Simulating the Reiner Gamma Swirl

Coupling simulations and observations.

Jan Deca

LASP, University of Colorado Boulder

In collaboration with A. Divin, C. Lue, B. Lembège, X. Wang, S. Markidis, G. Lapenta & M. Horányi.

Moon - plasma interaction

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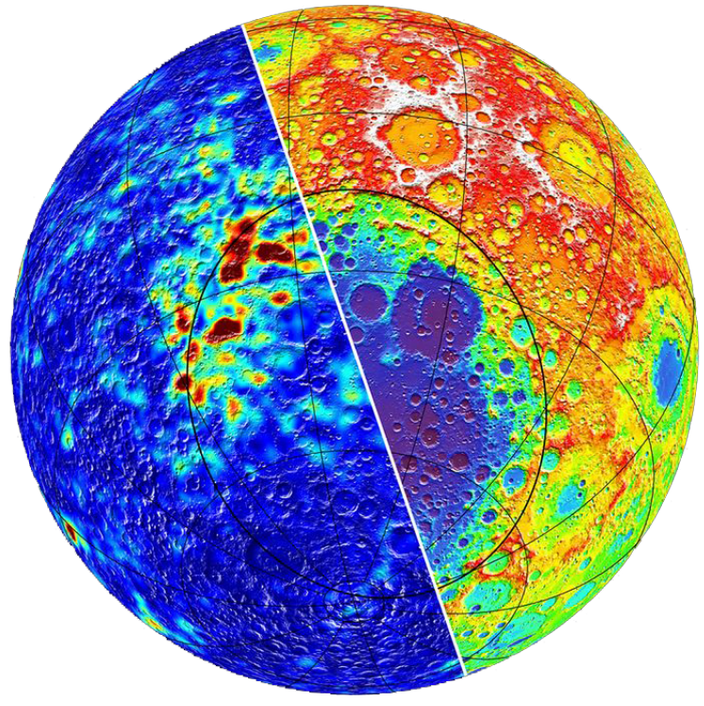
University of Colorado **Boulder**

- The Moon has no intrinsic magnetic field, but does possess regions of local magnetisation, called

  Lunar Magnetic Anomalies (LMAs).

  - Non-dipolar, small-scale, $B_{surface}$ ~ 0.1nT -> 1000nT.
  - Origin is unclear, correlation with lunar swirls suggested, ion reflection, surface shielding, … ???



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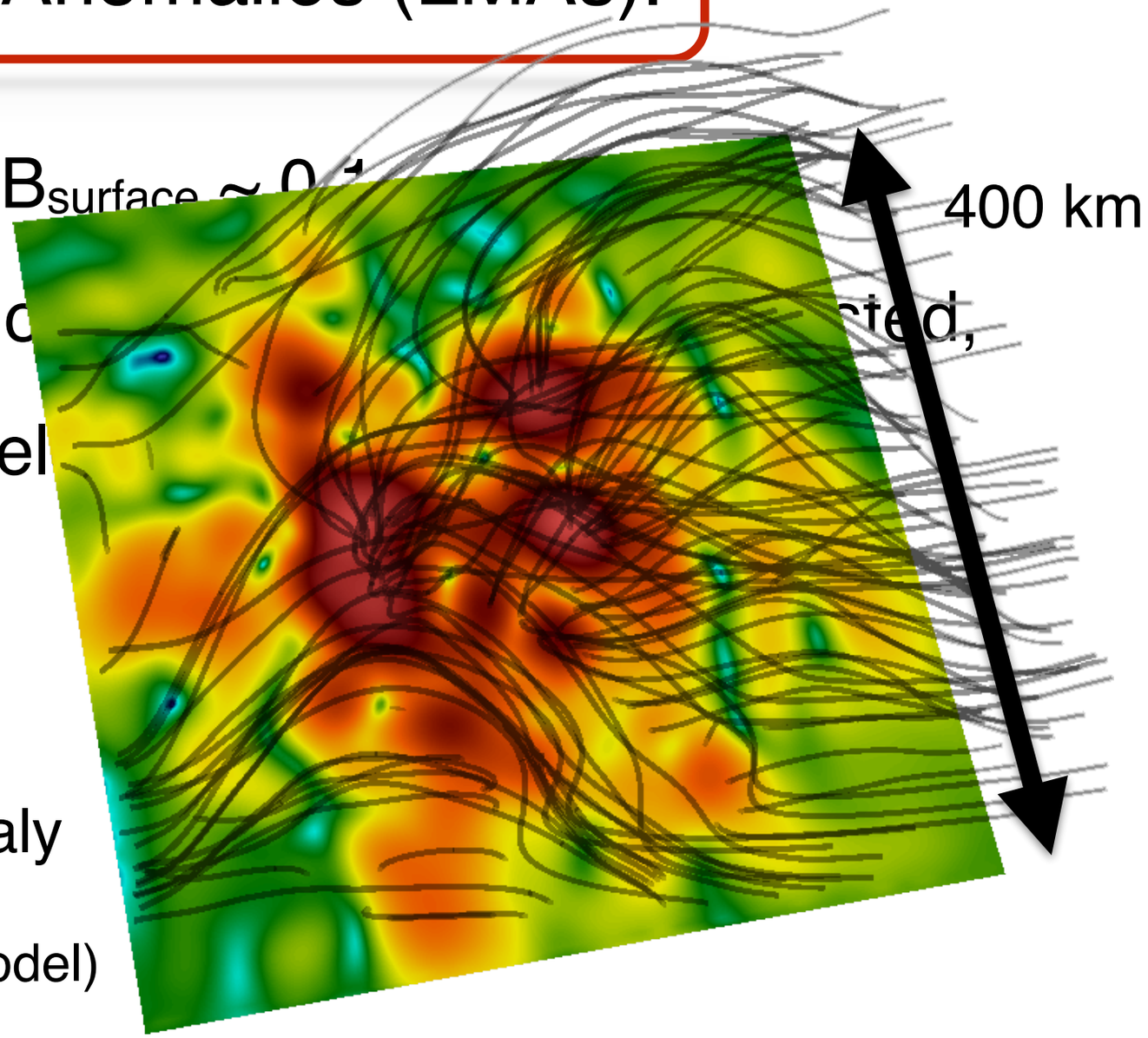
  - Origin is unclear, correlatic ted,

    ion reflection, surface shiel



Gerasimovich anomaly
(Generated using the
Tsunakawa et al. 2015 model)

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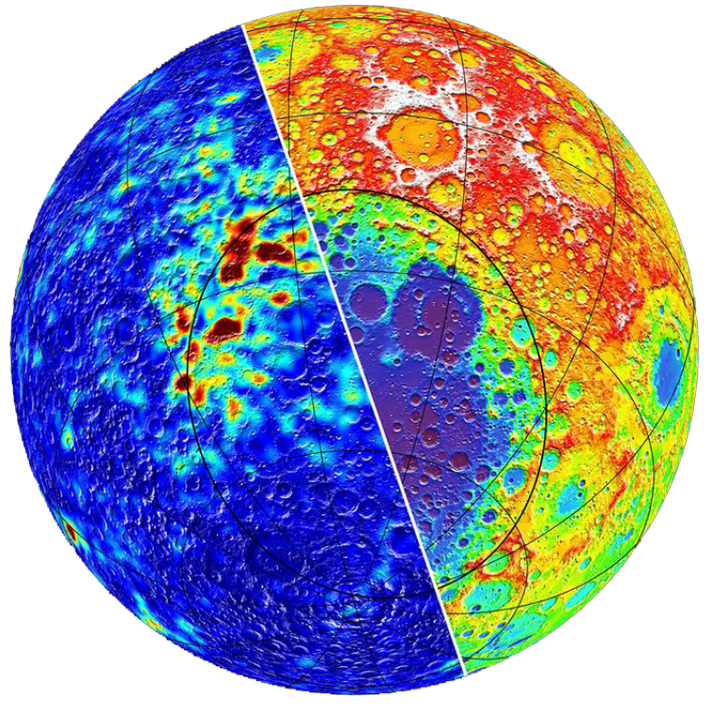

Lunar swirls

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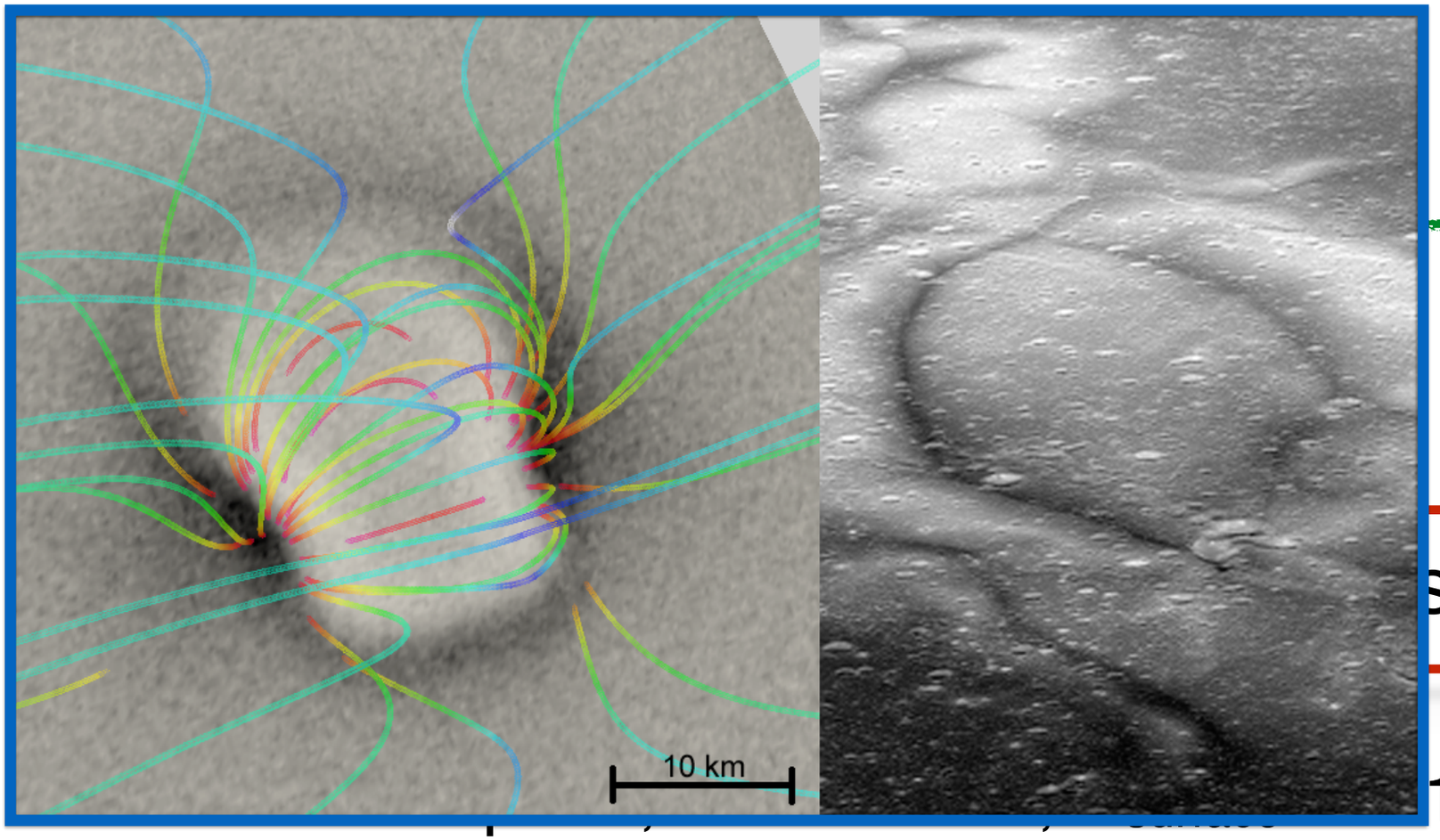
- All lunar swirls - the peculiar high-albedo markings on the Moon's surface - have been associated with LMAs. [Pieters&Noble 2016]
- <u>The opposite does **NOT** hold.</u>

- Three competing formation mechanisms:

1. Solar wind standoff. [Hood&Schubert 1980, Glotch et al. 2015]
2. Recent cometary and micrometeoroid impacts. [Pinet et al. 2000, Starukhina&Shkuratov 2004]
3. Electrostatic levitation and redeposition of high-albedo, fine-grained, feldspar-enriched dust. [Garrick-Bethell et al. 2011]

☑ *Why not bit of everything?*



but does possess

s (LMAs).

1nT -> 1000nT.

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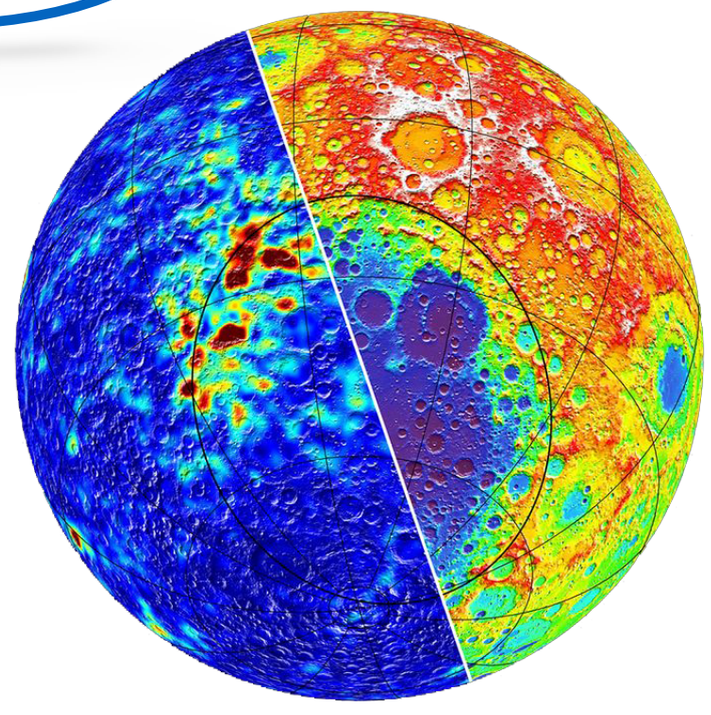
Solar wind standoff mechanism ?



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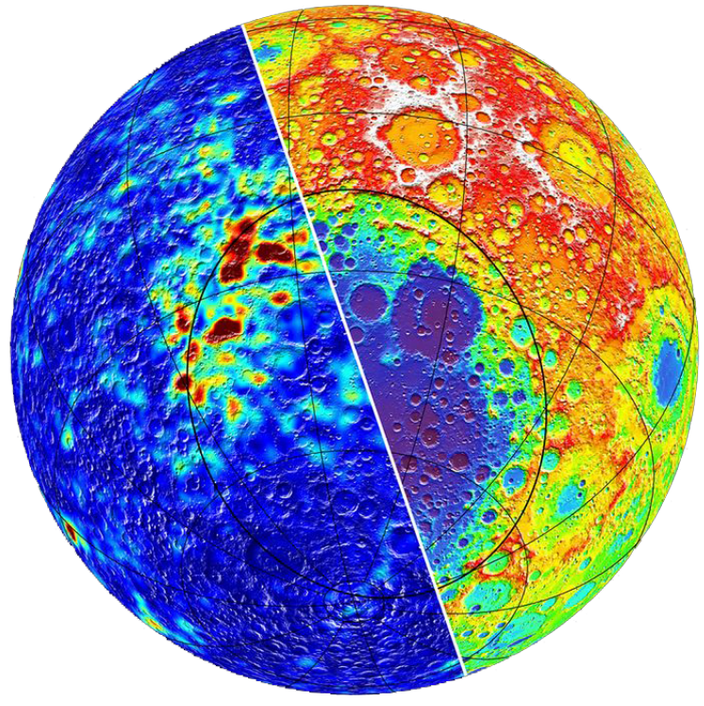

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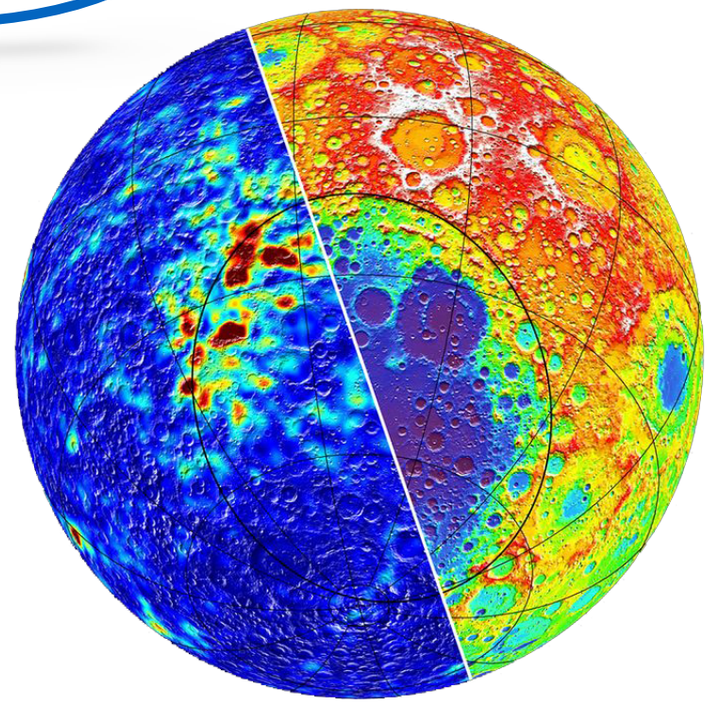

Reiner Gamma

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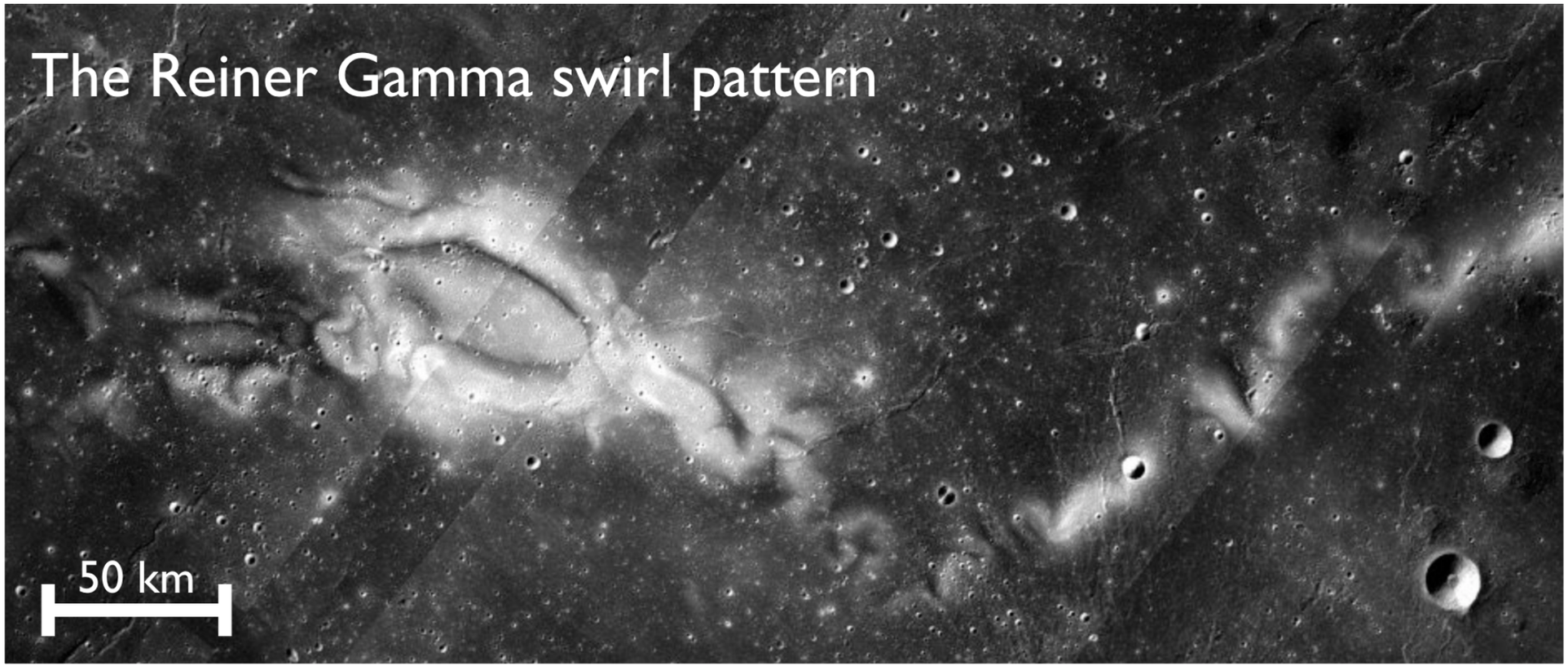
- Tadpole-shaped albedo marking found on the Oceanus Procellarum. Discovered during the Renaissance.
- Co-located with one of the strongest LMAs on the Moon (~500nT).
- Reasonably approximated by 2 horizontal dipoles [Kurata et al. 2005], or a series of many [Poppe et al. 2016].



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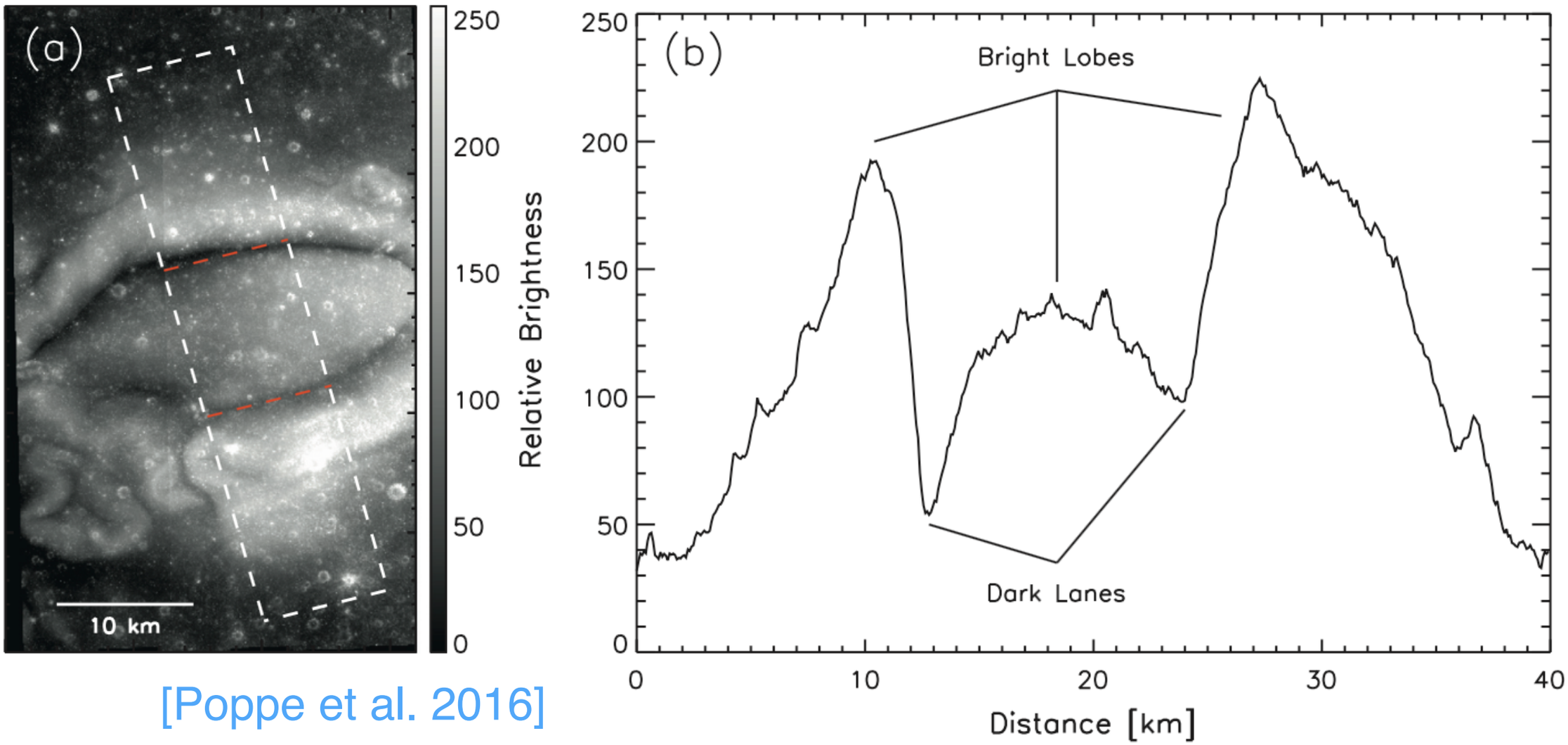

[Poppe et al. 2016]

Simulating LMAs

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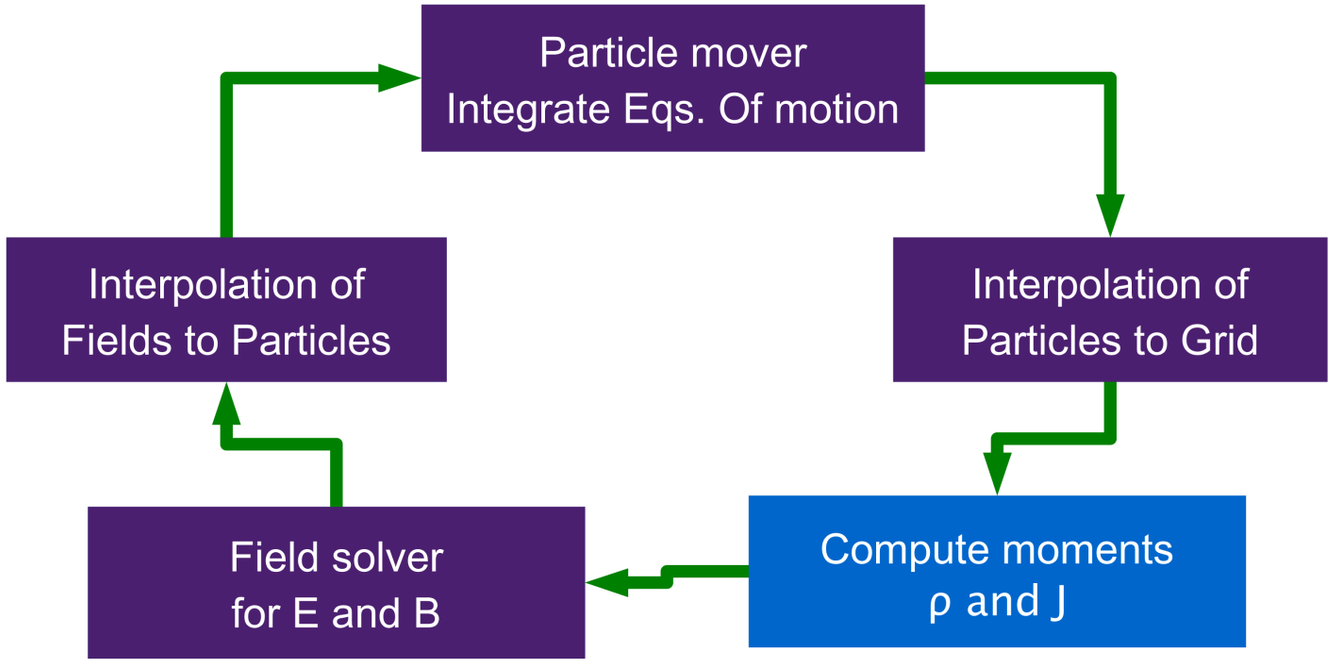
- Fully kinetic electromagnetic approach using **iPic3D,** the semi-implicit particle-in-cell code. [Markidis et al. 2012]
  - + Open boundaries. [Deca et al. 2015]
  - + Observed magnetic field model. [Tsunakawa et al. 2015]



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

The implicit PIC method

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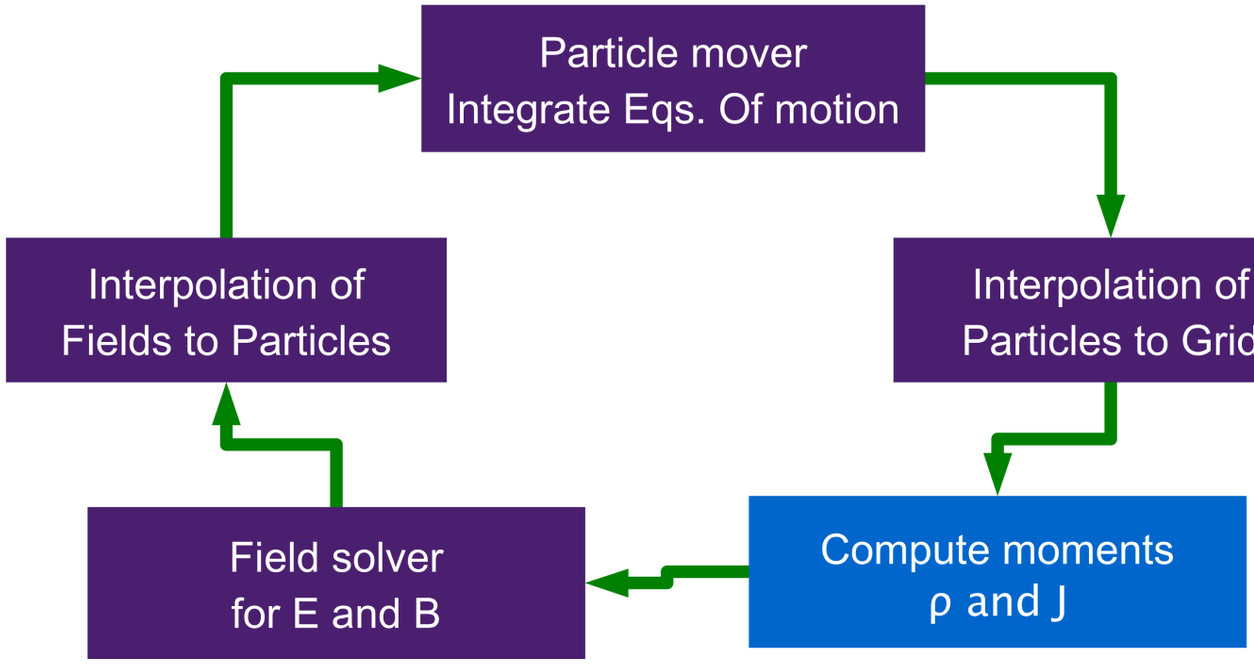
- A semi-implicit scheme,
  i.e., iPic3D.

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



	Explicit	Implicit	Gain
Dx	λ_{De}=100 m	d_e=10 Km	100
Dy	λ_{De}=100 m	d_e=10 Km	100
Dz	λ_{De}=100 m	d_e=10 Km	100
Dt	$\omega_{pe}\Delta t$=0.1 or 10^{-5}s	$\omega_{pe}\Delta t$=100 or 10^{-3}s	1000
Tot			10^9

An implicit
run that takes 1 day
would take 2,800,000 years
with an explicit code!

The magnetic field model

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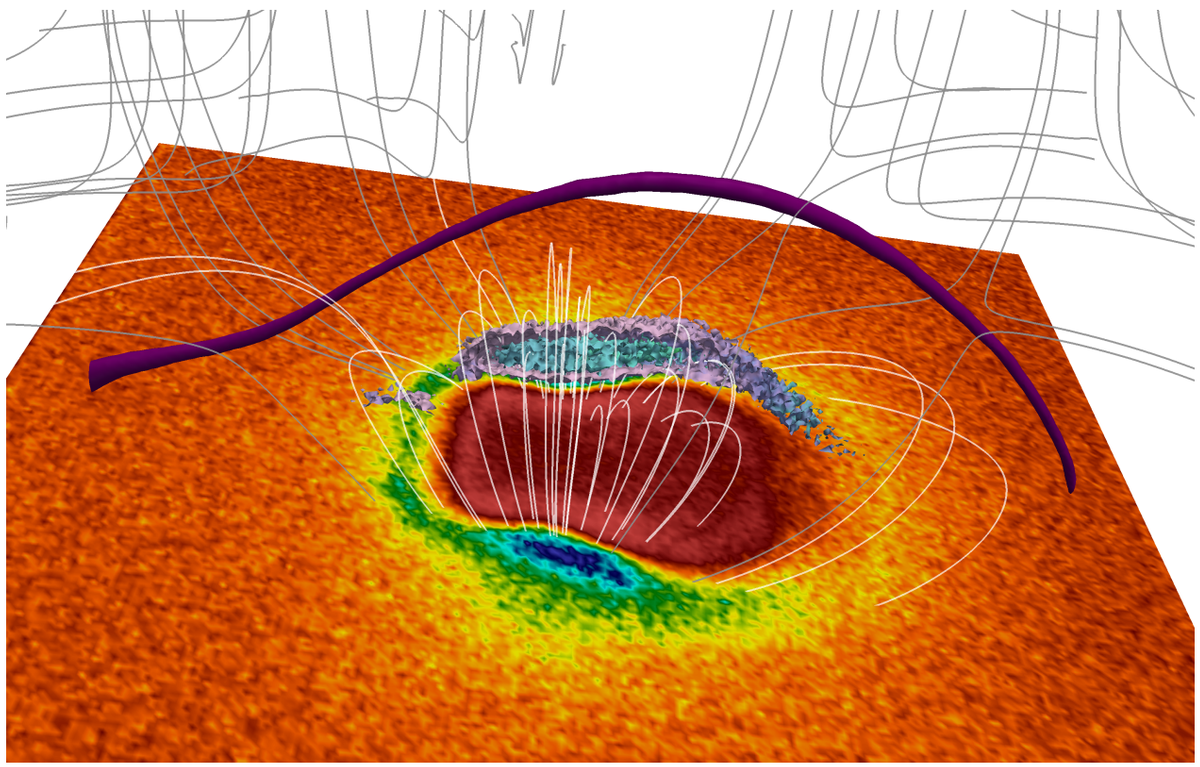
University of Colorado **Boulder**

- *Previously:* Simply (but therefore not simple) dipoles. [Deca et al. 2014->2016, Hemingway et al. 2015, Poppe et al. 2016, and many many others]
- *Now:* Observed magnetic field model:
  - Surface Vector Mapping about 5 million observations of the lunar magnetic field at 10-45 km altitude by Kaguya and Lunar Prospector. [Tsunakawa et al. 2015]
  - Corrected for solar wind pressure and IMF.

- Trustworthy at the surface?

- What about induced fields?



[Deca et al. 2014]

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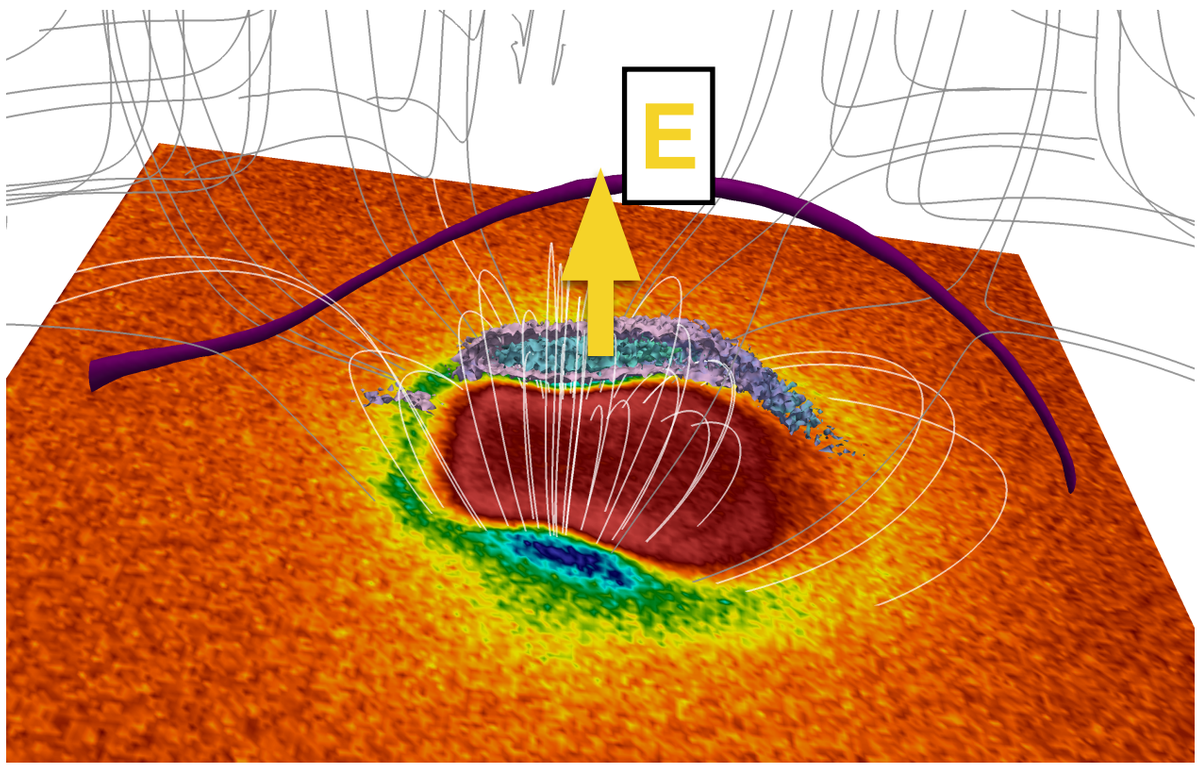
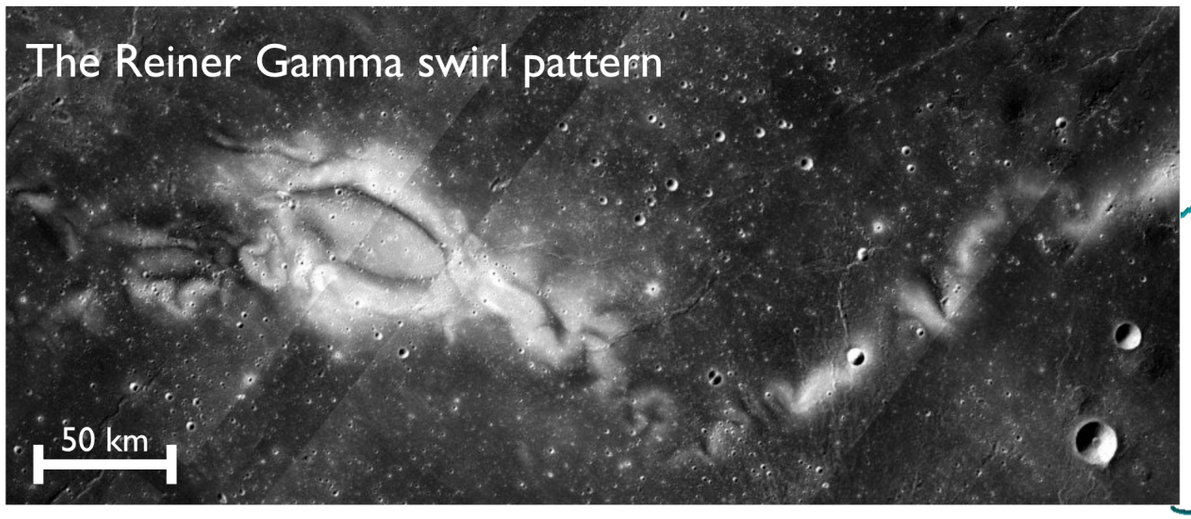
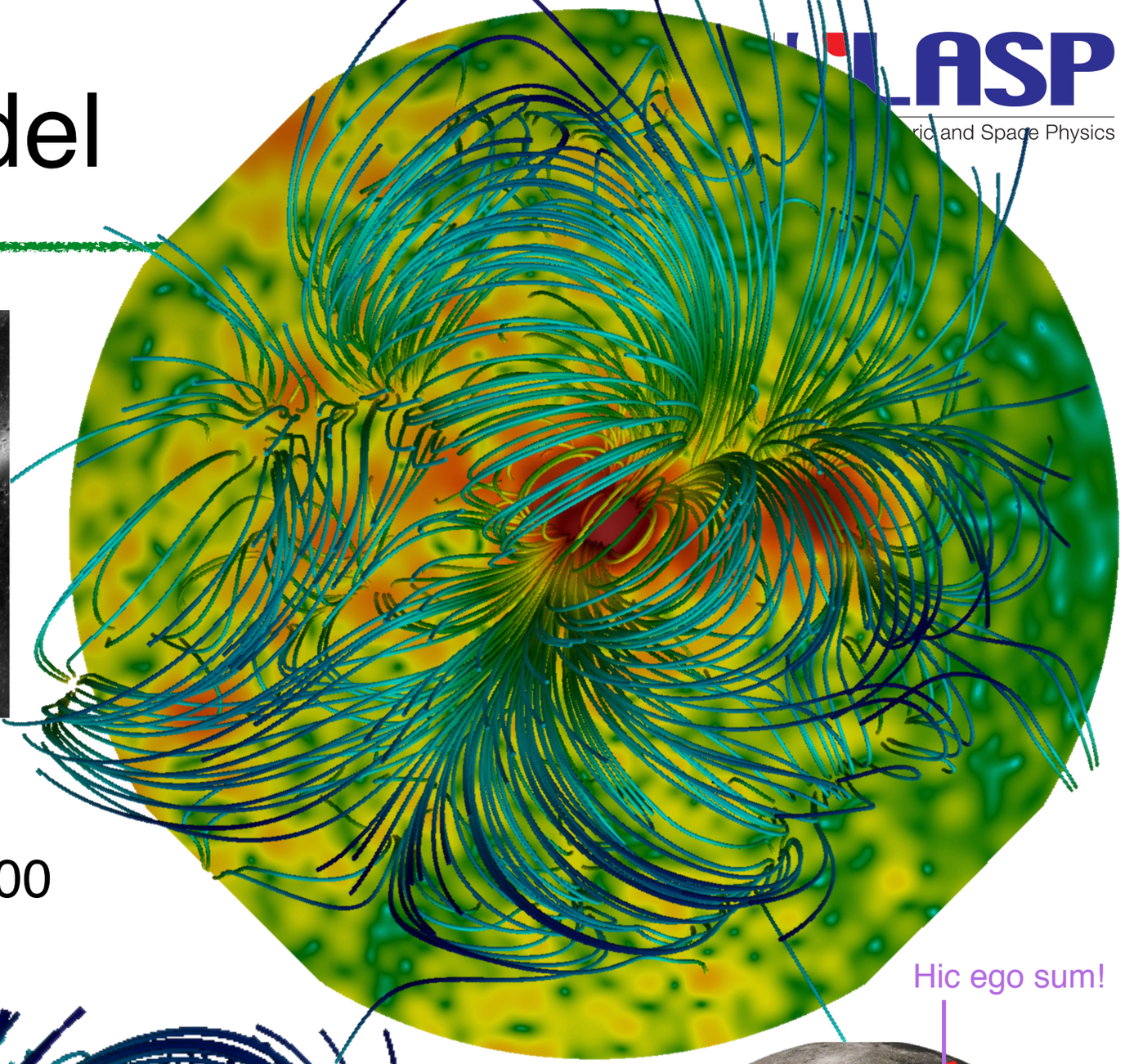


[Deca et al. 2014]

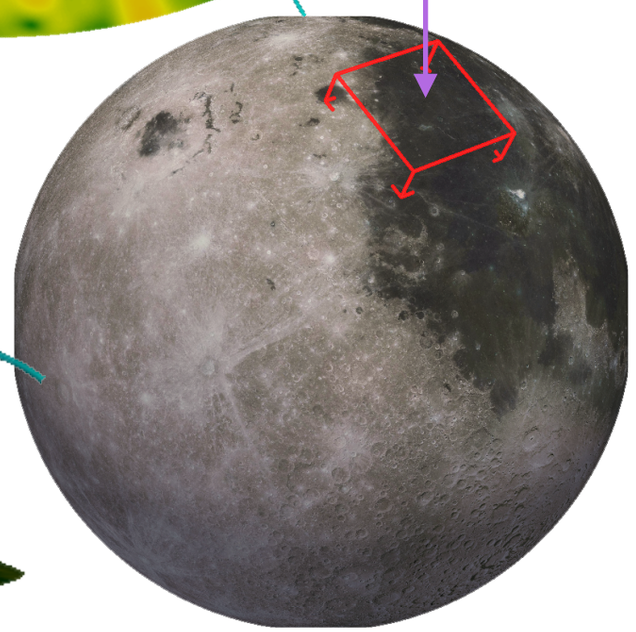
The Tsunakawa model





Magnetic field magnitude (nT)

0 0.5 5 50 500



Reiner Gamma (sort of…)

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- Steady-state situation.

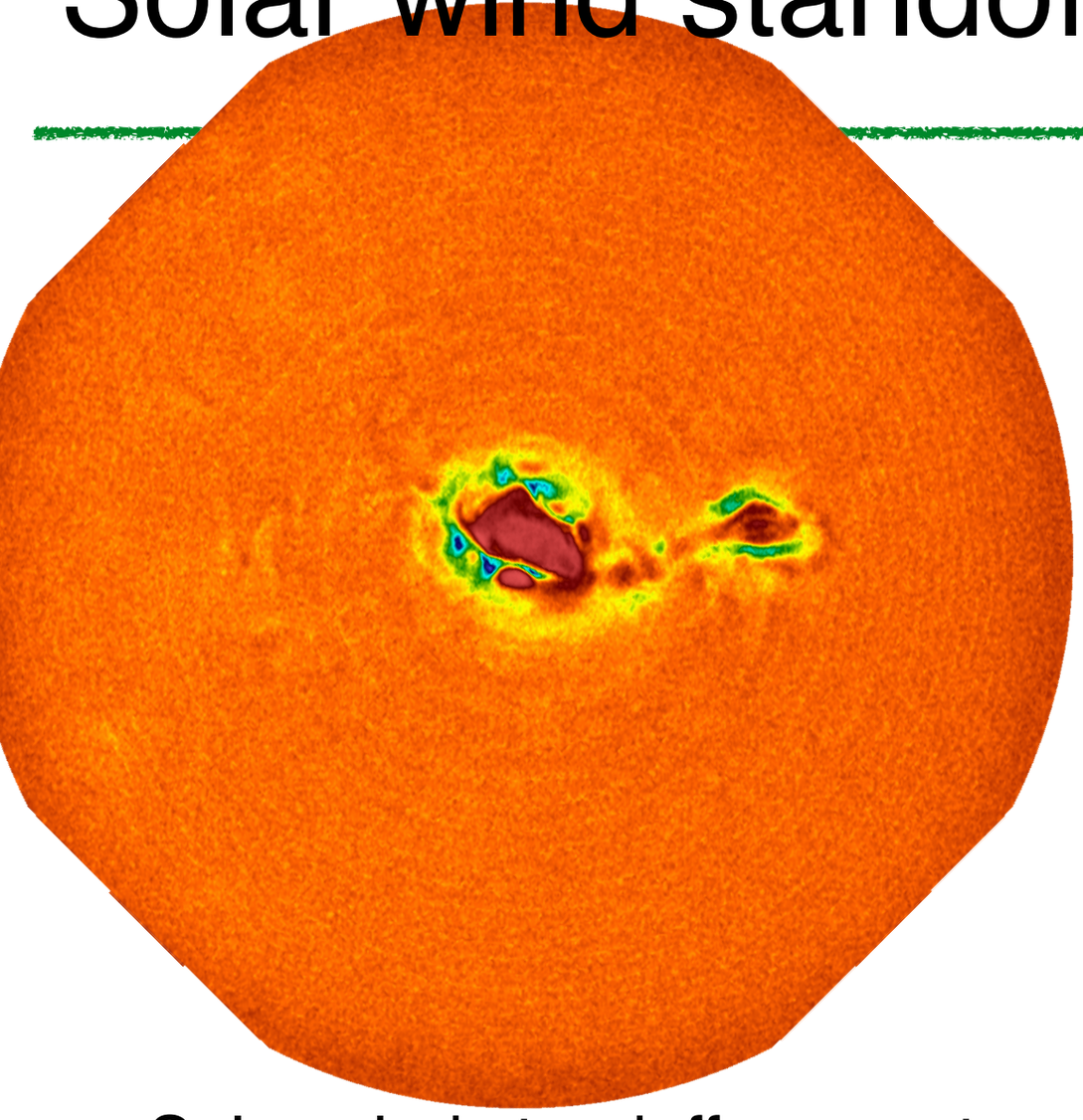
V_{SW}

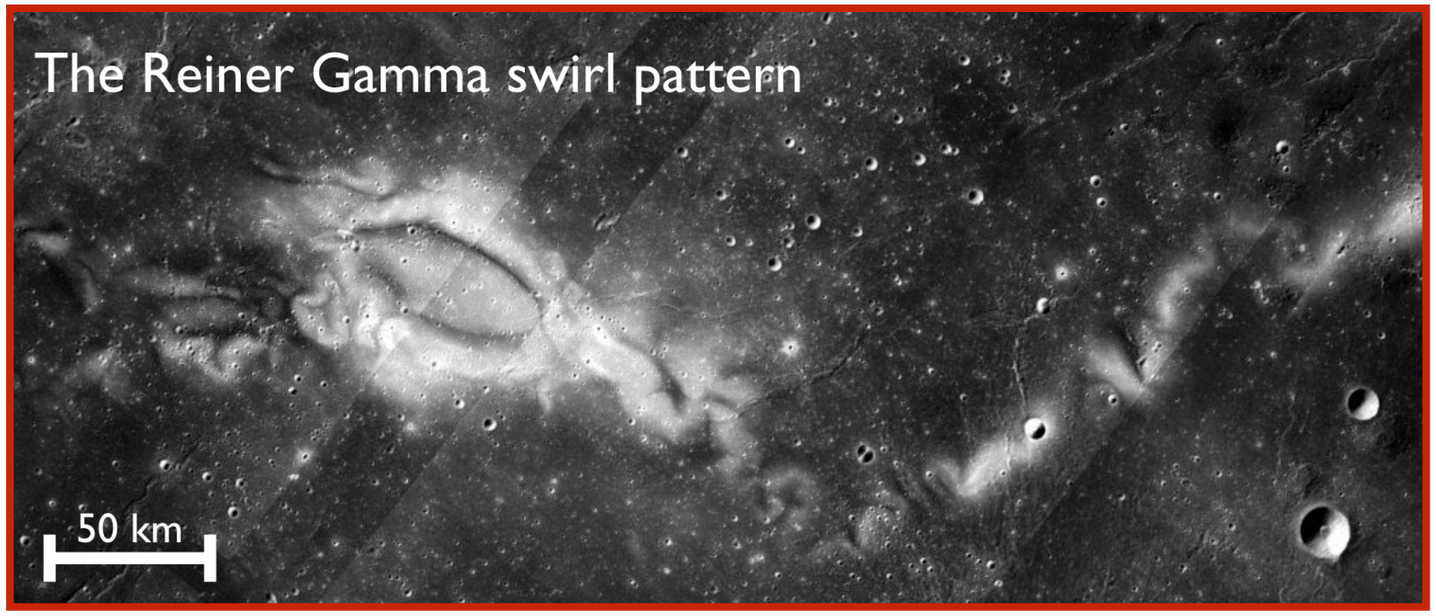
Ion charge density (norm. to n_{sw})

0.0
1.0
2.0
3.0
3.5

- Average SW conditions.

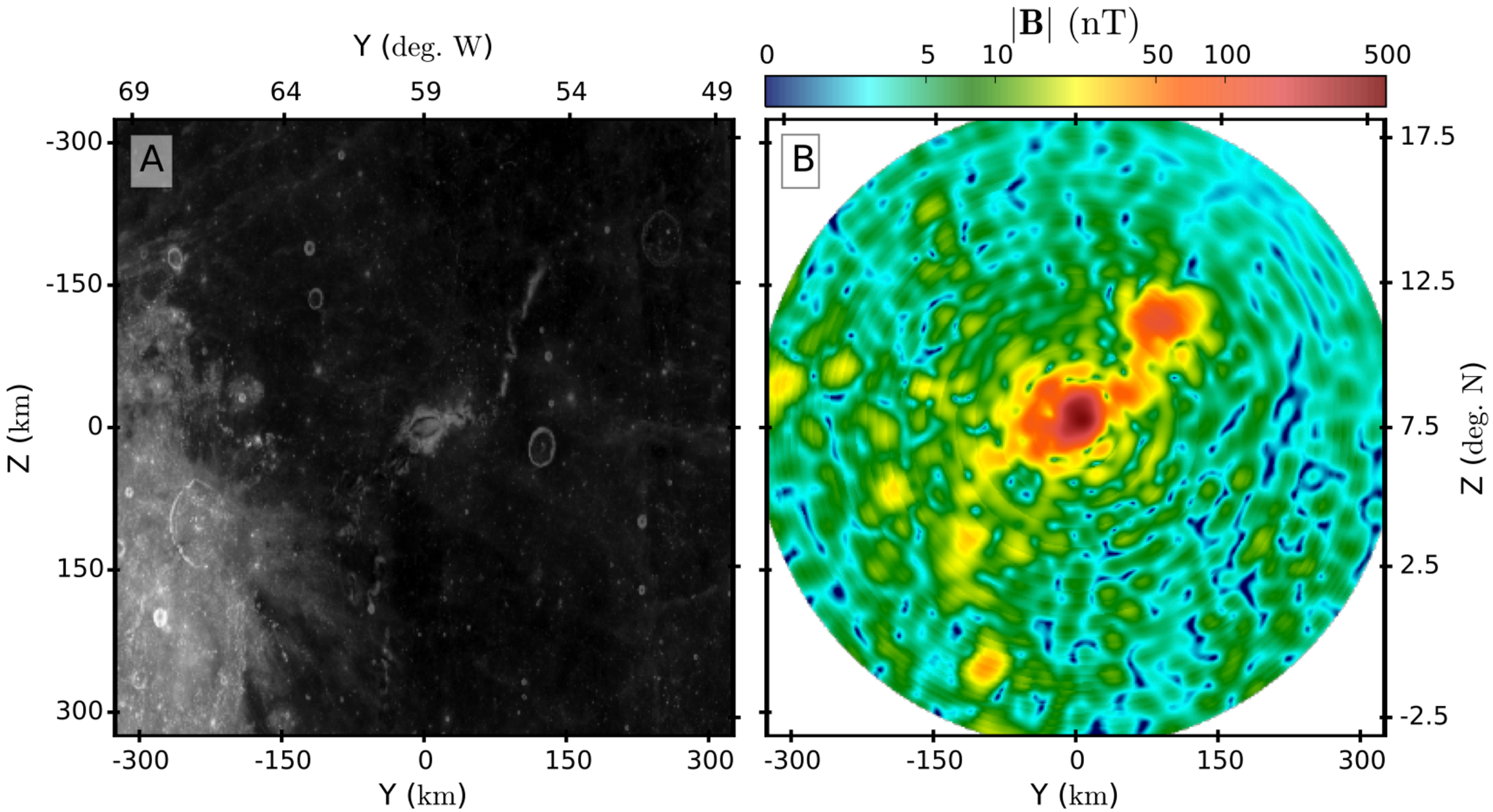
Solar wind standoff?





- Solar wind standoff seems to reproduce the main swirl features, supporting earlier evidence by Glotch et al. 2015, Hemingway et al. 2015, Poppe et al. 2016, …
- Small-scale features not reproduced. B-field not accurate enough? One of the other mechanisms responsible?
- *Higher density regions should be the darkest…*

Solar wind standoff?



- There might be one more issue…

Solar wind standoff?

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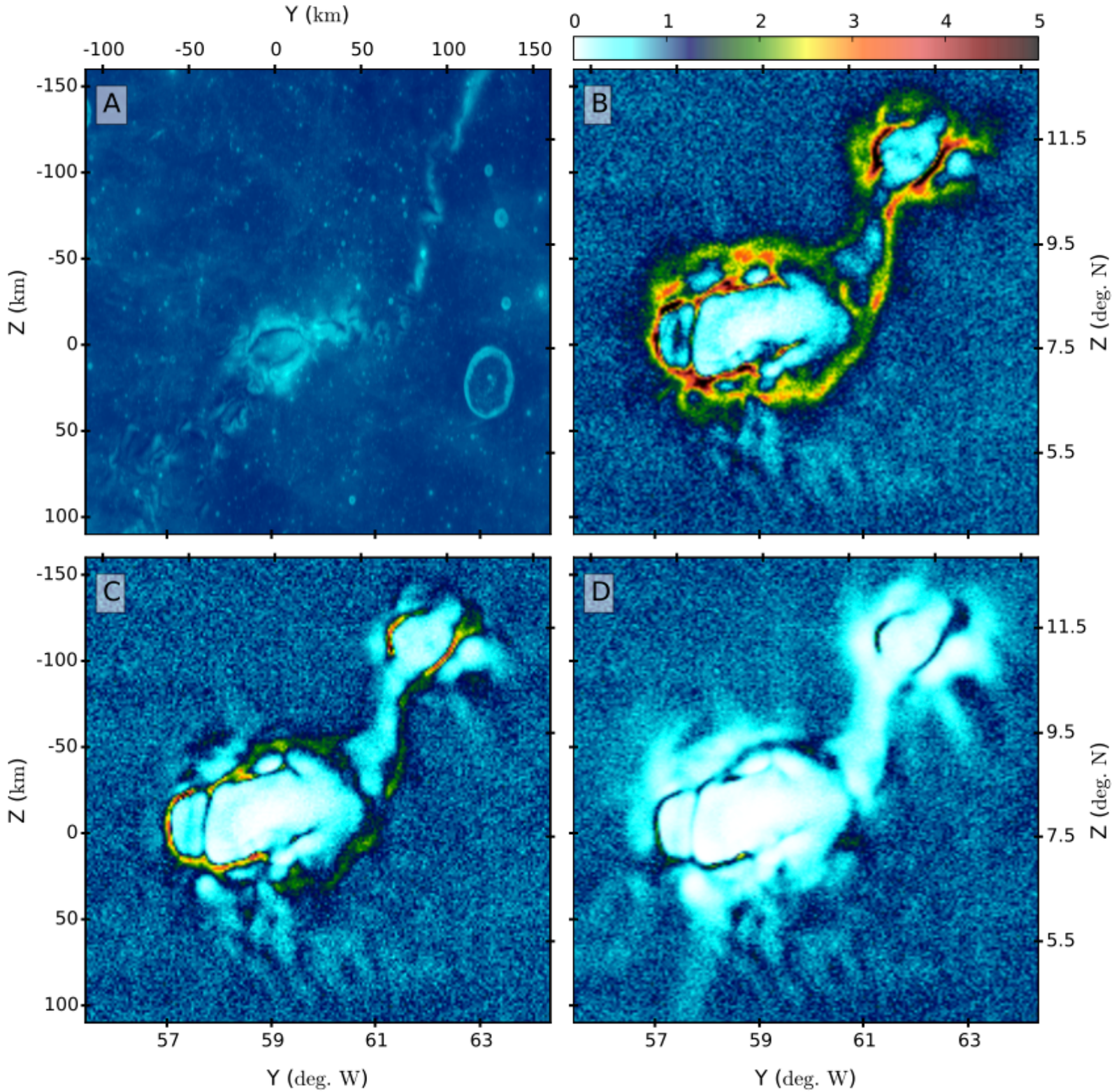
LRO-WAC



Surface ion number flux

Surface ion energy flux

Surface ion density

Solar wind standoff?

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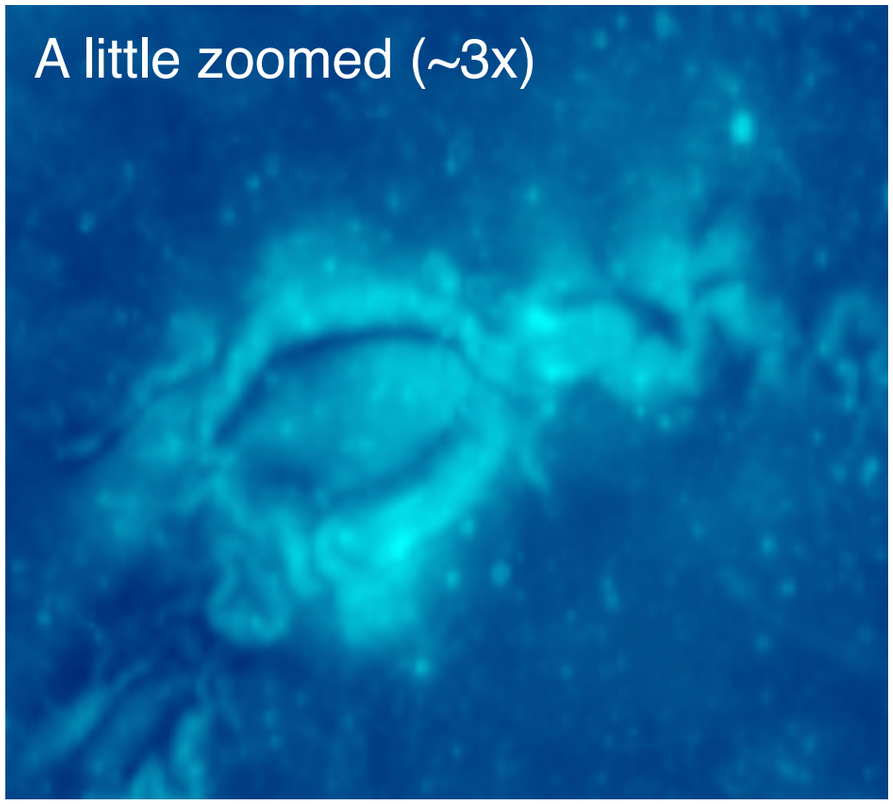
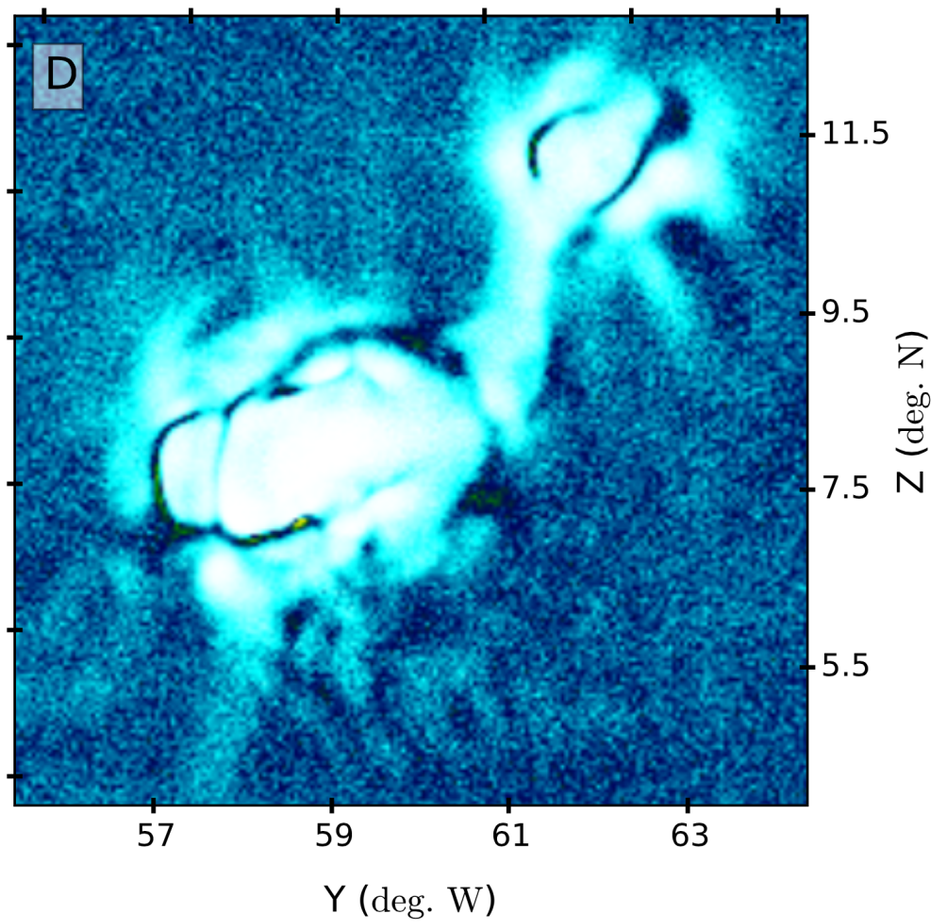
- Ion energy flux to the surface correlates best!
- What does this imply for the surface weathering mechanism?
- How about the other discrepancies?

	WAC	n	nv	nv^2	nv^3	WAC / nv^3
BG/OB	**0.18**	1.53	0.94	0.48	**0.46**	0.39
BG/IB	**0.27**	0.18	0.08	0.04	**0.22**	1.23
BG/DL	**0.50**	2.61	1.56	0.99	**0.65**	0.77
DL/OB	**0.36**	0.59	0.60	**0.48**	0.7	0.51
DL/IB	**0.54**	0.07	0.05	0.04	**0.34**	1.59
IB/OB	**0.66**	8.5	11.5	11.6	***2.09***	0.32





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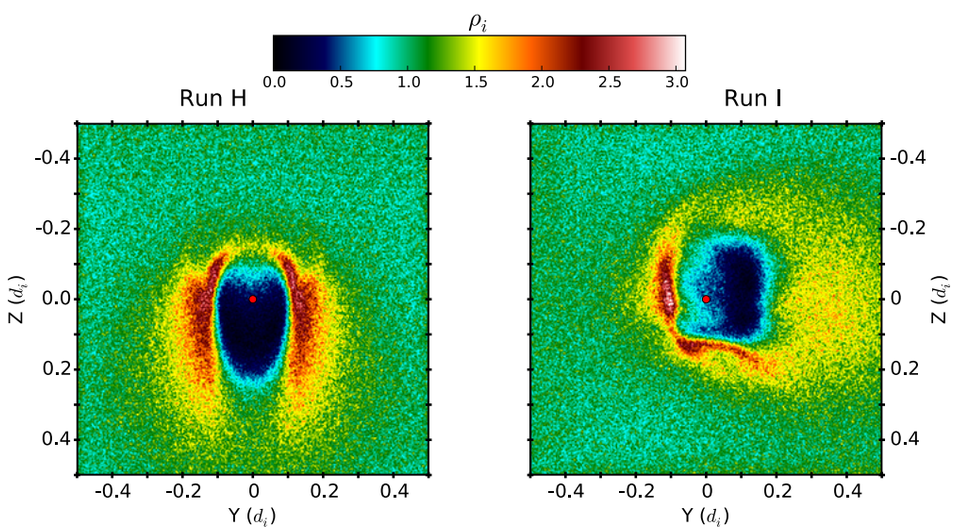

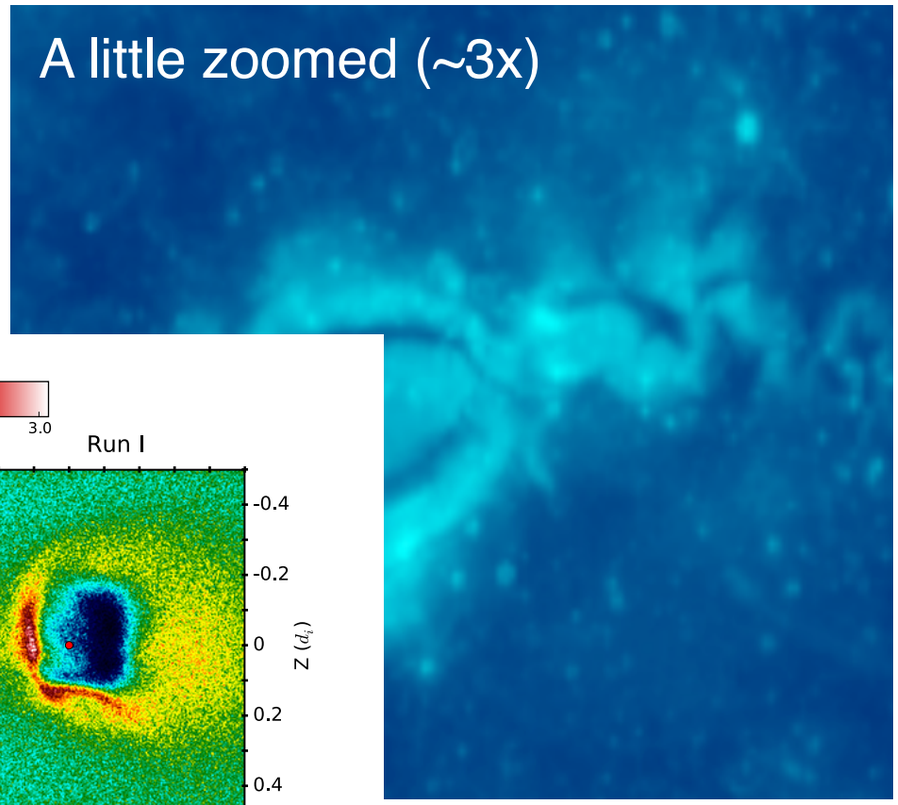

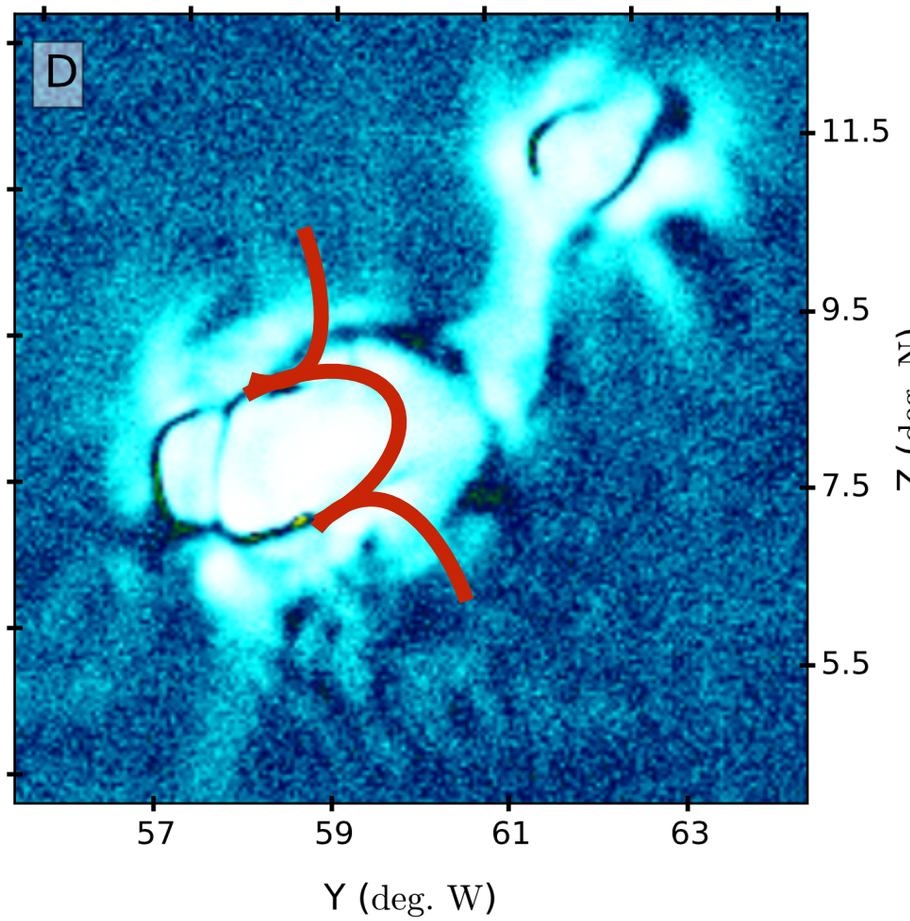

Reflected ion number flux

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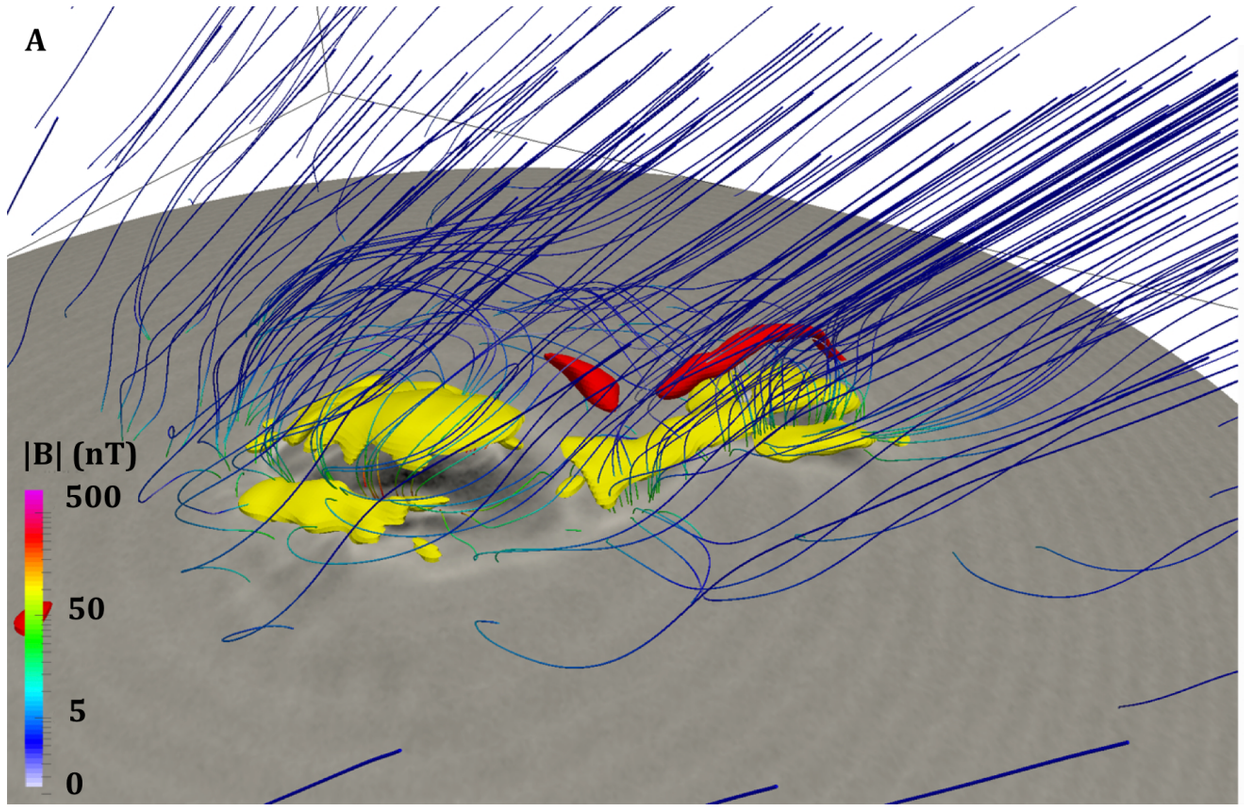
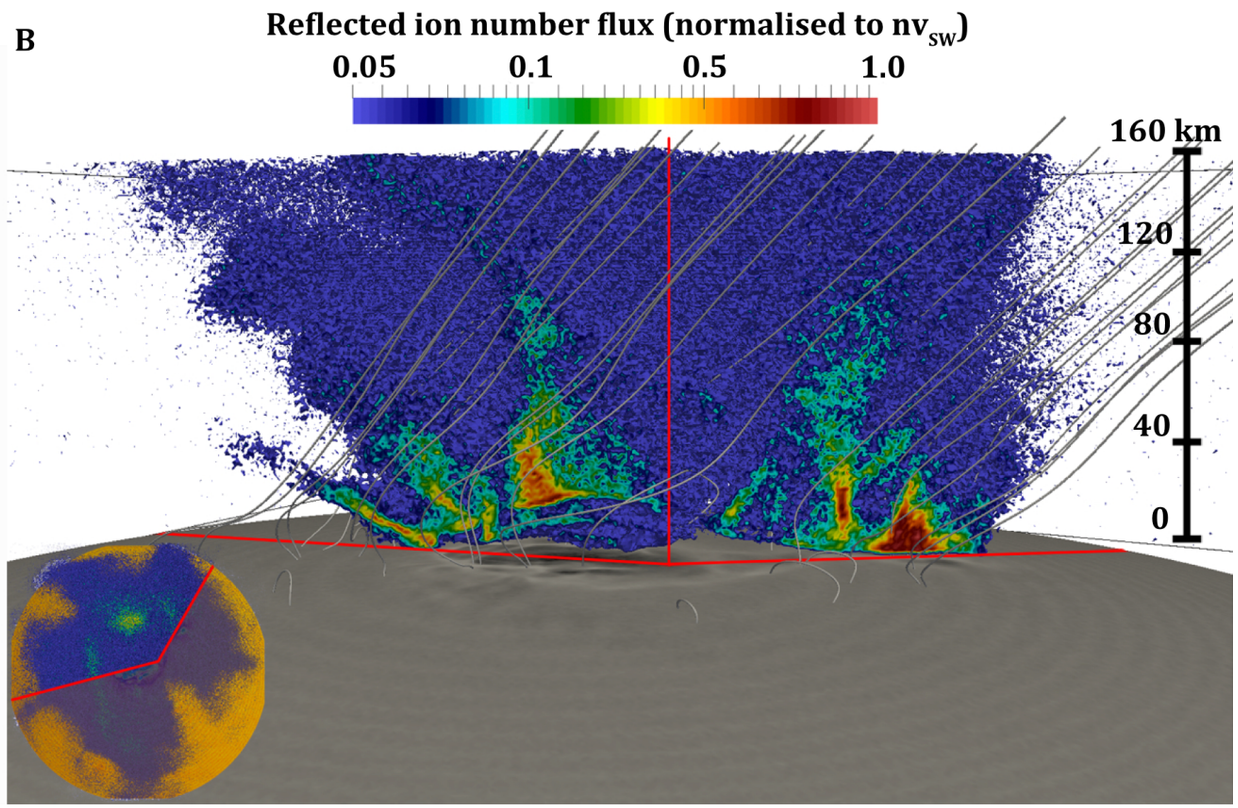
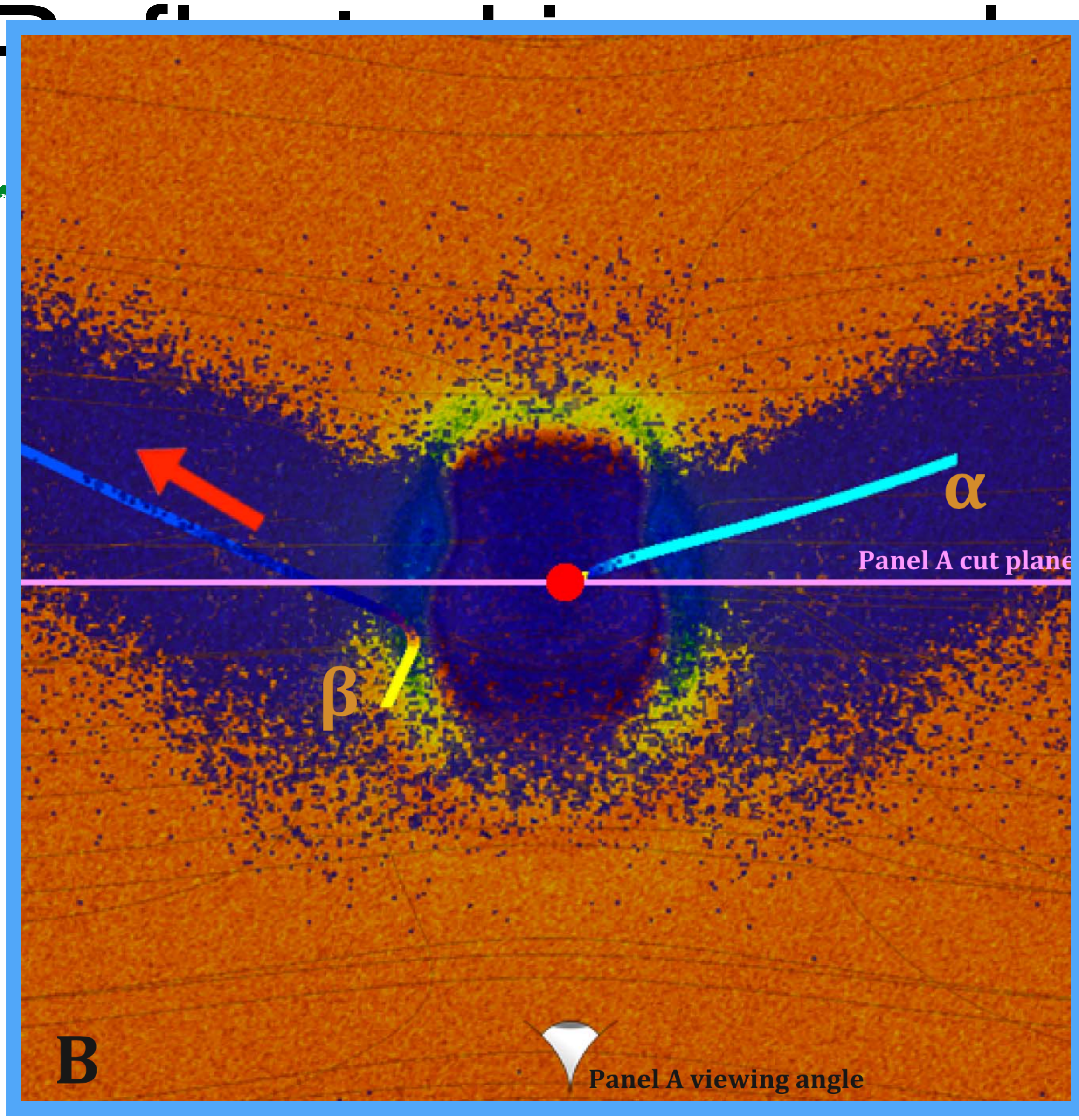
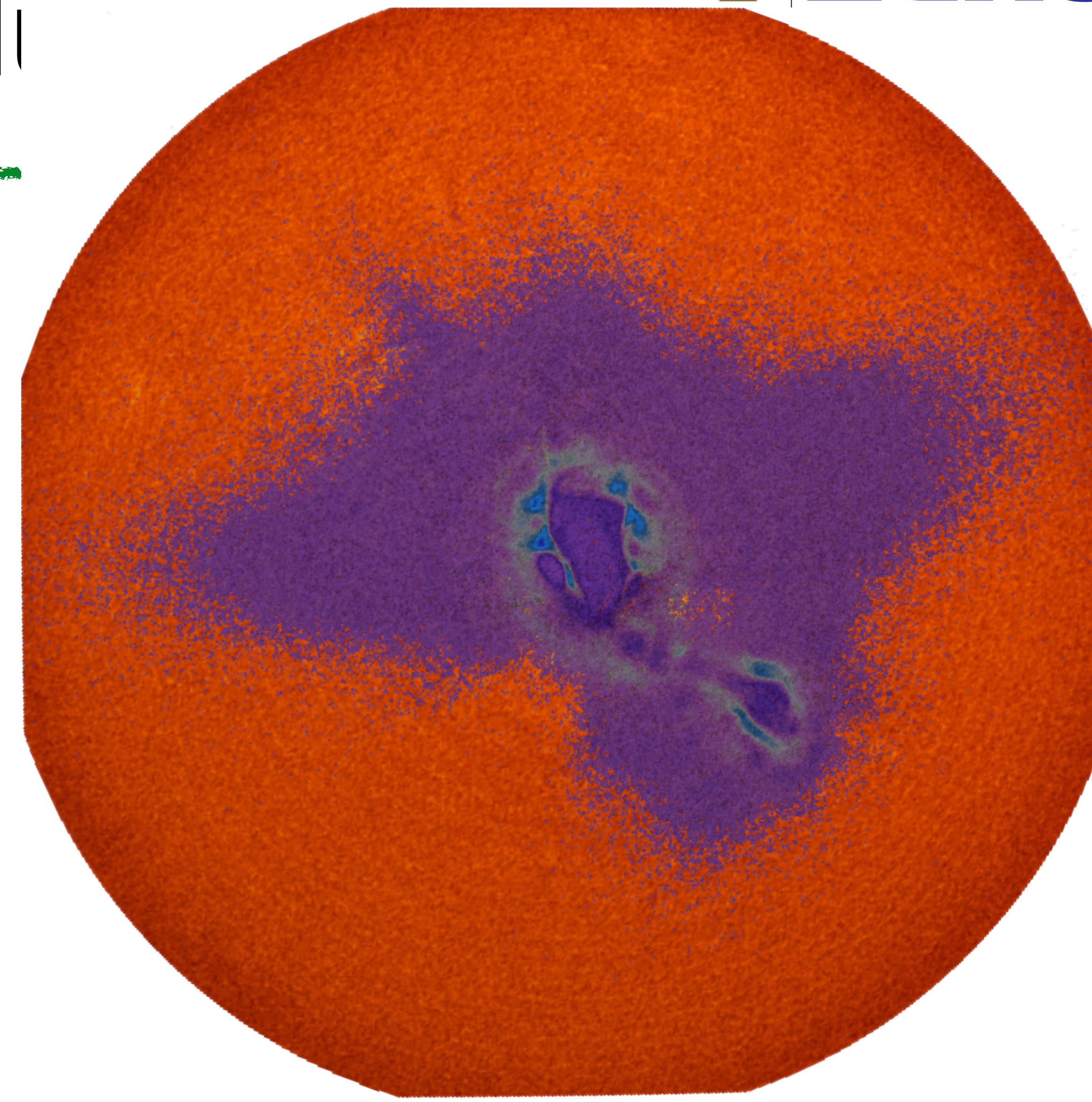




- Reflected flux not uniform, but focused along certain directions.
- To first order the reflected pattern resembles that of two horizontal dipoles located close to each other. [Deca&Divin 2016]





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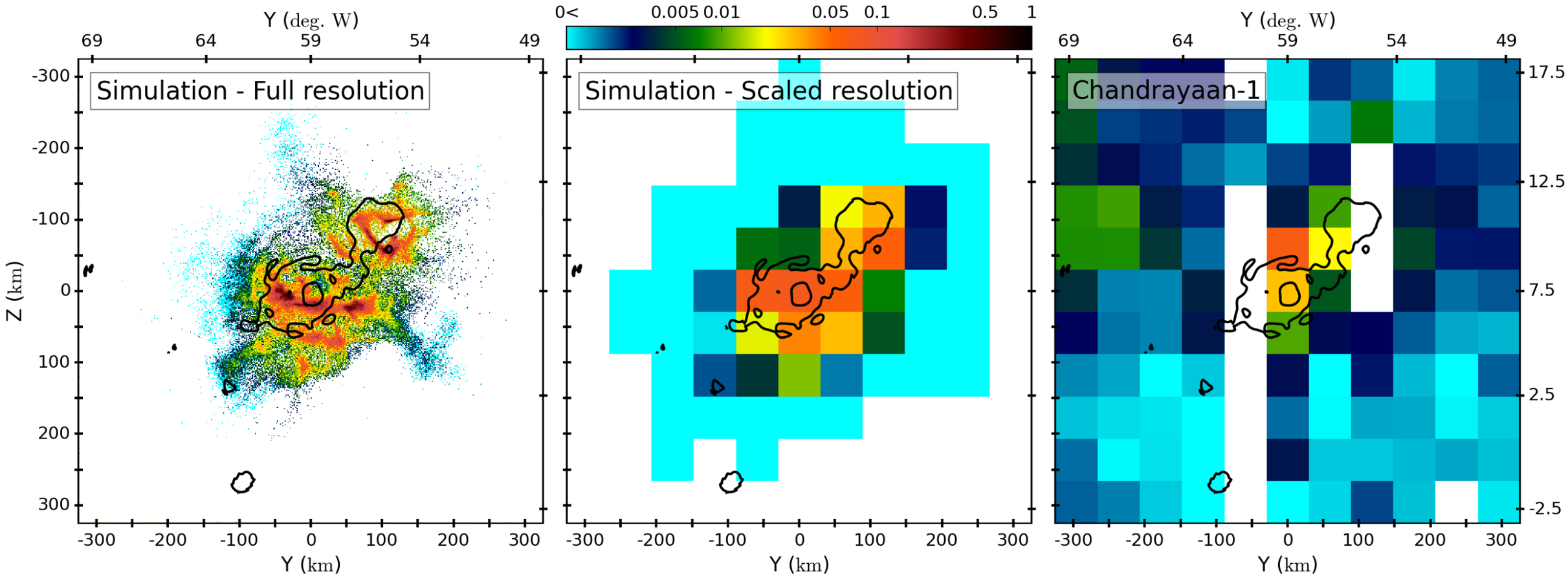

- Comparison with Chandrayaan-1 observations:
  - Maximum observed flux similar (~7%).
  - Simulations seem to predict a much wider pattern.

Charles' magic

- *How do other spacecraft compare?*

Take-aways.

Simulations are fun, use them!

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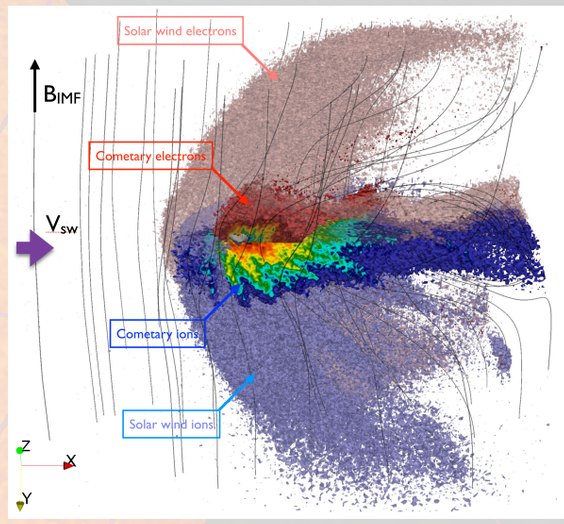
- First fully kinetic electromagnetic simulations of the solar wind interaction with the observed crustal magnetic field.
- We reproduce the large-scale features of the Reiner Gamma swirl region.
- We reproduce the observed ion number fluxes from Chandrayaan.
- We confirm solar wind standoff to have formed lunar swirls.
- Need more/better data if we would like to resolve the finer structure.



Poster teaser: Simulations of comet 67P/ Churyumov-Gerasimenko at 3.0 AU.

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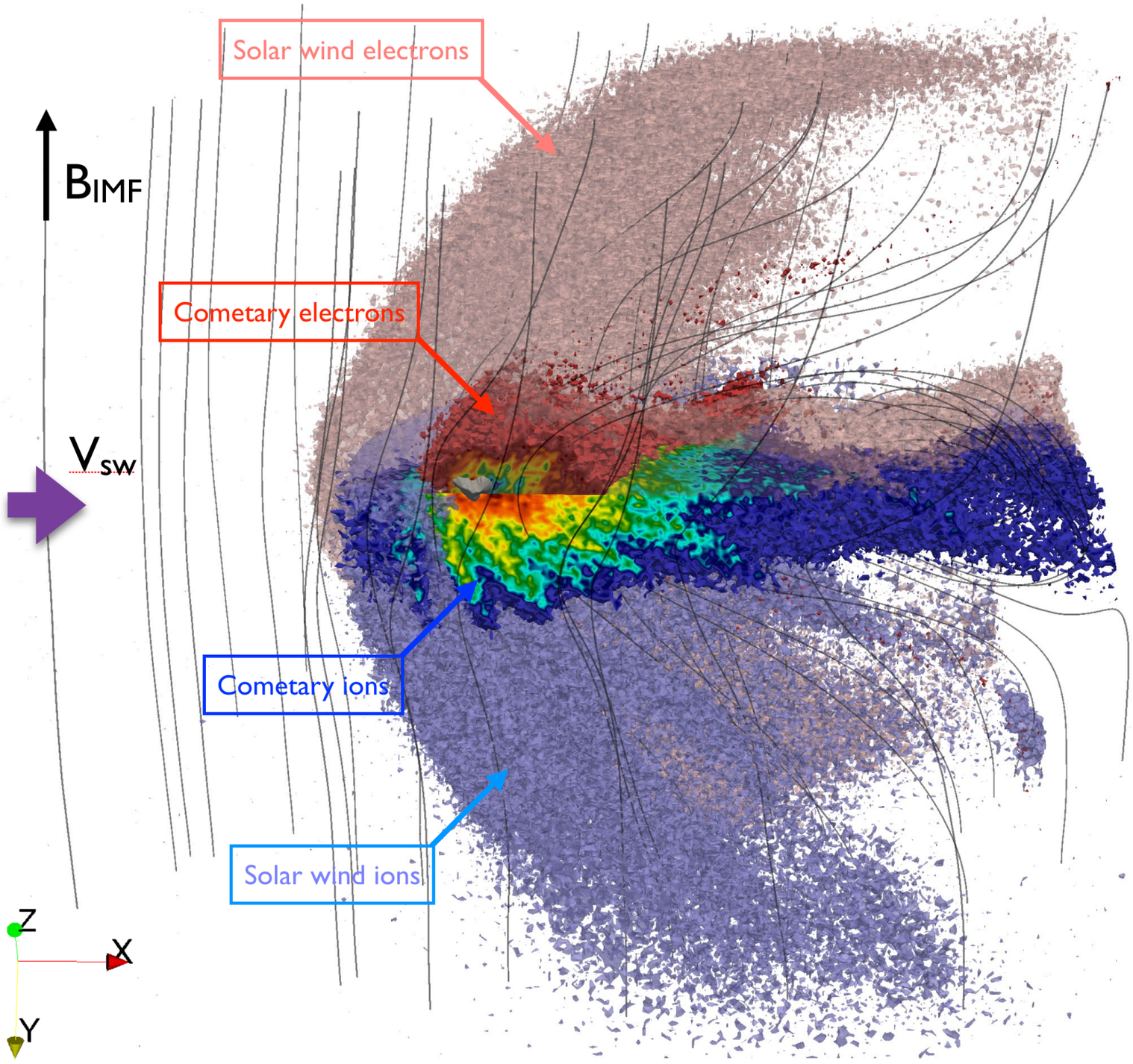
- First **3-D fully kinetic electromagnetic** particle-in-cell simulations.

- Showing that **a multi-species electron-kinetic description is a must** to fully capture the complex global solar wind - comet interaction process.

- Provide **vital information to disentangle the observations** made by the Rosetta instruments, in particular regarding the collisionless electron physics.



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