Foremoon cavity upstream of the Moon

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Planetary foreshock

Upstream of the bow shock is filled in by backstreaming particles

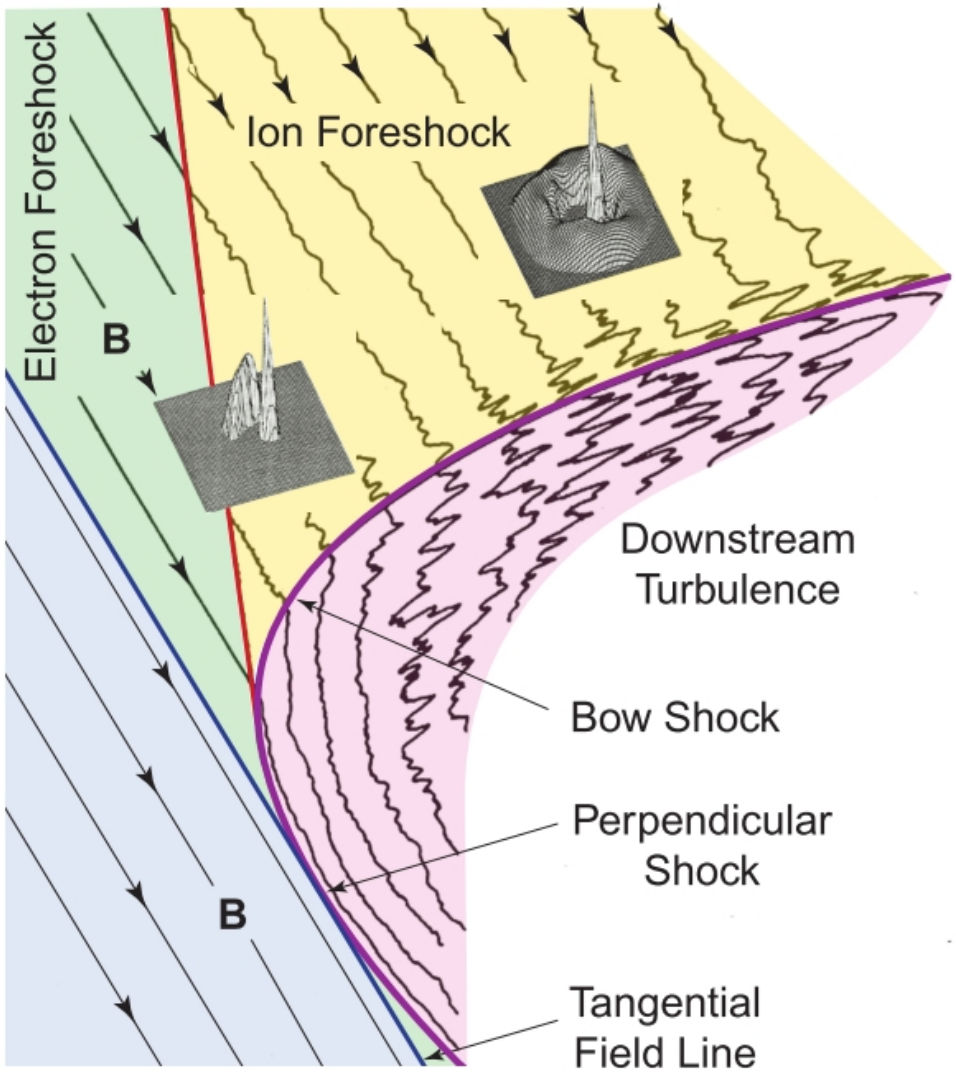
Reflected particles are interacting with the incoming solar wind

Plasma interaction with

- reflected particles
- waves

Foreshock processes affect the energy transfer between the solar wind and planetary magnetosphere

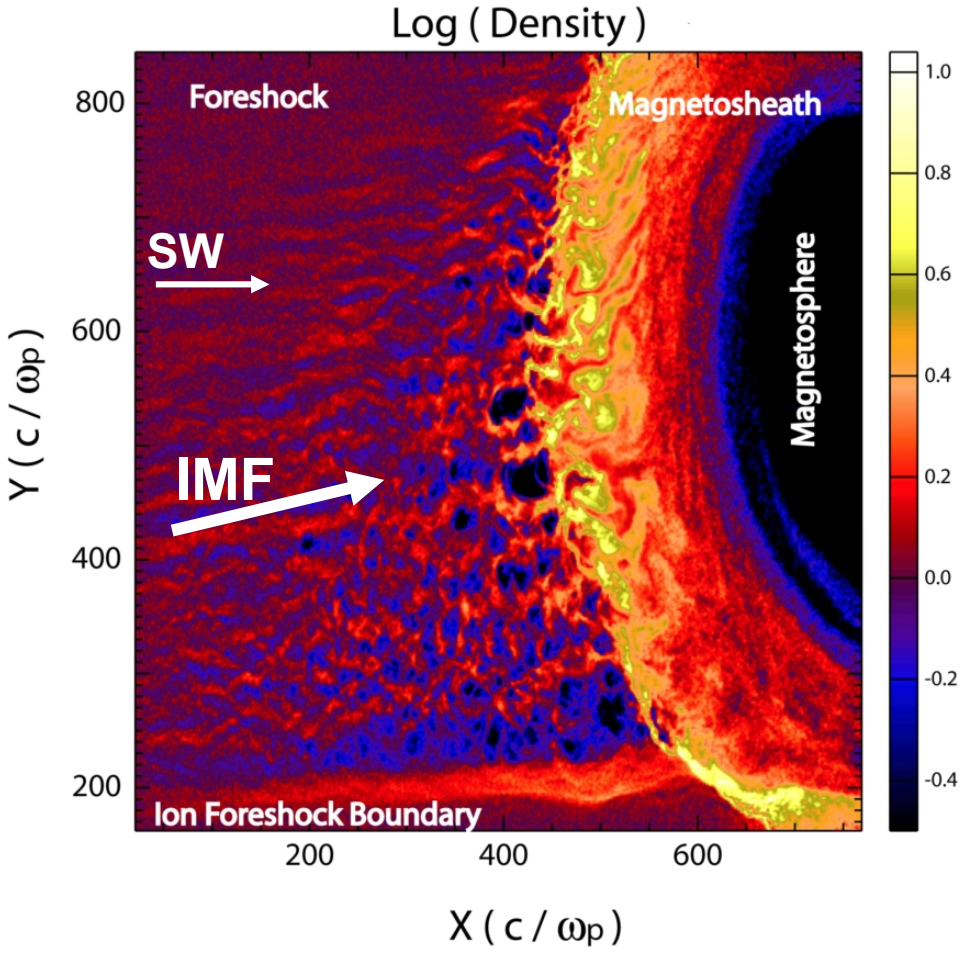
Natural plasma laboratory



[Treumann and Scholer, 2001]

Foreshock cavities

1) Foreshock cavities:
IMF connection to the shock

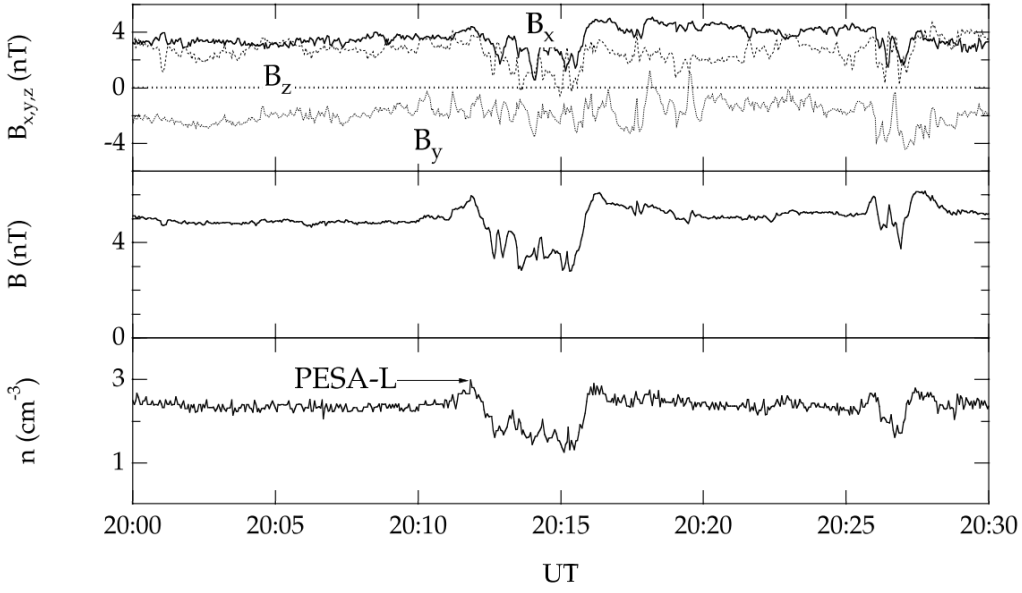


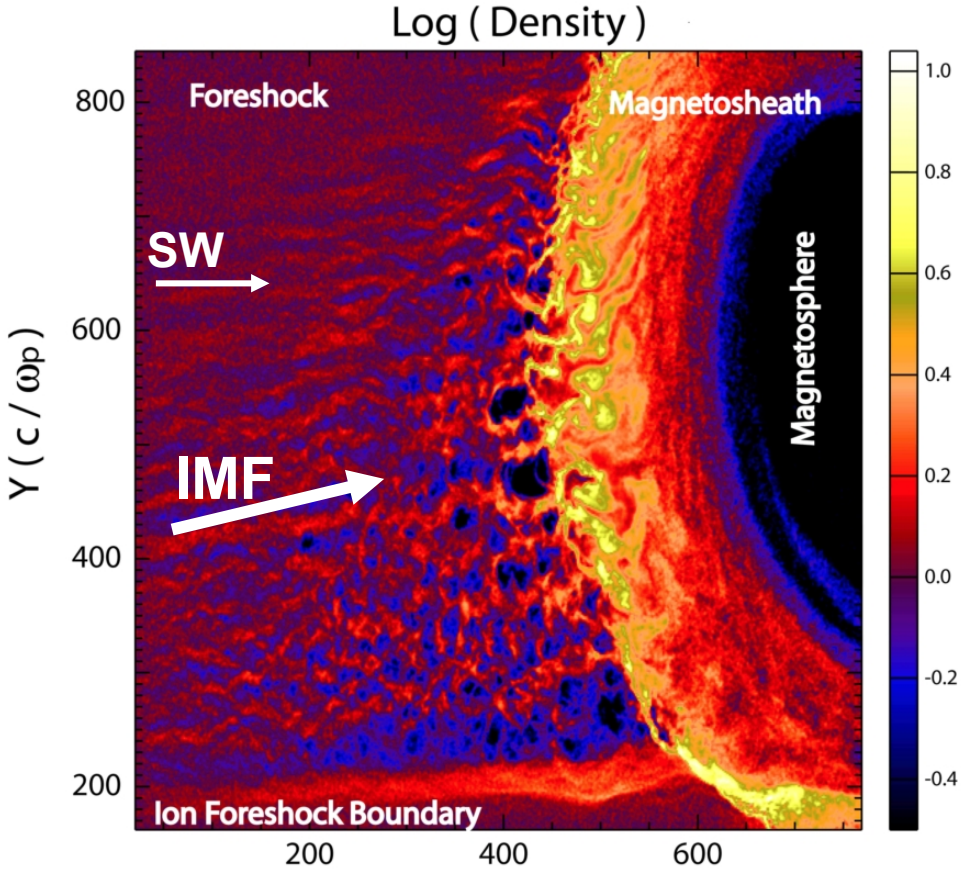
[N. Omidi, 2007]

Foreshock cavities

1) Foreshock cavities:
IMF connection to the shock

WIND observation [Sibeck et al., 2002]



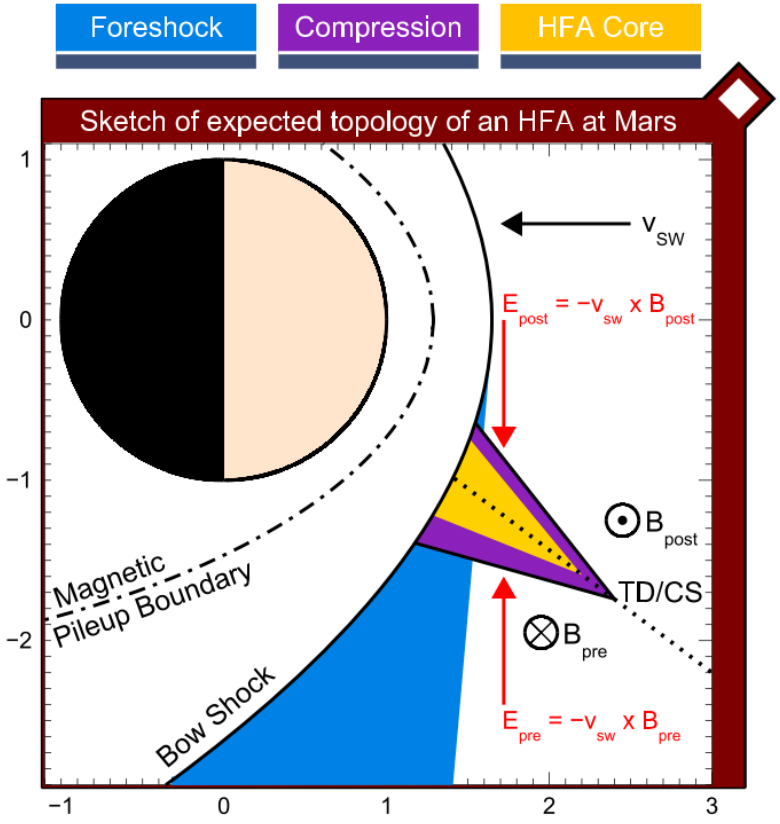


General characteristics:

- (center) Density and magnetic field reduction
- (flanks) Field and plasma compression

Foreshock transients (HFAs)

2) Hot Flow Anomalies (HFAs):
Discontinuity in contact with the shock.



[Collinson et al., 2015]

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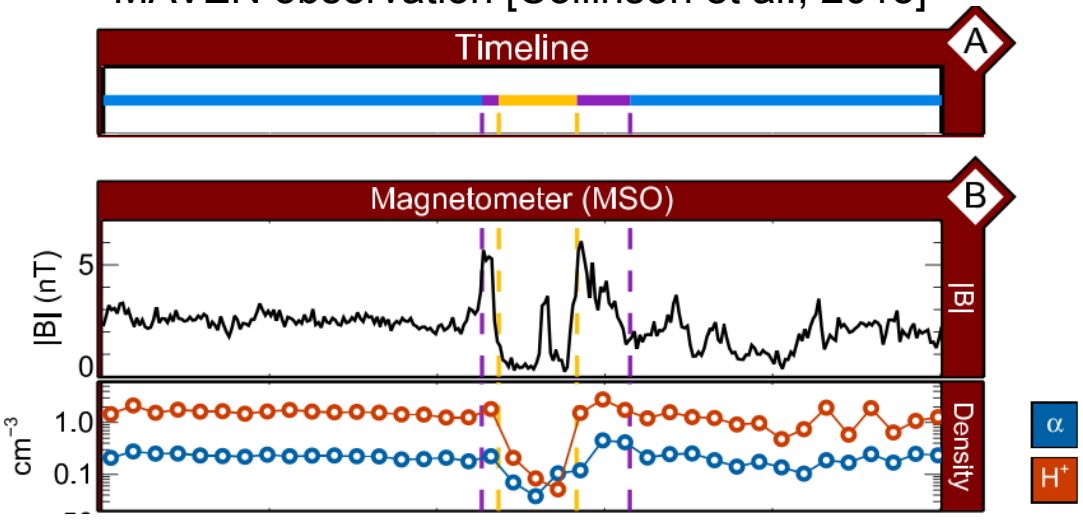
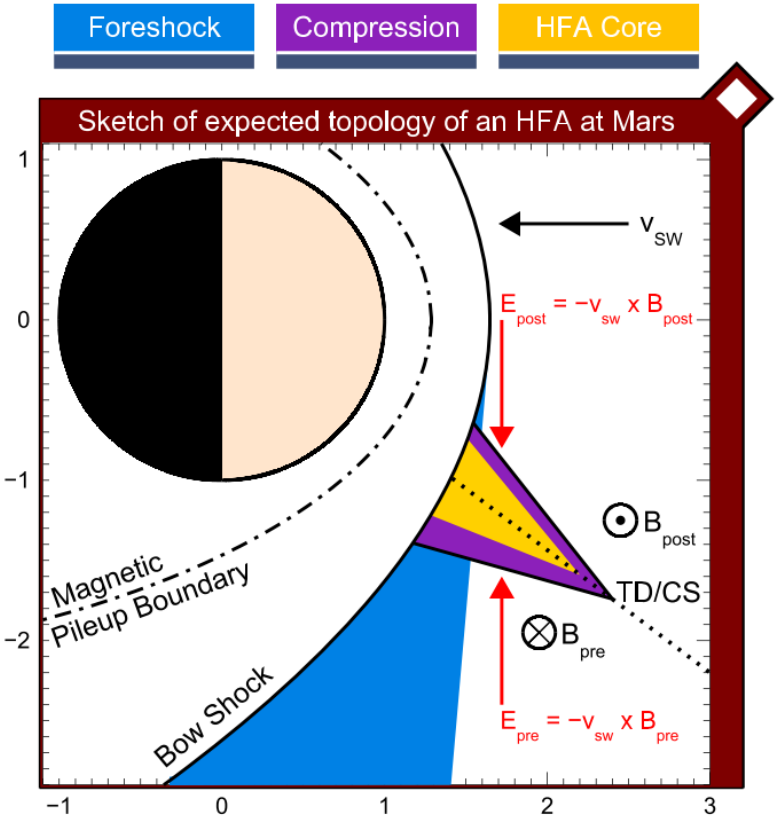
MAVEN observation [Collinson et al., 2015]





[Collinson et al., 2015]

Differences with cavities:
Fundamental differences in their formation mechanism and the following major differences in their characteristics

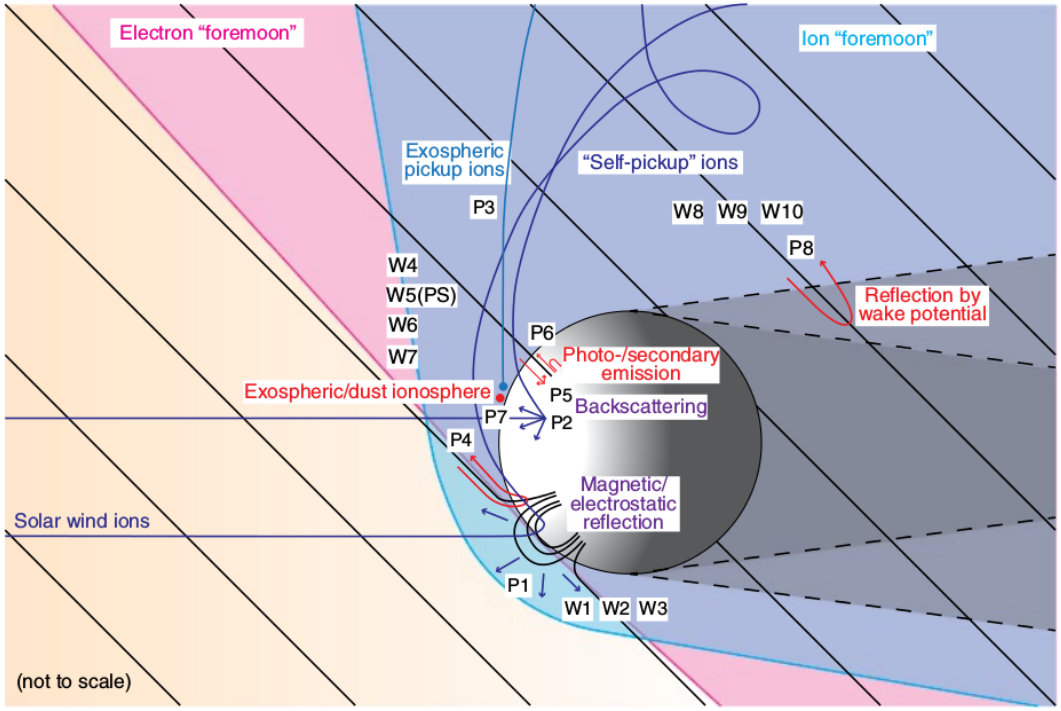
Foreshock cavity	HFA
Flow direction is not much affected	Deflected (~10-40 deg)
Slight increase in the SW temperature	Highly heated (~2-10x)

Foremoon cavity?

The Earth's Moon:

- No global magnetic field
  (small-scale crustal fields)
- No dense exosphere/ionosphere

Then no global bow shock.



[Harada and Halekas, 2016]

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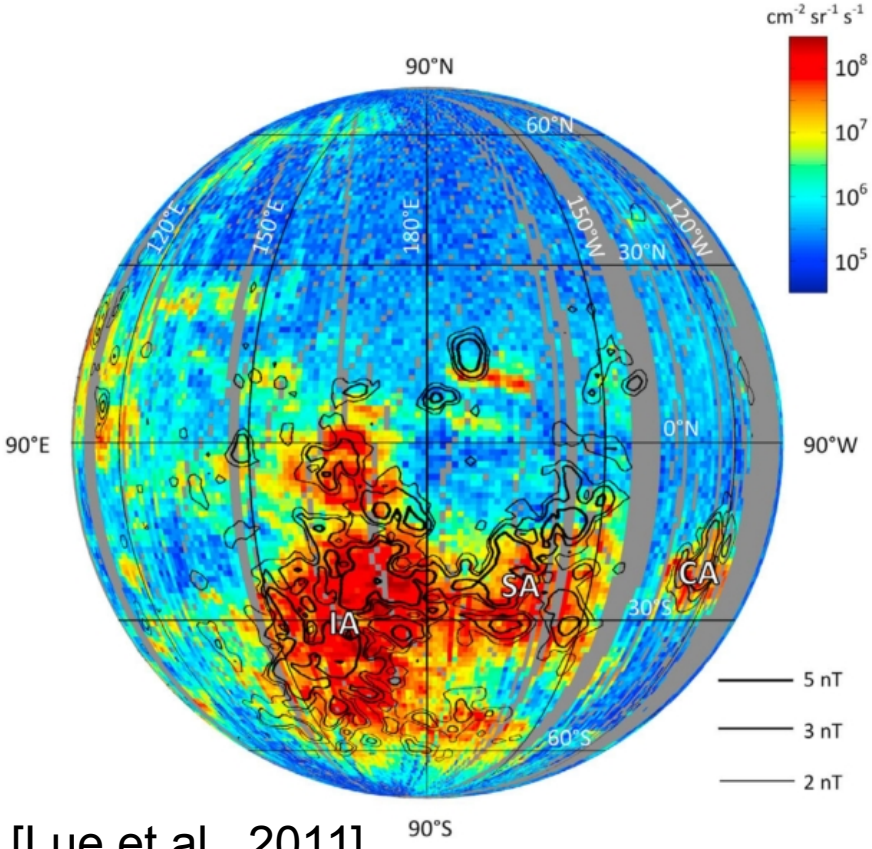
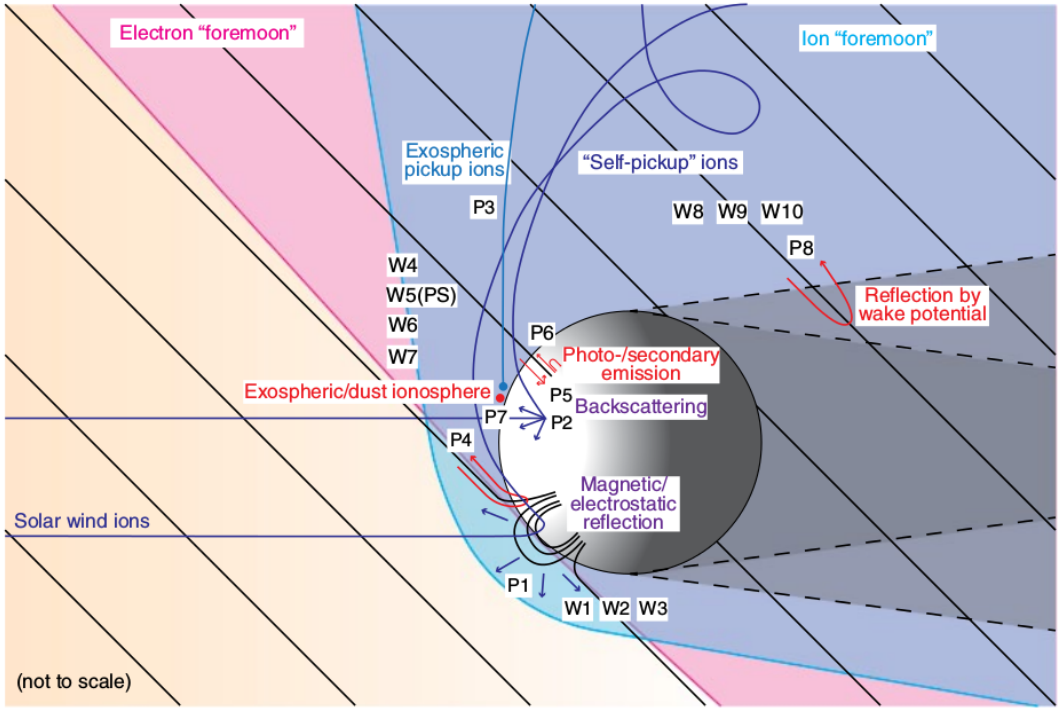


[Lue et al., 2011]



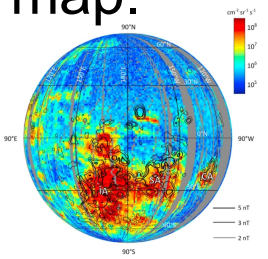
[Harada and Halekas, 2016]

But particles are reflected in charged form by the crustal magnetic fields (average ~10-20%, to >50%)

Surface reflection is small (<1%)

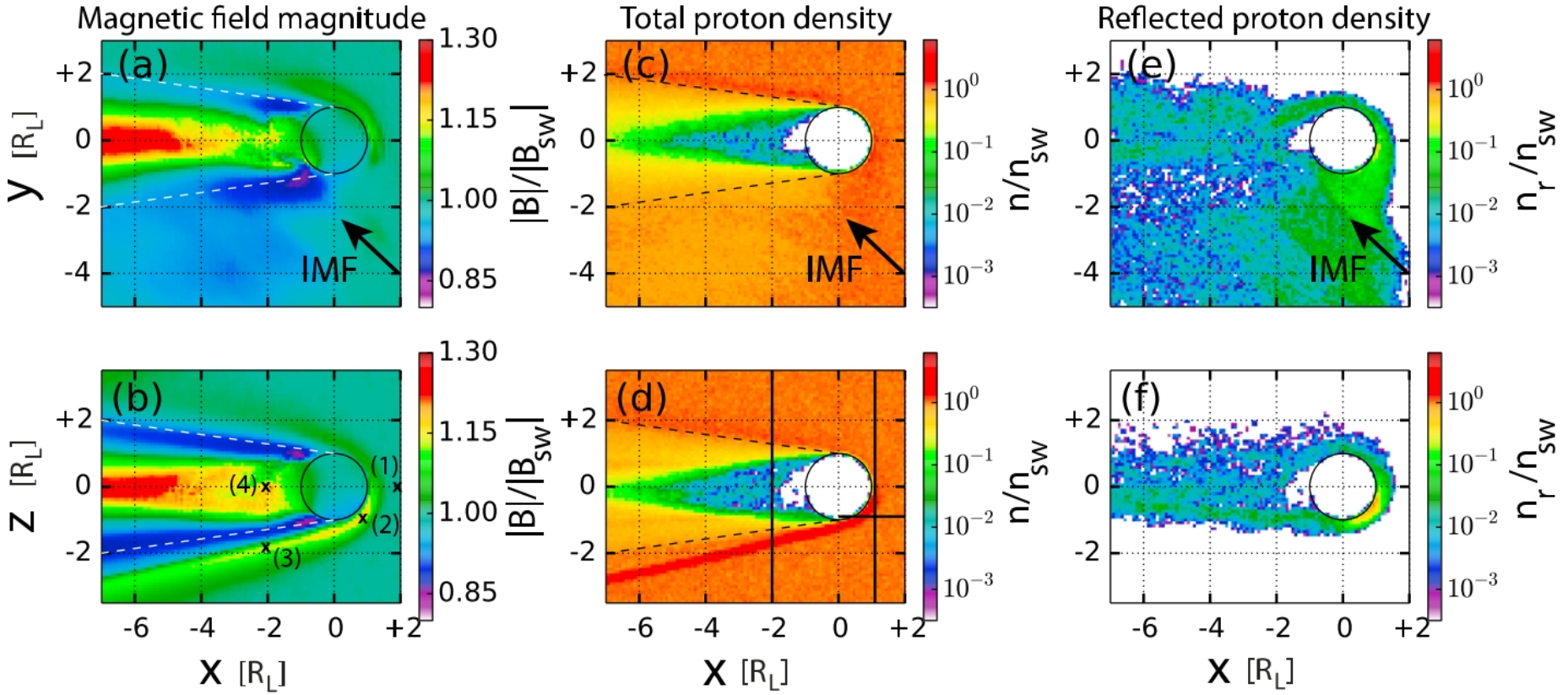
Global effects of plasma reflection

Plasma reflection from crustal magnetic fields using Chandrayaan-1 map.



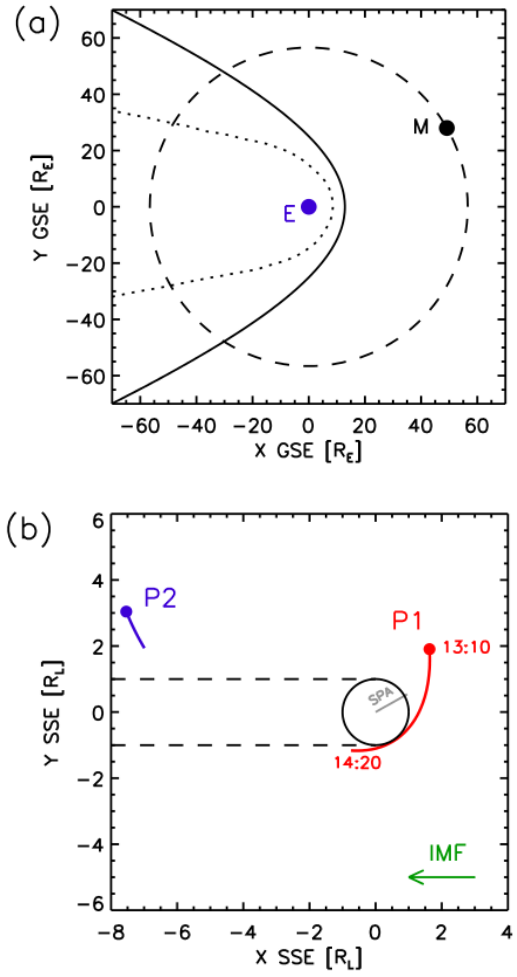
Field and plasma compression upstream, and adjacent to the plasma wake downstream of the moon.

Evidence of small-scale shocks are observed at the Moon [Halekas et al., 2015]



[Fatemi et al., 2014]

ARTEMIS observation of a foremoon cavity



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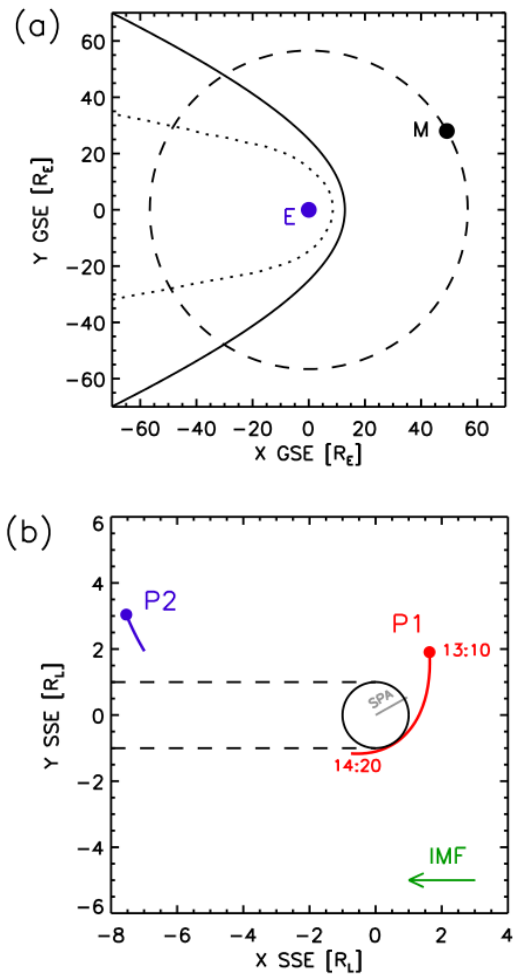
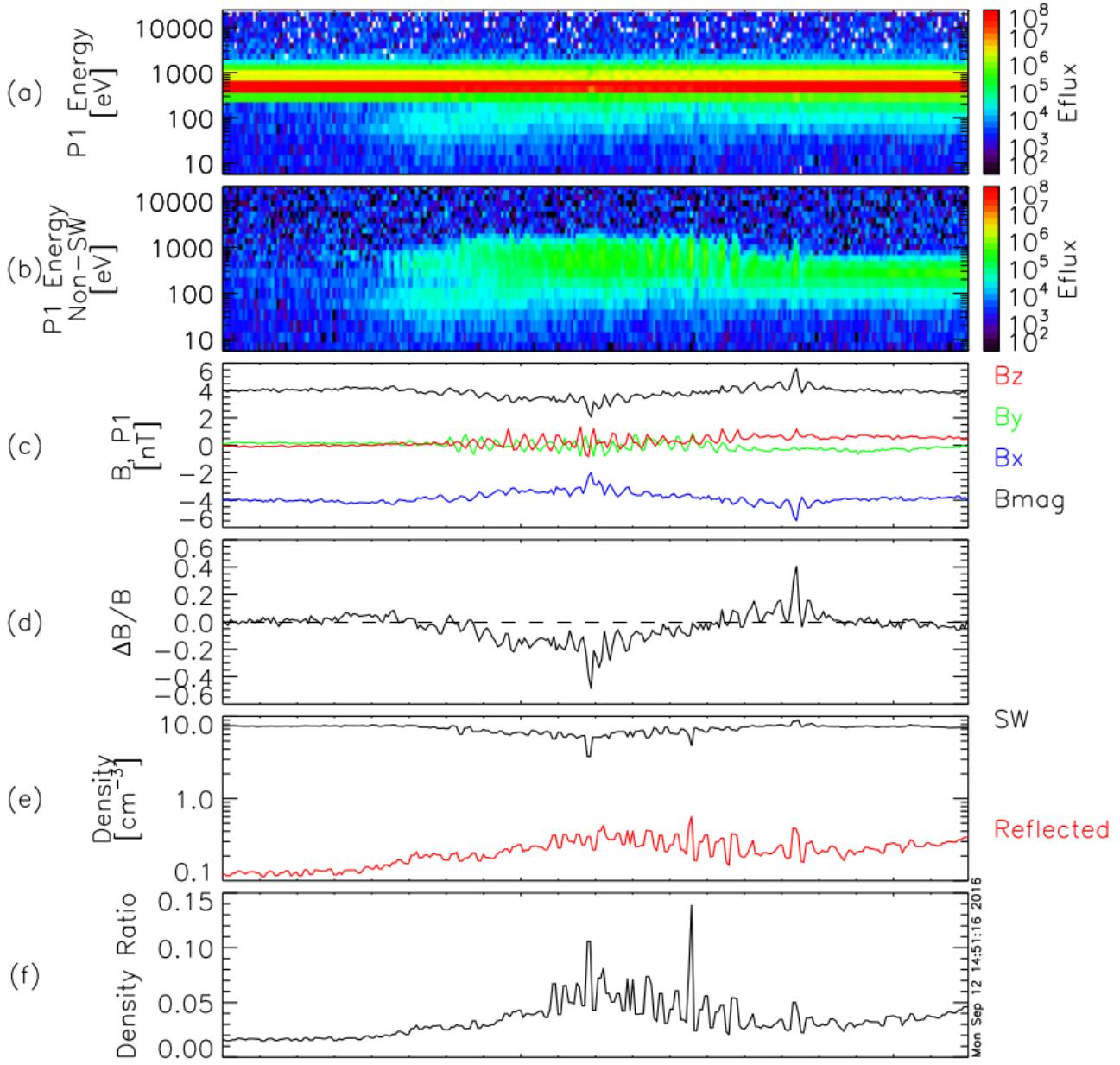




AMITIS: A GPU-based hybrid model

Three-dimensional hybrid model of plasma (kinetic ions, fluid electrons)

The first of its kind that runs on a single CPU-GPU pair (~10-20x faster than parallel models)

The code is in C/C++ language, uses CUDA library and runs on NVIDIA GPUs.

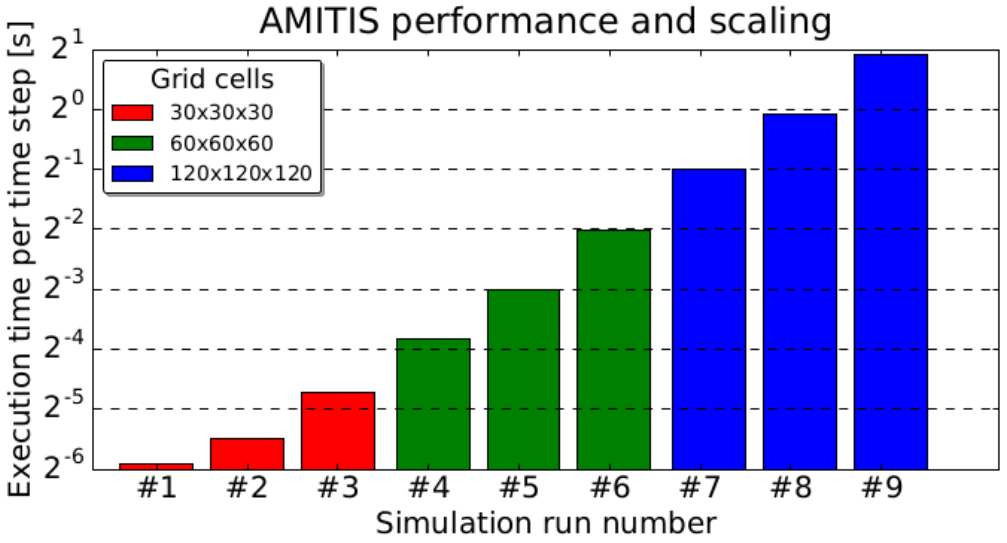
Enables us to use higher grid resolution and run for a longer simulation time.

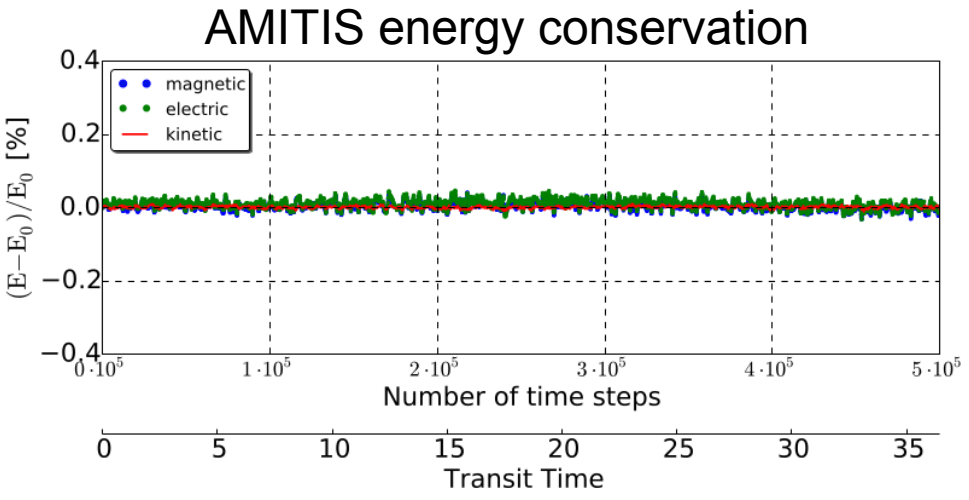
Novelty: self-consistently coupling electromagnetic response of an object's interior with the surrounding plasma environment using an implicit solver for an object's interior.

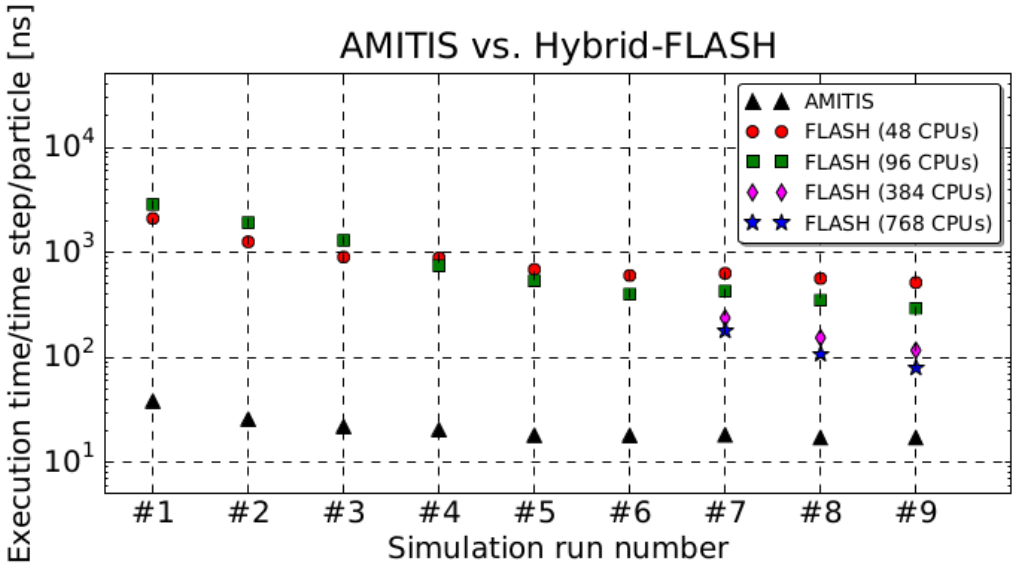
It will be publicly available, soon!

AMITIS performance and energy conservation

run	grid cells	cell size	ppc	total particles
#1	30×30×30	100 km	16	432,000
#2			32	864,000
#3			64	1,728,000
#4	60×60×60	100 km	16	3,456,000
#5			32	6,912,000
#6			64	13,824,000
#7	120×120×120	100 km	16	27,648,000
#8			32	55,296,000
#9			64	110,592,000







[Fatemi et al., 2017, J. of Phys., Accepted]

AMITIS hybrid simulation results

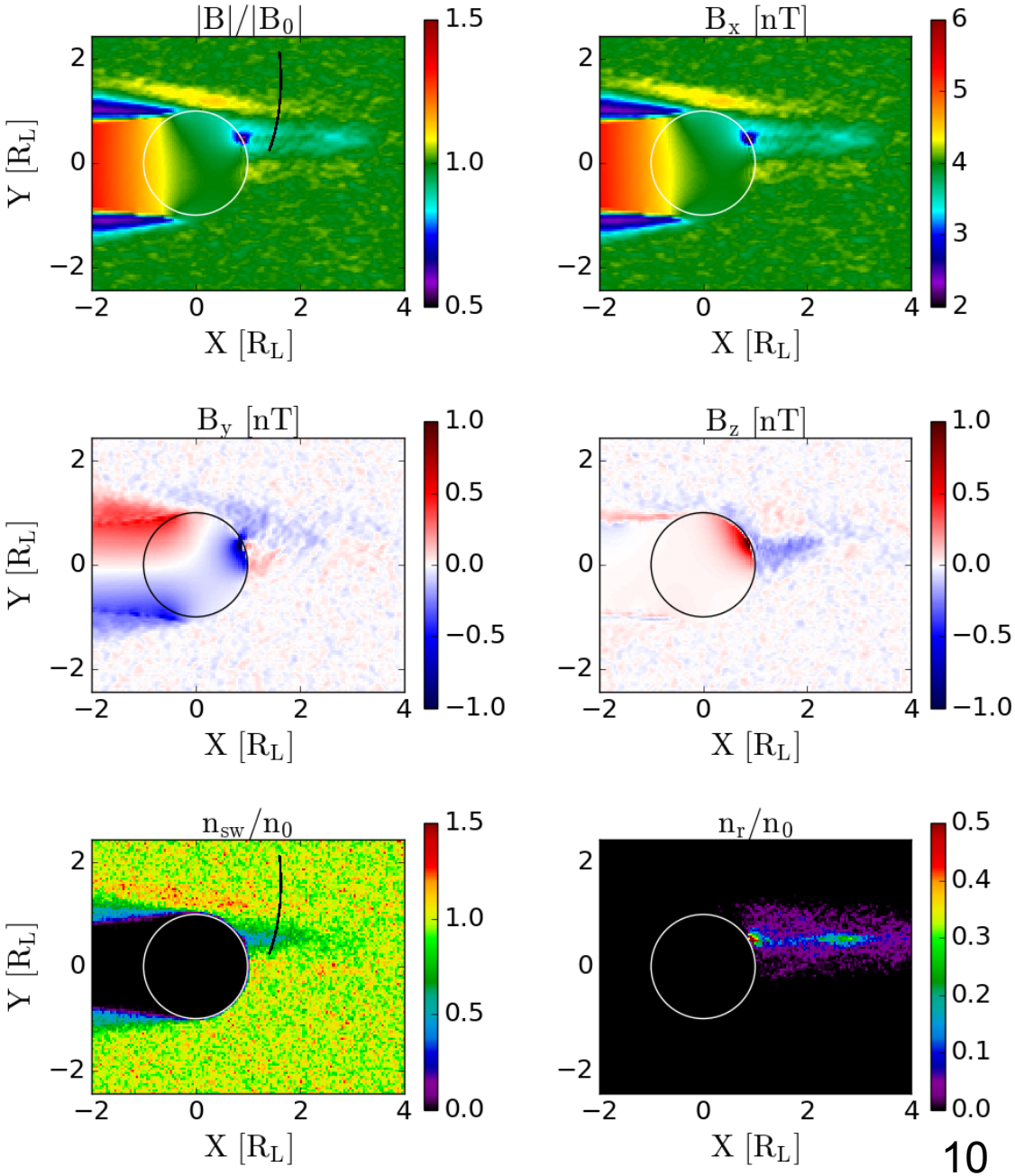
Snap-shot of our simulation

Foremoon cavity is formed upstream of the Moon

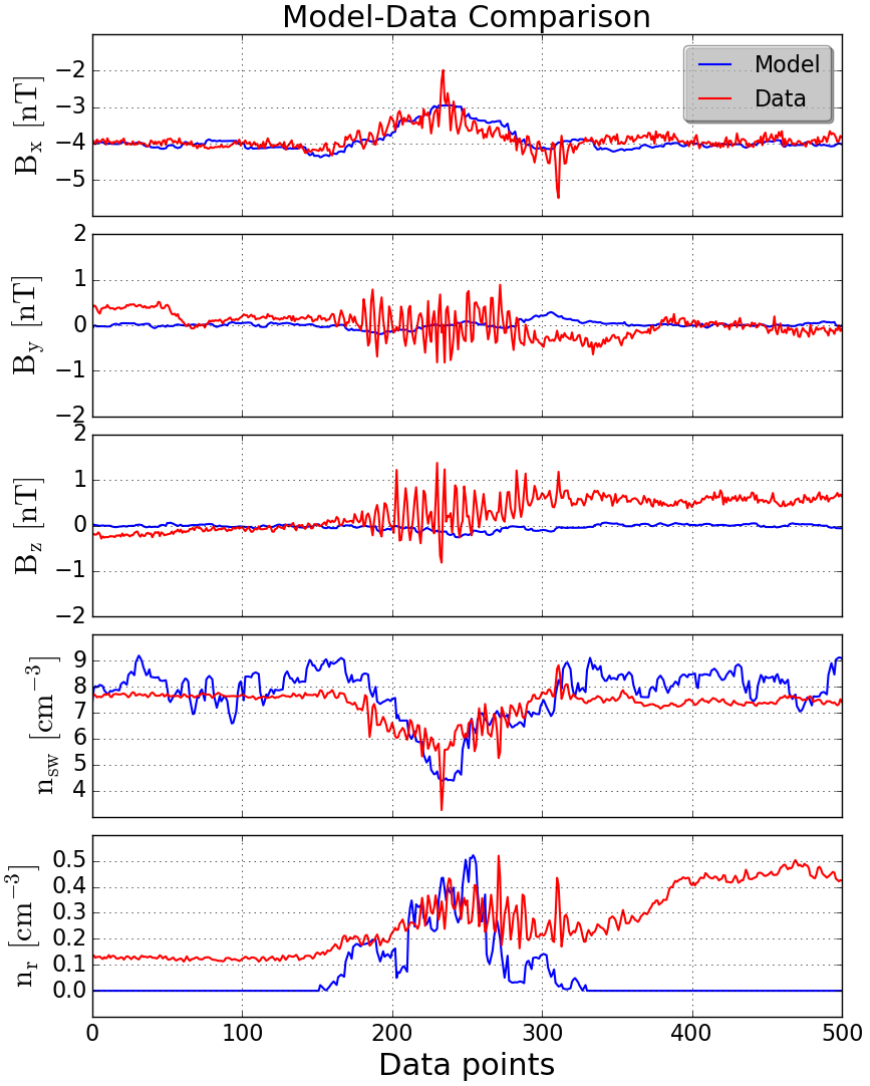
General characteristics match with observations

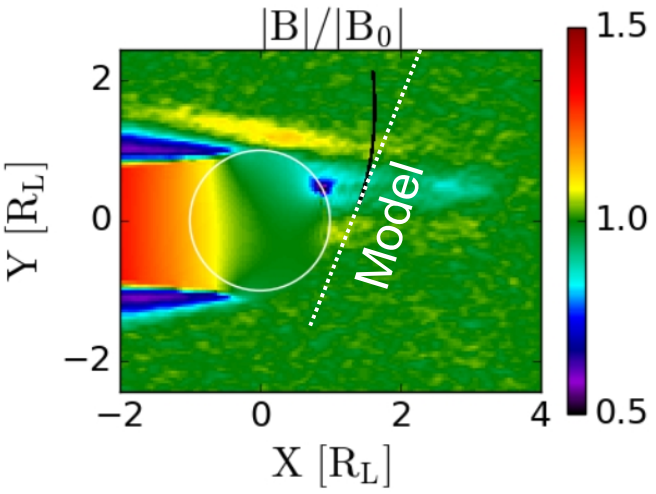
The width of the cavity predicted by our model is nearly 2x larger.

- Very localized reflection in data
- Finite cell size effect



Model-data comparison





Reduced the width of the cavity in simulations by a factor of ~2

Quantitative agreement between simulation results and observation

Summary

- The first direct observation of foremoon cavity.

- Similarities with foreshock cavity but formed due to plasma reflection from lunar crustal magnetic fields (any localized low-altitude bow-shock?)

- Quantitative agreement between hybrid simulations and observations.

- The width of the cavity in the data is narrower than that in the simulations.

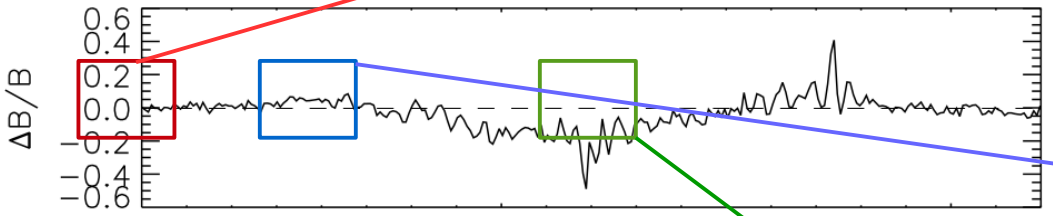
Future work:

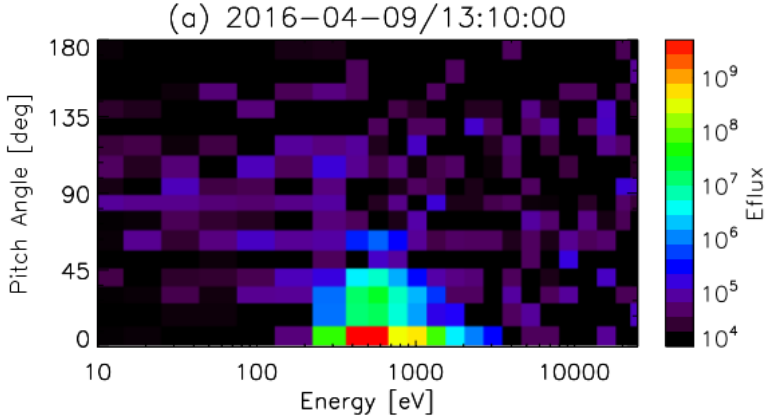
- Plasma velocity distribution in the simulation

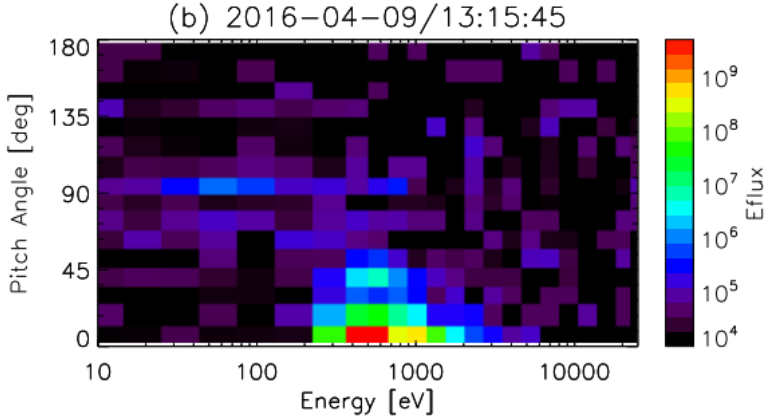
- Run the model for higher resolution with more localized plasma reflection

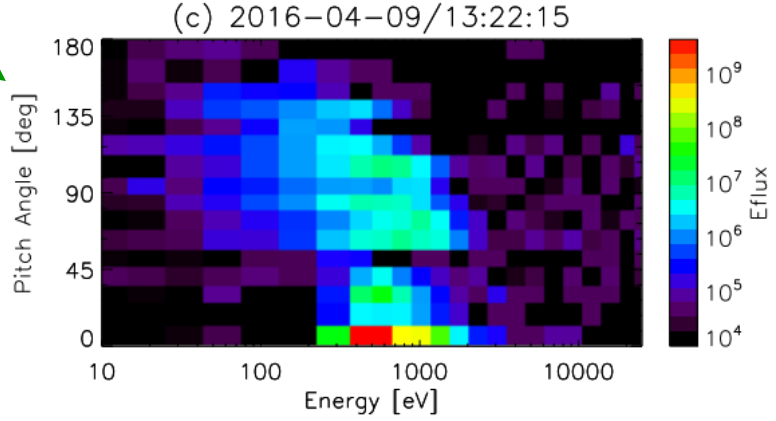
Backup slides

Pitch-angle distribution





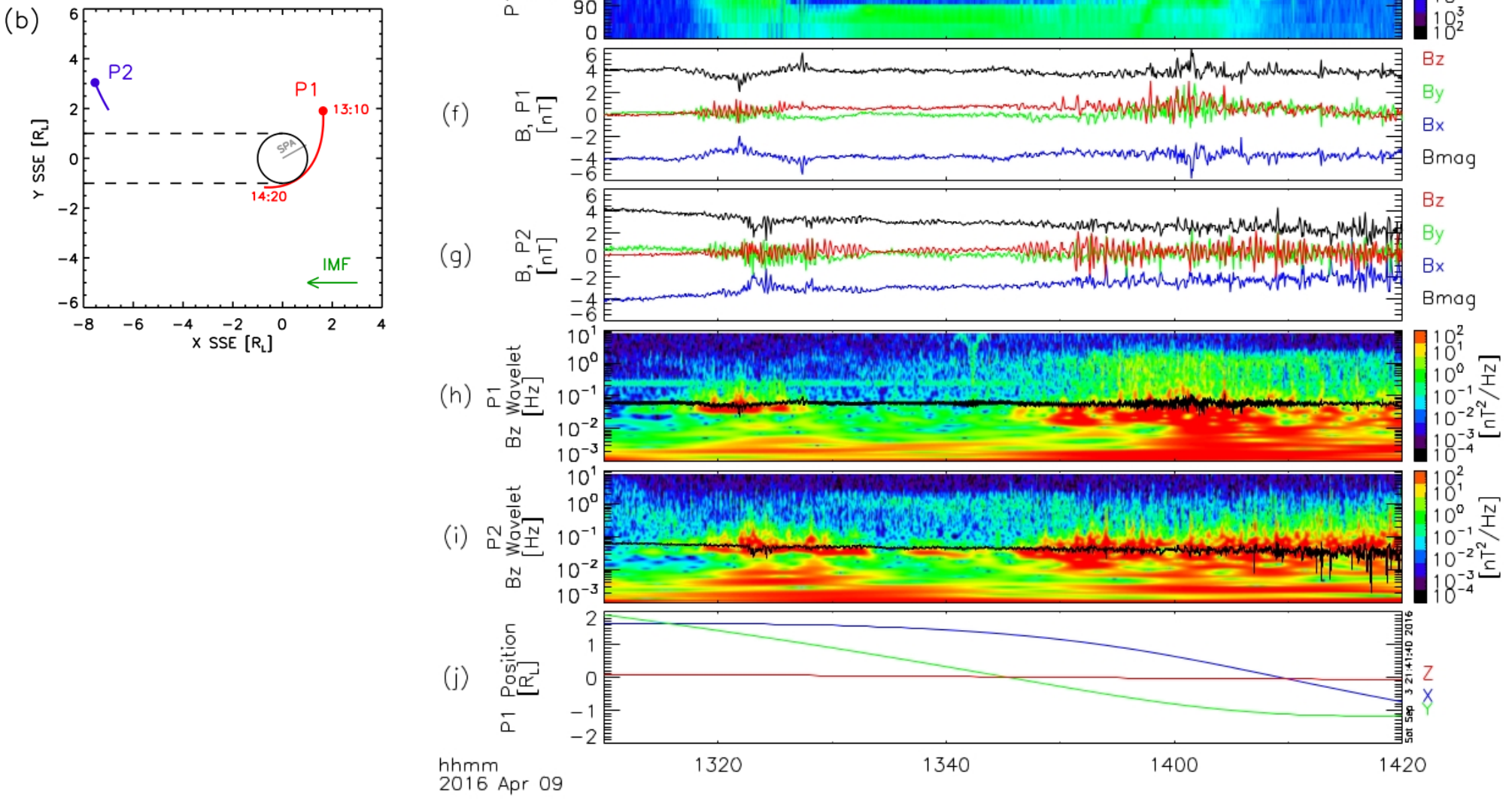




No evidence for solar wind plasma heating

No significant solar wind acceleration/deceleration

Reflected particles: ~90 deg pitch angle


(b)
P2
P1
13:10
14:20
SPA
IMF
Y SSE [R_L]
X SSE [R_L]
(c)
P1 Energy [eV]
(d)
P2 Energy [eV]
(e)
P1 Angle [deg]
Eflux
(f)
B, P1 [nT]
(g)
B, P2 [nT]
Bz
By
Bx
Bmag
(h)
P1 Bz Wavelet [Hz]
(i)
P2 Bz Wavelet [Hz]
[nT²/Hz]
(j)
P1 Position [R_L]
Z
X
Y
Sat Sep 3 21:41:40 2016
hhmm
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1320
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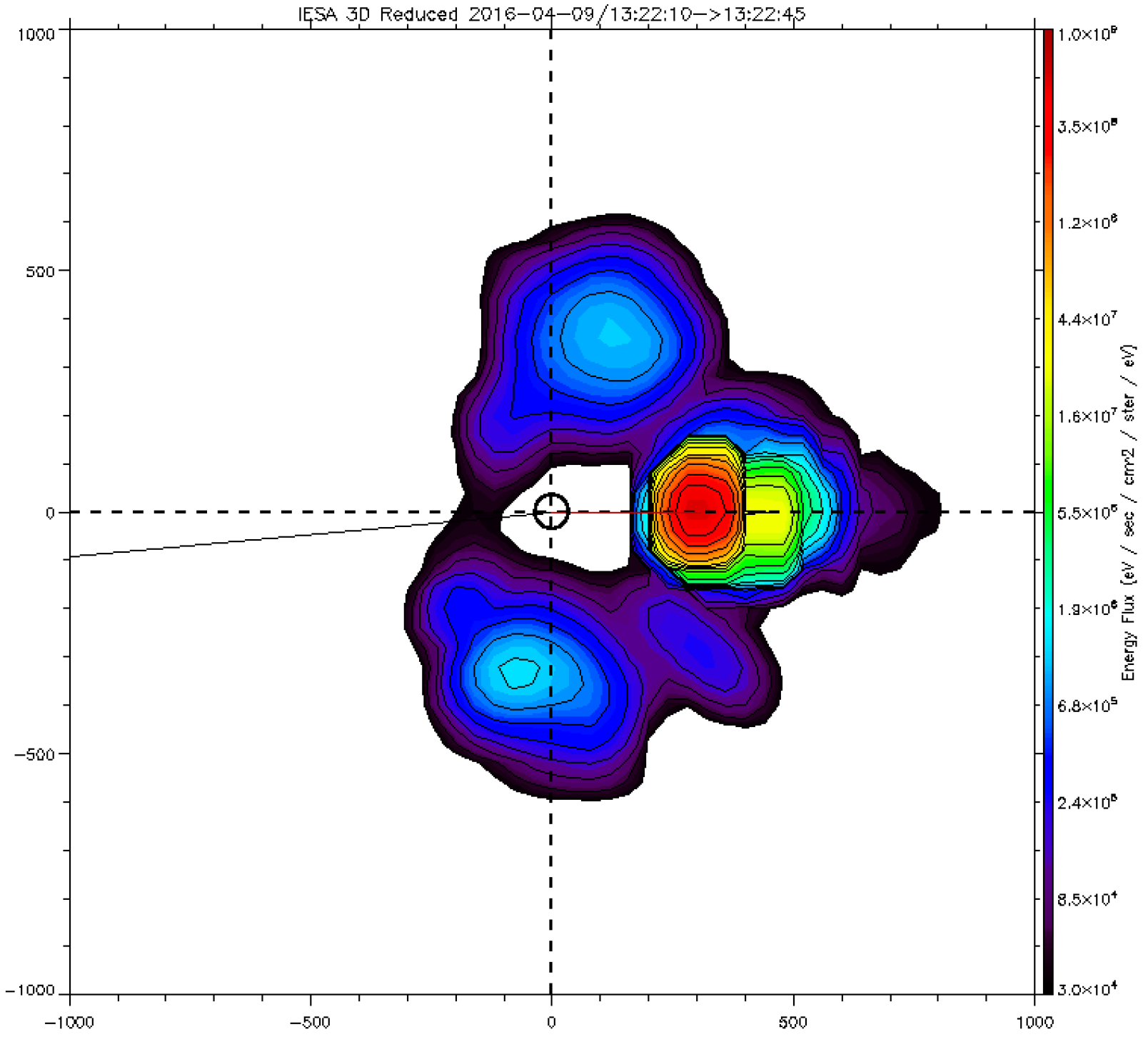
IESA 3D Reduced 2016-04-09/13:22:10->13:22:45
1000
500
0
-500
-1000
-1000
-500
0
500
1000
1.0×10⁹
3.5×10⁸
1.2×10⁸
4.4×10⁷
1.6×10⁷
5.5×10⁶
1.9×10⁶
6.8×10⁵
2.4×10⁵
8.5×10⁴
3.0×10⁴
Energy Flux (eV / sec / cm^2 / ster / eV)