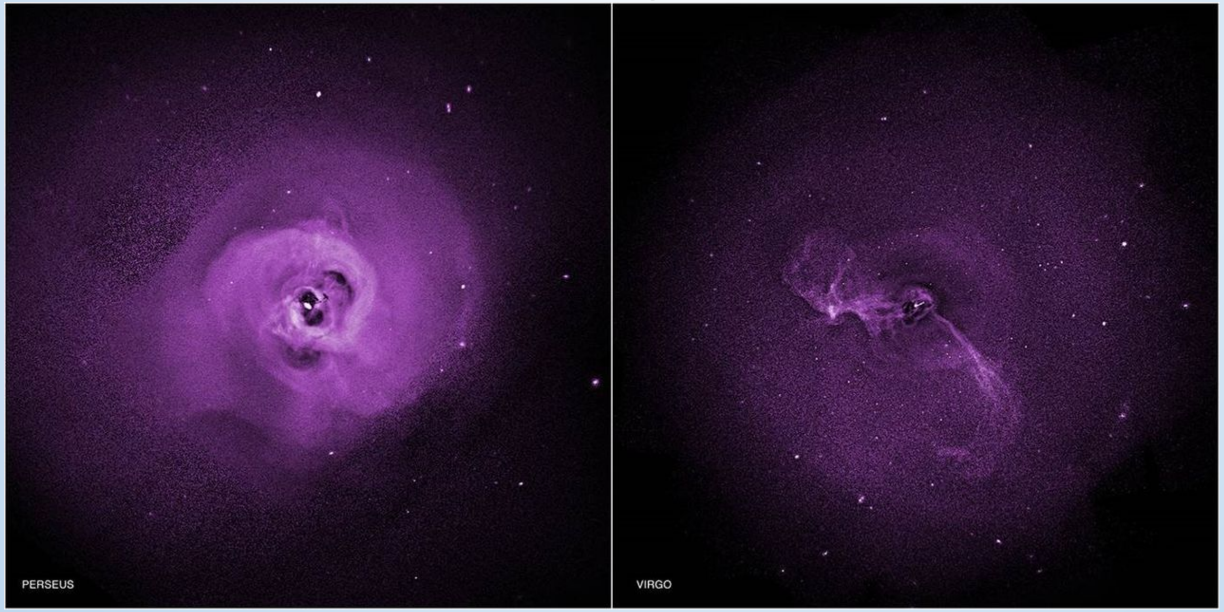

Fabian +

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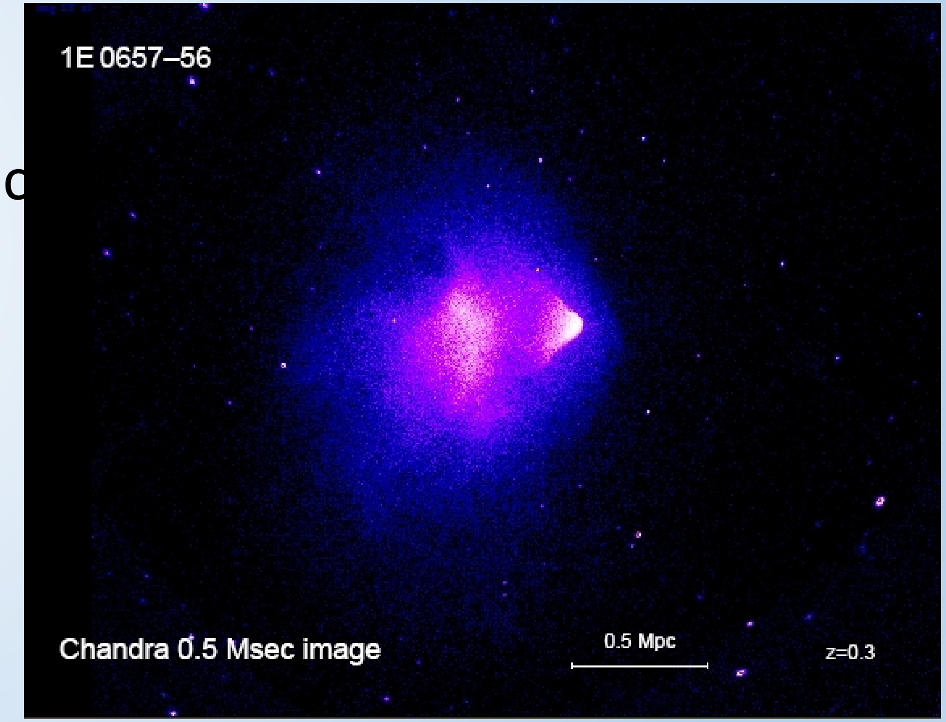

Markevitch +

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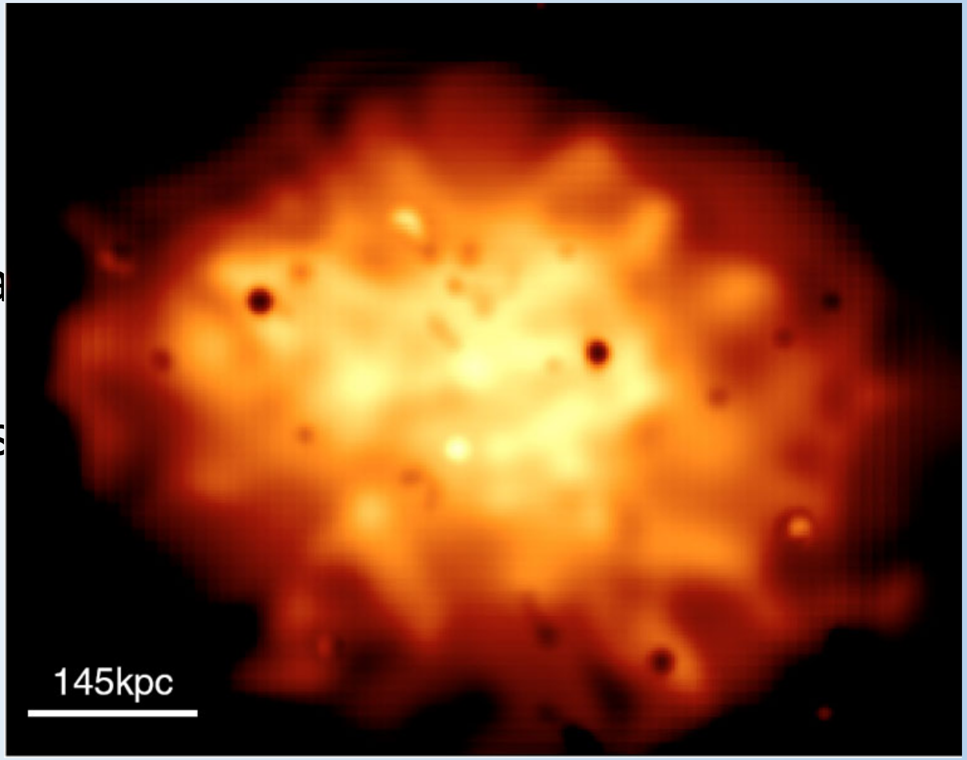

Coma
Schuecker + 04

The IPM is Very Hot, Very Dilute and Fully Ionized Plasma

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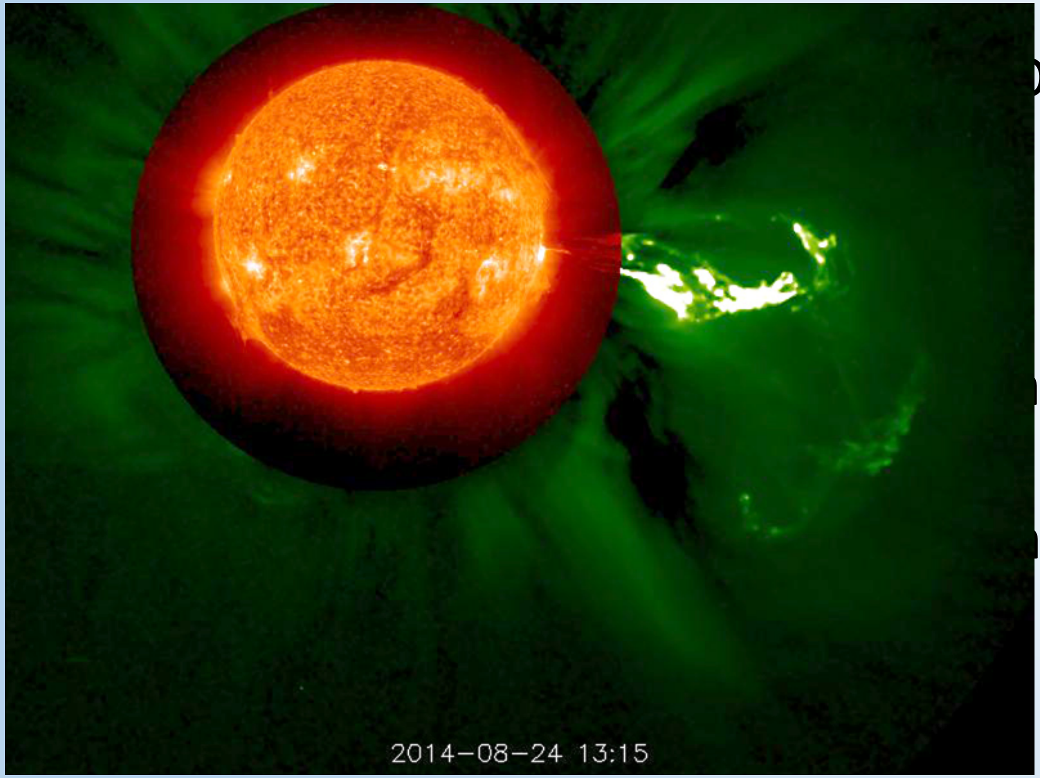
The IPM is Very Hot, Very Dilute and Fully Ionized Plasma



Coronal Mass Ejection (CME) STEREO-HI

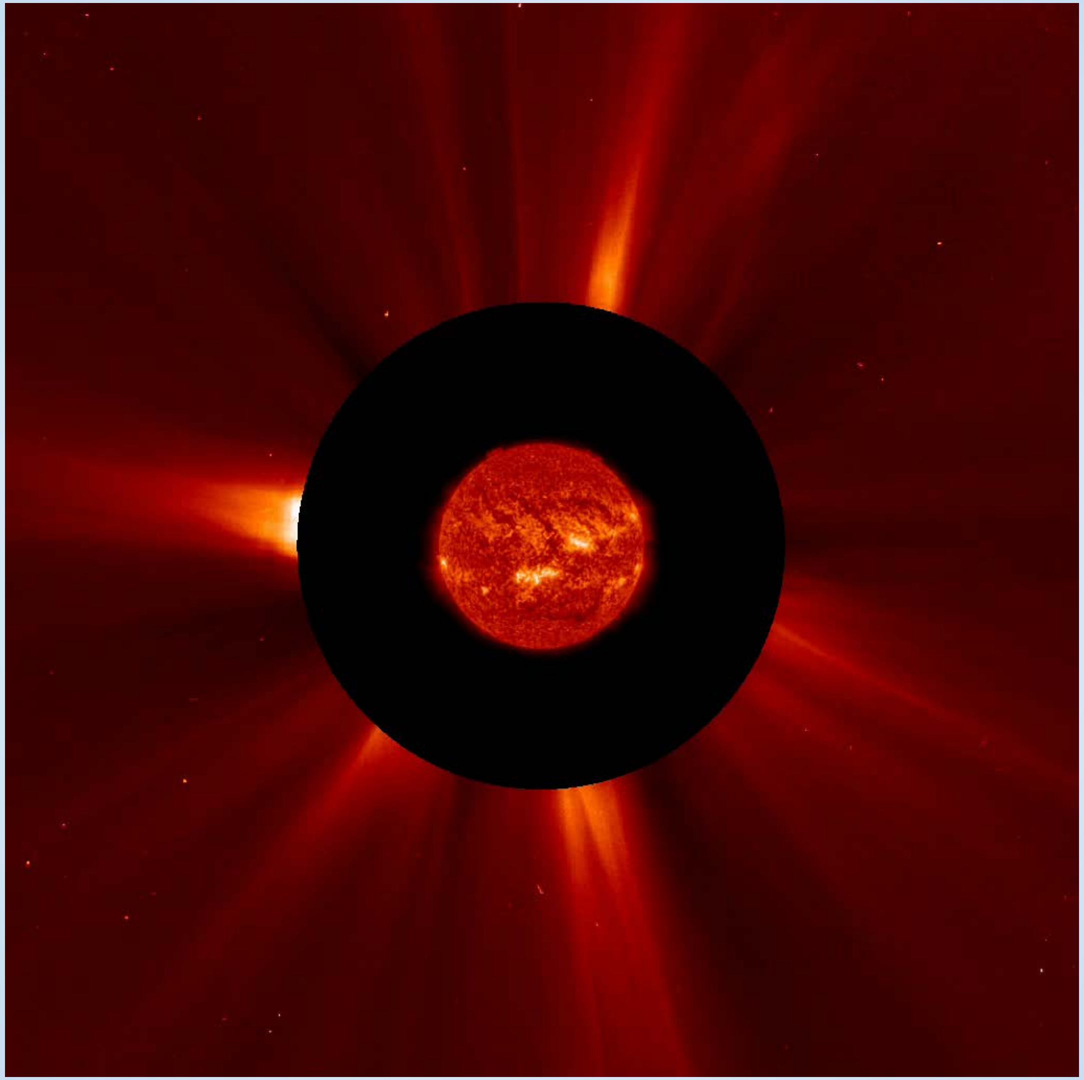
ynamic:

large scale, structured flows

ted by shocks

t

Solar Wind in Action:



Note Shocks from CMEs

STEREO-HI

The IPM is Very Hot, Very Dilute and Fully Ionized Plasma

More Shocks: Bow Shocks

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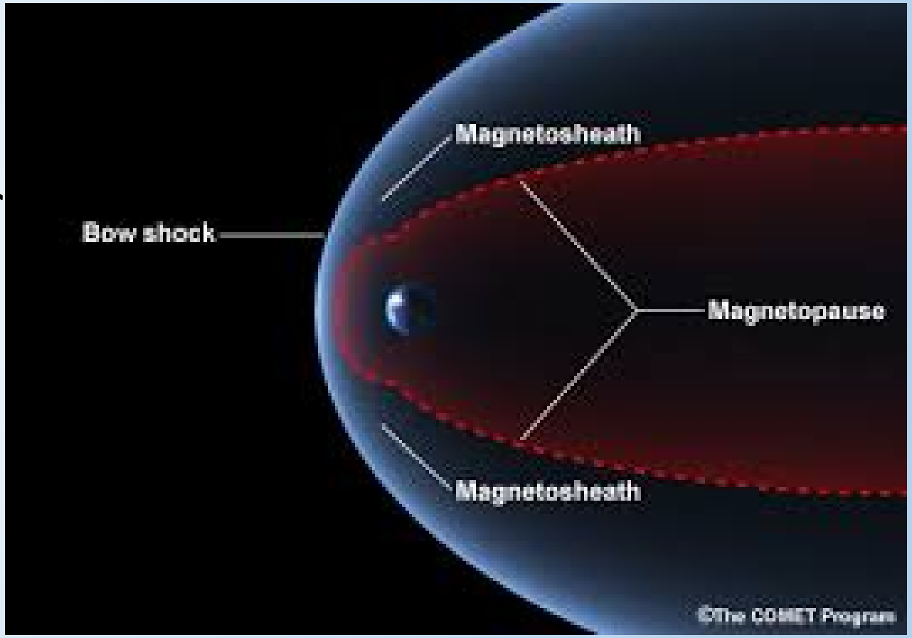


Earth's Bow Shock

The IPM is Very Hot, Very Dilute and Fully Ionized Plasma

The IPM is Dynamic:

- ✓ Exhibits large scale, structured flows
- ✓ Frequented by shocks
- ✓ **Turbulent**

Compare Some (Rough) Primitive IPM & ICM Values:

Measure:	Solar Wind (IPM): R ~ 1 AU	ICM: Outside of cores
kT_e (keV)	~0.01	~1 - 10
n_e (cm^{-3})	~ 1 - 10	~ 10^{-4} – 10^{-2}
P_e ~ 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

*1 μG = 0.1 nT

Some (Rough) Characteristic Micro-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} =ρ_I ~ 5.6x10^4 km $T_{keV}^{(1/2)}$ /$B_{\mu G}$	~ 50 - 500 km	~ 10^4 – 2x10^6 km (r_{sun} ~ 10^6 km)

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

Some (Rough) Characteristic Micro-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

IPM λ_i is comparable to r_{gp}

ICM λ_i is smaller than r_{gp}

*EM field penetration length

**Ions decouple from electrons

Some (Rough) Dimensionless Plasma Measures

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

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

Both media are "good plasmas" $N_d >> 1$
(support collective plasma wave families)

Some (Rough) Characteristic 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" ($\delta v > v_A$)
(MHD for $l < l_A \sim L\ (v_A/\delta v)^3$)

Some (Rough) Shock Parameters

Parameter:	Solar Wind (IPM):	ICM:
$M_s = V_s/c_s$	< 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

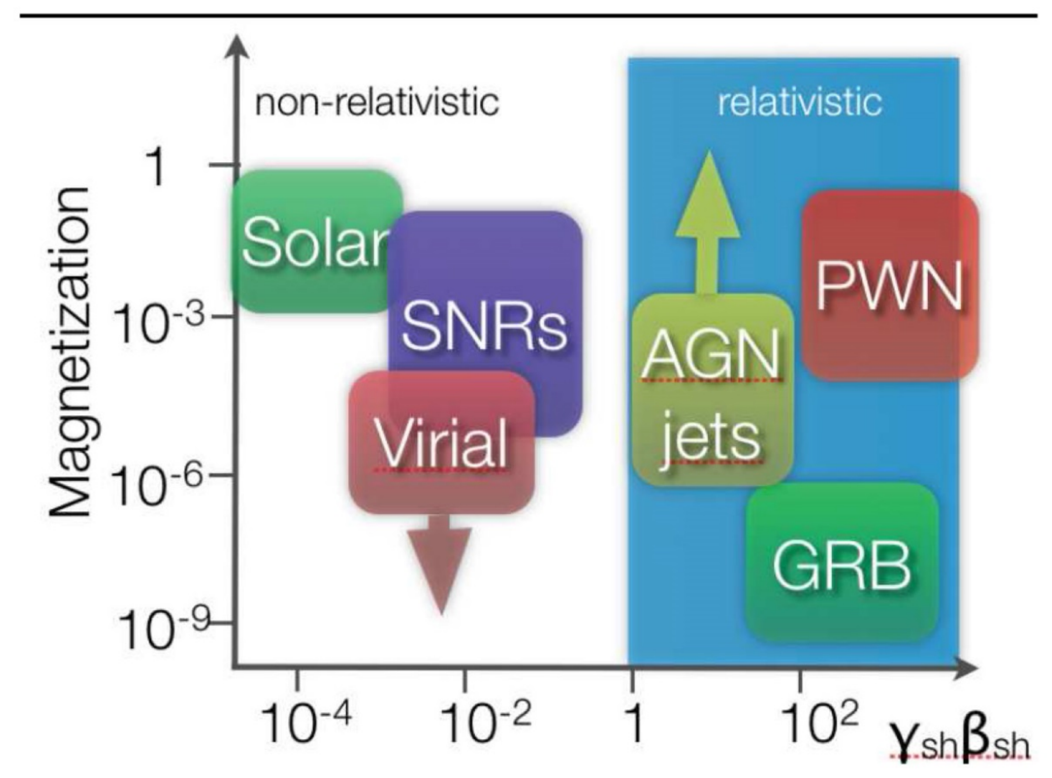
ICM shocks (mostly) have higher Alfvenic Mach numbers than IPM shocks

That is: IPM Shocks are more highly magnetized than ICM shocks

Magnetization:

$$\sigma = \frac{B_0^2/4\pi}{(\gamma-1)n_0 m_i c^2} \rightarrow_{nr} \frac{B_0^2/2\pi}{u_0^2\rho_0} = \frac{12}{5}\frac{1}{\beta M_s^2}$$

$$\gamma = \frac{1}{\sqrt{1-u_0^2/c^2}}$$



Spitkovsky

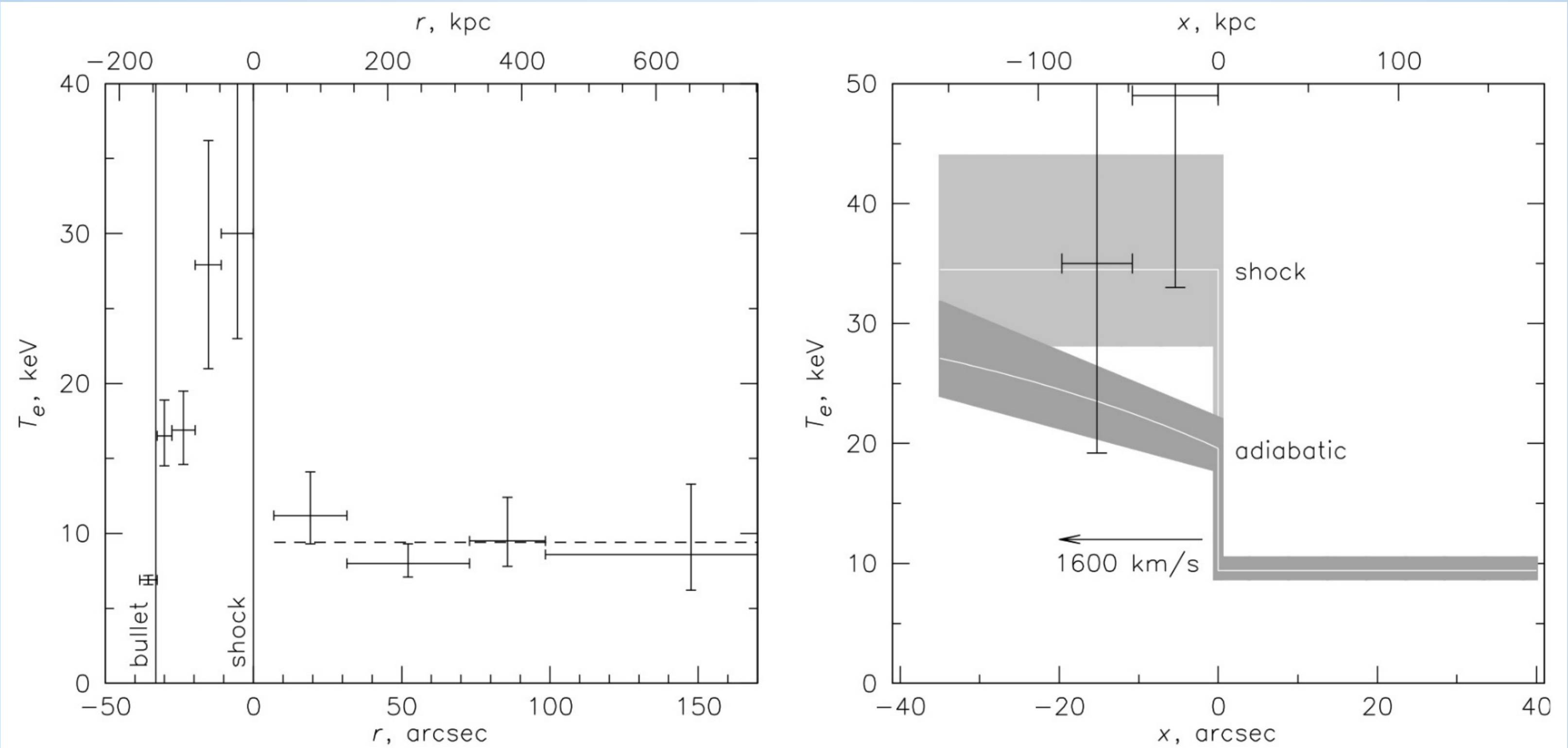
Intermediate Summary

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

IPM magnetic field is relatively stronger, so:
- ✓ 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 Shock Data:

Bullet Cluster Shock Profile

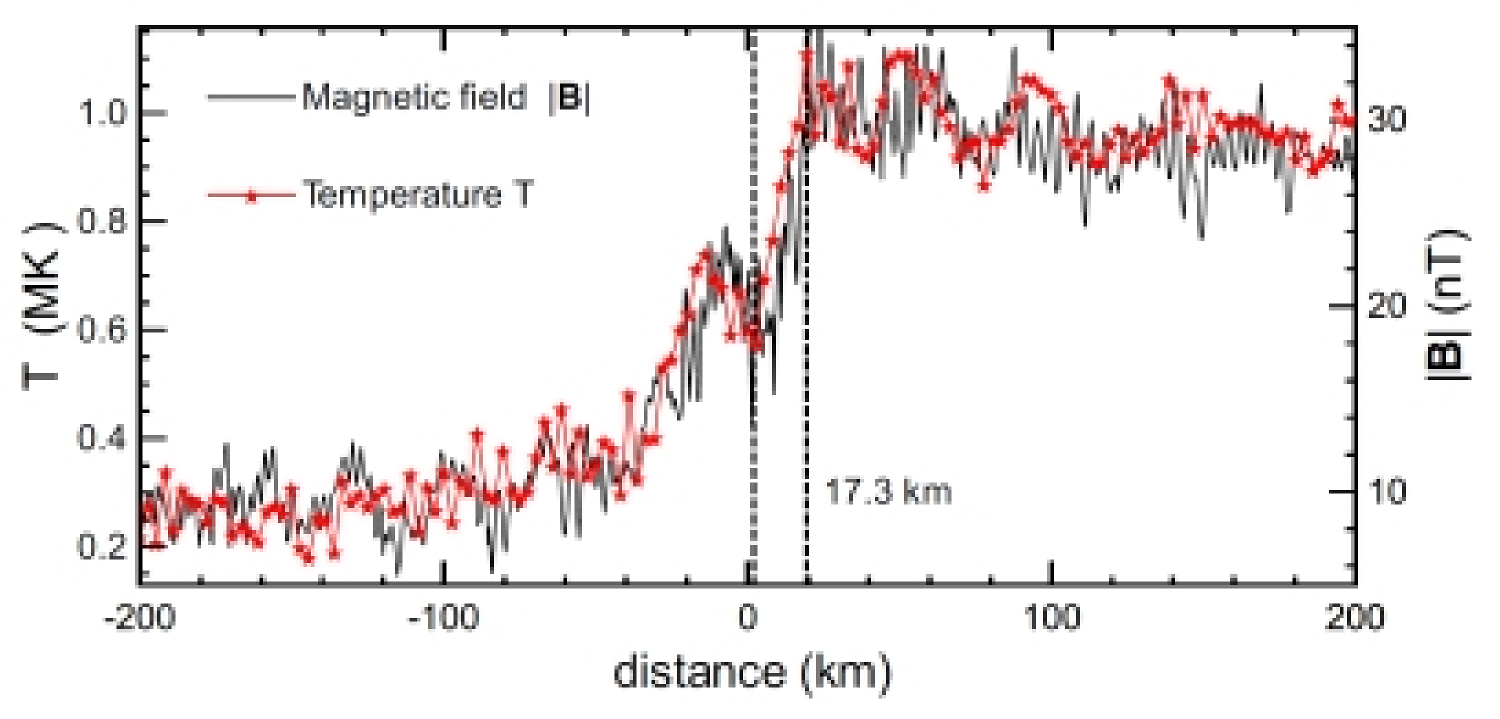


$M_s \sim 3$

Do not resolve shock discontinuity

Markevitch 06

Earth's Bow Shock Profile (Quasi-Perpendicular)



$M_s \sim 3.5$

Thickness "a few ion inertial lengths"

Schwartz + 11

Some Turbulence Data:

Coma Cluster Density Fluctuations (Compressible Turbulence)

In compressible turbulence

$(\delta\rho)^2 \approx \ln(1 + g^2 M^2)$

$M = \delta v / c_s$

g depends on "forcing"

g = 1/3 solenoidal

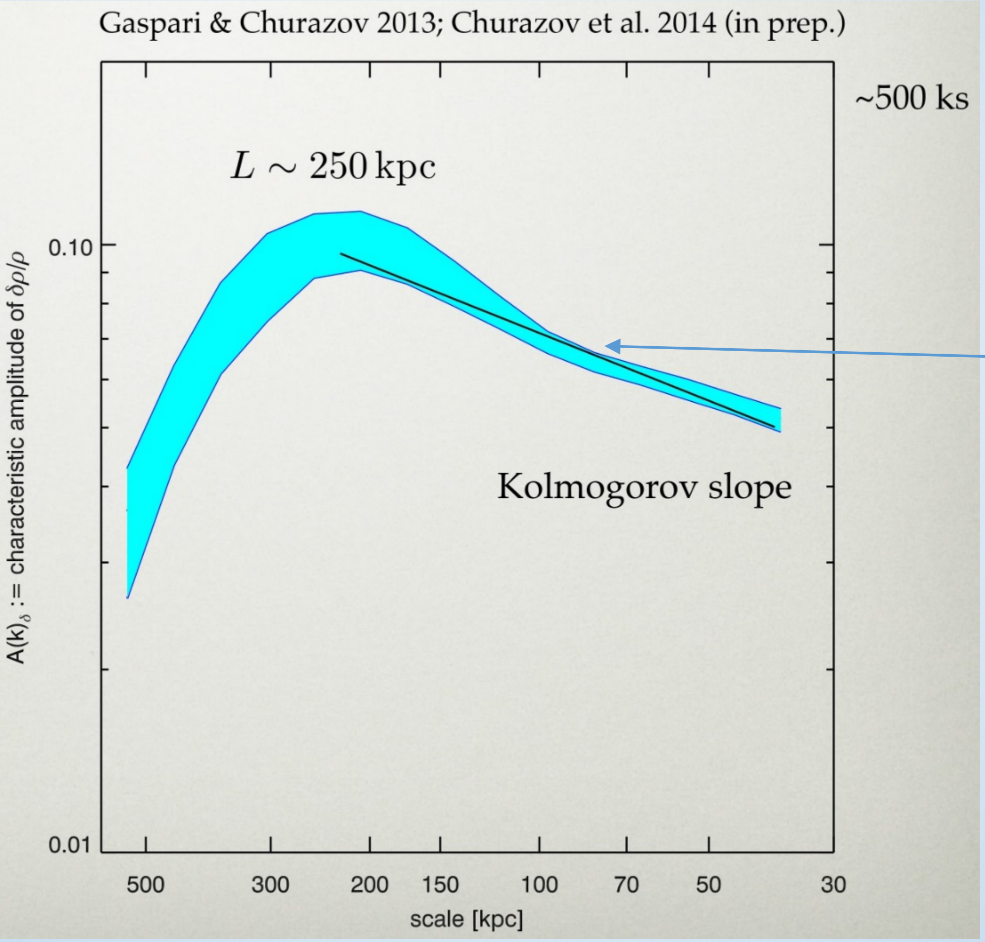
g = 1   compressive

Using g = 1/3

M ~ 0.5

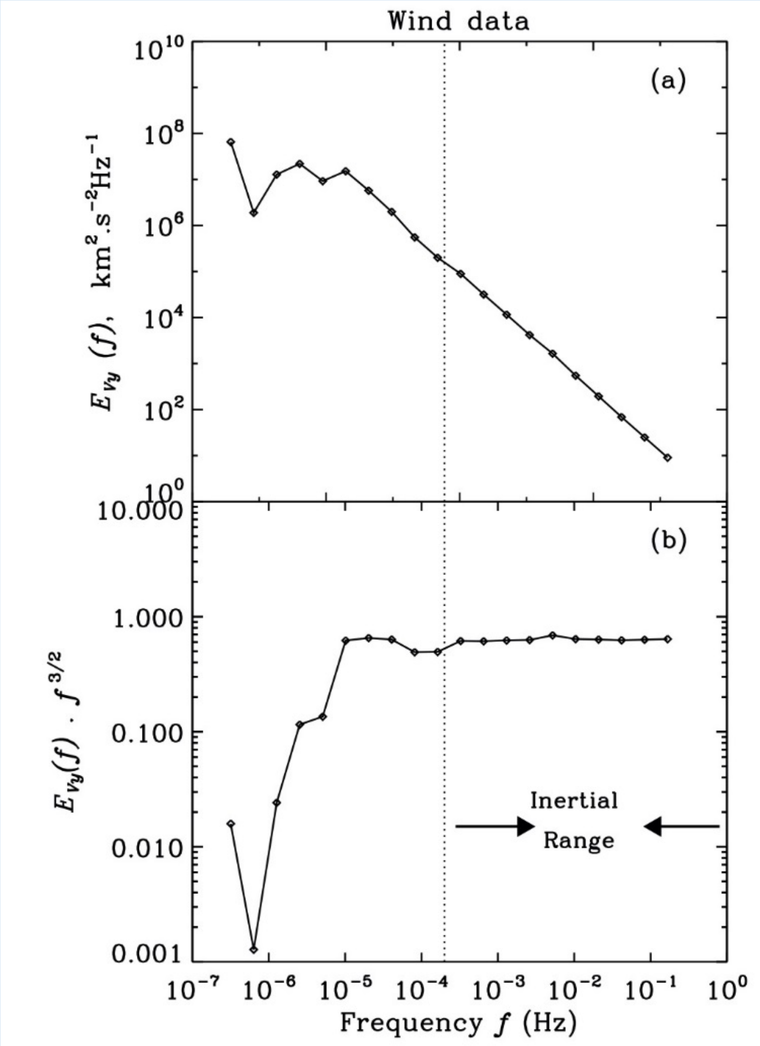
Using g = 1

M ~ 0.1



$\delta\rho \propto l^{(1/3)}$

IPM Turbulent Velocity Data



$$\ell \sim \frac{V_w}{f} \sim 400 \text{ km } \frac{1}{f} \sim 3 \times 10^{-6} \text{ AU } \frac{1}{f}$$

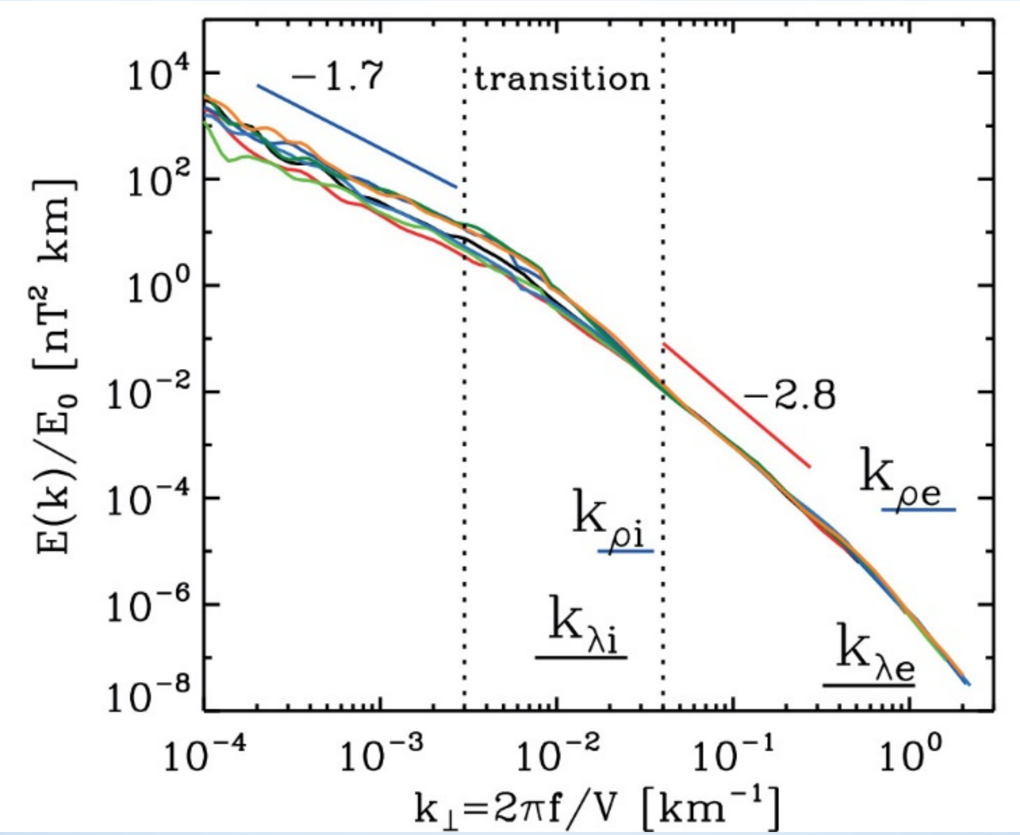
f ~ 10^{-1} Hz -> 4000 km (10s of λ_i)

Inertial range ~ 1000 km – .01 AU

Alexandrova + 13
(Salem + 09)

IPM Magnetic Field Turbulent Spectrum

Steepens below ~ 10 λ_i



Alexandrova + 13

Note: Compressive modes predominantly slow mode (δB & $\delta\rho$ anticorrelated)

Summary

- The Solar Wind and ICMs have important common properties

- Shocks & Turbulence of similar strengths

- The Solar Wind is somewhat more magnetized
  That may influence details

- The physics of the Solar Wind is known in some detail
  Down to kinetic scales

- This may be helpful in understanding what may be important in ICM physics

감사합니다!