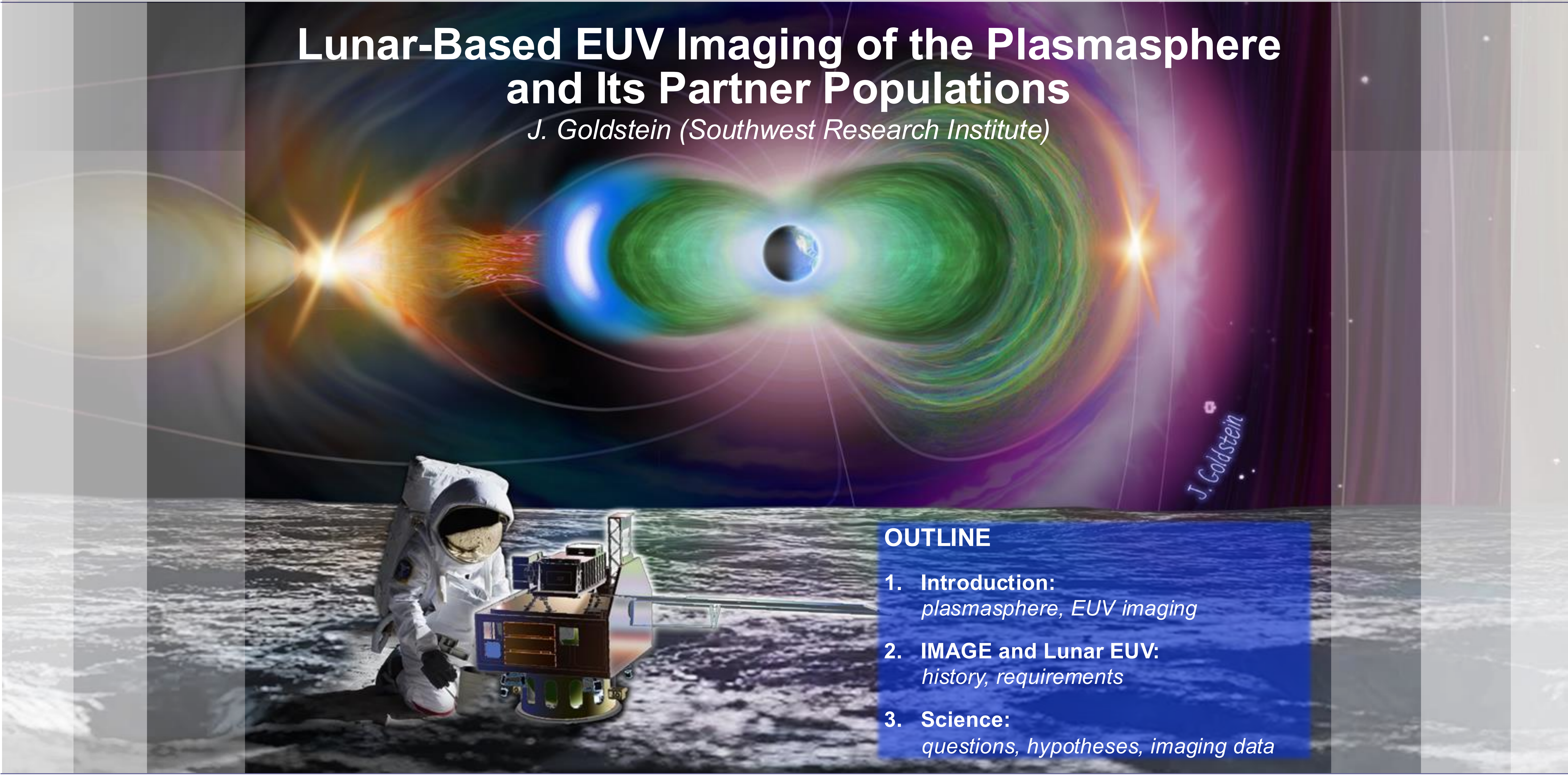
Lunar-Based EUV Imaging of the Plasmasphere and Its Partner Populations

J. Goldstein (Southwest Research Institute)



OUTLINE

1. **Introduction:**
   plasmasphere, EUV imaging
2. **IMAGE and Lunar EUV:**
   history, requirements
3. **Science:**
   questions, hypotheses, imaging data

The Plasmasphere

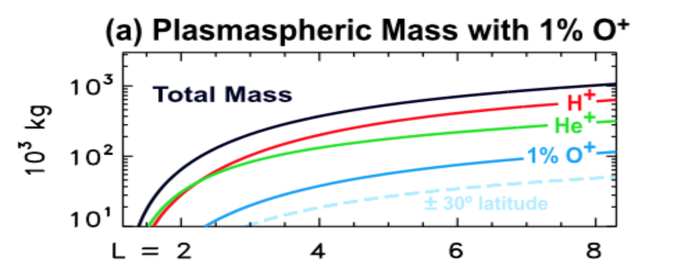
Plasma Mass, Space Weather Shield

Plasmasphere:

- Cold (<10 eV) H^+, He^+, O^+ 1 – 4 or 5 R_E
- MASS: 100s of metric tons [Goldstein+ 2019]
- DYNAMICS: Stormtime erosion, quiet recovery
- Enormous mass/inertia: impacts other populations, exerts basic control over currents, fields, particles
- *Cardinal population of the inner magnetosphere*

"Core Plasma"

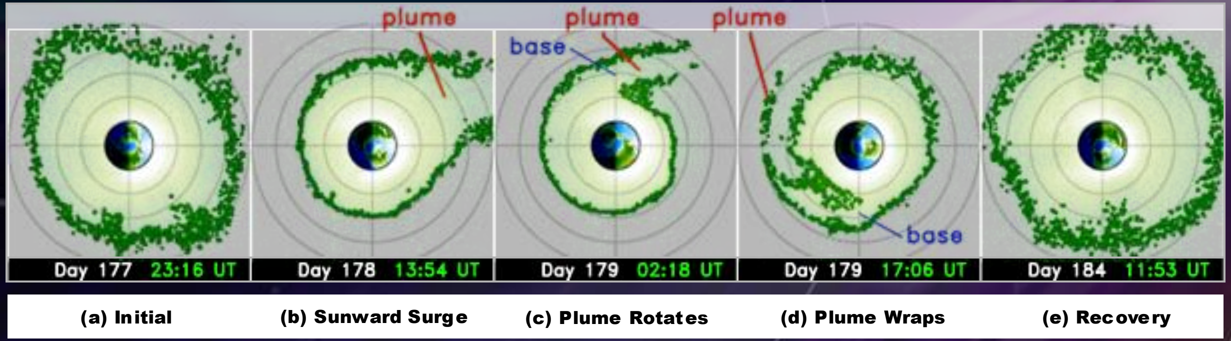
- Reservoir of cold ionosphere-origin plasma
- Central location and role in system of systems



tens to hundreds of metric tons of plasma
[*Goldstein*+2019 10.1029/2019JA026822]
- majority of mass/inertia in magnetosphere

Cycle of Erosion and Recovery

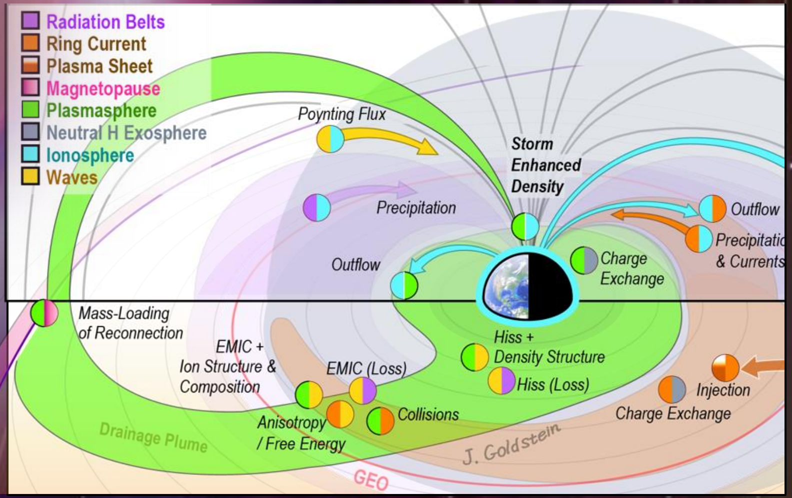
repeatable pattern of plasmasphere plume phases
[*Spasojevic*+2003; *Goldstein & Sandel* 2005; Goldstein+2022, **and many, many more**]



Decades of modeling studies had predicted these plume phases. IMAGE was able to see them for the first time.

Plasmaspheric Impact

part of a "system of systems"
[Claudepierre+2023; 10.3847/25c2cfeb.9ec7bba4]

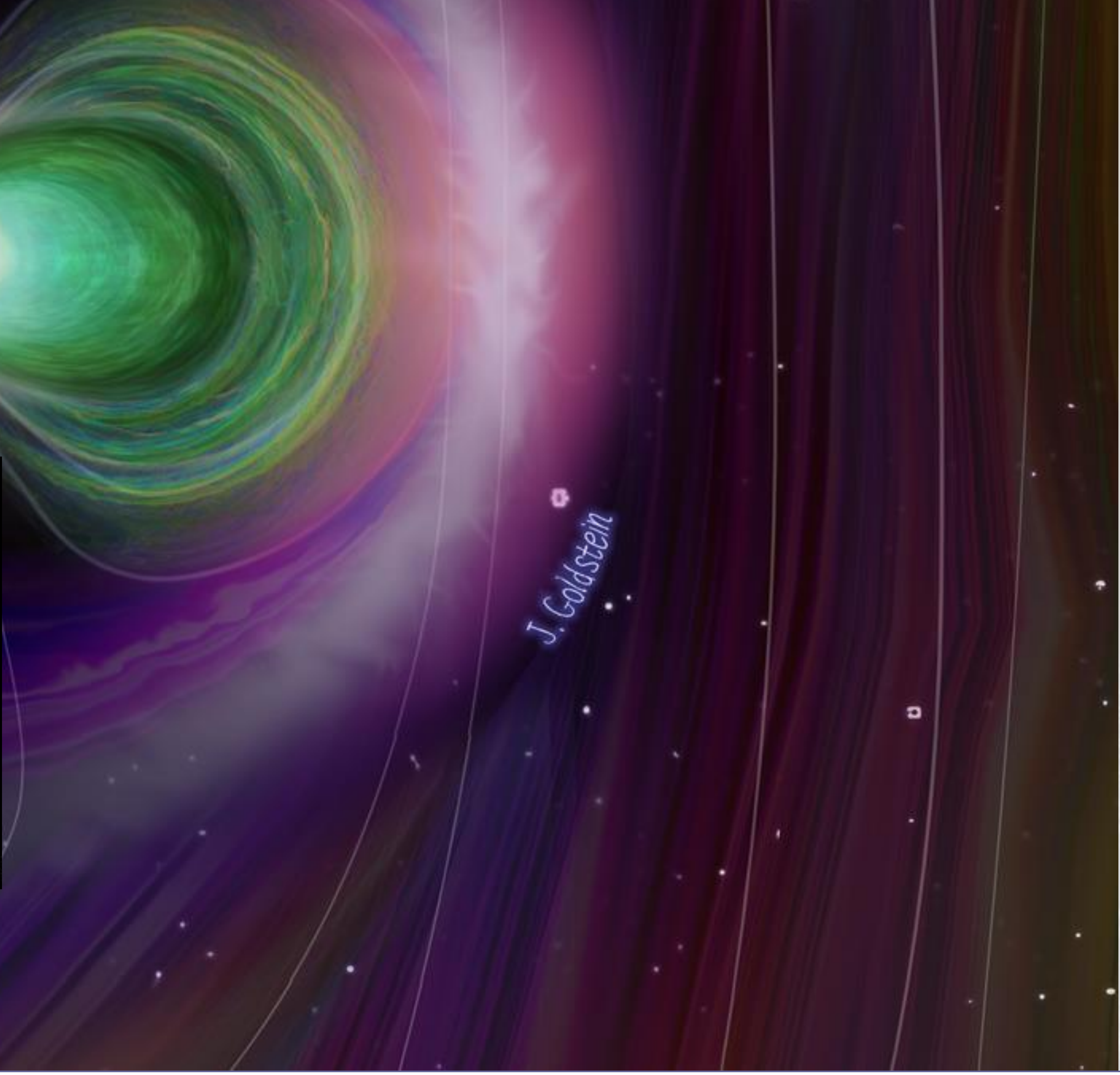


Plasmasphere exerts basic control over fundamental set of currents, fields, and particles
[Alfven waves, wave particle interactions, spacecraft charging, reconnection]

- suppression of warmer particles
- plumes (dayside reconnection, ionospheric SED)
- loss of exosphere, long-term water escape

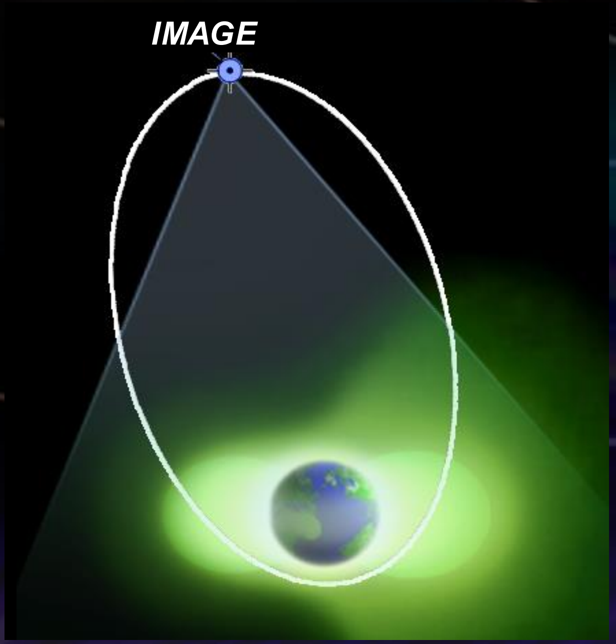
Imaging the Plasmasphere

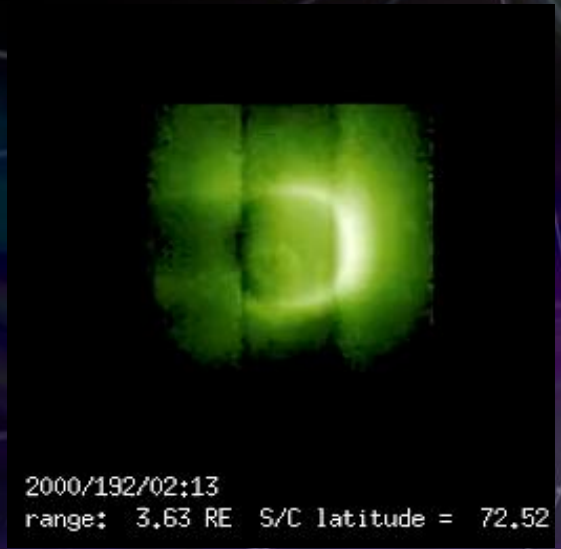
First Routine Global Views



NASA IMAGE Mission:

- March 2000 to December 2005
- Extreme Ultraviolet (EUV) Imager:
  - 130,000 global plasmasphere images
  - Confirmed decades-old hypotheses
  - Established new paradigm, dynamic plasmasphere
  - Revealed huge gaps in understanding





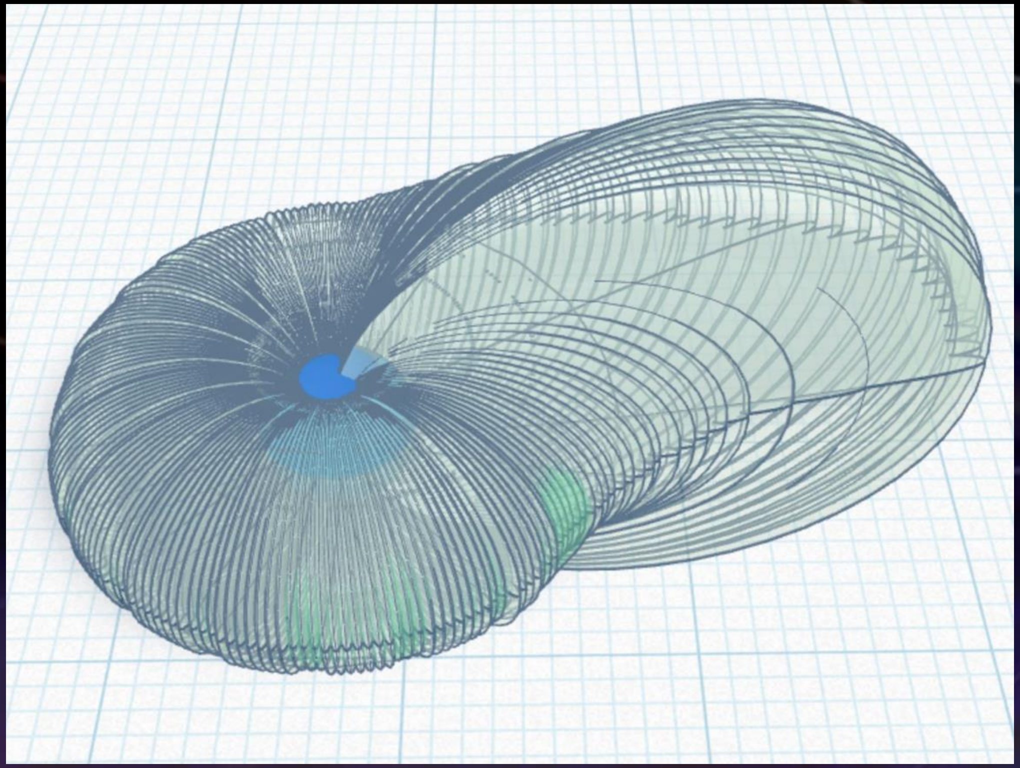
10 July 2000
1st erosion event identified by IMAGE
[*Goldstein*+ 2003a]

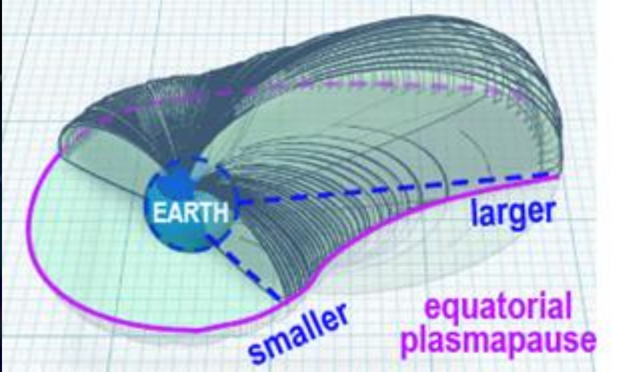
Imaging the 3D Plasmasphere

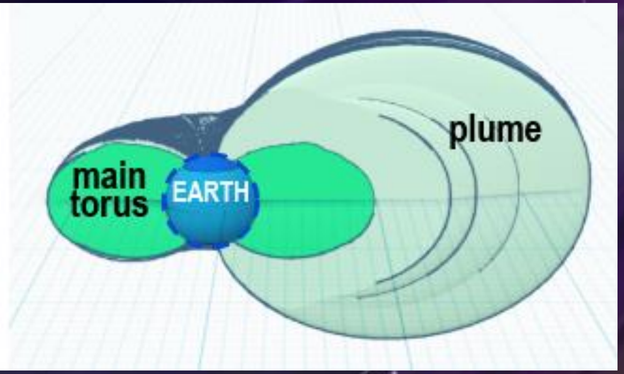
"Top View" versus "Side View"

3D Shape of the Plasmasphere

- "Torus" of plasma: follow magnetic field
- Variable radius of torus
  - Erosion, plume, creates more complex 3D shapes







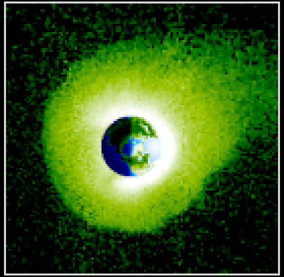
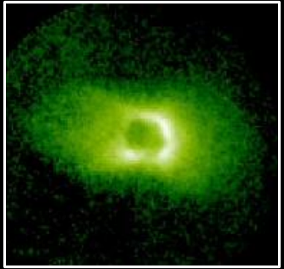


IMAGE EUV
top view
[Goldstein+2022]

equatorial distribution

Main torus = an oval,
Plume = sunward-pointed column



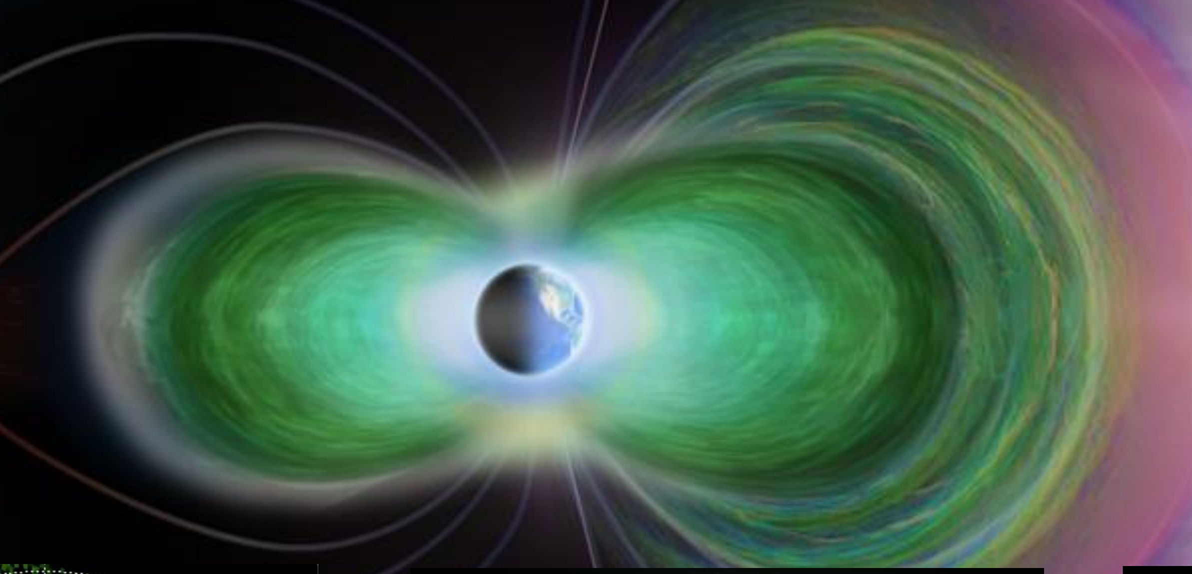
Chang'e-3 EUVC
side view
[He+2016]

meridional distribution

Main torus = day / night lobes,
Plume = larger dayside lobe

Imaging the Plasmasphere

Dawn of the Era of the Dynamic Plasmasphere



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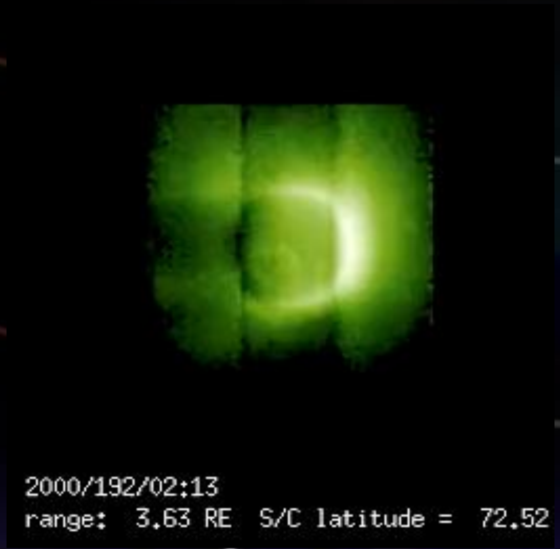

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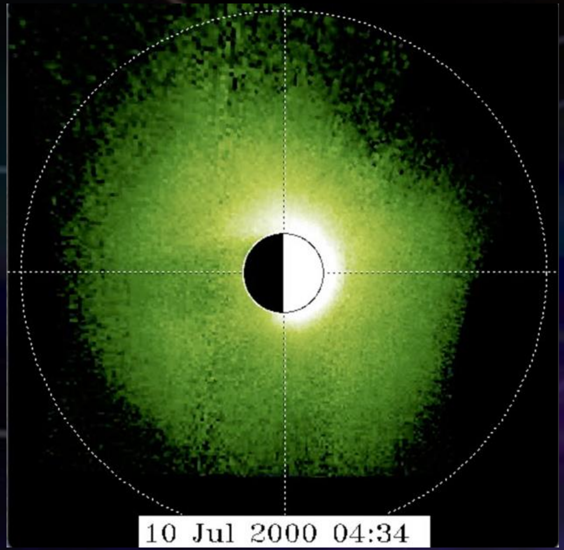
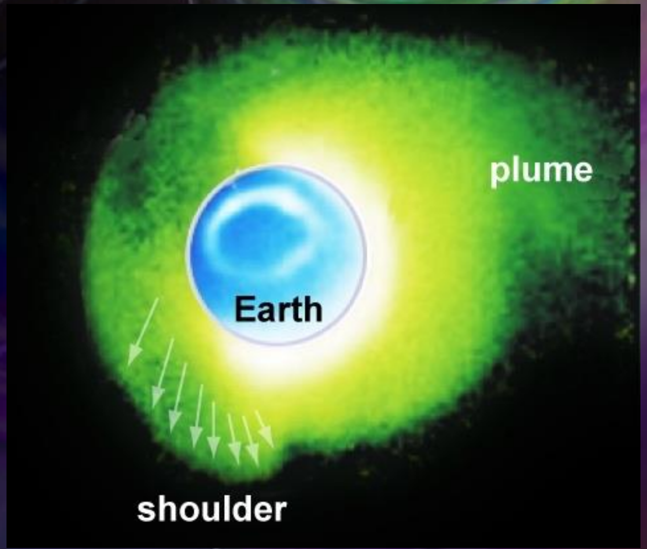
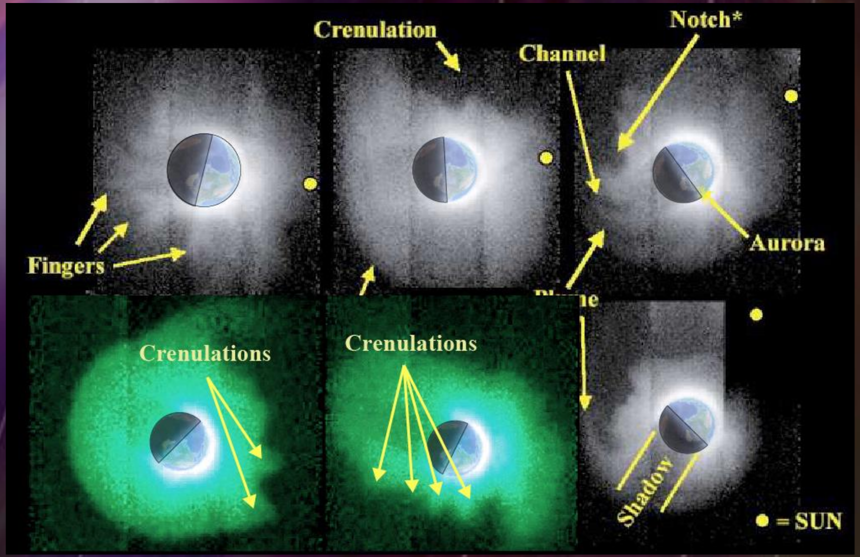


mapping to geomagnetic SM coord
⇒ real erosion
⇒ tens of tons of plasma removed
[*Grebowsky*+1970, Sandel+2001]



24 May 2000 Plasmaspheric Shoulder
overshielding after northward IMF
(i.e., time-dep shielding)
[*Goldstein*+ 2002; 2003b]



Unexplained Structure (occurs 90%)
[Darrouzet+2009 10.1007/s11214-008-9438-9]
Plasmasphere model only good ~10% of the time.
Most times, see structure we cannot explain.

Impact of the Dynamic Plasmasphere

Active Partner in Coupled System of Geospace Populations

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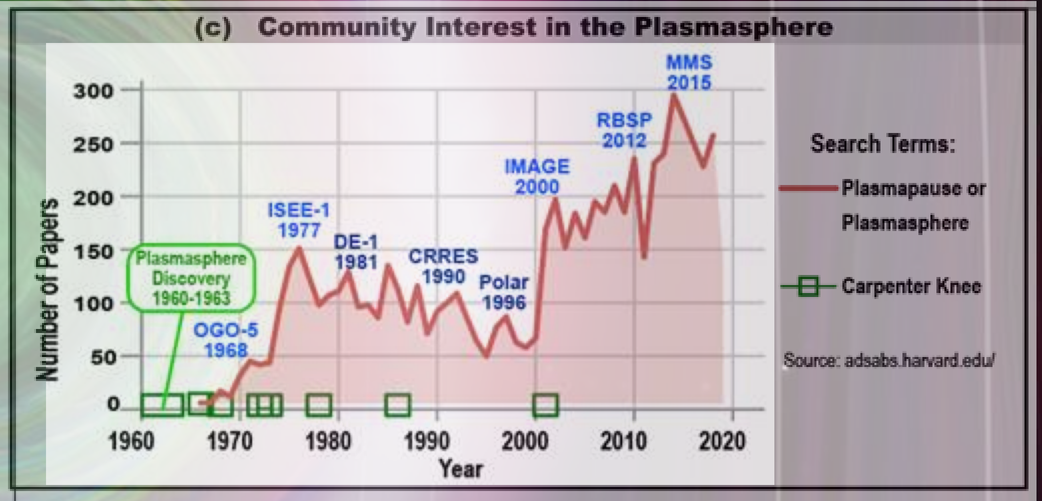
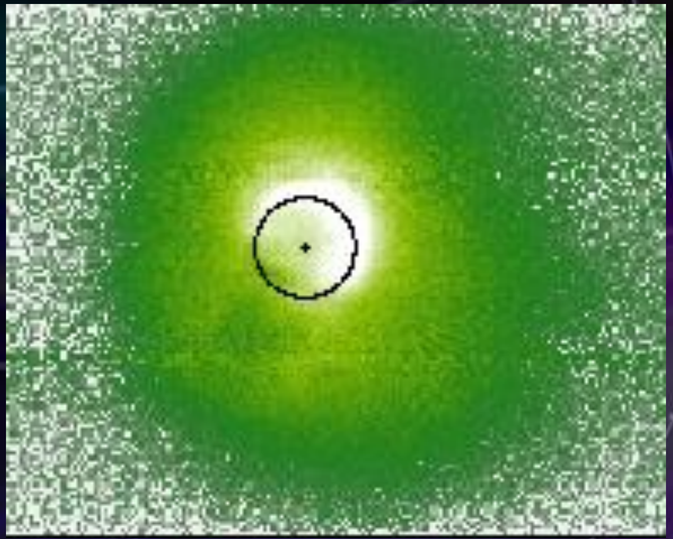


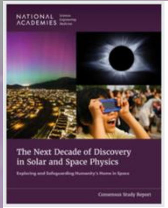
New Paradigm from IMAGE

Dynamic Plasmasphere: Huge shift:
"quiescent, passive" => "dynamic, active"
Direct result of new IMAGE EUV global images.

- **Before 2000:** Few plasmasphere papers, few researchers even including it
- **After 2000:** Steep rise in publications, inclusion, and perceived importance.
- **2024 HP Decadal:** First time prioritized science explicitly focused on plasmasphere, its life cycle, and its partner populations.



Year 2000, day 152–180
about 50 orbits (14.2 hr period)
[Goldstein+2017, 10.1002/2017JA024301]



The Next Decade of Discovery in Solar and Space Physics: Exploring and Safeguarding Humanity's Home in Space (2024)

Heliophysics Decadal Survey

Physics of Magnetospheres Panel:

Priority Science Goal (PSG) 2
What are the characteristics, life cycle, and magnetospheric impact of [ionospheric-origin] plasma?

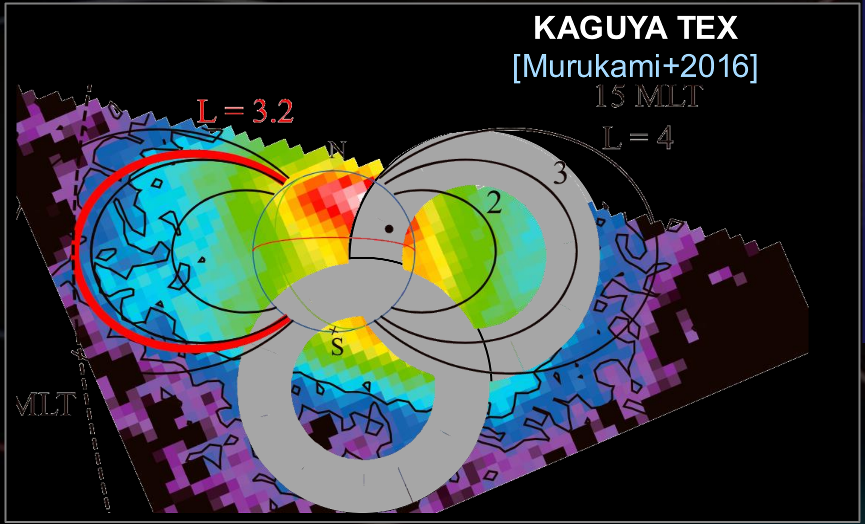
2a. Plasma formation and evolution
2c. Magnetospheric impacts
2d. Ultimate fate of ionospheric-source plasma

NEXT:
Lunar EUV: *history, requirements*

Lunar-Orbit EUV Imaging of the Plasmasphere

What's Been Done?

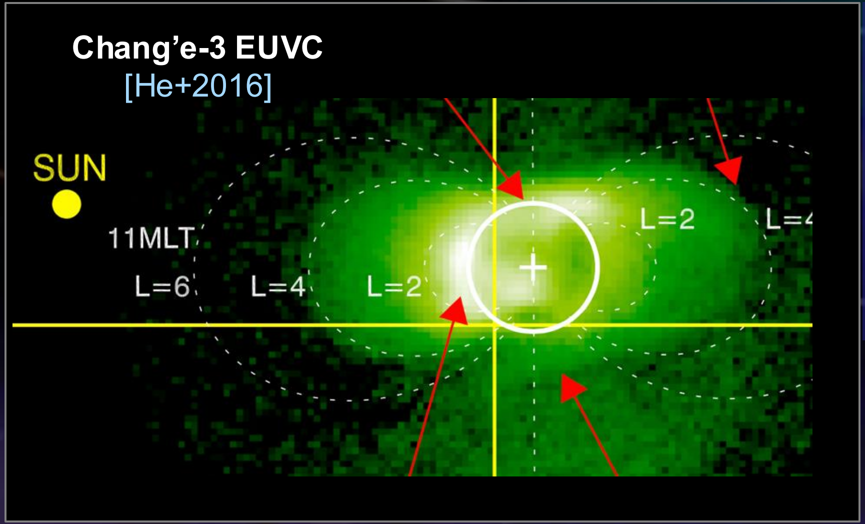
Two Missions so Far



KAGUYA Telescope of EXtreme ultraviolet (TEX)
[Murukami+2016, 10.1002/2016JA023377]

- **0.07º / 0.07 R_E resolution, 8.7º x 8.7º FOV**
- **0.02 counts $[R\ s\ pix]^{-1}$ => 320 cm^{-3} threshold.**

Very likely: apparent edge – plasmapause.



Chang'e-3 (CE-3) EUVC
[He+2016, 10.1002/2016JA023377]

- **0.08º / 0.08 R_E resolution, 15º field of view**
- **0.12 counts $[R\ s\ pix]^{-1}$**

High background (low SBR)

KAGUYA in lunar orbit

Lunar-Based EUV He⁺ Imaging of the Plasmasphere

What's Needed for 30.4 nm Imaging?

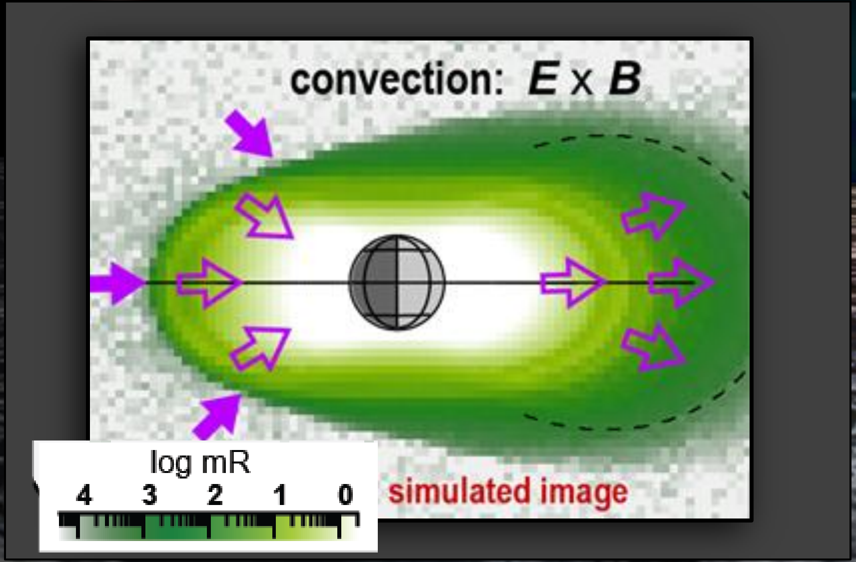
REQUIREMENTS for 30.4 nm IMAGER

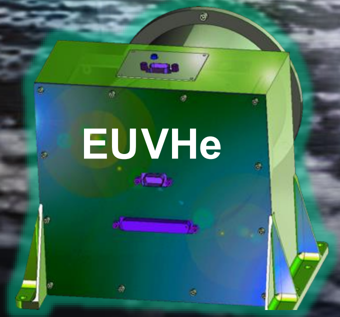
[Goldstein+2022, 10.1016/B978-0-12-820630-0.00010-6]

- **RESOLUTION:** 0.05º–0.01º
- **FOV:** 13º x 7º full angle
- **SENSITIVITY:** 2 [R s pix]$^{-1}$
- **REJECTION:** 58.4 nm, 121.6 nm, and IPM/ ISM 30.4 nm
- **ENV:** deal with dust, radiation

CRITICAL:

1. sensitivity
2. background rejection





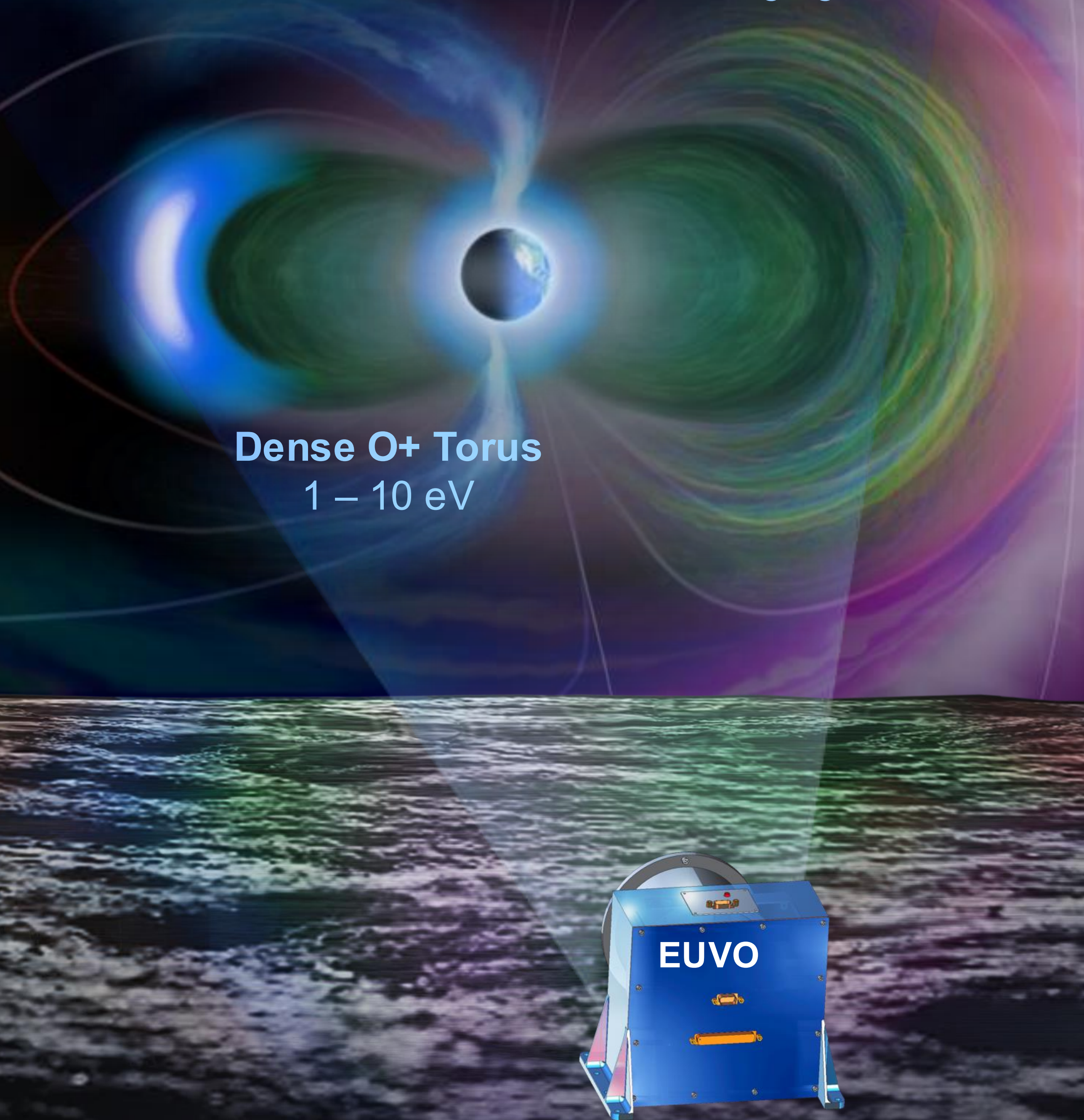
Lunar-Based EUV O+ Imaging of the Dense Torus

What's Needed for 83.4 nm Imaging?

REQUIREMENTS for 83.4 nm IMAGER

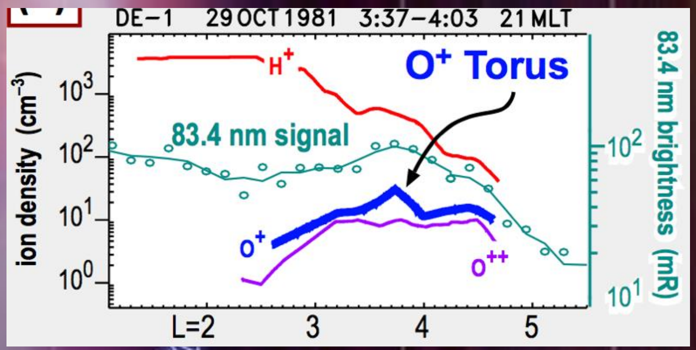
[Goldstein+2018, 10.1002/2017JA024531, Goldstein+2022, 10.1016/B978-0-12-820630-0.00010-6]

- **RESOLUTION:** 0.1º–0.2º
- **FOV:** 13º x 7º full angle
- **SENSITIVITY:** 0.5 – 2.0 [R s pix]$^{-1}$
- **REJECTION:** 58.4 nm, 121.6 nm, handle high-count 83.4 nm earthshine
- **ENV:** deal with dust, radiation

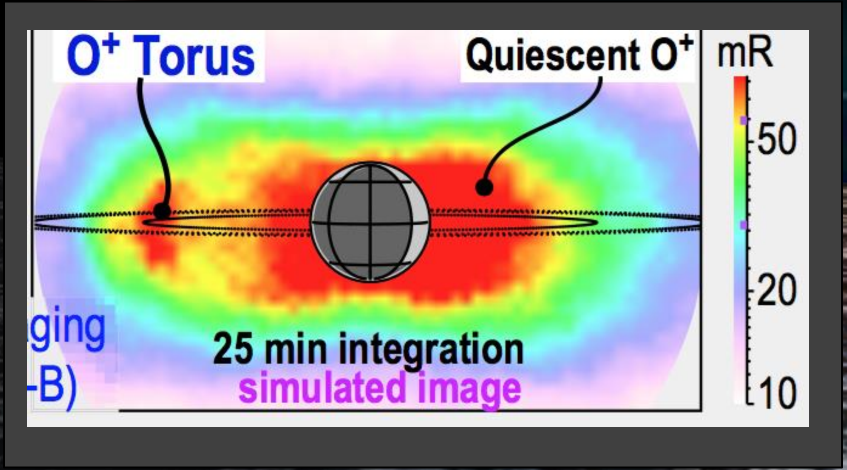


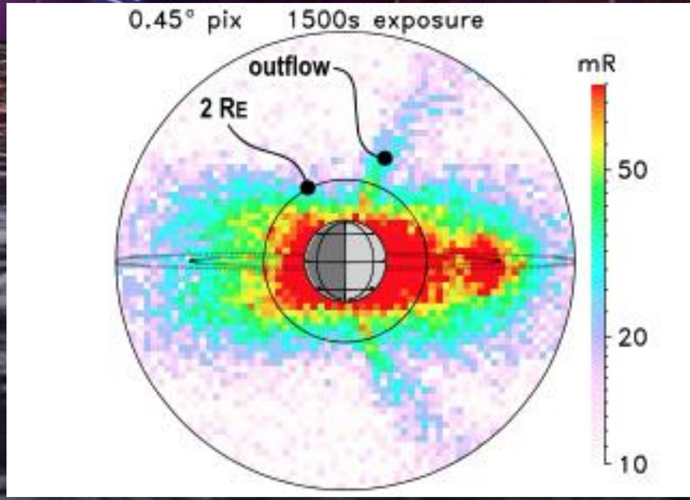
STILL CRITICAL:

1. sensitivity
2. background rejection



[Goldstein+2018, 10.1002/2017JA024531]





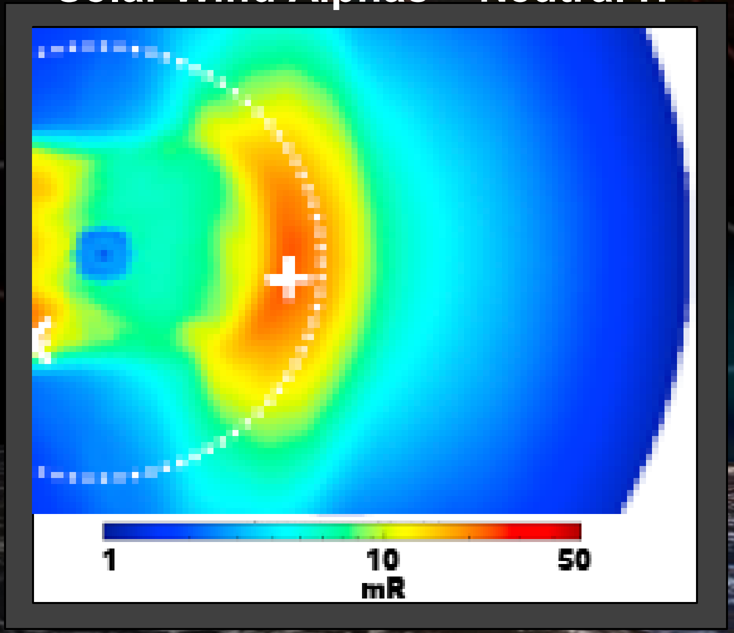
[Goldstein+2018, 10.1002/2017JA024531]

Lunar-Based EUV 30.4 nm Imaging of the Magnetosheath

Solar Wind Charge Exchange (SWCX)

BONUS

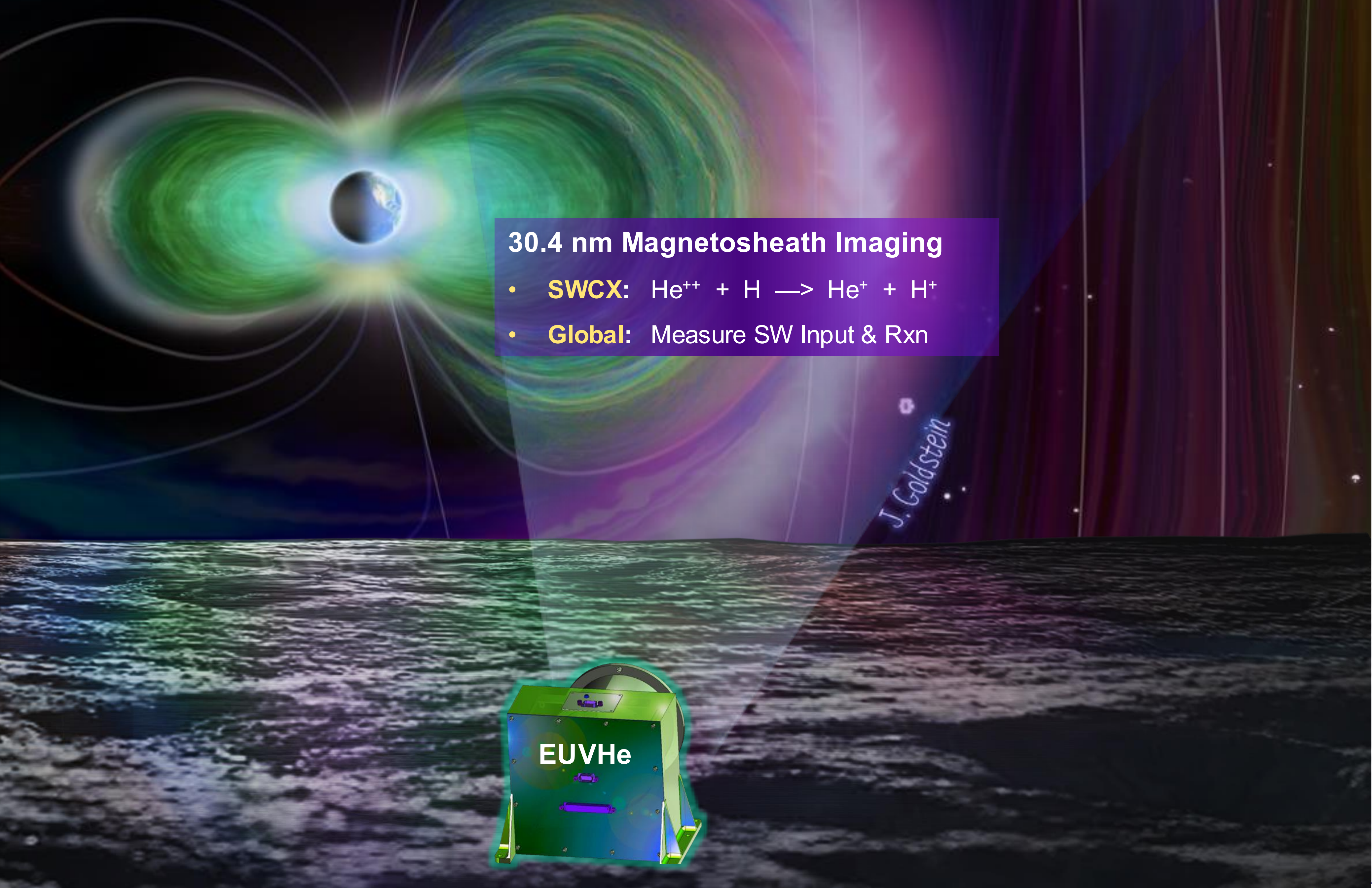
Solar Wind Alphas + Neutral H



Sheath He+ from SWCX: 30.4 nm
[He+2016, 10.1002/2014JA020521]

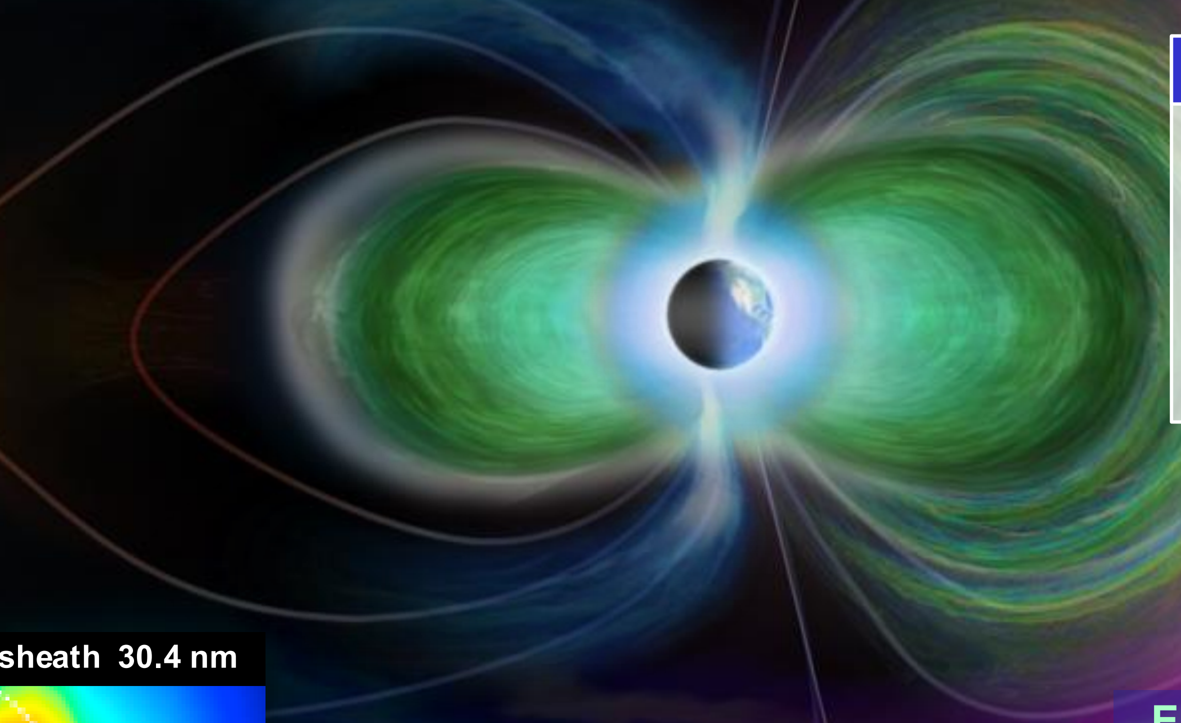
30.4 nm Magnetosheath Imaging

- **SWCX:** $He^{++} + H \longrightarrow He^{+} + H^{+}$
- **Global:** Measure SW Input & Rxn

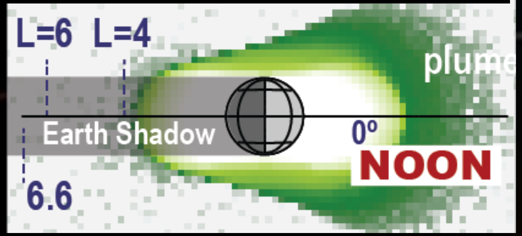


Imaging the Plasmasphere & Partner Populations

Coupled System => Complementary Imagers

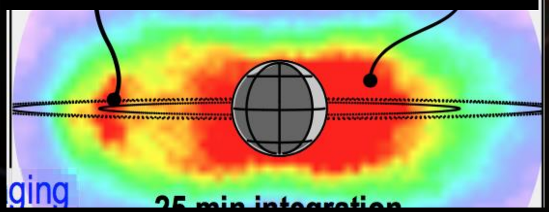


Plasmasphere He^+ 30.4 nm



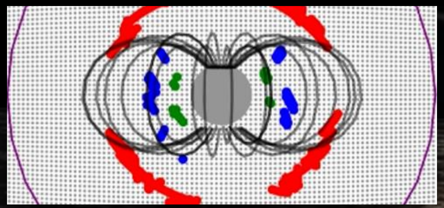
[Goldstein+2022, 10.1016/B978-0-12-820630-0.00010-6]

Dense O+ Torus 83.4 nm



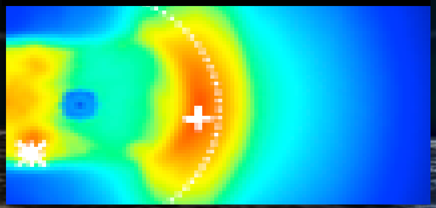
[Goldstein+2018, Goldstein+2022]

Plasmasphere TEC GNSS



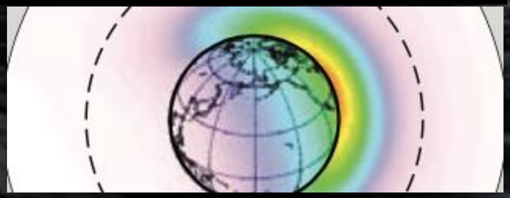
[Malaspina+2025, 10.1029/2024JA033426]

Magnetosheath 30.4 nm



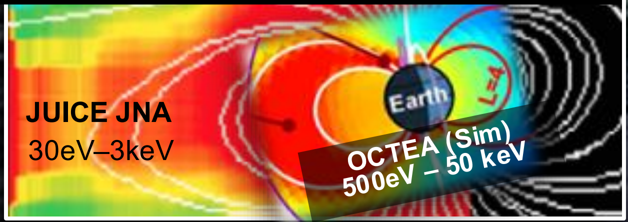
[He+2016, 10.1002/2014JA020521]

Neutral H Exosphere 121.6 nm



[Qin&Waldrop2016, 10.1002/2017JA024489]

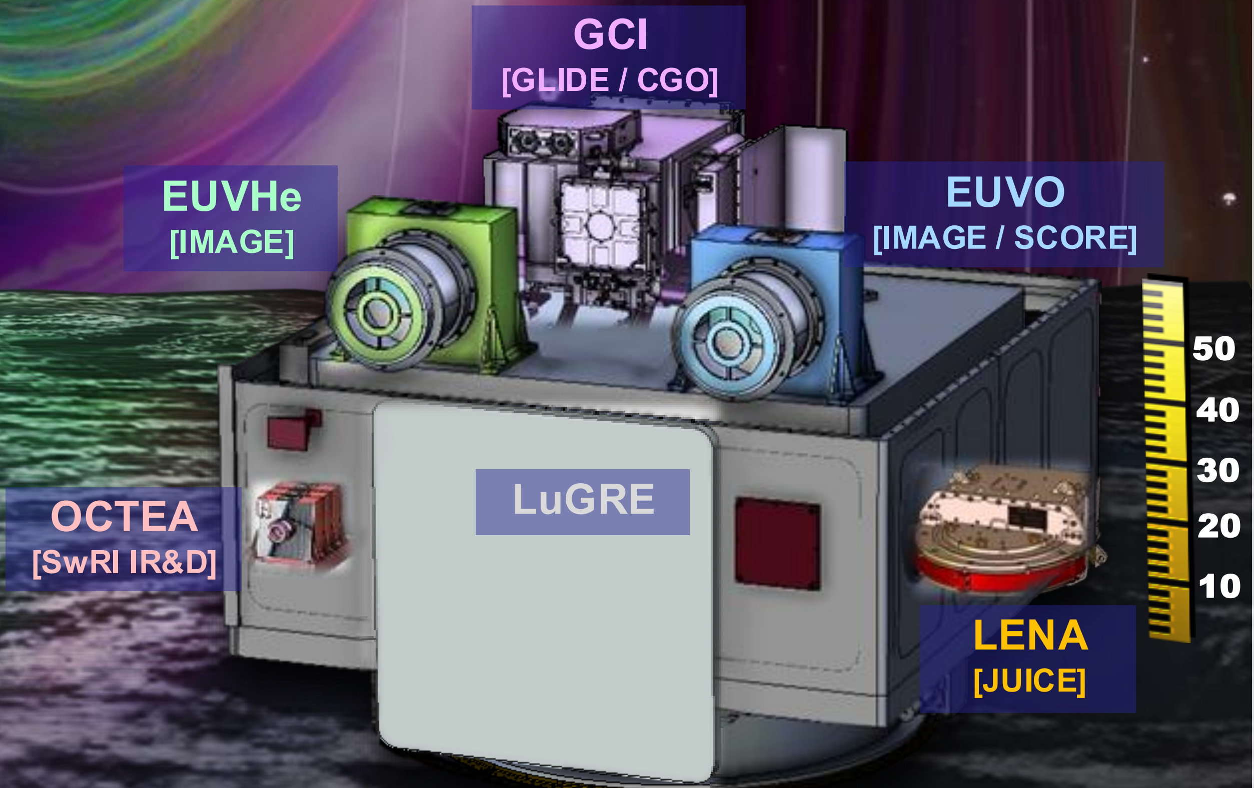
Plasma Sheet and Ring Current ENAs

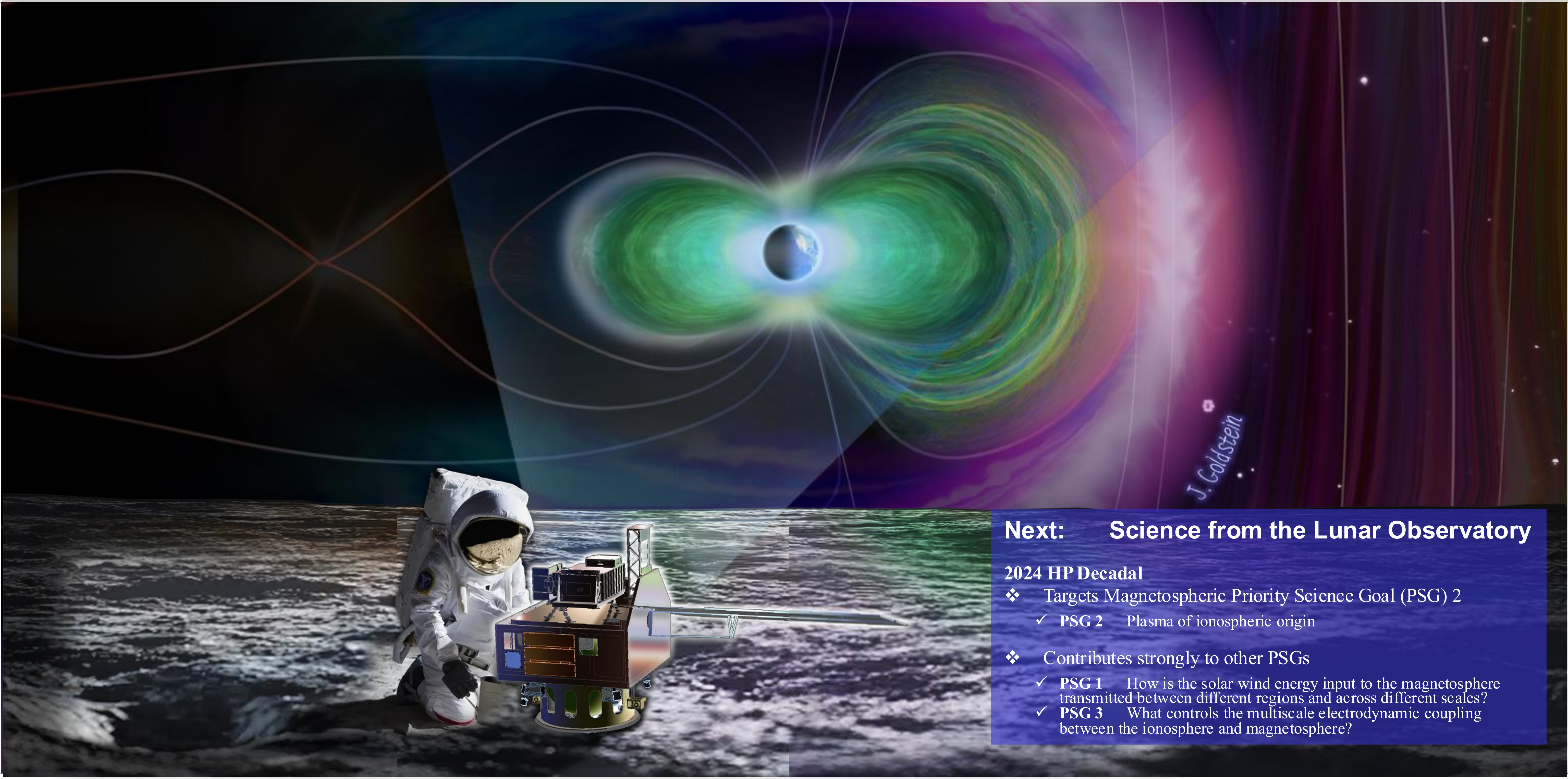


McComas+2011, Goldstein&McComas2013,2018

Observatory

• **EUVHe and EUVO**	He+ and O+ cold ions, and Sheath
• **LuGRE**	TEC from space
• => **Ion densities, mass density, Alfven, flows, E-fields**	
• **GCI**	Exospheric H (PS source, RC loss)
• **LENA**	JUICE JNA low energy RC
• **OCTEA**	1U cubesat sized ENA imager





Next: Science from the Lunar Observatory

2024 HP Decadal

- ❖ Targets Magnetospheric Priority Science Goal (PSG) 2
  - ✓ **PSG 2** Plasma of ionospheric origin
- ❖ Contributes strongly to other PSGs
  - ✓ **PSG 1** How is the solar wind energy input to the magnetosphere transmitted between different regions and across different scales?
  - ✓ **PSG 3** What controls the multiscale electrodynamic coupling between the ionosphere and magnetosphere?

1A Plasmasphere Formation

Refilling from the Ionosphere: *High Altitude View*

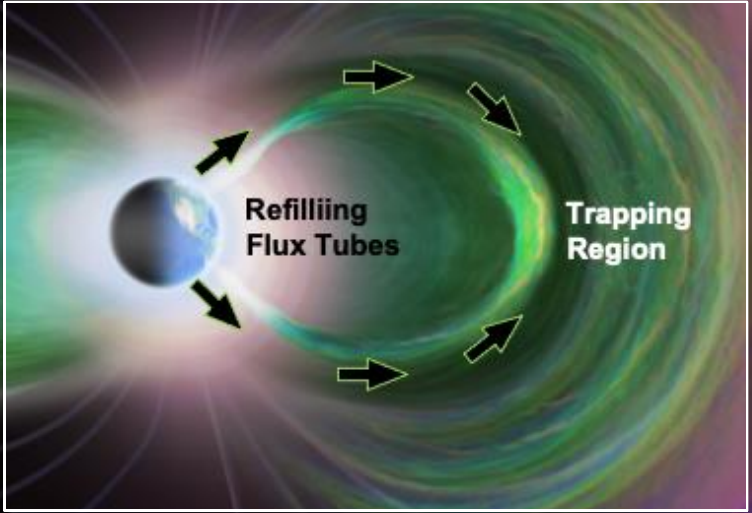
HP Decadal Priority Science Goal 2

- **PSG 2a.** Plasmasphere formation and evolution
- **PSG 2c.** Magnetospheric impacts
- **PSG 2d.** Ultimate fate of ionospheric-source plasma

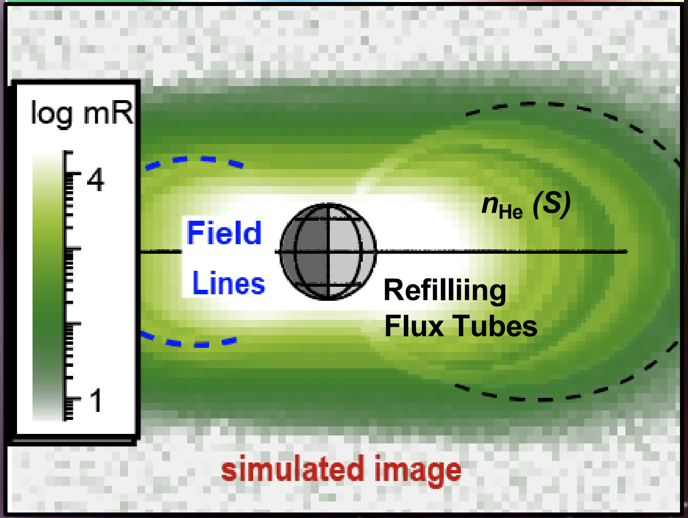
Plasmaspheric Filling ("Refilling")

[Singh & Horwitz 1992, Gallagher & Comfort 2016, Goldstein+2022, Krall & Huba 2013, 2021]

- **Question 1A: How are outflowing ions trapped in the plasmasphere?**
- **Measurement: Spatial variation, evolution of density n_{He+} (S, t) along the field**



EUVHe 30.4 nm Image



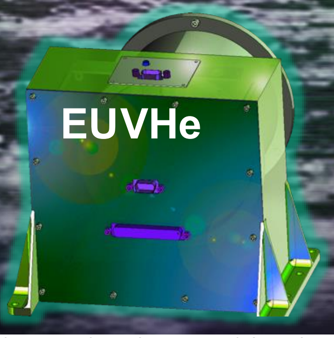
Significance & Impact

Applicable for all science questions

- **Significance:** Hundreds of metric tons of plasma supplied or removed.
- **Impact:** Mass controls energy transport and reconnection. Density, composition regulate wave-particle interactions with RB, RC.

EUVHe Method: Hypothesis Testing

- Density inversion or forward model => n_{He+} (S, t)
- Time dependence => 2 Stage Refilling hypothesis
- Equatorial peak => Early-stage shocks
- Compare with Refilling Models

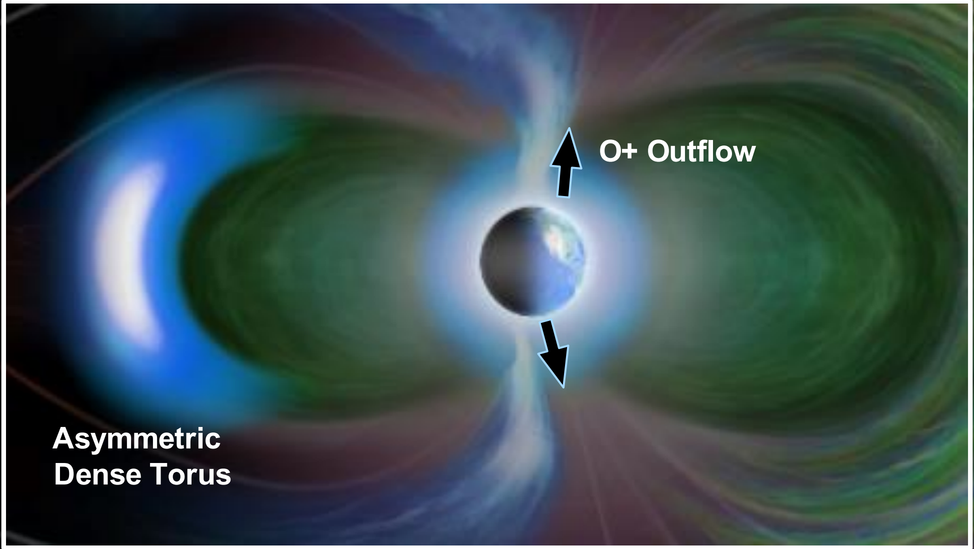


1B Dense Oxygen Torus Formation

Heavy Ion Outflow

HP Decadal Priority Science Goal 2

PSG 2a. Plasmasphere formation and evolution
PSG 2c. Magnetospheric impacts
PSG 2d. Ultimate fate of ionospheric-source plasma

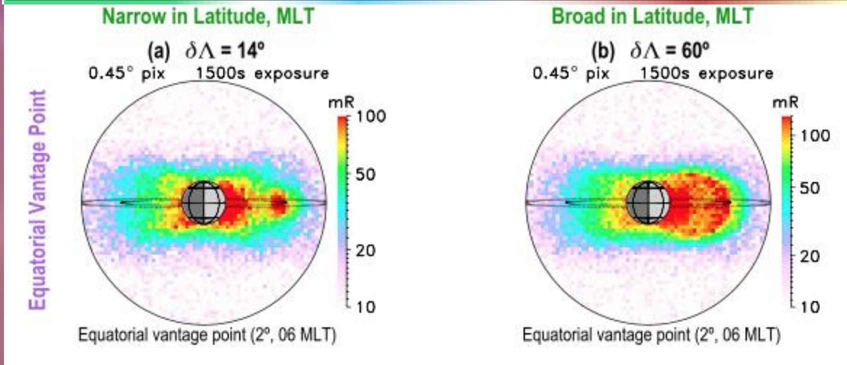


Oxygen Reservoir

[Singh & Horwitz 1992, Gallagher & Comfort 2016, Goldstein+2022, Krall & Huba 2013, 2021]

- **Question 1B:** What are the structure and dynamics of the dense O+ torus?
- **Measurement:** Spatial variation, evolution of density n_{O+} (L, S, t)

Sim EUVO First-Light Images



EUVO Hypothesis Testing

- Density inversion or forward model => n_{O+} (L, S, t)
- Time dependence => Formation mechanism, participation in convection, erosion
- Latitudinal extent => Trapped or Bi-directional
- Asymmetry => Day vs night mechanism

1C Plasmasphere Formation

Refilling from the Ionosphere: Low Altitude View

HP Decadal Priority Science Goal 2

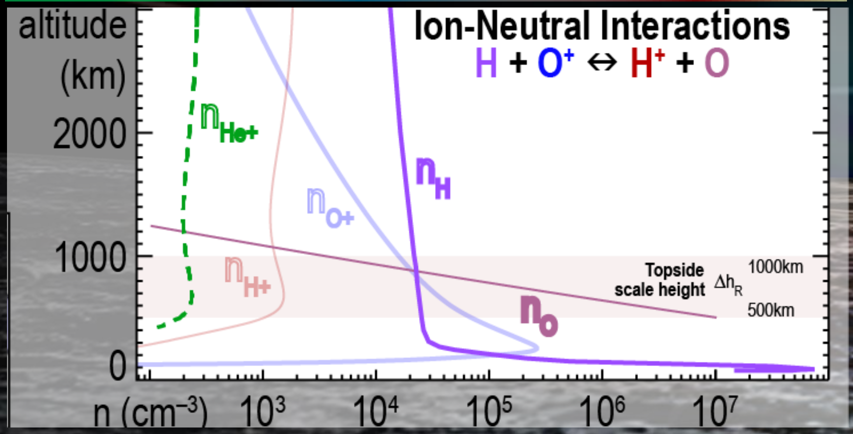
- **PSG 2a.** Plasmasphere formation and evolution
- **PSG 2c.** Magnetospheric impacts
- **PSG 2d.** Ultimate fate of ionospheric-source plasma

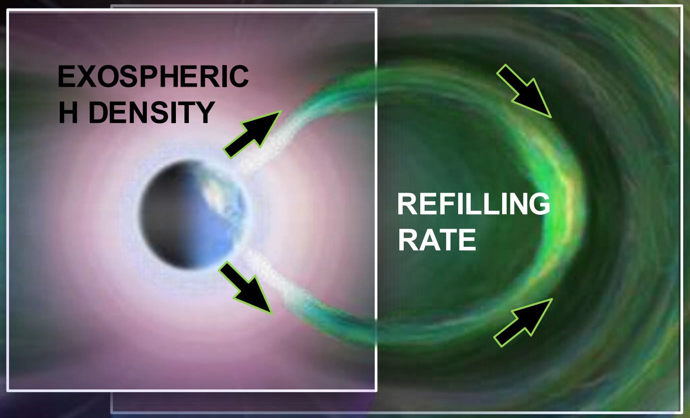
Ionospheric Escape

[Geisler1967, Krall+2018, Cucho-Padin&Waldrop 2019, Qin & Waldrop 2016]

- **Question 1C: How do exospheric variations control light-ion refilling?**
- **Measurement: Exospheric H density**

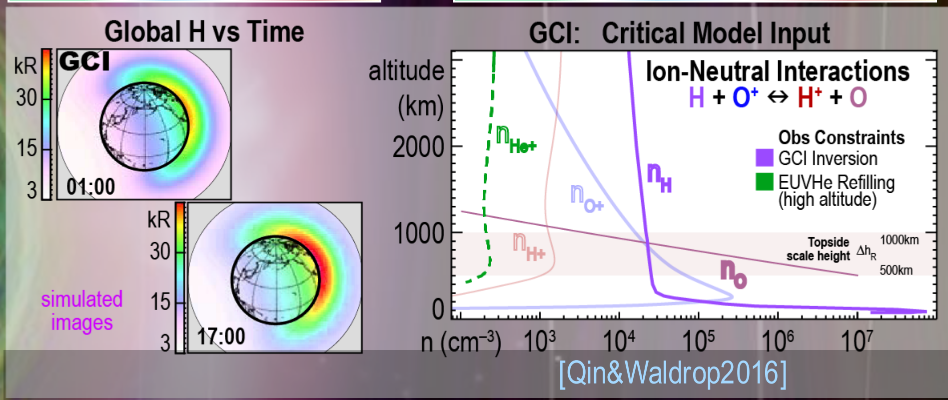
Low Altitude Light-Ion Escape





GCI 121.6 nm Images

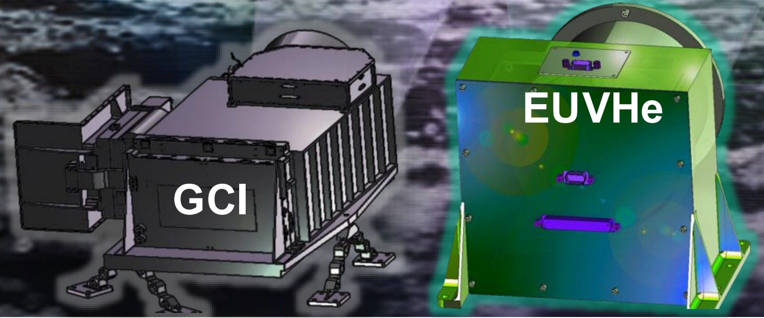
Neutral H Retrievals



GCI Method: Hypothesis Testing

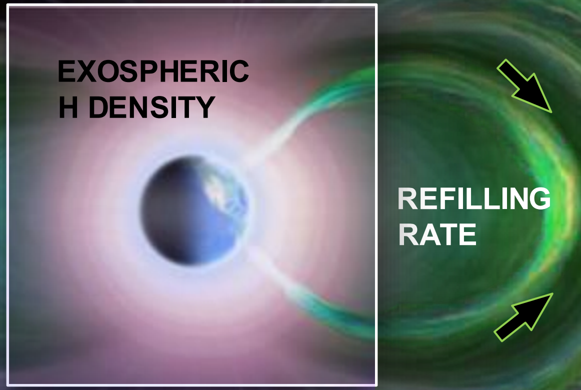
- H Density vs altitude, angle, time => $n_H(h, q, t)$
- H variation => Does H escape drive $dn_{He+}(t) / dt$?
- Complement with Ionospheric & Refilling Models

GeoCoronal Imager [GLIDE / CGO]

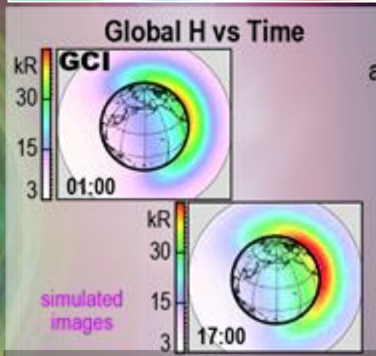


Neutral H "Geocorona" Imaging

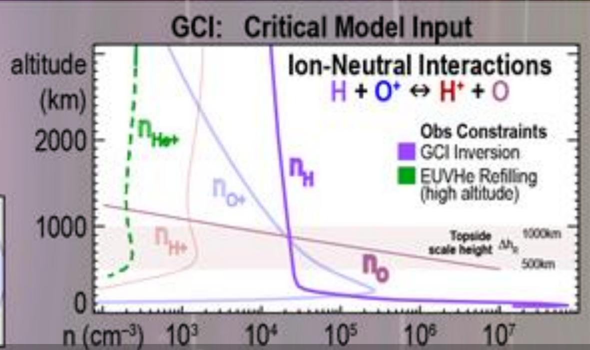
The Dynamic, Asymmetric Exosphere



GCI 121.6 nm Images

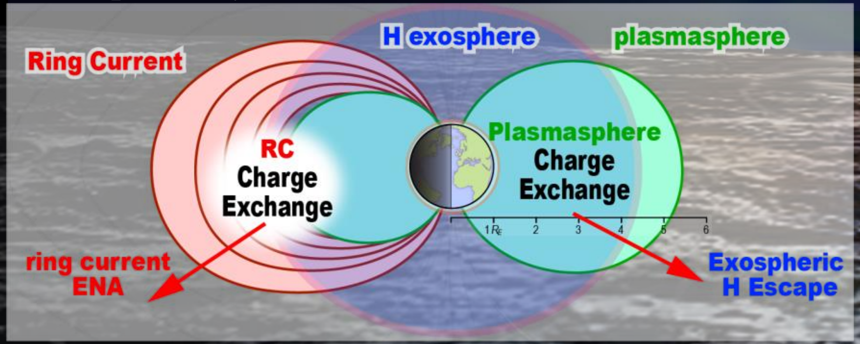


Neutral H Retrievals

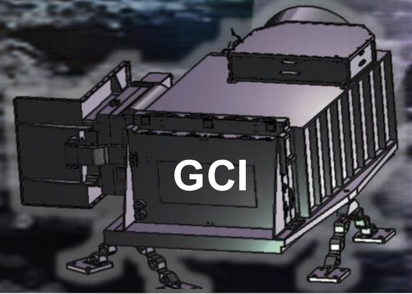


[Qin&Waldrop2016]

- **Added Impact:** ***Exospheric charge exchange*:**
  - **with** the ring current => controls storm recovery
  - **with** the plasmasphere => controls long-term planetary H loss rates (and H_2O loss)



GeoCoronal Imager
[GLIDE / CGO]

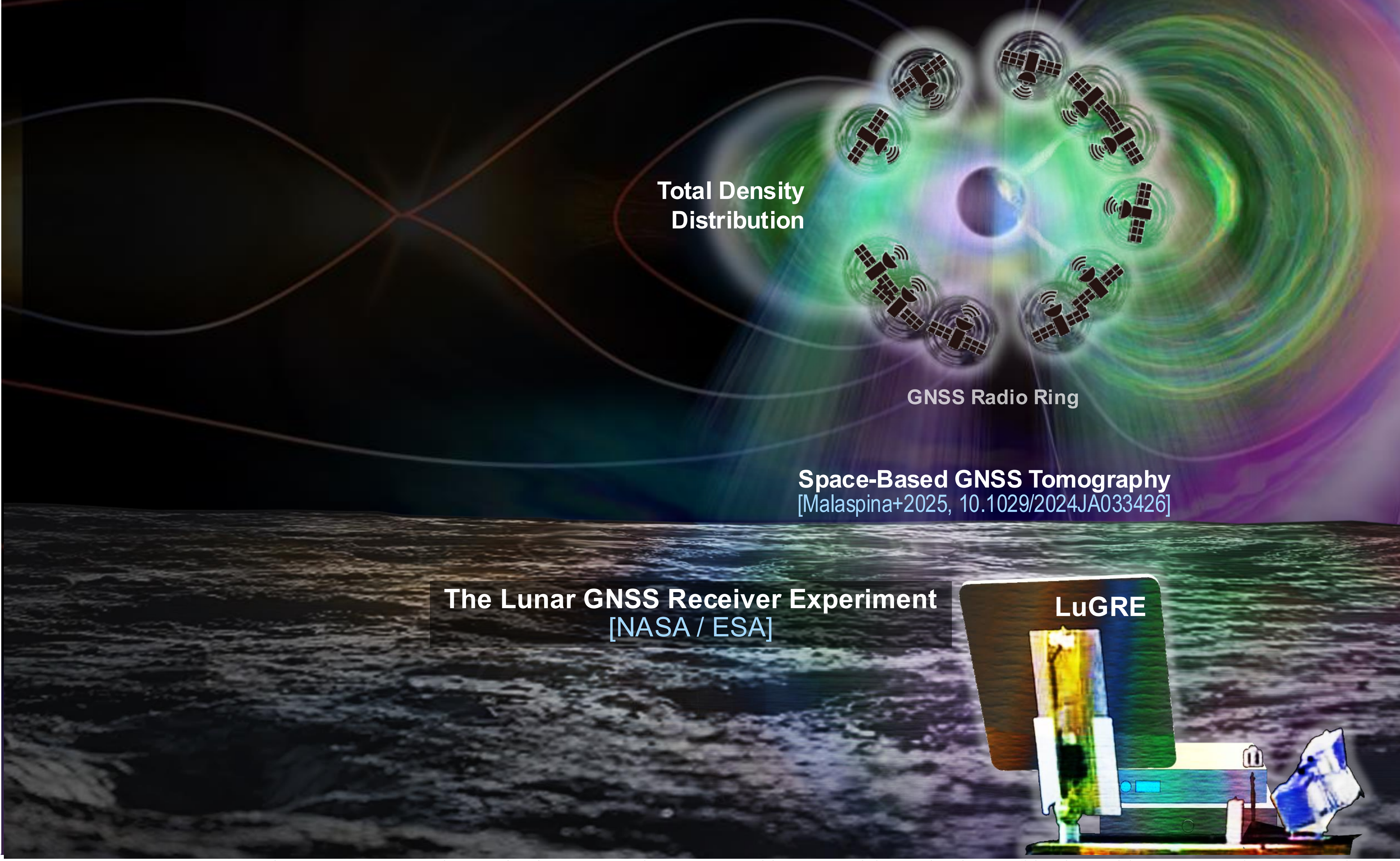


GCI Instrument Requirements

SNR@limb:	> 250	GCI:	378
OOB subtraction		GCI:	30% accuracy
IN-band subtraction		GCI:	IPH 30% acc
angular resolution	< 0.22º	GCI:	0.09º (200 km)

Lunar-Based GNSS Tomography

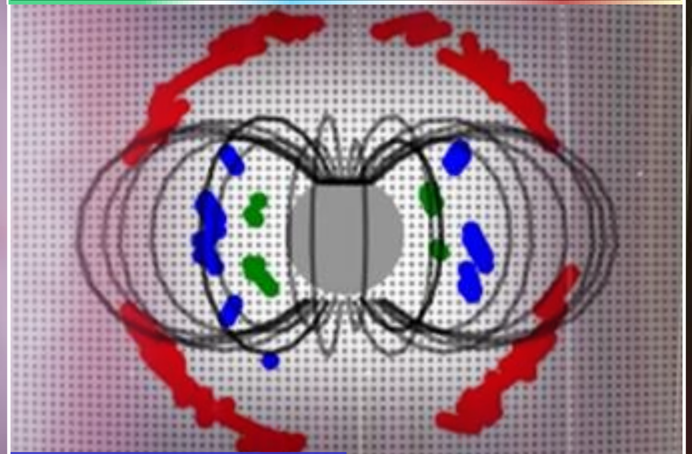
Using Already In-Place GNSS Assets



Space-Based GNSS Tomography
[Malaspina+2025, 10.1029/2024JA033426]

The Lunar GNSS Receiver Experiment
[NASA / ESA]

LuGRE TEC in EUVHe FOV



[Malaspina+2025]

LuGRE "Bridge" Measurements

- Sparse matrix of plasmaspheric TEC assimilated => n_{H+} and n_{e-} => improve n_{He+}
- Light ion refilling: $n_{e-} = n_{H+} + n_{He+} + n_{O+}$

Instrument Requirements

- **Freq, Signal Acq Time:** L1 + L5 319s
- **Carrier/Noise:** 25-45 dB-Hz
- **Simult GNSS Contacts:** 13

2A Plasmasphere Evolution

Mass Coupling and Transport ("Follow the Mass")

HP Decadal Priority Science Goal 2

- **PSG 2a.** Plasmasphere formation and evolution
- **PSG 2c.** Magnetospheric impacts
- **PSG 2d.** Ultimate fate of ionospheric-source plasma

Plasmaspheric Erosion

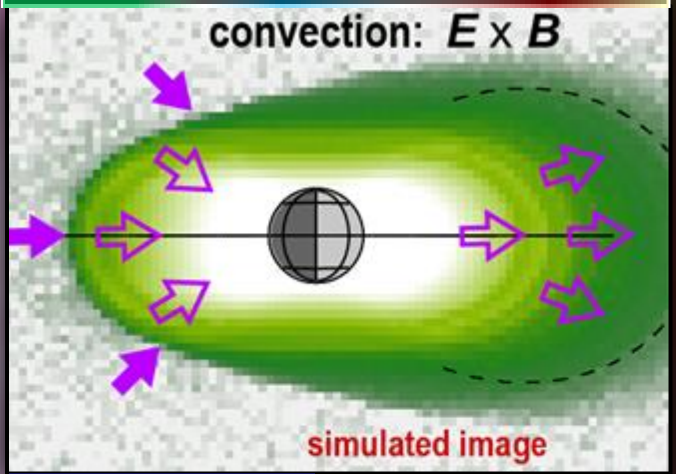
[Goldstein+2003, 2004, 2020, 2022, & Sandel 2005, Spasojevic & Sandel, 2010, Nakano+2014a, b]

- **Question 2A: How is plasmaspheric mass removed, and where does it go?**
- **Data Products:** From EUVHe + LuGRE + EUVO obtain the global time evolution (vs L, S, t) of
  - ✓ number density — n_{He+} n_{e-} n_{H+} n_{O+}
  - ✓ mass density, Alfven speed — ρ V_A
  - ✓ flows, electric fields — $\mathbf{v}$ and $\mathbf{E}$.

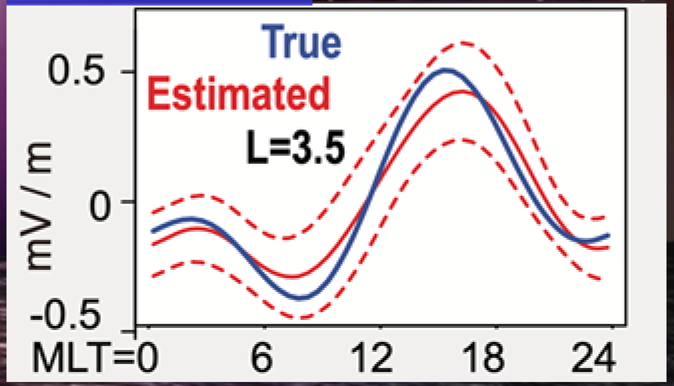
- **Follow the Mass**:** These data products enable answering Question 2A, and several others as well.

** [Malaspina+2022, 10.3389/fspas.2022.910730]

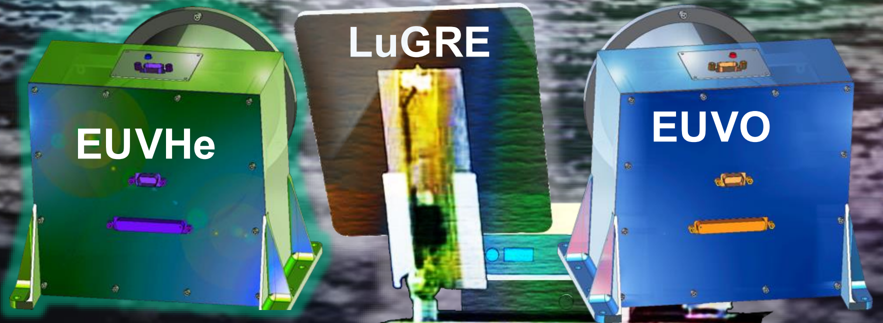
EUVHe Erosion Images



[Goldstein+2022]

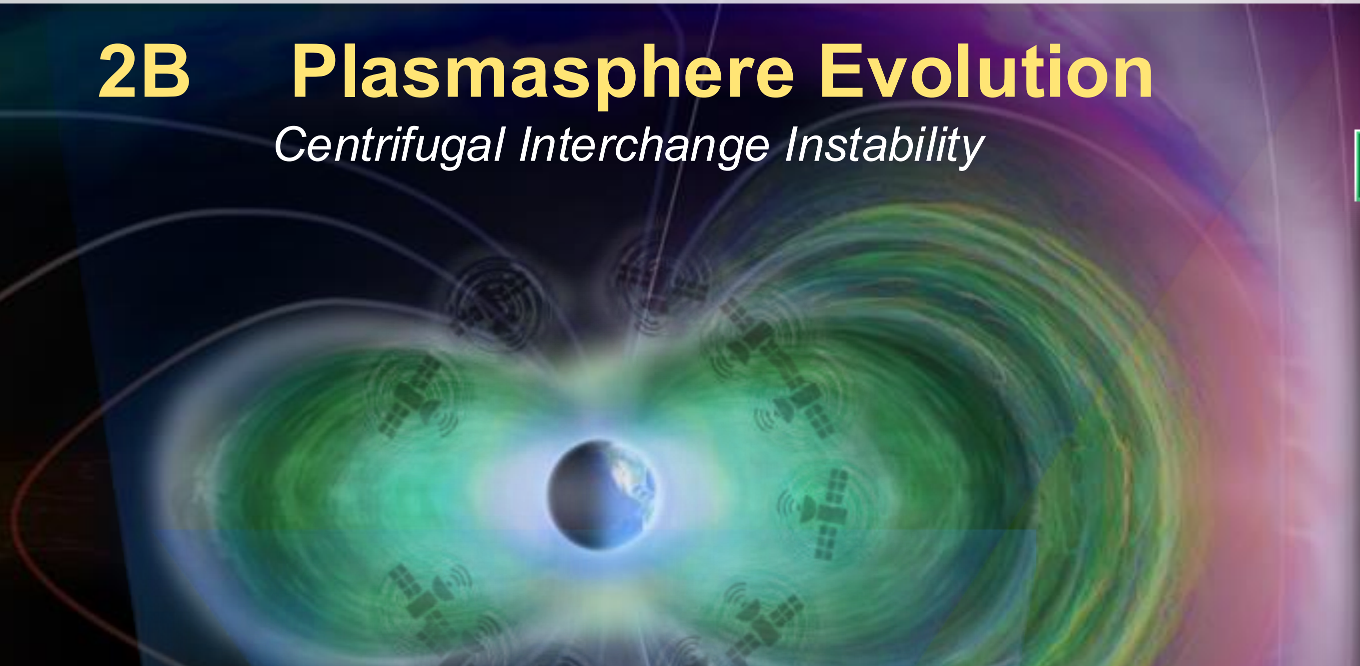


[Nakano+2014a, b]



2B Plasmasphere Evolution

Centrifugal Interchange Instability



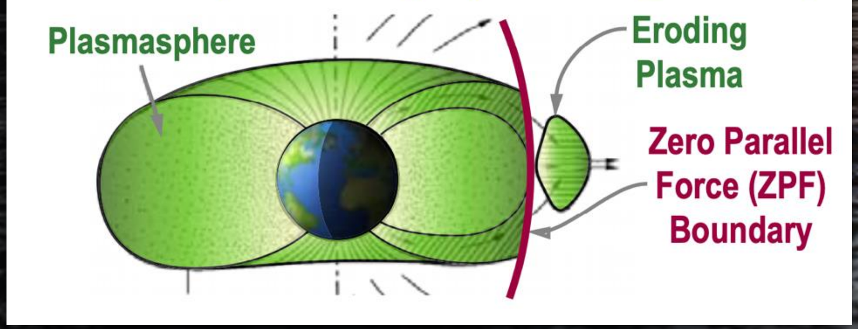
HP Decadal Priority Science Goal 2

PSG 2a. Plasmasphere formation and evolution
PSG 2c. Magnetospheric impacts
PSG 2d. Ultimate fate of ionospheric-source plasma

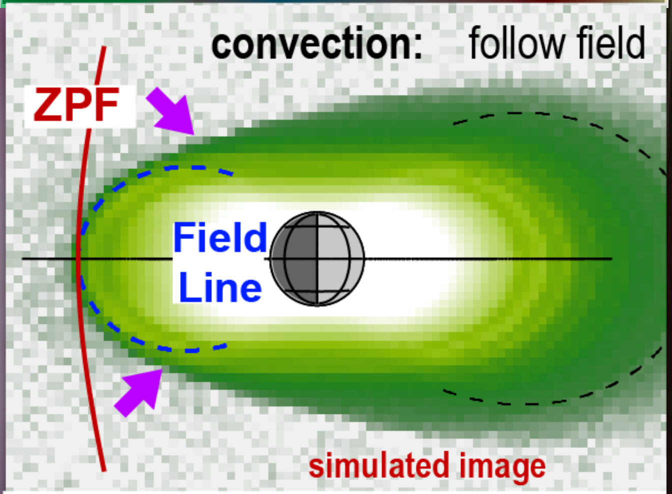
Interchange at the Plasmapause

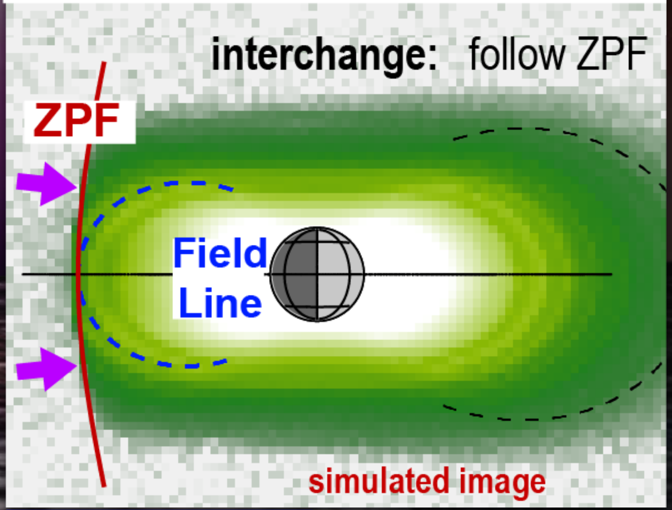
[Lemaire & Gringauz 1998, Lemaire & Pierrard 2008, Goldstein+2022]

- **Question 2B: What mechanisms cause erosion of the plasmasphere?**



EUVHe Hypothesis Testing

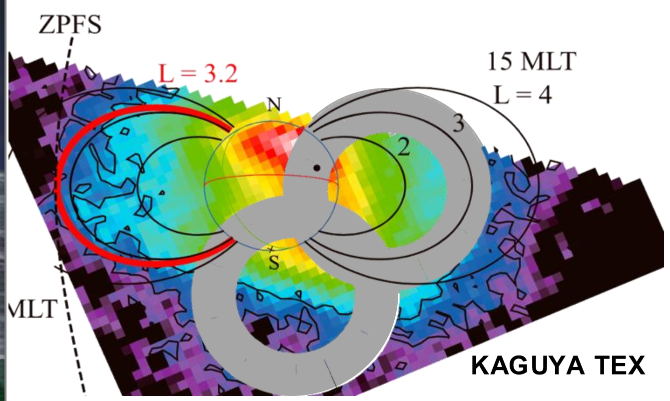




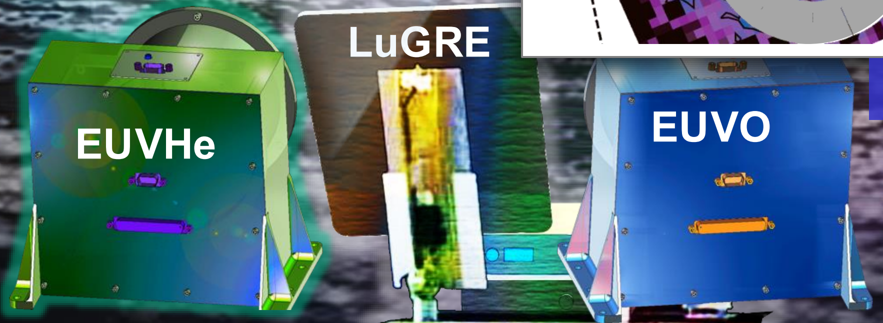
[Goldstein+2022]

Kaguya ZPF Measurement

At >300 cm^{-3} (probably not plasmapause)

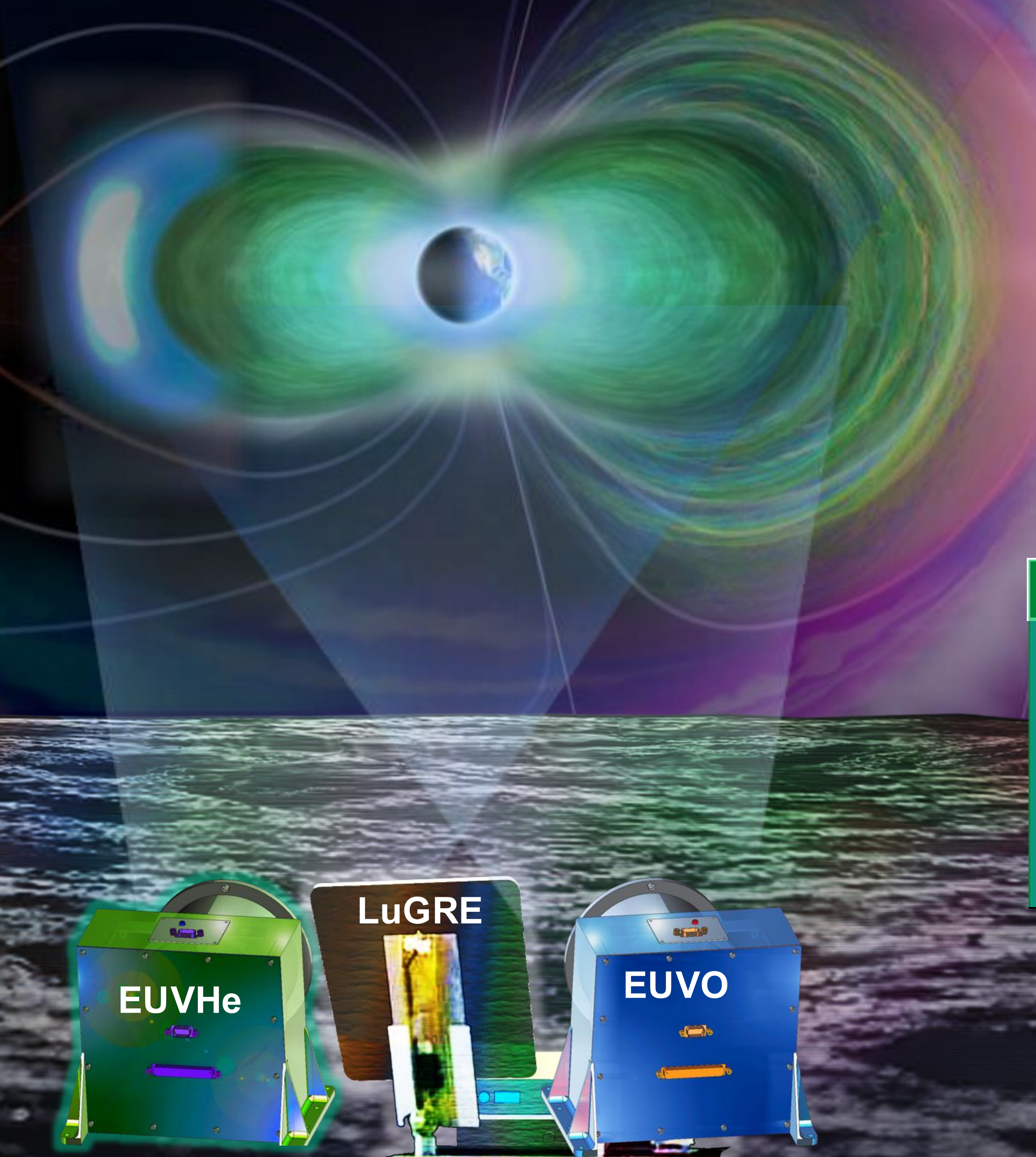


[Murukami+2016]



3A Plasmasphere Control

Effect on Partner Populations



HP Decadal Priority Science Goal 2

- **PSG 2a.** Plasmasphere formation and evolution
- **PSG 2c.** Magnetospheric impacts
- **PSG 2d.** Ultimate fate of ionospheric-source plasma

Currents, Fields, Energetic Particles

- **Question 3A: What system-level control is exerted by plasmaspheric changes (density, structure, composition)?**

Plasmasphere Control

- **Impact:** Mass controls energy transport and reconnection. Density, composition regulate wave-particle interactions with RB, RC.
- **Data Products:** Global time evolution (vs L, S, t)
  - ✓ **number density** — n_{He+} n_{e-} n_{H+} n_{O+}
  - ✓ **mass density, Alfven speed** — ρ V_A
  - ✓ **flows, electric fields** — $\boldsymbol{v}$ and $\boldsymbol{E}$.

Plasmasphere exerts basic control over fundamental set of currents, fields, and particles [Alfven waves, wave particle interactions, spacecraft charging, reconnection]

- suppression of warmer particles
- plumes (dayside reconnection, ionospheric SED)
- loss of exosphere, long-term water escape

[Claudepierre+2023; 10.3847/25c2cfeb.9ec7bba4]

Method: Global Input to Models

EUVHe, EUVO, LuGRE data products to models:

- Ring current ions (EMIC, Coulomb collisions)
- Radiation belt electrons (wave-particle)
- EMIC, chorus, hiss, Alfven wave growth and propagation
- spacecraft charging

3B, 3C Tracking Energy Through the System

System-Level Electric Field, Timing, Feedback

HP Decadal Priority Science Goal 2

PSG 2a. Plasmasphere formation and evolution
PSG 2c. Magnetospheric impacts
PSG 2d. Ultimate fate of ionospheric-source plasma

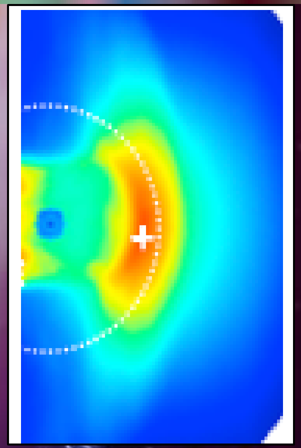
Magnetic Reconnection
2
INJECTION
3
Erosion, Plume
4
Magnetic Reconnection
1
Solar Wind

2 + 3 = 30 min
to the nightside

Energetic Neutral Atoms (ENAs)

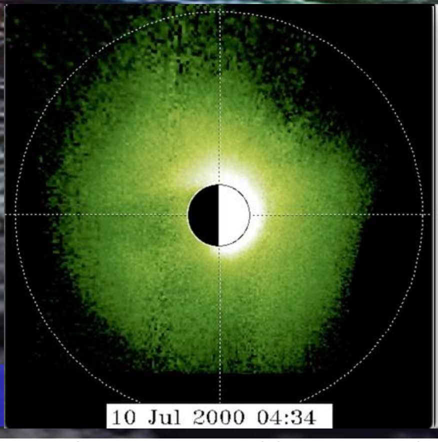
McComas+2011, Goldstein&McComas2013,2018

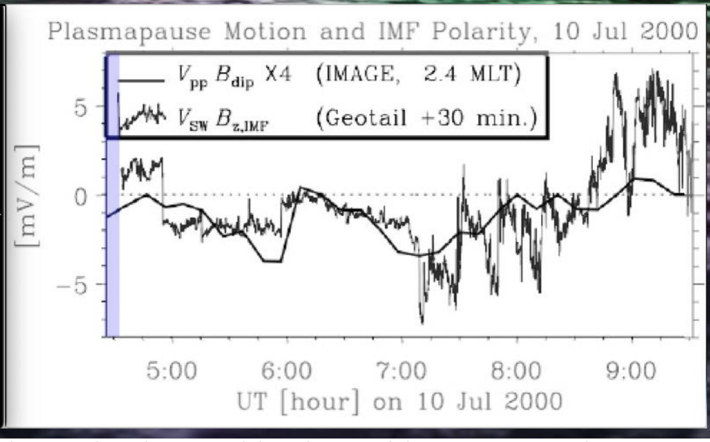
EUVHe Sheath



[He+2016, 10.1002/2014JA020521]

Direct Driving by IMF *with a 30 min propagation delay*





[Goldstein+2003]

Energy Flow

[Goldstein+2003, 2004, 2020, 2022, & Sandel 2005, Nakano+2014a, b, Borovsky & Denton 2006]

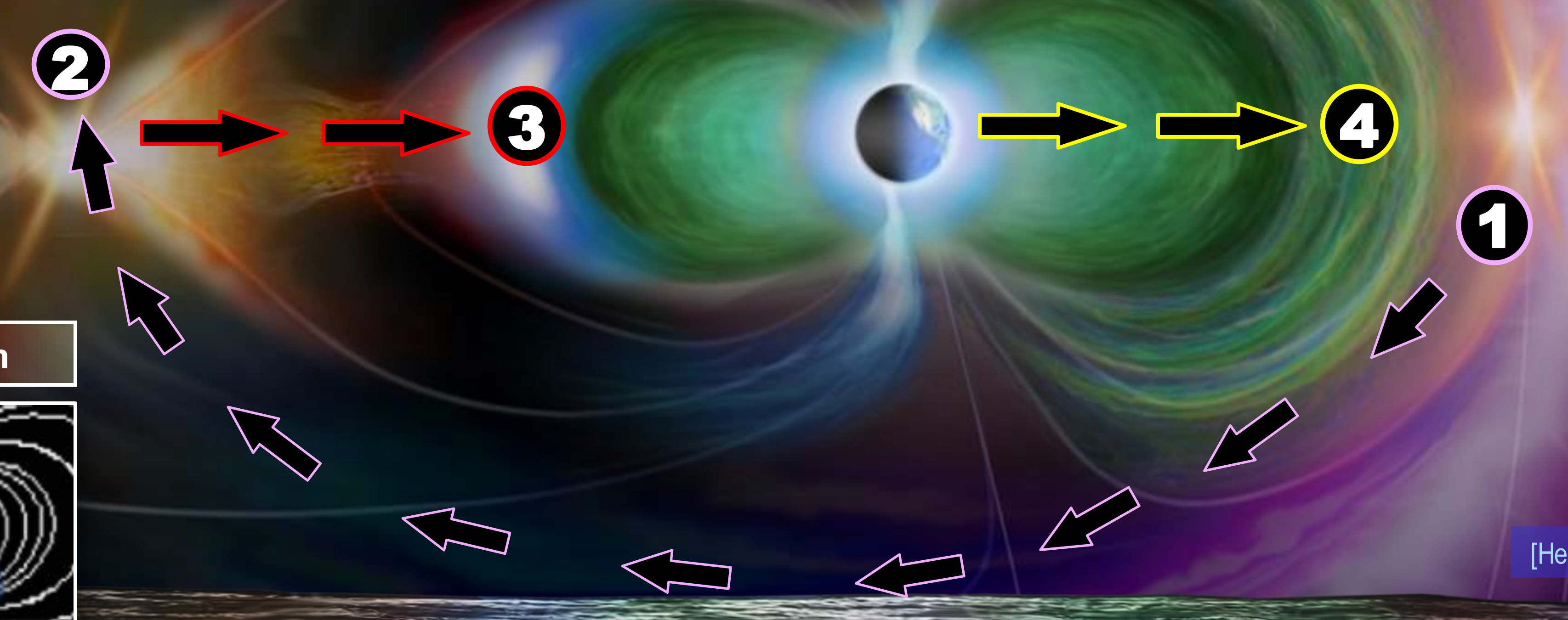
- **Question 3B:** How does solar wind energy flow through the geospace system?
- **Question 3C:** Do plumes modulate dayside reconnection?

3D Core Plasma Recirculation

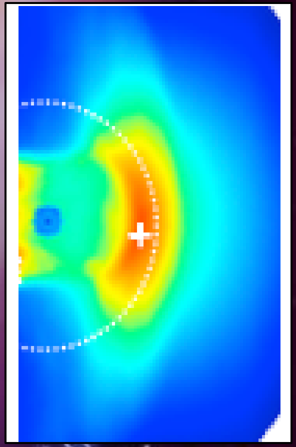
The fate of plume plasma... and a source of RC plasma

HP Decadal Priority Science Goal 2

PSG 2a. Plasmasphere formation and evolution
PSG 2c. Magnetospheric impacts
PSG 2d. Ultimate fate of ionospheric-source plasma

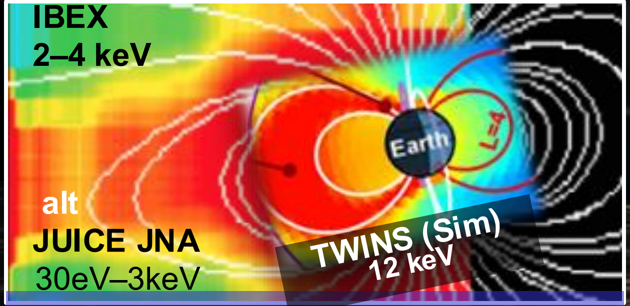


Reconnection

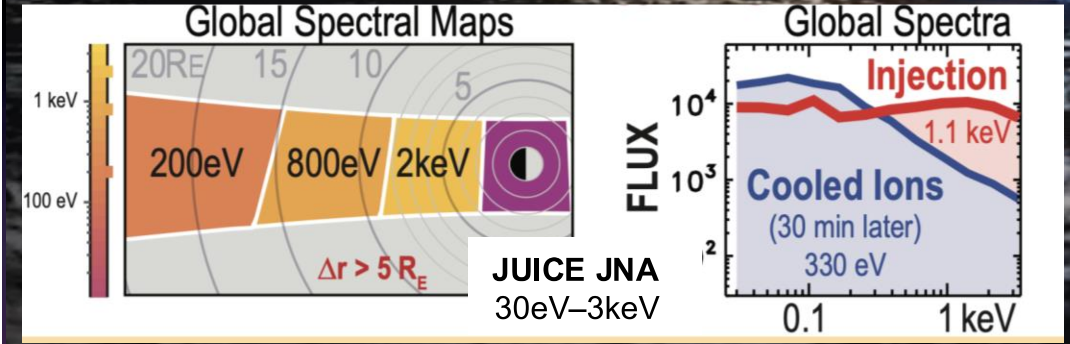


[He+2016, 10.1002/2014JA020521]

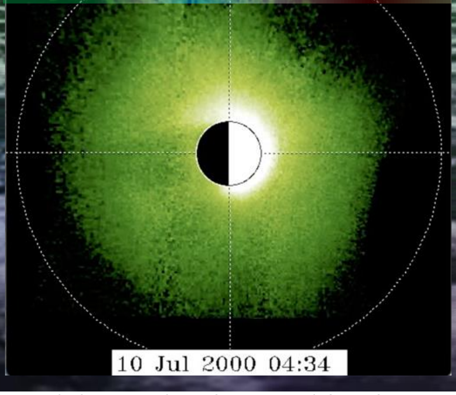
Recirculation and Injection



McComas+2011, Goldstein&McComas2013,2018



Erosion Event



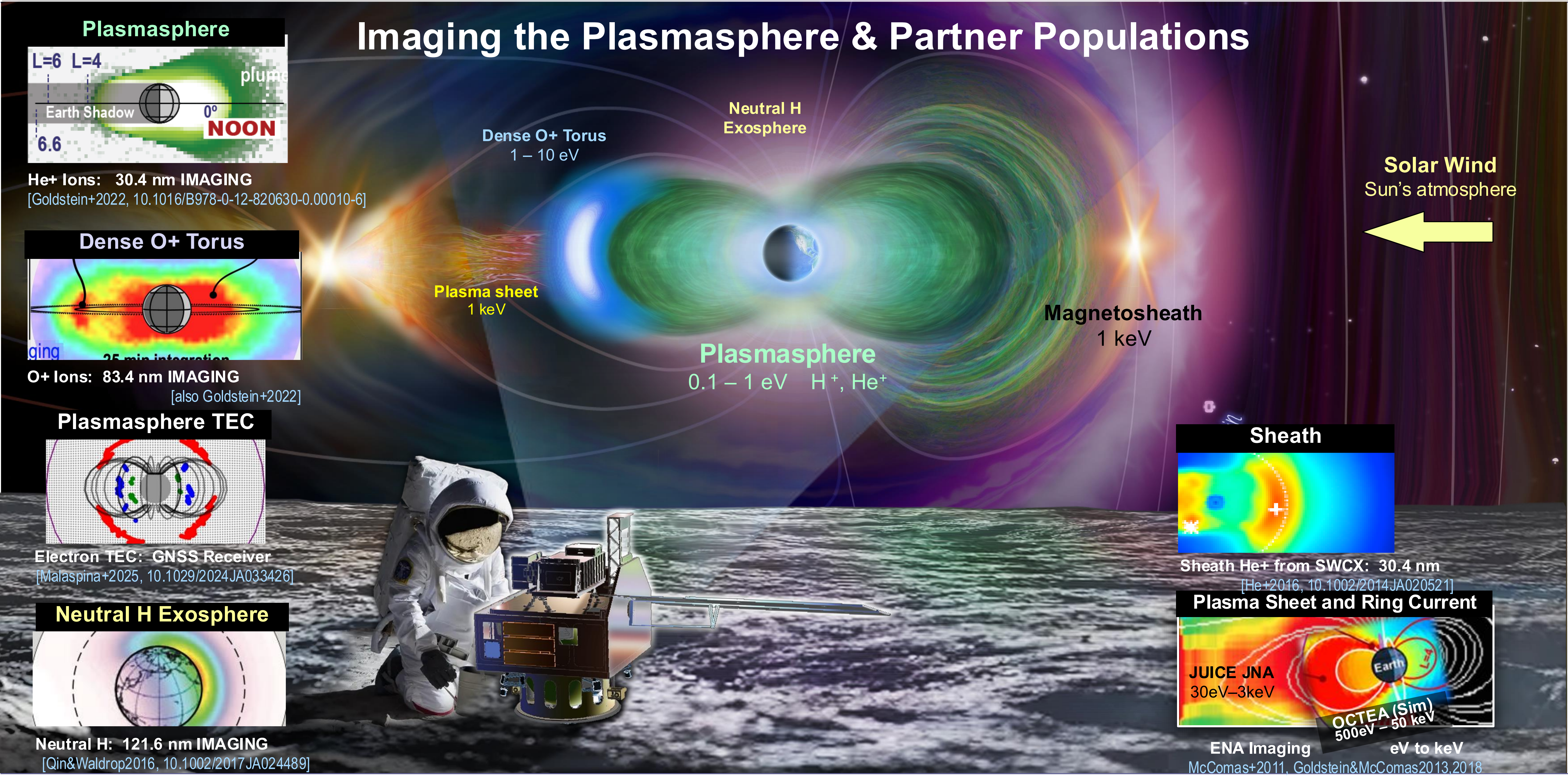
[Goldstein+2003]

Mass Flow

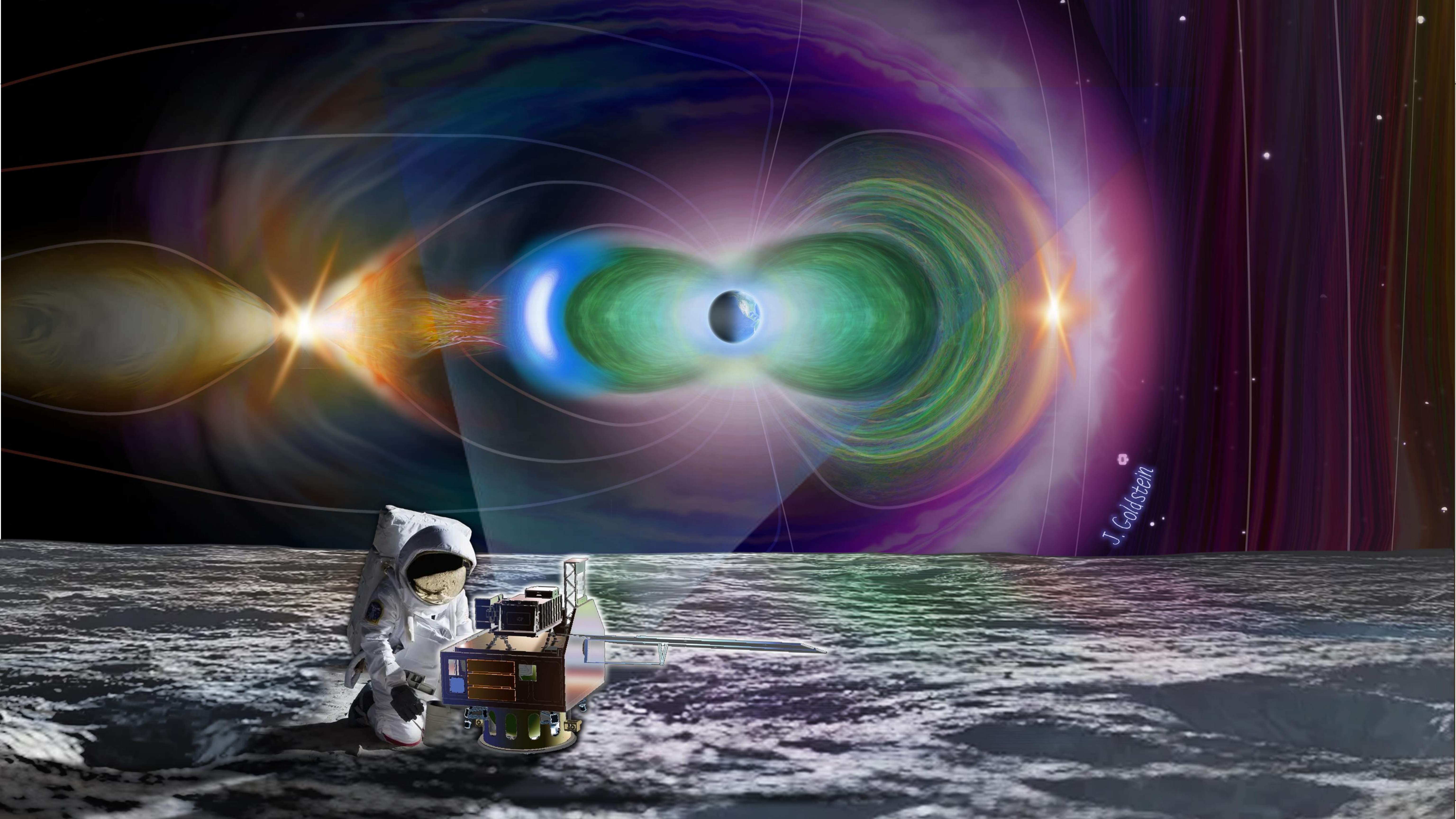
[Bagby-Wright+2022]

- **Question 3D: Do recirculated plumes supply significant plasma to the stormtime RC?**

Imaging the Plasmasphere & Partner Populations



J. Goldstein


J. Goldstein

Lunar-Based EUV Imaging of Geospace: *Conclusions*

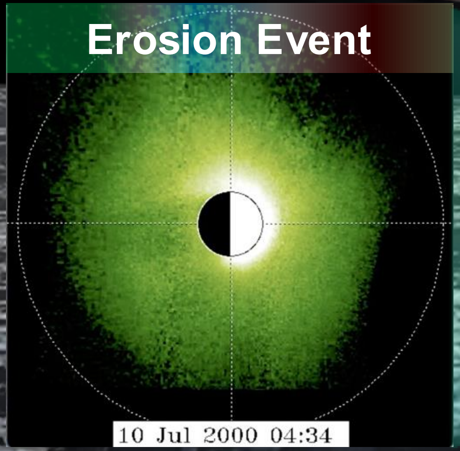
Science

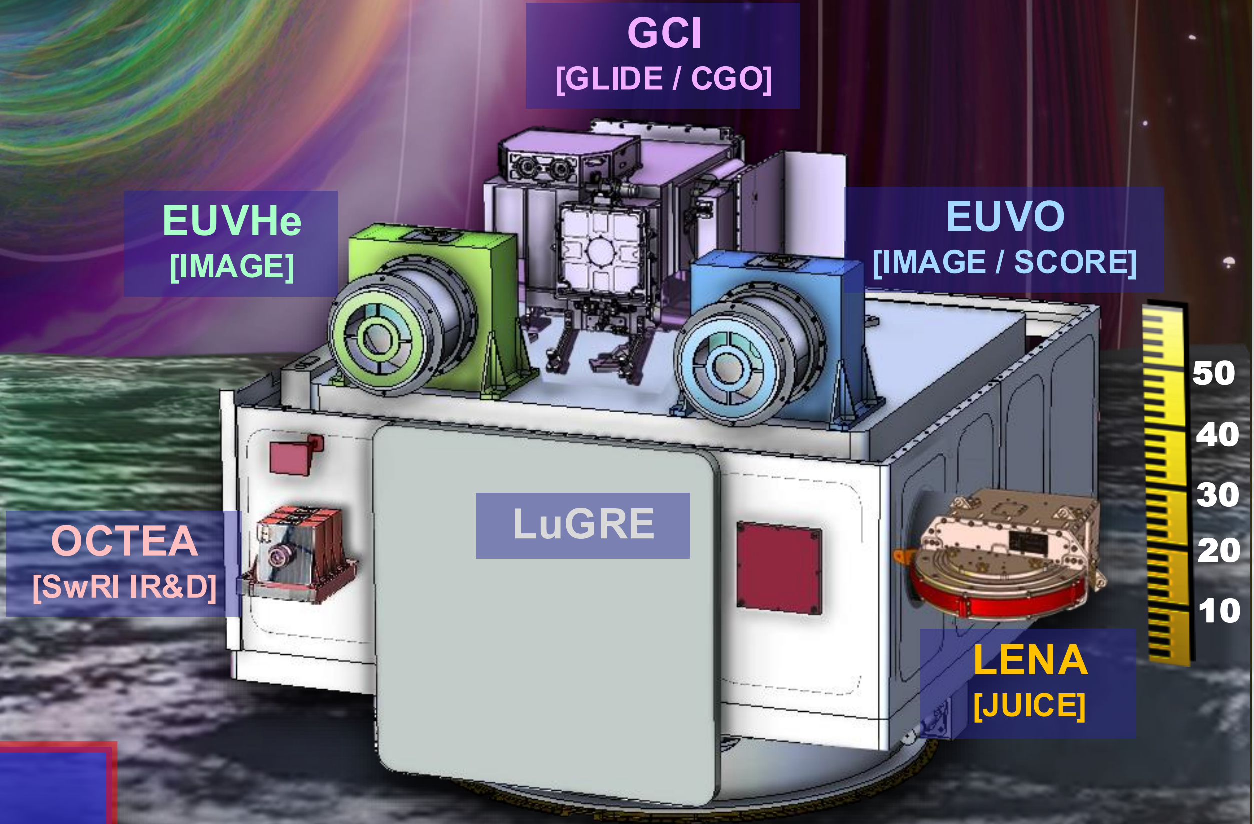
2024 HP Decadal

- ❖ Targets Magnetospheric Priority Science Goal (PSG) 2
  - ✓ **PSG 2** What are the characteristics, life cycle, and magnetospheric impact of plasma of ionospheric origin?
- ❖ Contributes strongly to other PSGs
  - ✓ **PSG 1** How is the solar wind energy input to the magnetosphere transmitted between different regions and across different scales?
  - ✓ **PSG 3** What controls the multiscale electrodynamic coupling between the ionosphere and magnetosphere?

Observatory

• **EUVHe and EUVO**	He+ and O+ cold ions, and Sheath
• **LuGRE**	TEC from space
• => **Ion densities, mass density, Alfven, flows, E-fields**	
• **GCI**	Exospheric H (PS source, RC loss)
• **LENA**	JUICE JNA low energy RC
• **OCTEA**	1U cubesat sized ENA imager





Questions?