Using the Virial Theorem to Analyze Effects of Energy Dynamics in the Magnetosphere

This presentation participates in OSPP

UNIVERSITY OF MICHIGAN

EGU 2022

EGU

Outstanding Student & PhD candidate Presentation contest

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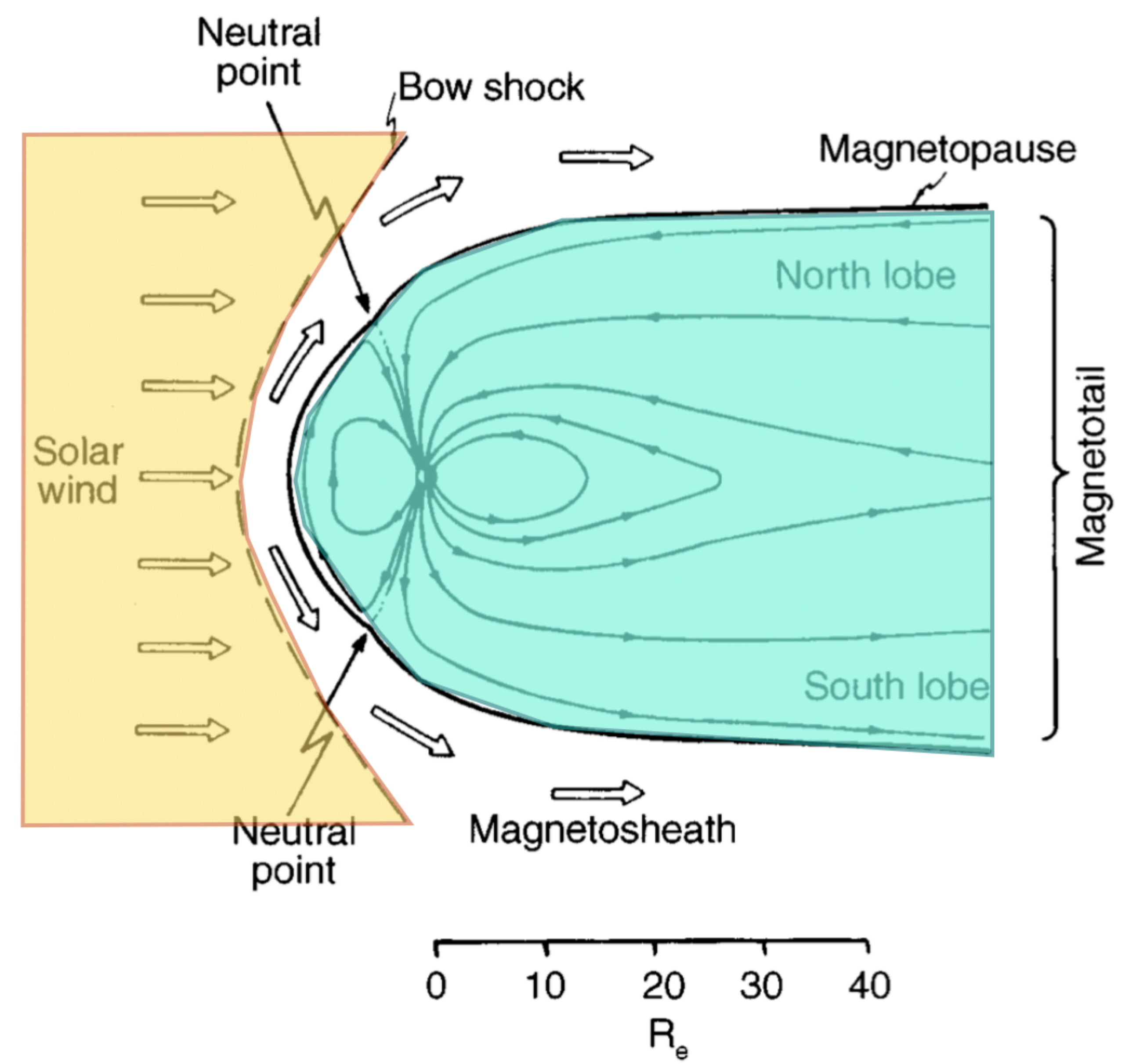
ST2.7 EGU22-5549

Background

- Solar wind magnetosphere coupling -> energy:
  - ✦ Deformation of the magnetopause
  - ✦ *Balance* of energy flux through the magnetopause surface
  - ✦ Internal capture, organization and decay of captured energy
  - ✦ Current systems cause magnetic perturbations



Vasyliunas, V. M., "Large-scale morphology of the magnetosphere," in Solar Terrestrial Physio R. L. Carovilano and J. M. Forbes, eds., p. 243, D. Reidel, Dordrecht, The Netherlands. 1983.

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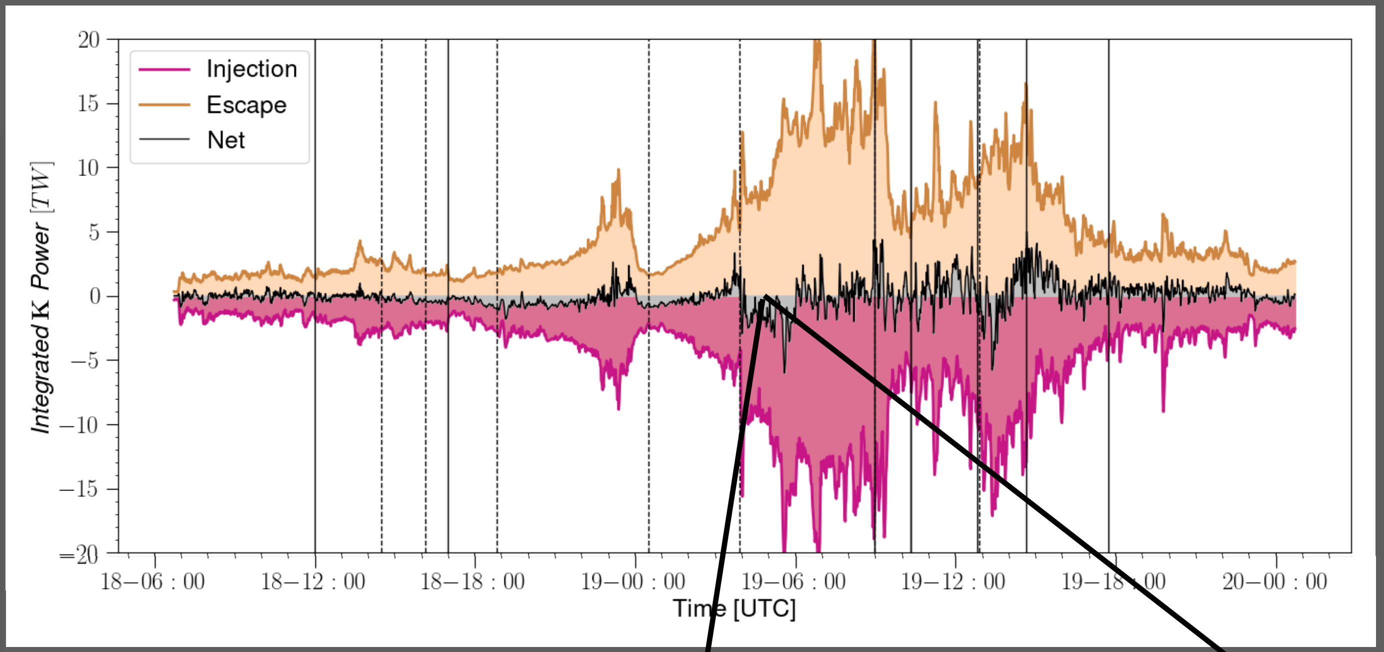
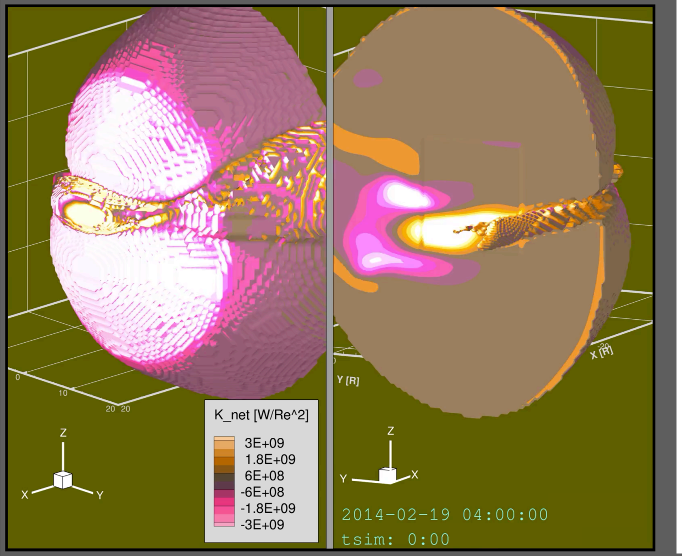
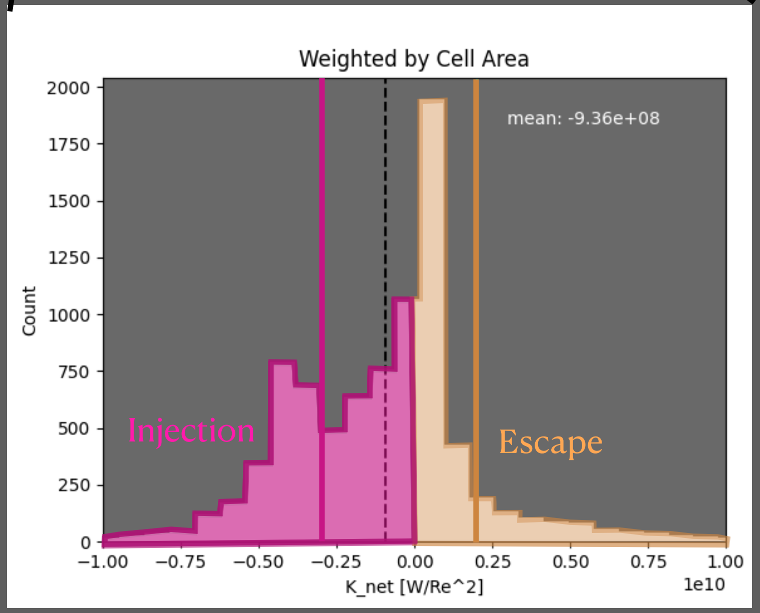


Brenner et al. Frontiers 2021





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Dessler-Parker-Sckopke Relation

Ring Current energy is related directly to ΔB

Virial Theorem

ALL changes to the system momentum balance can be averaged to calculate ΔB

MHD momentum

$$\frac{\partial(\rho\mathbf{V})}{\partial t} + \nabla\cdot\left(\rho\mathbf{V}\mathbf{V} + p\bar{I} + \frac{B^2}{2\mu_0}\bar{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_o}\right) = 0$$

Virial Theorem

$$\begin{aligned}\mu\cdot\mathbf{b}(0) = \; & +2U_k + U_b + \cancel{U_G} \\ & -\frac{\partial}{\partial t}\int d\mathbf{r}(\rho\mathbf{V})\cdot\mathbf{r} + \frac{1}{\delta t}\int \delta V\left[(\rho\mathbf{V})\cdot\mathbf{r}\right] \\ & -\int d\mathbf{S}\cdot\left[\rho\mathbf{V}\mathbf{V}\cdot\mathbf{r} + \mathbf{r}P_{th}\right] \\ & -\int d\mathbf{S}\cdot\left[\mathbf{r}\frac{B^2}{2\mu_0} - \mathbf{r}\frac{B^2}{2\mu_0} + \mathbf{B}\mathbf{B}_\mathbf{d}\cdot\mathbf{r} - \mathbf{B}\mathbf{B}\cdot\mathbf{r}\right] \\ & -\int d\mathbf{\Omega}\cdot\left[\rho\mathbf{V}(\mathbf{V}\cdot\mathbf{r}) + \mathbf{r}P_{th} + \mathbf{r}\frac{b^2}{\mu_0}\right]\end{aligned}$$

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MHD momentum

$$\frac{\partial(\rho \mathbf{V})}{\partial t} + \nabla \cdot \left(\rho \mathbf{V}\mathbf{V} + p\bar{I} + \frac{B^2}{2\mu_0}\bar{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_o} \right) = 0$$

Virial Theorem

Volume Energy

$$\mu \cdot \mathbf{b}\,(0) = +2U_k + U_b + \cancel{U_G}$$

$$-\frac{\partial}{\partial t}\int d\mathbf{r}(\rho \mathbf{V})\cdot \mathbf{r} + \frac{1}{\delta t}\int \delta V\left[(\rho \mathbf{V})\cdot \mathbf{r}\right]$$

Surface Flux

$$-\int d\mathbf{S}\cdot\left[\rho \mathbf{V}\mathbf{V}\cdot \mathbf{r} + \mathbf{r}P_{th}\right]$$

$$-\int d\mathbf{S}\cdot\left[\mathbf{r}\frac{B^2}{2\mu_0} - \mathbf{r}\frac{B^2}{2\mu_0} + \mathbf{B}\mathbf{B}_{\mathbf{d}}\cdot \mathbf{r} - \mathbf{B}\mathbf{B}\cdot \mathbf{r}\right]$$

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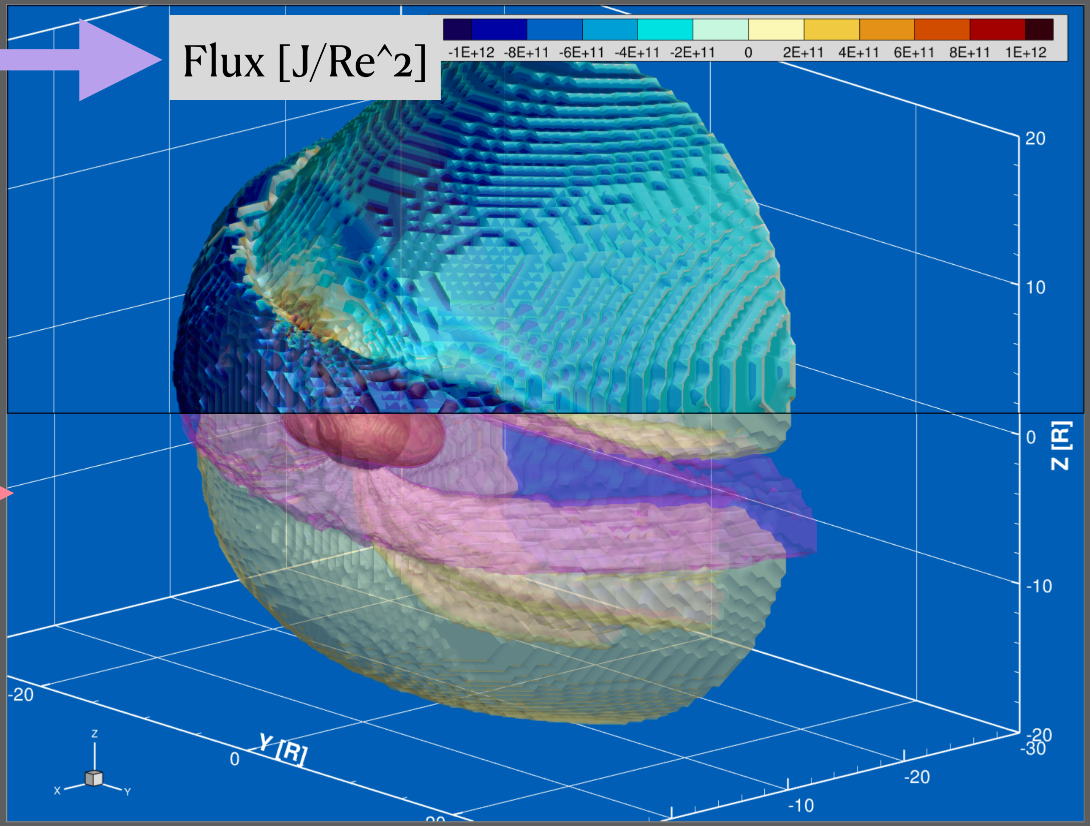

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Virial Theorem

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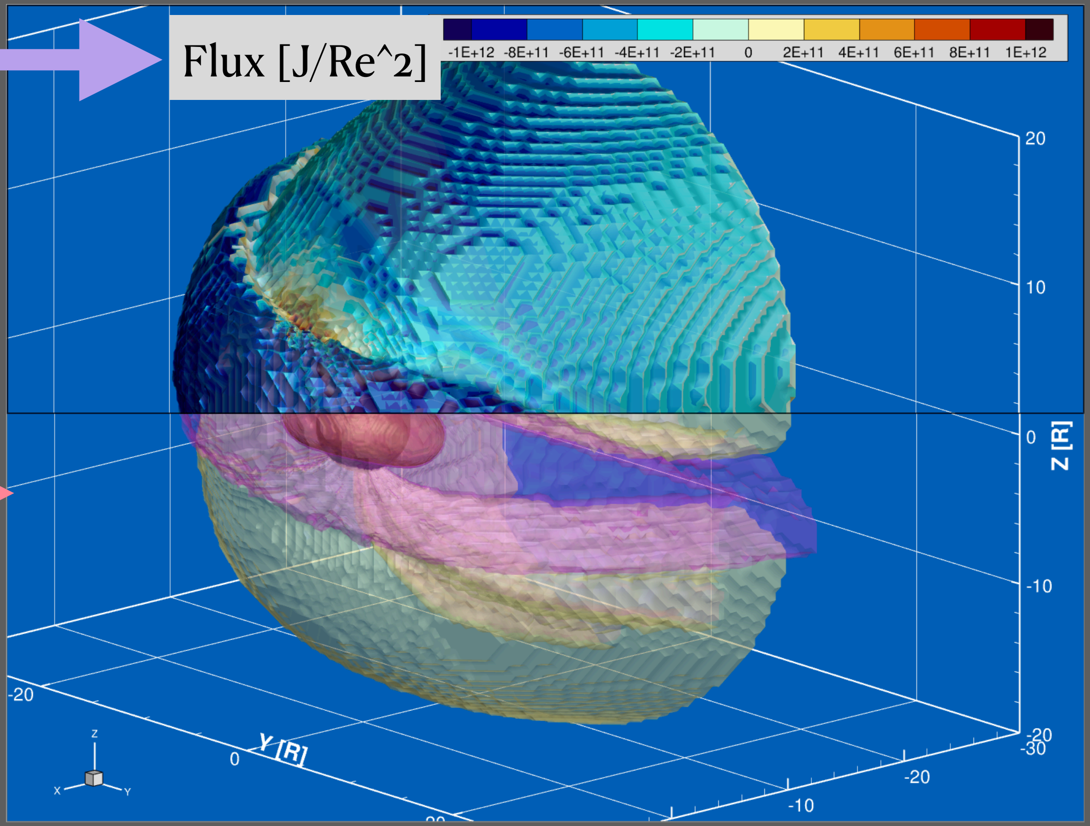
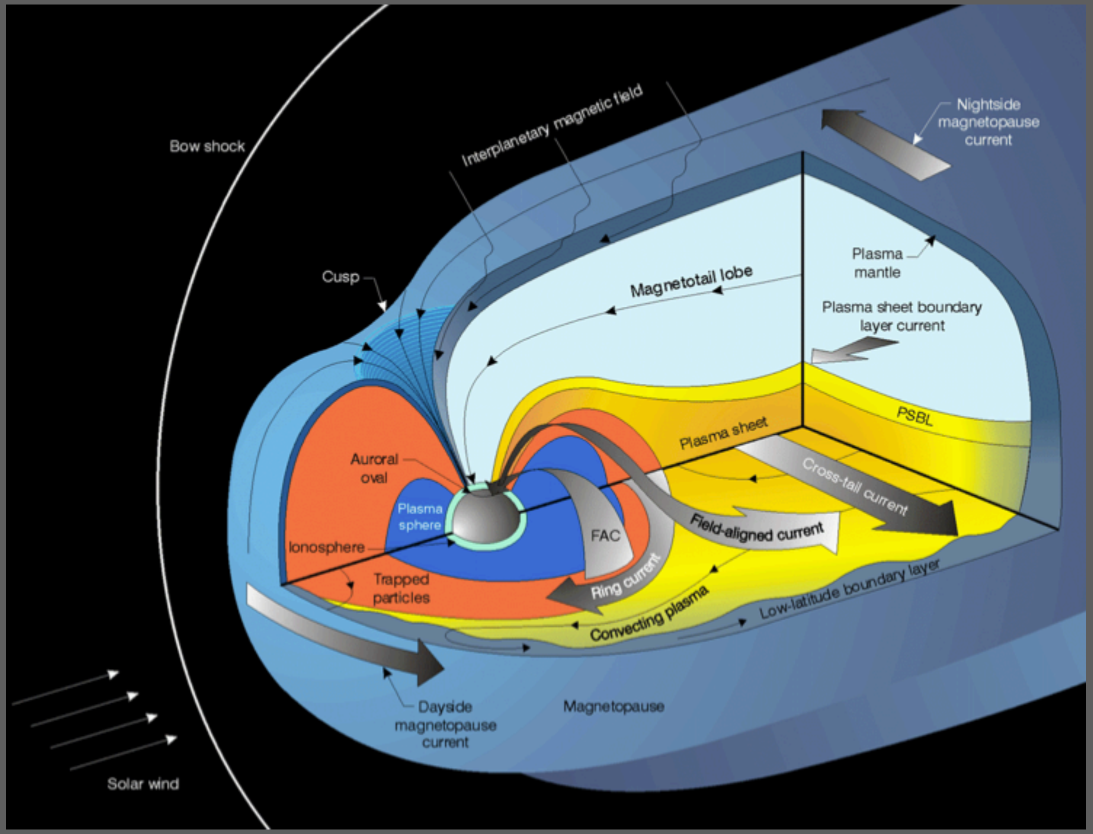


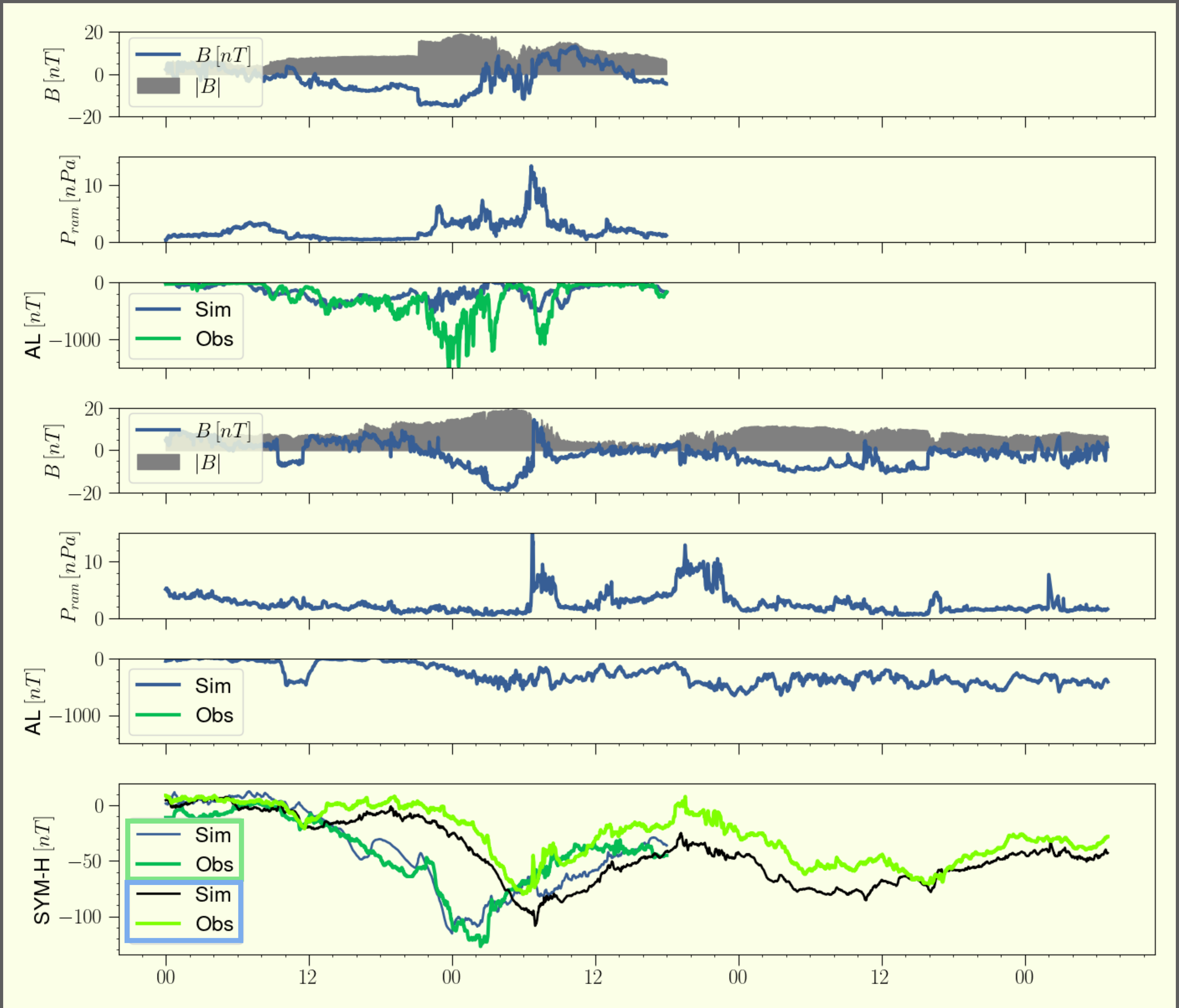
Biot Savart law

Measure Currents

$$\mathbf{B}(\mathbf{r})=\frac{\mu_0}{4\pi}\iiint_V\frac{(\mathbf{J}dV)\times\mathbf{r}'}{\left|\mathbf{r}'\right|^3}$$



Methods: Global Simulation



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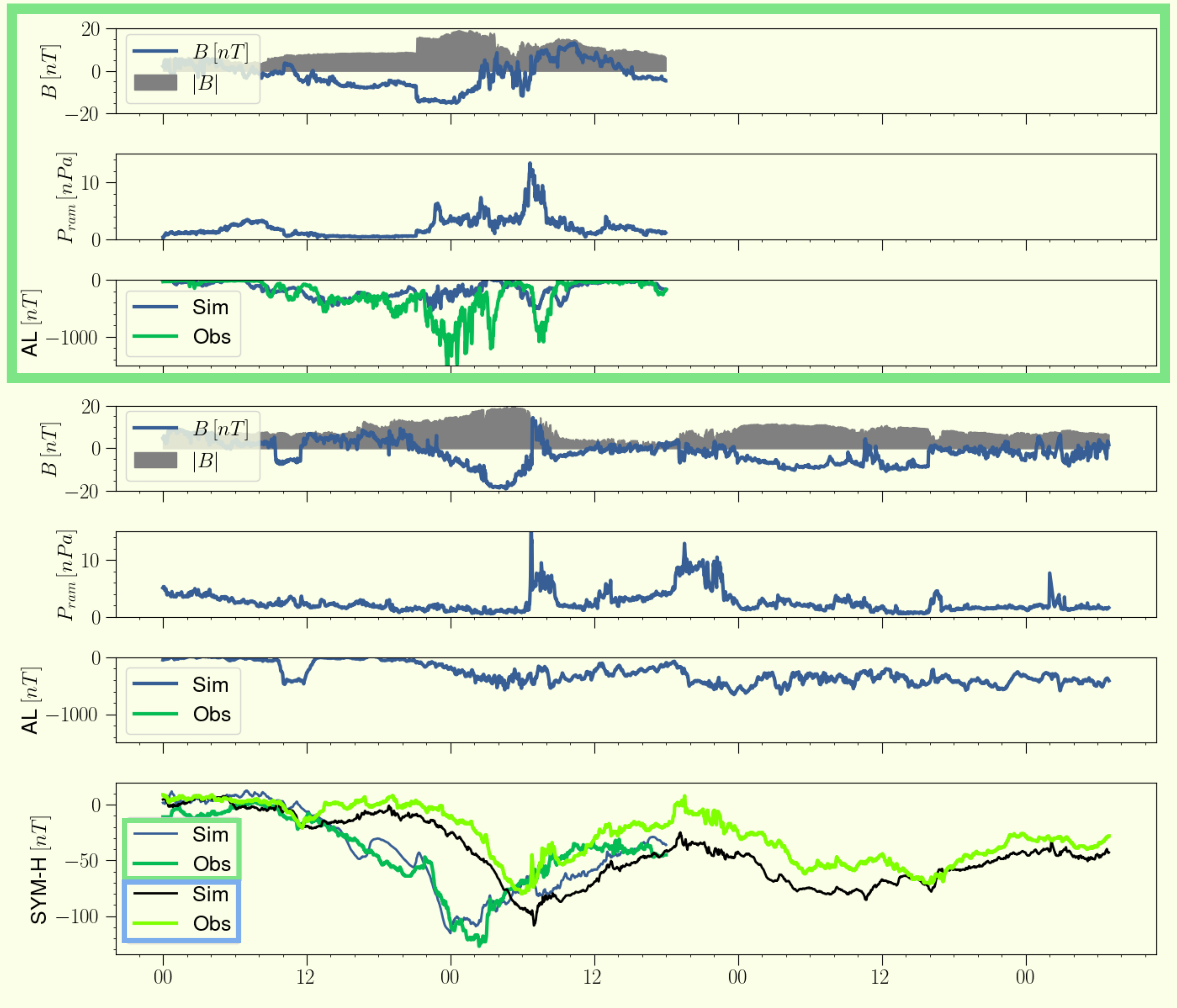

Feb 18-20, 2014

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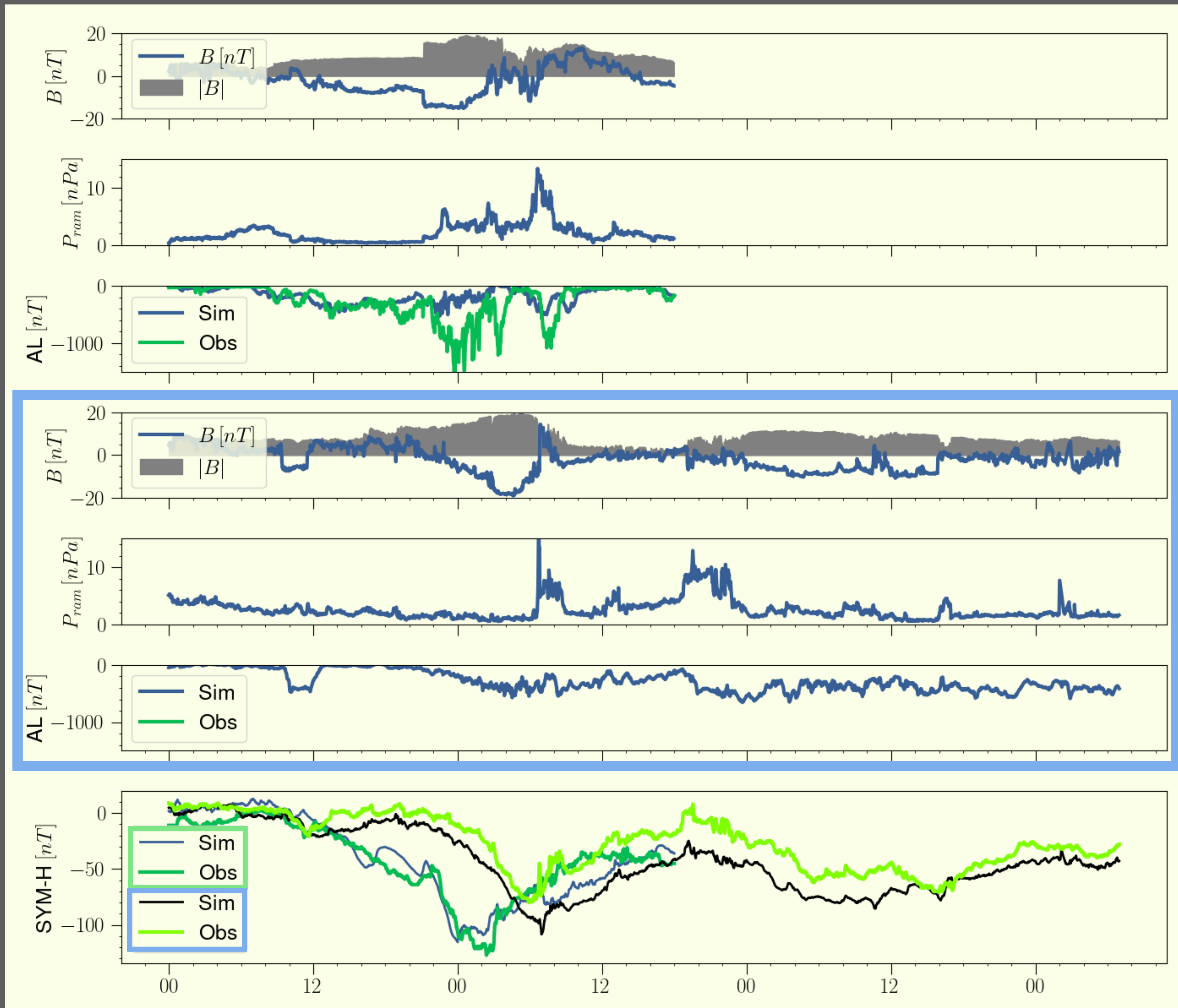
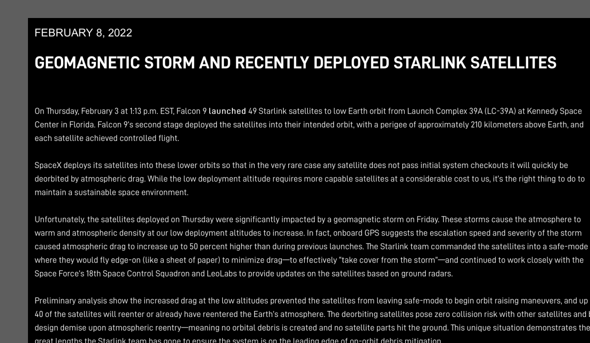
Methods: Global Simulation



Feb 2-5, 2022
'Starlink' event



FEBRUARY 8, 2022

GEOMAGNETIC STORM AND RECENTLY DEPLOYED STARLINK SATELLITES

On Thursday, February 3 at 1:13 p.m. EST, Falcon 9 **launched** 49 Starlink satellites to low Earth orbit from Launch Complex 39A (LC-39A) at Kennedy Space Center in Florida. Falcon 9's second stage deployed the satellites into their intended orbit, with a perigee of approximately 210 kilometers above Earth, and each satellite achieved controlled flight.

SpaceX deploys its satellites into these lower orbits so that in the very rare case any satellite does not pass initial system checkouts it will quickly be deorbited by atmospheric drag. While the low deployment altitude requires more capable satellites at a considerable cost to us, it's the right thing to do to maintain a sustainable space environment.

Unfortunately, the satellites deployed on Thursday were significantly impacted by a geomagnetic storm on Friday. These storms cause the atmosphere to warm and atmospheric density at our low deployment altitudes to increase. In fact, onboard GPS suggests the escalation speed and severity of the storm caused atmospheric drag to increase up to 50 percent higher than during previous launches. The Starlink team commanded the satellites into a safe-mode where they would fly edge-on (like a sheet of paper) to minimize drag—to effectively "take cover from the storm"—and continued to work closely with the Space Force's 18th Space Control Squadron and LeoLabs to provide updates on the satellites based on ground radars.

Preliminary analysis show the increased drag at the low altitudes prevented the satellites from leaving safe-mode to begin orbit raising maneuvers, and up to 40 of the satellites will reenter or already have reentered the Earth's atmosphere. The deorbiting satellites pose zero collision risk with other satellites and by design demise upon atmospheric reentry—meaning no orbital debris is created and no satellite parts hit the ground. This unique situation demonstrates the great lengths the Starlink team has gone to ensure the system is on the leading edge of on-orbit debris mitigation.

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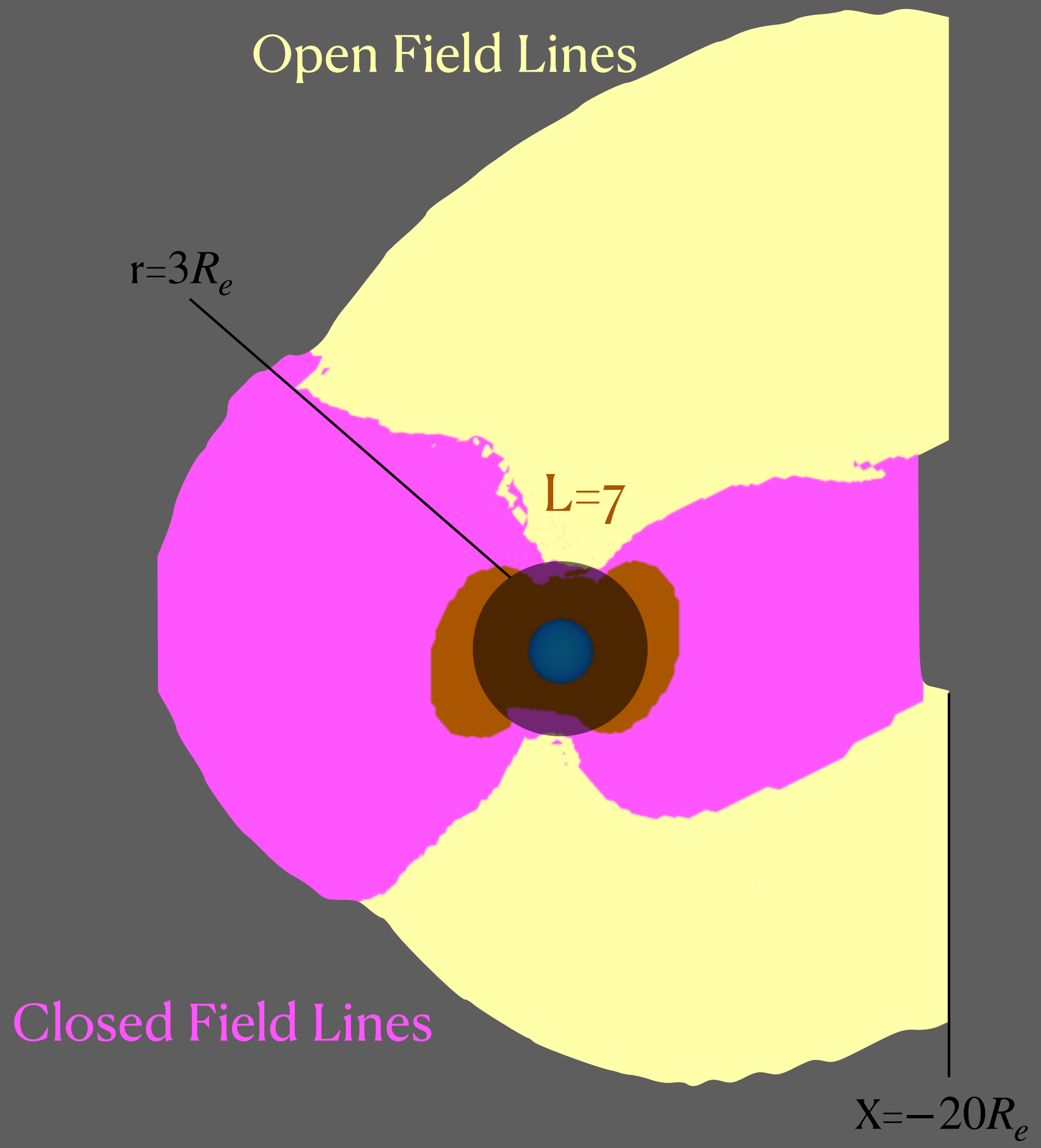
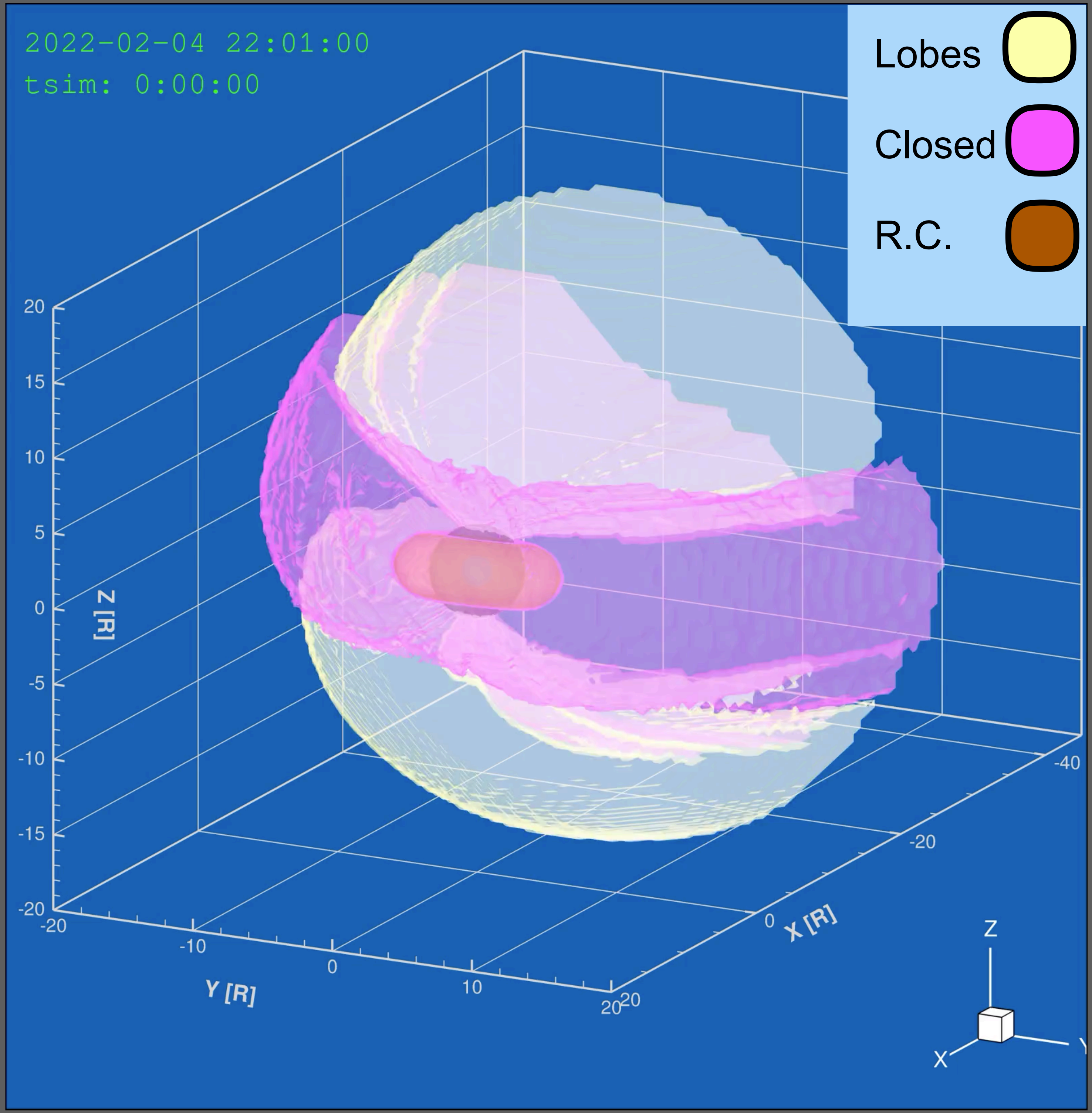
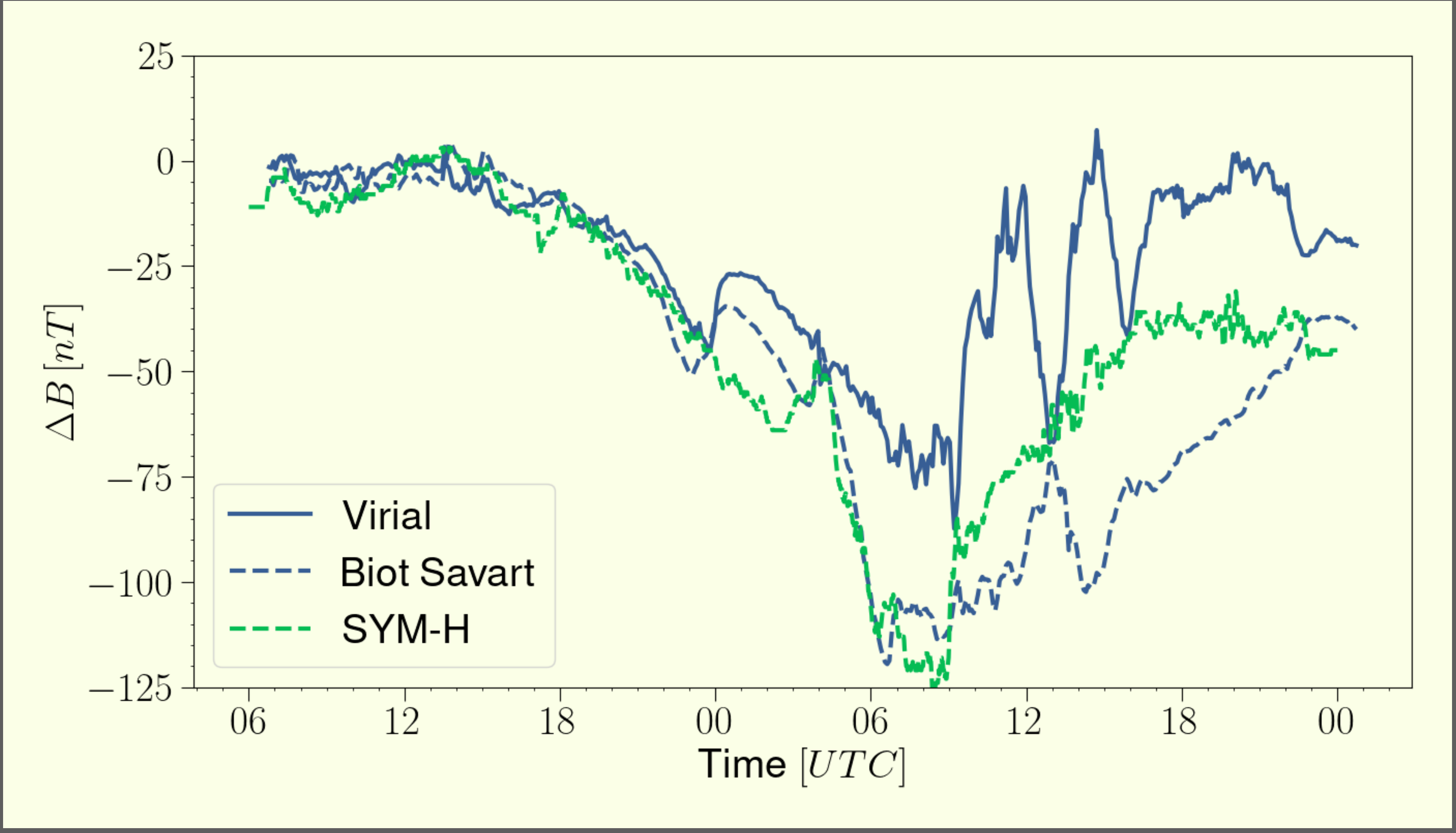
Methods: Region Defintion





Results: ΔB

Feb 18-20, 2014



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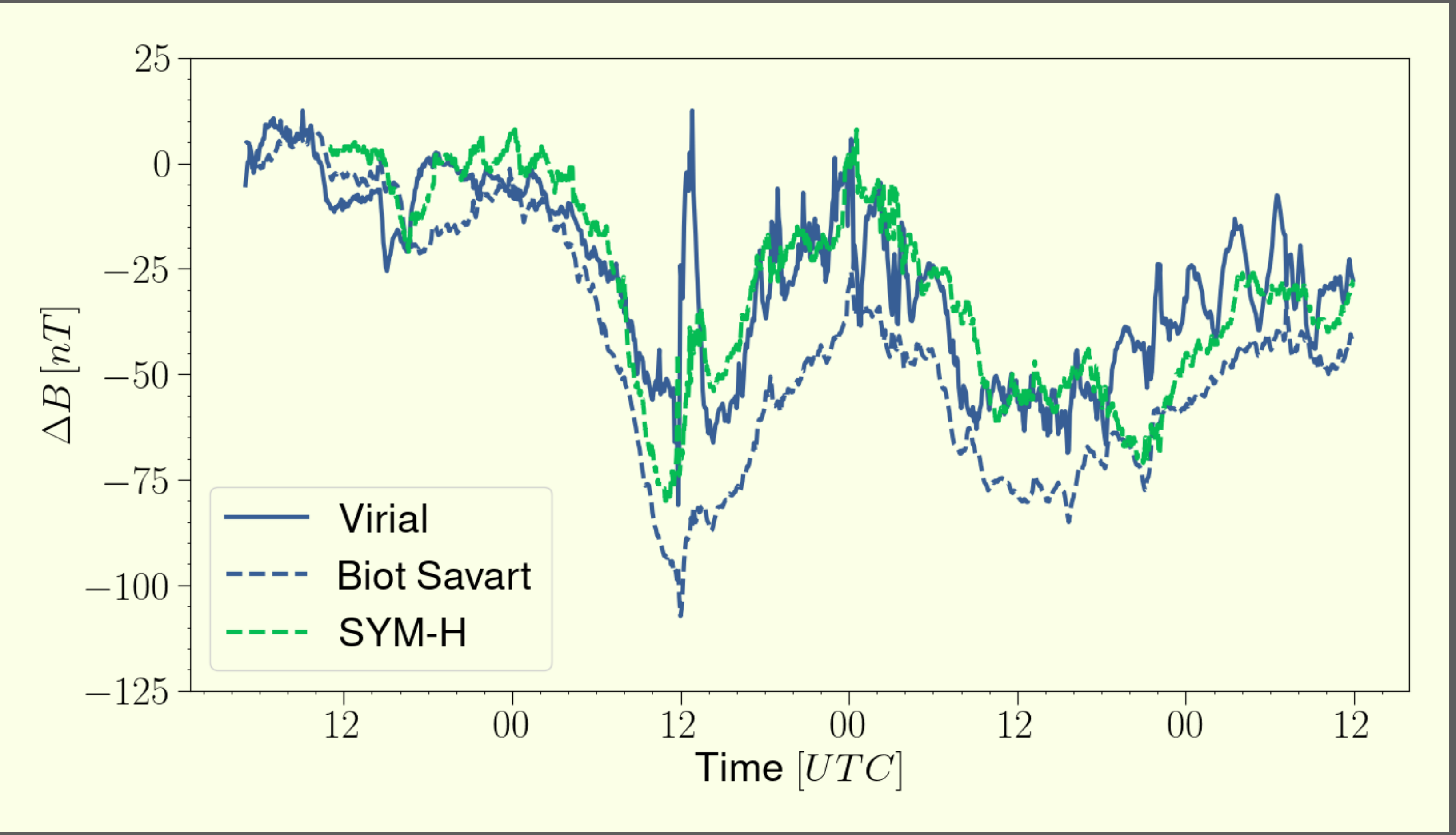

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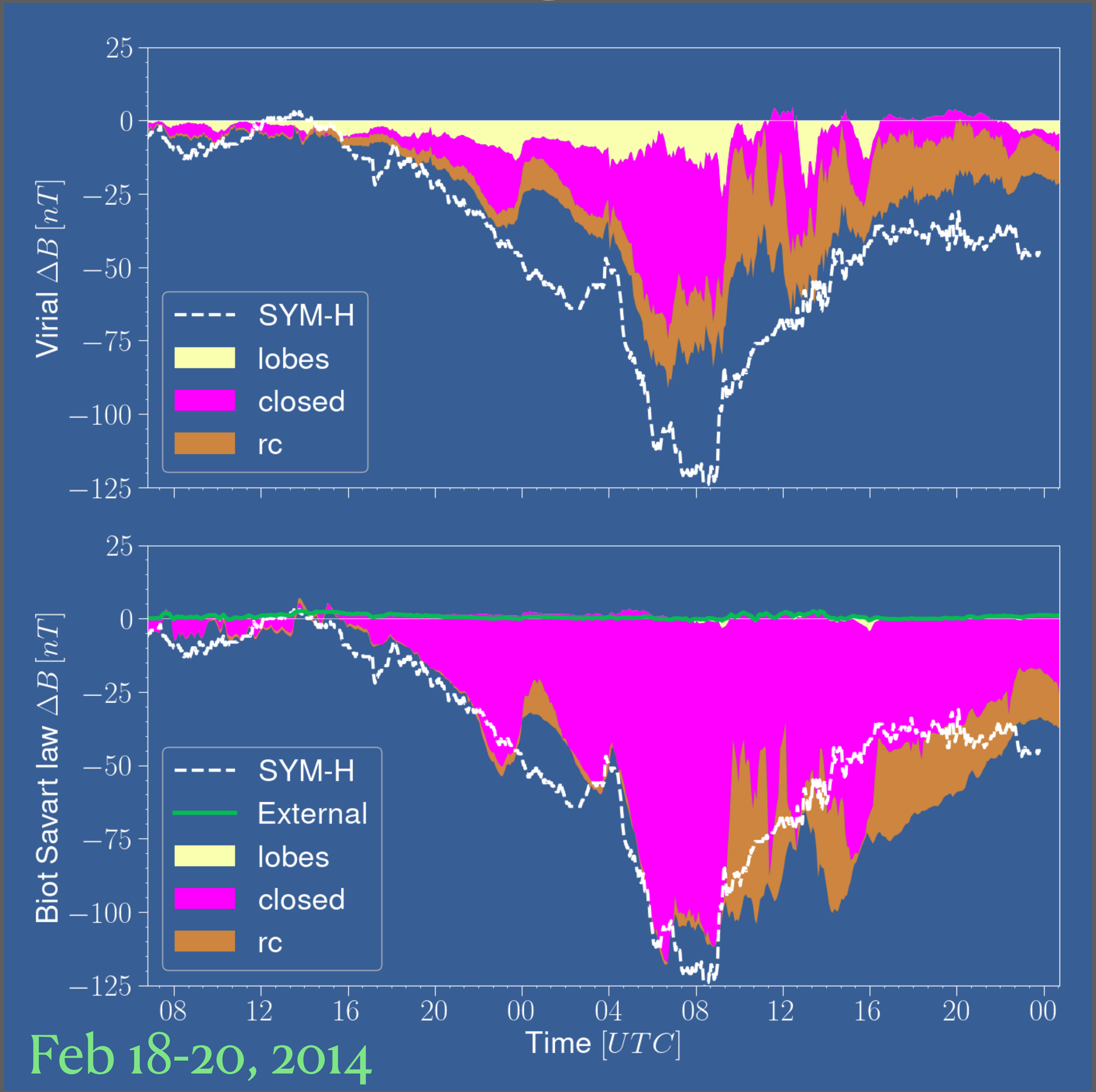
Results: Regional Contributions



- Biot Savart method (traditionally used) matches observed SYM-H ✓
- Biot Savart omit lobes entirely, currents form just outside lobe boundary definition
- Virial missing perturbation near peak and recovery

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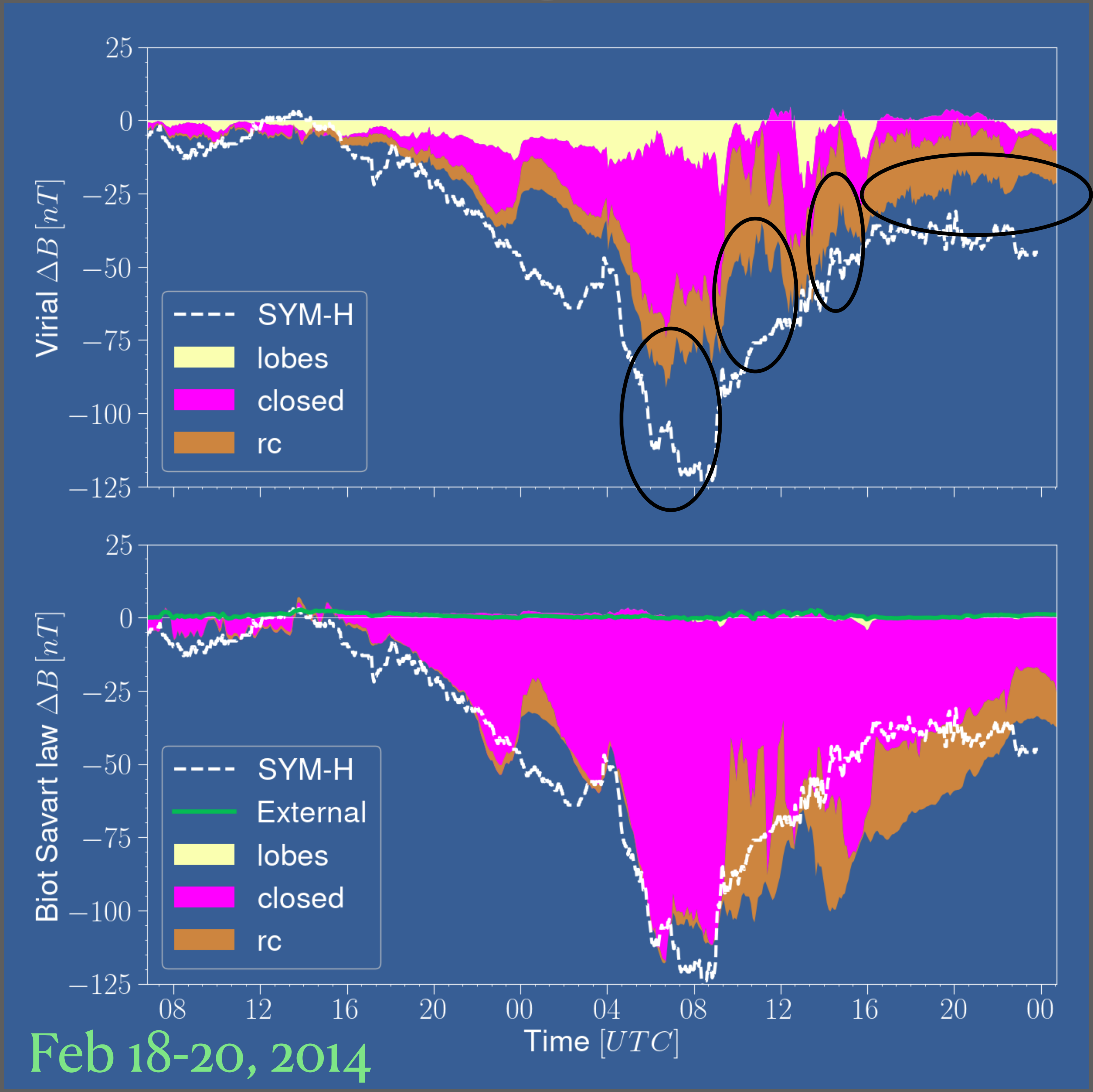
Results: Regional Contributions



- Biot Savart method (traditionally used) matches observed SYM-H ✔
- Biot Savart omit lobes entirely, possibly due to currents forming just outside lobe boundary definition
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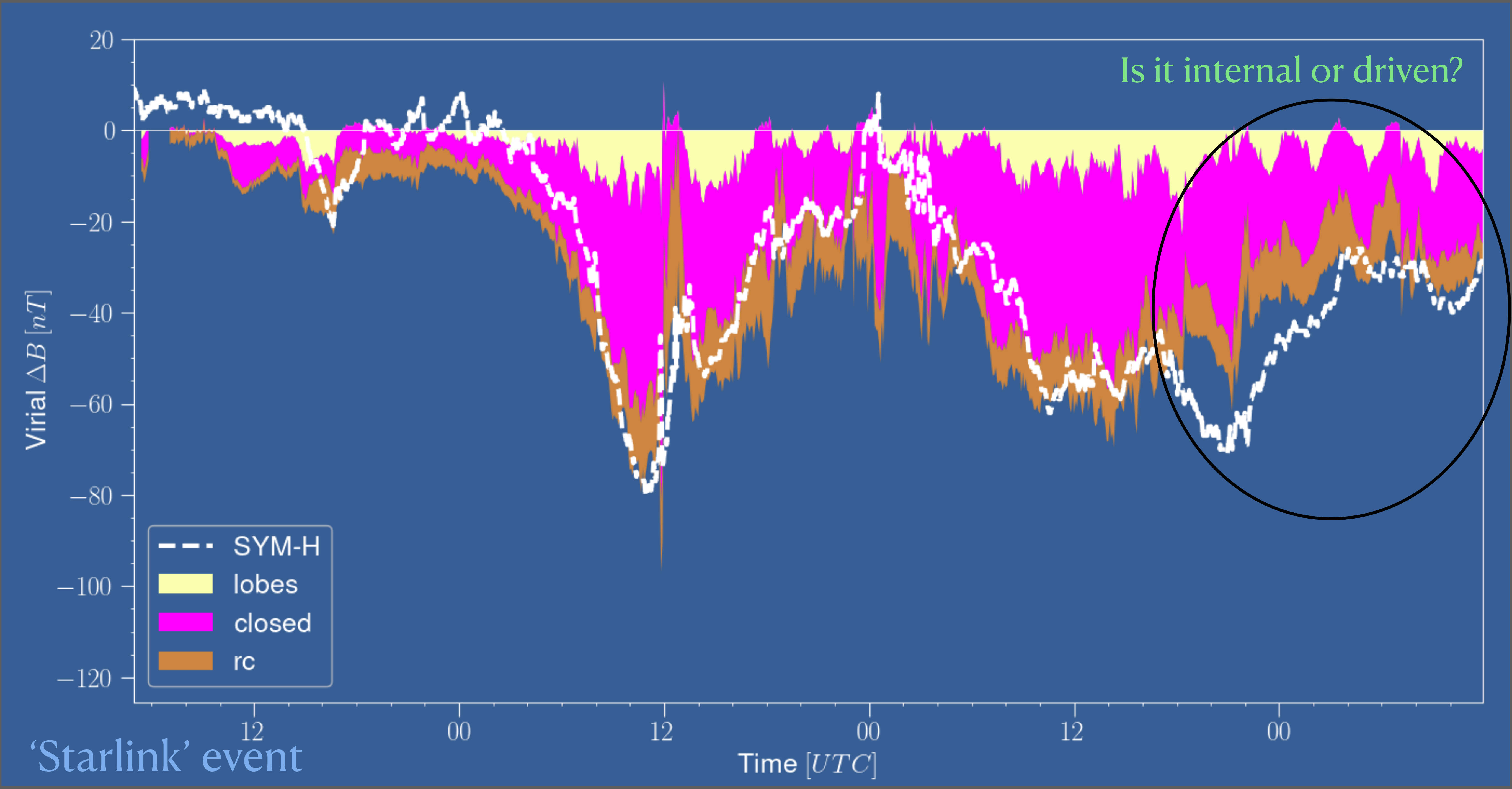
Results: Signal Analysis



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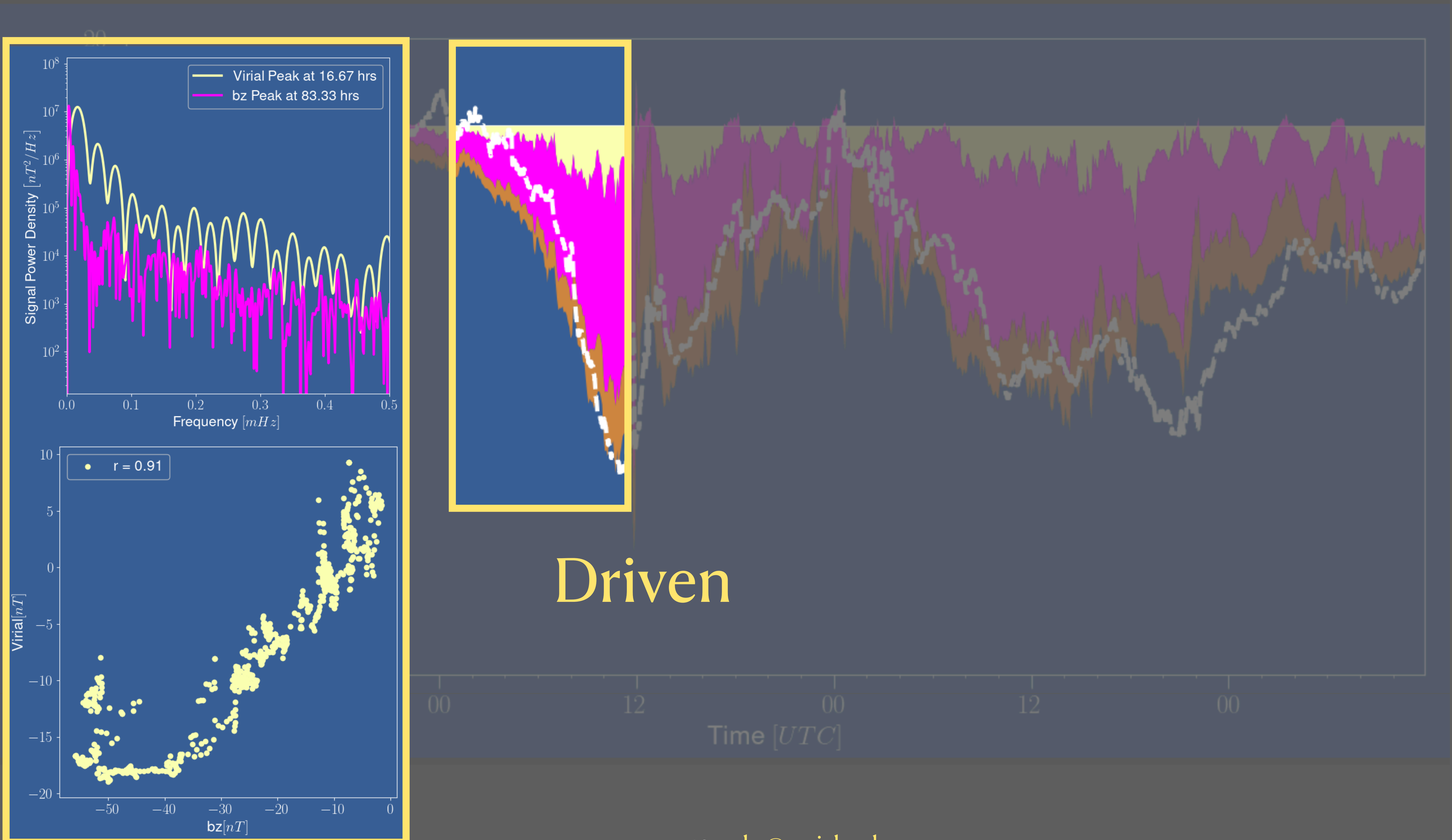

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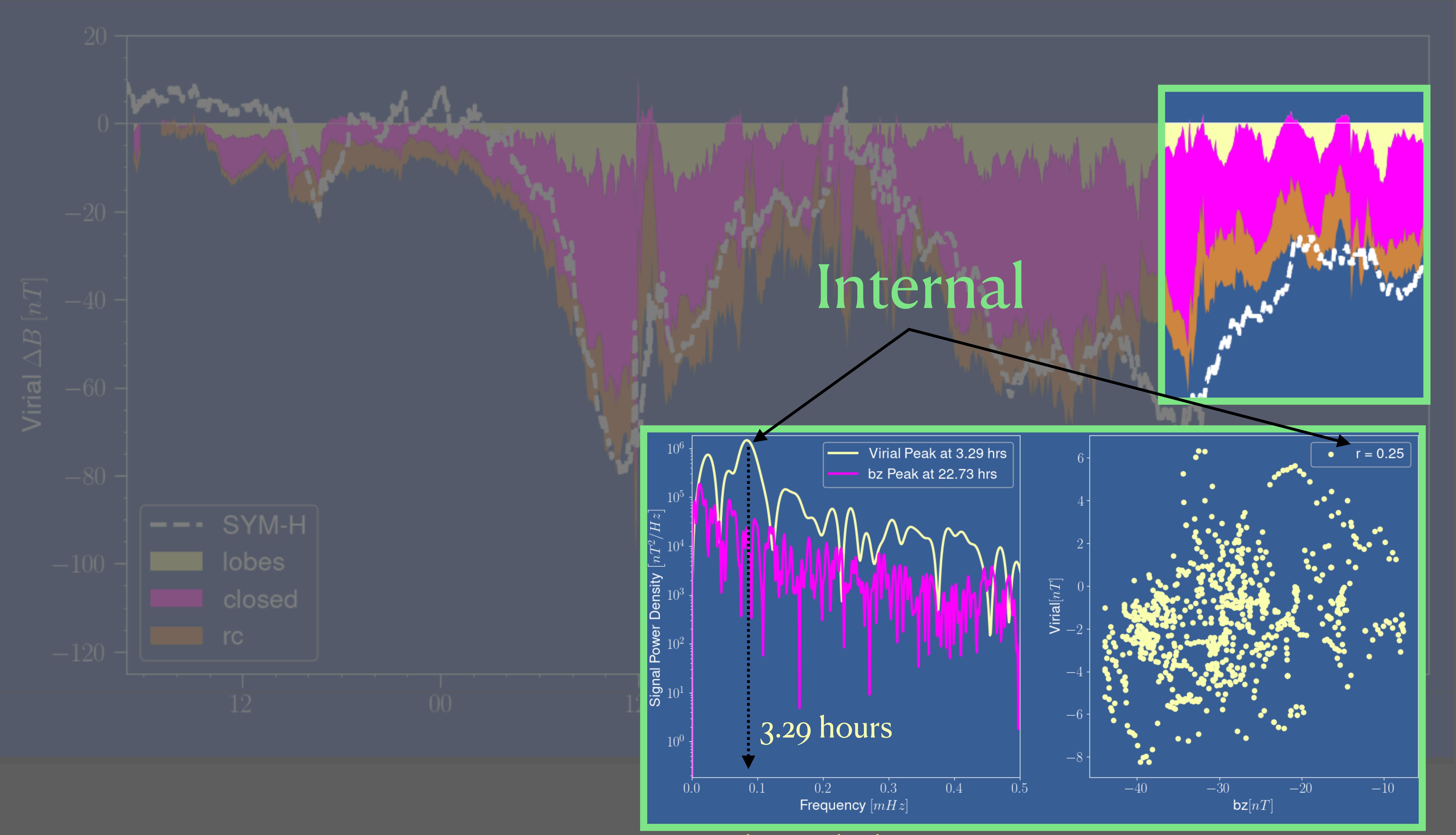

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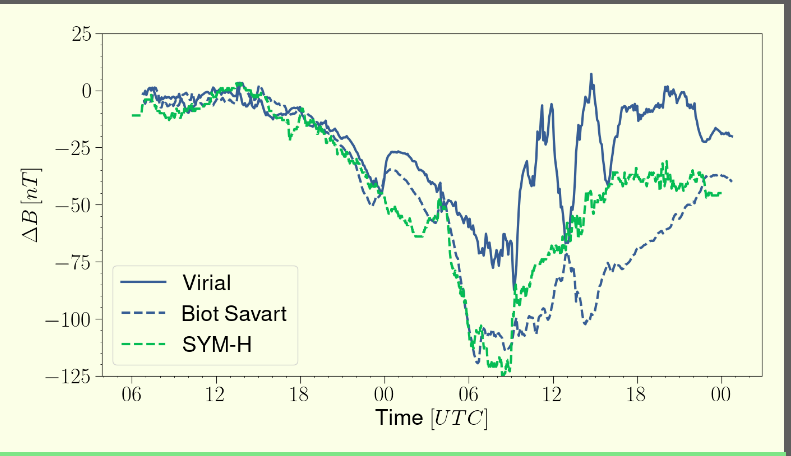
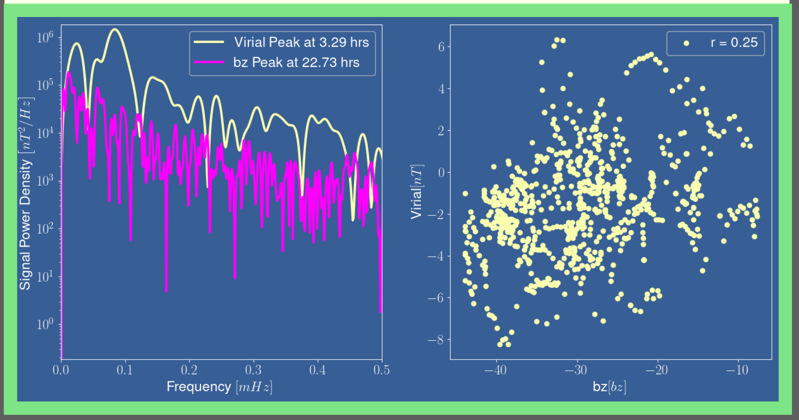
Discussion/ Conclusion

- Two events show similar evolution and distribution of ΔB
- Virial perturbation is similar in magnitude but differs from Biot Savart method
- Observations indicate virial method may be systematically under reporting
- Differences are clearly connected to an internal dynamic process (substorm)





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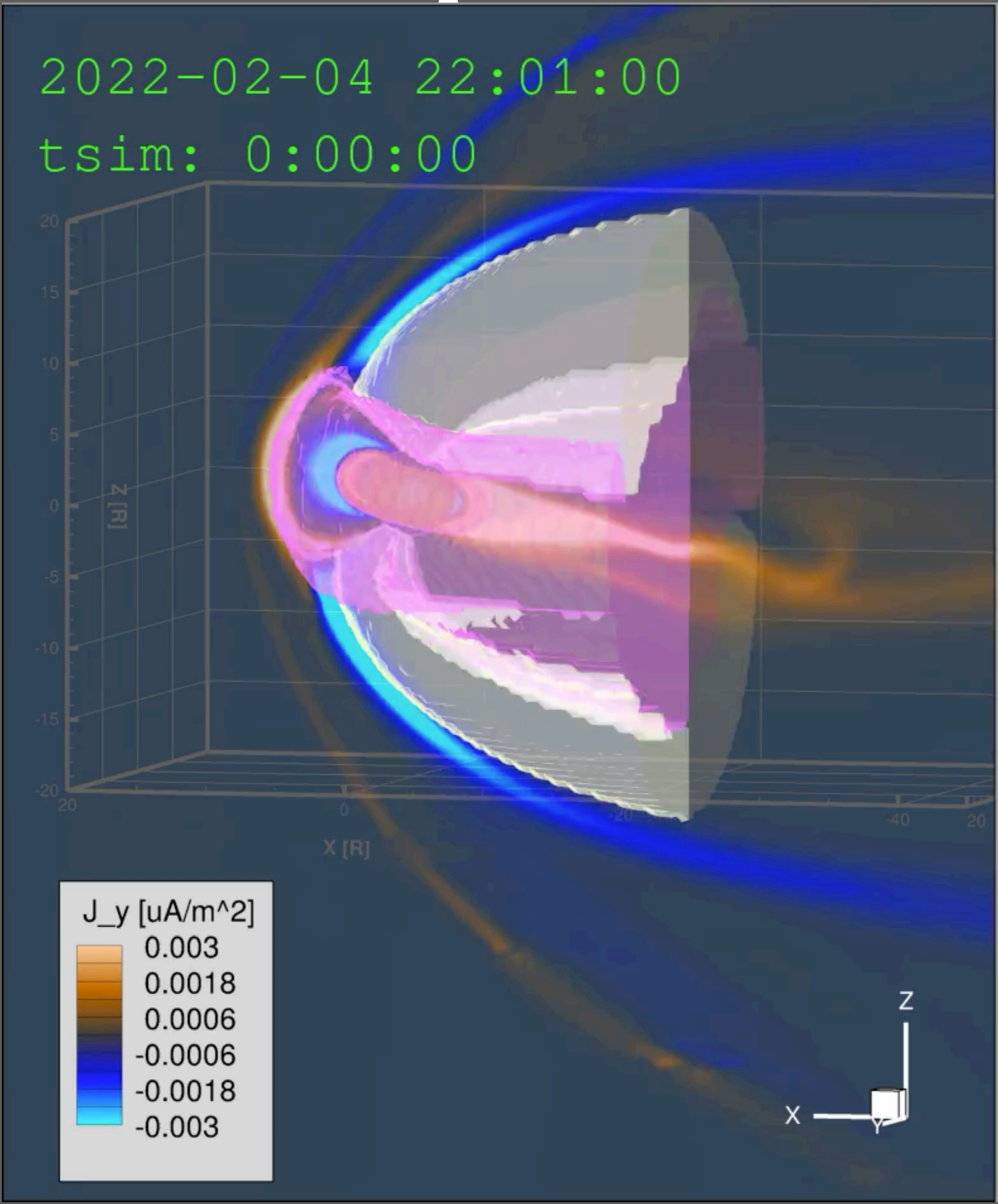
Next Steps



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tsim: 0:00:00
X [R]
Z [R]
J_y [uA/m^2]
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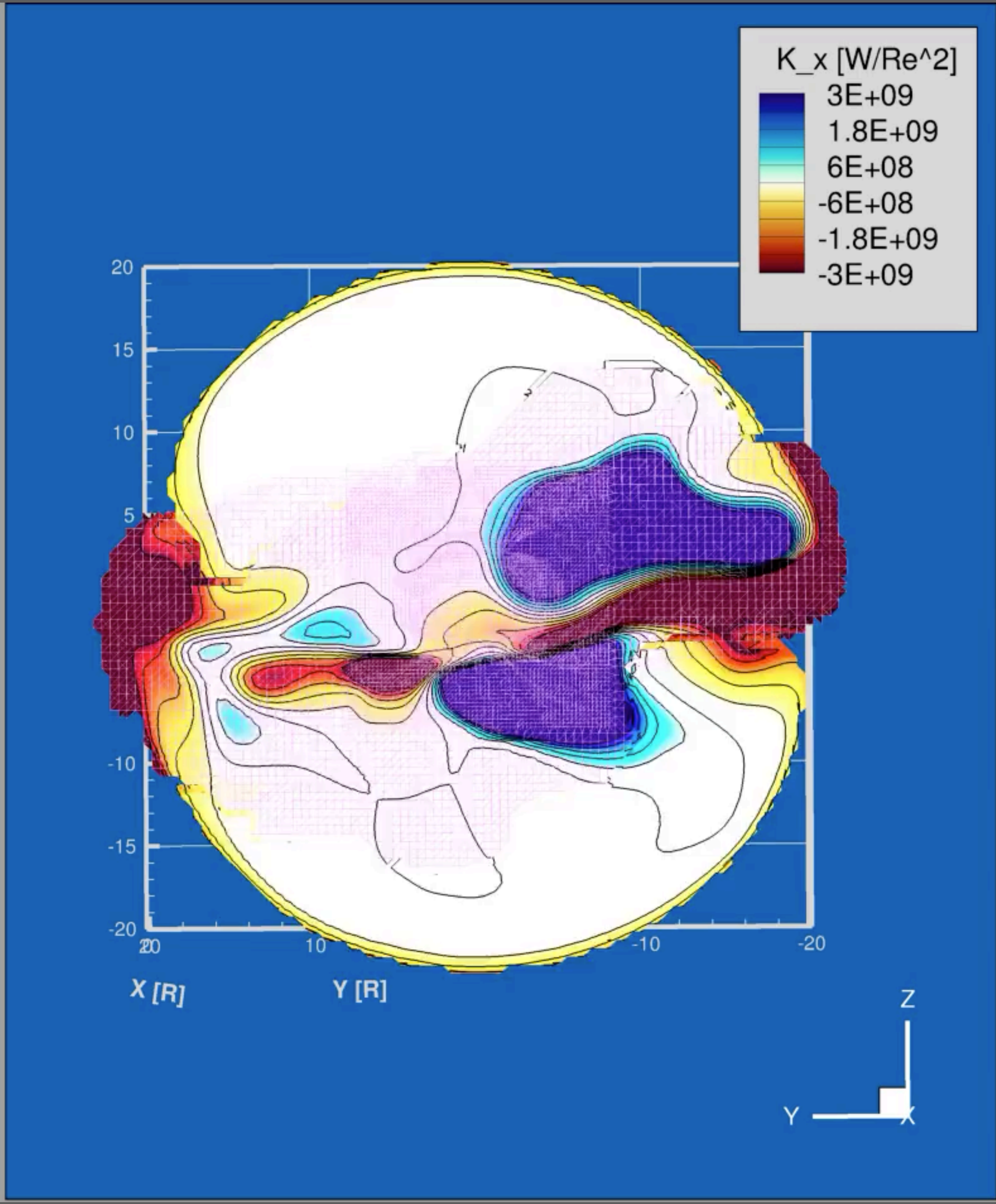
0.0018
0.0006
-0.0006
-0.0018
-0.003
Z
X
Y



K_x [W/Re^2]
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1.8E+09
6E+08
-6E+08
-1.8E+09
-3E+09
X [R]
Y [R]
Z
Y
X