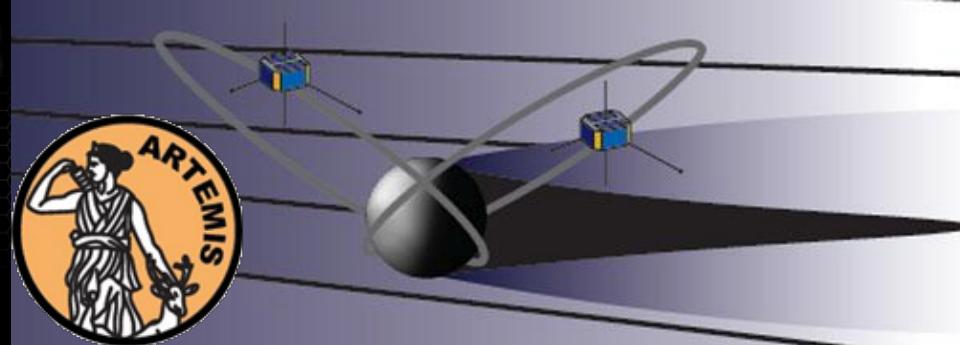




DREAM2

Dynamic Response of the Environments
at Asteroids, the Moon, and moons of Mars



The Plasma Environment of the Moon

J.S. Halekas [jasper-halekas@uiowa.edu]

Department of Physics and Astronomy, University of Iowa

The Moon is a Keystone



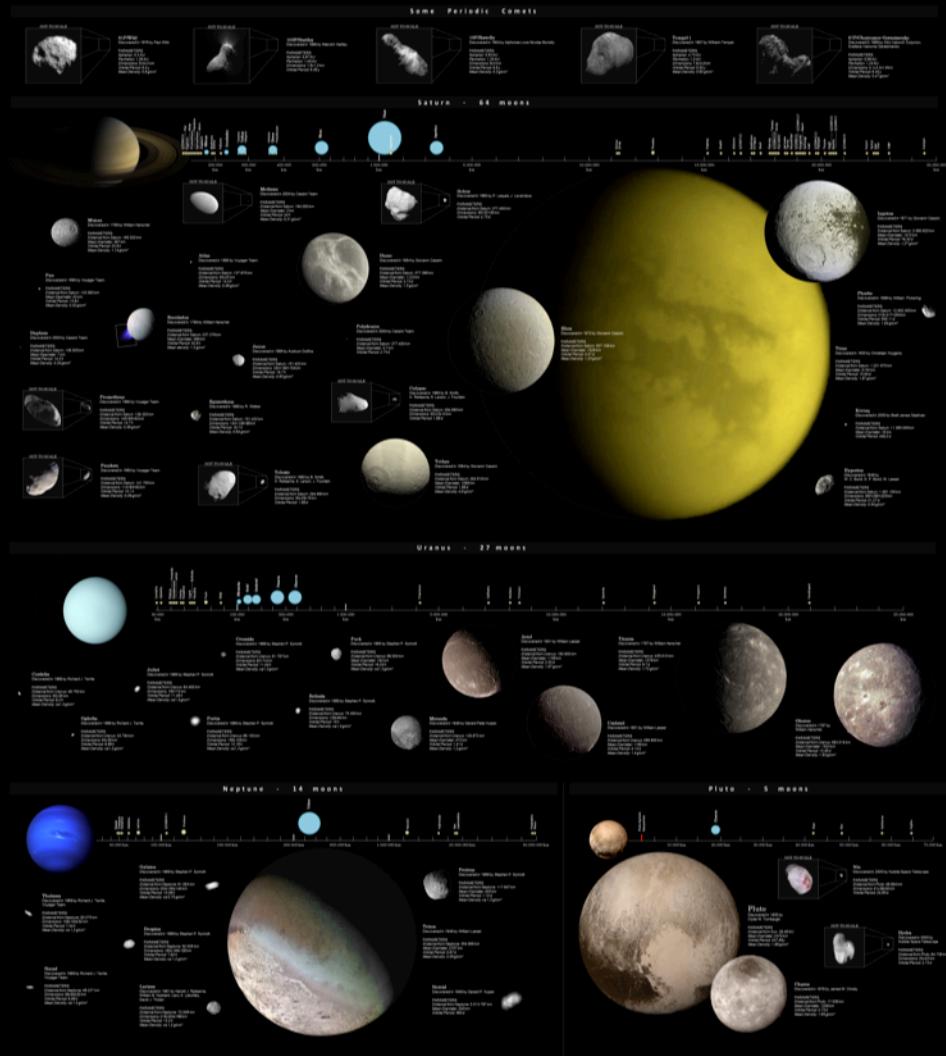
Non-Planet of the Solar System to scale

Dwarf Planets (Ceres & Pluto) – Moons of Planets and Dwarf Planets – Asteroids – Comets

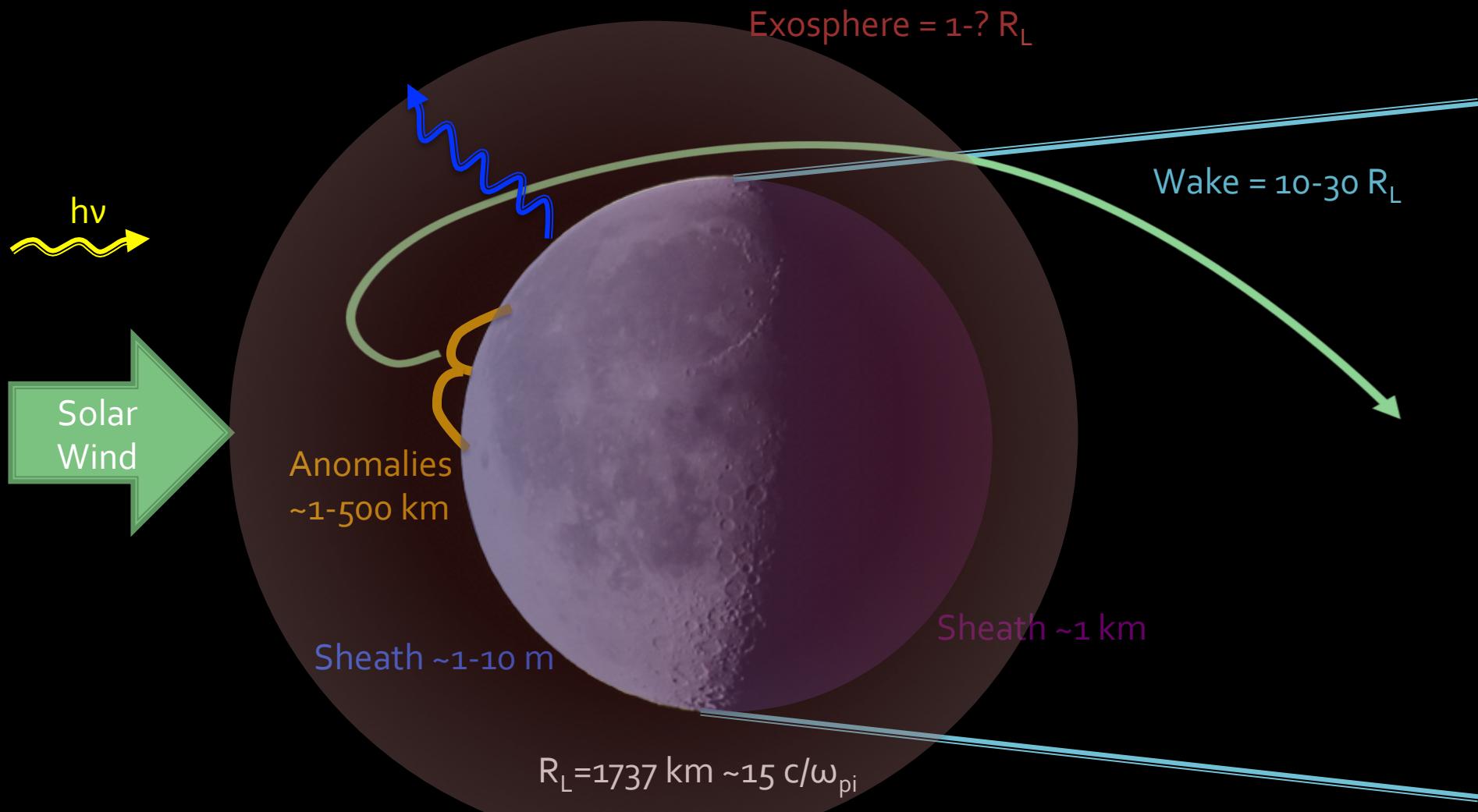
Images from Missions:

Voyager 1 – 2, Hubble Space Telescope, Mars Reconnaissance Orbiter, Deep Impact-EPOXI, Stardust, Galileo, Near-Shoemaker, Cassini, Rosetta, Dawn, New Horizons

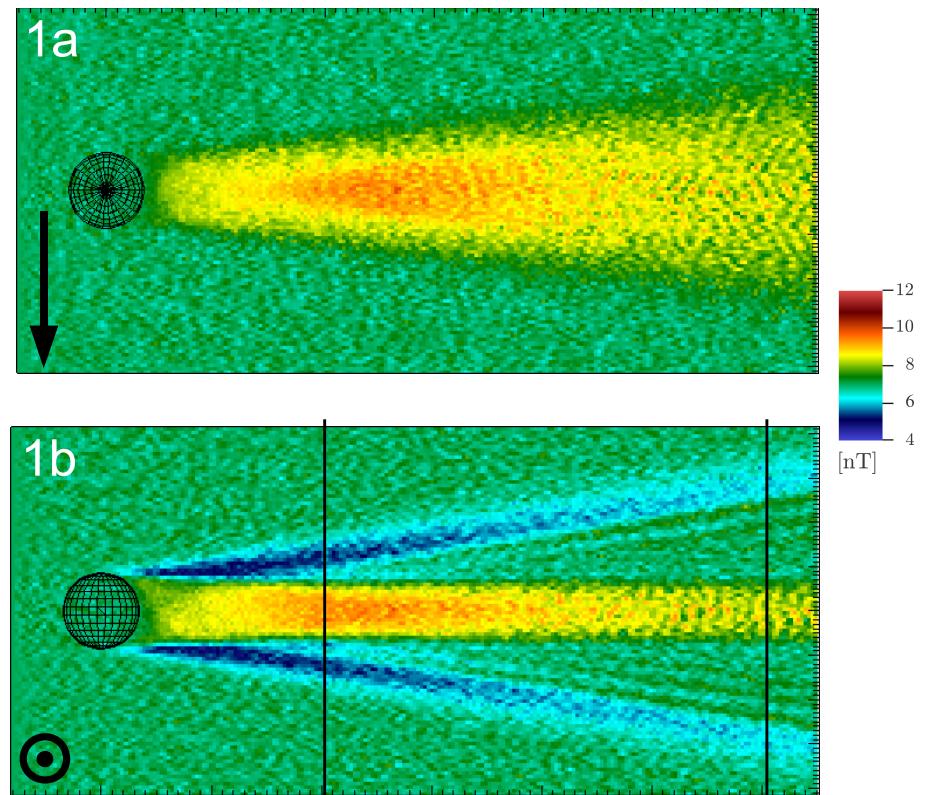
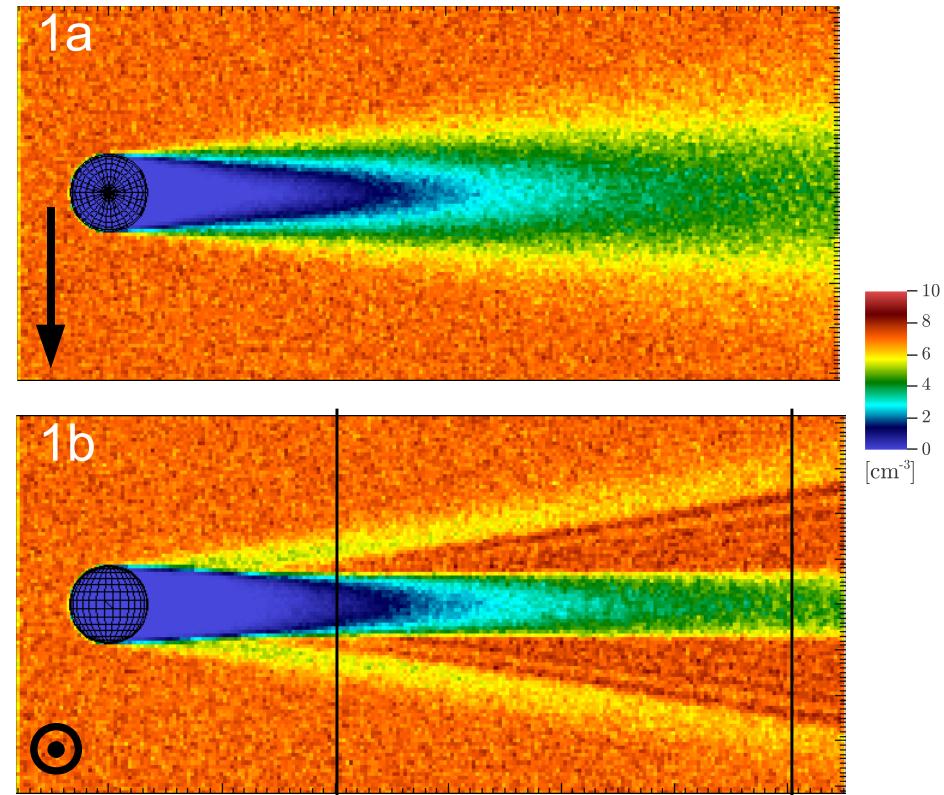
THE REPRESENTATION BETWEEN MOONS & PLANET ON DISTANCE LINE AND PLANET & PLANET OF DISTANCE LINE IS NOT TO SCALE



Overview: A Moon of Many Scales



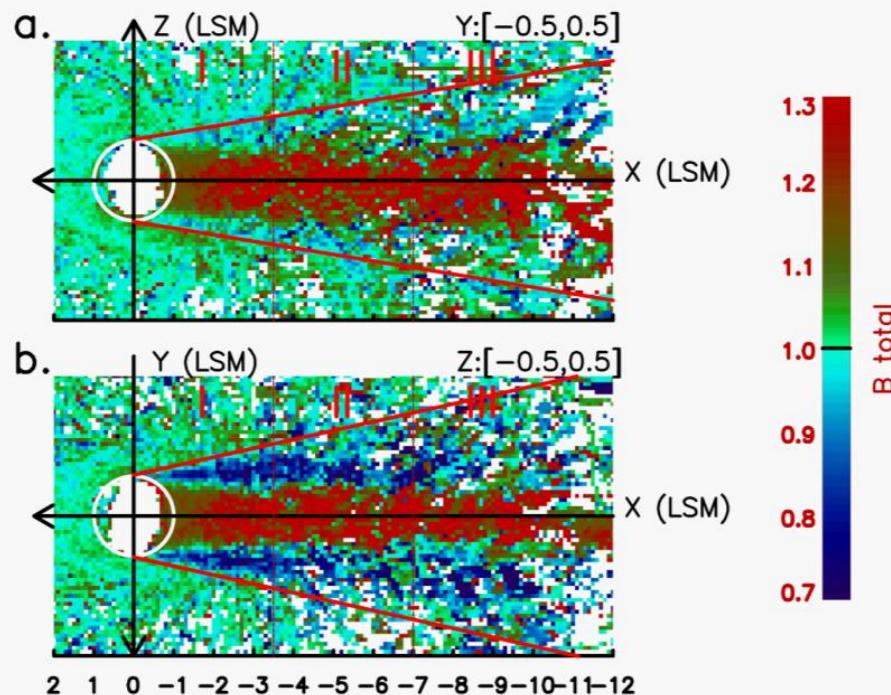
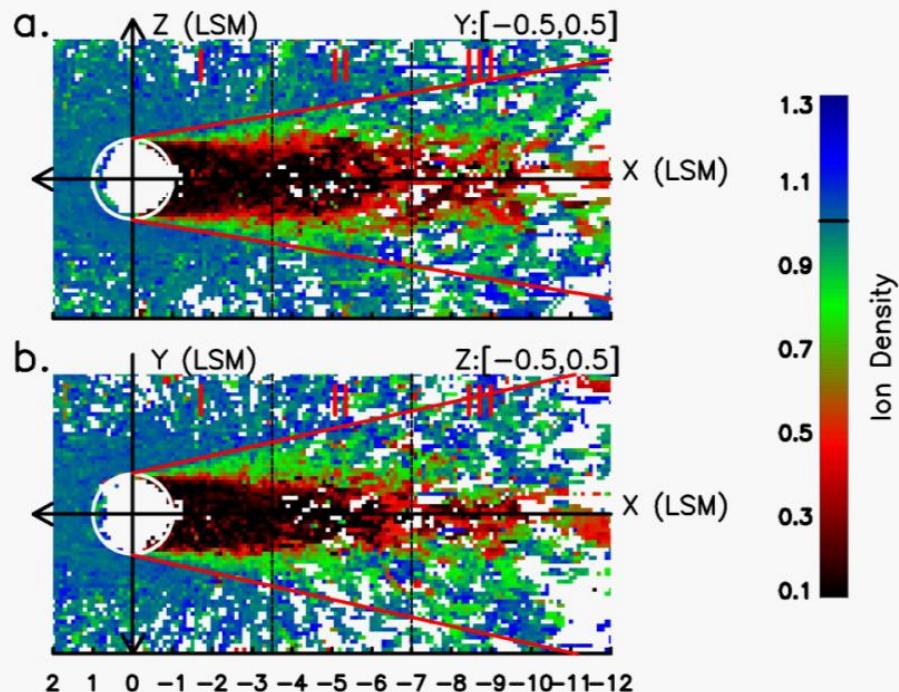
The Wake: Simulations



Holmstrom et al., 2012

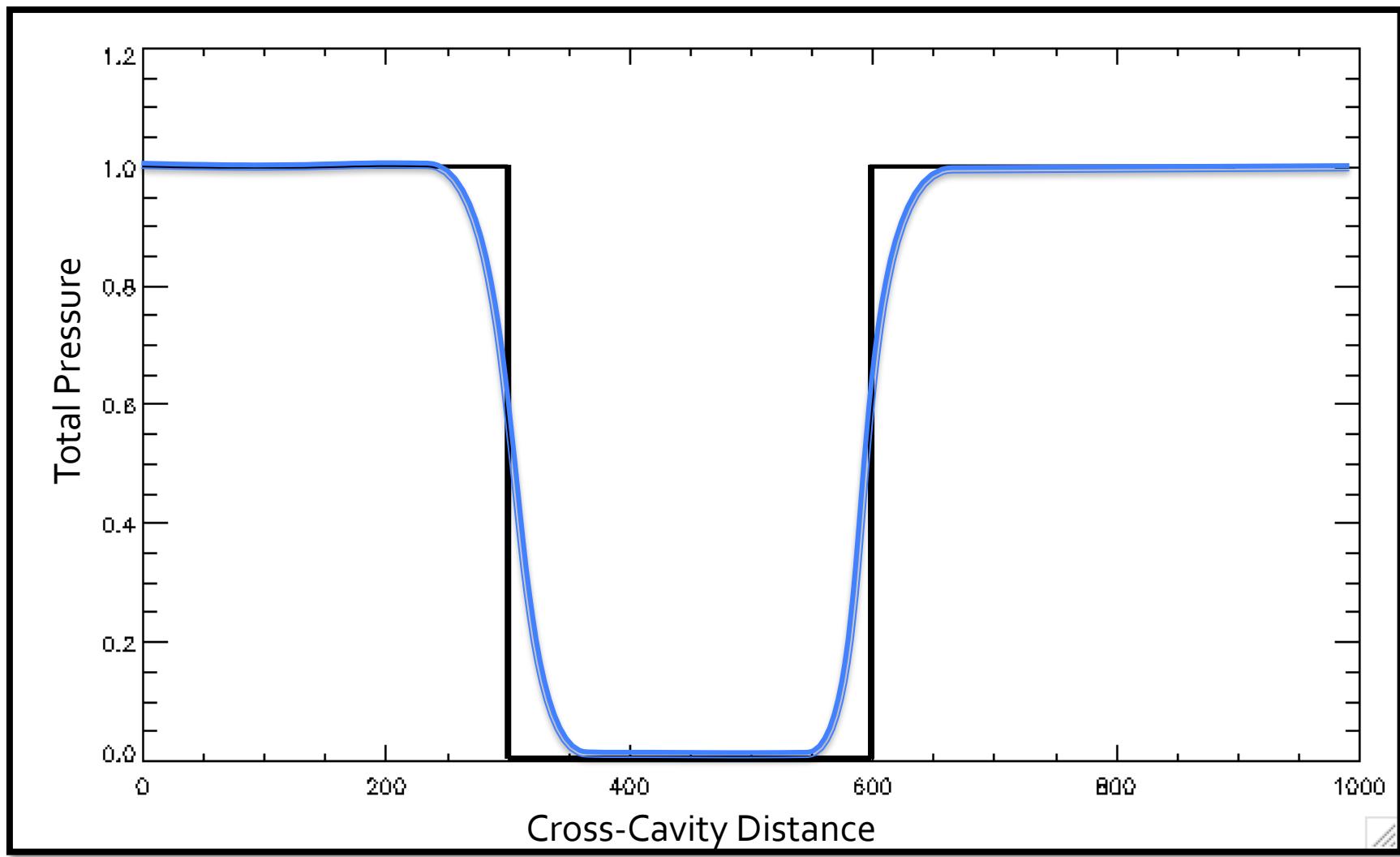
The Wake: Observations

Upstream B in X-Z plane

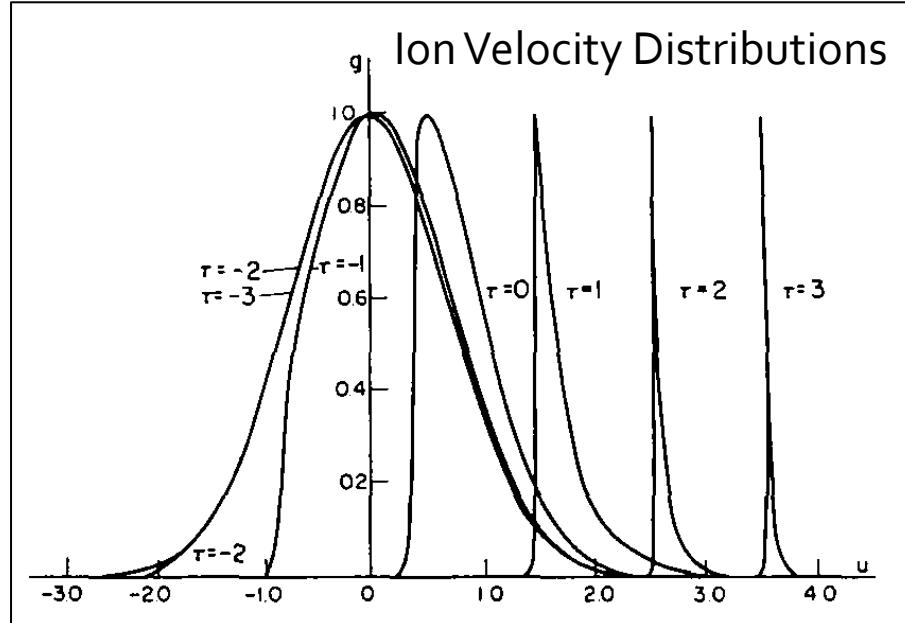


Zhang et al., 2014

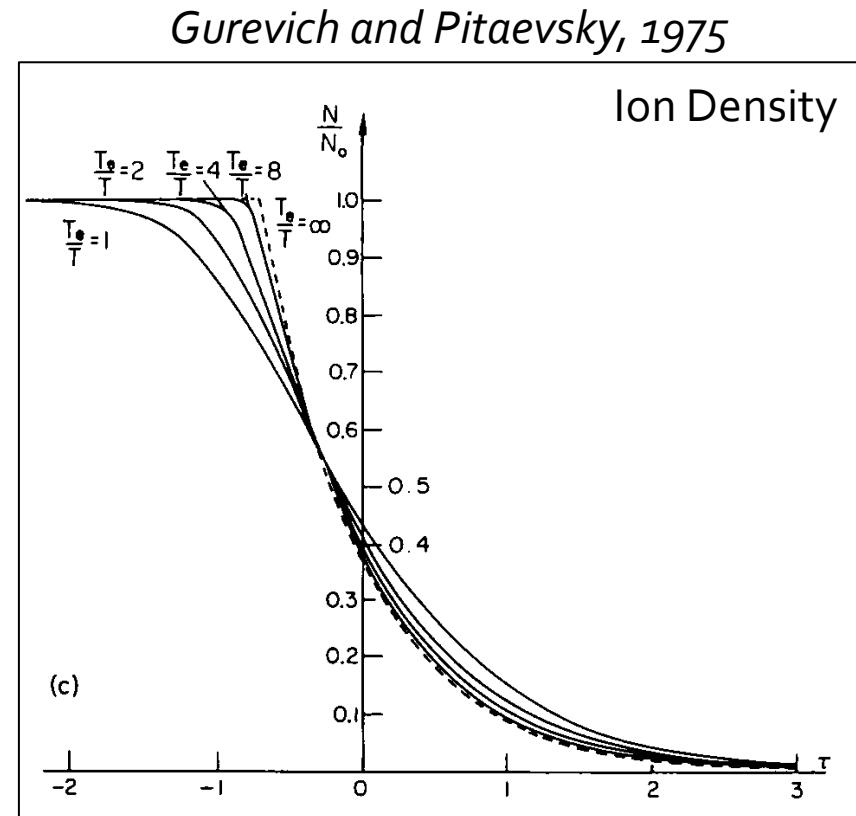
Parallel Expansion



Parallel Expansion Theory

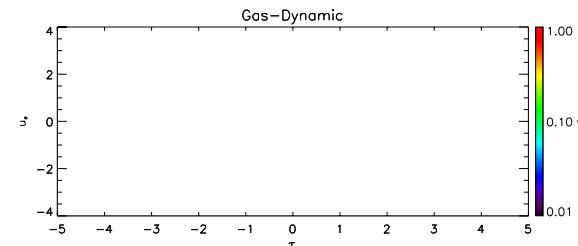
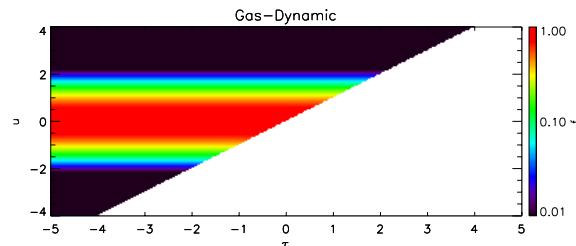


Electric field maintains quasi-neutrality – retards electrons and accelerates ions into wake

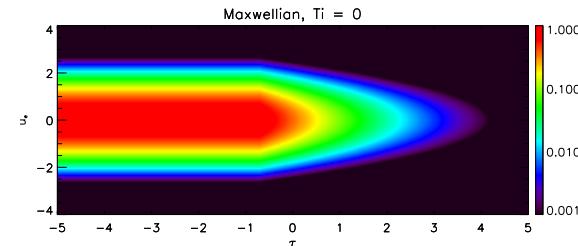
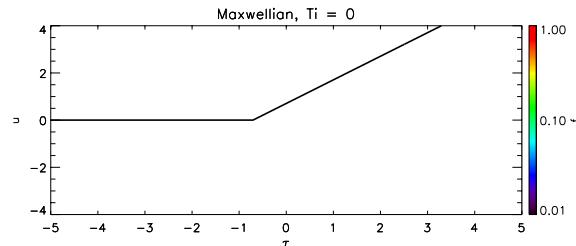


Parallel Expansion Theories

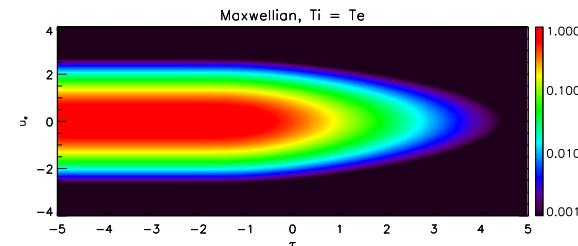
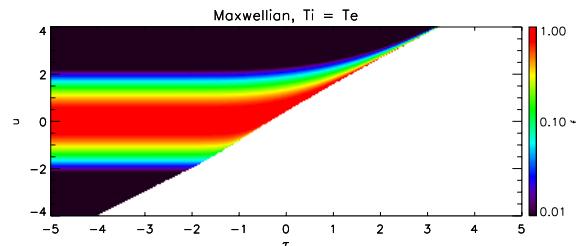
Gas-Dynamic



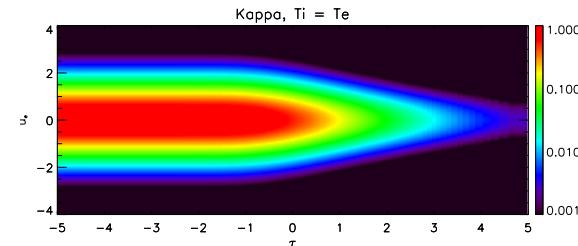
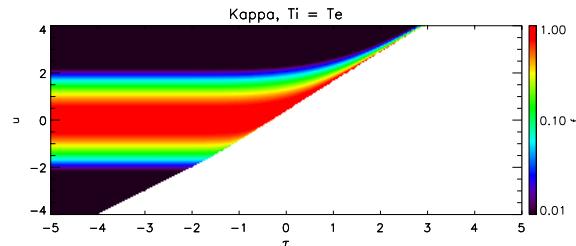
Cold Ion Plasma



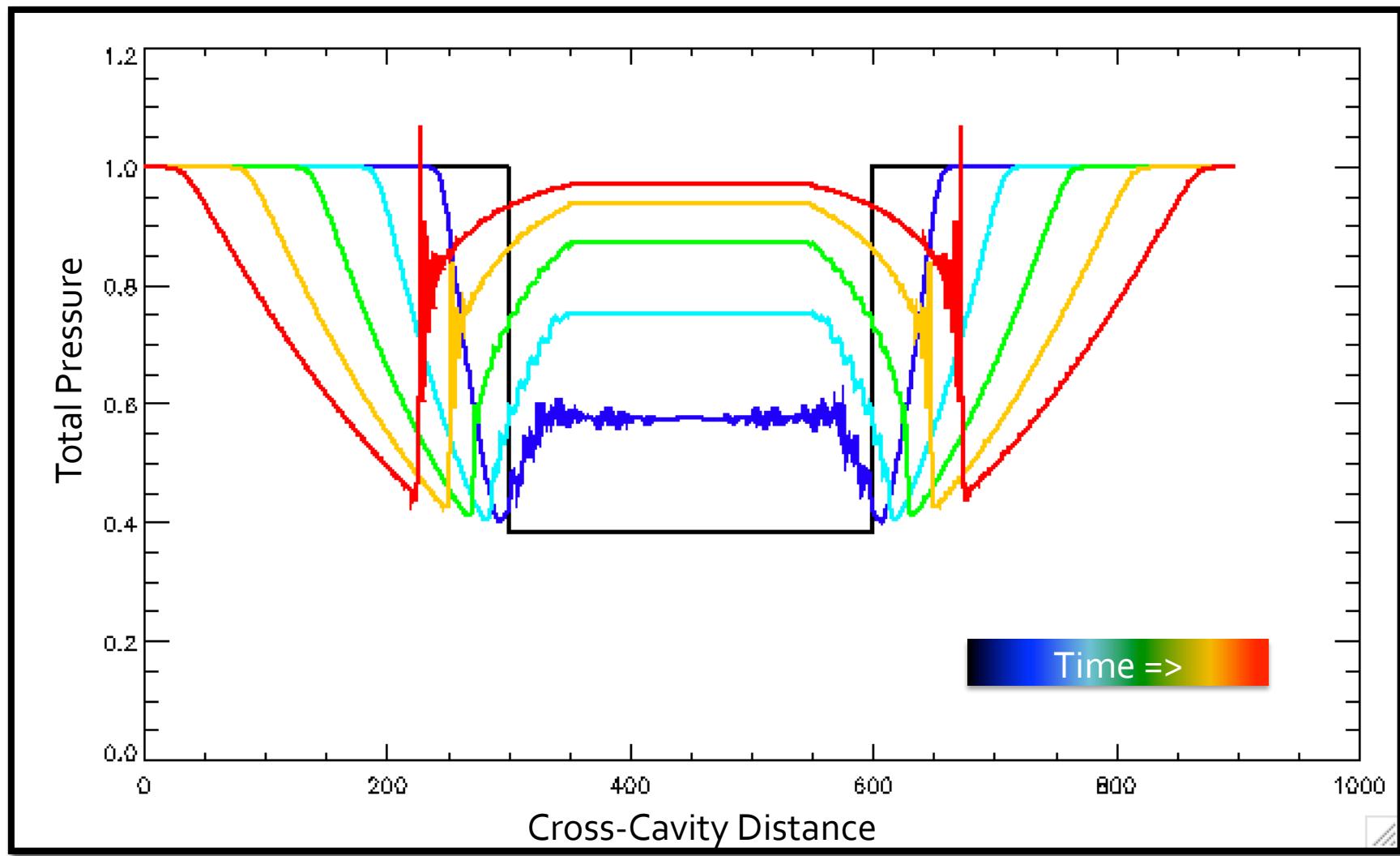
Warm Ions



Warm Ions,
Kappa Electrons

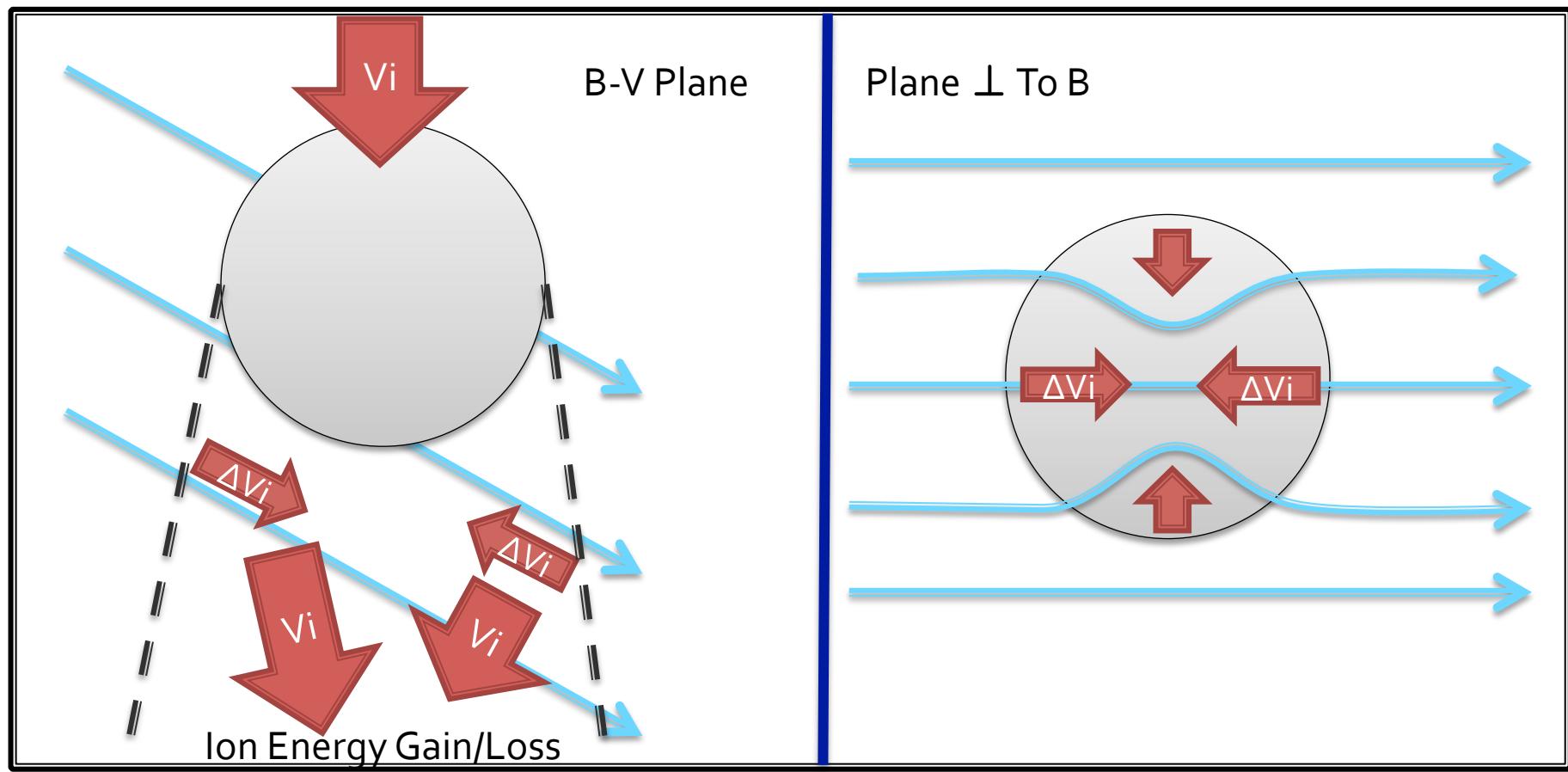


Perpendicular Expansion

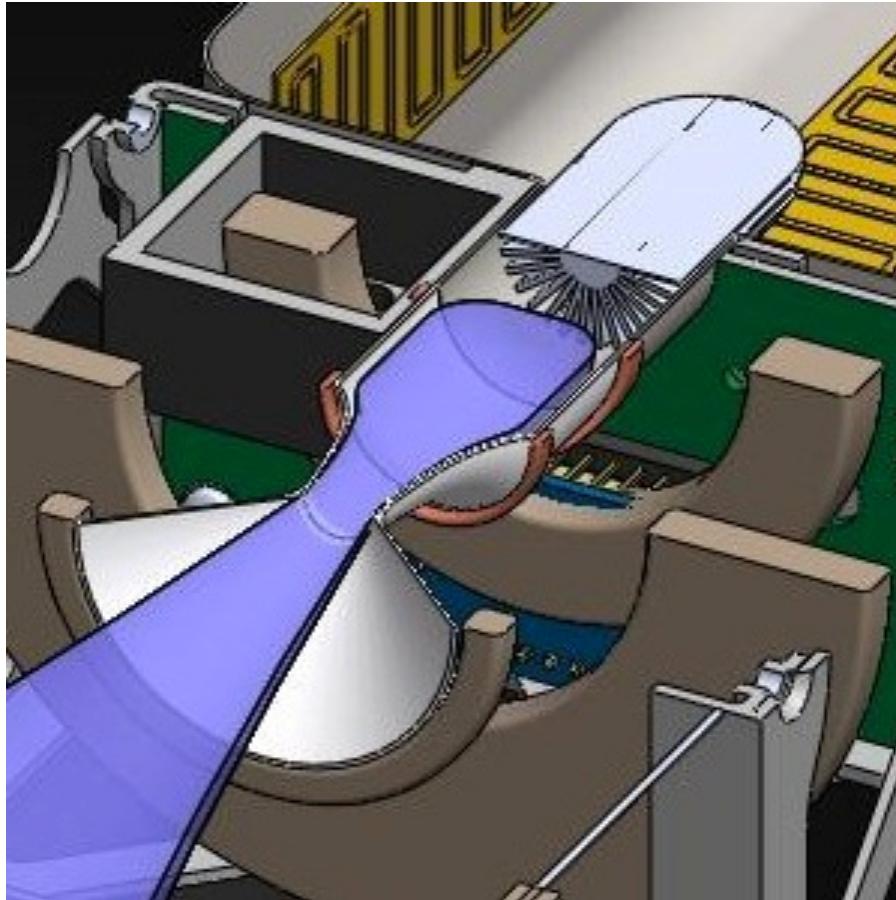


Role of Magnetic Field

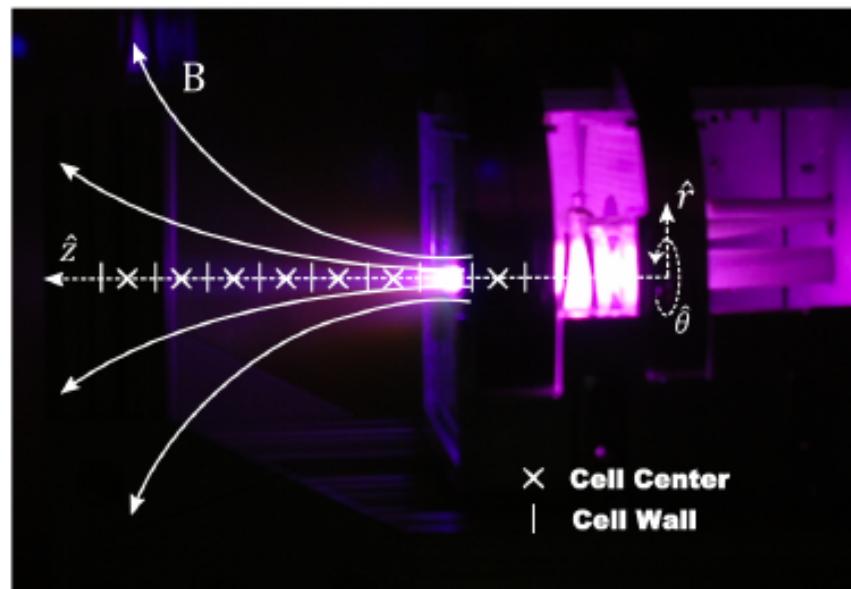
- $R_i \ll R_m \Rightarrow$ particles flow along magnetic field
- If [particle pressure]/[magnetic pressure] significant, magnetic field can be compressed by perpendicular flows



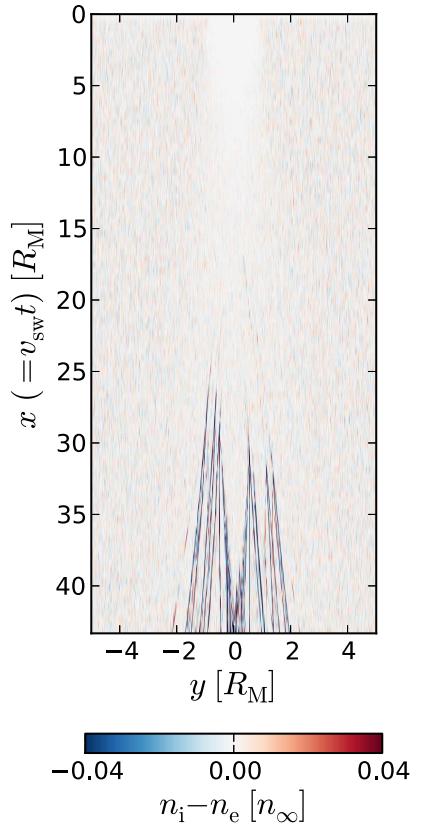
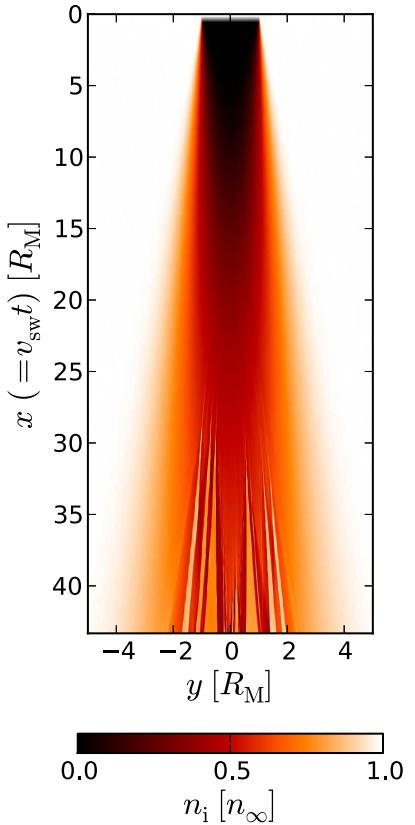
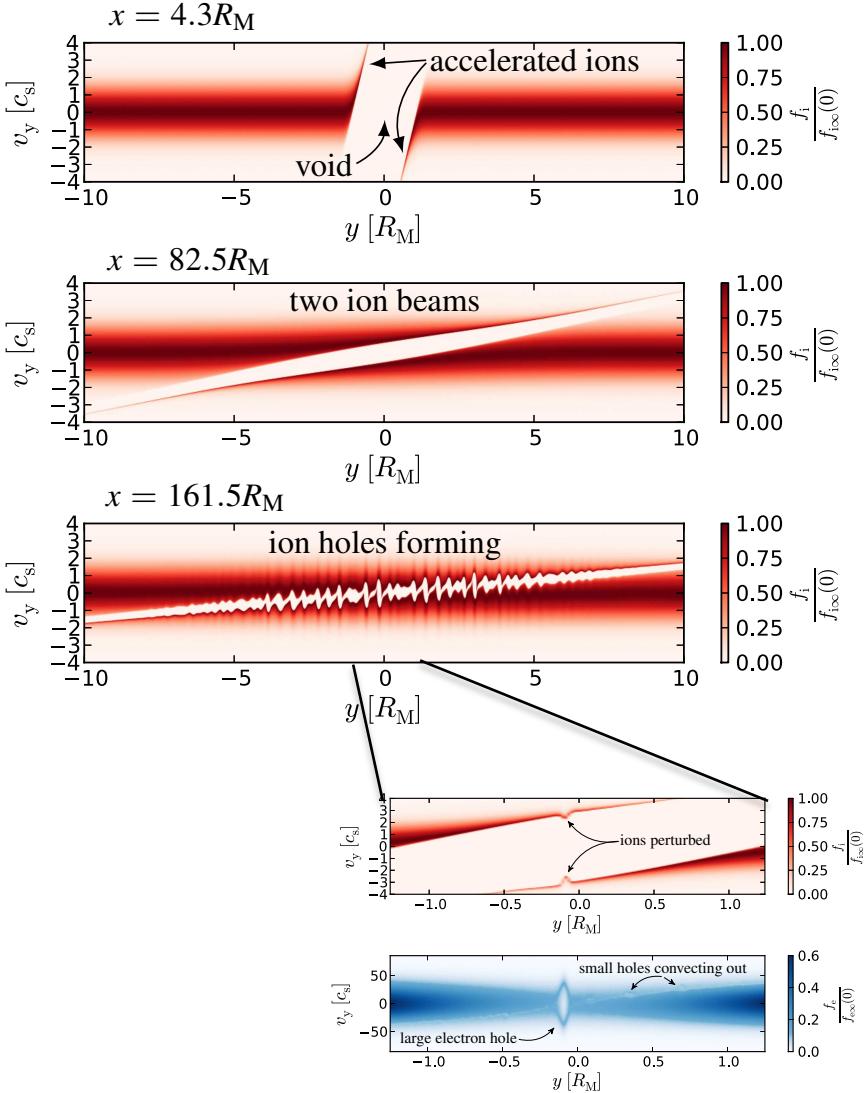
Plasma Expansion into a Vacuum



“Cubesat Ambipolar Thruster”

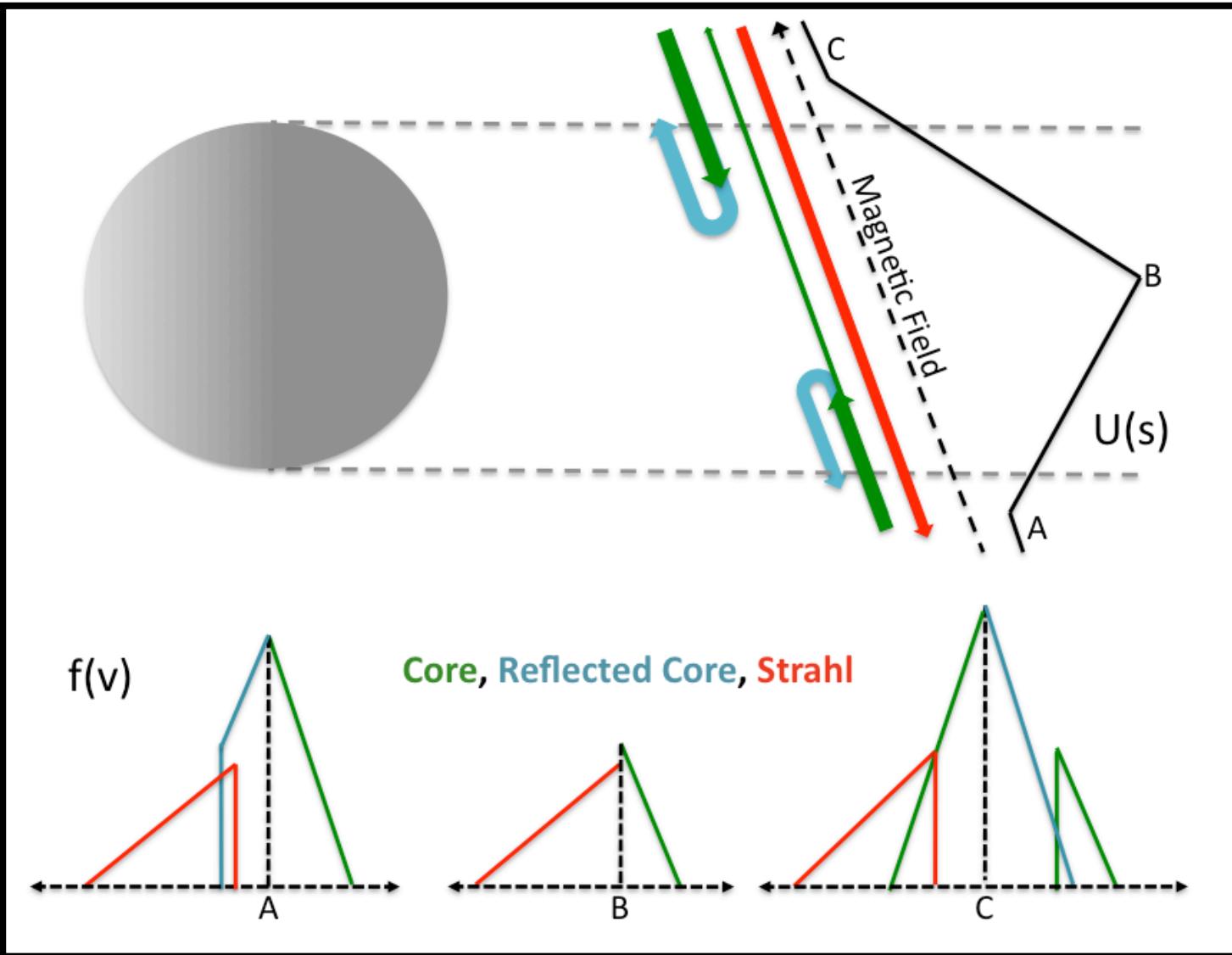


The Wake: An Instability Generator

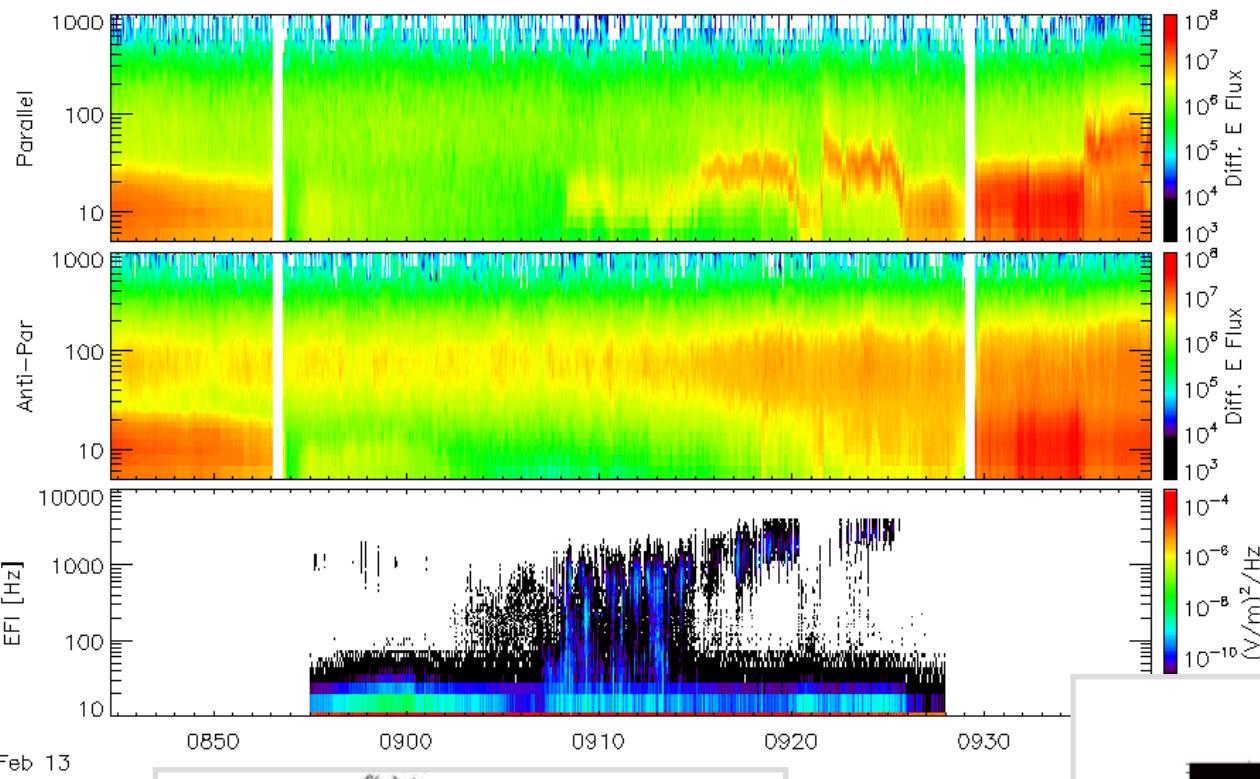


Haakonsen et al., 2015

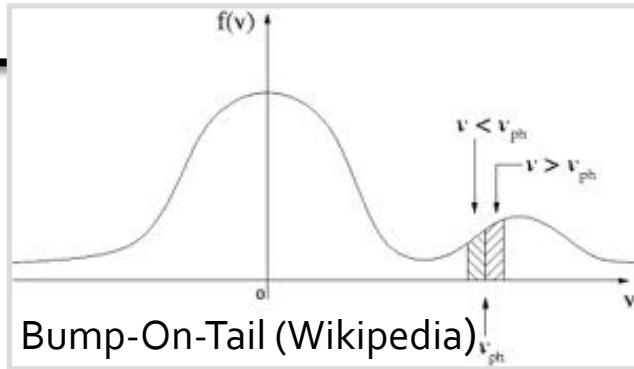
Velocity-Filtered Electrons



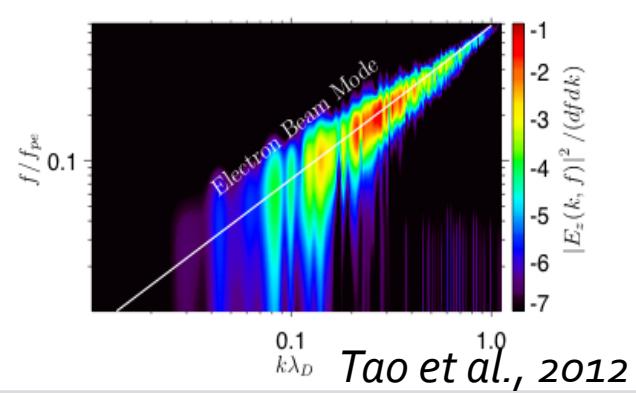
Streaming Instabilities



Halekas et al., 2011

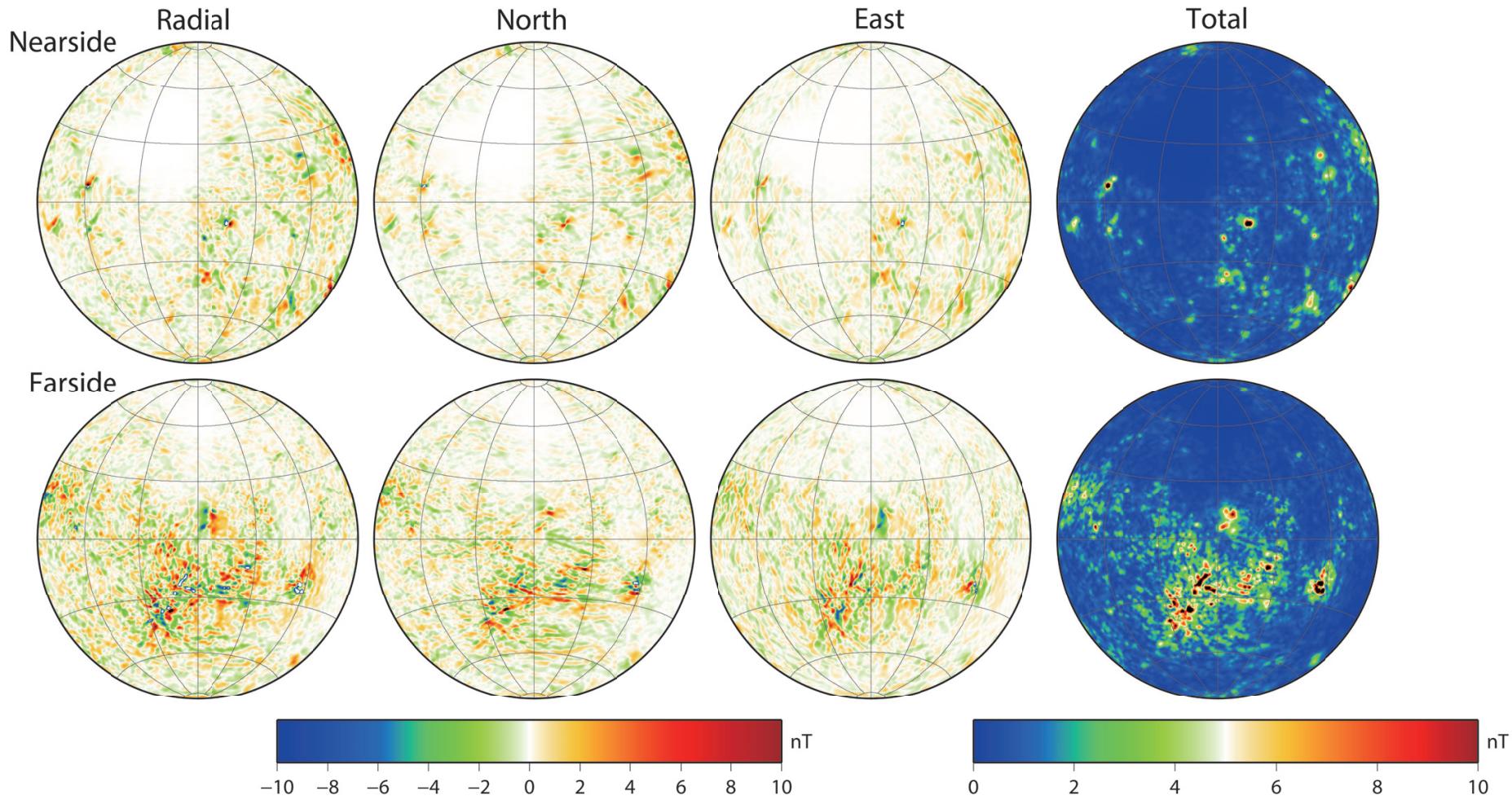


Bump-On-Tail (Wikipedia)



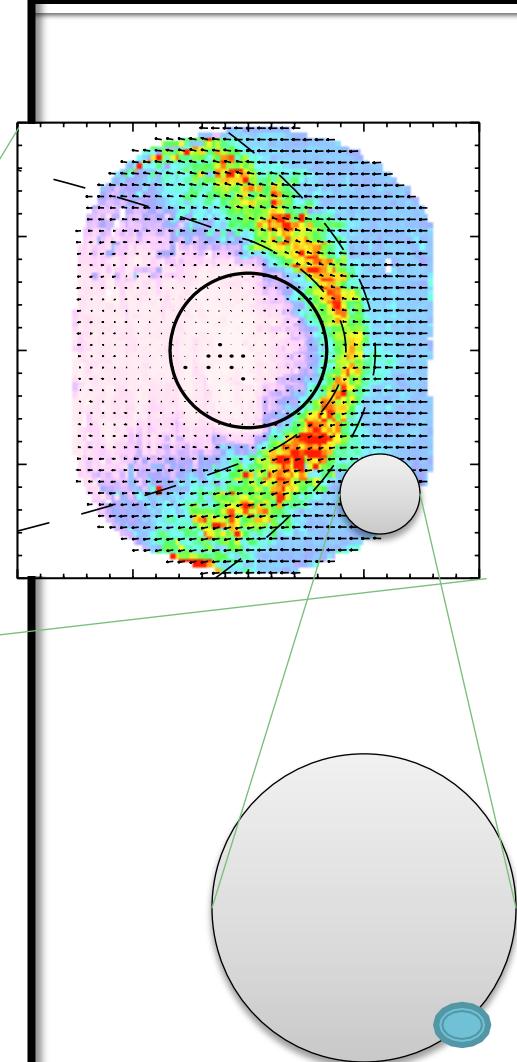
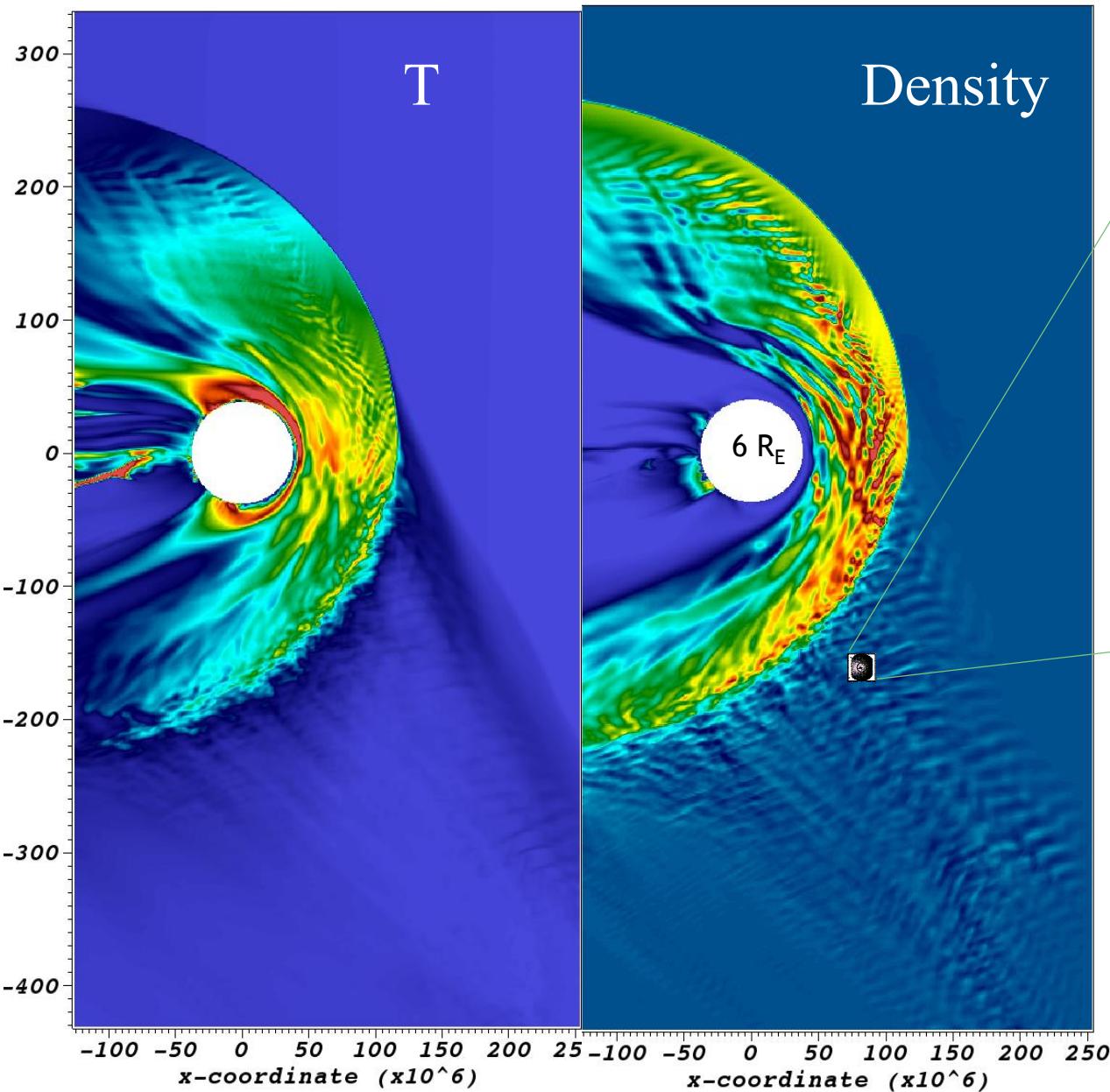
Tao et al., 2012

Lunar Magnetic Anomalies

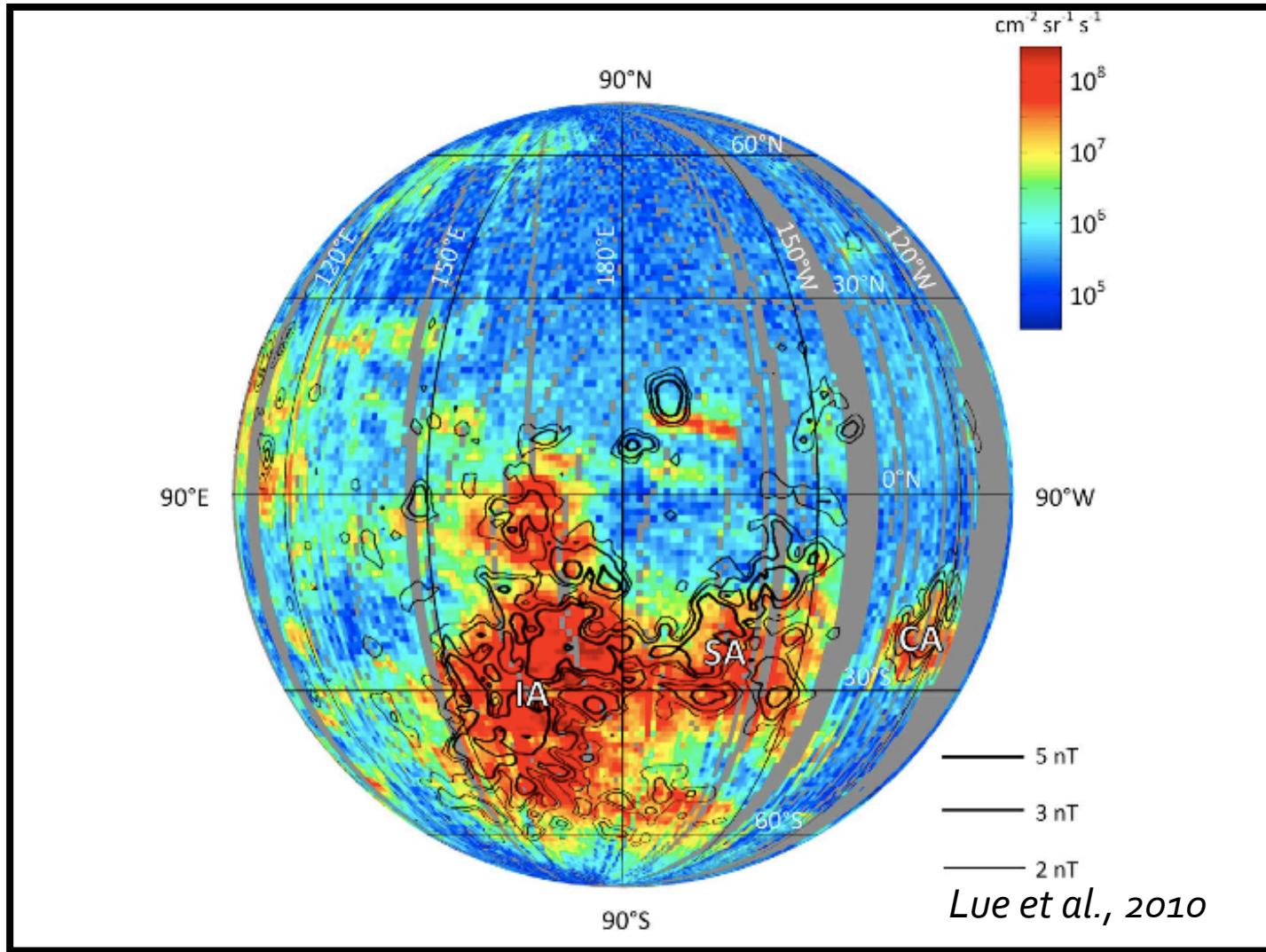


[Tsunakawa et al., 2015]

The Moon is Small

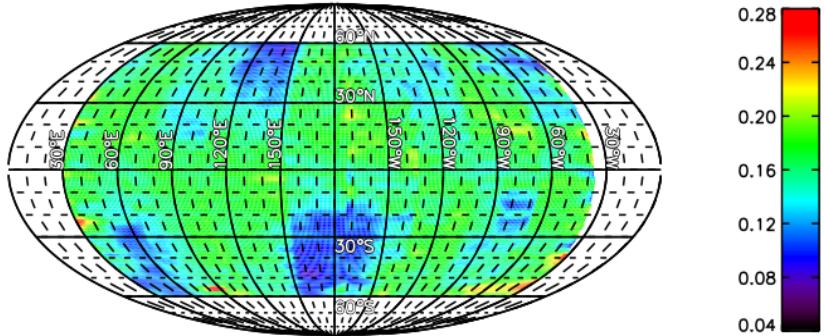


Solar Wind Reflection

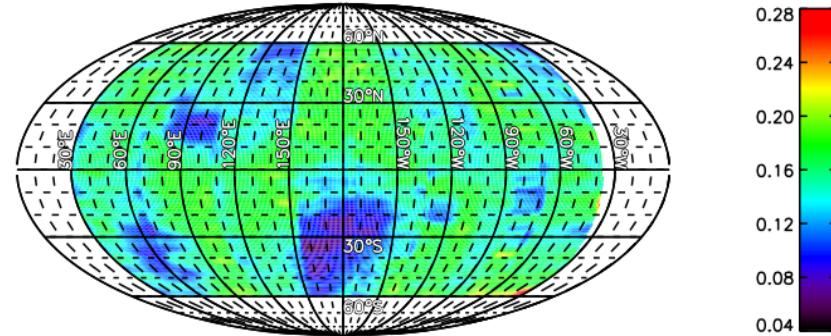


Solar Wind Reflection

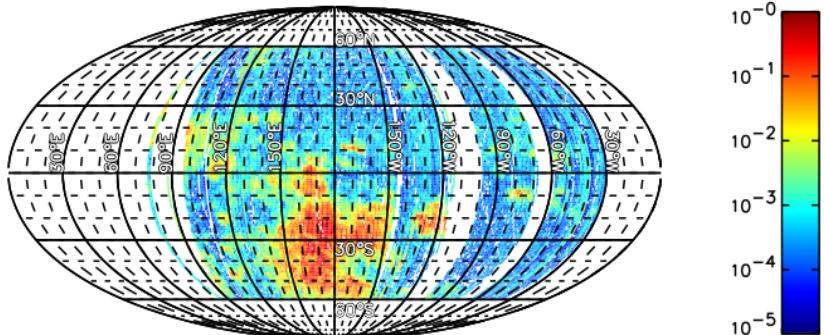
a) Low energy ($<30\% E_{\text{solar wind}}$) ENAs



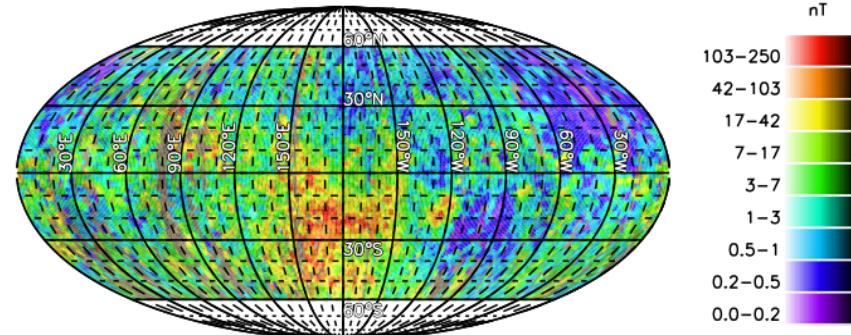
b) High energy ($>30\% E_{\text{solar wind}}$) ENAs



e) Proton deflection ratio



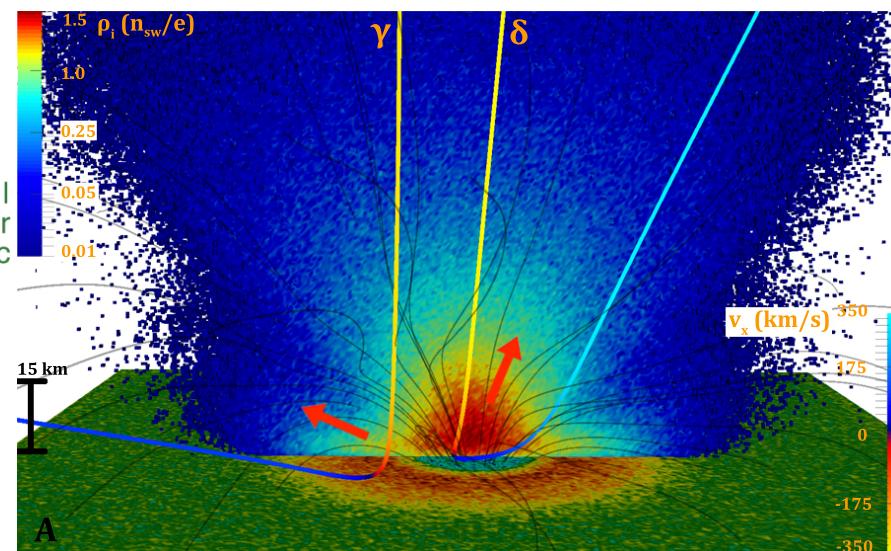
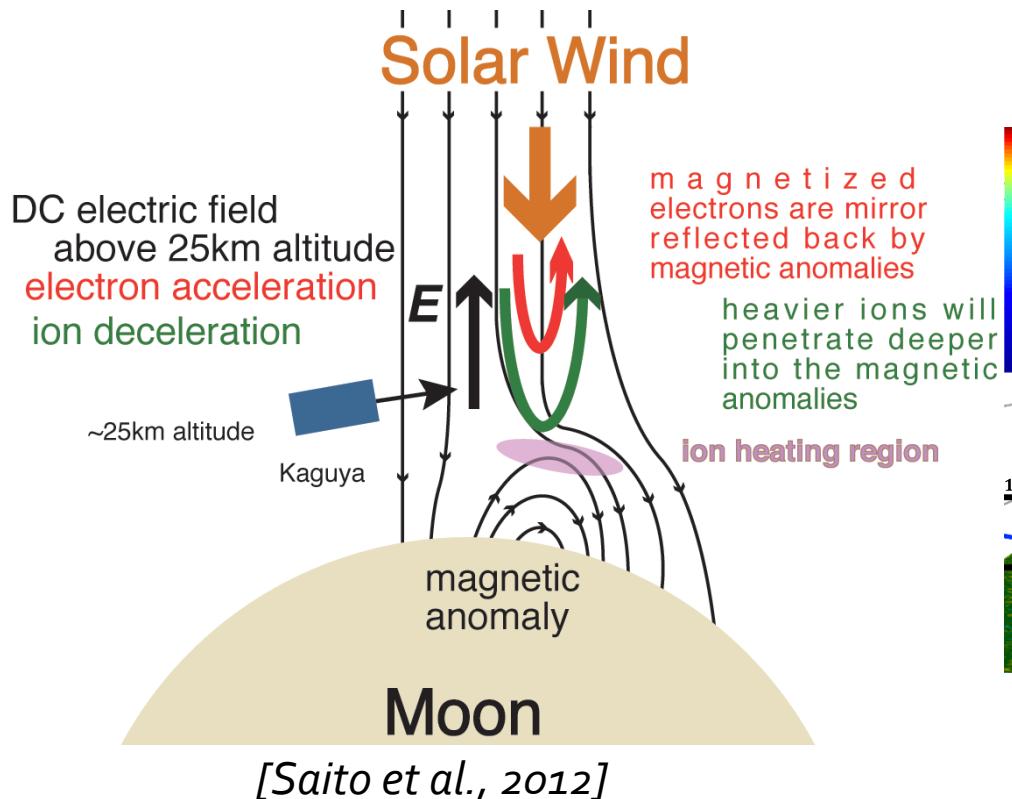
f) Measured magnetic surface field



Vorburger et al., 2013

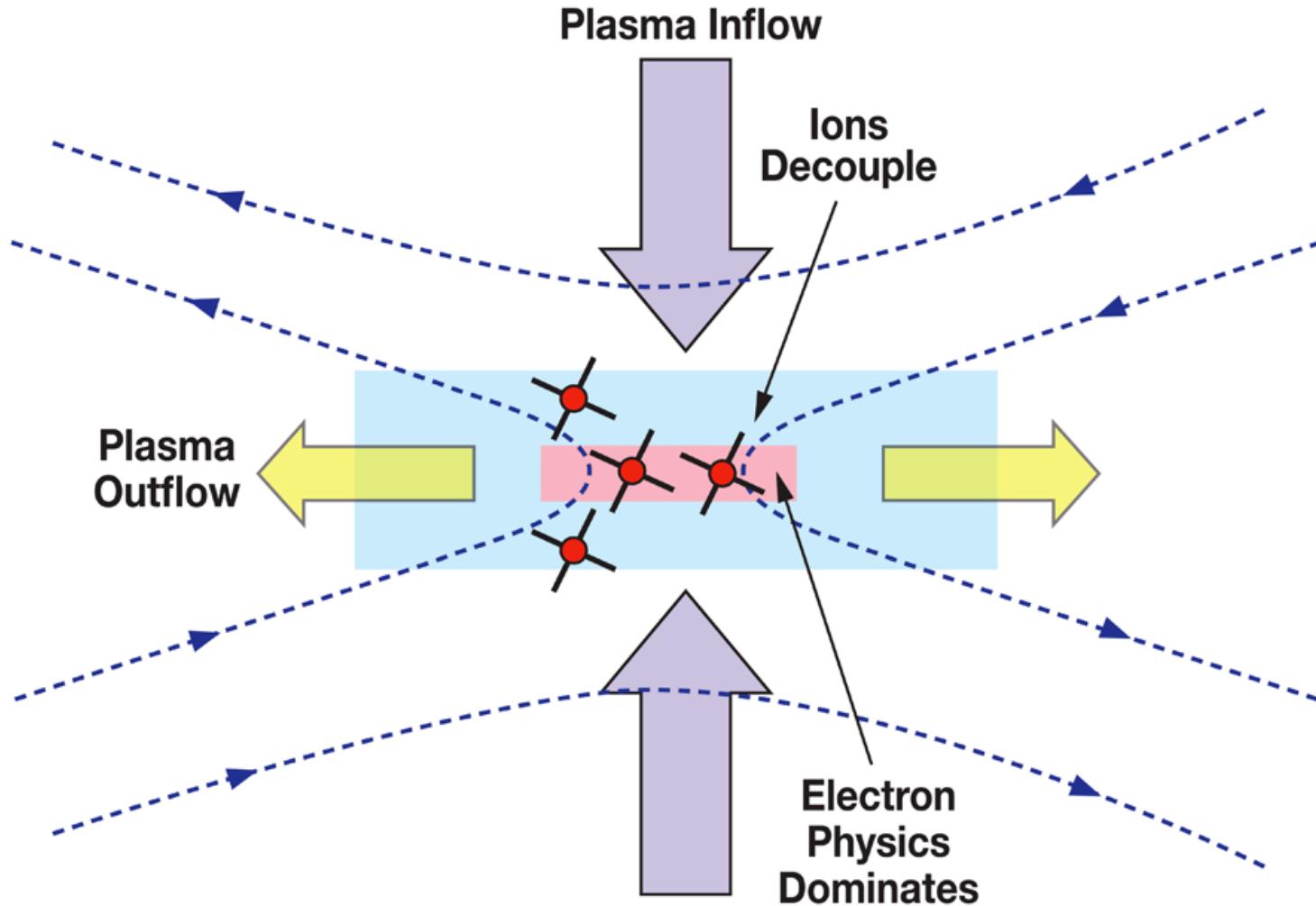
Low Altitude Micromechanics

It's all in the E!



[Deca and Divin, 2016] (and many others)

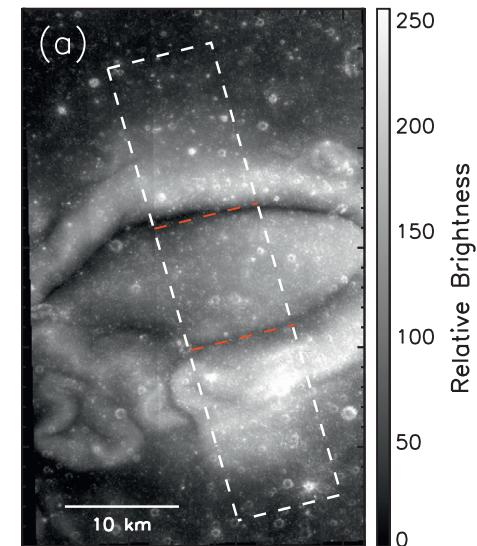
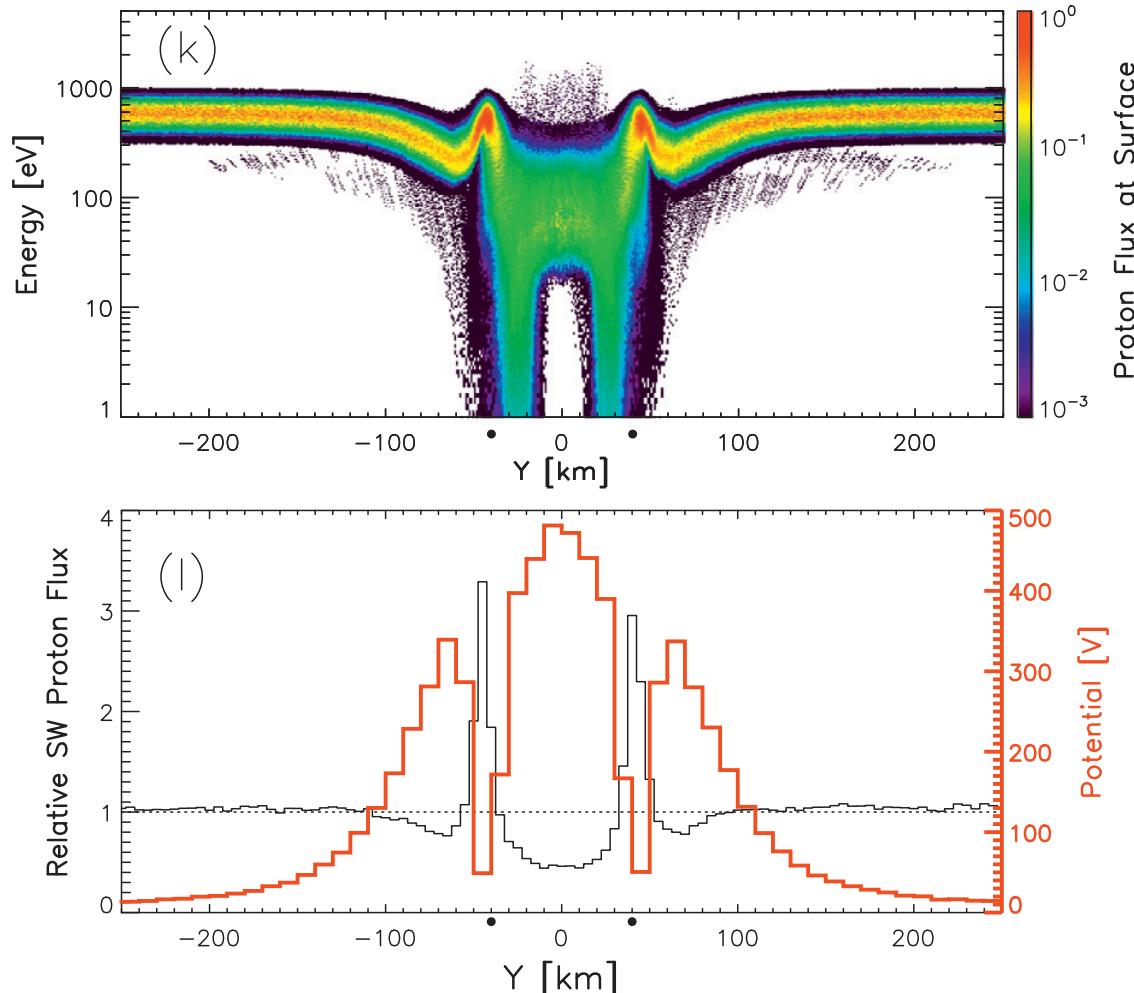
Electron-Scale Magnetic Gradients



Reflection: Observed vs. Simulated

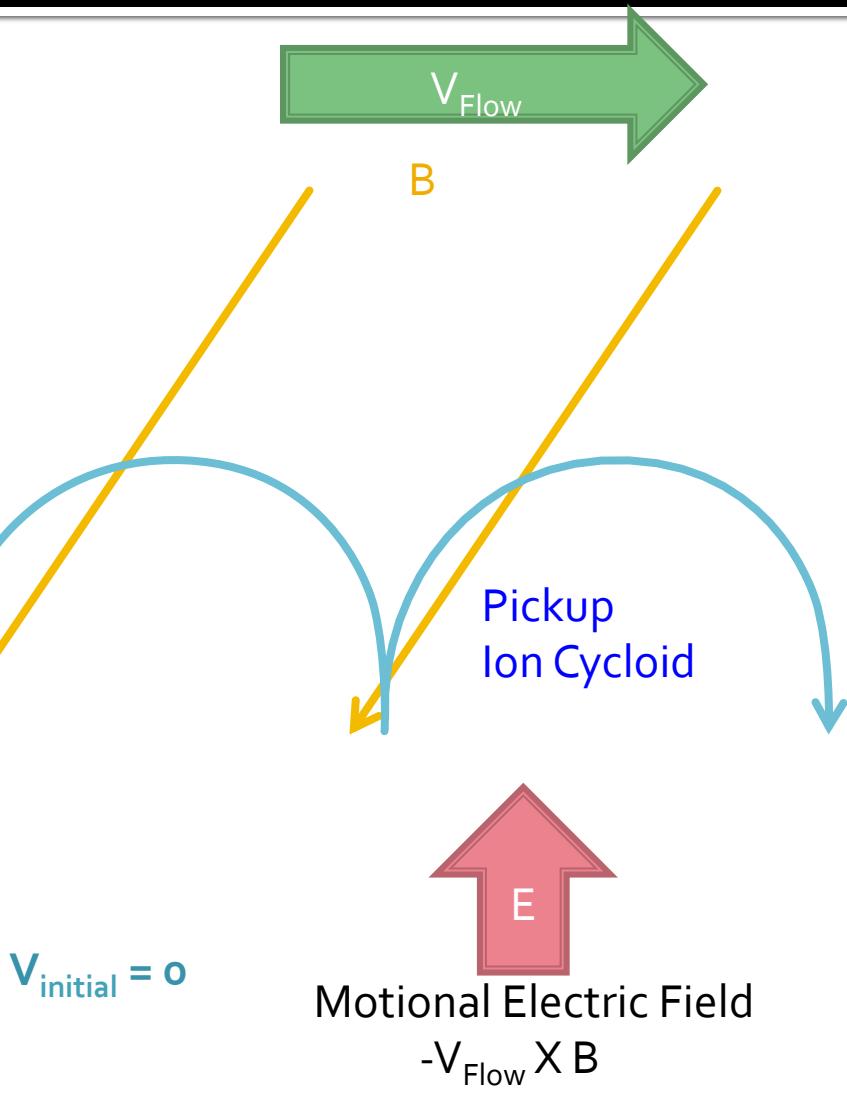
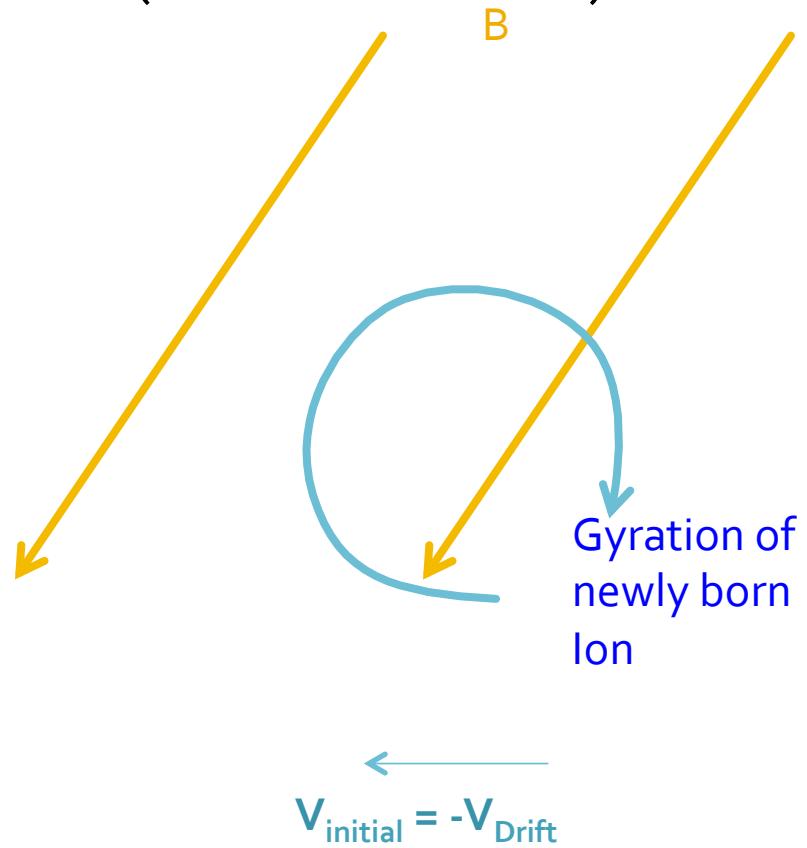
- Observed:
 - >50% locally [*Saito et al., 2010; Lue et al., 2011*]
- Simulated:
 - 10% [*Deca et al., 2014*]
 - <10%? [*Jarvinen et al., 2014*]
 - <5% [*Giacalone et al., 2015*]
 - 50% for 10,000 nT field [*Poppe et al., 2012*]
 - 50-100% in very small (sub-km) regions [*Zimmerman et al., 2014*]

Connecting to the Surface



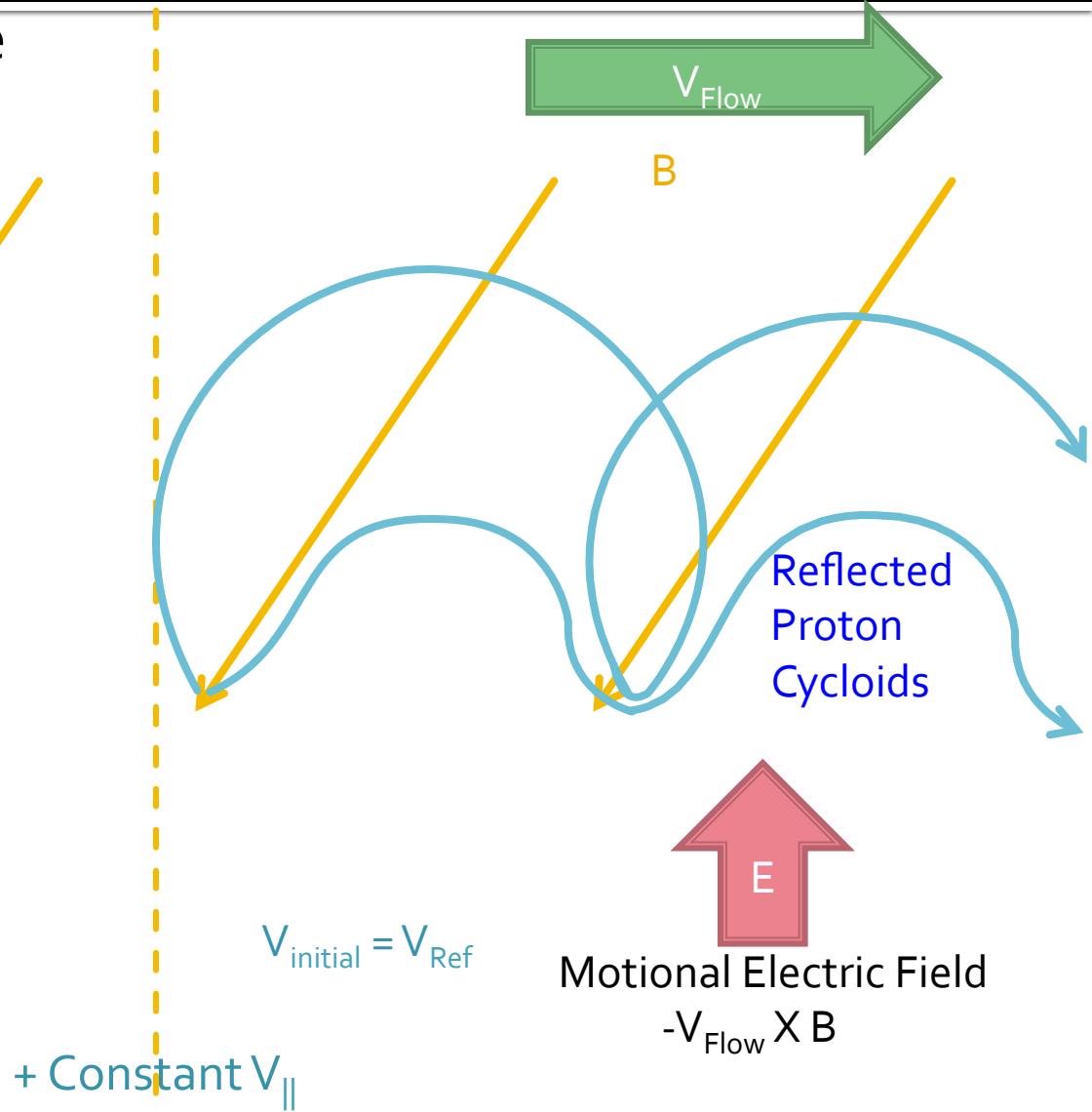
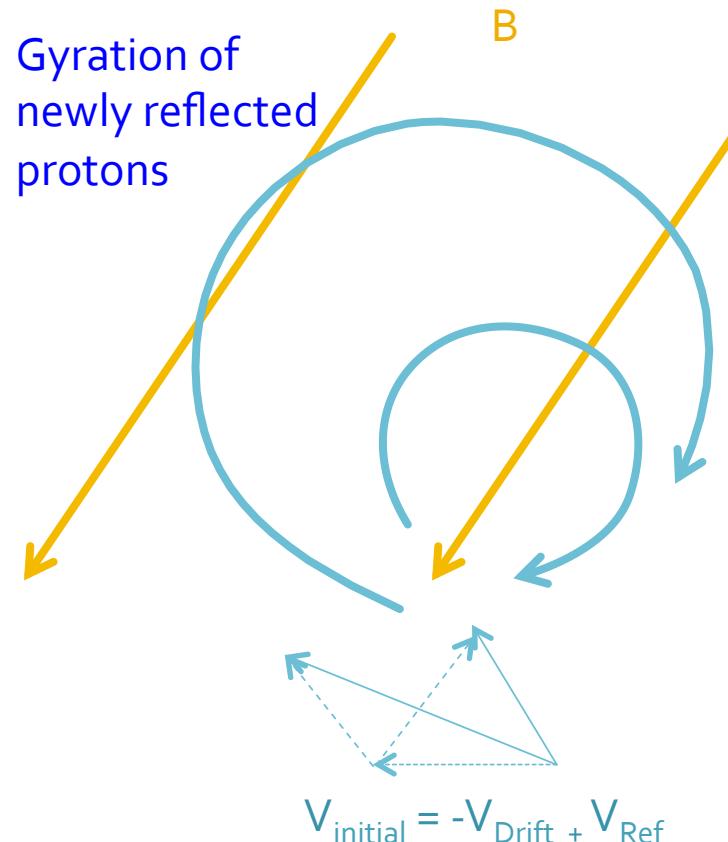
Pickup Ion Physics

Drift Reference Frame
(No flow across B)



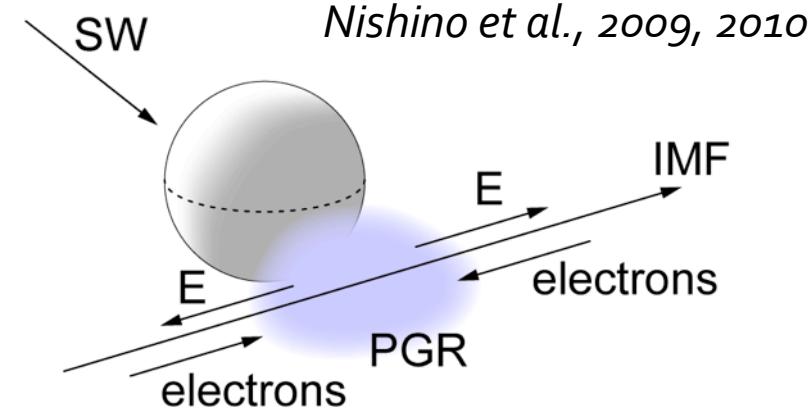
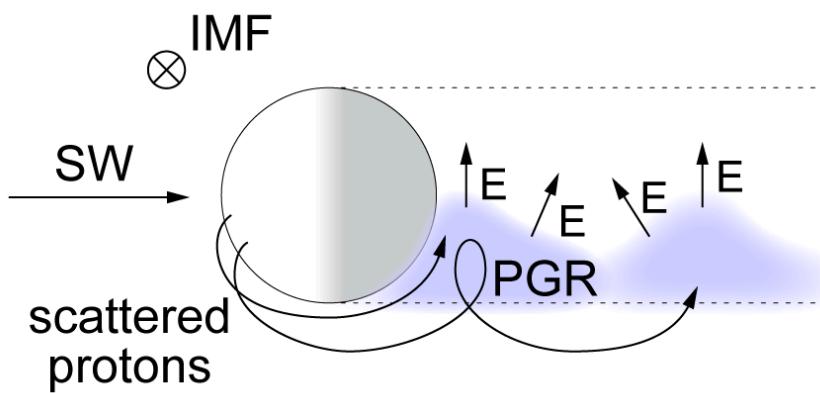
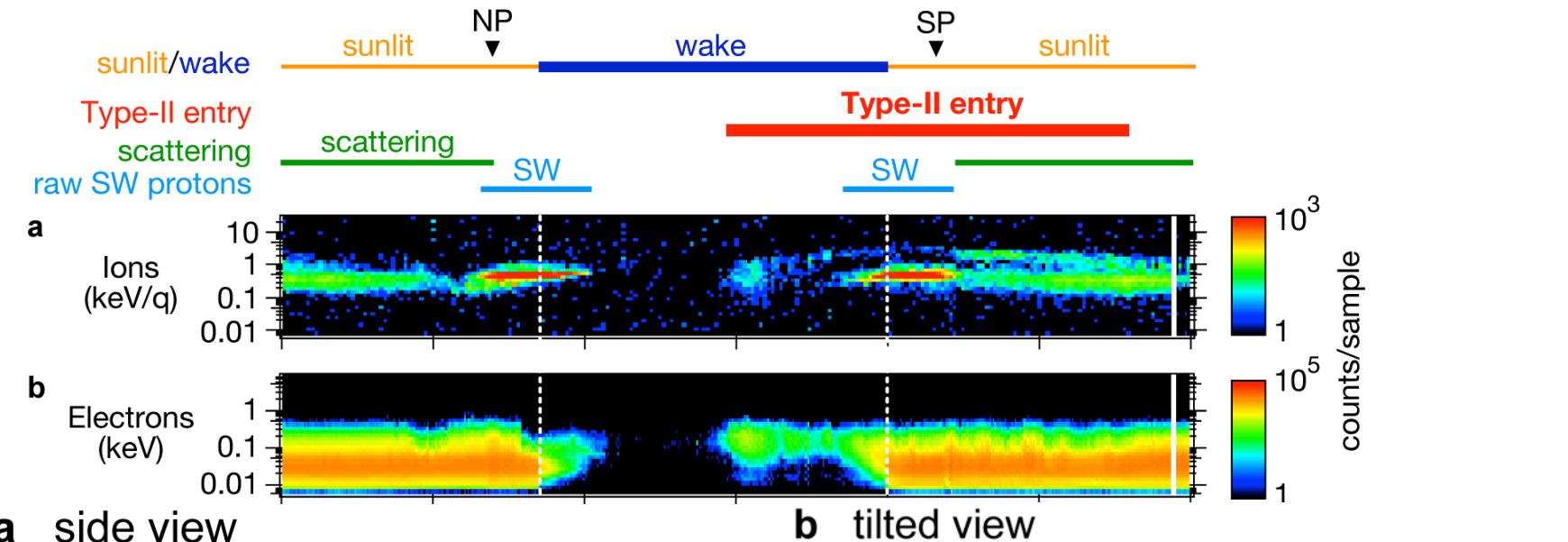
Reflected Proton Physics

Drift Reference Frame
(No flow across B)

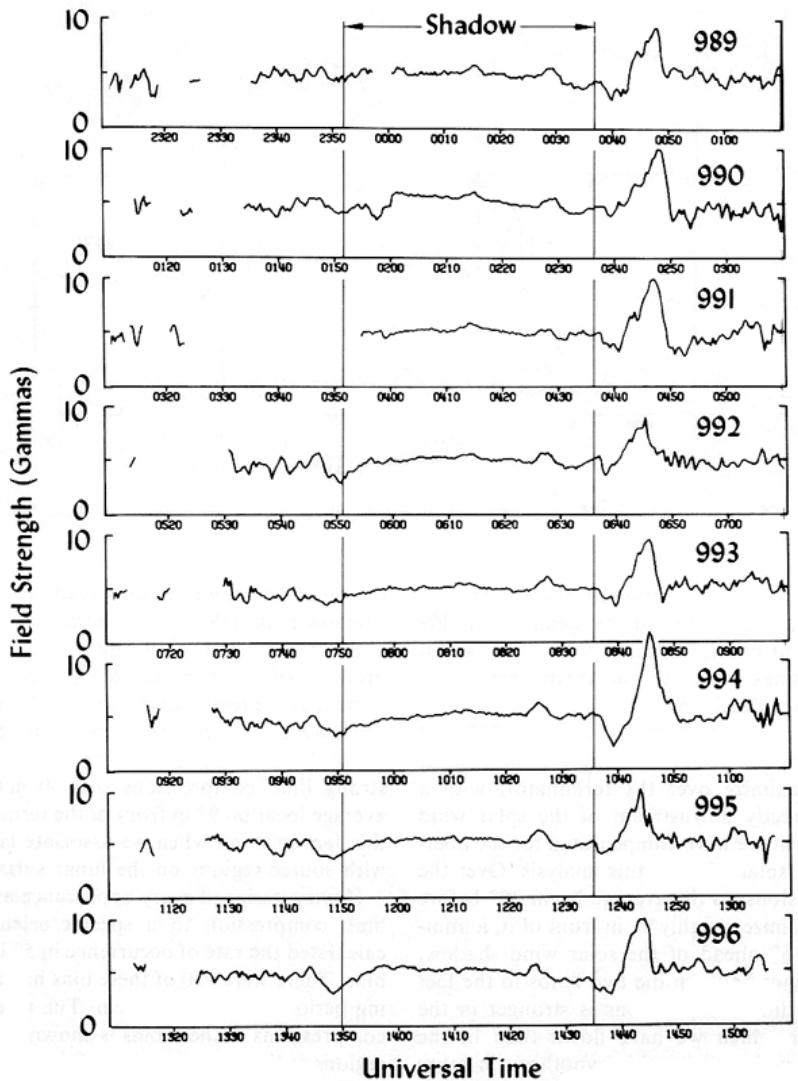


Type-II Entry

SELENE PACE and LMAG September 24, 2008 09:10-11:10 UT



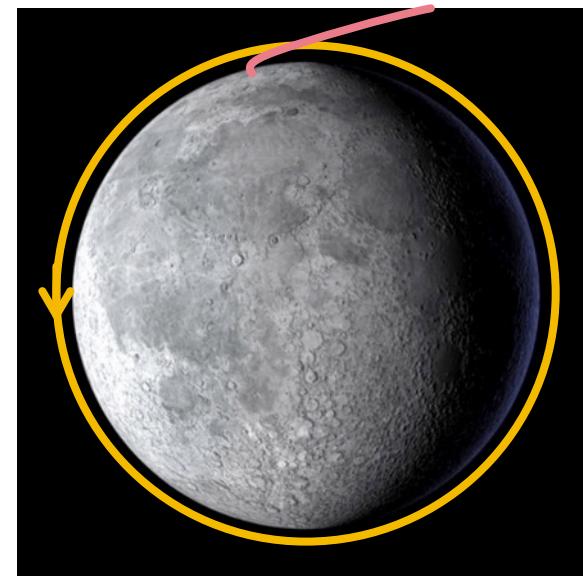
Macroscopic Interactions



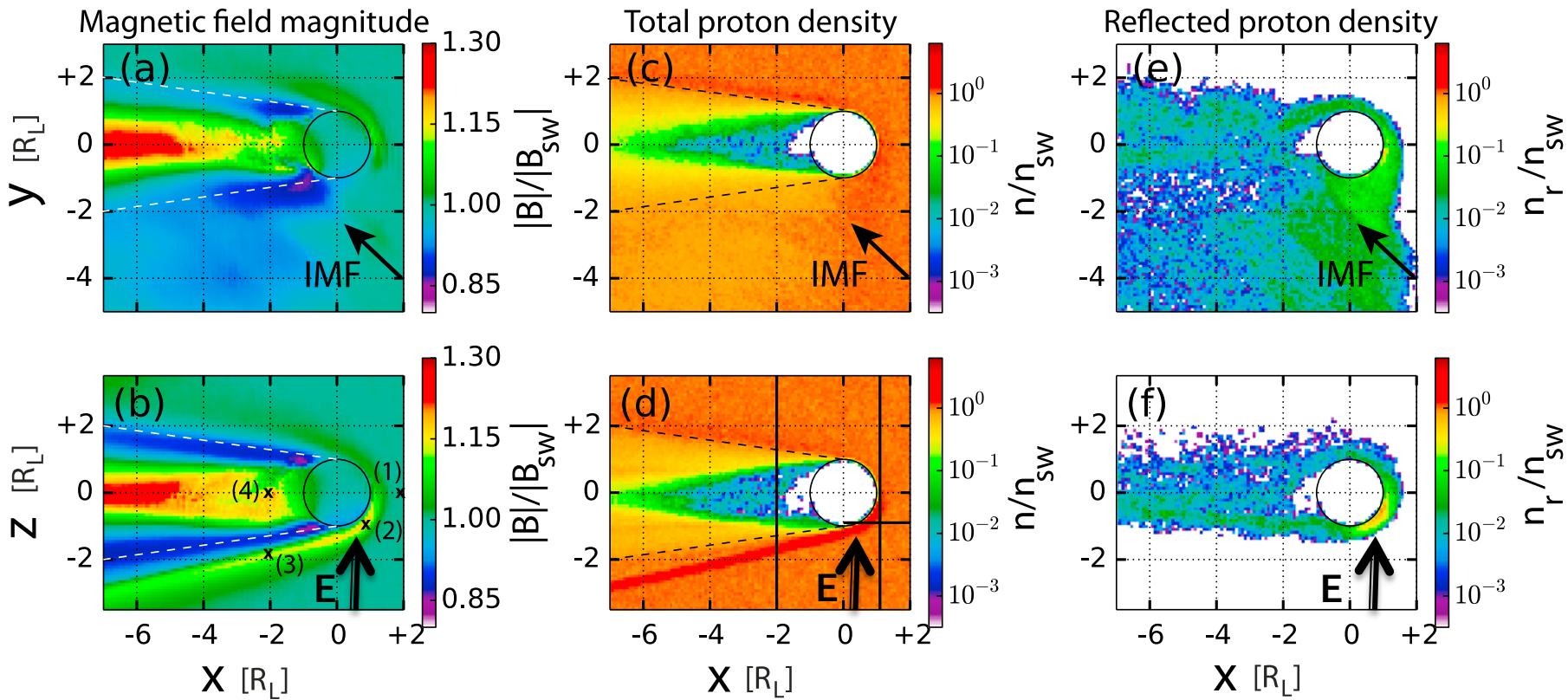
Limb Shocks?
Limb Compressions?

"there is no evidence that the plasma is shocked on passage through the features"

[Russell and Lichtenstein, 1975]

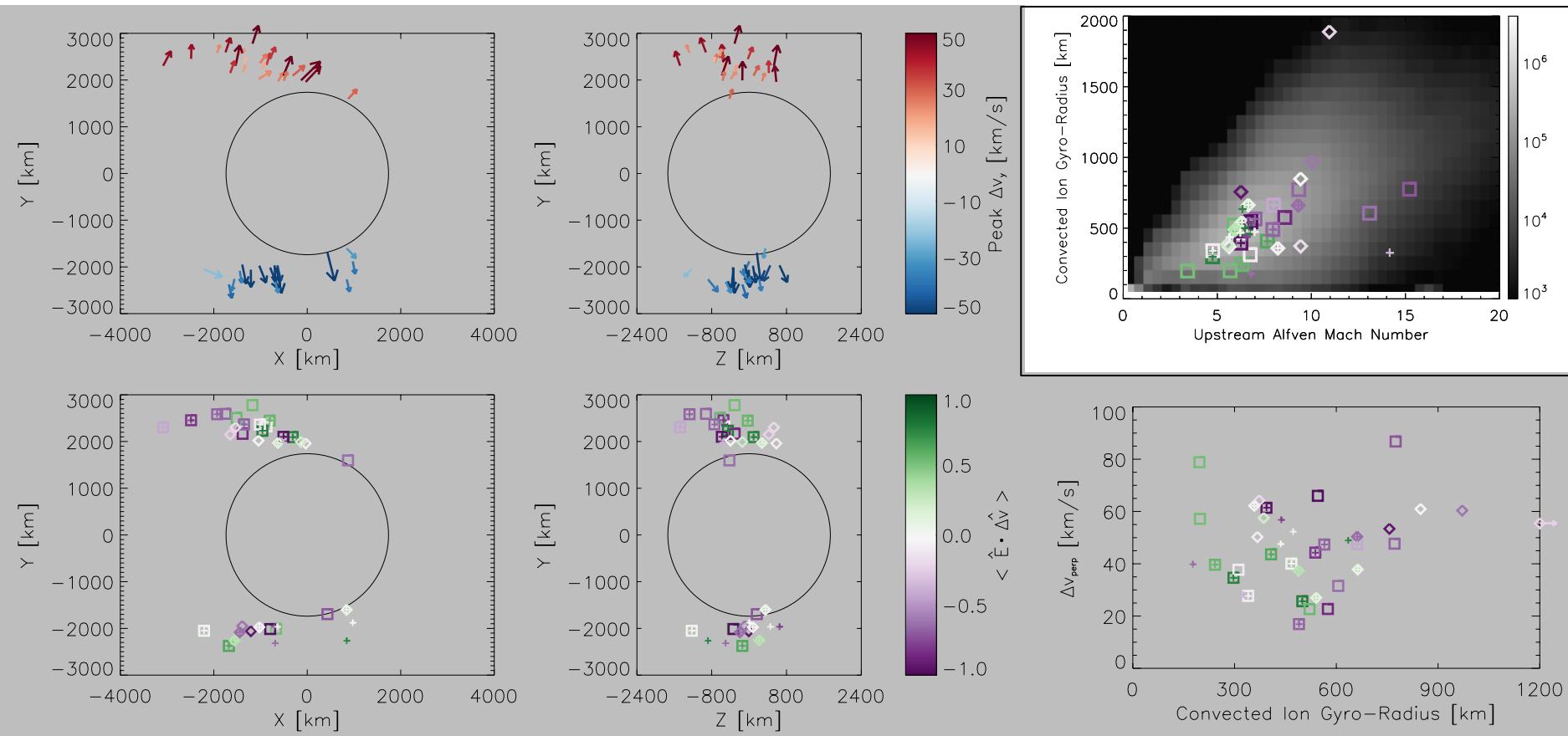


Connecting Microphysics to Macroscopic Effects



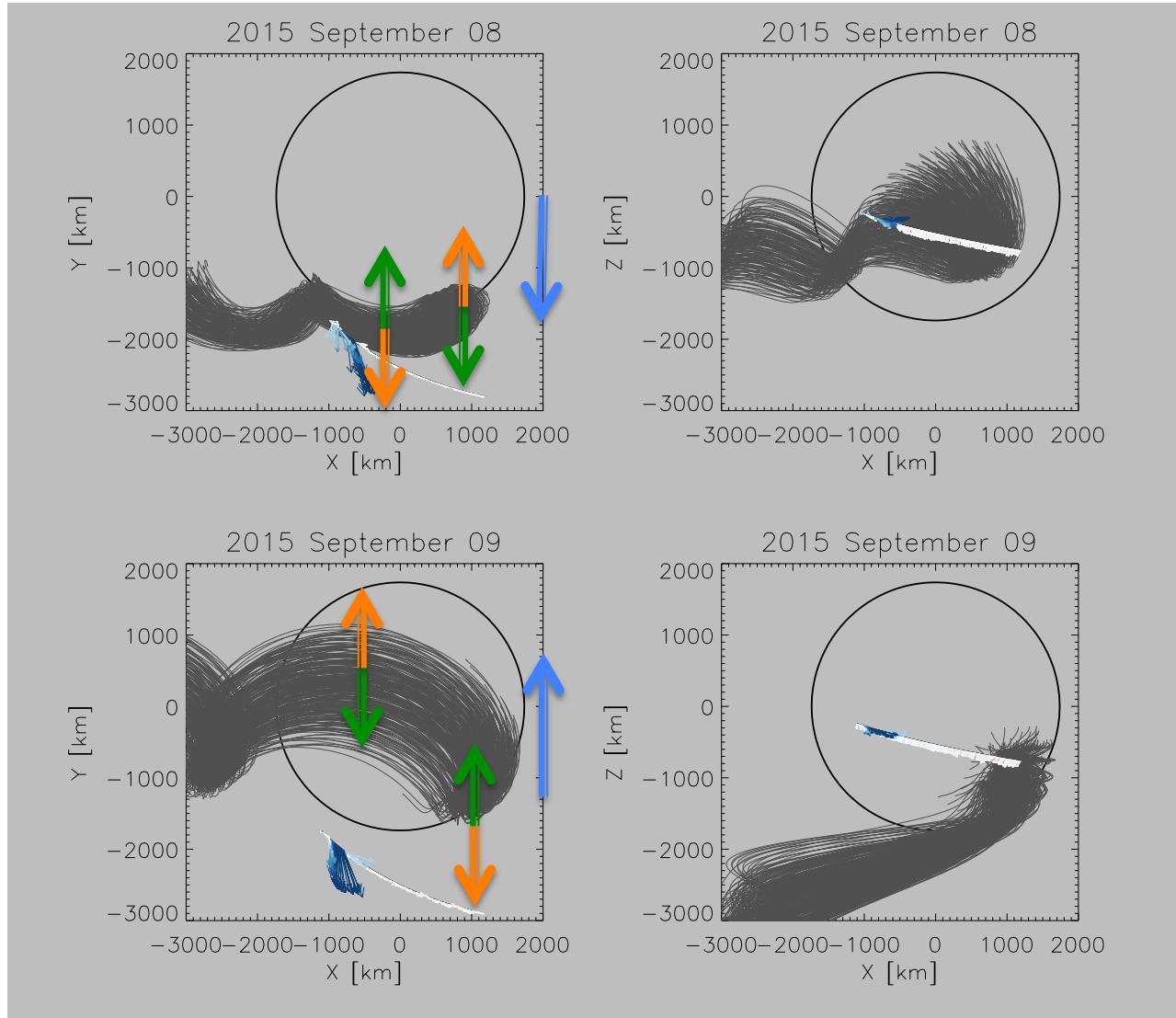
[Fatemi et al., 2014]

Two Kinds of “Limb Shocks”



Halekas et al., 2017

Two Kinds of “Limb Shocks”



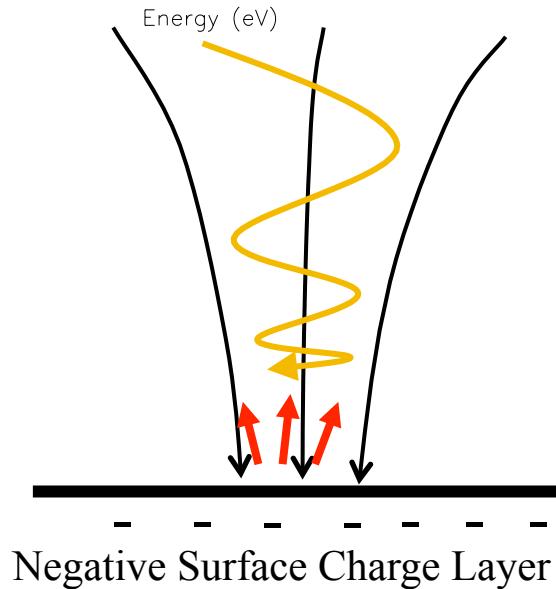
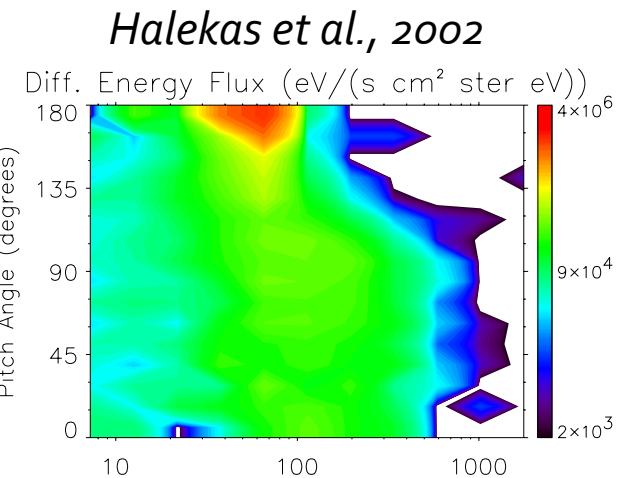
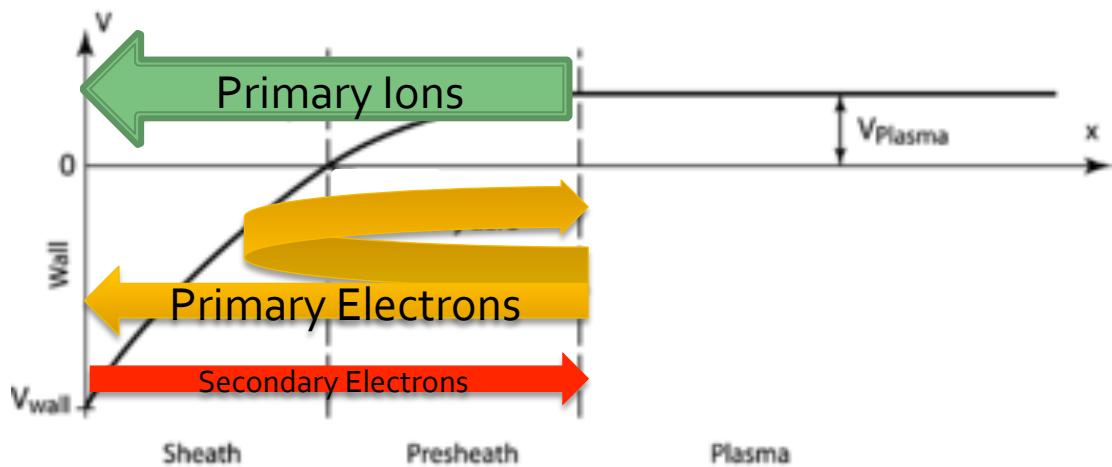
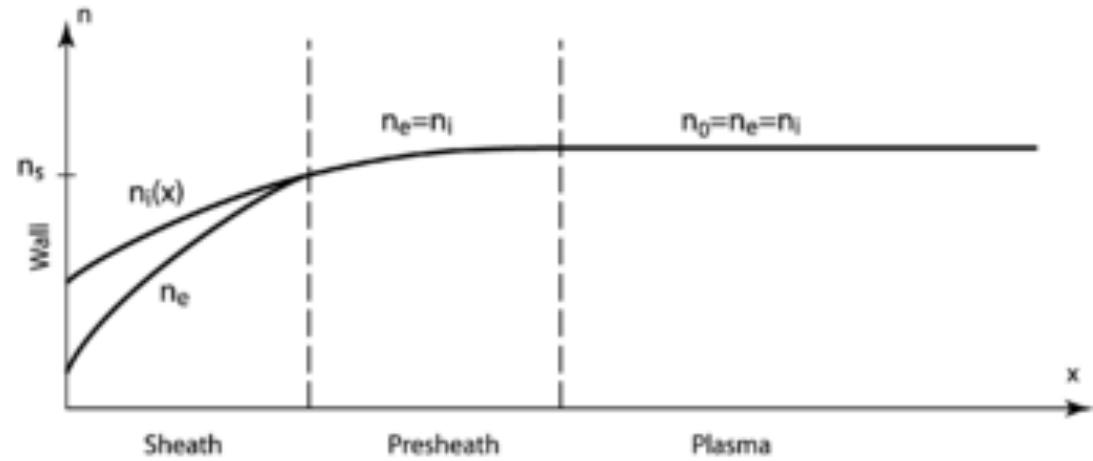
Upstream Motional
Electric Field

Force on Reflected
Protons

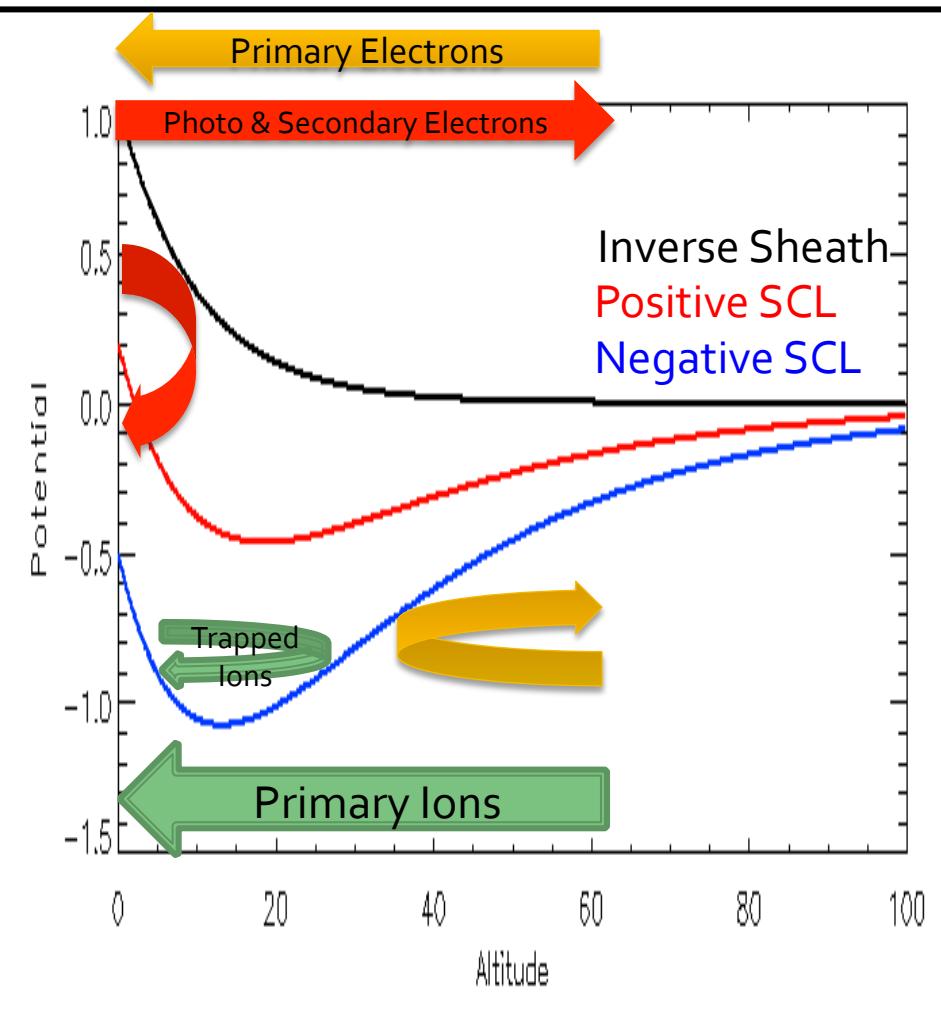
Force on Solar Wind

Halekas et al., 2017

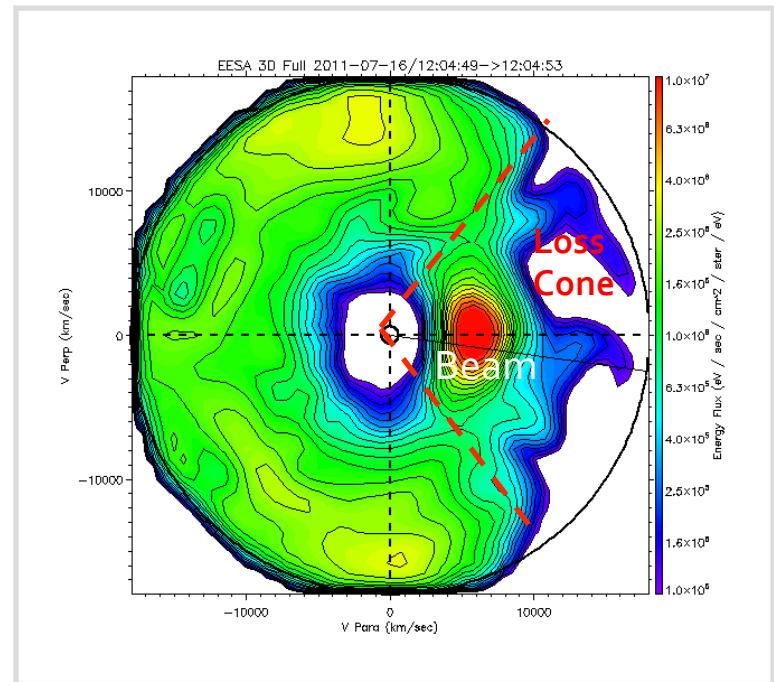
Night Side: Ion Sheath



Day Side: Photoelectron Sheath

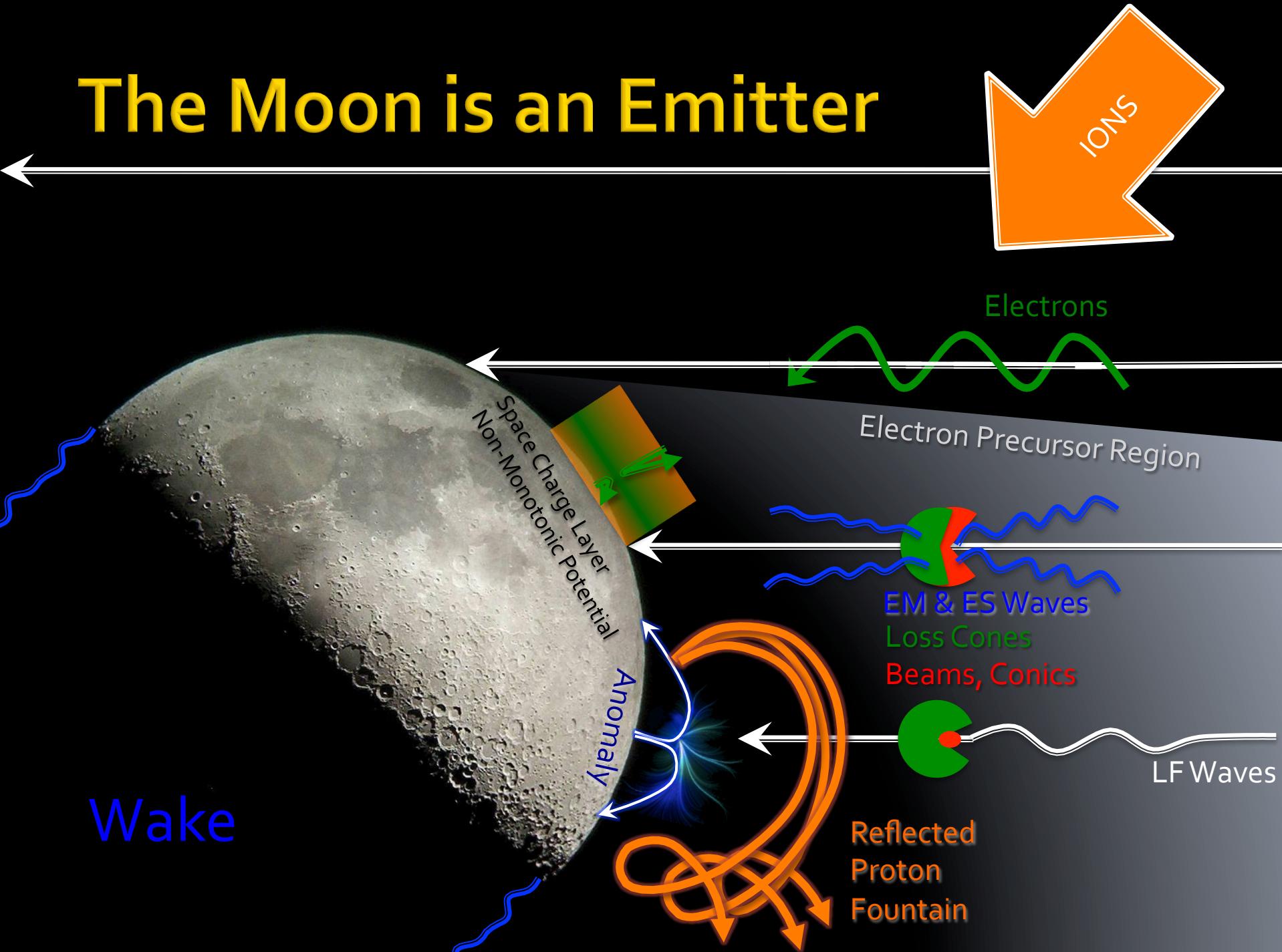


Halekas et al., 2011

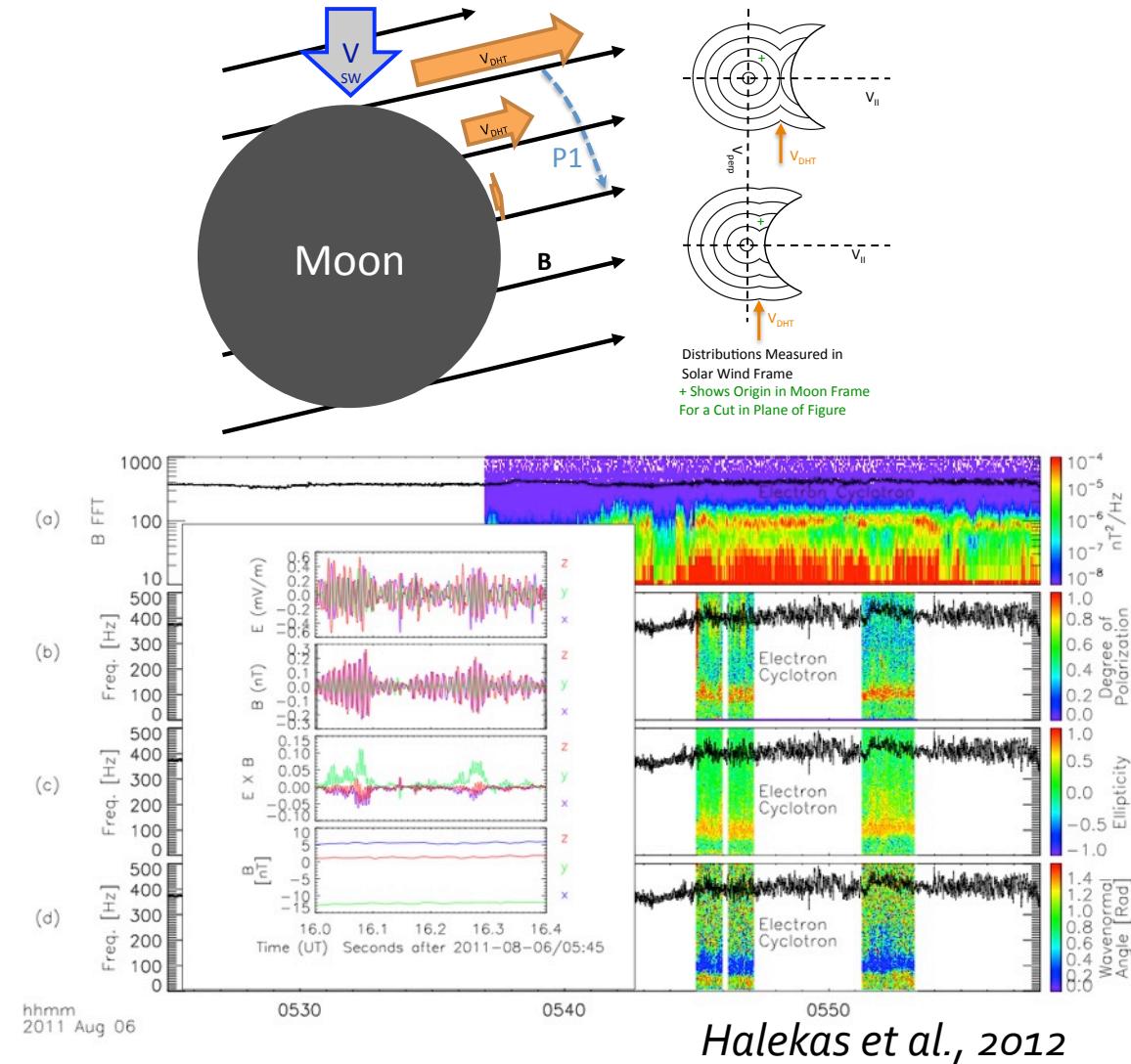
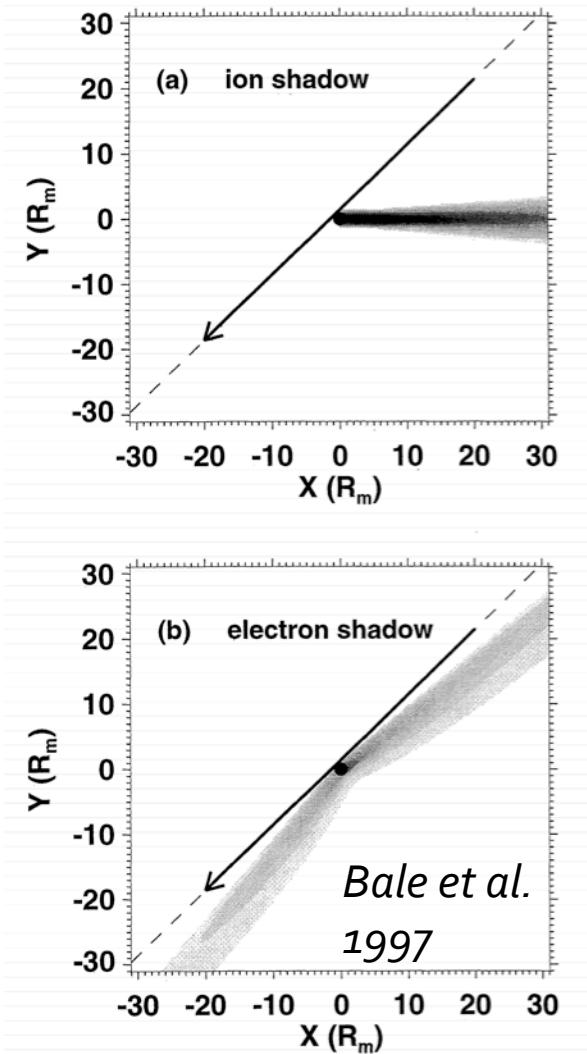


Beam + Loss Cone: Produced By Combined Magnetic & Electrostatic Effects Near Surface

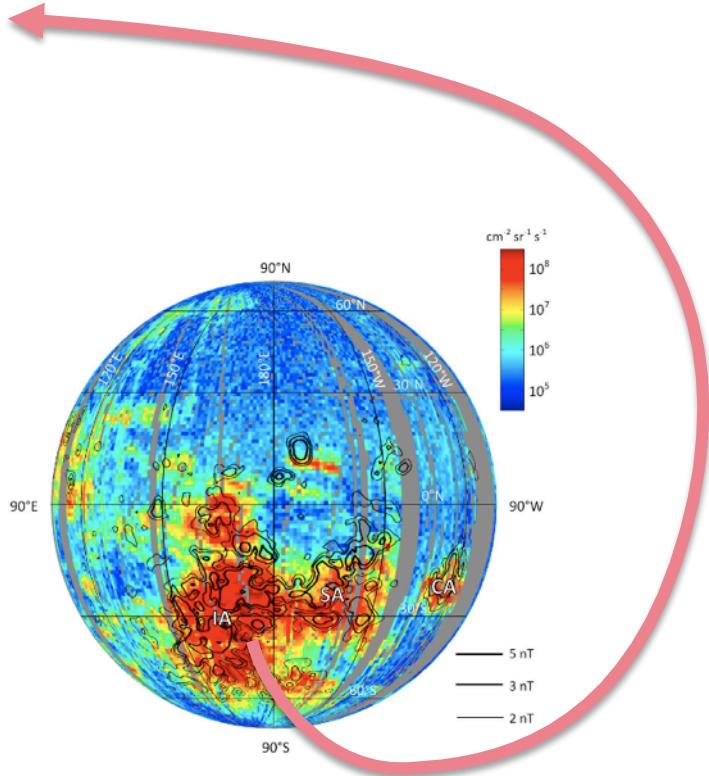
The Moon is an Emitter



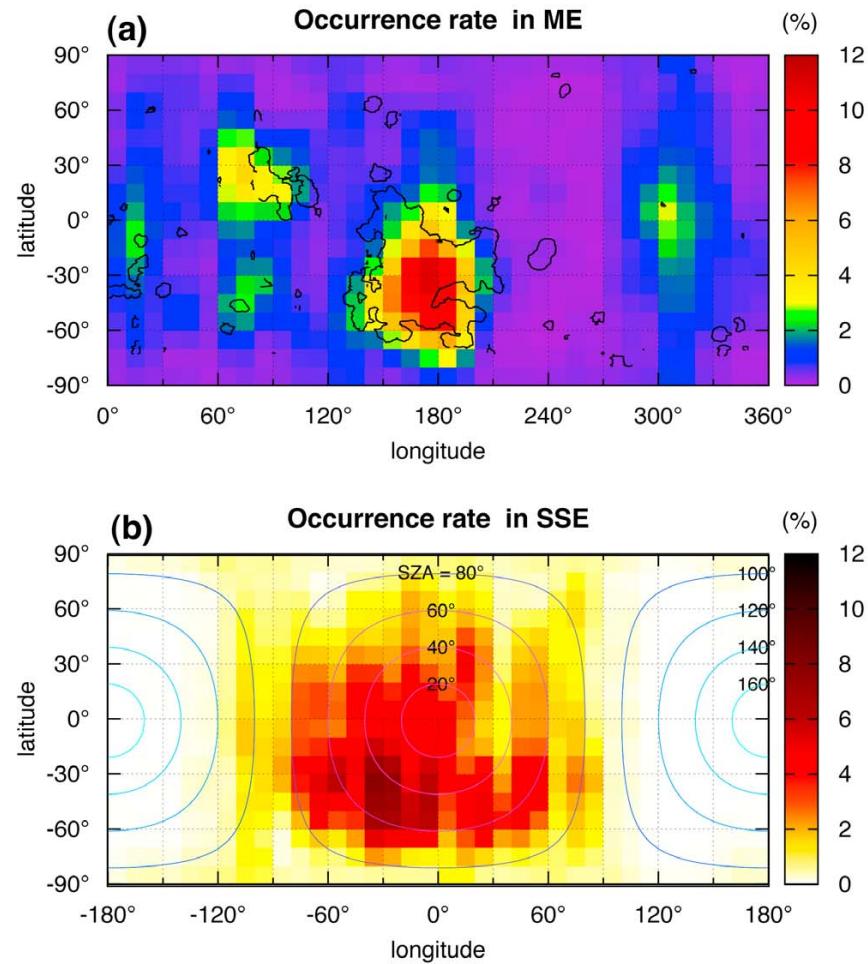
Electron-Driven Waves in the “Foremoon” and “Forewake”



Ion-Driven Low Frequency Waves



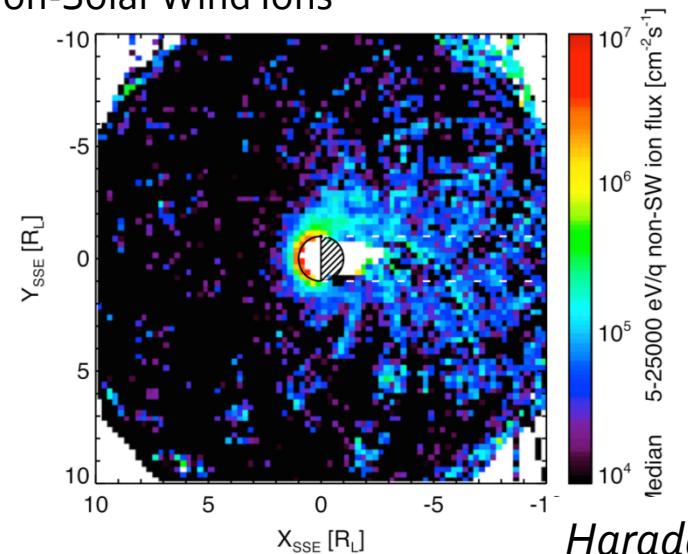
$$\omega \mp \mathbf{k} \cdot \mathbf{V}_{ion} = \Omega_i$$



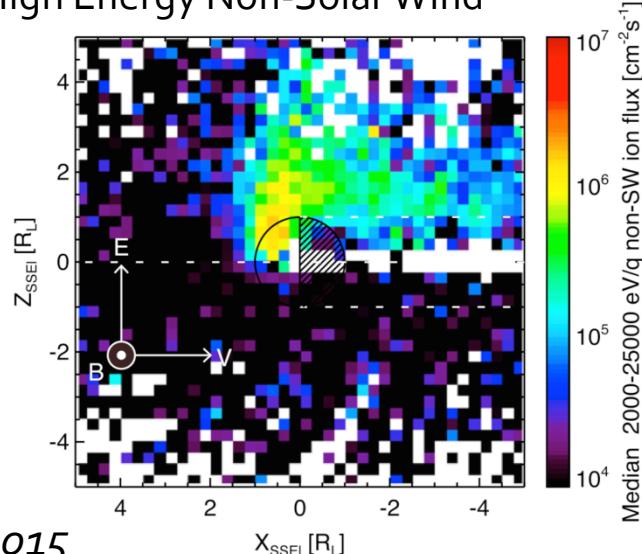
Tsugawa et al., 2012

Widespread Lunar Influence

Non-Solar Wind Ions

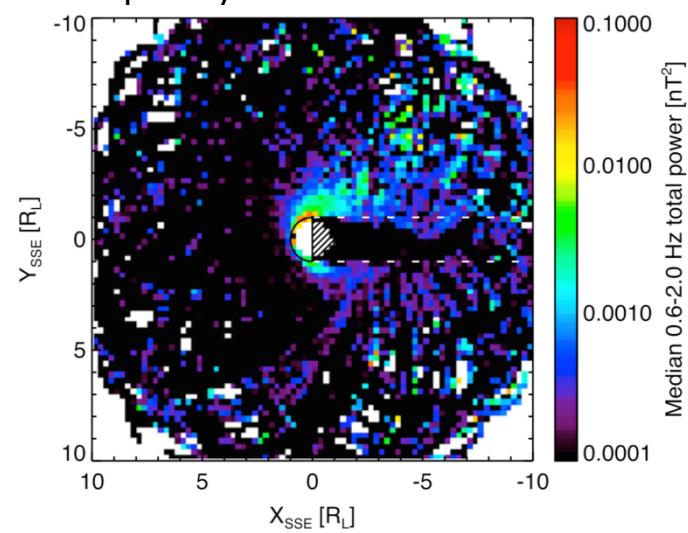


High Energy Non-Solar Wind

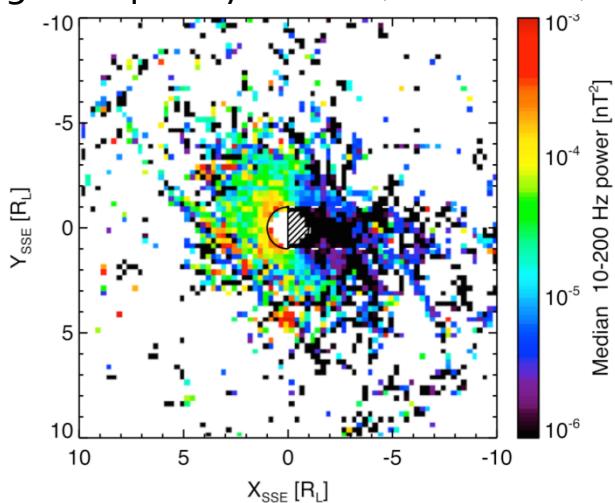


Harada et al., 2015

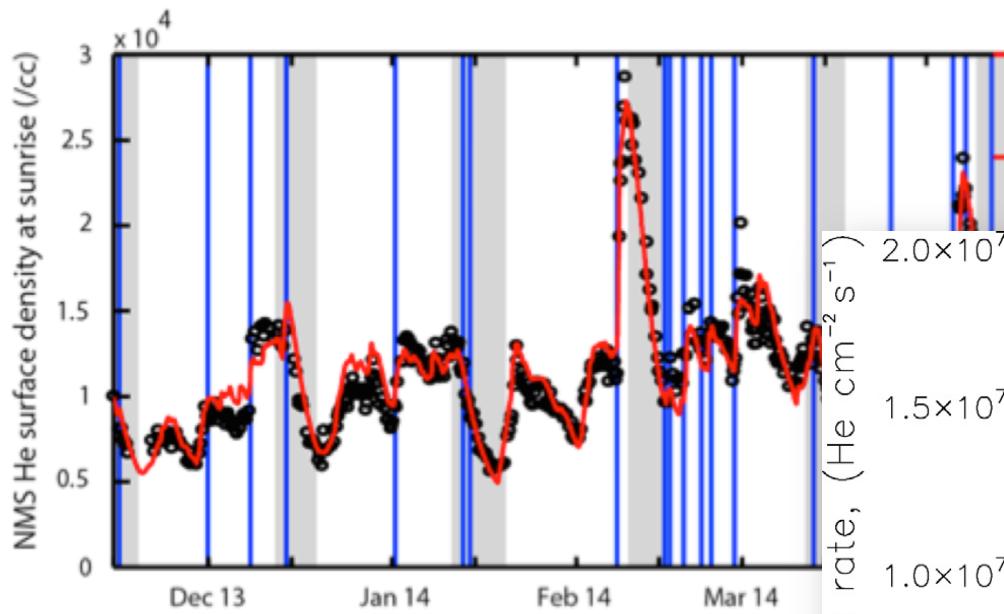
Low Frequency Waves



High Frequency Waves (Connected)

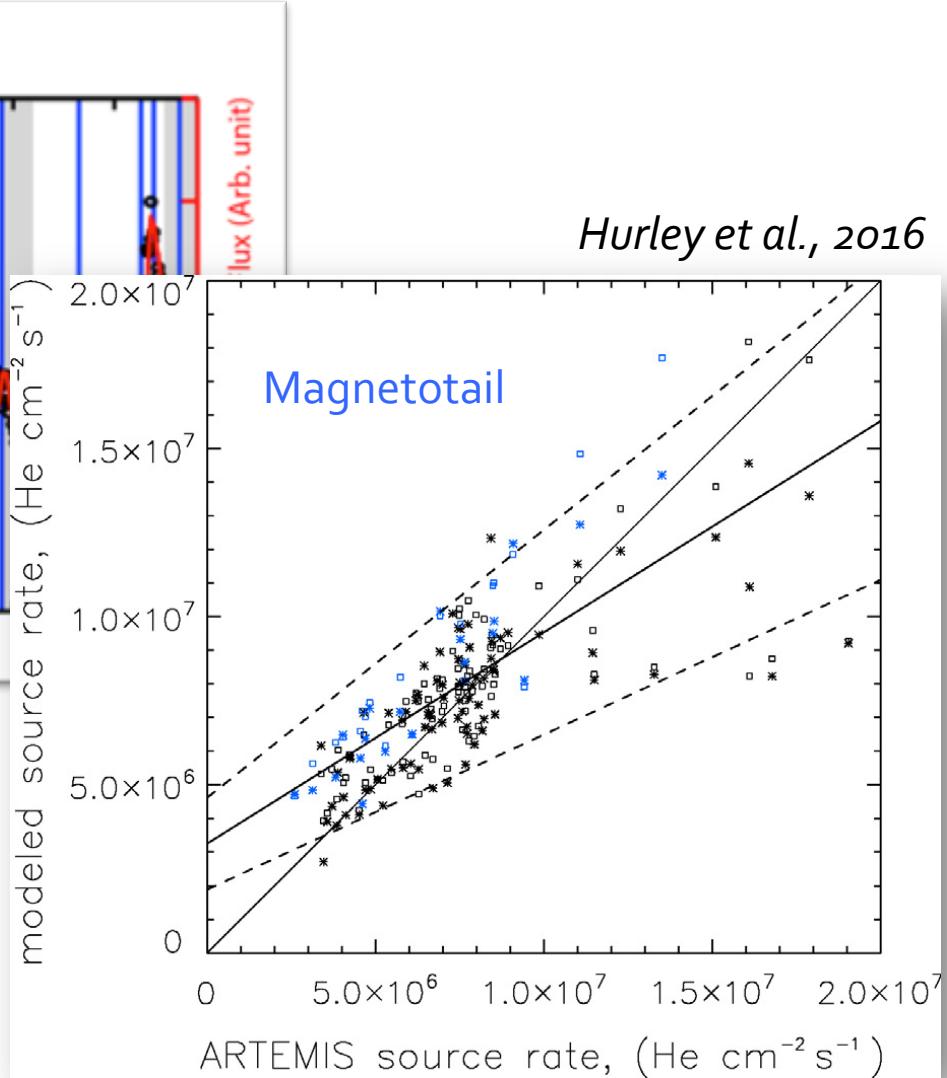


Plasma as an Exospheric Source

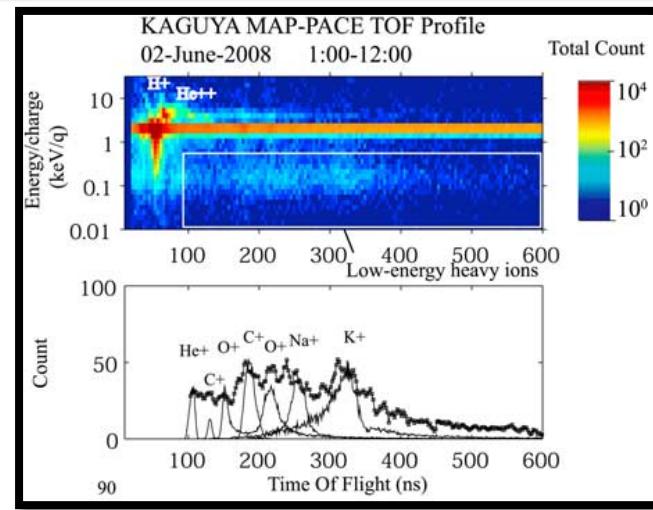
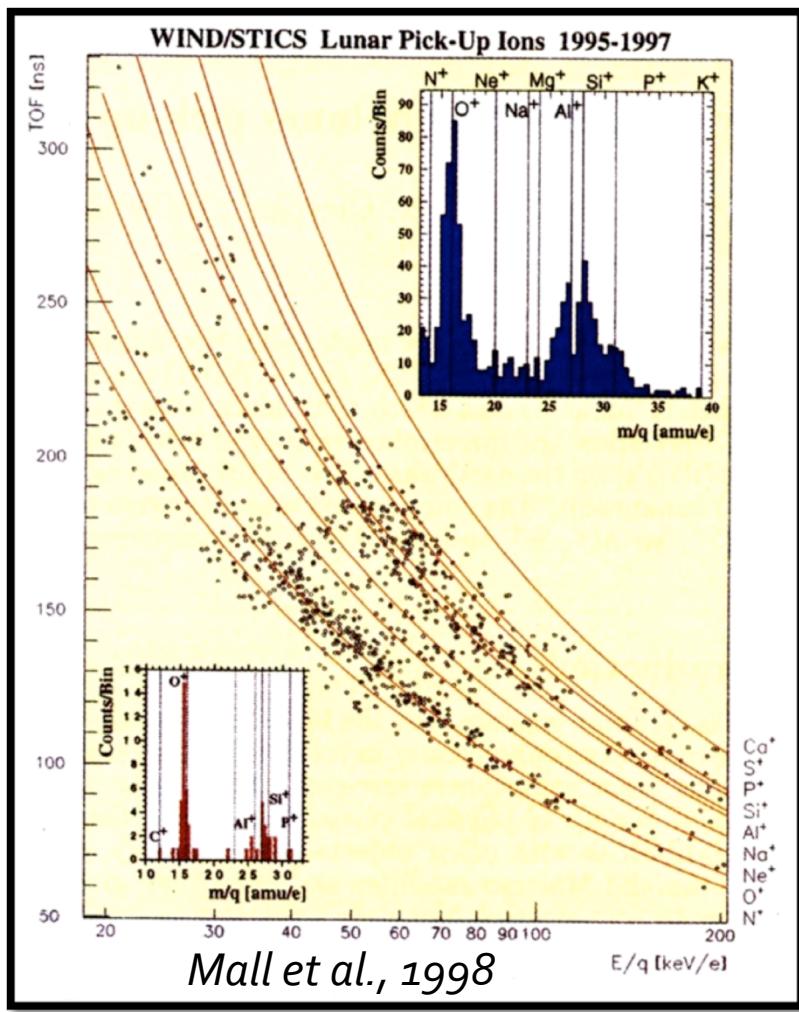


Benna et al., 2015

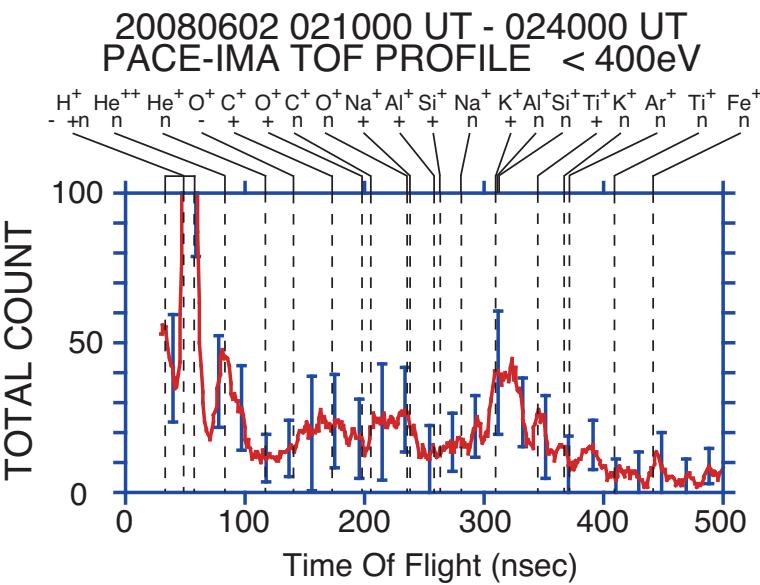
Also See: Solar Wind Sputtering...



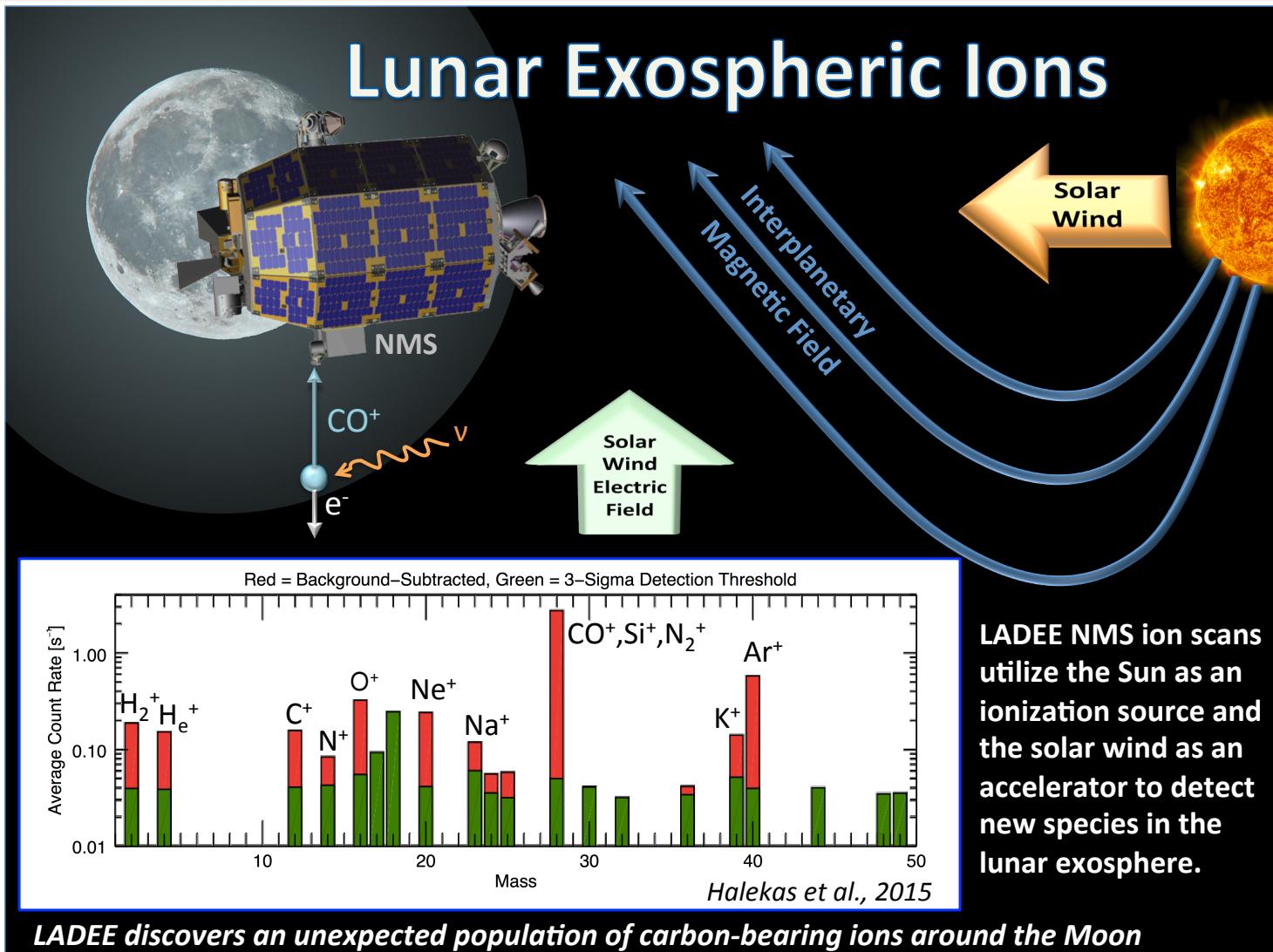
Plasma as an Exospheric Sink



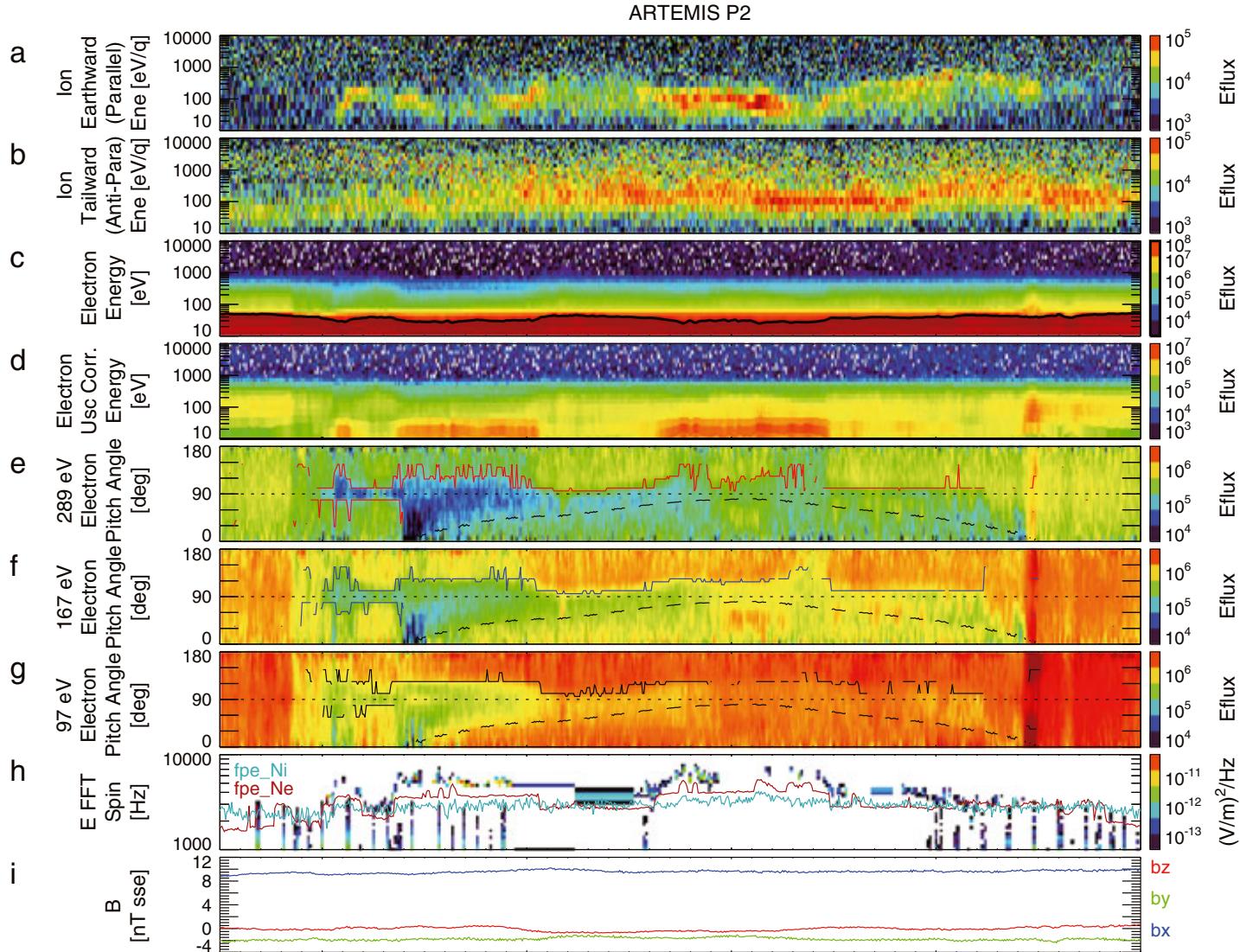
Yokota et al., 2009



Plasma as an Exospheric Sink



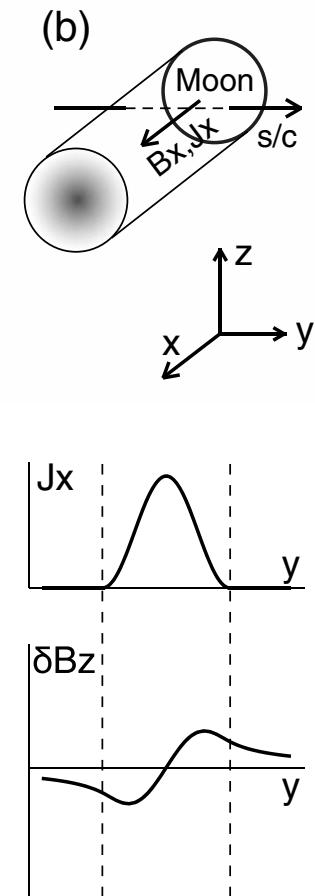
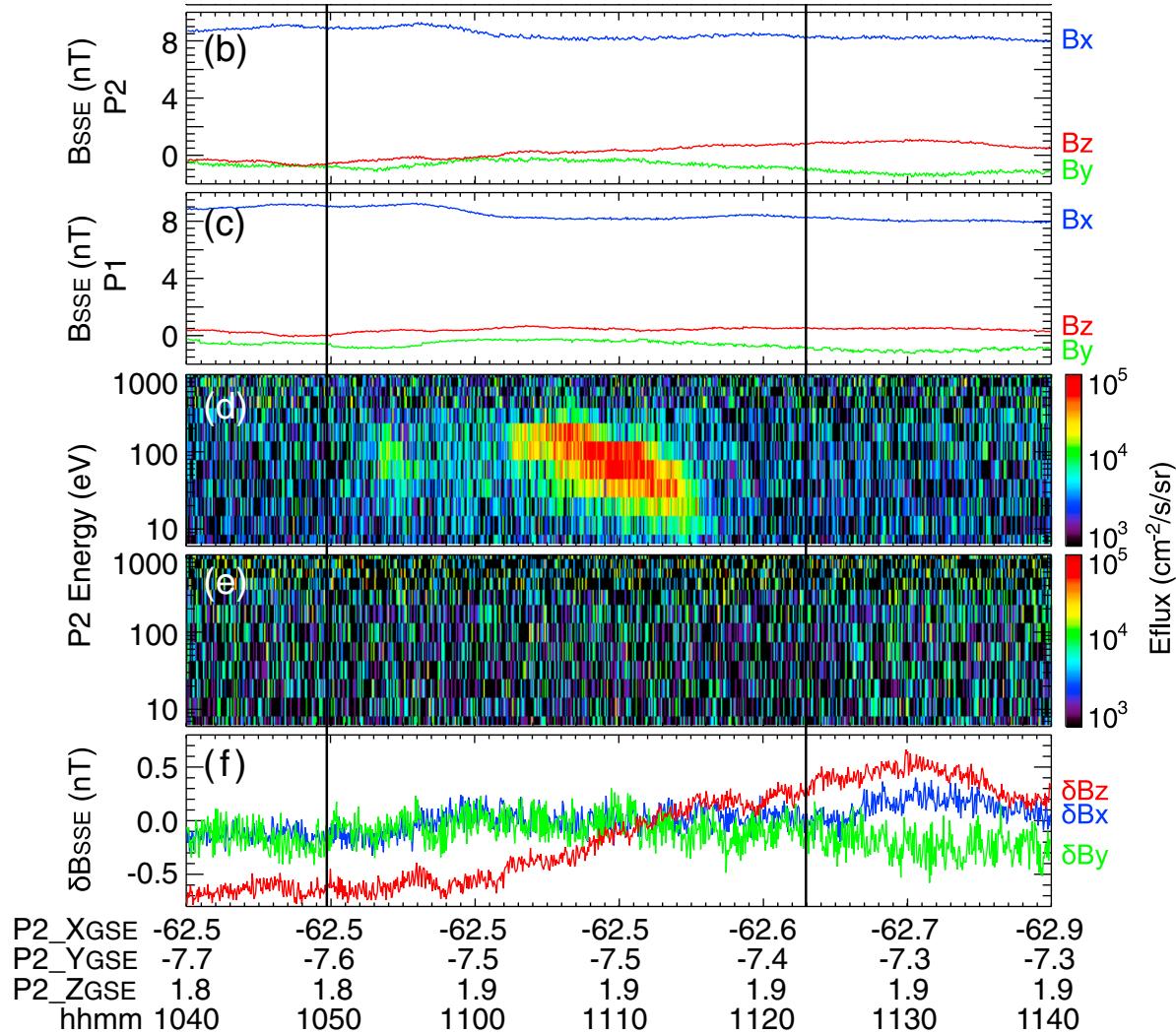
Weirdness: Moon in Magnetotail



Harada et al., 2013

- Lunar Ions
- Cold Electron Enhancements
- 90° Dropouts in Energetic Electrons
- Dens. Increases
- Few Magnetic Perturbations

Weirdness: Moon in Magnetotail



Zhou et al., 2014

Moon in Magnetotail: Some Thoughts

- The Moon in the magnetotail is **not** a “pickup” situation
 - The density of lunar exo-ions **exceeds** that of the lobe plasma
- The Moon is more like a comet...
 - But, it's a very very low-beta comet
 - The dominant force on lunar ions in the magnetotail should probably be $J \times B$ (*not* $-v \times B$!)

Frontiers

[Paraphrased from Schubert and Lichtenstein, 1974]

- What properties of the solar wind or lunar surface are responsible for the highly variable nature of the interaction?
- What is the structure of the lunar cavity far downstream from the Moon?
- What are the sources of the limb disturbances?
- The physics of the Moon-magnetosheath and the Moon-plasma sheet interactions.
- Possible upstream influences of the Moon in the solar wind, especially at high frequencies
- What is the nature of the Moon-solar wind interaction over the lunar polar regions?

Frontiers

[Paraphrased from Schubert and Lichtenstein, 1974]

- What properties of the solar wind or lunar surface are responsible for the highly variable nature of the interaction?
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- What are the sources of the limb disturbances?
- The physics of the Moon-magnetosheath and the Moon-plasma sheet interactions.
- Possible upstream influences of the Moon in the solar wind, especially at high frequencies
- What is the nature of the Moon-solar wind interaction over the lunar polar regions?

“New Frontiers”

- What is the time-dependent 3-d electric field structure of the wake?
- How do lunar interactions compare with other small-scale magnetic field gradients (e.g. RX diffusion regions, shocks) in the heliosphere?
- How does the presence of the surface and sheath affect the magnetic anomaly interaction?
- What is the composition of lunar exo-ions and what do they tell us about the exosphere and/or surface?
- How does the Moon interact with the Earth’s magnetotail?