Numerical simulation of ion reflection by lunar crustal magnetic fields

Andrey Divin (1), Jan Deca (2,3), Charles Lue(4), Roman Beliaev (1)

St. Petersburg State University, (2) University of Colorado Boulder,
(3) Institute for Modeling Plasma, Atmospheres and Cosmic Dust, NASA/SSERVI,
(4) Swedish Institute of Space Physics

andrey.div@gmail.com

Abstract

We investigate the dynamics of solar wind - Moon interaction by means of large-scale Particle-in-Cell (PIC) simulations in this study. Implicit moment PIC method and open boundaries are implemented in the code (iPIC3D) allowing to use large-scale domains in three dimensions. Even though the Moon has no global dipolar magnetic field, satellite magnetic field measurements at low-altitude (8-80 km) orbits discovered the presence of patches of intense remanent magnetization of the lunar crust. In order to simulate the scattering effect of the lunar remanent magnetic field we implemented an empirical proton reflection model based on low-attitude survey by the Chandrayaan-1 spacecraft [Lue, 2011]. Reflected ions are found to create an energized population of particles in the solar wind. Enhanced electron heating correlates with reflected ion density, which we interpret as adiabatic heating parallel to the magnetic field.

Motivation and goals

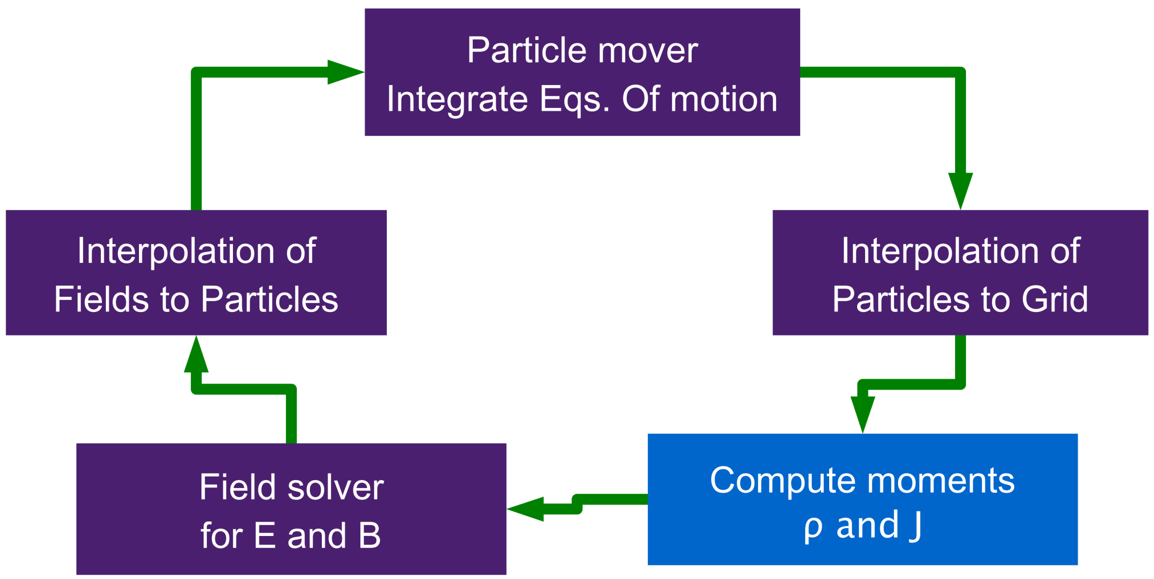
- Moon has no global magnetic field, **but** there are local crustal fields (Lunar Magnetic Anomalies, LMAs)

- LMAs are highly nondipolar and scatter plasma on sub-ion scales [Purucker, N=180], [Tsunakawa, N=450]. Limb shocks are rarely observed [Halekas et al. 2014].

- LMAs and minimagnetospheres are modelled by high-res hybrid (kinetic i, fluid e) and PIC (kinetic i/e) methods on the scales of several x100 km.

- We introduce the empirical model [Lue, 2011], [Fatemi, 2014] of ion reflection into iPIC3D [Markidis, 2011] to model the dayside plasma and characterize upstream wave activity.

The particle-in-cell method



Solution 1: Explicit PIC

$$c\Delta t < \Delta x$$

$$\omega_{pe}\Delta t < \Delta x$$

$$\Delta x < \zeta \lambda_D$$

Solution 2: Fully Implicit PIC

Solve entire system at once using the current and future time step.

Add extra equations to decouple particles and fields:
$\rho = qn \qquad \mathbf{J} = \rho \mathbf{u}$

Solution 3: Semi-implicit PIC

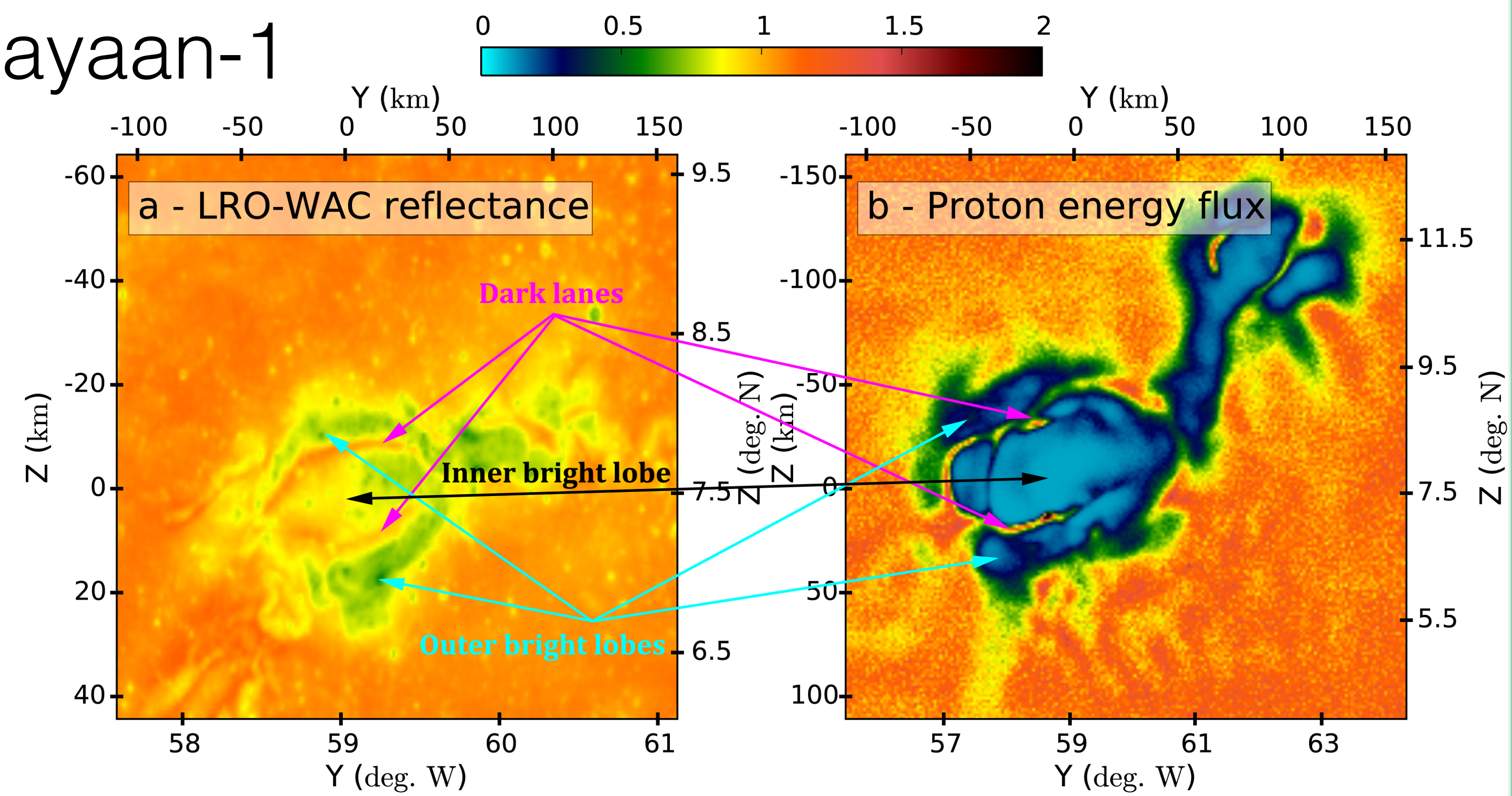
$$0.1 < v_{the}\frac{\Delta t}{\Delta x} < 1$$

iPic3D - the (semi-) implicit particle-in-cell code

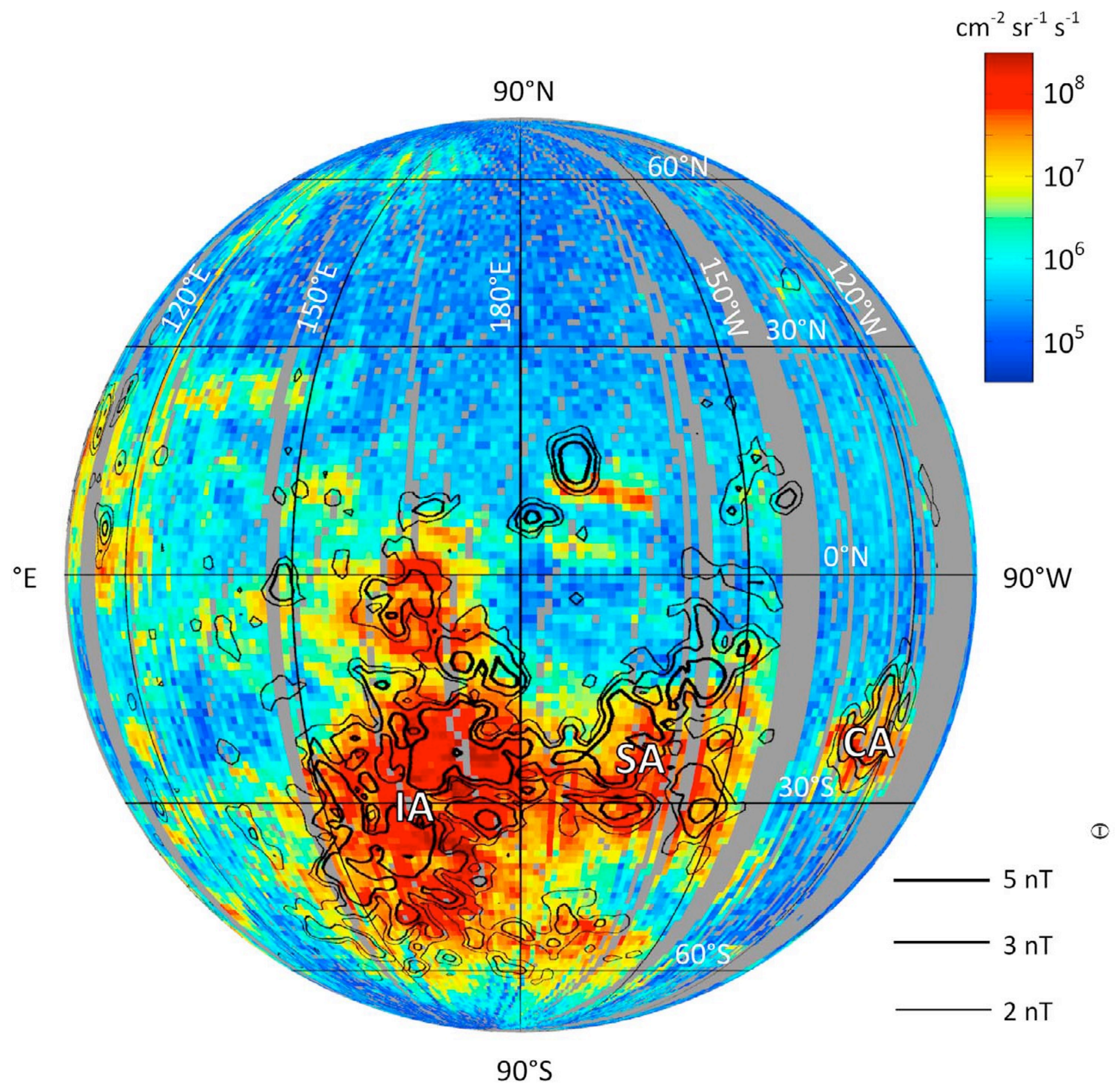
We use semi-implicit PIC!

The magnetic field model (*not used here*)

- *Previously*: dipoles. [Deca et al. 2014->2016, Hemingway et al. 2015, Poppe et al. 2016, and quite a few others] **(next slide)**
- Observed magnetic field model:
- Surface Vector Mapping about 5 million magnetic field observations by Kaguya and Lunar Prospector. [Tsunakawa et al. 2014, 2015]
- 3D PIC simulation of Reiner Gamma Anomaly, [Deca et al. 2018] comparable to Chandrayaan-1
- Fine-scale (10 km), but how to model the global LMA effects (ion scattering, etc.)?



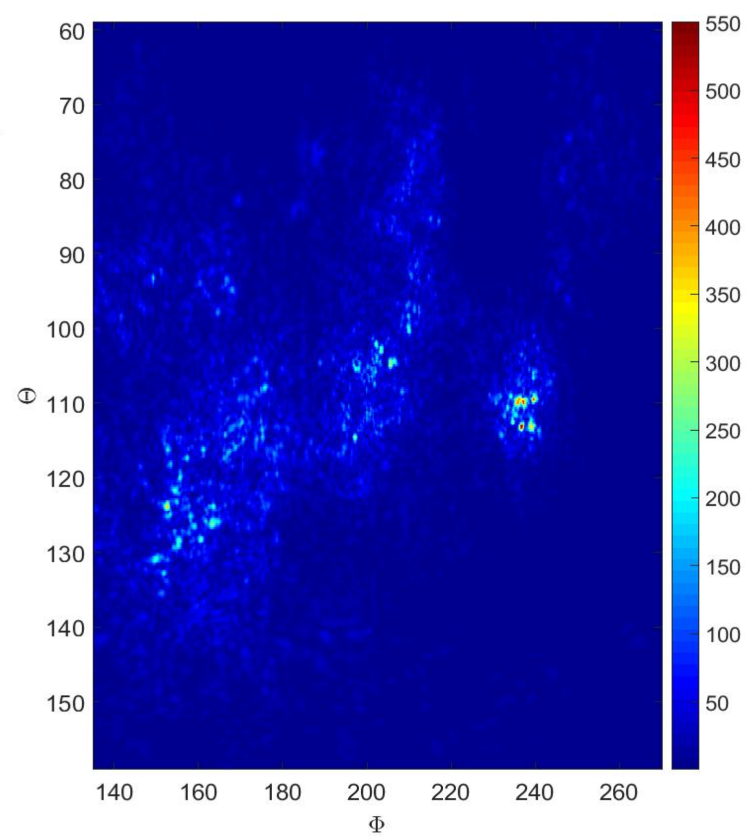
Observed reflection (R) vs SVM model IBI



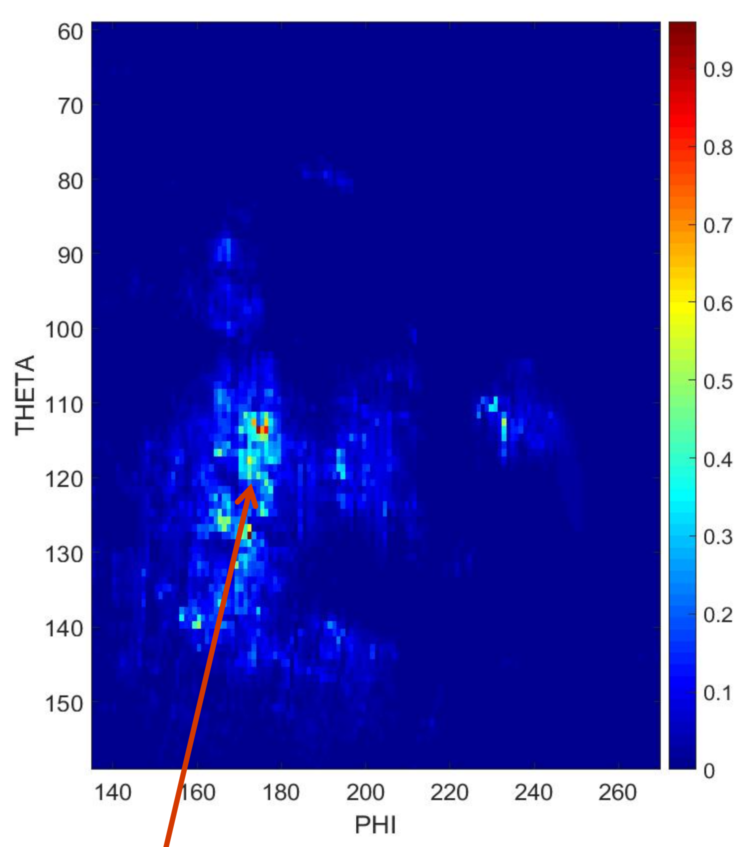
- [Lue, 2011]: Chandrayaan-1 map of protons reflection ratio [90°W-0°-90E°] longitude, upstream/directional dependence [Poppe, 2017]

IBI

at the surface (h=0), SVM for N=450



R

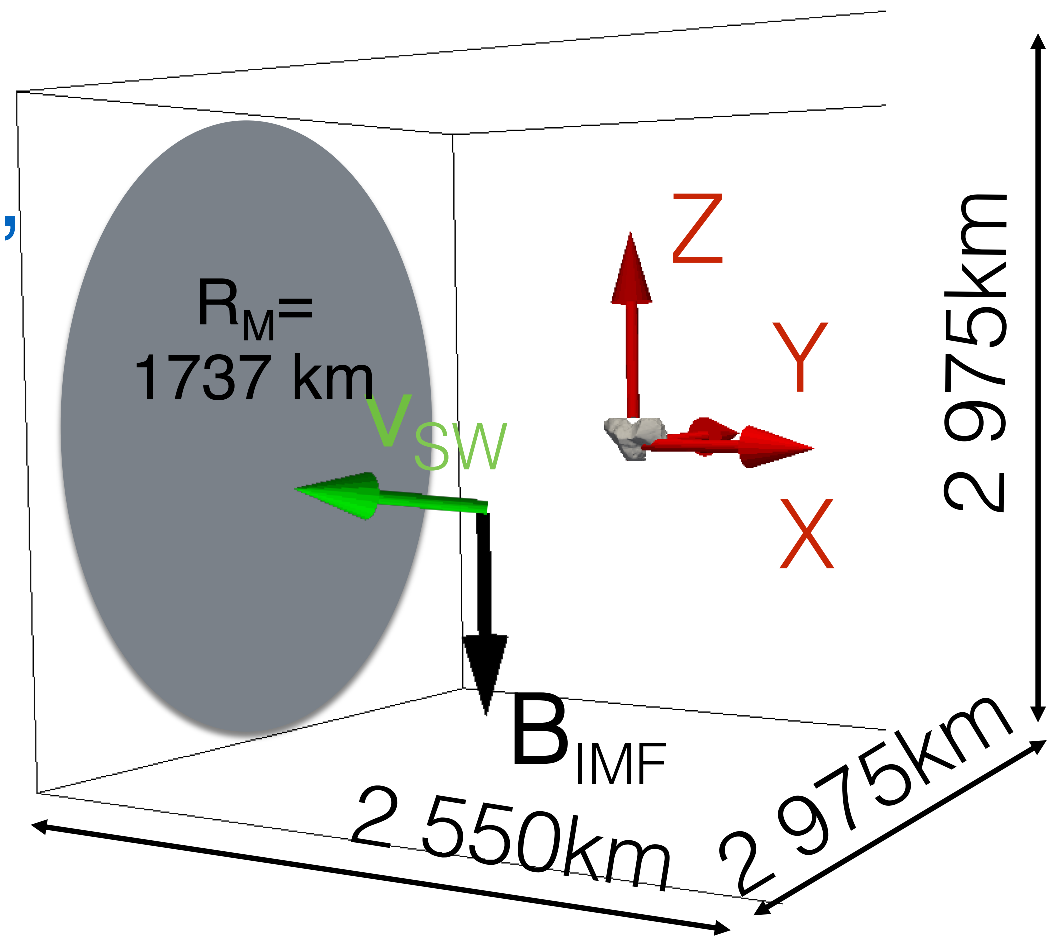


Peaks at R~1 at the strongest anomalies!

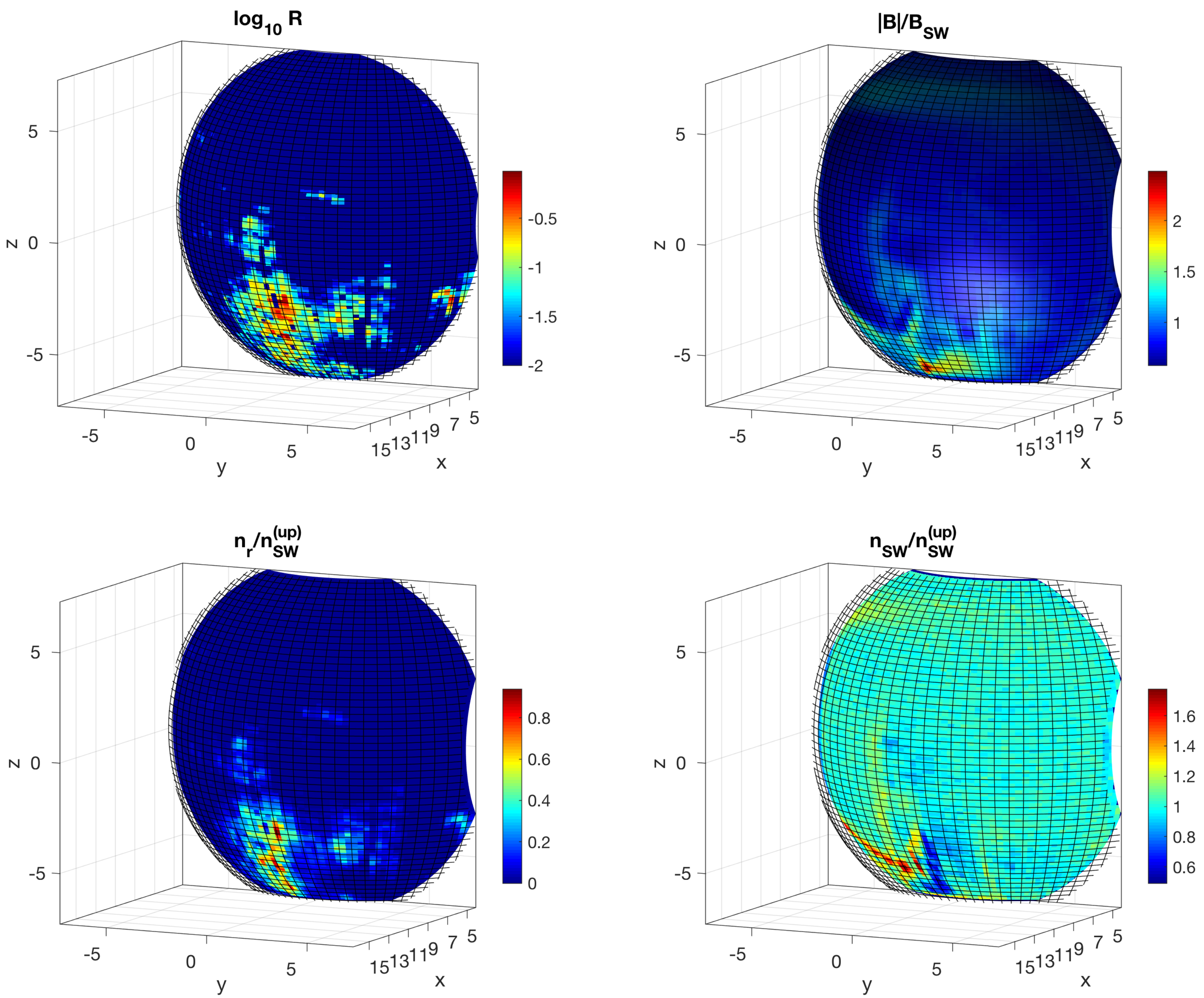
Simulation setup

Dayside simulation

- Solar wind protons and electrons ($\mathbf{v}_{sw}$ = 400 km/s, m_p/m_e = 100, $T_{i,sw}$ = 10 eV, $T_{e,sw}$ = 10 eV, n = 1 cm^{-3})
- Interplanetary magnetic field ($\mathbf{B}_{IMF}$ = 6 nT)
- Ion reflection ([Lue, 2011], [Fatemi, 2014]), specular; treat reflected ions as separate species

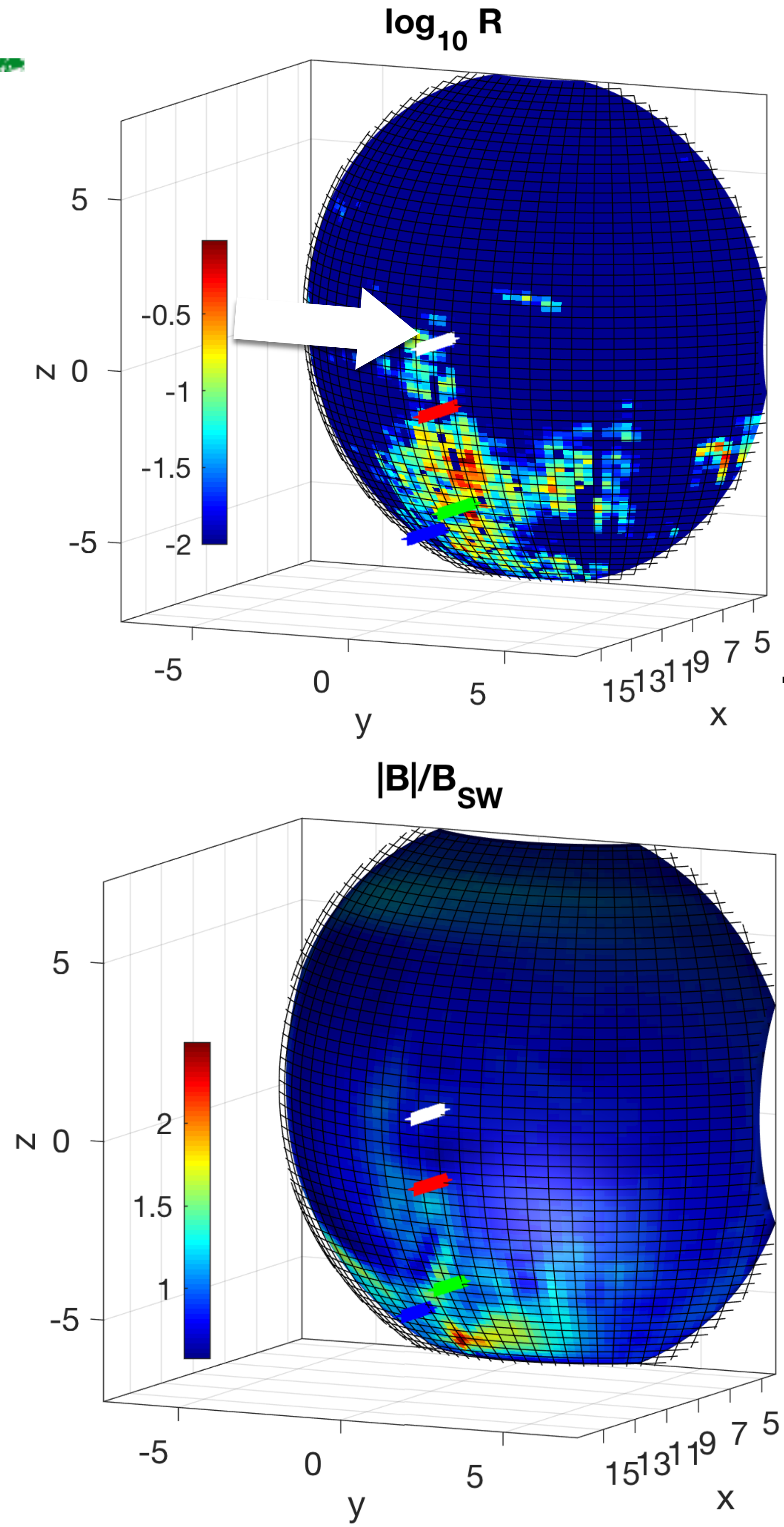


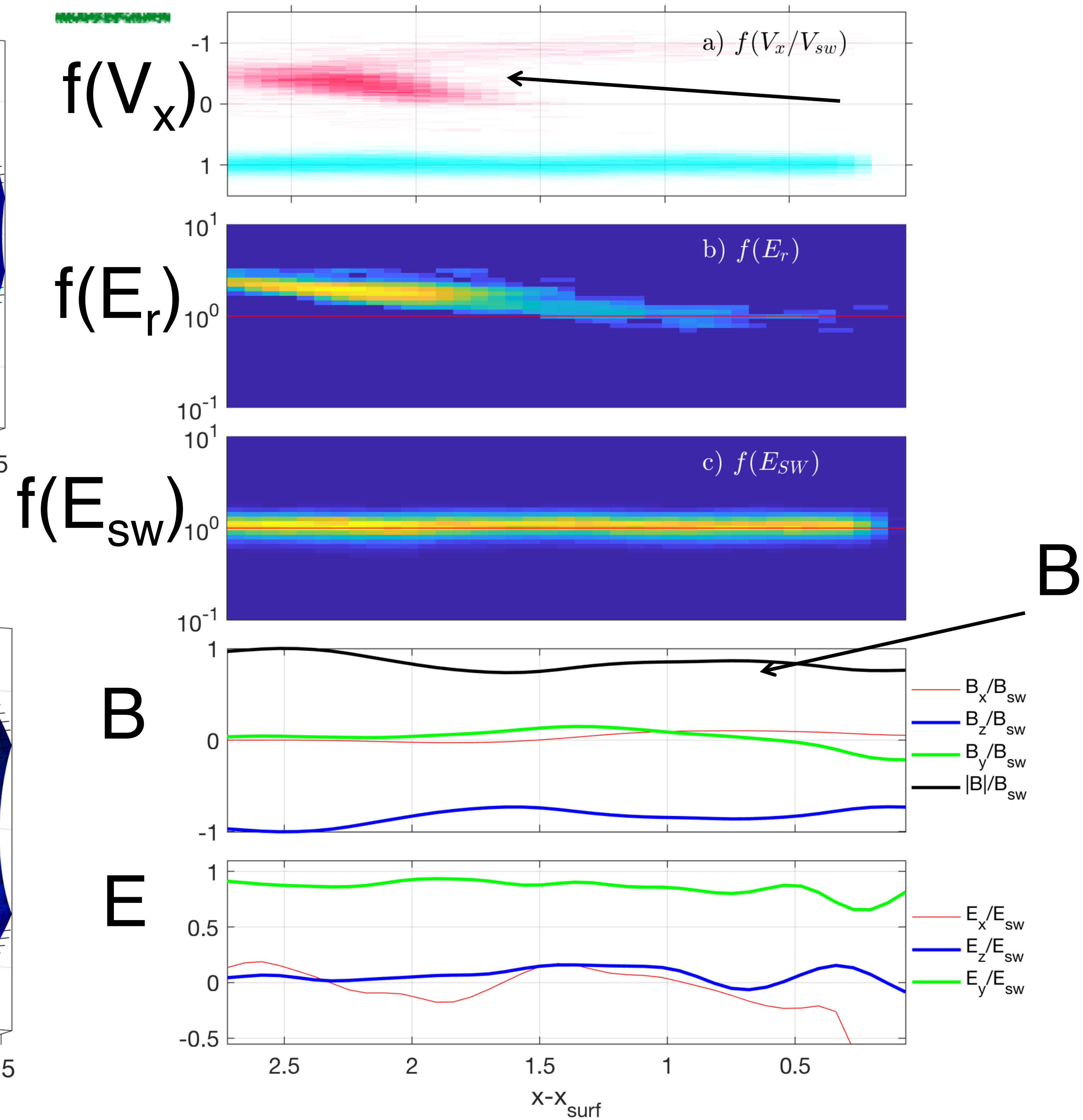
Simulation overview



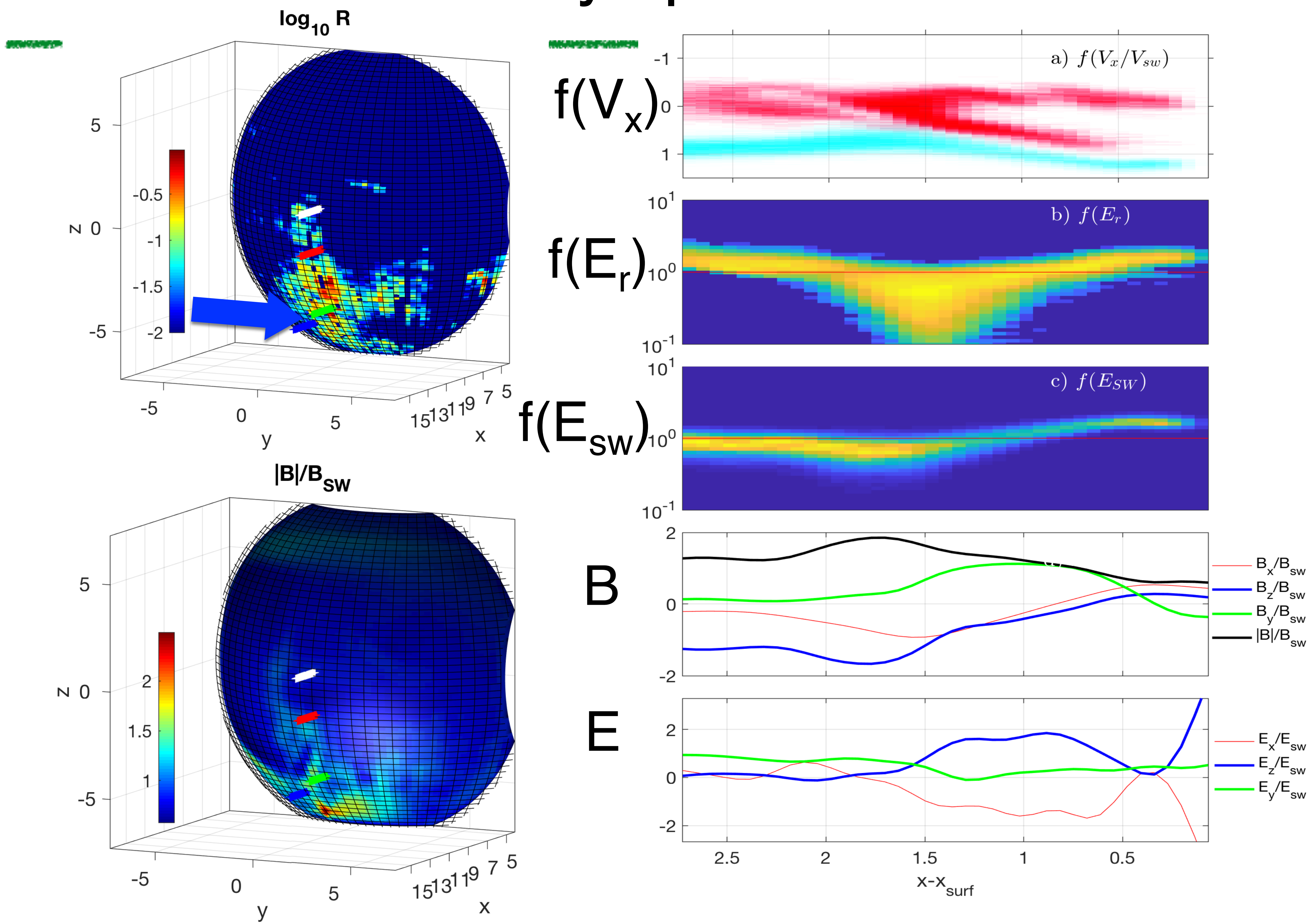
- **Induced** magnetic field, not the LMA fields, up to ~2.5 B_{sw}.
- Reflected population density peaks at ~n_{sw}
- Solar wind population decreases to ~0.5 n_{sw}. Deflection because of induced fields and upstream waves.

Simulation: velocity space



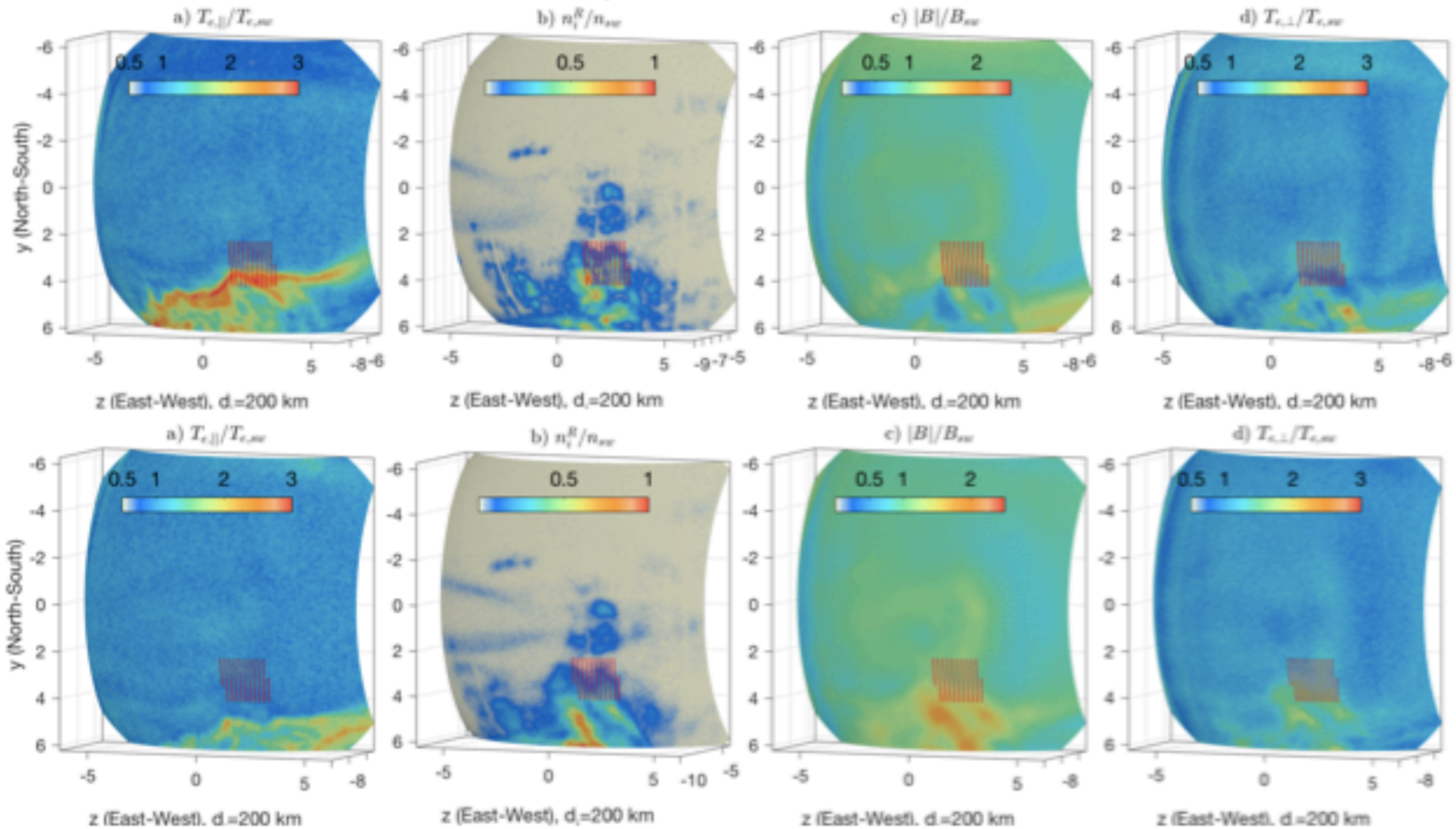


Simulation: velocity space



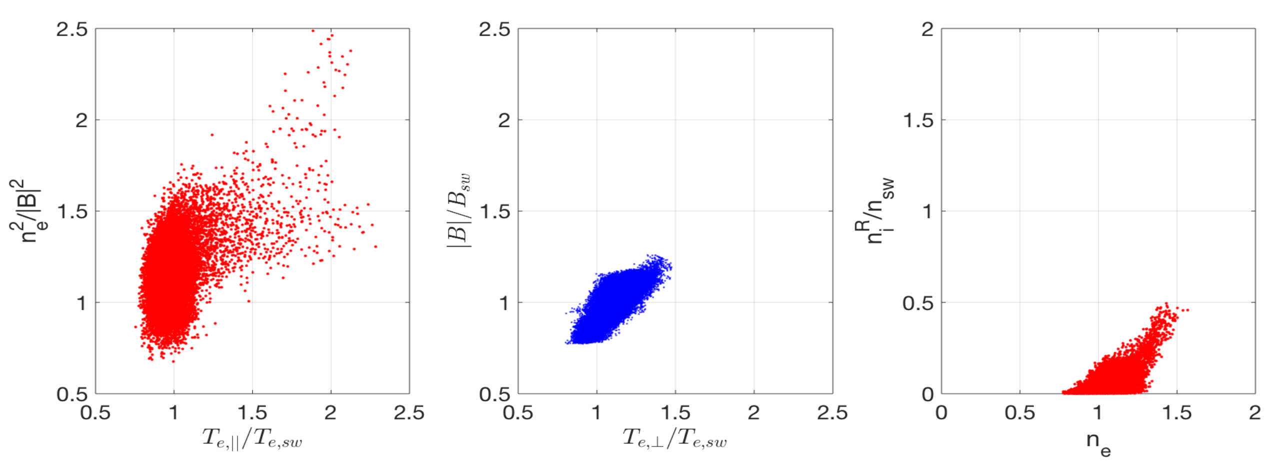
Simulation: electrons are heated, too!

T_{ell} n_r B $T_{e,\,perp}$



0.4 di ~40 km

1 di ~100 km



Adiabatic electron heating due to local variation of n, B near anomalies:

$T_{ell} \sim n^2/|B|^2$

$T_{e\ perp} \sim |B|$

Conclusions and Results

- We performed 3D PIC simulations of the solar wind – Moon interaction based on [Lue, 2011] reflection model
- Reflected population produces upstream waves and instabilities on ion- and sub-ion scales, resulting in thermalization and scattering.
- Electrons are heated adiabatically when strong fluxes of reflected particles appear.
- Induced magnetic field peaks at ~2 x B_{sw}
- Solar wind ion population is disturbed upstream of the strongest LMAs (*should be important for local simulations of LMAs*).