LEM and M-SWCX

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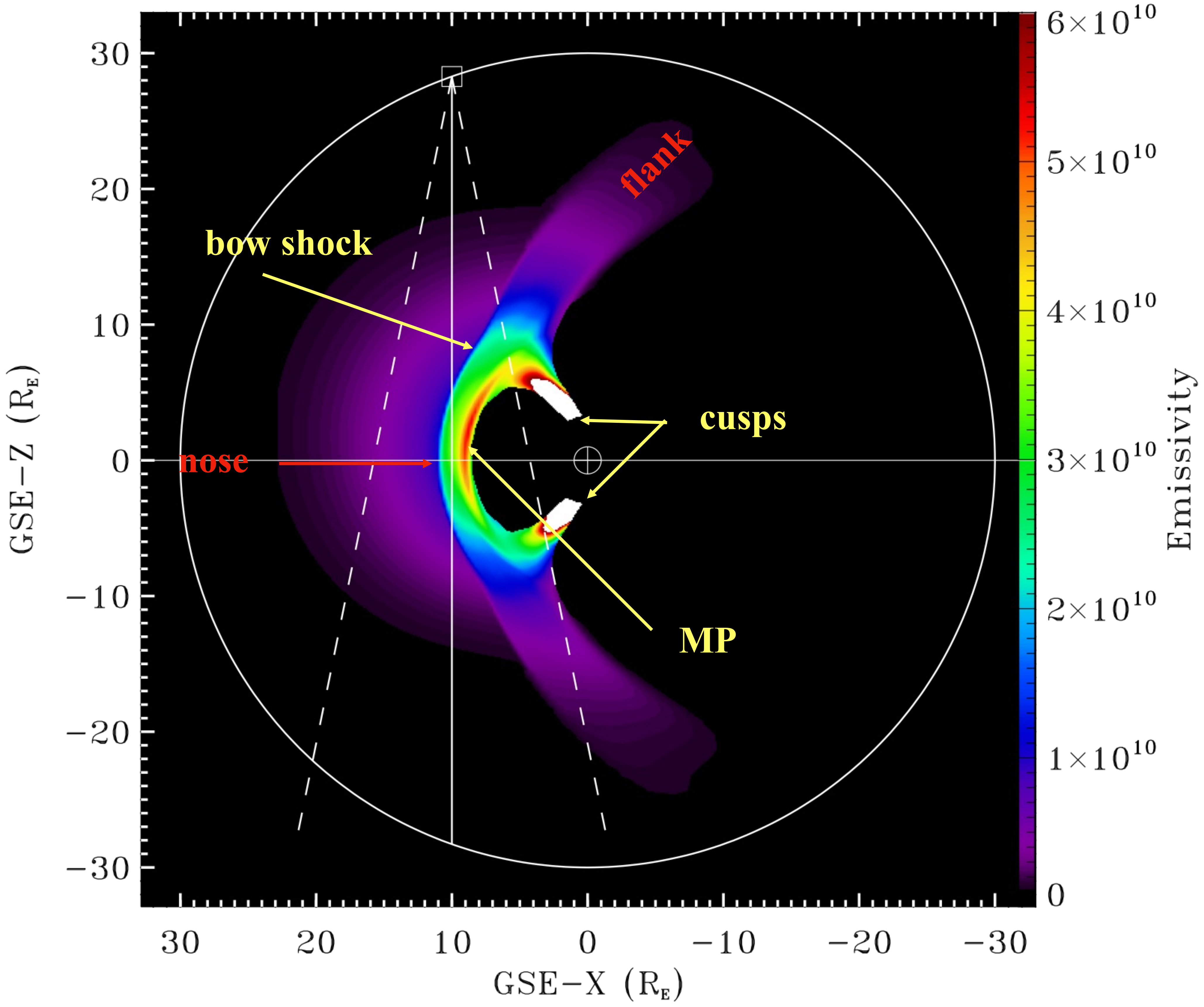
Intro to the Magnetosheath

SWCX in the Earth's exosphere:

- neutral targets mostly H in the exosphere,
- solar wind ion density increased by 4× due to shock
- strongest emission in cusps and magnetopause (MP)
- emission strongest along tangent to the MP
- emission has a broad spread of velocities

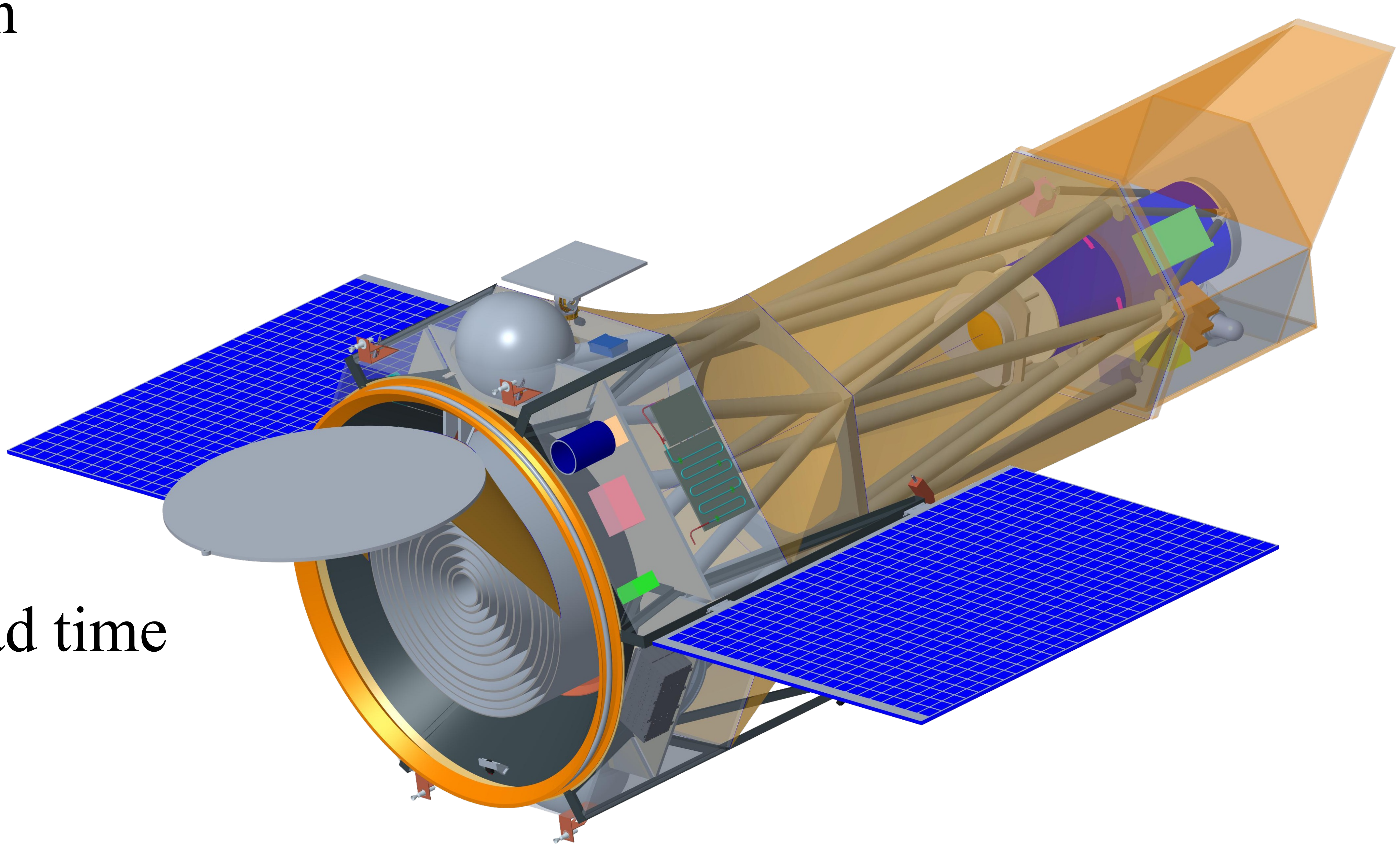
Magnetosheath is the brightest source of SWCX!

First observed by ROSAT as the "LTE"s.



Line Emission Mapper

- A proposed mission to study faint, extended X-ray emission in 0.2–2 keV band with high spectral resolution
- Large-area Si-shell X-ray mirror (Wolter type optic)
  - 1.5 m diameter, 4 m focal length
  - 10″ HPD PSF
- X-ray microcalorimeter array
  - 30′×30′ FOV
  - 15″ pixels
  - 1-2 eV resolution
  - Possibly E down to 0.1?
- 1600 cm^2 at 0.5 keV
- TOO opportunities w/ 48 hour lead time
- L1 orbit



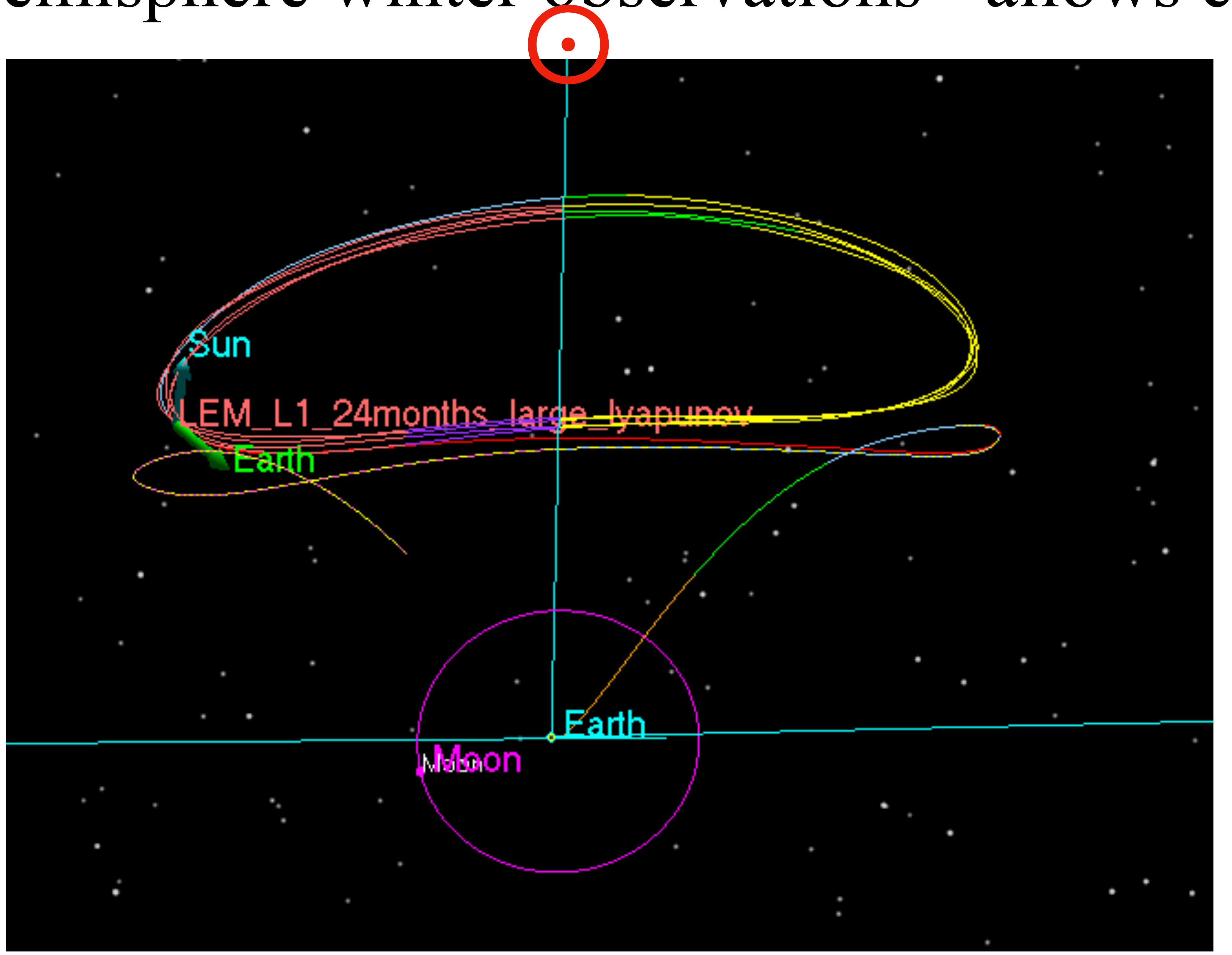
Mission Comparison

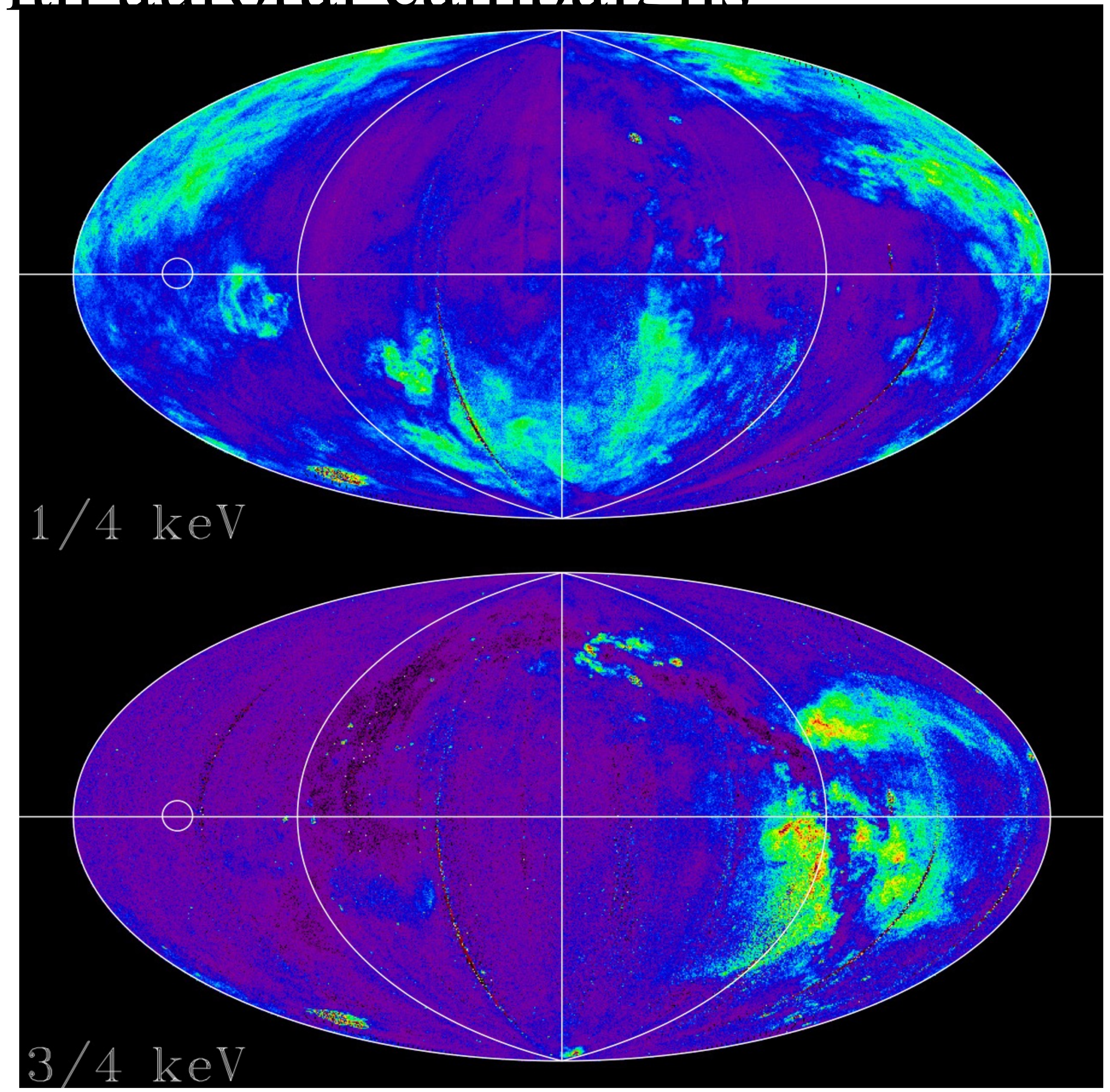
	XMM	eROSITA	LEM	XRISM Resolve	ATHENA XIFU	HUBS
Energy band, keV	0.3-11	0.1?-11	0.2–2	0.4–12	0.2–12	0.2–2
Effective area, cm^2 0.5 keV	700	700	1600	50	6000	500
Effective area, cm^2 6 keV			0	300	2000	0
Field of view (Equiv. Square)	26’	53’	30'	3'	5'	60'
Grasp, 10^4 cm^2 $arcmin^2$	50	216	140	0.05	12	180
Angular resolution		7.6-9.2’’	15"	75"	5"	60"
Spectral resolution (FWHM)	~40 eV (0.5 keV)	56-65 eV (0.5 keV)	1 eV central 7x7' 2 eV rest of FOV	7 eV	3 eV	2 eV
Detector size (equiv. pixels)			118 x 118	6 x 6	50 x 50	60 x 60

The Orbit

Lyapunov Quasi-Halo, kidney shaped orbit in GSE Z=0 plane

- Maximal GSE Y extent ~ 47º, with R~330 R_E
- Extremes for four ~month-long periods each year
- View Earth against ecliptic equator (±20º) - relatively smooth background for North Hemisphere winter observations - allows coordination with auroral campaigns

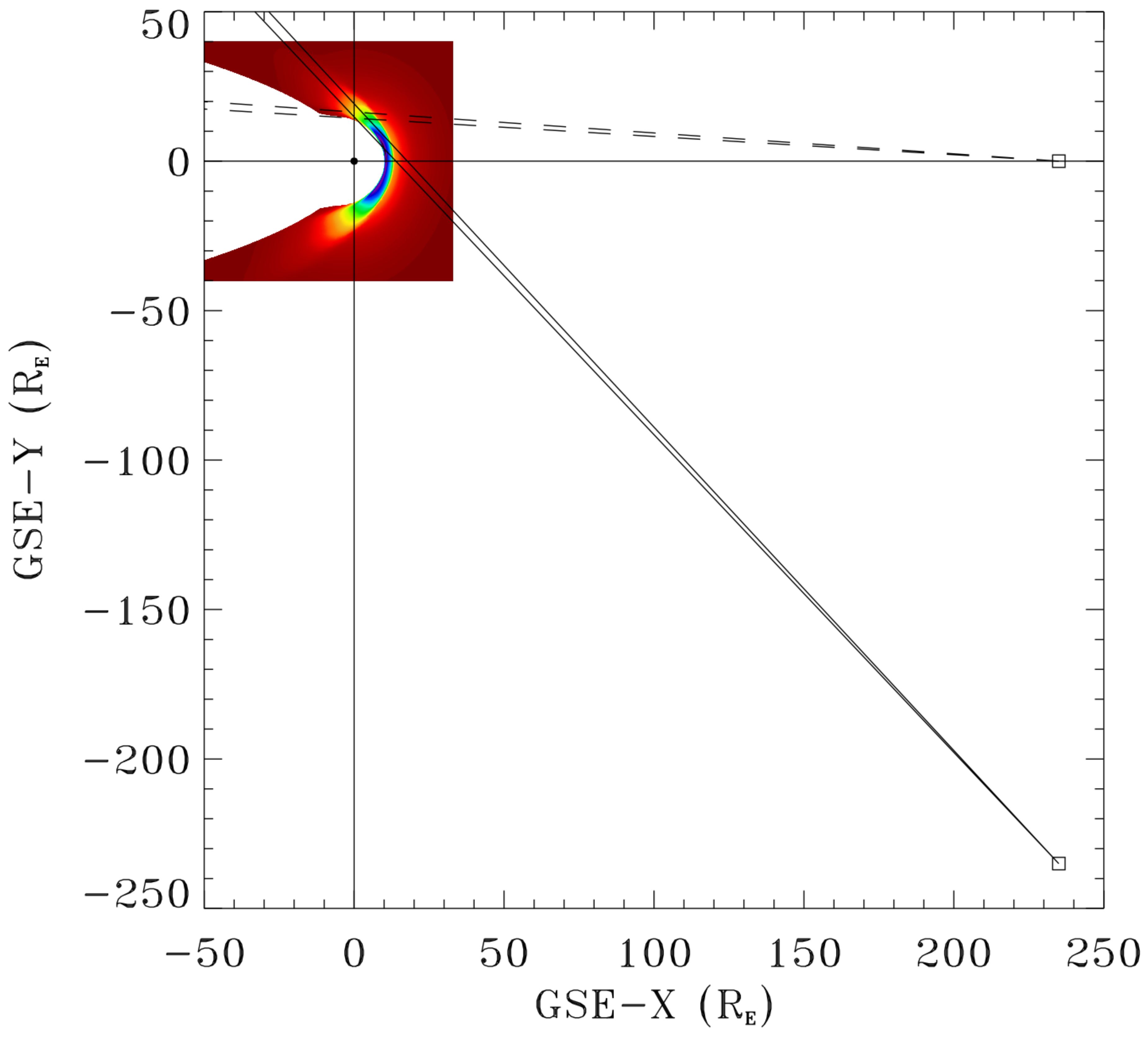


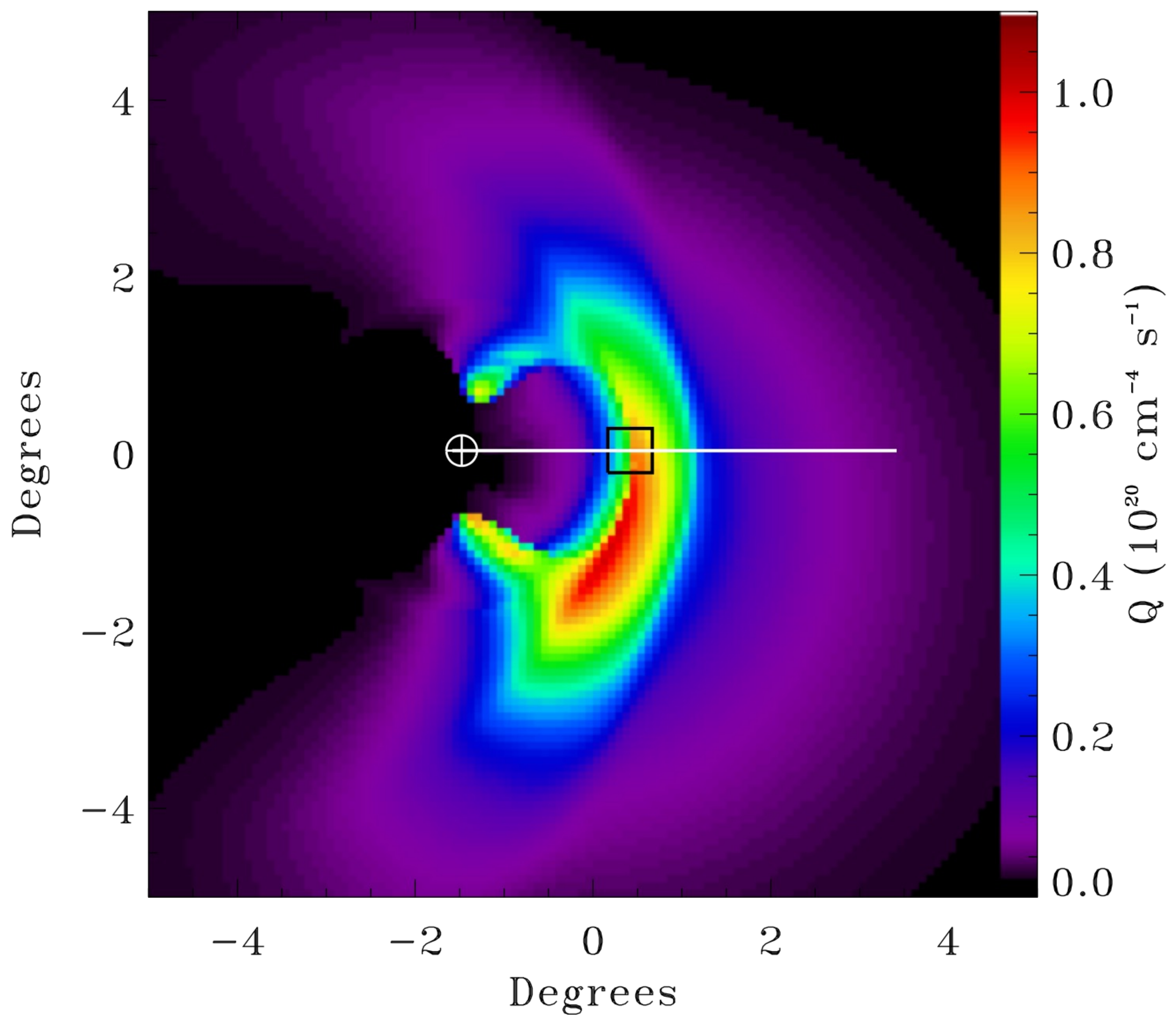


The Orbit

Lyapunov Quasi-Halo, kidney shaped orbit in GSE Z=0 plane

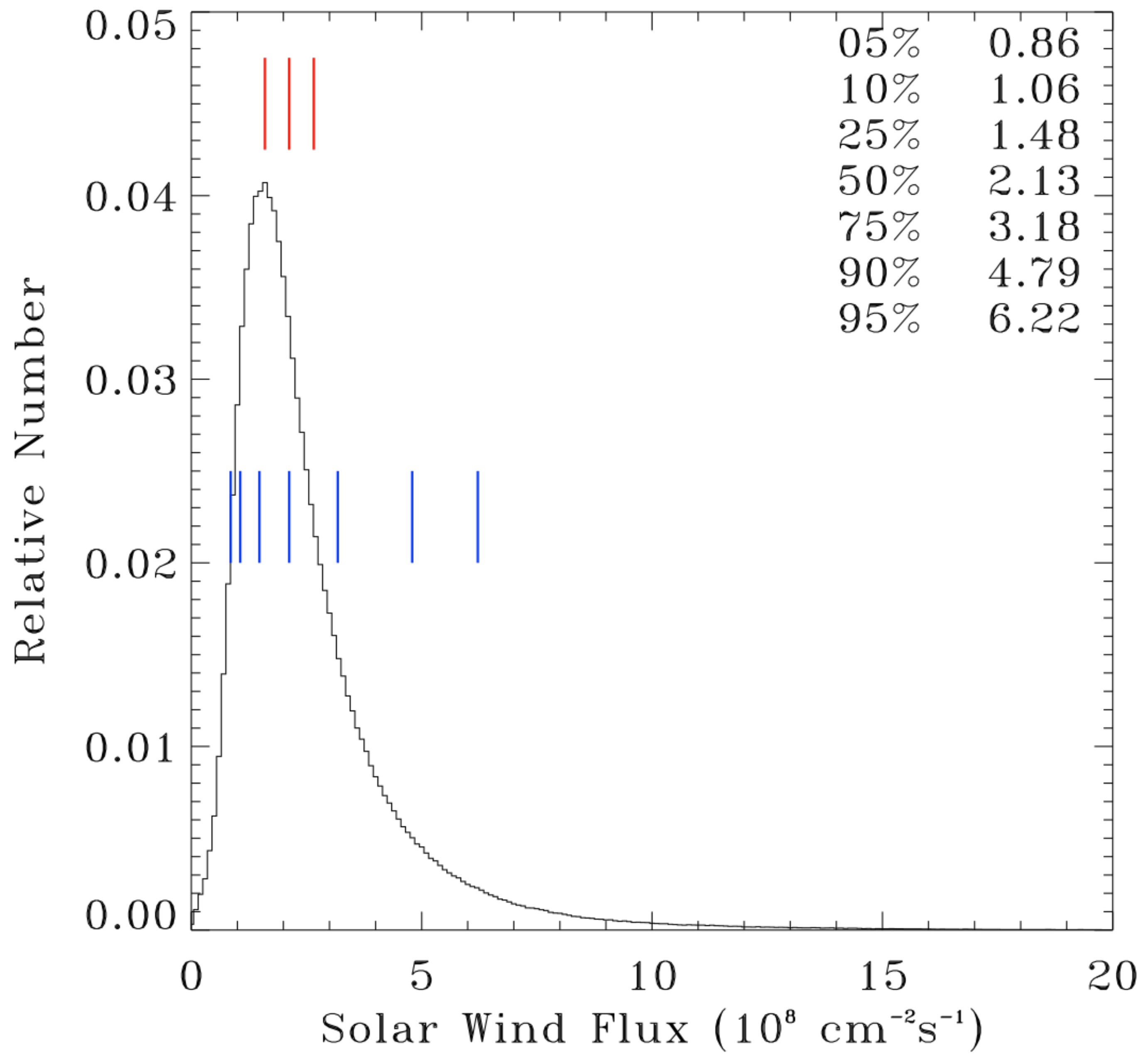
- 15″ subtends 0.024 RE at the Earth, FOV subtends ~3 RE at the Earth
- Allows a LOS tangent to the magnetopause relatively close to the nose of the MS
- Cusp observations probably too close to the bright Earth

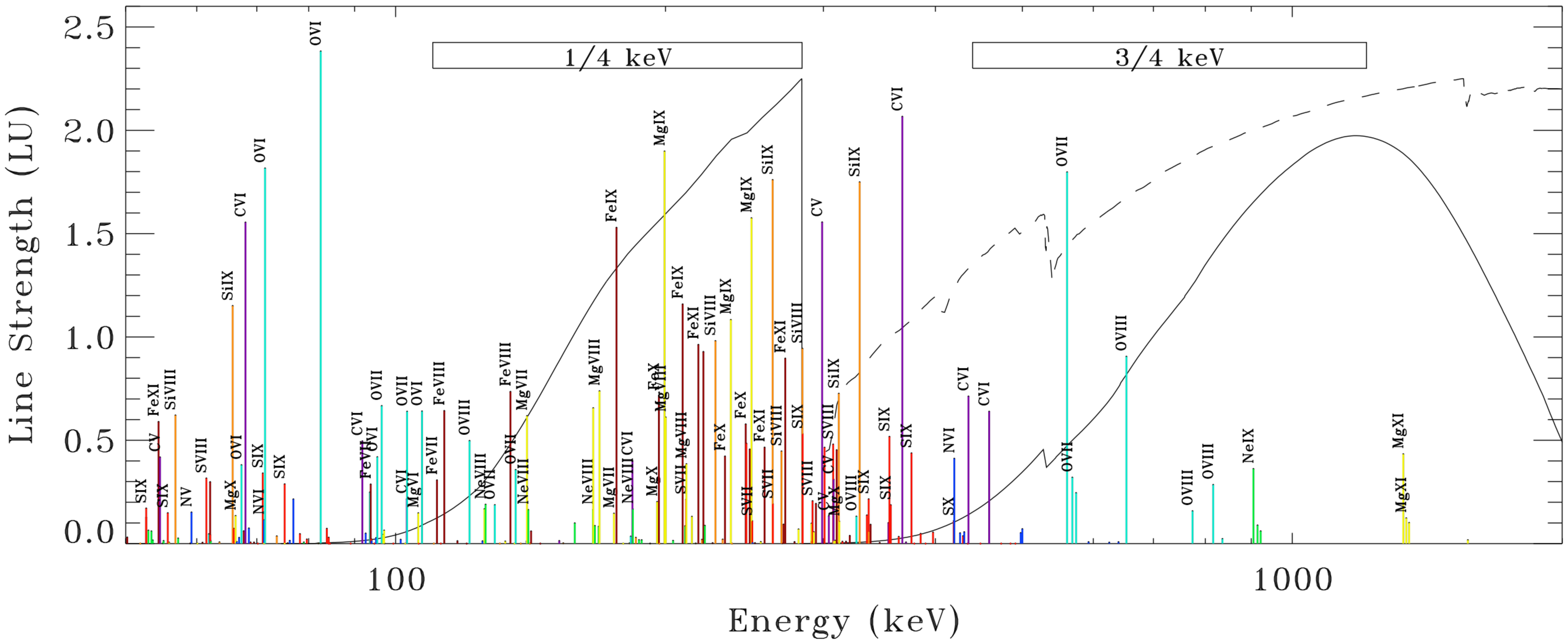




Simulations

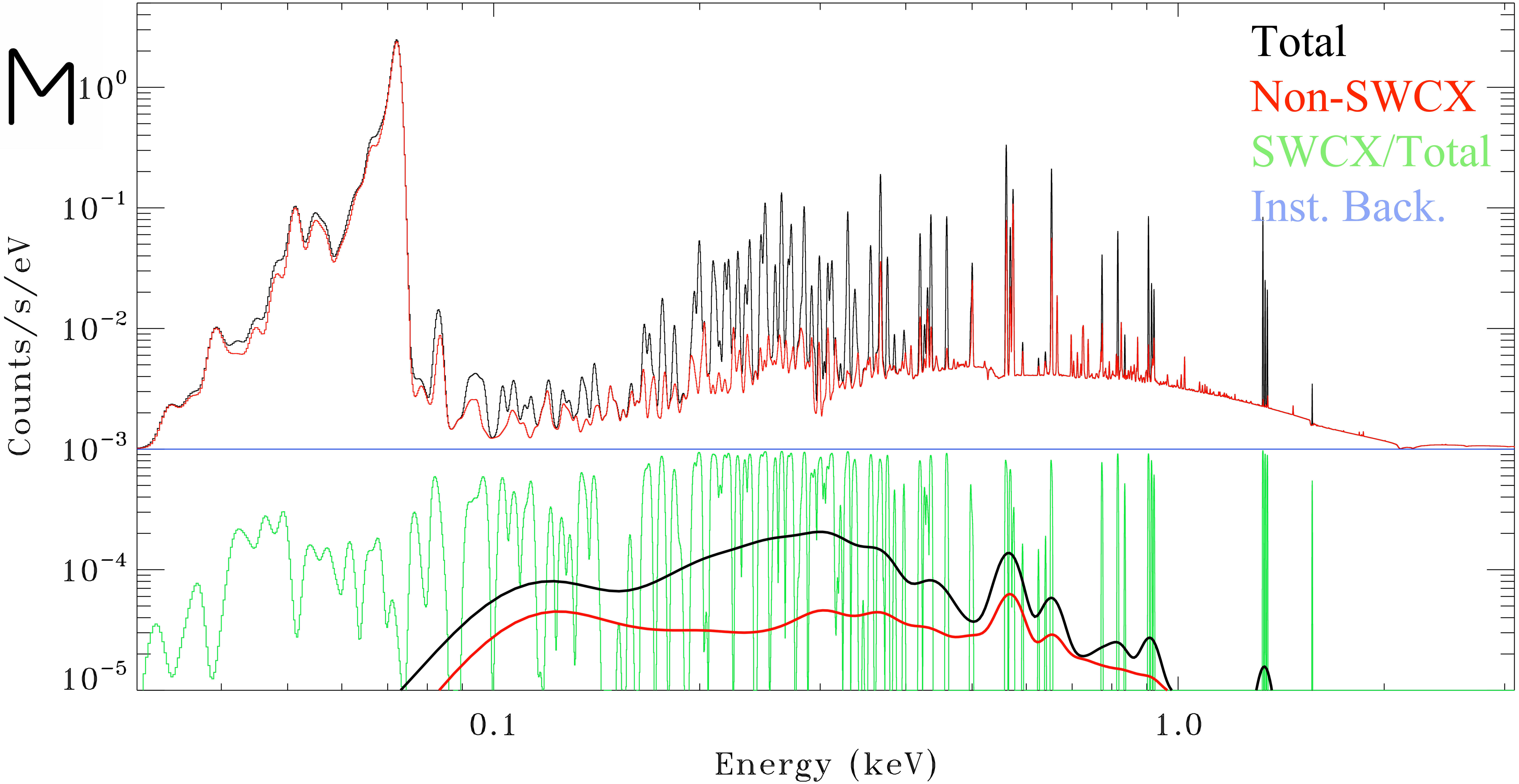
- Assumed a median solar wind flux (2.13×10^{8} cm^{-2}s^{-1})
- Used a SWCX spectrum constructed for the slow solar wind
  - Carefully curated cross-sections, branching ratios, & abundances (VK & DK)
  - LEM target launch during solar minimum → slow s.w. dominates
- Spectrum normalized to produce correct ROSAT LTE - nv_{sw} relation
  - (see Kuntz et al 2015) → spectral norm = scale factor × Q
- X-ray background model





Simulations

- X-ray background model
  - Use HaloSat data
  - Used Local Hot Bubble normalization from Snowden+ (1998)
    - corrected for SWCX by Lui+ (2017)
    - kT_{LHB}=0.84 from Bluem+ (2022)
  - Assume mean high North Galactic spectrum from Bluem+ (2022)
    - kT_{soft}=0.166
    - kT_{hard}=0.69
  - Assume Cappeluti+(2017) unresolved X-ray background
  - Assume 1 count KeV^{-1} s^{-1} for instrumental background



Taking a FOV that is maximally filled with magnetosheath emission
- assuming 2 eV resolution but not accounting for thermal or velocity broadening
- assuming background emission at 0 km/s
- total counts/line is ~8.5×max(count/ks/chan)

Simulation

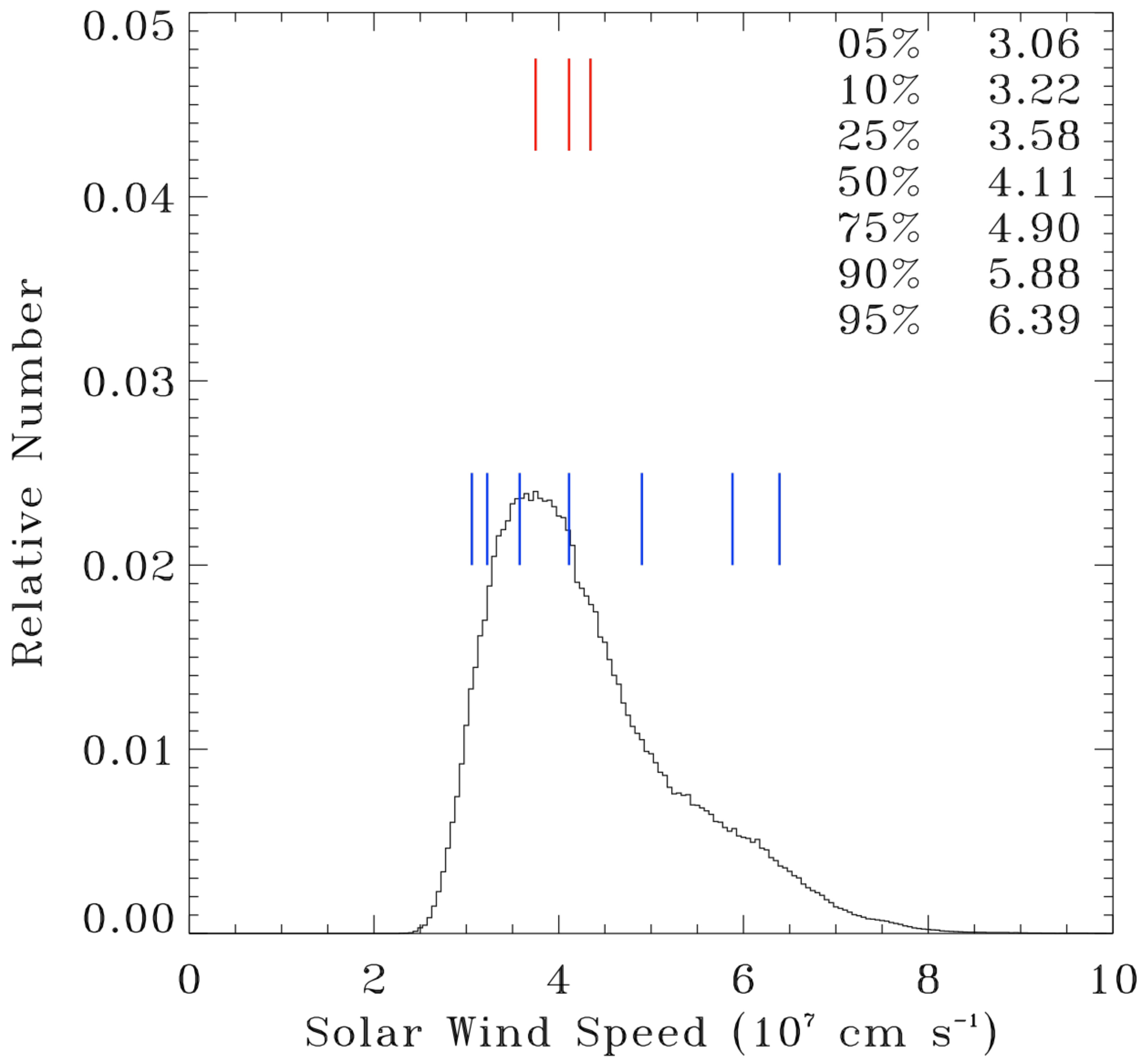
Assuming a reliable background spectrum:

- Easy: species with at least one line with SWCX/Total= $f > 0.5$; at 10 ks, ~1000 counts
  Direct summation of counts sufficient
- Moderate: species with at least one line with $f > 0.2$; at 10 ks, ~100 counts
  Fitting a small spectral interval required
- Fainter lines/species can be extracted by fitting multiple small intervals of spectrum

Simulations

And even better, the MS emission will be shifted with respect to the background!

From the OMNI database, the 95 percentile for solar wind speed ~640 km/s.
Since the peak LOS velocity is ~0.75% of the free-flowing solar wind
→ ~490 km/s is the highest LOS likely to be observed
However, we may not be lucky enough to observe it.
Likely range of v_{rel} accessible to LEM observations is
225-400 km/s ~ 0.2-0.35 energy resolution elements,
readily detectable for lines with a few hundred counts.
CMEs may reach higher velocities!



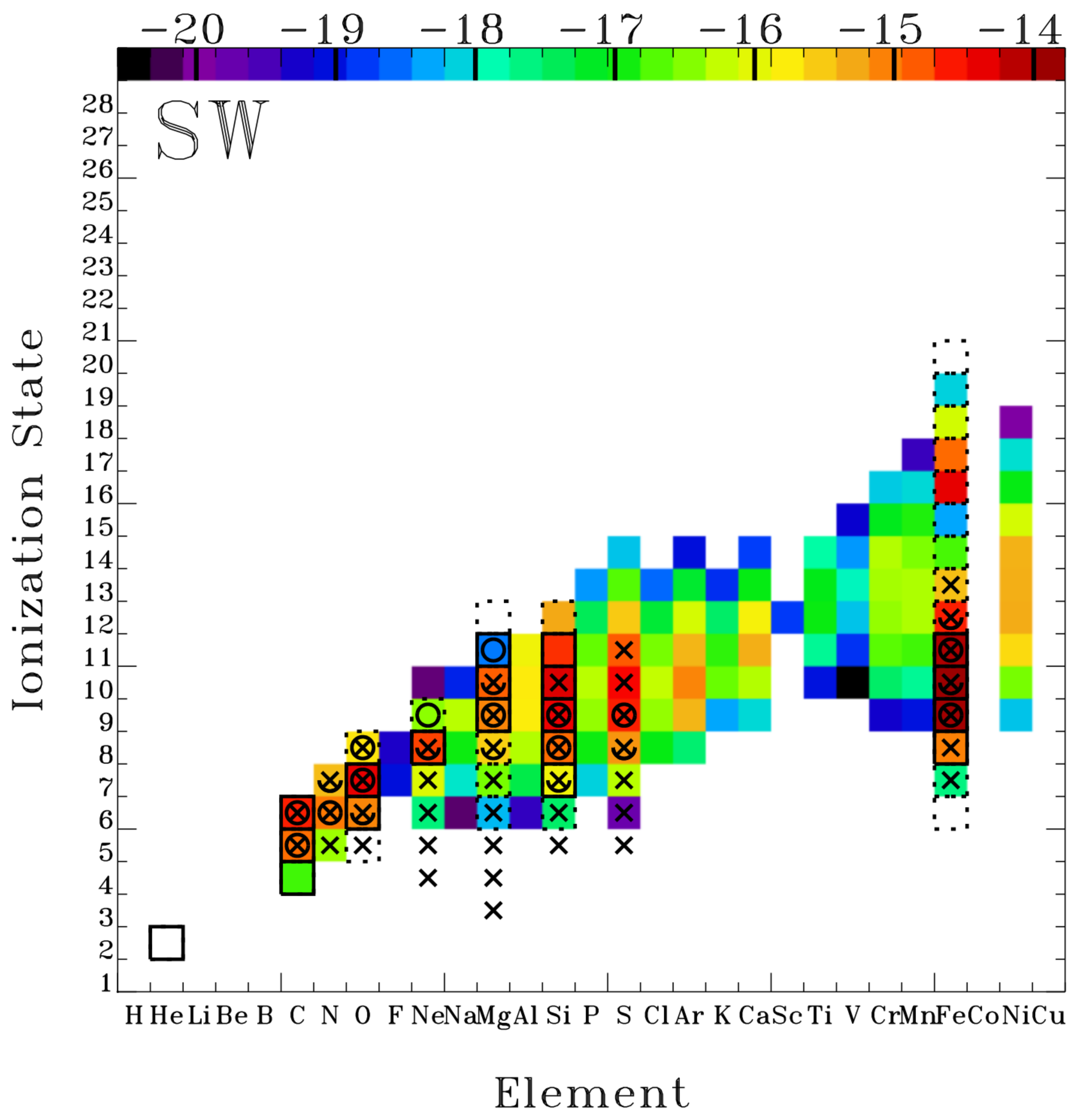
Simulation

- Using typical freeze-in T(Z) to determine relative level populations, then using the X-ray emissivities to approximate the brightness of each species/charge state. (Logarithmic)
- LEM covers most of the species that contribute to the X-ray background, usually with multiple lines per species.

□: ACE measures possible
×: Ulysses measures possible
○: Easy
◡: Medium

Odd z species not included due to lack of data.

Most species/states accessible through fitting!
And X-ray important species will be the easiest.



Why?

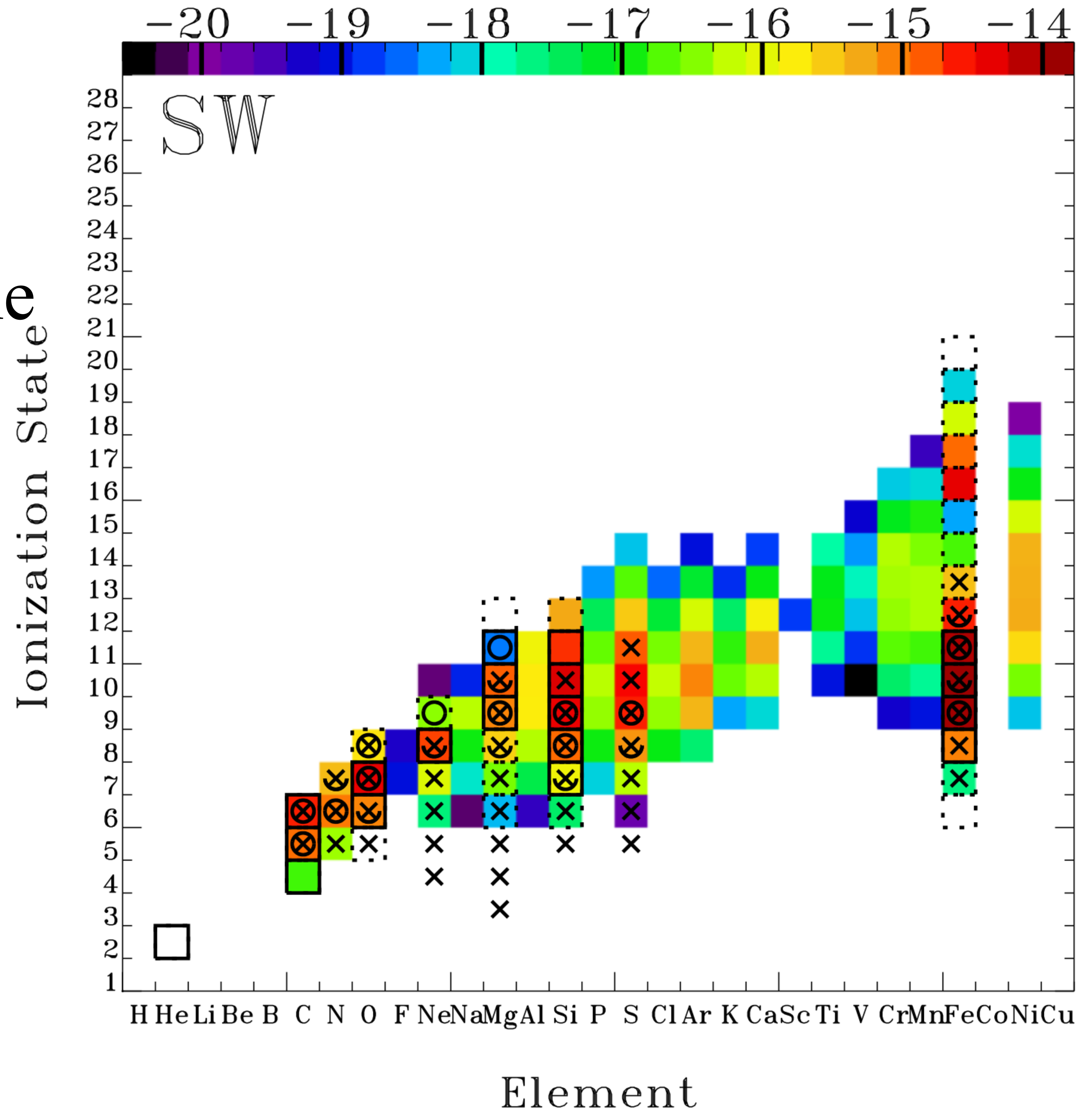
Lab-Astro Motivation

- All astrophysical observations contaminated with SWCX
- Attempts to characterize SWCX emission problematic:
  - Lack of Data
    - cross-sections
      - don't know correct ℓ distribution of the transferred e^-
    - instantaneous solar wind ion abundances
      - in situ measures often don't cover X-ray important species
      - In situ ion coverage limited and unlikely to improve
  - Temporally Variable

Observations of the magnetosheath provide the highest S/N spectrum
- does *not* provide a standard SWCX spectrum for background subtraction
- *does* provide information to model *astrophysical* charge-exchange

Astrophysical Motivation

- Even at CCD resolution we have measured differences in solar wind abundances using CX from comets (C V, C VI, N VI, N VII, O VII, O VIII)
- A LEM 10 ks exposure allows easy/medium measurement of many of the species previously measured with ToF instruments.
- Spectral fitting allows access to many more species.
- LEM can access species not available to ToF instr's
  Rare species whose M vs. M/q falls near an abundant one
- LEM can access some odd-z elements
  Just need one line in quiet part of spectrum!
  (but not included here due to lack of data)



Solar Wind abundances are one of the three measures from which we derive the abundance of the Sun…
…LEM can contribute!

Heliophysics Motivation

Solar wind abundance in streamers (equatorial flow) is not the solar abundance.
The solar wind abundance modified by:
- FIP fractionation
- mass fractionation
- many other fractionation processes (von Steiger & Zurbuchen 2016)

These processes are understood(?) by comparing photospheric abundances (optical/UV) with *in situ* abundances.

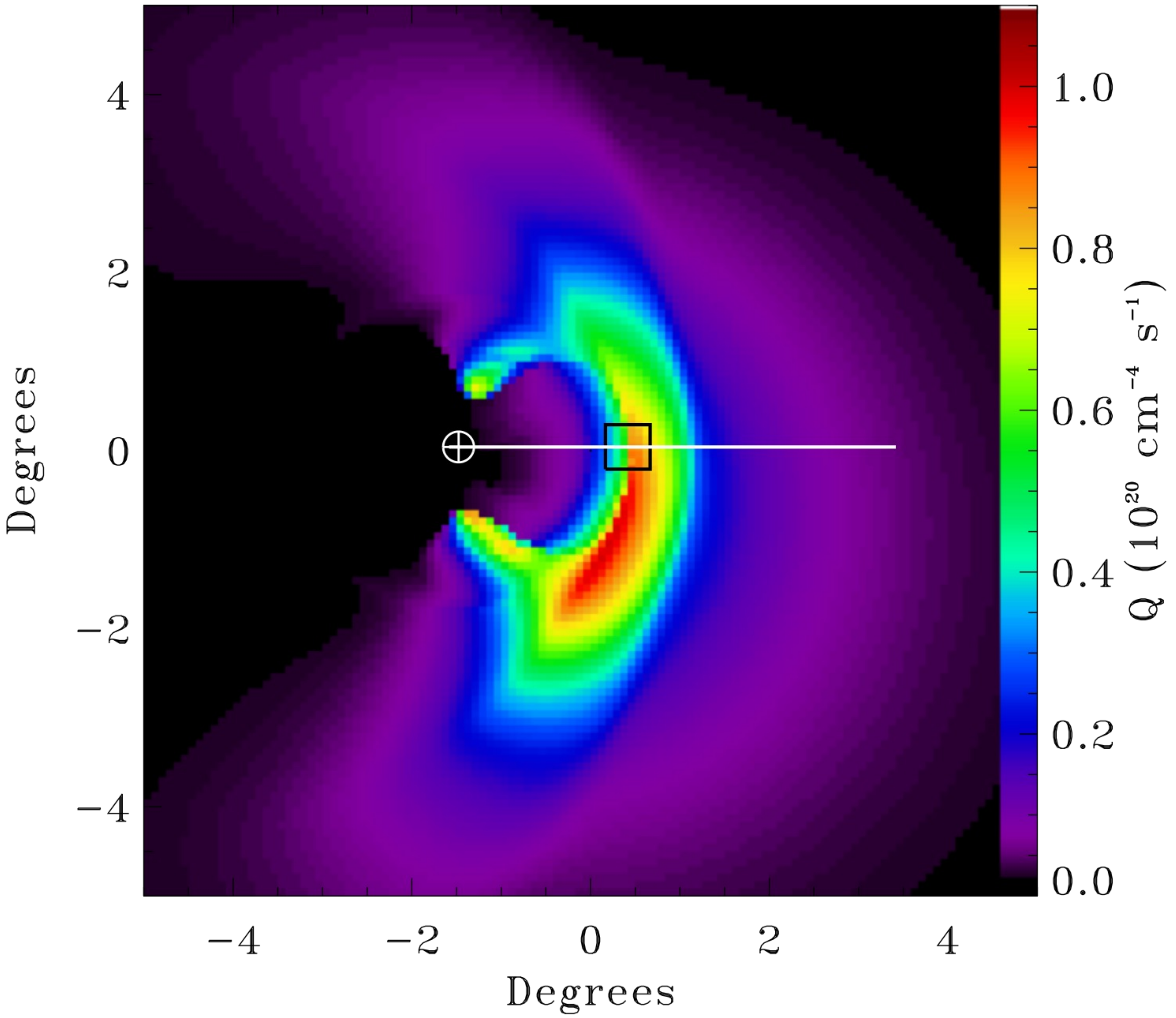
However, several important elements needed for comparison are not measured by *in situ* measures: S, P, and Ar, **all of which are expected to be accessible in the X-ray**.

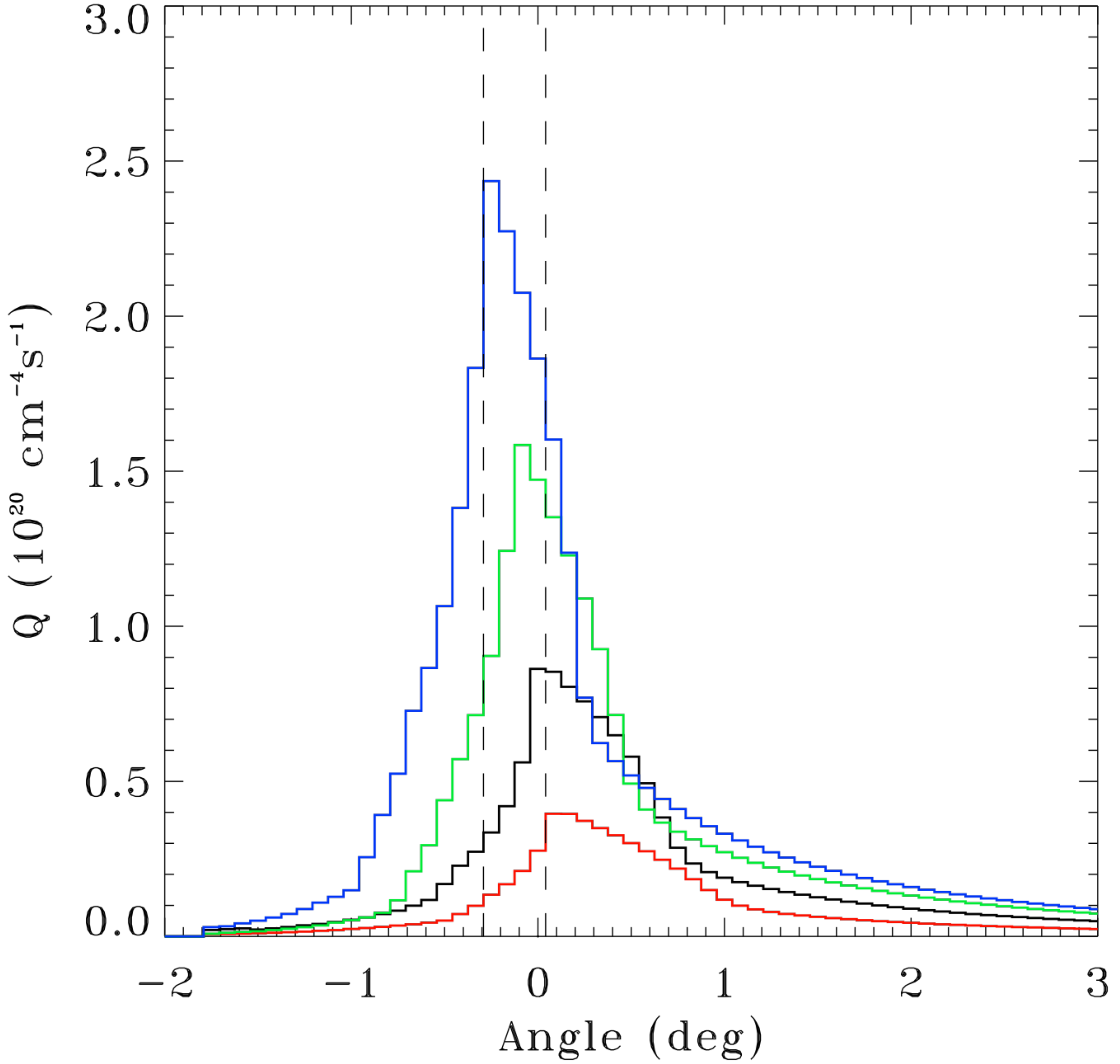
SWCX spectra of the the magnetosheath will provided abundances that can be used to understand these fractionation processes.

Space Physics Motivation

Imaging the magnetosheath in soft X-rays allows large scale mapping!

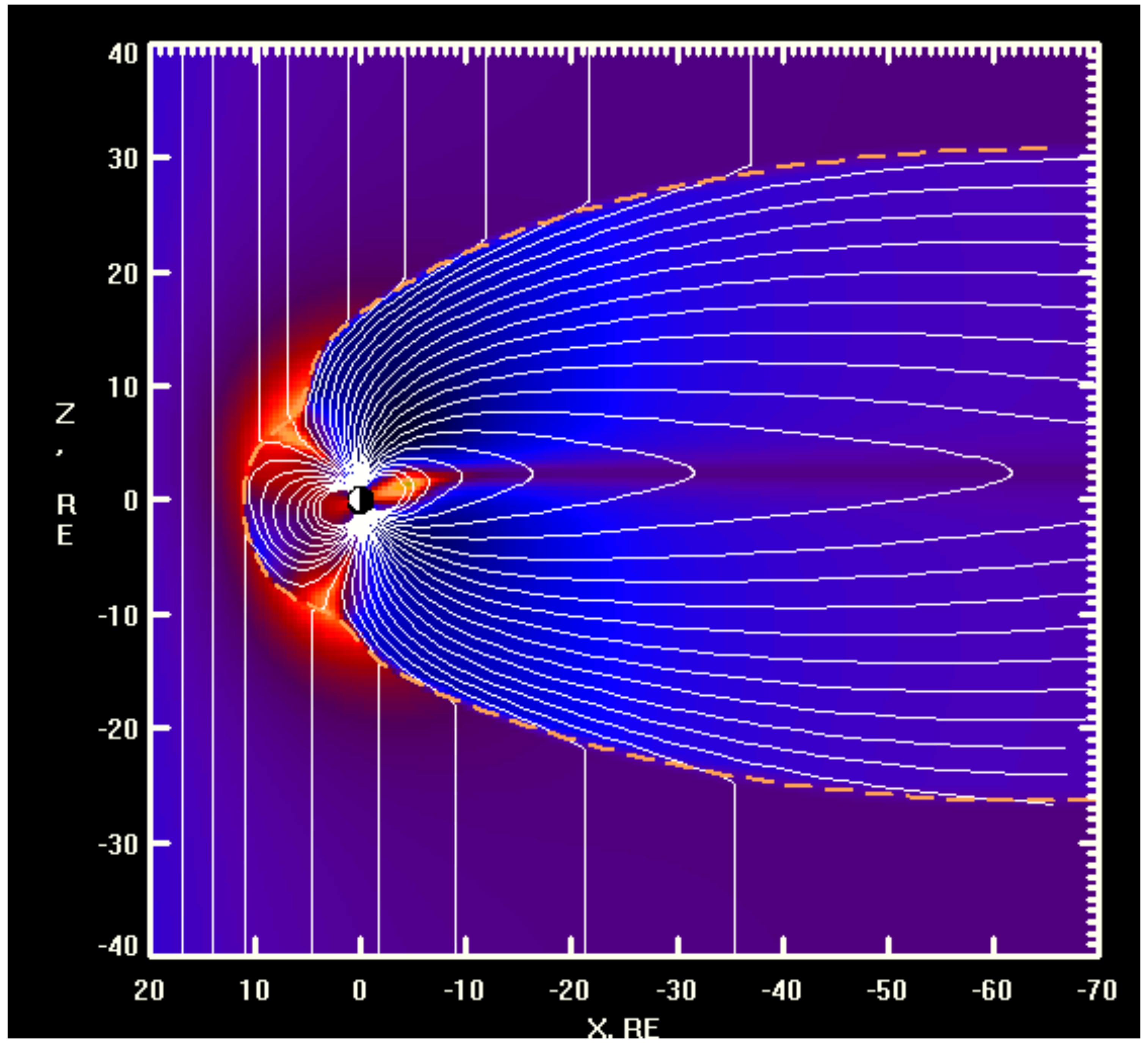
- This motivates LEXI, SMILE, and STORM missions, but LEM can't do that.
- LEM can measure motion of the magnetopause!
  - Between 25th and 92nd percentile solar wind speed - motion is 20′, almost the FOV





LEM

Space Physics Motivation



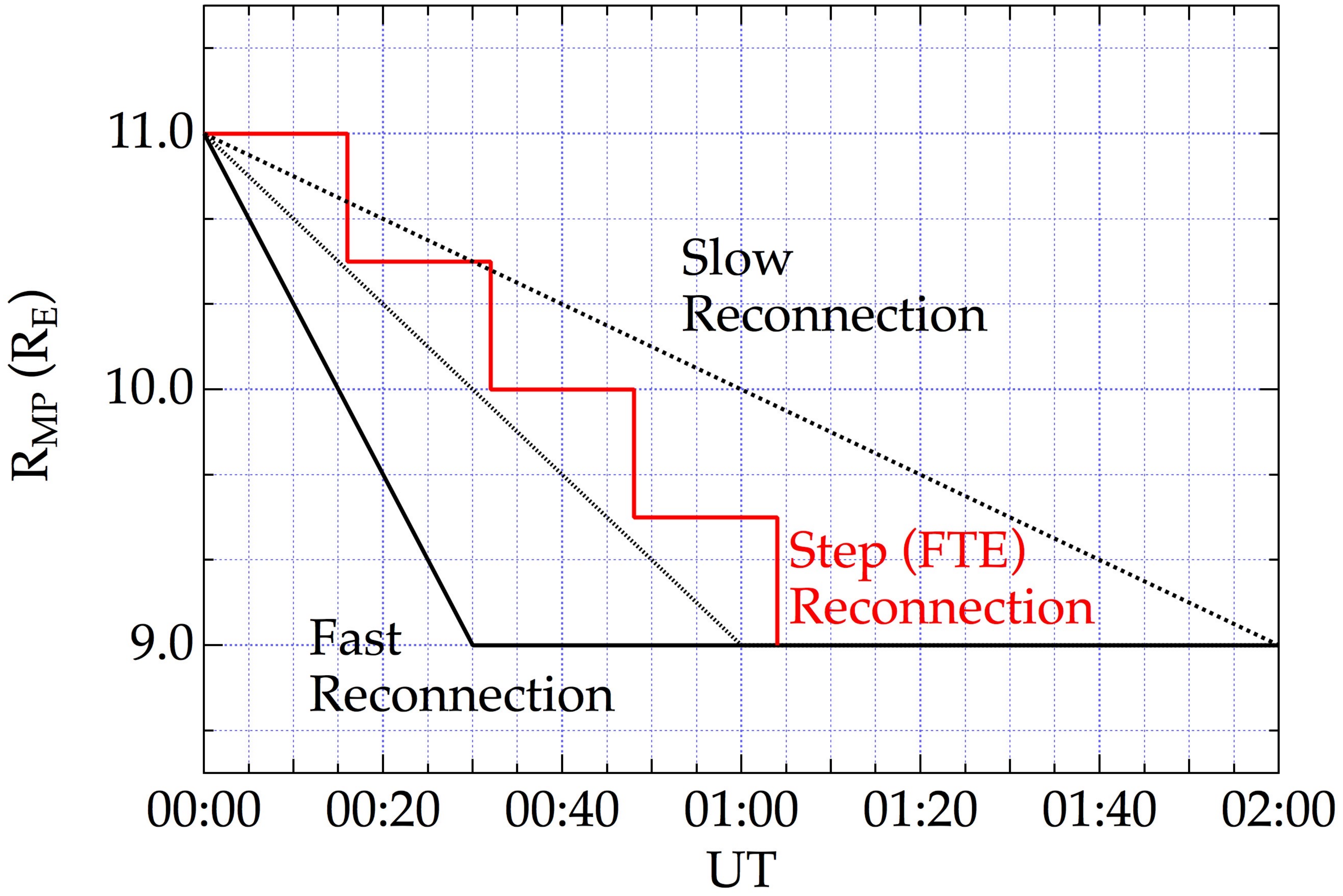
The MP moves due to

- changes in the solar wind pressure (nv^2_{sw}) well understood
- reconnection - not understood!
  - how does reconnection actually "work"?
    - steady vs. bursty?
    - single step vs. incremental?
    - slow vs. fast?
  - → watch MP in conjunction with
    - solar wind measures
    - auroral measures

Another motivation for SMILE & STORM…

…but LEM can do it too!

Subsolar Magnetopause Motion Due to Reconnection
Grids show anticipated 5 min and 0.3 R_E temporal and spatial resolution.



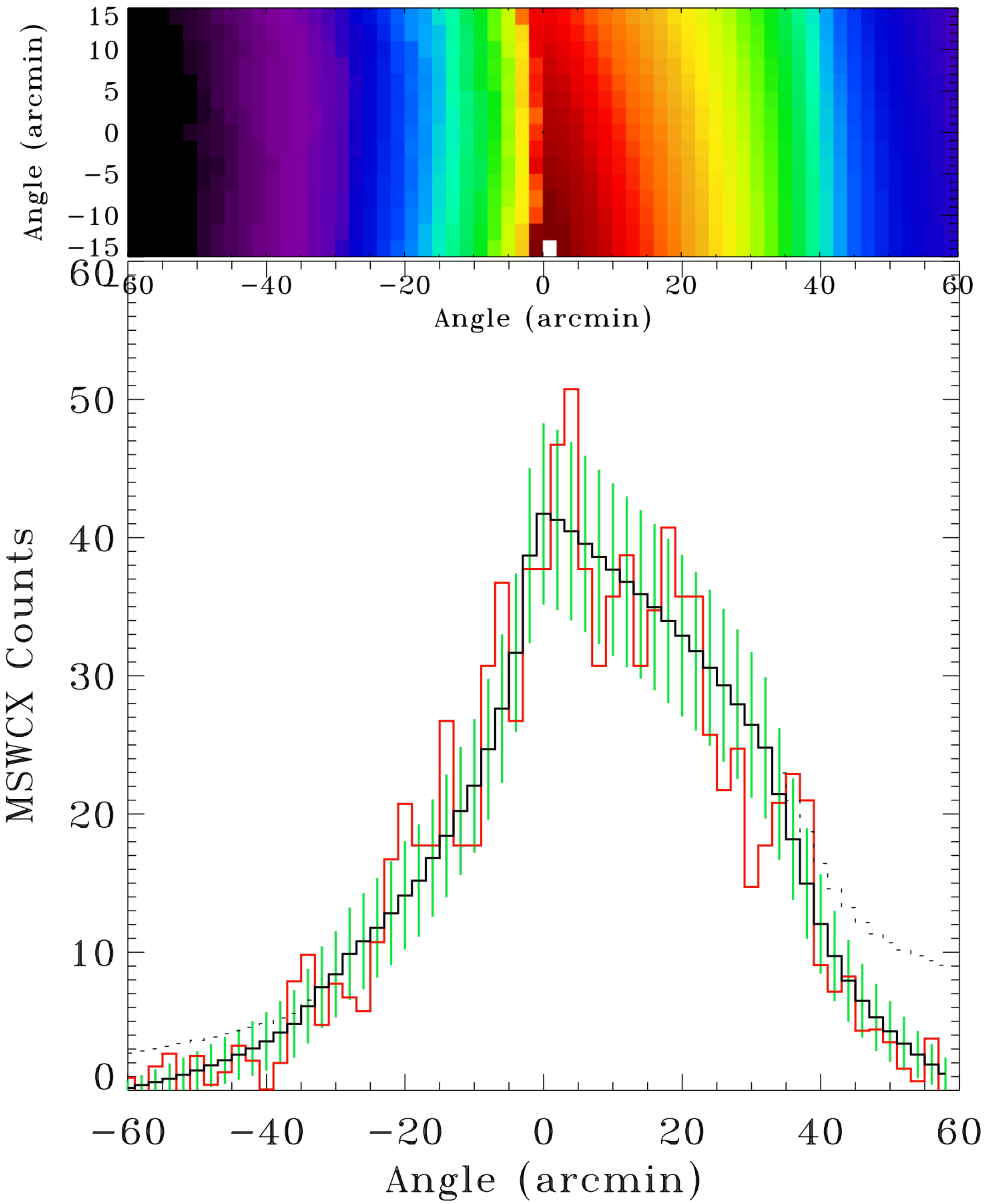
Space Physics Motivation

The STORM STM required:

- localization of the magnetopause to within 0.25 R_E
- for a 3 minute exposure
  (due to variability and reconnection time-scales)
- for times when $nv_{sw} > 2.5\times10^8$ cm^{-2} s^{-1}

LEM can do this by imaging the soft emission

- "nodding" across the magnetopause
- using model/measured cross-correlation techniques
  MonteCarlo→1σ=1.3 2′ or ~ ±0.22 R_E



Space Physics Motivation

The magnetopause is expected to show ripples, waves, and other kinetic structures.
- The scale of these structures is expected to be 0.1-1 R_E i.e., very uncertain.

There are expected to be high density foreshocks.
- Again, the details are relatively poorly constrained,
- but have a critical impact on energy deposition in the magnetosheath.

LEM's relatively high angular resolution (compared to MPO based missions) will allow detection or constraint on all of these features.

Summary

The Earth's magnetosheath provides the *brightest* SWCX emission.

Observations of the magnetosheath
- provide direct measurements of the important SWCX lines
  (i.e. the lines that will interfere with astrophysical observations)
- help determine of which ℓ-entry schemes are important

- allow study of solar wind abundances in species not (well) measured by *in situ* TOF instruments
- allow further exploration of the processes that modify the solar wind abundances compared the underlying solar abundances

- allow study of the magnetosheath at a spatial resolution un-matched by any currently accepted mission, certainly better than SMILE, and comparable to the planned (but not yet funded) STORM mission.

Title