Helium in the Earth's foreshock: a global Vlasiator survey

ST2.1: Open Session on the Magnetosphere

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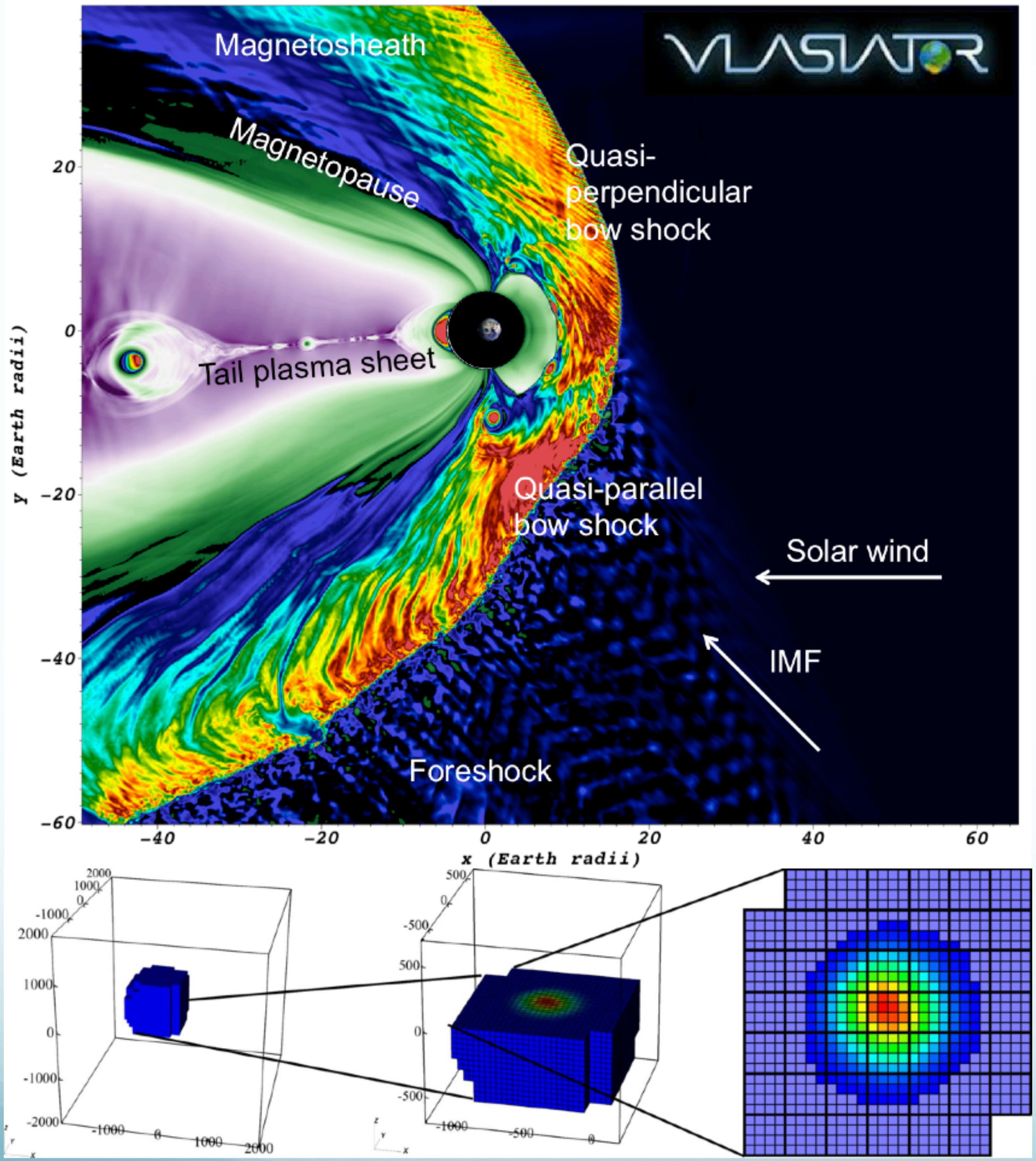


http://physics.helsinki.fi/vlasiator

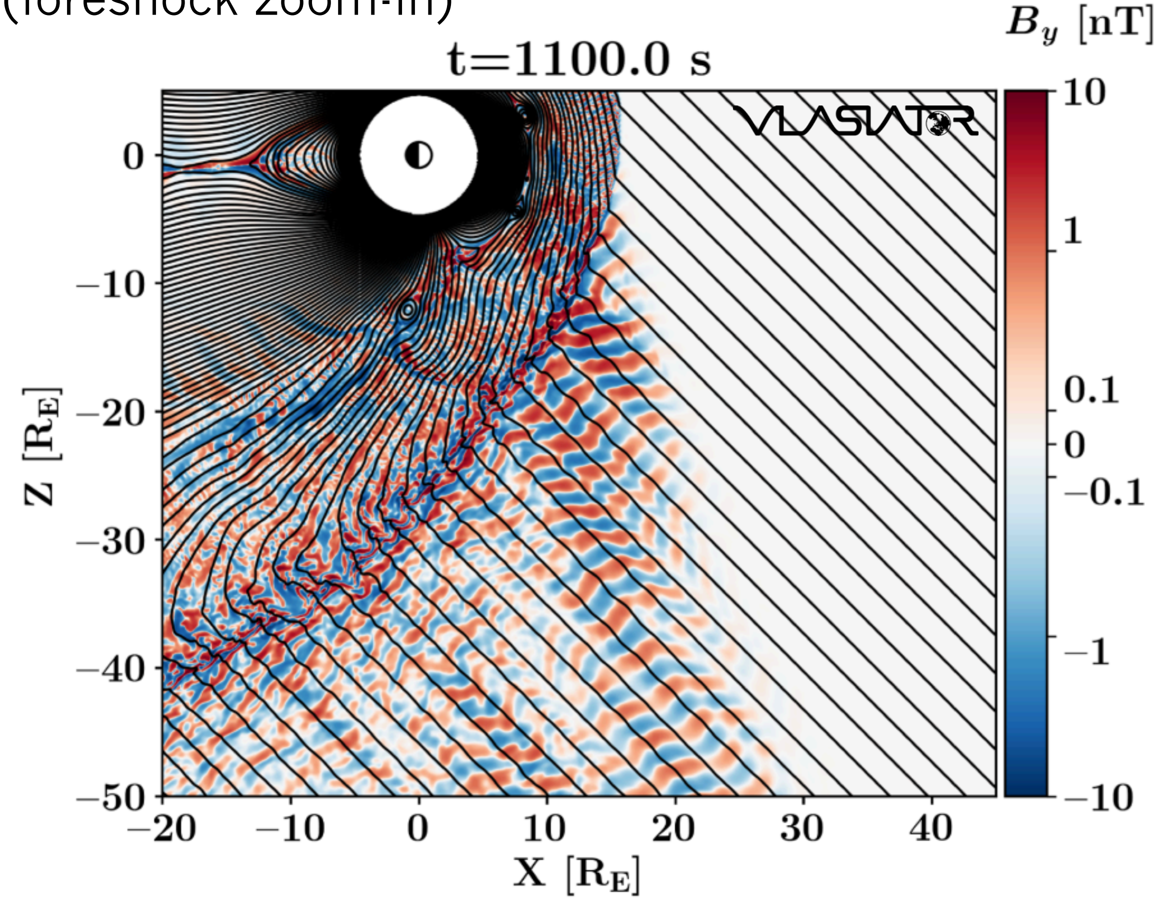
Palmroth et al. (2018) Living Reviews in Computational Astrophysics

Vlasiator is available on GitHub (GPL2)

- Collisionless ion-kinetic plasma physics: Vlasov equation for ions, cold charge-neutralising fluid electrons.
- Cartesian spatial grid, each spatial cell contains a cartesian 3D velocity space
- Semi-Lagrangian solver for the Vlasov equation
- **E**, **B** fields: upwind constrained transport (Londrillo & Del Zanna 2004) and divergence-free reconstruction (Balsara 2009)

Helium in the Earth's foreshock: a global Vlasiator survey

(foreshock zoom-in)



Global simulation with two self-consistent ion species: p^+ and He^{2+}

M_A = 6.9
M_{ms} = 5.6
$n_{p,sw}$ = 1 cm^{-3}
$n_{\alpha,sw}$ = 0.01 cm^{-3}
B = 5 nT
(45° IMF cone angle)
u_{sw} = 750 km/s
$T_{p,sw}$ = 0.5 MK
$T_{\alpha,sw}$ = 1.0 MK
β = 0.7

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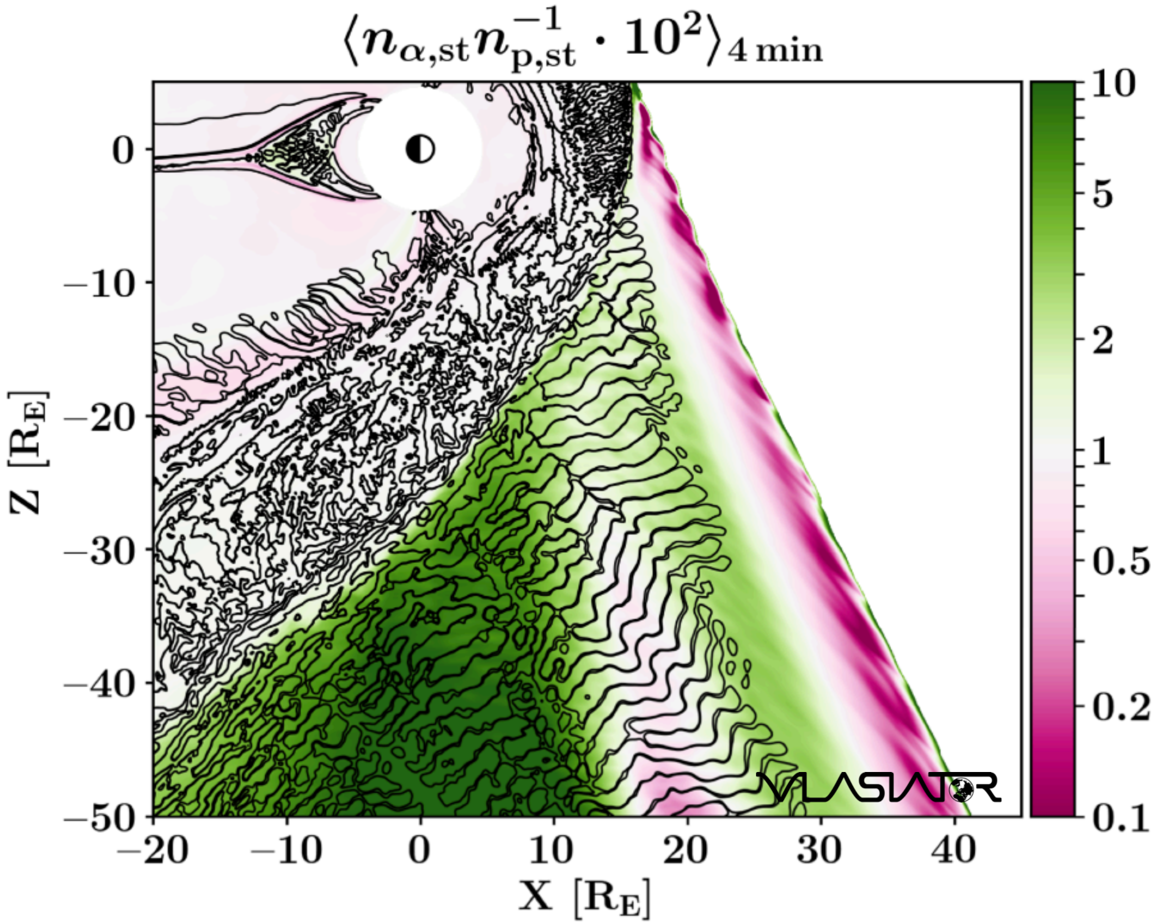


Foreshock region in front of quasi-parallel bow shock

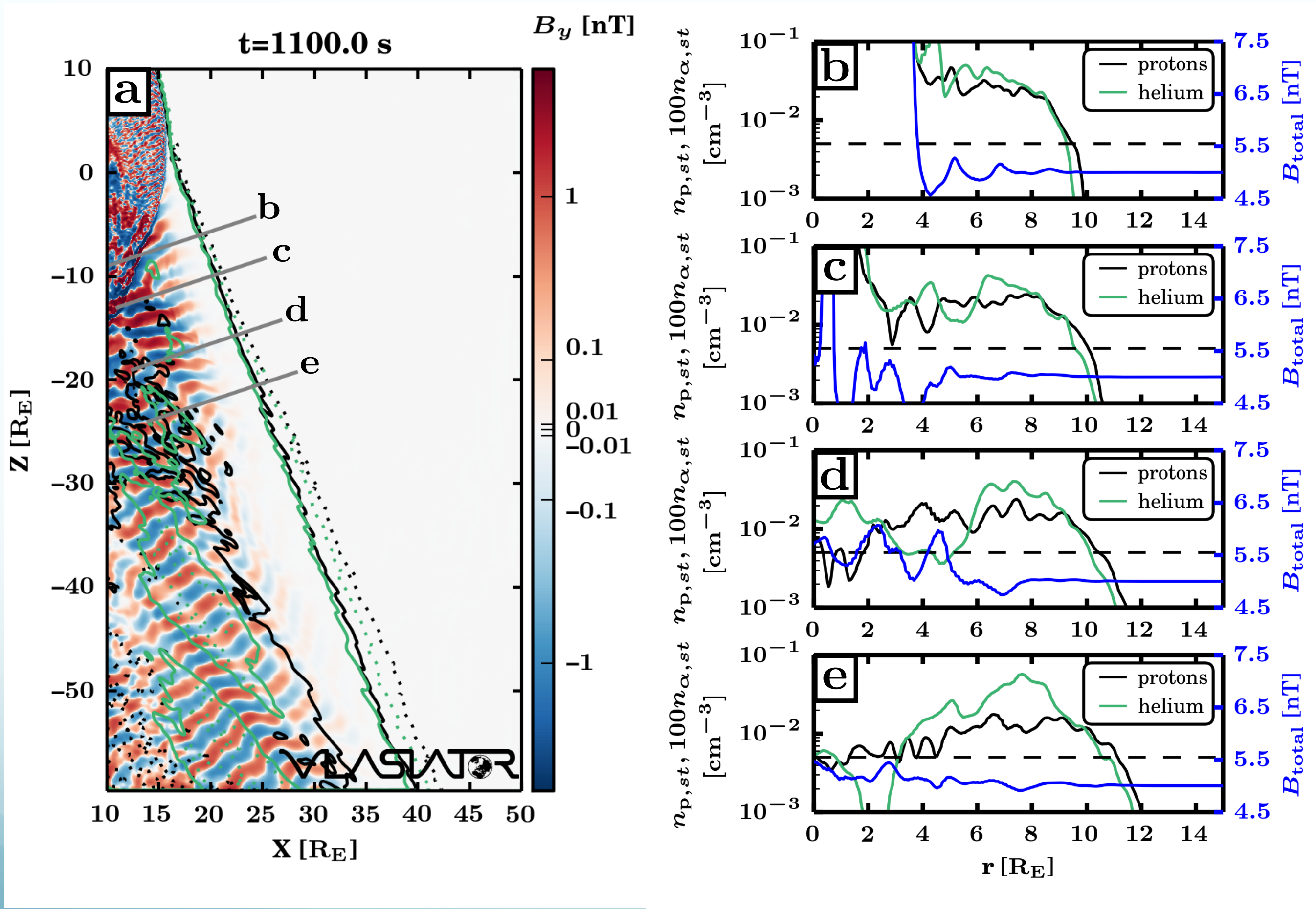
ULF waves are excited by counterstreaming ions reflected at the shock.

ULF and ion foreshock extents are not identical, and ion ratios can vary within the foreshock.

Foreshock edge profiles

Black: p^+ suprathermal density $n_{p,st}$
Green: He^{2+} suprathermal density $n_{\alpha,st}$

Dotted: 0.1% of n_{sw}
Solid: 0.5 % of n_{sw}



As expected, lack of magnetic field fluctuations at ion foreshock edge

Close to bow shock: densities fall rapidly

Further out: Gradual decrease

p^+ always extends further than He^{2+}

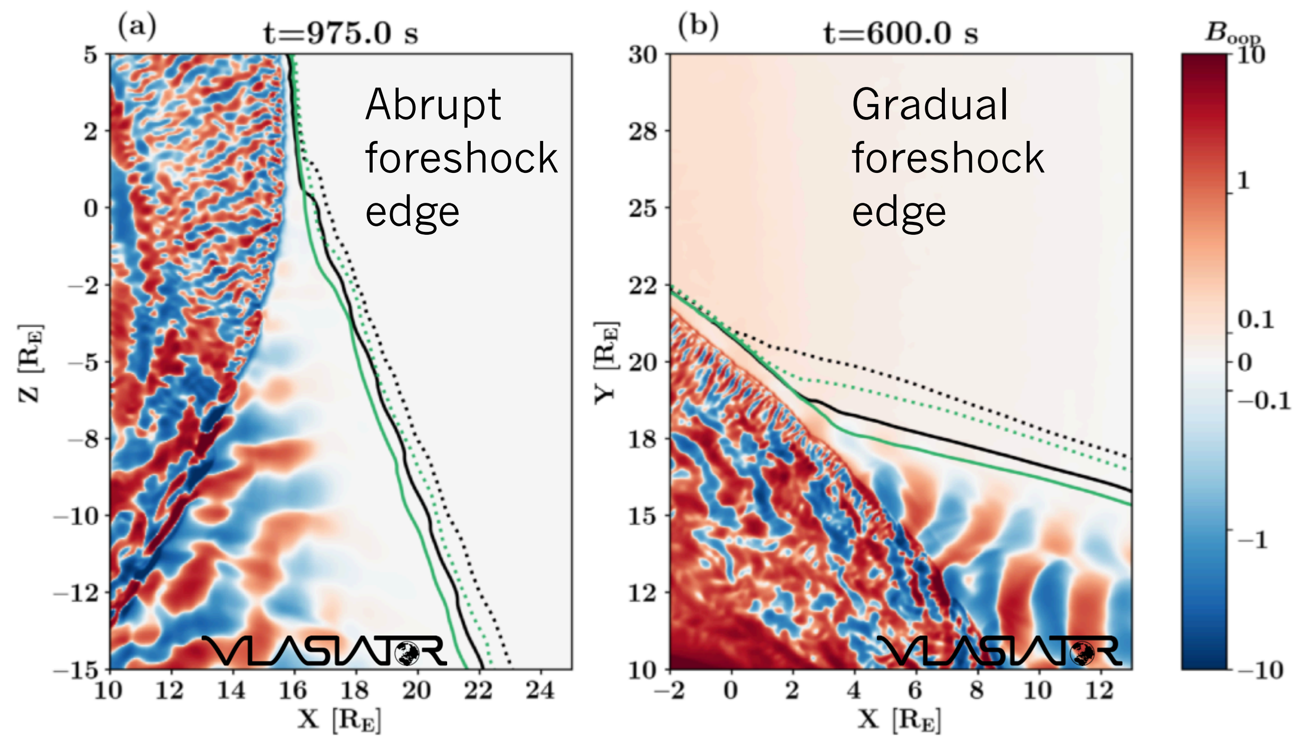
Far inside foreshock: suprathermal ion densities begin to oscillate

Foreshock edge vs IMF

Comparison simulation: equatorial plane, 5° IMF cone angle

$n_{p,st}$ and $n_{\alpha,st}$ averaged over 2 minutes

β=2.3, M_A =10, n_p =3.3cm^{-3}, n_α =3.3·10^{-2} cm^{-3}, $u_{sw,x}$ = −600 km/s.



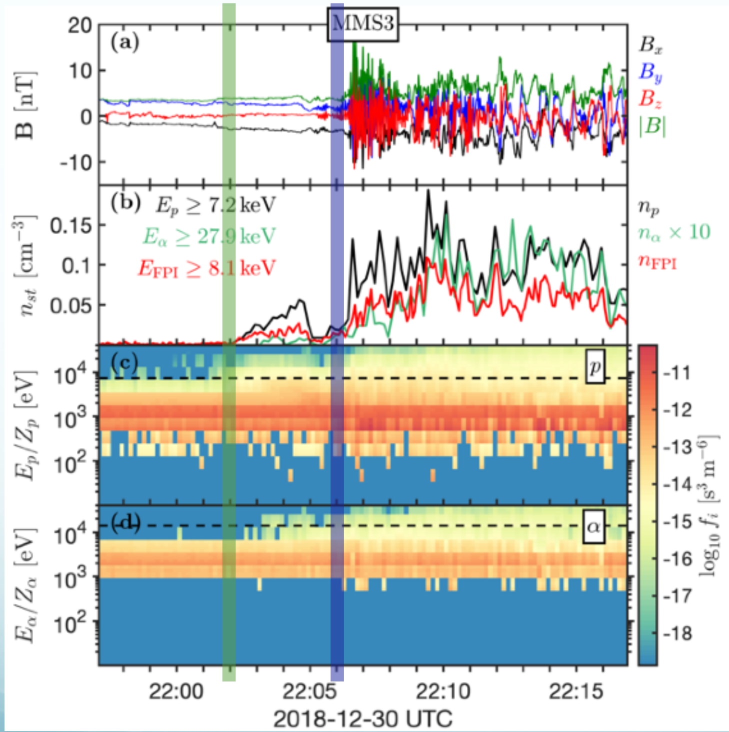
Large vs small

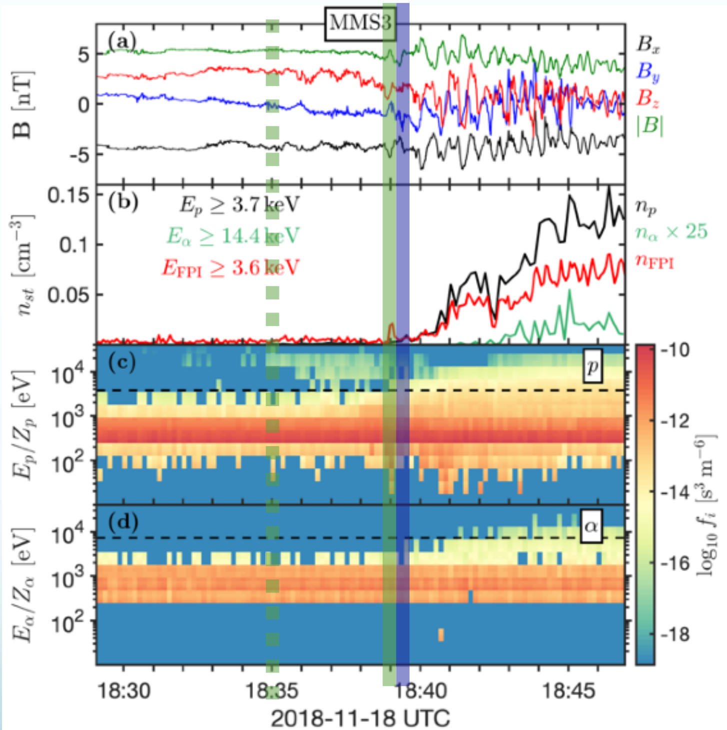
$$\frac{d\theta_{Bn}}{d\tilde{r}_{\perp \mathrm{FSedge}}}$$

could explain some variation in foreshock edge profiles

Foreshock edge variation (MMS)

Magnetosphere Multiscale mission (Burch+2016)
FGM (Russell+2016), HPCA (Young+2016) FPI/DIS (Pollock+2016)
Survey mode, require smooth MMS and OMNI fields before and after event for foreshock edge crossing without rapid foreshock movement. $He^{2+}{}_{sw}/p_{sw} \sim 3\%$

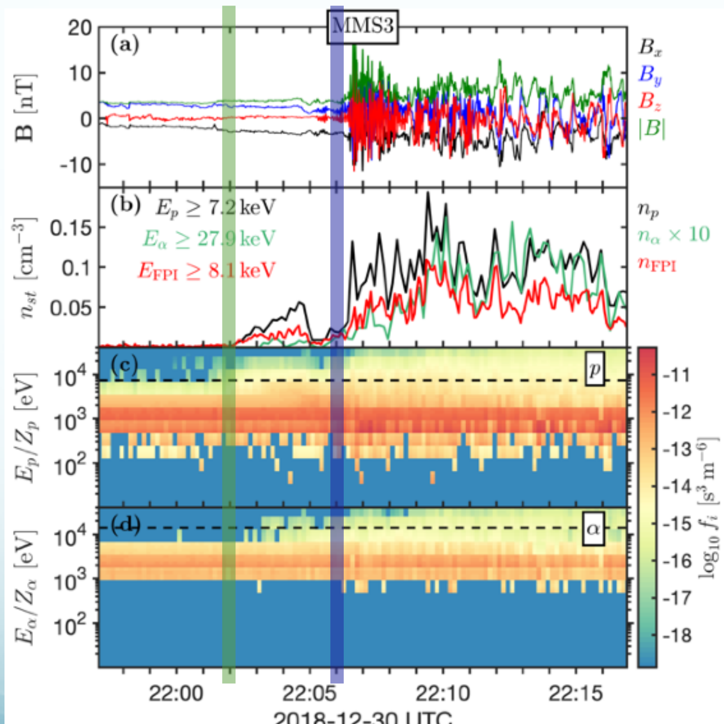


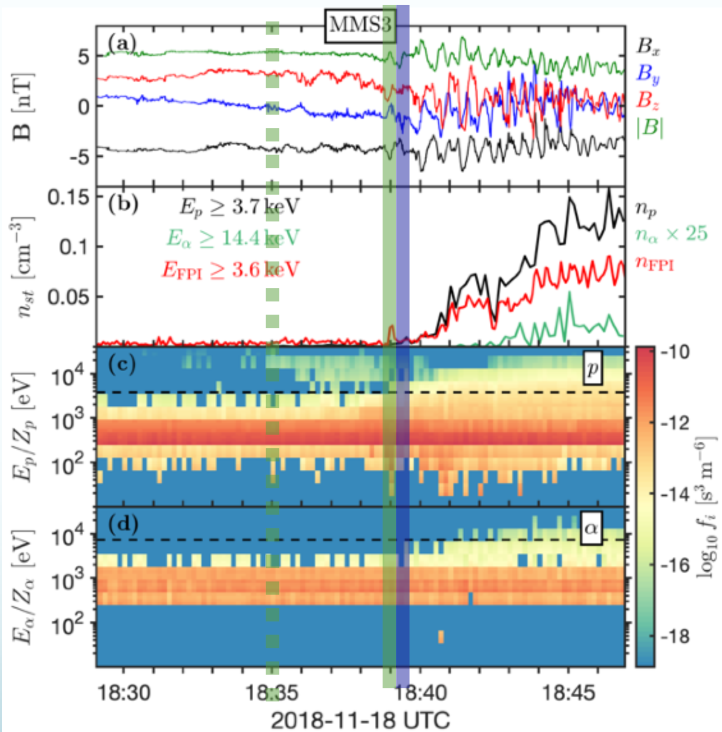


Foreshock edge variation (MMS)

Ion foreshock from ~22:02
ULF waves after 22:06
Initial H^{2+}_{st} densities are low but reach ~10% of p_{st} densities

Ion foreshock from 18:39
ULF waves after ~18:39
H^{2+}_{st} densities remain low (~1% of p_{st}) well into the foreshock





Global survey of Helium

Identify field-aligned beams with temperature anisotropy $\frac{T_\perp}{T_\parallel}$

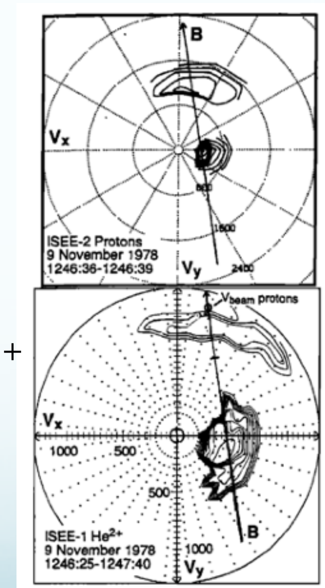
Calculate specular reflection from shock-normal angle

Find gyrating distributions with the agyrotropy measure (Swisdak 2016) $Q_{\mathrm{ag}} = \frac{P_{12}^2 + P_{13}^2 + P_{23}^2}{P_\perp^2 + 2P_\perp P_\parallel}$

Field-aligned beams

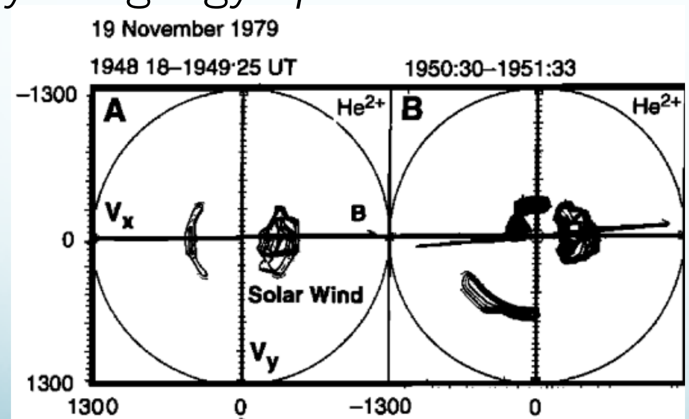
p^+

He^{2+}



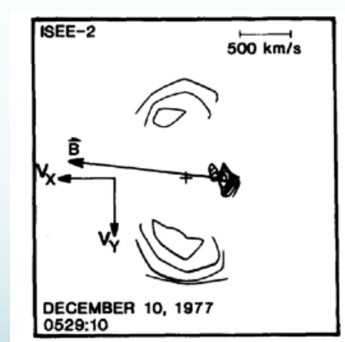
Fuselier+1992

Gyrating / gyrophase-bunched ions



Fuselier+1995

Specular reflection



Fuselier1995

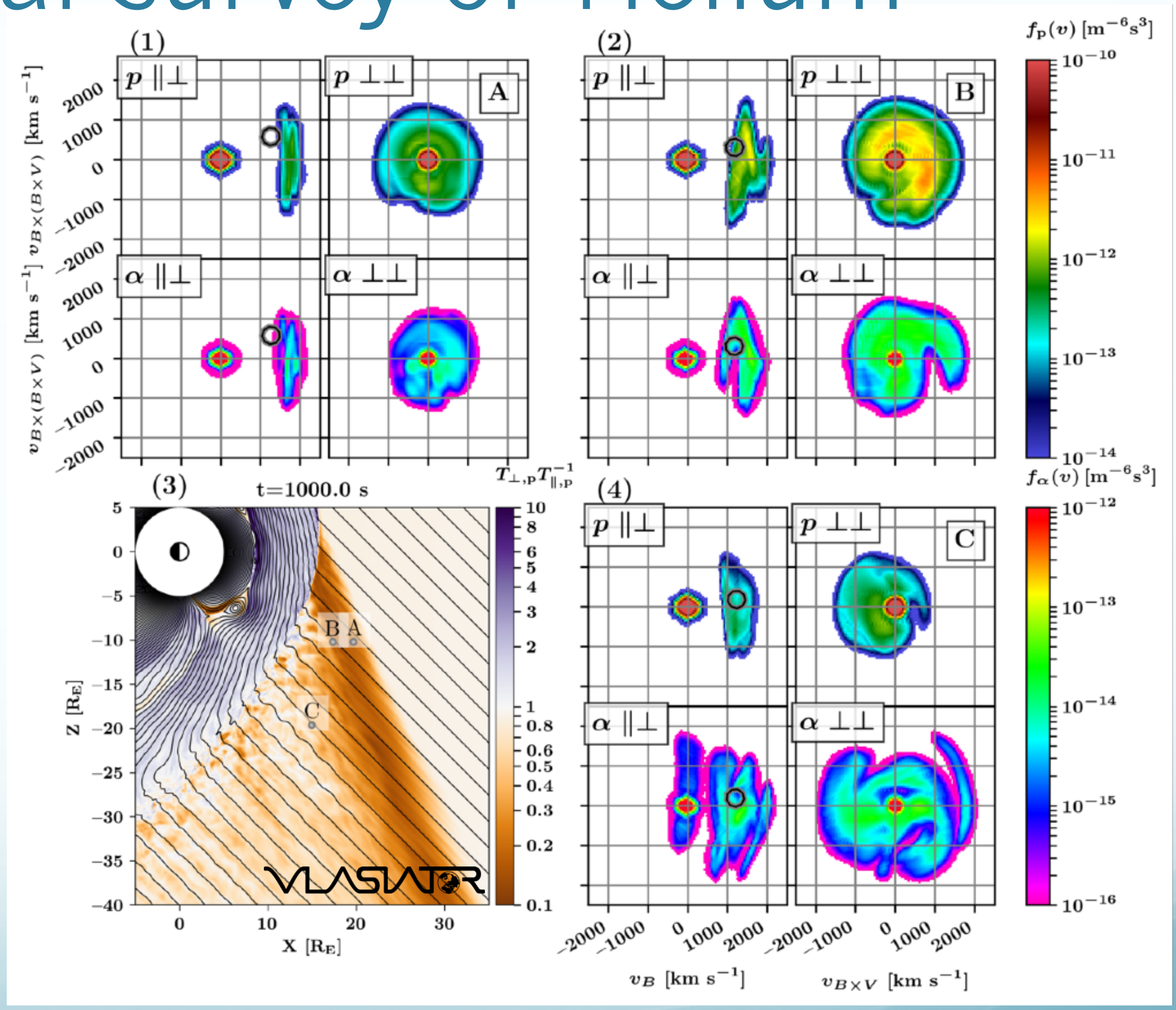
Global survey of Helium

Virtual spacecraft (VSC) velocity distribution function projections close to foreshock edge

VSC A
E>E$_{specular}$ (ring shape):
Field-aligned beams from shock drift acceleration

VSC B
gyrophase-bunched ions, spatial samping of large gyroradii

VSC C
Slower beams further in, erratic gyration



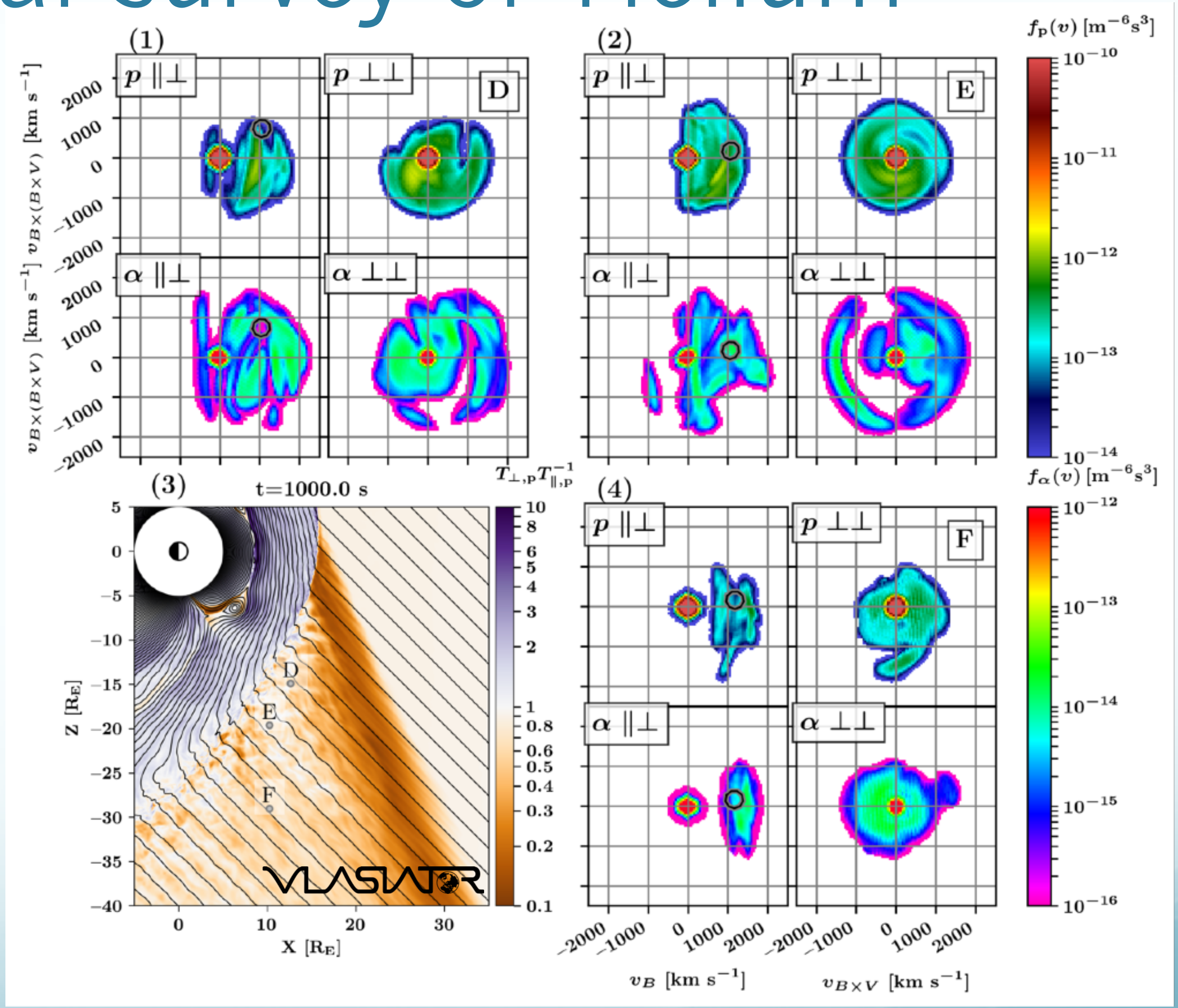
Global survey of Helium

Virtual spacecraft (VSC) velocity distribution function projections deeper in foreshock

VSC D
Lots of gyrating and even counterstreaming ions. Specular reflection.

VSC E
Nearly diffuse p^+ ions, erratic gyrating He^{2+}

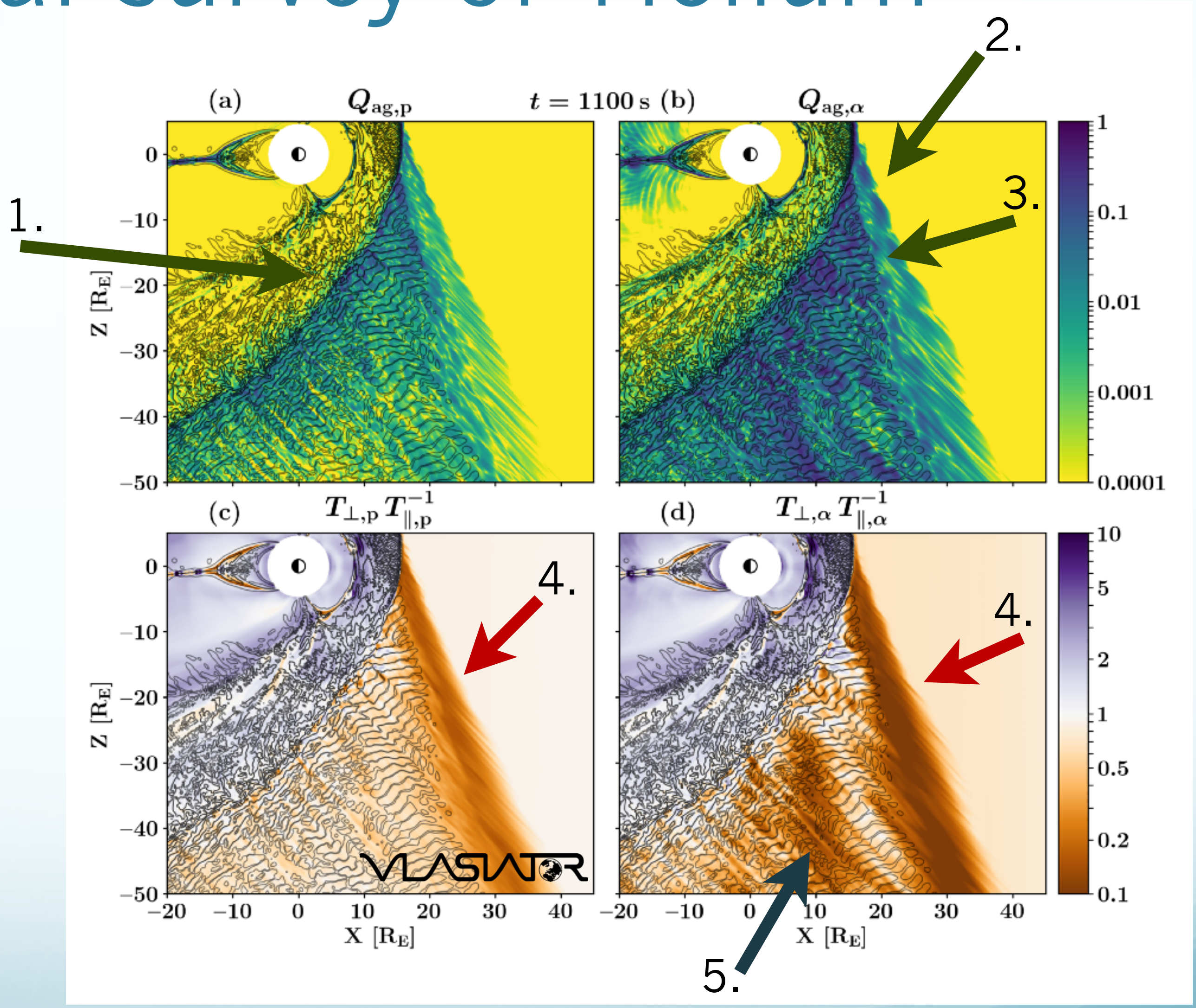
VSC F
Most ions have become diffusive (dropped from simulation)



Global survey of Helium

Enhancements of p+ and He2+ agyrotropy near $Q_{||}$ bow shock (specular reflection, 1.) and both ion (2.) and ULF (3.) foreshock edges (spatial sampling of gyrating ions)

Enhancements in $T_{||}$ near ion foreshock edge (4. field-aligned beams) and also deeper in for He^{2+} in region (5.) with less coherent wavefronts



VLASIATOR

Foreshock waves and He^{2+}

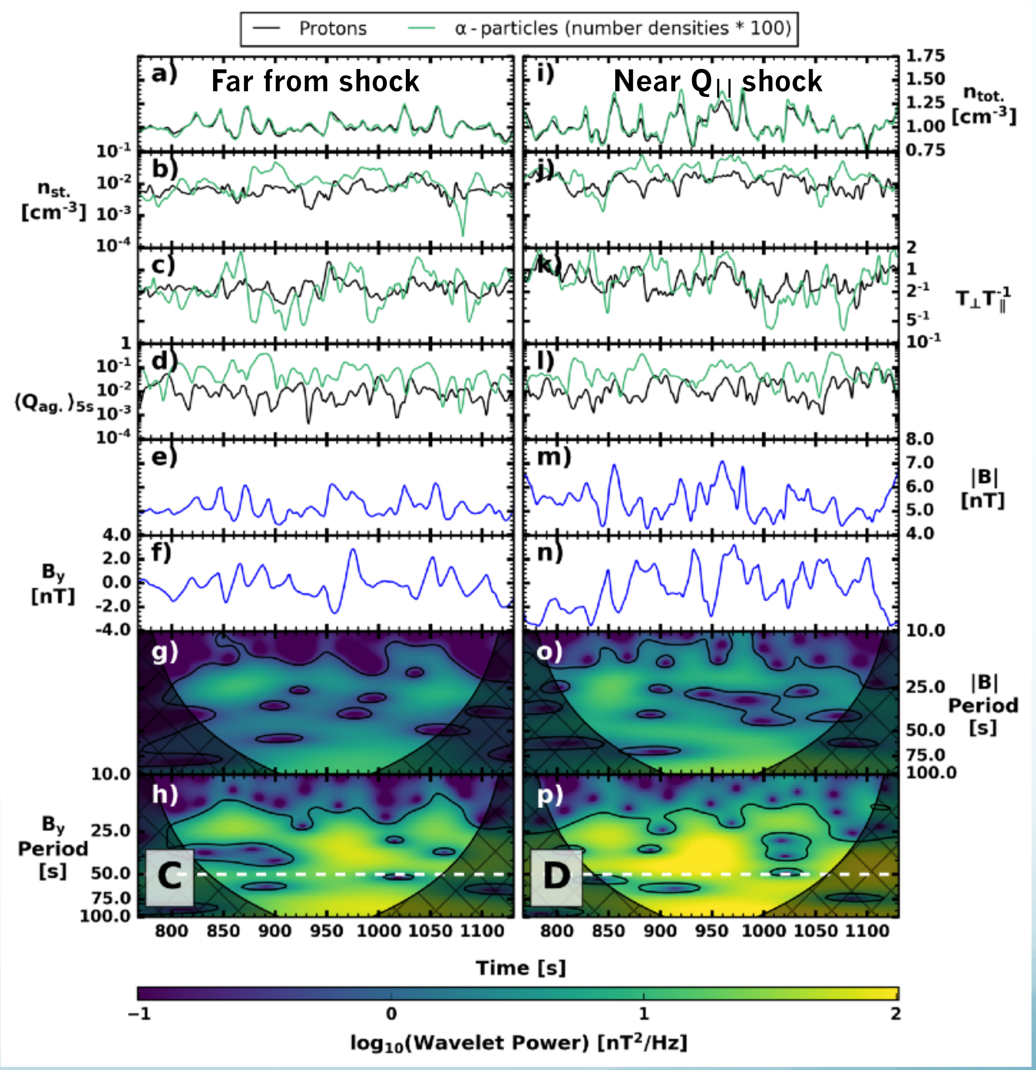
Wave-ion interactions: "30s" waves (white dashed line), right-hand resonant ion-ion beam instability, left-hand in s/c frame

VSC C,D: *near ULF foreshock edge*

1% of SW He^{2+} does not noticeably excite ULF waves (at ~100s period)

He^{2+} responds to waves with greater agrotropy and more variation in temperature anisotropy than p^+

Both compressional and transverse waves are present



Foreshock waves and He^{2+}

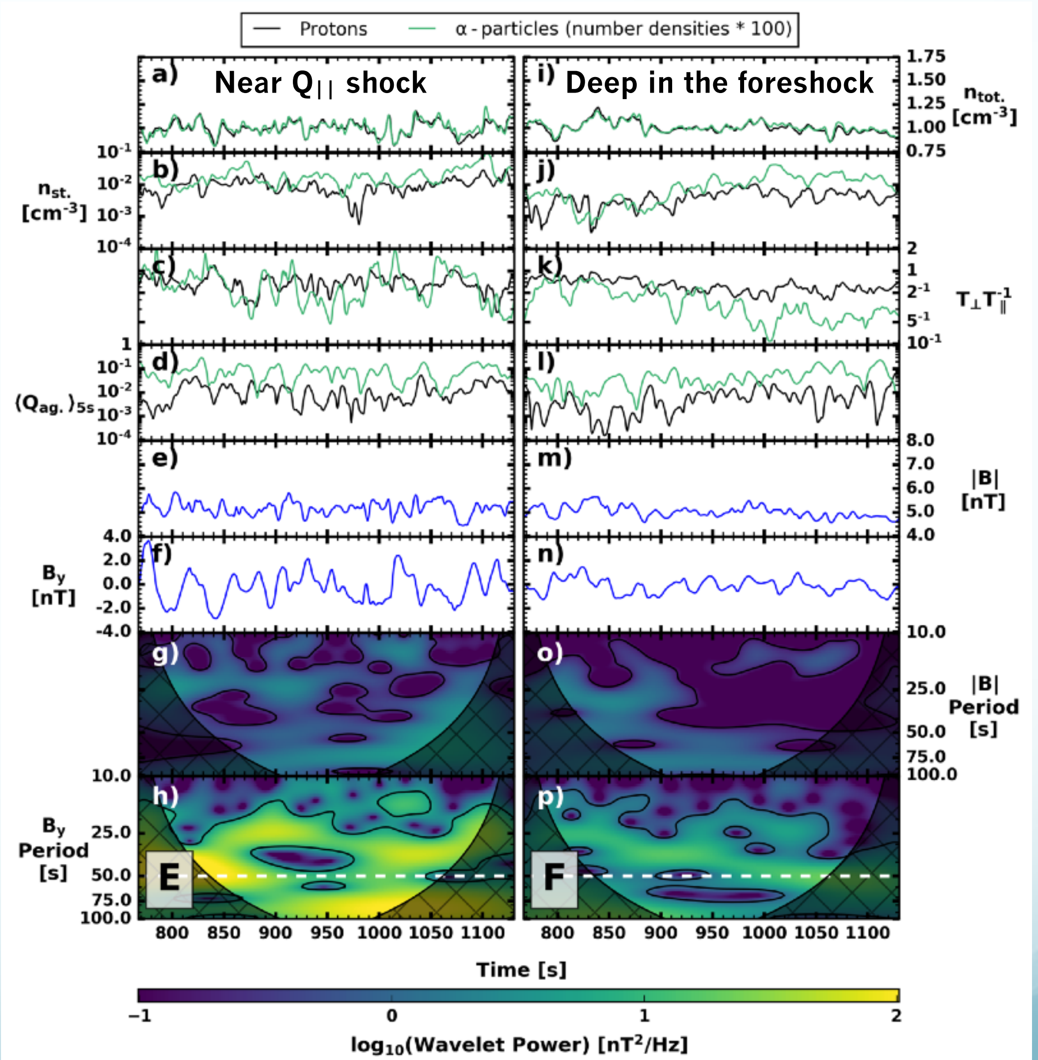
Wave-ion interactions: "30s" waves (white dashed line), right-hand resonant ion-ion beam instability, left-hand in s/c frame

VSC D,F: *far downstream from ULF foreshock edge*

Less compressional waves found far from ULF region edge

Deep in the foreshock all wave power decreases

Virtual spacecraft F:
n_{st} and $T_{\perp}T_{\parallel}^{-1}$ appear to anti-correlate (few gyrating ions)



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Conclusions

1. He^{2+} is a dynamic foreshock species which acts different from protons
2. Both He^{2+} and p^+ field-aligned beams are found at edge of the ion foreshock
3. The p^+ foreshock extends further out than He^{2+}, though large gyroradius He^{2+} ions can sometimes reach further out.
4. P^+ and He^{2+} VDFs suggest specular reflection is a major source of reflected particles
5. Proton-driven ULF heat and disturb He^{2+} efficiently, increasing agyrotropy.
6. He^{2+} increases $P_{dyn,sw}$, but $n_\alpha/n_p=1\%$ does not excite ULF waves.
7. Wave-wave interactions deep in the foreshock cause breakup of the ULF wavefronts, at which point He^{2+} experiences less scattering
8. Different foreshock edge profiles may be explained via $\frac{d\theta_{Bn}}{d\tilde{r}_{FSedge}}$

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https://www.ann-geophys-discuss.net/angeo-2020-29