New Research Needs

Moderator: Christina Cohen, Committee

Drew Turner *JHUAPL*

LWS Gap analysis

Judy Karpen *NASA/GSFC/SWL*

Adequacy of and gaps in existing programs (LWS, NSF Geospace, NOAA)

Noé Lugaz *UNH*

What do we need to understand to predict ICMEs (including stealth) and IMF Bz?

Katie Whitman *NASA/JSC/SRAG*

What do we need to understand to predict “all clear” SEP periods?

Jeff Love *USGS*

What do we need to understand to predict ground magnetic perturbations & GICs?

NASA's Space Weather Science and Observational Gap Analysis

A Brief Summary of the Report and Findings

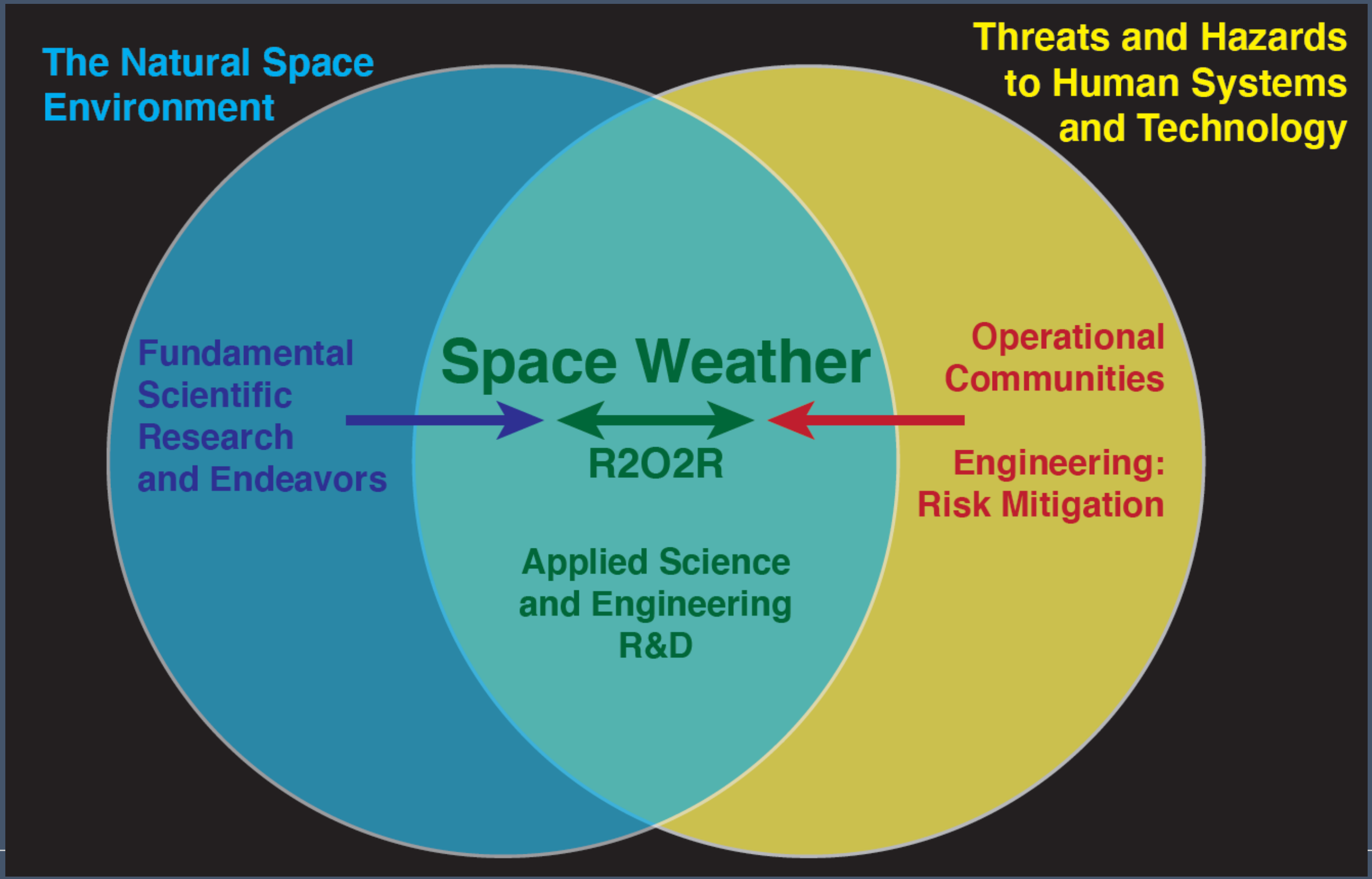
Dr. Drew L. Turner
(*on behalf of the SWx Gap Analysis Committee*)
Johns Hopkins Applied Physics Laboratory
11 April 2022

Contact: drew.turner@jhuapl.edu

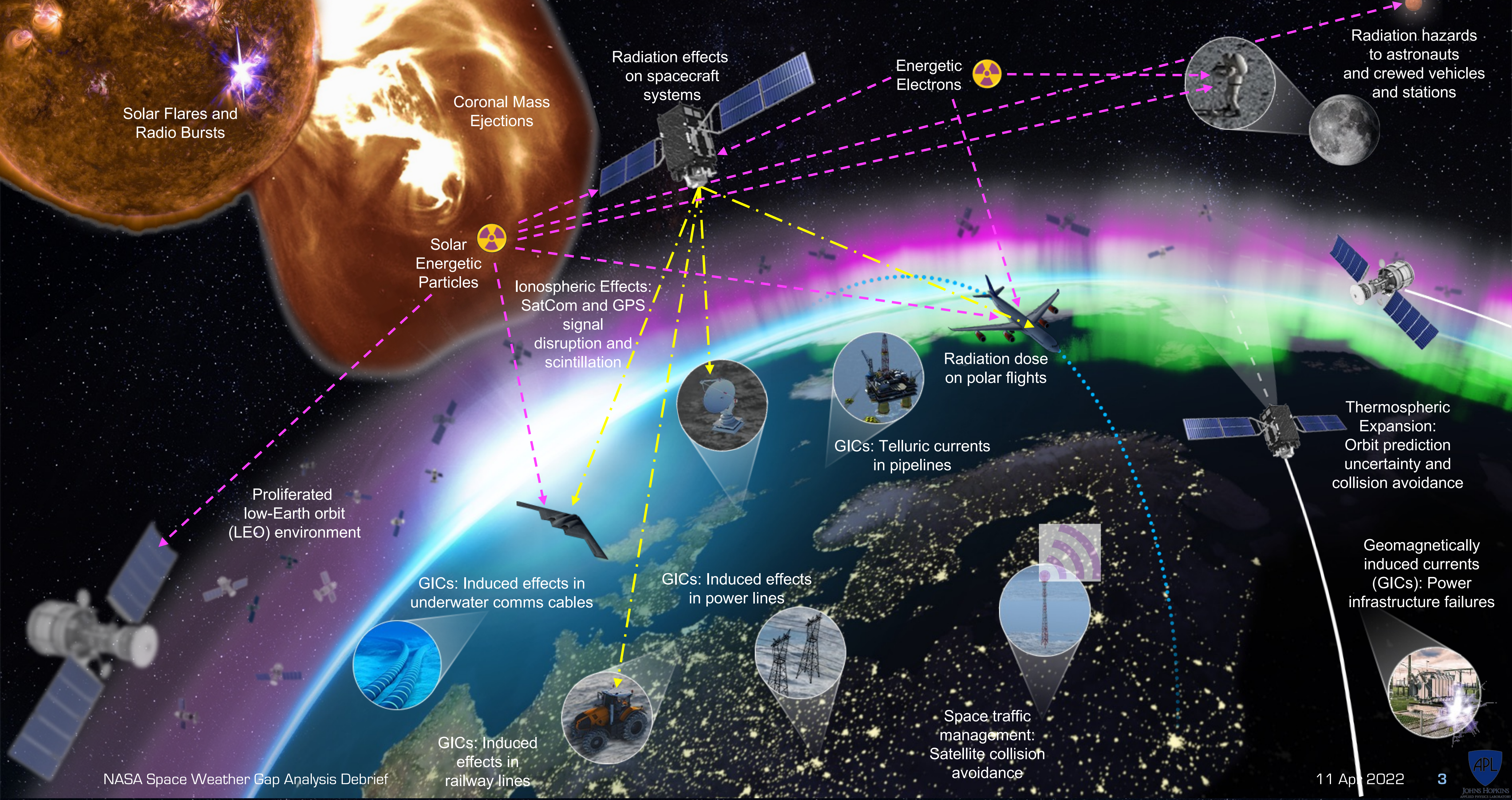
Defining Space Weather (SWx)

NOAA's definition:

"Space Weather describes the ***variations in the space environment*** between the Sun and Earth… ***that impact systems and technologies in orbit and on Earth***."



Space Weather Effects in Geospace and Beyond



Space Weather Hazards and Prioritization

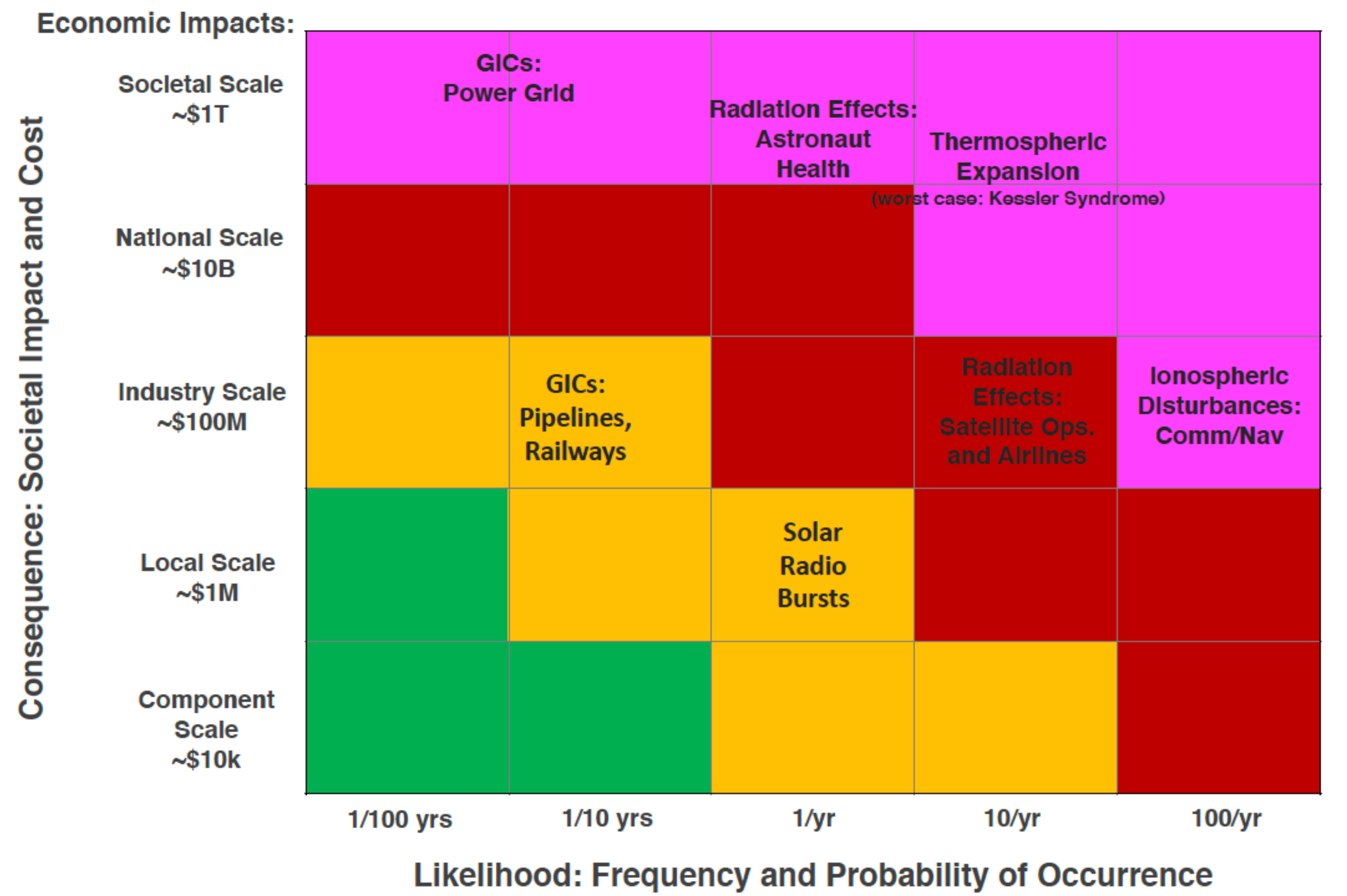


Figure 2-3. Top-level space weather hazard categories organized by likelihood (rough order of magnitude frequency of occurrence) and societal consequence (rough order of magnitude cost and impact level). Color coding approximately corresponds to worst-case damages.

Table 6-1. Top-ranked current SWx observation gap categories

	Rank	Current Observation Gaps	Normalized Weighted Score
Solar/Helio	1	Solar/solar wind observations, including off-SEL	0.74–1.00
Geospace	2	Ionospheric key observables	0.93
Solar/Helio	3	Solar wind in peri-geospace	0.83
Geospace	4	Thermospheric key observables	0.64
Geospace	5	Ionospheric D- and E-region EPP and E- and F-region cusp and auroral precipitation	0.55–0.60
Geospace	6	Ring current and radiation belt electrons	0.58
Geospace	7	Plasma sheet electrons and injections/bursts from cislunar into GEO and MEO regions	0.50

NOTE: Task was limited to space-based observational gaps

See NASA SWx Gap Analysis Full Report here:
https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf

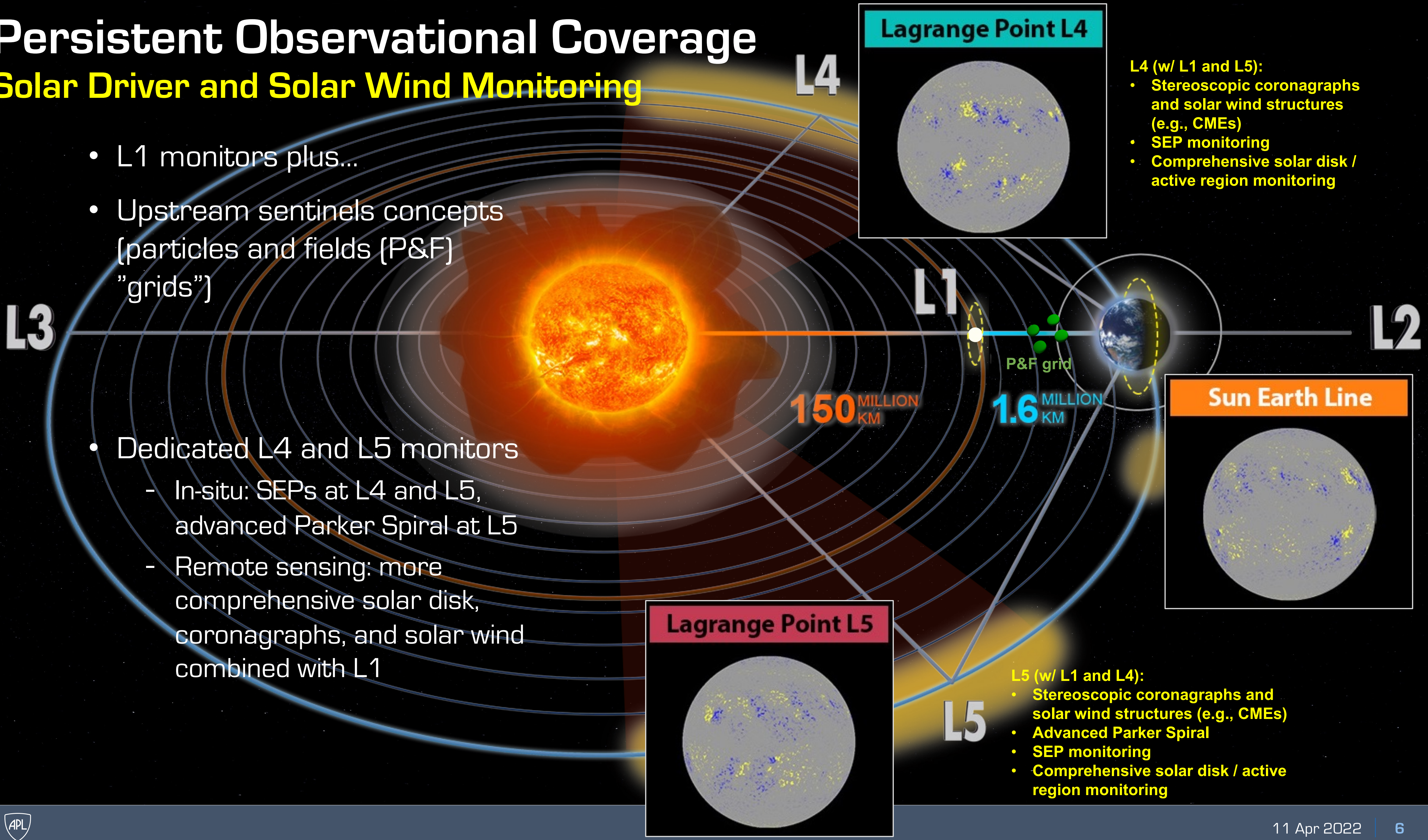
And now for something a little different…

Let's look at how we might approach filling some of the highest priority observational gaps with a near-future system-of-systems approach

Persistent Observational Coverage

Solar Driver and Solar Wind Monitoring

- L1 monitors plus…
- Upstream sentinels concepts (particles and fields (P&F) ”grids”)
- Dedicated L4 and L5 monitors
  - In-situ: SEPs at L4 and L5, advanced Parker Spiral at L5
  - Remote sensing: more comprehensive solar disk, coronagraphs, and solar wind combined with L1



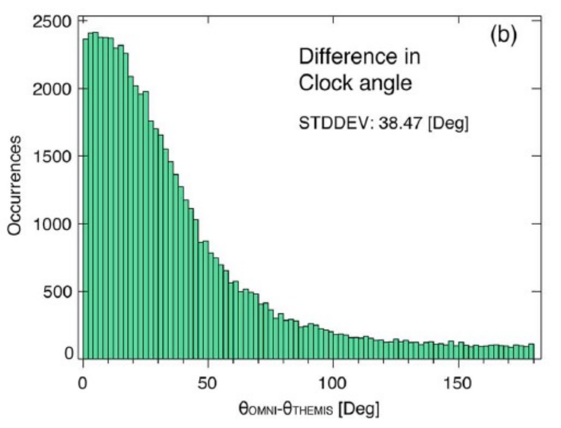
L4 (w/ L1 and L5):
- Stereoscopic coronagraphs and solar wind structures (e.g., CMEs)
- SEP monitoring
- Comprehensive solar disk / active region monitoring

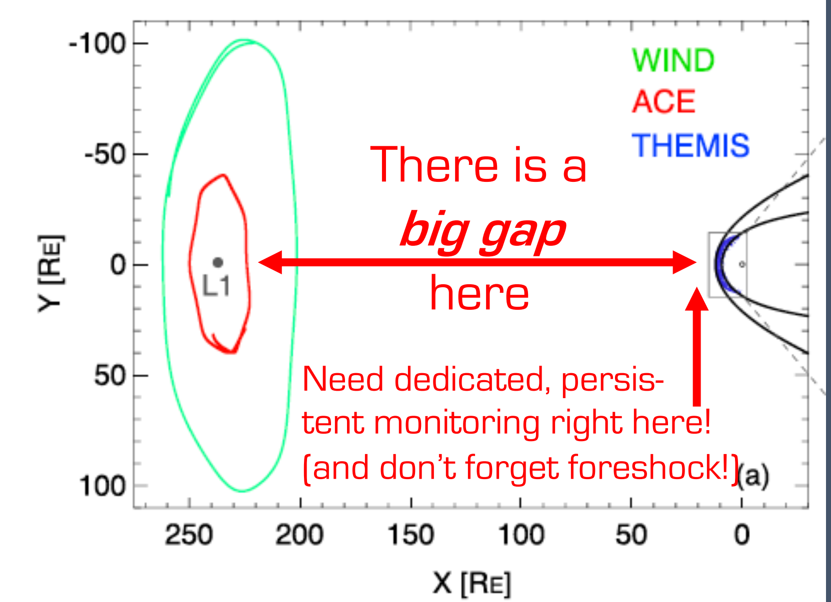
L5 (w/ L1 and L4):
- Stereoscopic coronagraphs and solar wind structures (e.g., CMEs)
- Advanced Parker Spiral
- SEP monitoring
- Comprehensive solar disk / active region monitoring

Persistent Observational Coverage

Solar Wind in Peri-Geospace

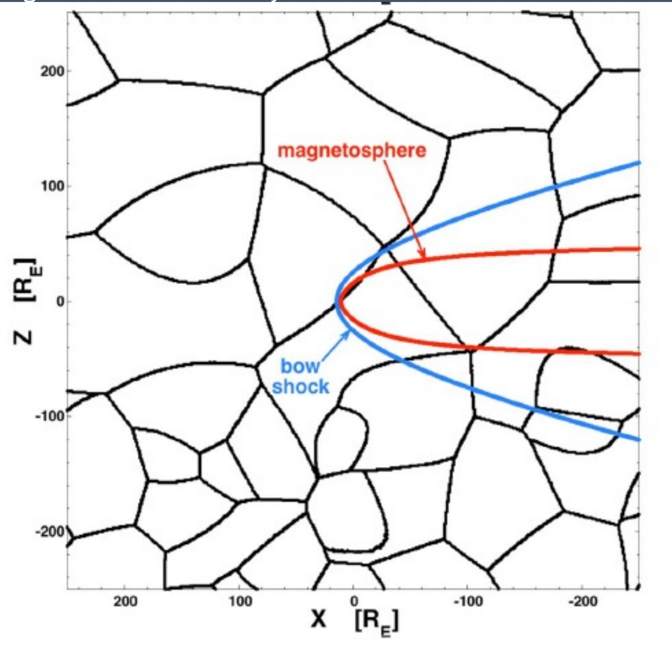
- Solar wind at 1 AU:
  - Is highly structured (meso-scales to MHD scales)
  - undergoes spatiotemporal evolution in peri-geospace
- ***L1 monitors are insufficient for accurate magnetospheric driving (boundary) conditions***

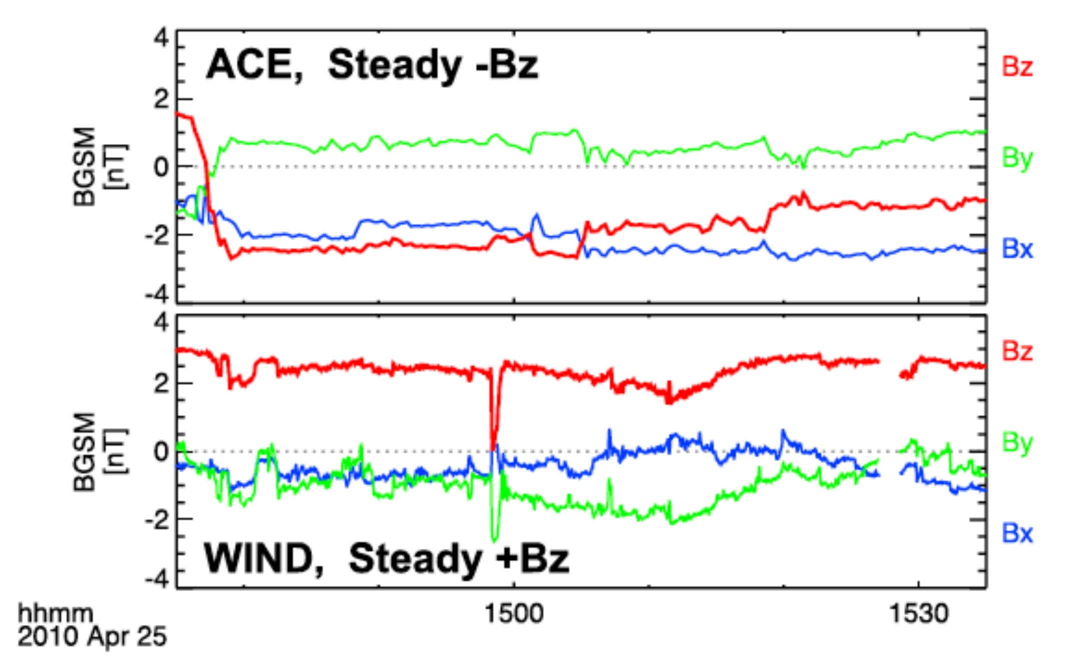




Figures from
Walsh+ JGR 2019

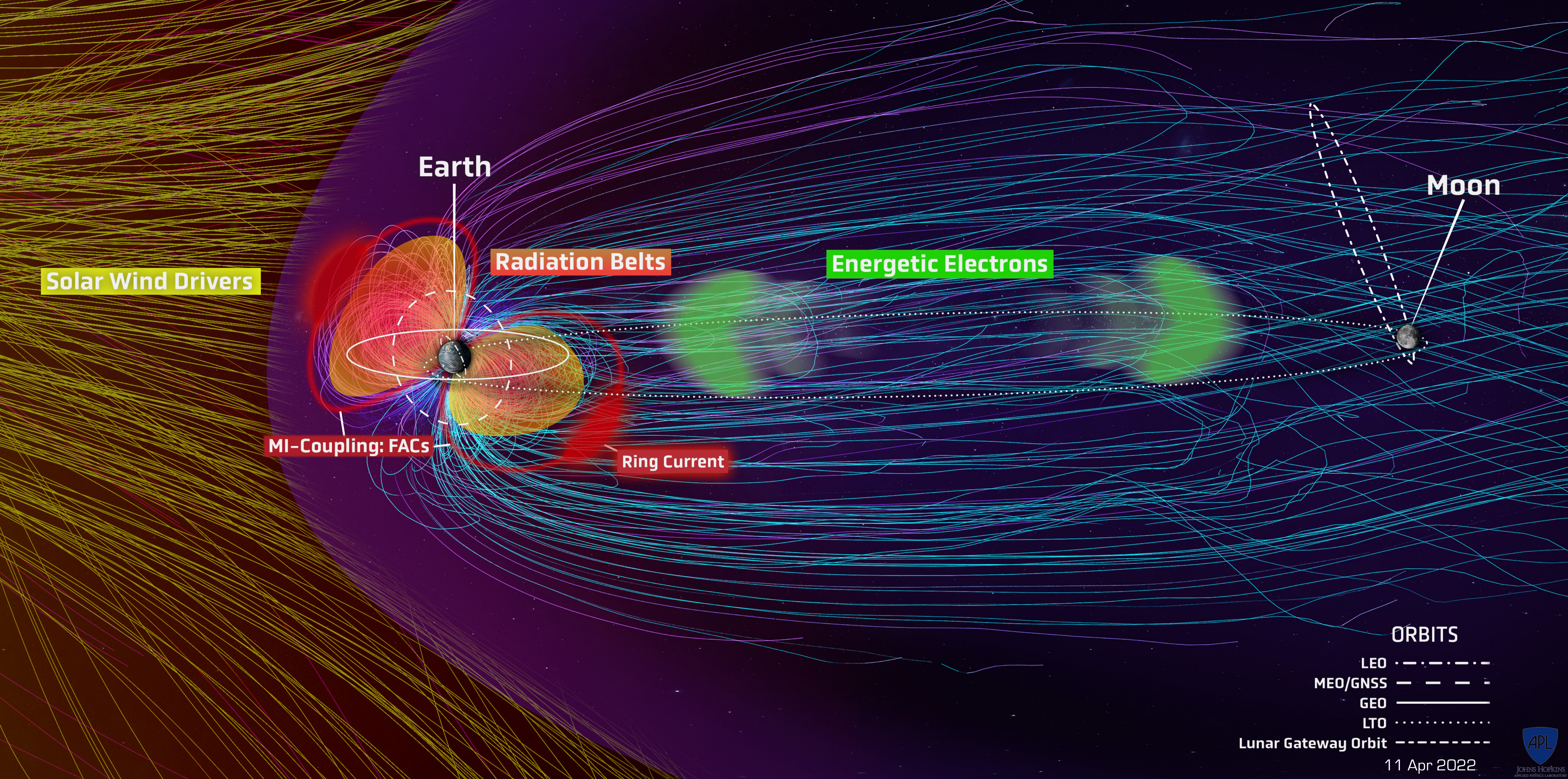
Figure from Borovsky JASTP 2017





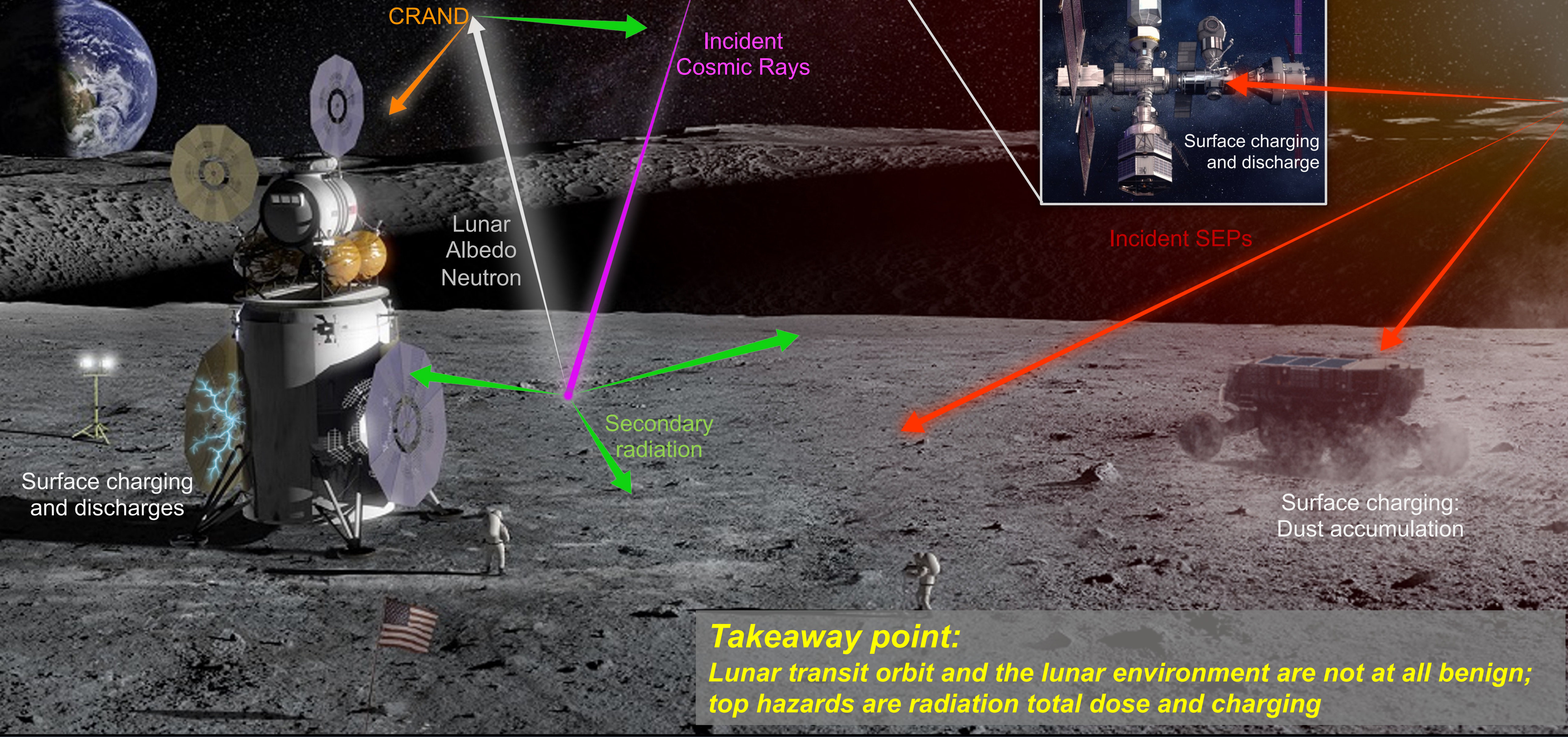
Persistent Observational Coverage

Radiation in Geospace



Persistent Observational Coverage

Lunar and Cis-Lunar Environments



Takeaway point:

Lunar transit orbit and the lunar environment are not at all benign; top hazards are radiation total dose and charging

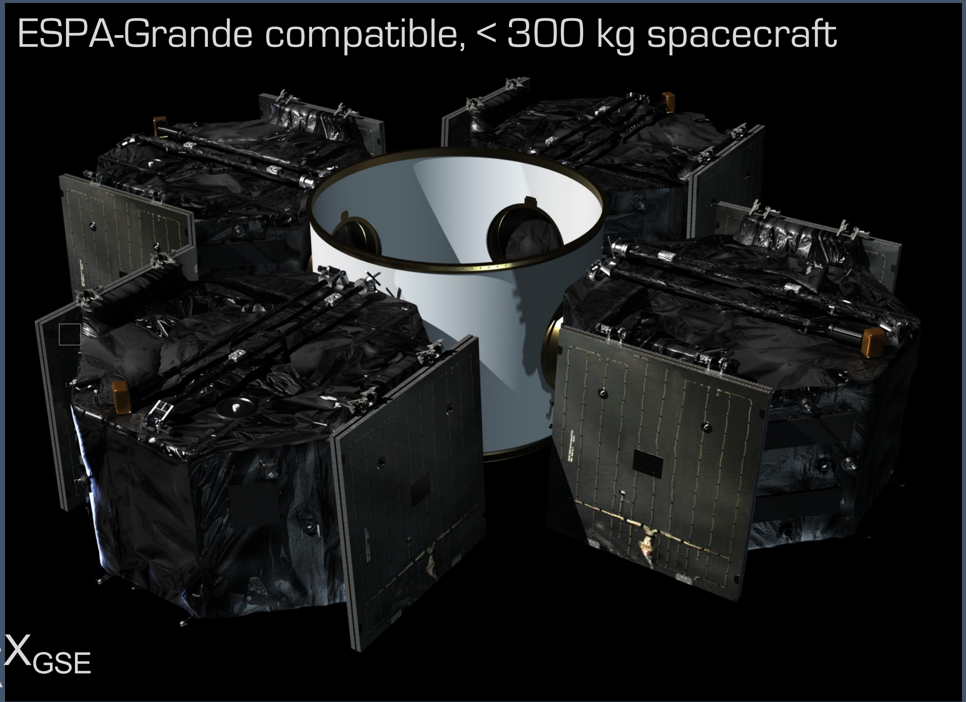
Persistent Observational Coverage

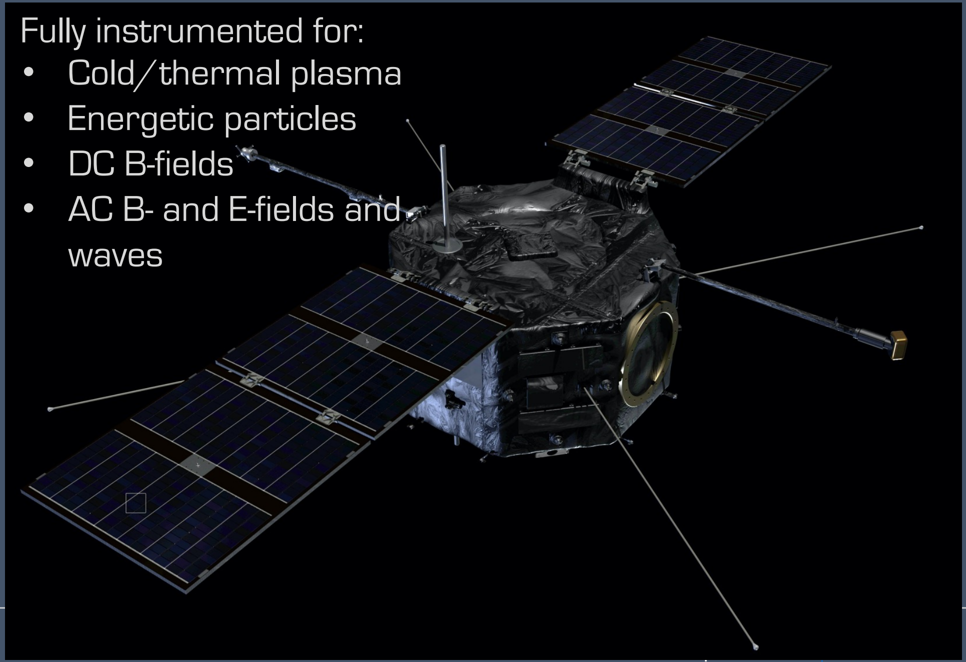
Comprehensive Radiation Belt Science and Monitoring

- Charging and Radiation Environment Observatories (CREO)
  - Architecture study completed by NASA/LWS Committee: 1 of 12 mission concepts considered
  - To be submitted for consideration by the upcoming Heliophysics Decadal Survey
- OSSE: Orbital coverage optimization result: 9 s/c in GTO/superGTO
  - Near-equatorial orbits, MLat < 30-deg
  - L-shell revisit time ≤ 2-hours
  - Full magnetic local time coverage with routine multipoint configurations within ΔMLT < 3-hours
- ESPA-Grande compatible, < 300 kg spacecraft
- Networked comm architecture enabling:
  - < 5-min latency for onboard measurement to cloud availability on the ground

CREO OSSE: 9-s/c optimal, spaced around MLT in super-GTO

See also: GTOSat: Launching June'22

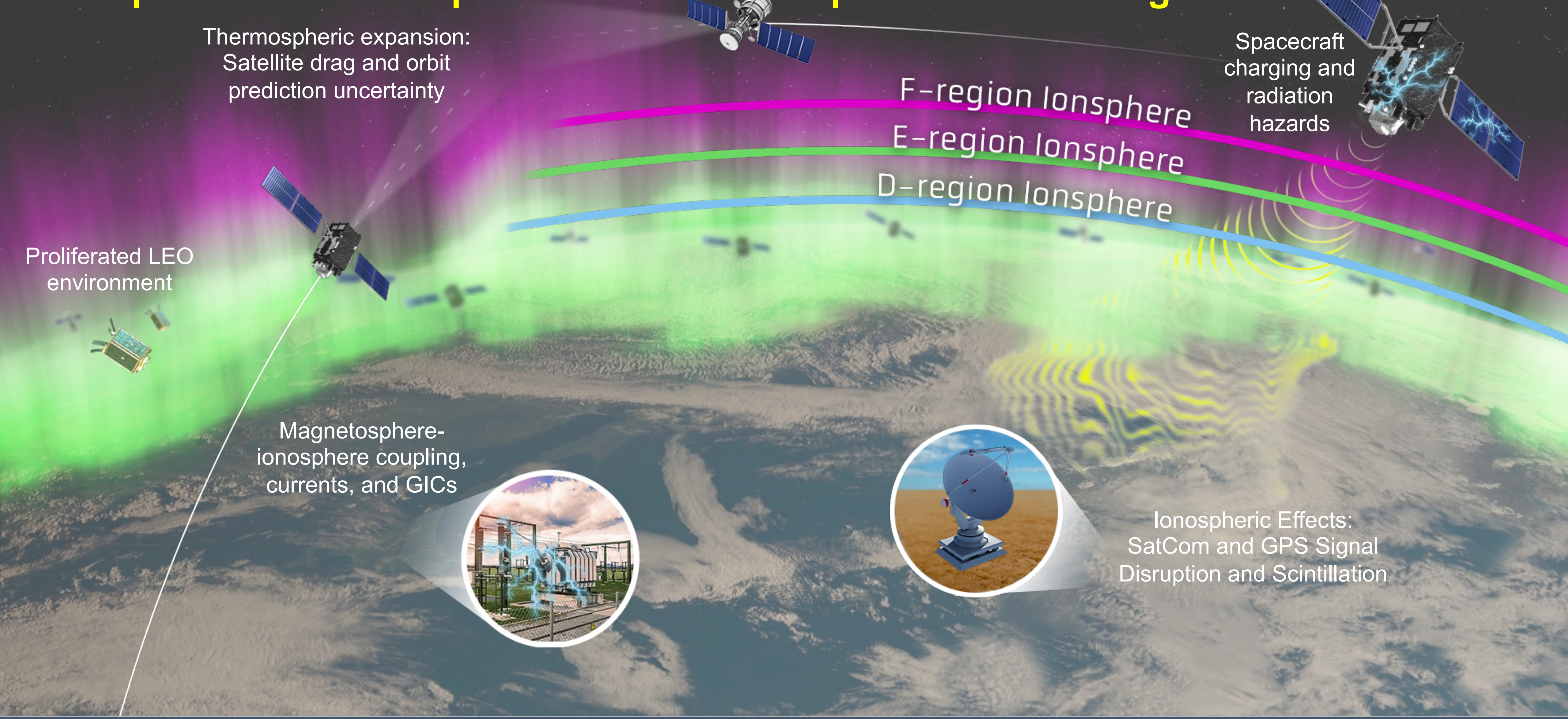




Lessons learned from Van Allen Probes – GEO is only the tip of the iceberg – and critical gaps in its wake

Persistent Observational Coverage

Comprehensive Ionospheric and Thermospheric Monitoring



Persistent Observational Coverage

Comprehensive Ionospheric and Thermospheric Monitoring *via Proliferated LEO*

- Proliferated LEO: 10,000s of spacecraft operating within a few 100s km altitude shell (*it's already happening!*)
- LEO is not a benign environment:
  - Thermospheric variability and satellite drag
  - Ionospheric coupling to neutral atmosphere and magnetosphere (complex system-of-systems)
  - Spacecraft charging and SEE radiation hazards
- Sufficient monitoring requires measurements of key observables (see right) at ≤ 100 km resolution, full-altitudinal, real-time observations *over full globe*

Takeaway point:* *Spatial resolution and comprehensive coverage are critical; leverage proliferated LEO and hosted payloads if at all possible

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NEWS

SpaceX loses 40 satellites to geomagnetic storm a day after launch

7 days ago

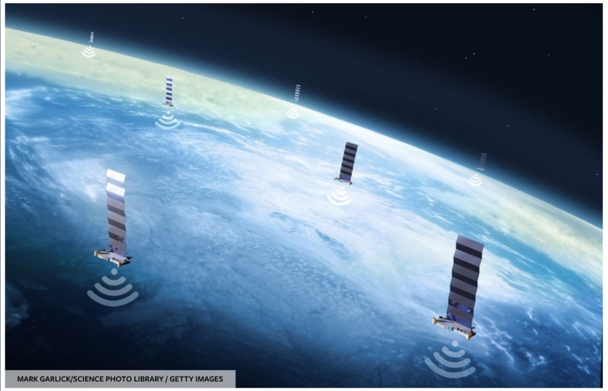


Table 6-5. Geospace priorities for improving, advancing, and closing critical gaps prohibiting advancement of SWx *-casting

Improve/Advance/Close	Description/Requirements
Ionospheric Key Observables	
Close	F-region plasma density (in situ plus remote sensing profiles), electric fields, plasma velocities, neutral winds, ion and neutral composition, and cusp and auroral electron and proton precipitation from a network of observatories enabling regular (daily or more frequently), full globe observations at ≤100 km spatial resolution and real-time data transmission.
	E-region: Continuous auroral imaging of both hemispheres from observatories in MEO/HEO dedicated to providing continuity in measurements (spatial and temporal). Full coverage in both hemispheres at 100 km spatial resolution and real-time data transmission would allow immediate nowcast of auroral activity and, with the buildup of modeling capability, an hour advance prior to the arrival of auroral effects (e.g., heating and EPP) and neutral density perturbations at middle and low latitudes, after which all satellite orbits will be affected.
	E-region: Continuous ≤100 km spatial resolution, real-time data transmission from cusp, auroral, ring current, and radiation belt EPP monitors distributed around MLT and spanning polar latitudes.
	D-region: Continuous ≤100 km spatial resolution, real-time data transmission from SEP and radiation belt EPP monitors distributed around MLT and spanning polar latitudes.
	E-region and D-region: SEP forecast from solar active region monitors spanning beyond the eastern and western limbs.
Thermospheric Key Observables	
Close	Continuous ≤100 km spatial resolution, real-time data transmission from neutral density, temperature, composition and wind, ionospheric E-field, velocity, and current, and energetic particle precipitation monitors distributed around MLT and spanning polar latitudes.

Space Weather:

See Top-Level Summary here: https://civspace.jhuapl.edu/sites/default/files/2021-12/21-04124_Space-Gap-Analysis_v13-Digital.pdf

WHERE DO WE STAND?

State of U.S. Terrestrial Weather circa 1960

Our current ability to predict space weather is in many ways like our ability to predict terrestrial weather was several decades ago, before global weather station networks and satellite imagery and observations were available. With only sparse and often partial weather stations and observatories available, predicting space weather today is something like asking a forecaster to predict tornado activity in Kansas given only weather data from stations in New York City and Los Angeles—an area that spans 2,800 miles (~4,500 kilometers).

Current State: Geospace

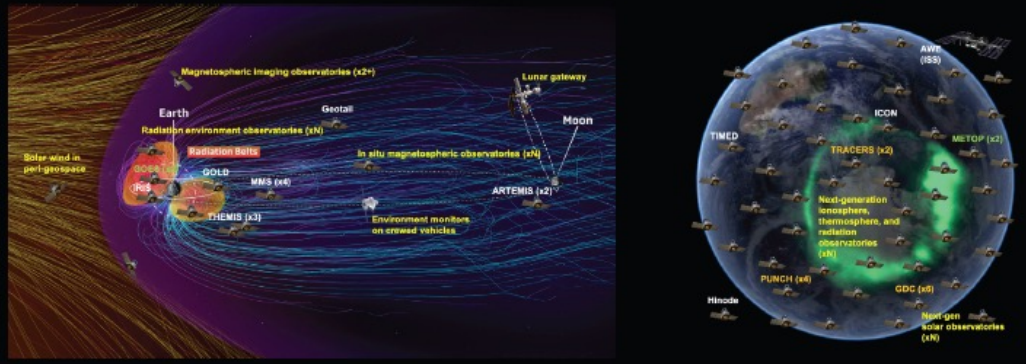
Current operational (in white) and in-development (in orange) NASA (and NOAA/European Space Agency [ESA] in green) missions that provide key measurements for space weather prediction. In geospace, around Earth, there are multiple critical blind spots, including the solar wind at the magnetopause, comprehensive ionospheric and thermospheric observatory networks in LEO, and dedicated radiation belt and charging environment monitors throughout the cislunar magnetosphere.

WHERE DO WE NEED TO BE?

Current State of Global Terrestrial Weather

By improving our understanding of how solar disturbances propagate and how the near-Earth space environment reacts to them, we can increase our forecast horizon and deliver more accurate and useful forecasts. With an expanded network of space weather stations and observatories, we can better predict the current and future states of the space environment relevant to known space weather hazards.

Critical Gaps: Geospace



In geospace, around Earth, there are multiple critical blind spots including the solar wind at the magnetopause, comprehensive ionospheric and thermospheric observatory networks in LEO, and dedicated radiation belt and charging environment monitors throughout the cislunar magnetosphere. Observatories marked in yellow indicate identified observation gaps.

NASA SWx Gap Analysis
Take-Home Points

- Most gaps can be addressed with ***current technology and capabilities***
- Concrete advances in SWx *-casting require a ***systems approach*** → coordinated concurrent measurements along 3-axes, SWx data analysis and modeling hubs, and low-latency, networked, cloud-based infrastructure:
- An effective systems approach requires: ***a long-term strategy, coordinated agency efforts (e.g., PROSWIFT), and dedicated and supported ($) implementation plans***
- Use ***Observing System Simulation Experiments (OSSEs)*** to prove conceptual observatory networks
- Advanced ***data assimilative modeling*** and ***machine learning applications*** can be used to fill data gaps
- Identify and ensure ***continuous coverage of core "backbone" and standardized measurements*** for solar/heliosphere and geospace (and ***don't forget ground-based observatories!***)
- Employ ***SWx beacon*** capabilities and invest in ***very-low-latency satellite communication networks and technology***
- Develop innovative solutions via ***strategic agreements and partnerships*** (civil, commercial, national security, international) and ***leverage increasing access-to-space opportunities***
- Establish ***clearinghouse for SWx relevant measurements and datasets*** from operational and end-user communities

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Research Needs in Theory/Modeling for Space Weather

Outline

1. **Physical understanding ⟹ improved predictions**
2. **From idealized to realistic models**
3. **Crucial computational advances**
4. **Programmatic recommendations**

Space Weather Workshop II
Judy Karpen
NASA GSFC
11 April 2022
judy.karpen@nasa.gov

Take Away Messages

- **Attract and retain people from broader range of backgrounds: plasma physics, astrophysics, CFD, software engineering, etc.**
- Employ more computational physicists in heliophysics
- **More funding opportunities for theory and model development aimed at physical understanding of key SWx phenomena**
- Joint/interagency programs share the cost, tap into more communities
- **Use space weather funding to support opportunities for maximizing SWx return from science missions – data processing, model development, tools (not covered by H-GI, H-SR, etc.)**
- Boost NASA's investment in high-performance systems or partner with DoD, NSF

Physical understanding ⟹ improved predictions

❖ Energy buildup to eruption: active region emergence and evolution, filament channel structure

- Filament channels are the birthplaces of solar eruptions
- Observations don't reveal filament-channel coronal morphology (yet)
- Formation/structure models are largely idealized

❖ Energy release and partitioning

- Solar eruptions generate most destructive space weather
- Use theory to identify and quantify precursors vs impacts
- Models are largely idealized, missing physics (e.g., thermodynamics, particle acceleration)

❖ Particle acceleration and transport everywhere

- Solar energetic particles pose major hazards to tech and humans
- Origin and properties of injected/seed particles
- Acceleration mechanism models – room for improvement
- Gaps between transport models and observations (e.g., spread)

Eruptive Flare seen by SolO/EUI (T ~ 10^6 K)

Physical understanding ➡ improved predictions

- Solar wind structure, turbulence, magnetic-field connectivity
- Nonlinear response of magnetosphere to impacts
- Ionospheric conductance, winds, and outflow
- **Neutral atmosphere-ionosphere vertical coupling**
  - Best model is restricted to DoD (Navy)
  - Efforts underway to expand weather models upward and/or ionospheric models downward, but Earth Science is not motivated to help with this

Goal: Geospace without borders!

From idealized to realistic models

- **Data driving (solar)**
  - Need 360º continuous coverage of solar magnetic field with adequate cadence
  - Data preprocessing required
  - Complex time-dependent boundary conditions
  - Numerical stability
- **Data assimilation (geospace)**
  - Sparse data in time and space
  - Intercalibration
  - Numerical stability
- **Model coupling**
  - Hard to link models from different developers/teams
  - Still no self-consistent Sun-to-heliosphere eruption model
  - Trade-offs abound (some regions in SWx chain better simulated than others)

Crucial computational advances

- **Faster and bigger massively parallel systems**
  - GPUs are fast but require special programming
  - Quantum computing???
- **Adopt latest algorithms and techniques**
  - Partner with computational physics/fluid dynamics experts
  - Quantification of numerical artifacts and uncertainties
- **Hybrid calculations spanning kinetic to MHD scales**
  - More feasible for regions of heliosphere with smaller range of characteristic scales
- **Coupling physical regimes**
  - MHD CME models + particle-acceleration & transport models
  - Effects of gravity waves and other low-atmosphere events on upper atmosphere
  - Transition regions (e.g., from neutral gas to ionized plasma, high β to low β, collisional to collisionless)
  - Subgrid modeling

Programmatic recommendations

- **Attract and retain people from broader range of backgrounds: plasma physics, astrophysics, CFD, software engineering, etc.**
- Employ more computational physicists in heliophysics
- **More funding opportunities for theory and model development aimed at physical understanding of key SWx phenomena**
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- Boost NASA's investment in high-performance systems or partner with DoD, NSF

NASA

University of New Hampshire

Berkeley
UNIVERSITY OF CALIFORNIA

What do we need to understand to predict CMEs (including stealth) and IMF B_z?

Noé Lugaz (University of New Hampshire)

Nada Al-Haddad, Réka Winslow, Charles Farrugia, Toni Galvin

(University of New Hampshire)

Christina O. Lee, David Curtis (University of California-Berkeley)

and discussions with many others

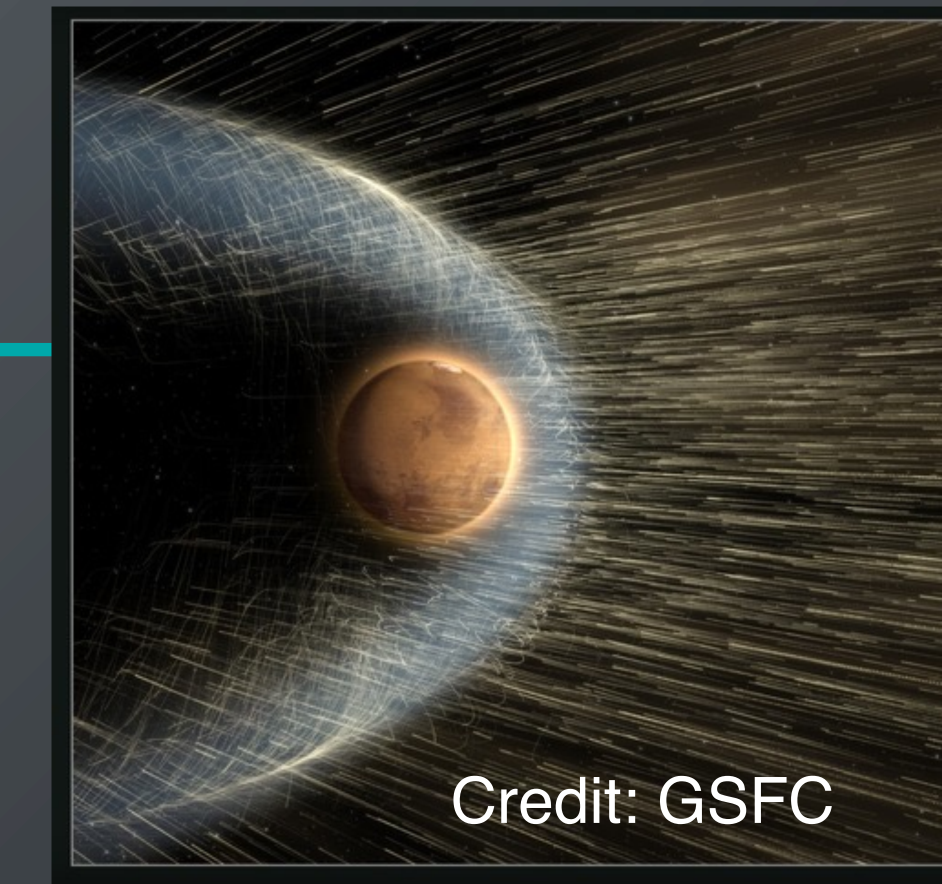
A. Vourlidas, C. Möstl, B, Zhuang, T. Salman, C. Scolini…

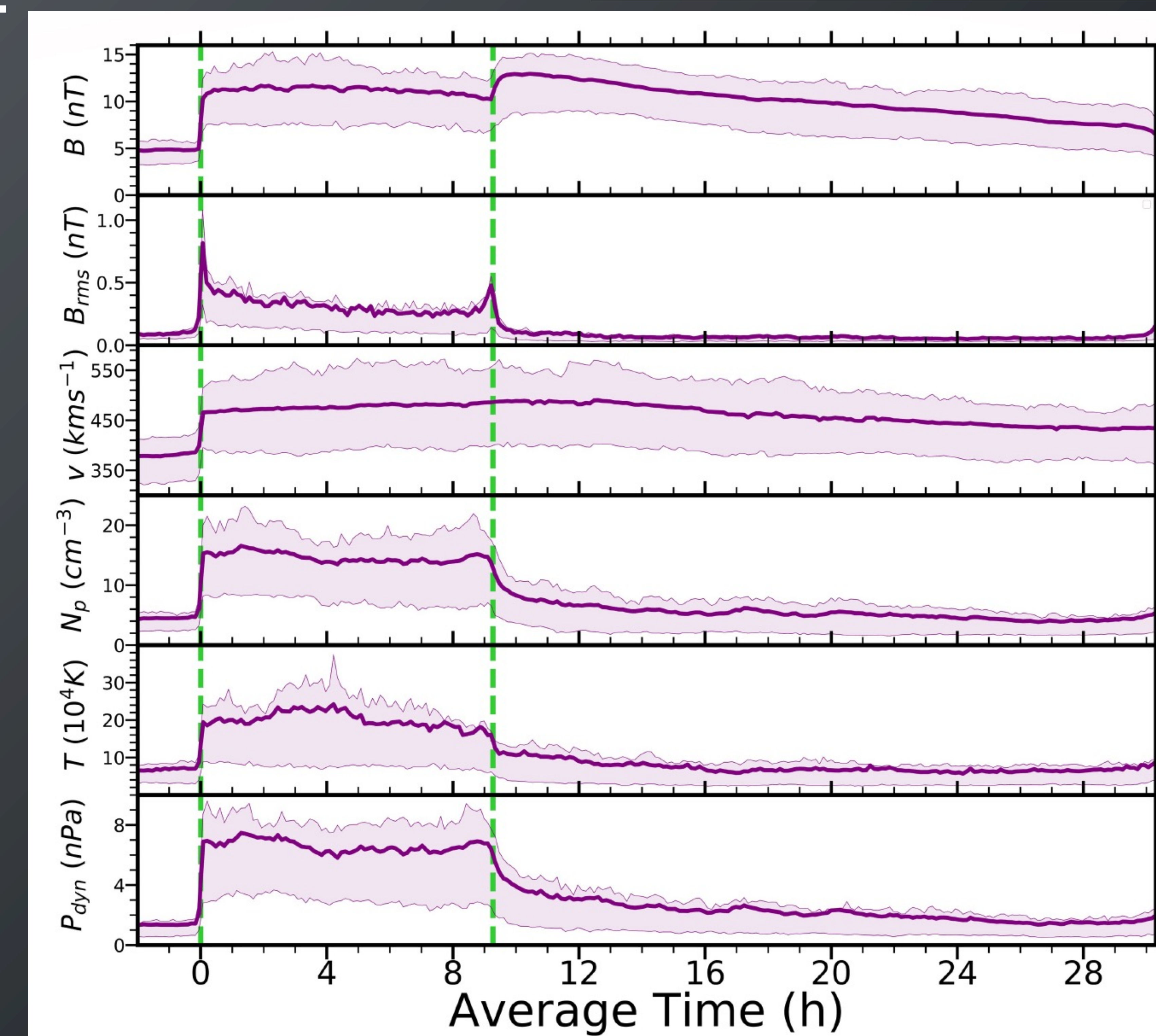
NAS – Space Weather Workshop: Phase II

April 11, 2022

What do we want to forecast?

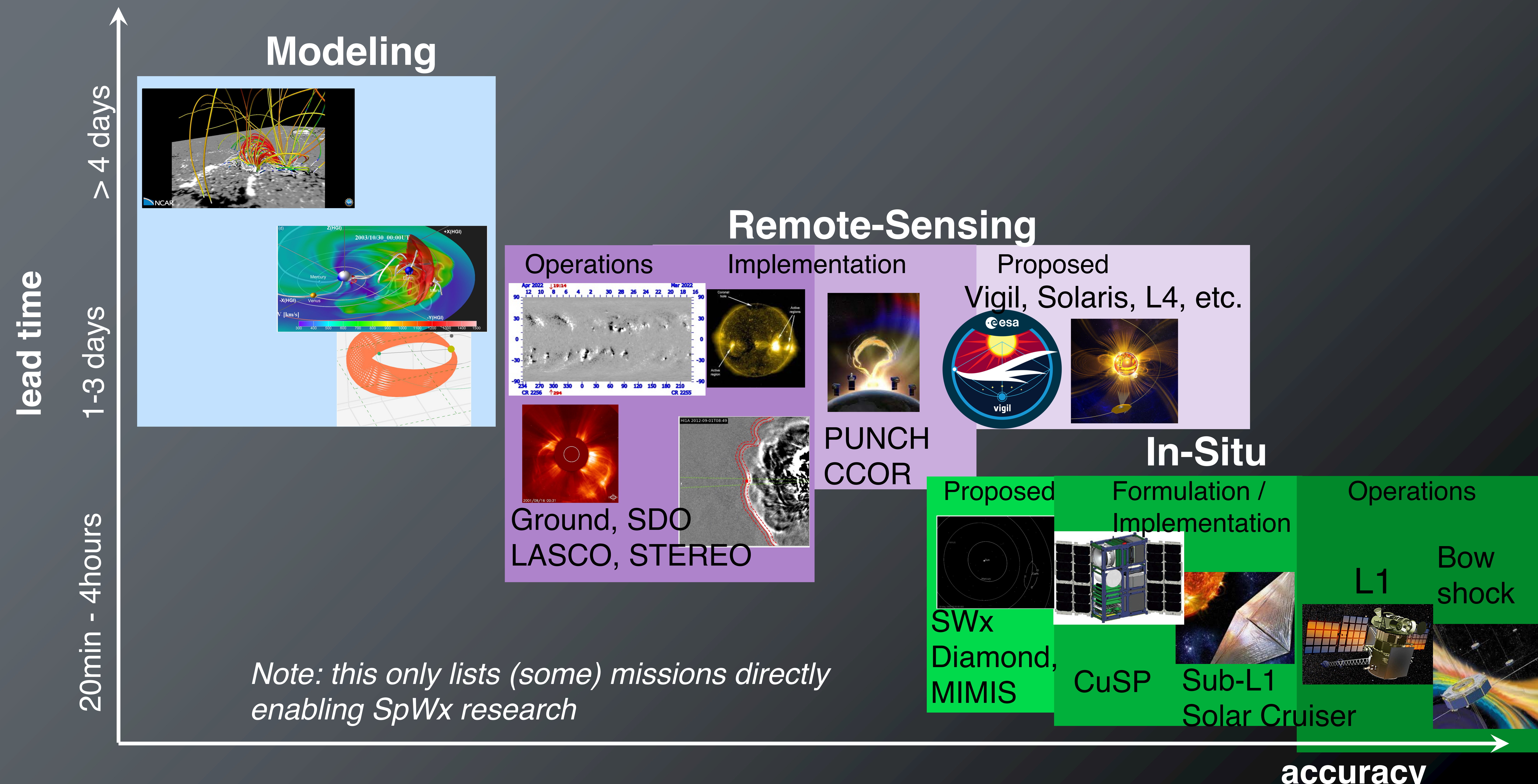
- Full plasma and magnetic field measurements upstream of Earth
  - (V)B_z and dynamic pressure (density, velocity).
    - Needed to forecast geomagnetic storms, and to model the radiation belts.
  - Ideal forecast would be before plasma leaves the Sun.
- CMEs are the source of the largest B_z
  - **Duration**: Typical CME lasts ~30 hours at Earth
  - **Propagation**: 1-5 days (~3 days) from Sun to Earth.
- Non-CME IMF B_z mostly associated with CIRs.
- Complex events:
  - Unexpected miss/low impact: (e.g. G3 forecasted for March 31st, G1 observed)
  - CME-CME and CME-CIR interaction (enhanced or reduced impact)
  - Hard to observe ('stealth') events.



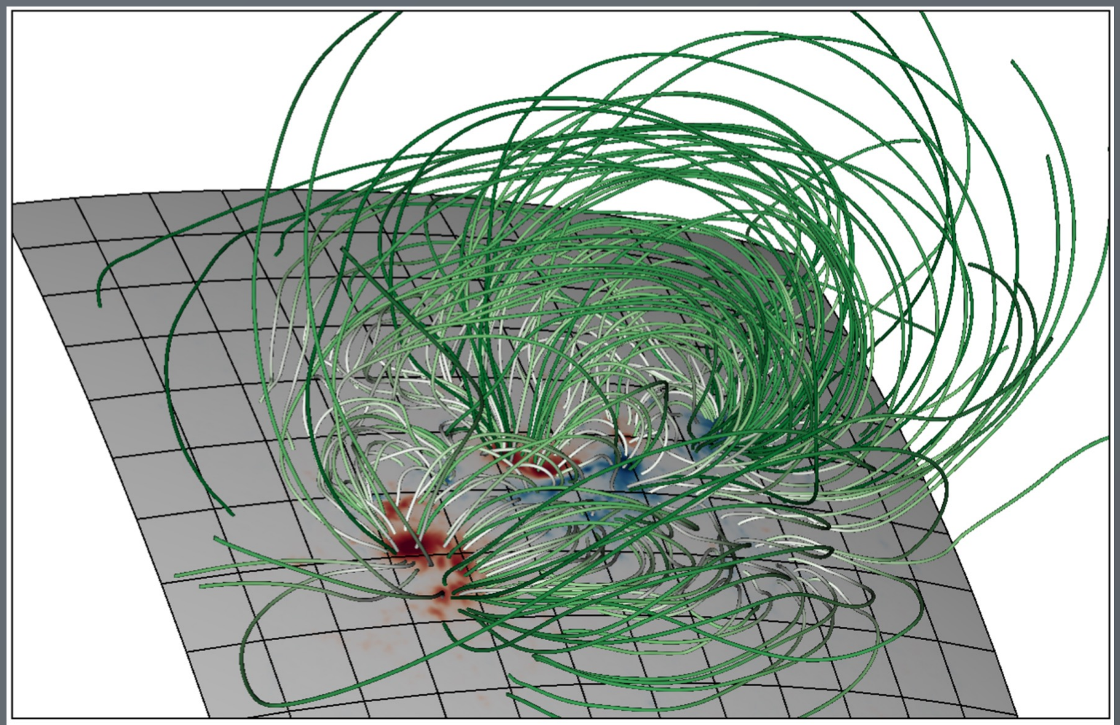


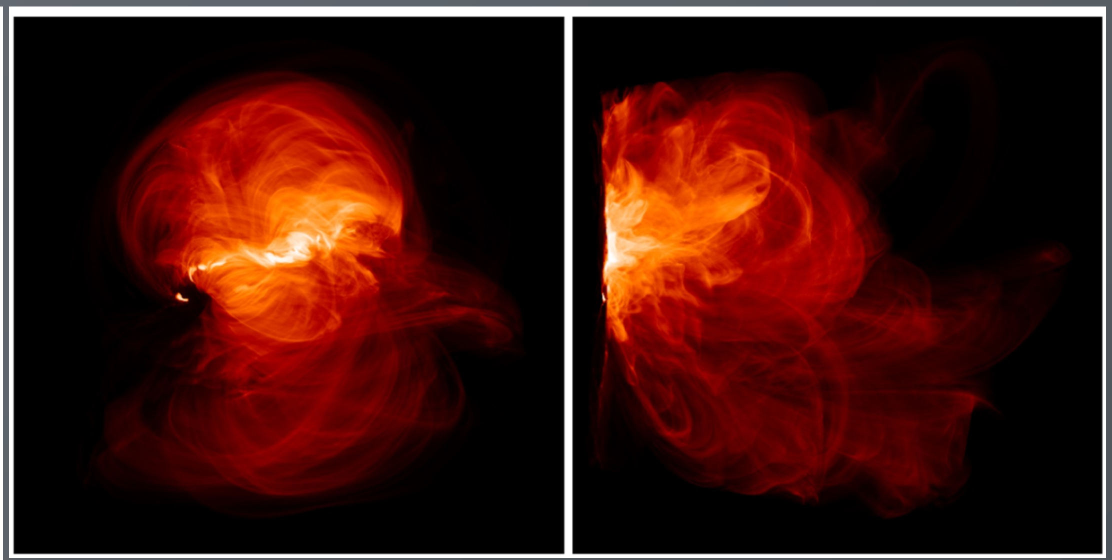
Superposed epoch analysis of 106 shock-driving CMEs measured by STEREO (from Salman et al., **ApJ**, 2020).

Lead time vs accuracy: Different Approaches

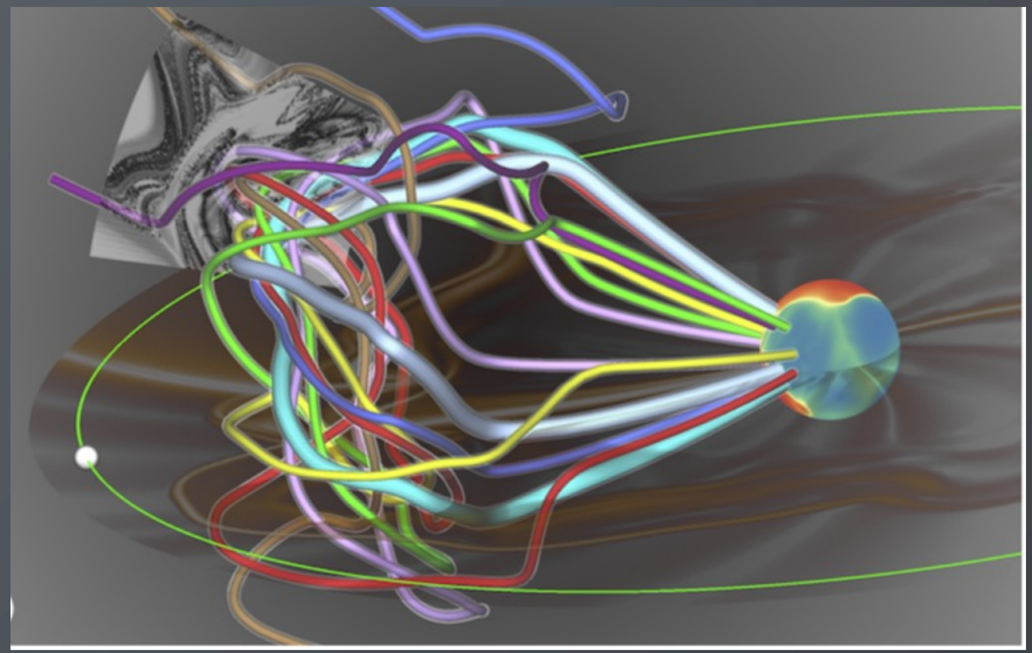


Simulations: Key science insights needed

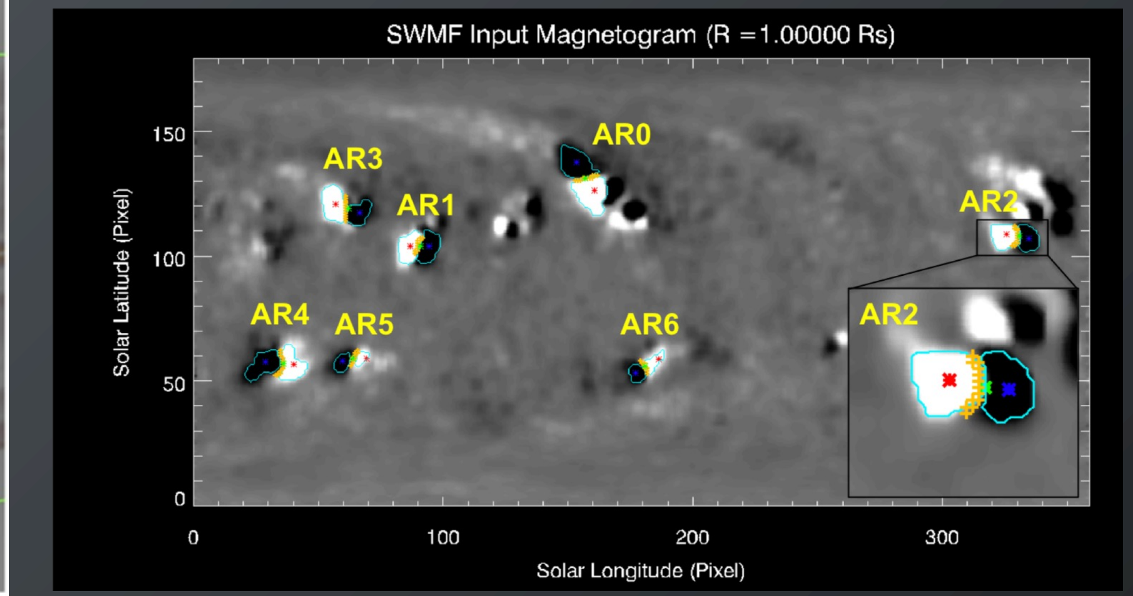




Hoeksema, Abbett et al., ApJ, 2020



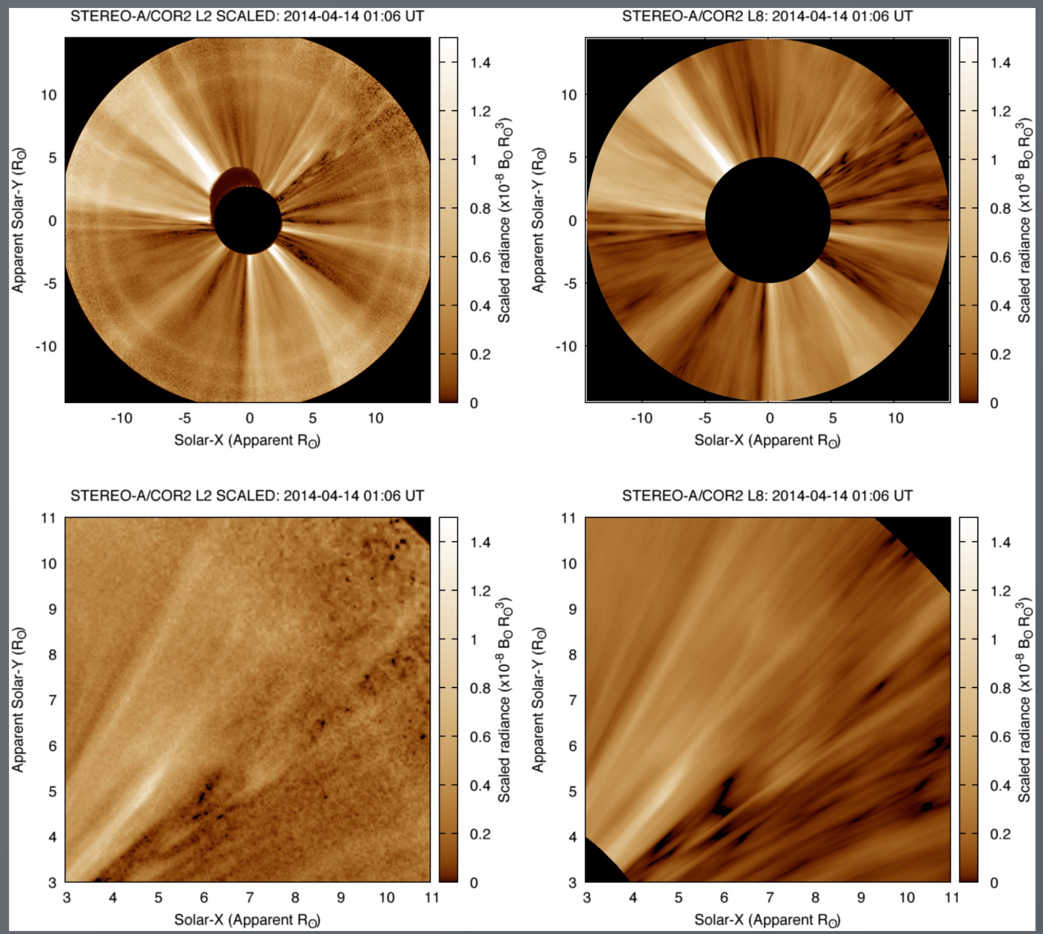
Török et al., ApJ, 2018



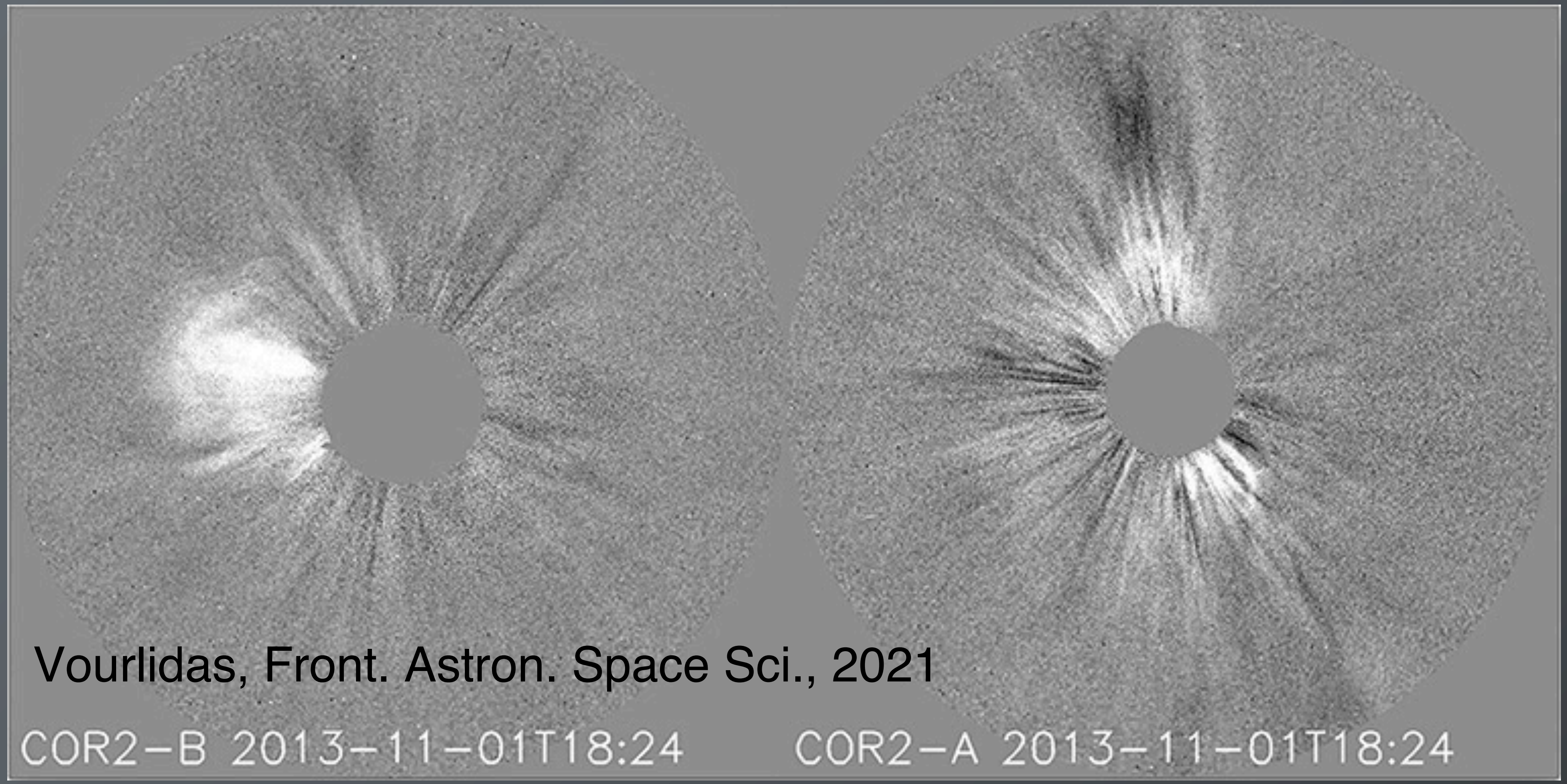
Jin, Manchester et al., ApJ, 2017

- **Key science questions**: (1) how do active regions emerge and evolve?, (2) which active regions and coronal structures result in (fast) CMEs, how and when?
- Realizing strengths and weaknesses of different approaches
  - Simulations and remote solar observations **are needed** for > 4-day forecast (**before eruption**).
  - Pseudo-simulations/empirical models + remote observations may be the best way to get moderately accurate forecast of typical CMEs with lead times of 1-3 days (**after eruption**).
  - Full simulations may be needed for solar maximum, complex events and superstorms (no steady solar wind, succession of CMEs, complex interaction, unusual conditions).

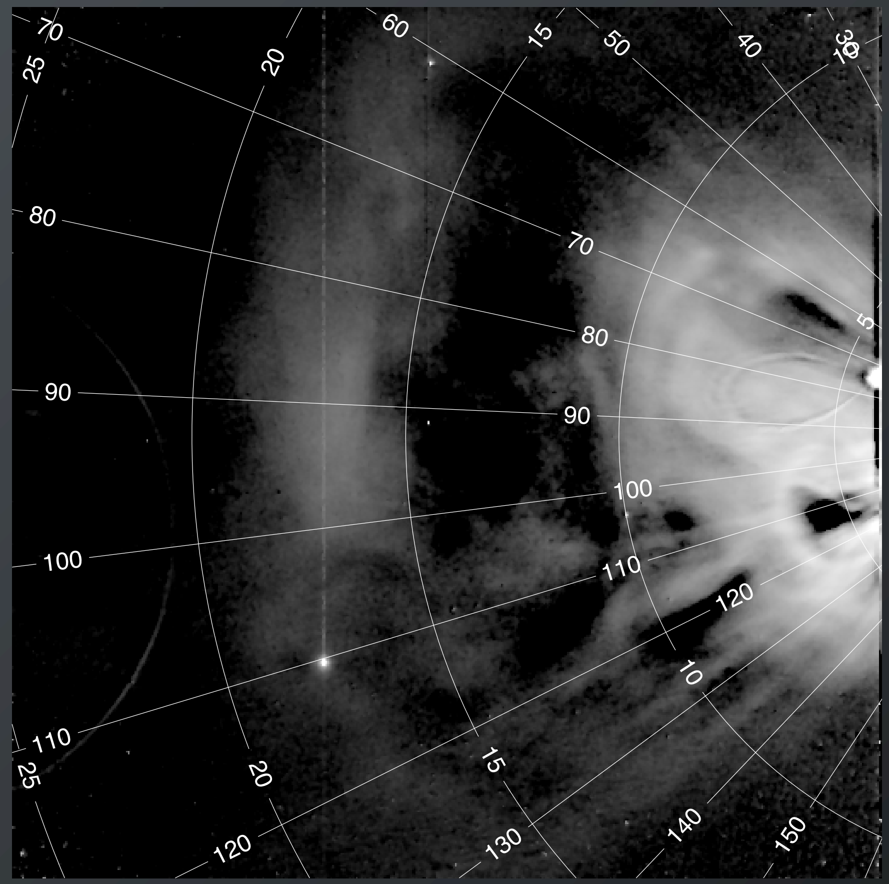
Remote-sensing: Key science insights needed



DeForest et al., ApJ, 2018



Vourlidas, Front. Astron. Space Sci., 2021

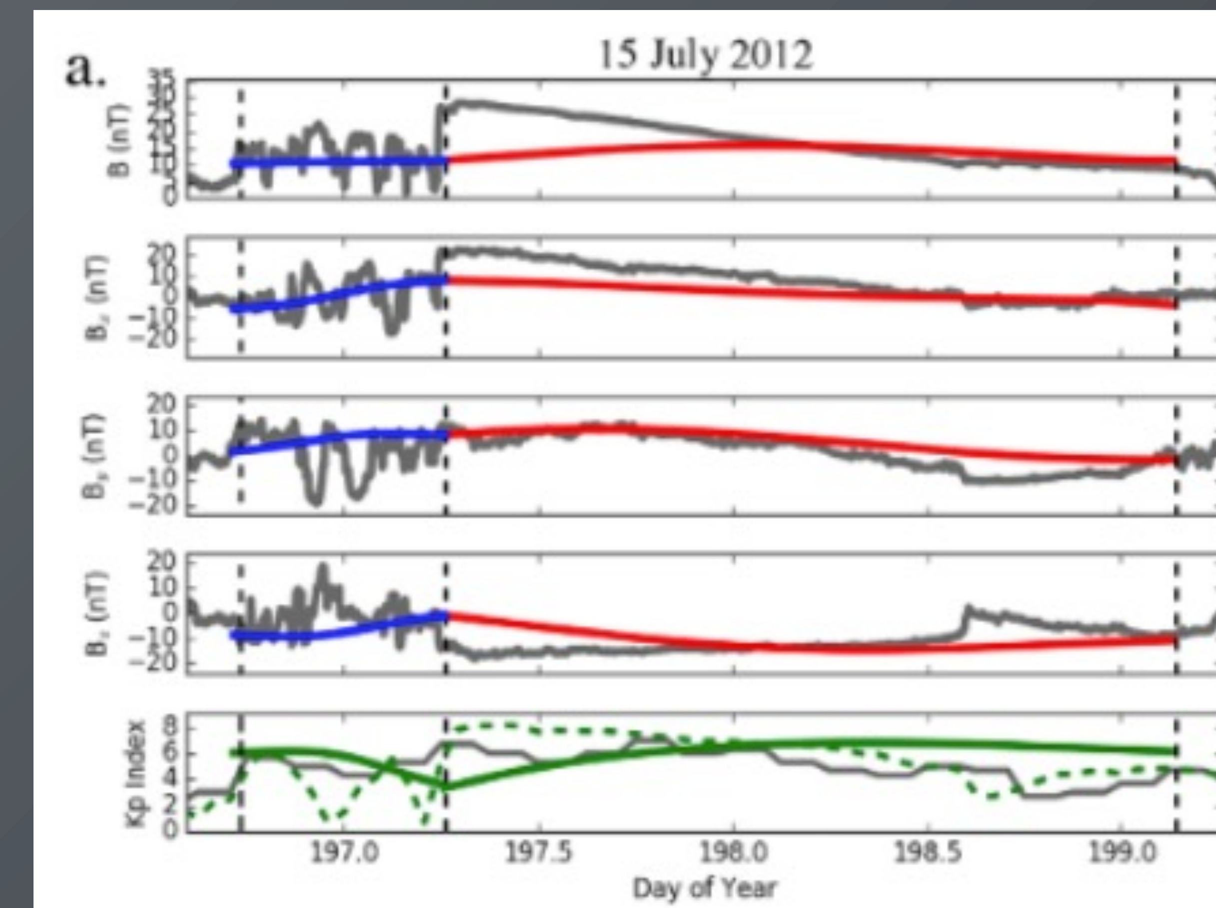


Lugaz et al., ApJ, 2012

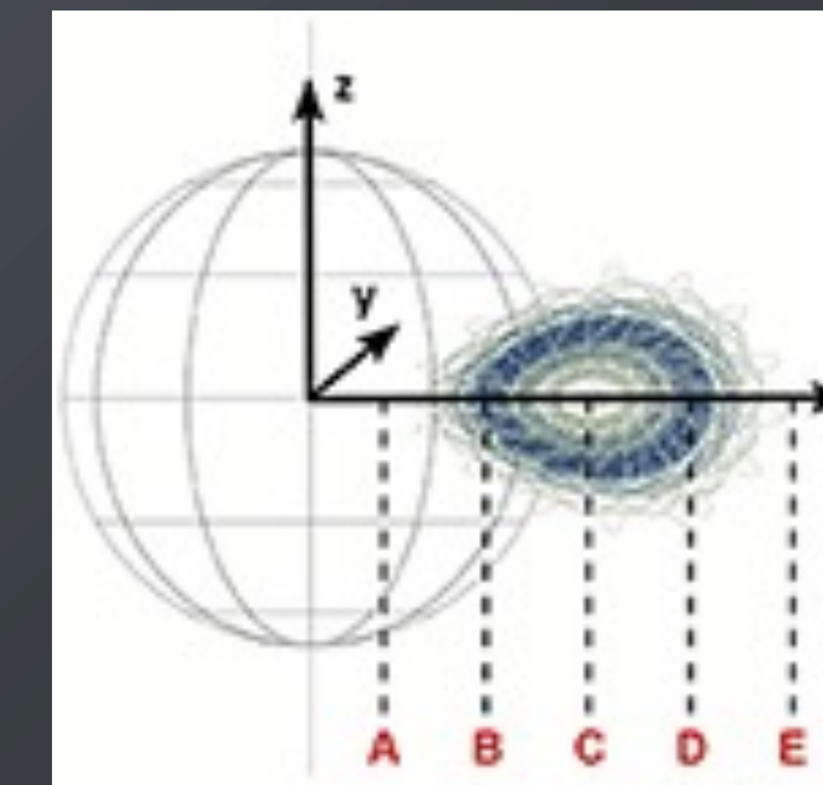
- **Key science questions**: (1) formation and variability of CIRs, (2) CME evolution, including shock/sheath (3) Complex events: CME-CME interaction, stealth CMEs.
- Remote-sensing as key input for all models and simulations:
  - ***Two or three views are needed***. View from east of the Sun-Earth line (L5) favorable.
  - More research needed to understand complex cases and how to forecast |B|.
  - More research with HI and PUNCH to understand formation of solar wind streams and CIRs.
  - Heliospheric imagers should provide more accurate forecast, further validation needed.

Simulations and Remote-sensing: Where are we going?

- “Pseudo”-simulations (drag-based, 3DCORE, ForeCAT).
- Merging of approaches:
  - Data Assimilation, both in-situ and remote-sensing.
  - Ensemble simulations.
  - Database of large-scale simulations/parametrization of simulations (ML with simulations).
  - Probabilistic/parametrization of turbulence for IMF and CME sheaths.
- ***Polar magnetic fields:***
  - poorly observed from the ecliptic
  - key to understand high-speed solar wind and non-CME B_z events.
  - Polar coronagraphic views of CMEs would also help understanding sheath, deflection.



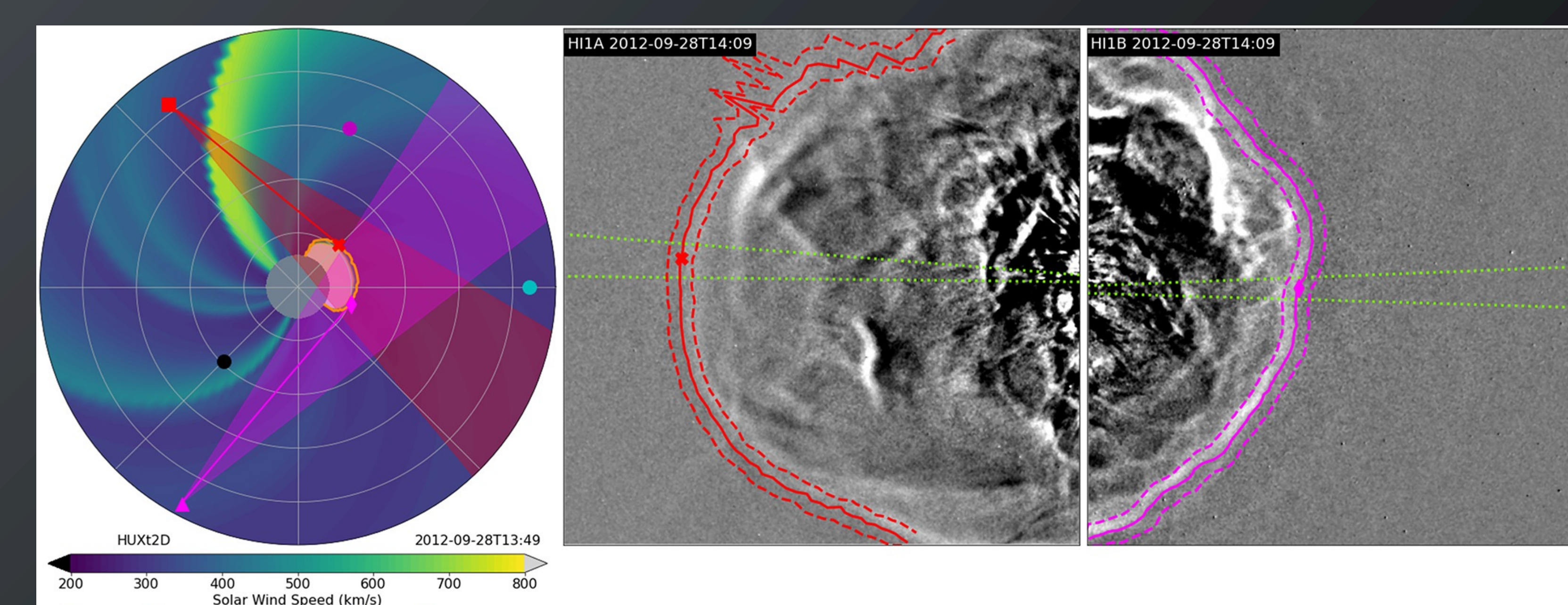
Kay et al., JGR, 2020



Parameter	Notation	Min	Max	N_{steps}[a]
Front height	f	$1.3R_\odot$	$2.5R_\odot$	6
Angular size	Ω	10°	45°	8
Topology	τ_1	0.5	$\min(4.1, \tau_{1,max})$[b]	6[c]
Orientation	σ	0°	330°	12
Latitude	θ	$-0.8\Omega/2$	$0.8\Omega/2$	9

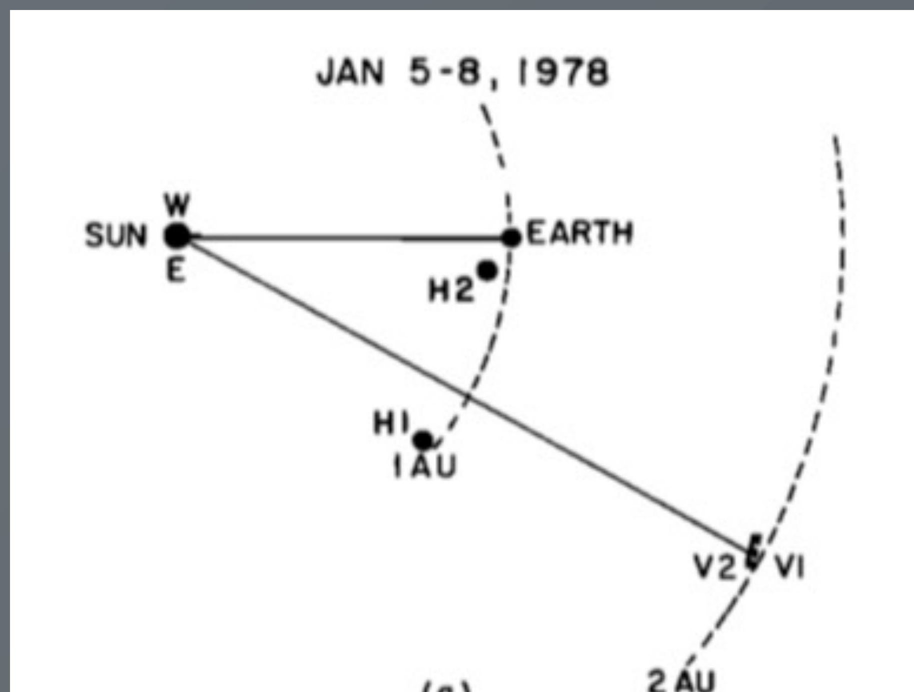
[a] *Uniform steps for all parameters.*
[b] *See section 2.3 for description.*
[c] *See note on coupling of the parameters in section 2.2.1.*

Malanushenko et al. Front. Astron. Space Sci, 2020

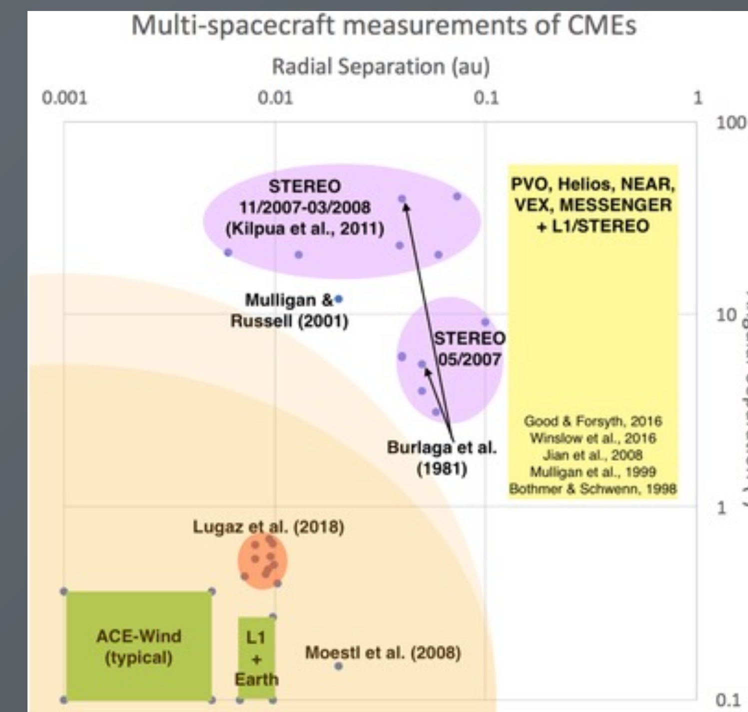


Barnard et al., AGU Advances, 2020

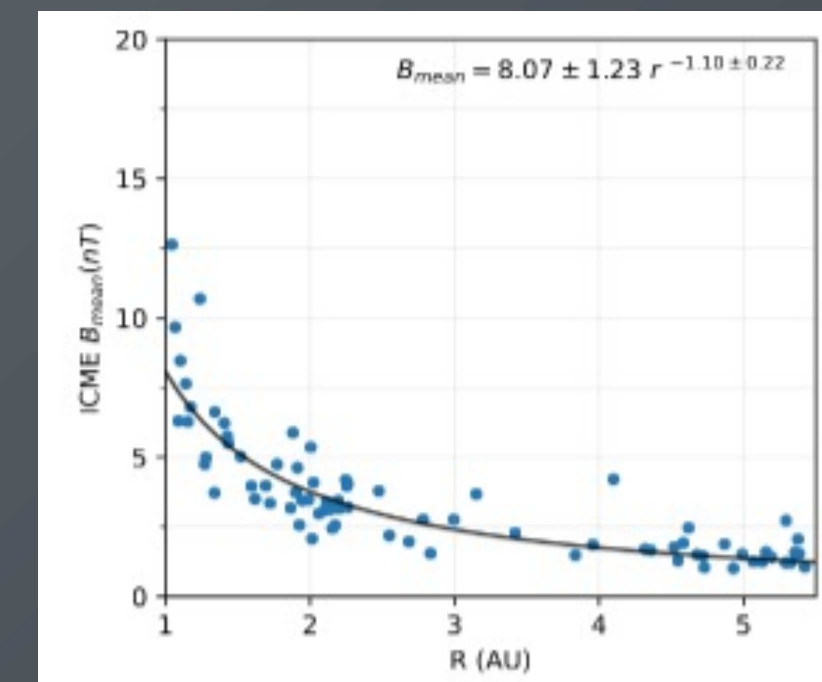
In-situ Measurements: What have we done?



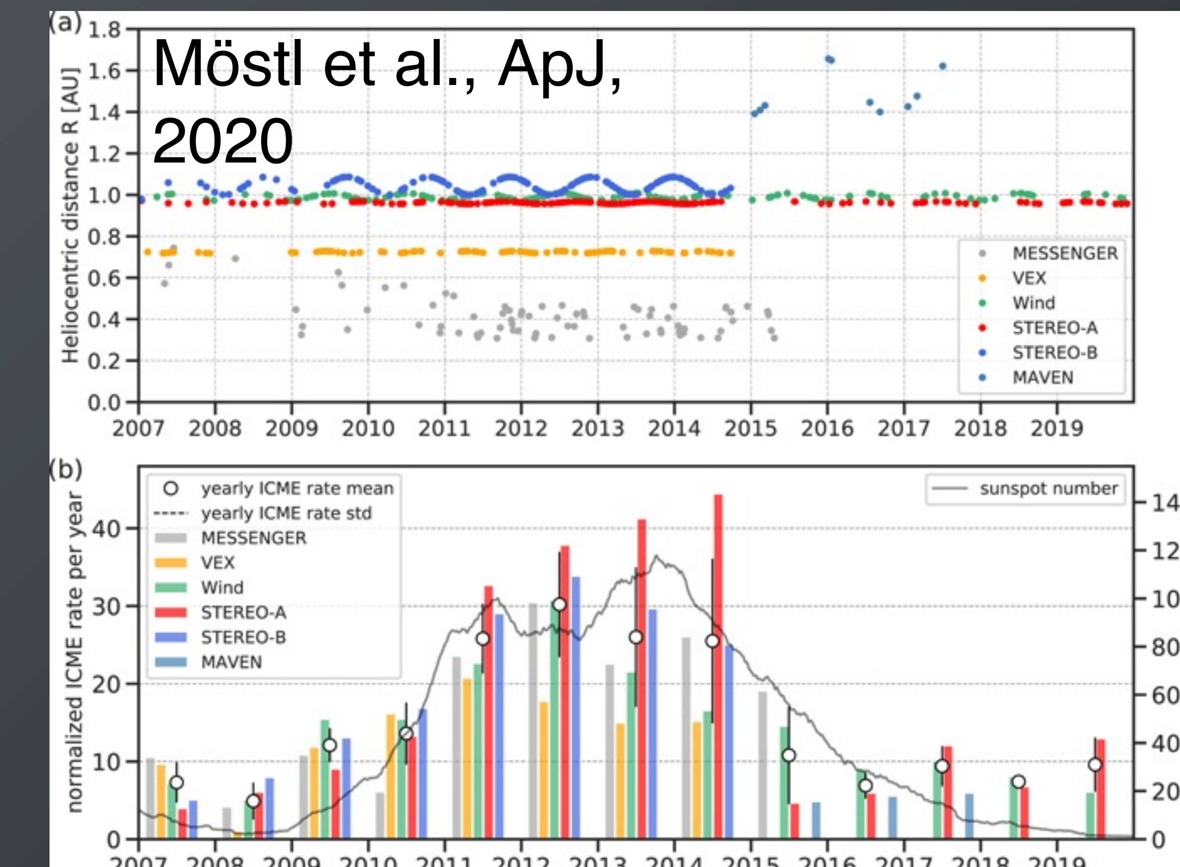
Burlaga et al., JGR, 1981



Lugaz et al., ApJL, 2018



Davies, E. et al., ApJ, 2021

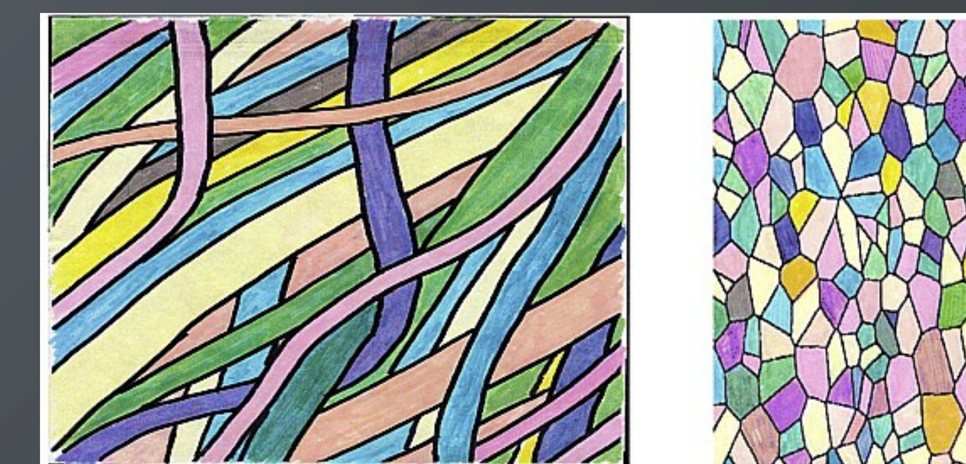


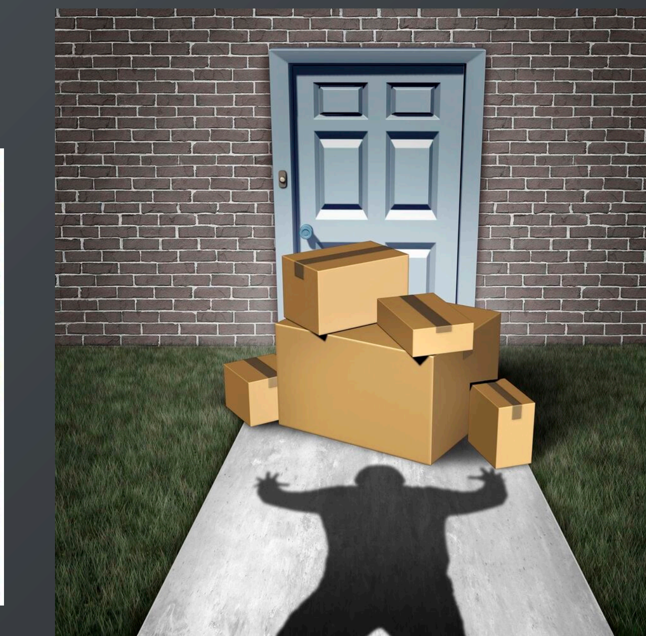
Möstl et al., ApJ, 2020

- **The best way to *accurately* forecast B_z is to measure it!**
  - Best way to understand a CME or solar wind structure is to have 4-12 spacecraft crossings.
  - Most focus has been on ensuring L1 measurements rather than “pushing the envelope”.
  - 30+ year gap in **Heliophysics** missions in the inner heliosphere from Helios (70’s) to *PSP / SolO* (20’s). Lack of “pure” IP in-situ missions between ACE (98) and IMAP (25).
- In term of research, the community has been resourceful.
  - Significant research with planetary missions (MESSENGER, Venus Express, NEAR, MAVEN).
  - Multi-spacecraft studies use “random” conjunctions between PSP, SolO, STEREO, L1.
    - At most, “constellation” of 2 spacecraft: Helios (2), STEREO (2).
    - Compare with Cluster (4), THEMIS (5), MMS (4), PUNCH (4), HelioSwarm (9).

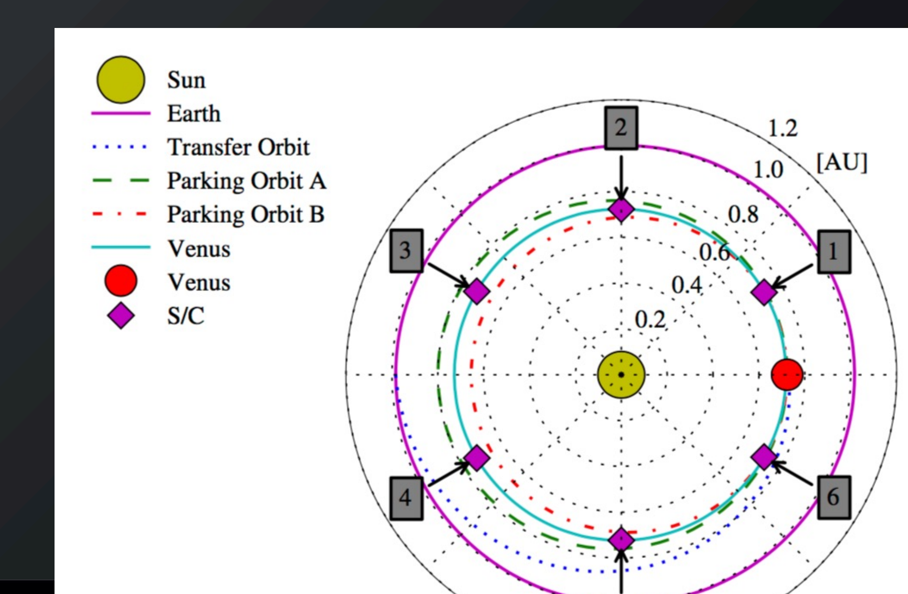
In situ measurements: Key science insights: The last day (and the last mile)

- The last mile: we care about bow shock solar wind, not L1.
  - Small-scale features (Borovsky, 2008).
  - Need more work on comparing THEMIS/MMS and L1.

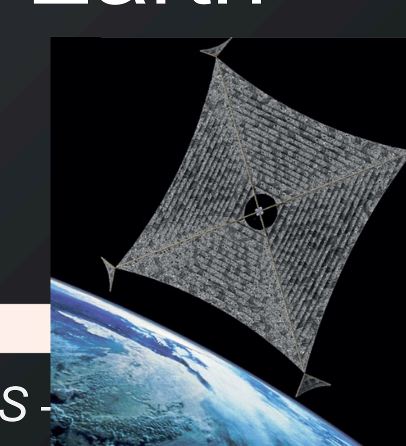




- **Key science question: (1) the last day**
  - How do CMEs and the solar wind evolve on timescale < 1-day is unknown.
  - We have a decent understanding of ***average*** evolution of structures over time of > 1-day.
  - Conjunction reveals that there can be large ***event-to-event variability***.
  - Uncertainty (~±25% at 0.8 AU) could be an issue for sub-L1 SpWx measurements.
- **Key science question**: (2) Structure and length-scale of CMEs and solar wind/IMF
  - CME magnetic structure is still unknown (lack of measurements).
  - Spacecrafts measure differences in CMEs at 1° longitudinal separations; some CMEs are not observed by 2 spacecraft separated by 7°.
  - Sub-L1 architecture depends on how far we can go from the Sun-Earth line (solar sail for close, heliocentric for far).
  - Significant changes in CIRs as they corotate from L5 to L1.

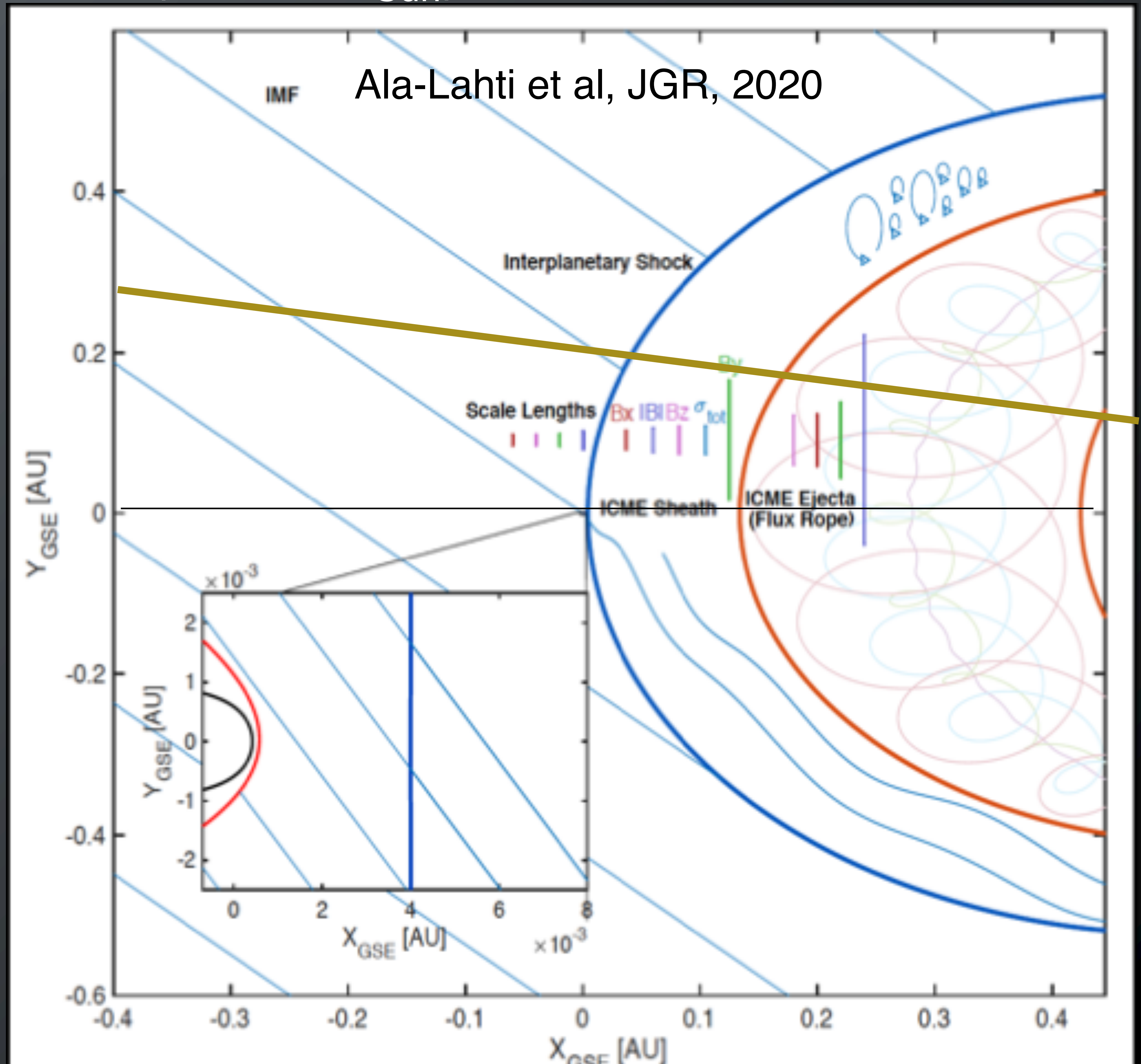


Ritter+, 2015



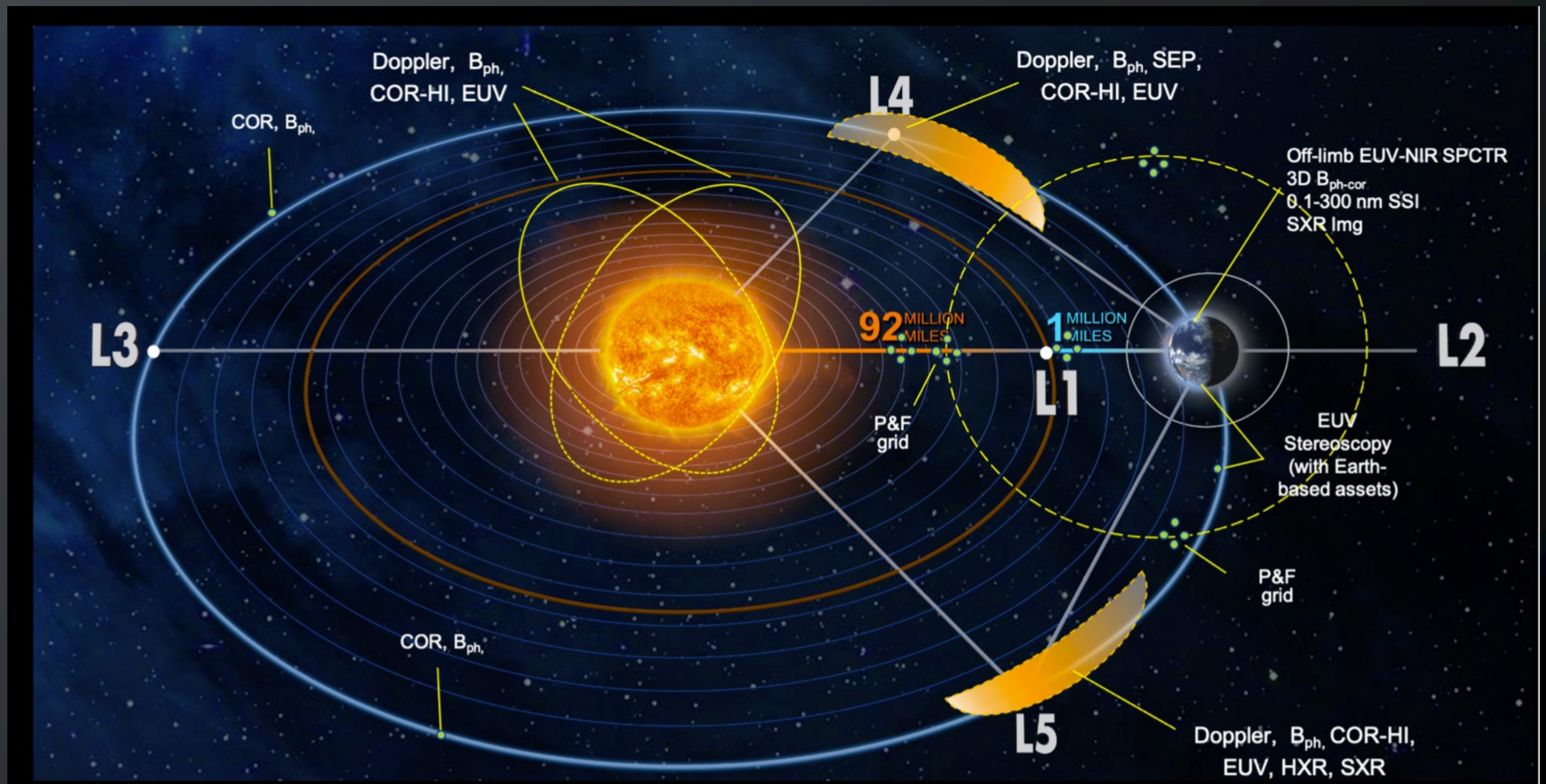
Ideal Location For In-Situ: Lack of Physical Knowledge

- Which one is more valuable/actionable?
  - Measuring a CME 10° from the Sun-Earth line at 0.8 AU? (10° = 0.175 AU)
  - Measuring a CME 1° from the Sun-Earth line at 0.95 AU (1° ~ 4 R_{Sun})
- We (I) don't know how to answer because of the lack of multi-s/c interplanetary measurements of CMEs "close" to Earth.
  - This is a dire need to advance our space weather capabilities.
  - We need in-situ science missions that will enable the next generation of Space Weather observatories.
    - Same way than STEREO will enable L4/L5.
    - Smallsat and rideshare are the perfect venue for this (light, high heritage instruments, low telemetry requirements).
    - An exact orbit attained is less important than having more datapoints through the solar wind, IMF and CMEs.



In-situ Recommendations

- Report to NASA on space weather gap analysis (D. Turner’s talk).
  - Priorities for solar/helio are **multi-s/c remote** off the Sun-Earth line + **grids** of plasma & field ***in situ* measurements**.
- So far, the smallsat/CubeSat revolution hasn’t reach IP science yet.
  - Launch is the primary issue. Heliophysics SIMPLEX calls (15-50M$) needed.
  - I believe that **25-100 kg observatories (dry mass) provide the highest RoI.**
- If smallsat launch opportunities become reality for IP/heliospheric physics.
  - ***No mass should be wasted***. How to have fast development of small missions to take advantage of reduced mass uncertainty for flagship missions past PDR/CDR?
  - Launching constellations one s/c at the time should be considered.
  - How to combine this + the desire to have near-uniform datasets + training the next generation?
  - In addition, ***please*** give us magnetometers on missions from other SMD divisions).



Graphic representation of the results of the gap analysis with respect to solar and heliospheric observational gaps. ‘P&F grid’ represents multipoint measurements of particles and fields that make up the in situ solar wind.

technologies or high-risk

Final thoughts

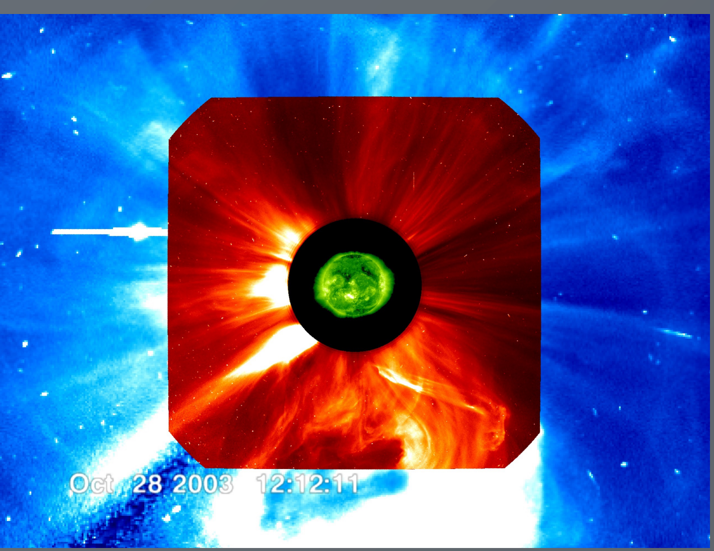
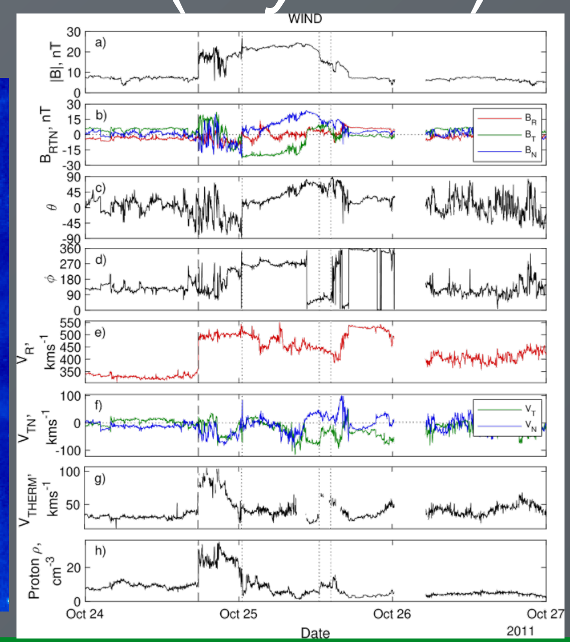
SC23:
Consistent L1 data
Amazing solar/coronal remote
Out of the ecliptic P&F (*Ulysses*)

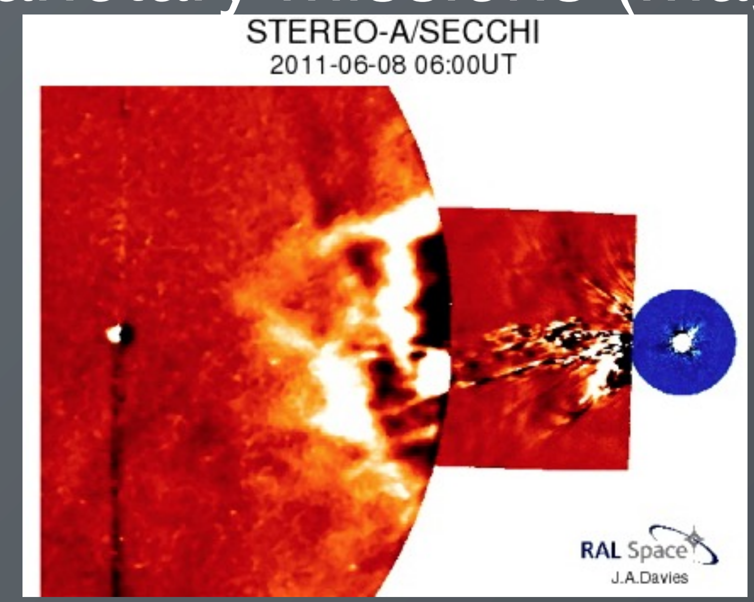
SC24:
STEREO P&F (multi in-situ at 1AU)
SDO + SECCHI (remote to 1 AU)
Planetary missions (mag from 0.3 to 5 AU)

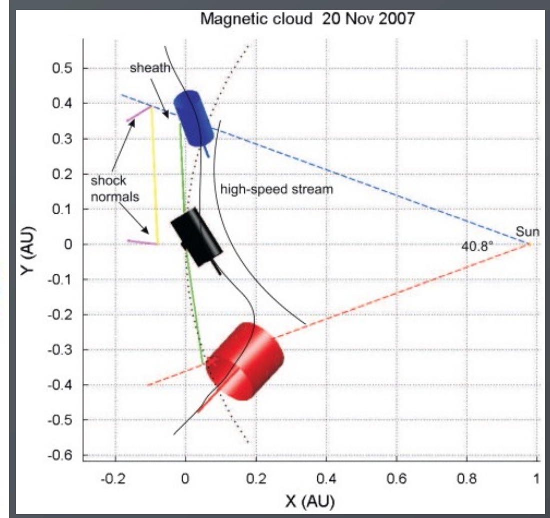
SC25:
Dedicated inner heliospheric measurements (SolO, PSP)
New remote obs (PUNCH)
IP Cubesat (CusP)
Planetary Smallsat (ESCAPADE)

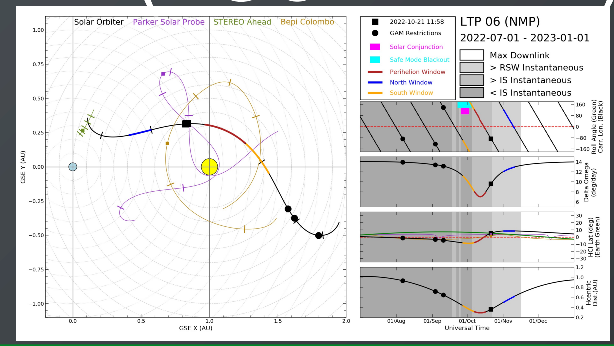
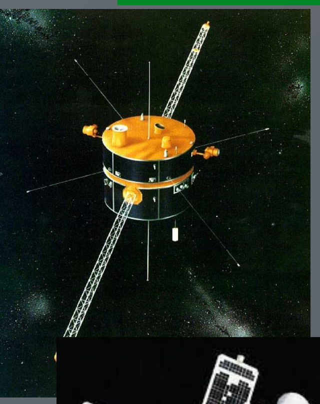
SC26:
Dedicated multi-spacecraft measurements: remote + P & F

Polar remote observations

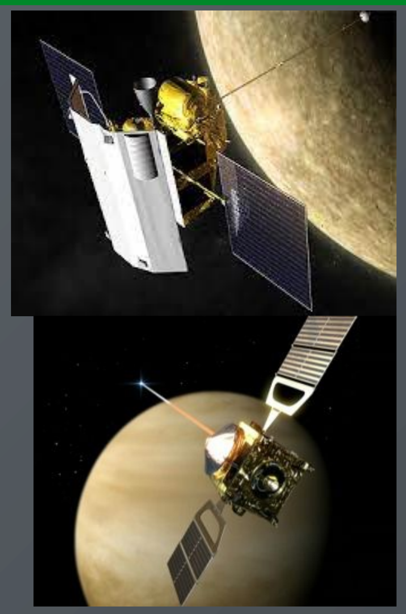





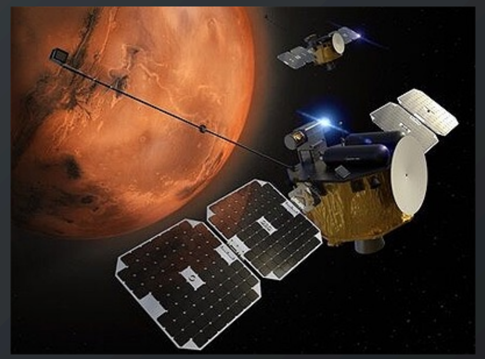








IP Smallsat
Multi-s/c (>2) IP missions

- We will reach solar maximum of SC25 (2024-2026) with similar but more resilient space weather capabilities as SC24 (2012-2014).
- Let's ensure new capabilities by the maximum of Solar Cycle 26 (2035)!
  - **This requires enabling science missions in the next decade.**

WHAT DO WE NEED TO UNDERSTAND TO FORECAST ALL CLEAR SEP PERIODS?

Kathryn Whitman

NASA JSC Space Radiation Analysis Group (SRAG)

National Academies Space Weather Operations and Research Infrastructure Workshop, Phase II

2022-04-11

SPACE RADIATION ANALYSIS GROUP (SRAG)

- SRAG’s mission is the protection of humans from space radiation
- Philosophy: As Low As Reasonably Achievable (ALARA)
  - *Accomplish mission goals while minimizing astronaut radiation dose*
- Establish human radiation exposure standards (career/acute)
- Operators support the Flight Control Team in Mission Control by monitoring the space weather and radiation environment and evaluating impact to crew
- Build and monitor a wide variety of vehicle-mounted and personal dosimeters
- Model the radiation environment in free space and within the vehicle
- Model and assess the biological risks due to radiation
- Develop flight rules that define requirements regarding radiation sources and actions in response to radiation events

SOLAR ENERGETIC PARTICLES AT THE ISS

- Current operations on the International Space Station take place in Low Earth Orbit (LEO) inside of the Earth's protective magnetosphere, which reduces the time that the ISS is impacted by SEP events

ISS Orbits only encounter SEPs near the geomagnetic poles during 5-10 minute passes (purple ovals).

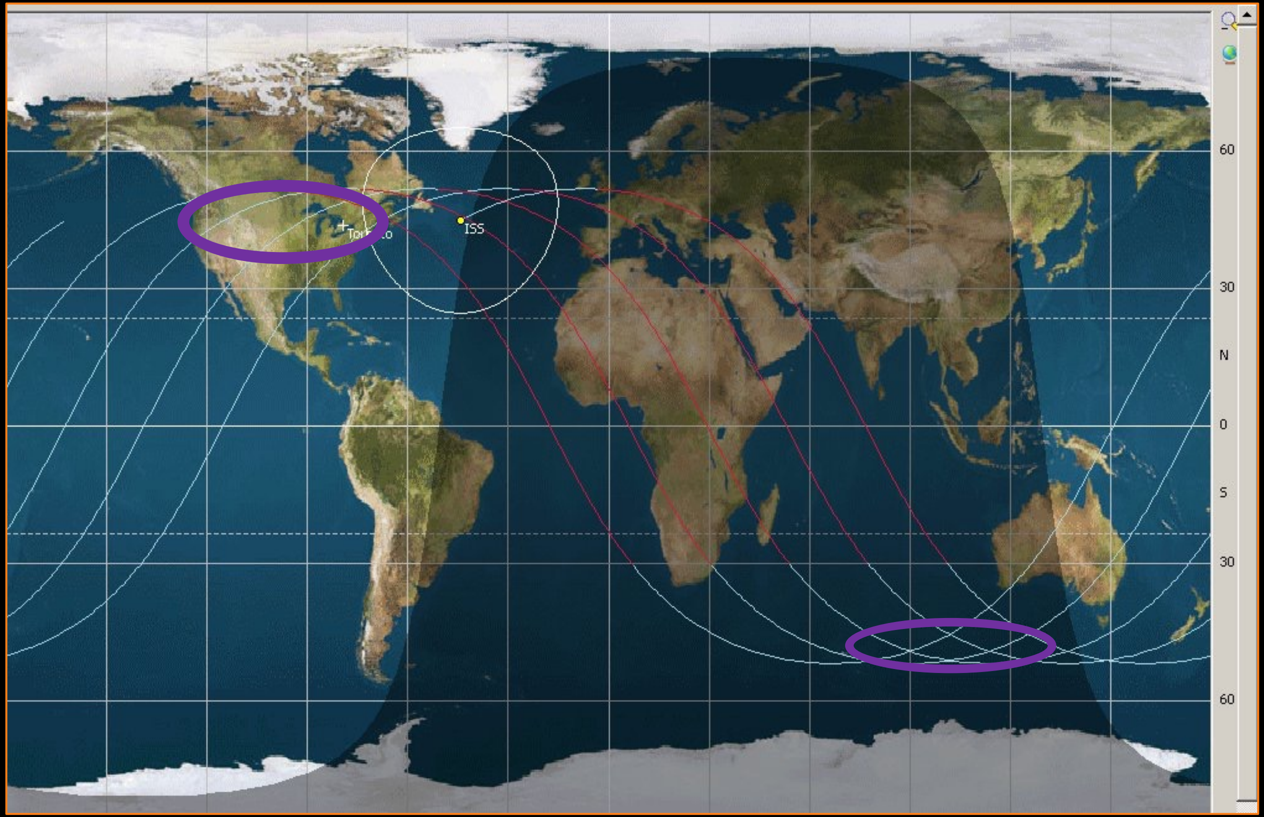


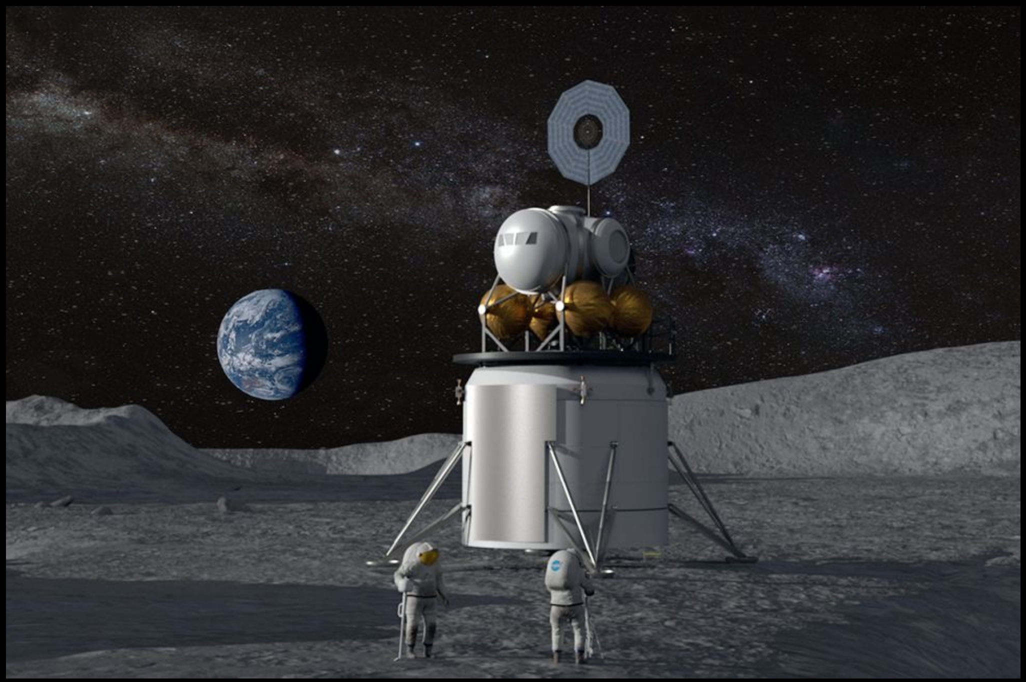
Image credit without circles: Wikipedia

SPACE RADIATION DURING HUMAN EXPLORATION MISSIONS OUTSIDE OF LOW EARTH ORBIT

Missions beyond LEO where crew-vehicle system spends substantial time in 'free-space' the scenario is very different:

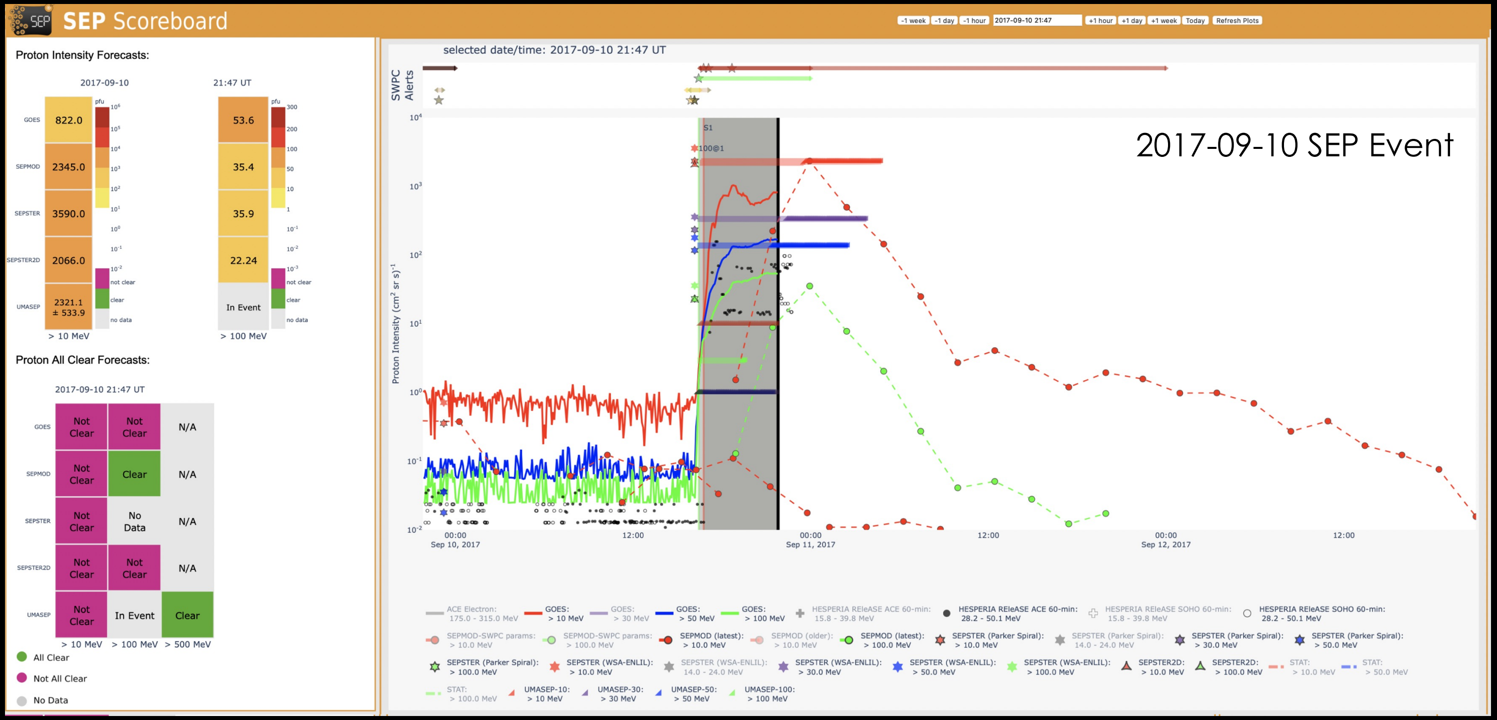
Human-vehicle will see full extent of SEP event.

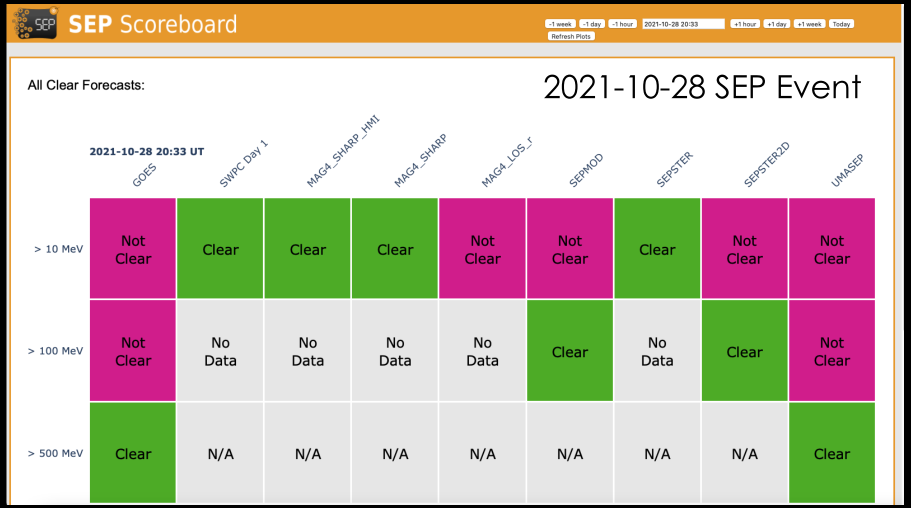
Image credits: NASA



THE ISEP PROJECT AND SEP SCOREBOARDS

- In a collaborative effort between SRAG, Moon to Mars Space Weather Analysis Office (M2M), and Community Coordinated Modeling Center (CCMC), called the Integrated Solar Energetic Proton Event Alert/Warning System (ISEP) project, CCMC has developed three SEP Scoreboards
- The SEP Scoreboards are running in real time and are being used by SRAG operators
  - All clear, Probability, Proton intensity
- Established SEP models have been integrated in the SEP Scoreboards (ongoing effort)
- Work directly with modelers to expand, improve, and validate their models for operations in R2O2R effort





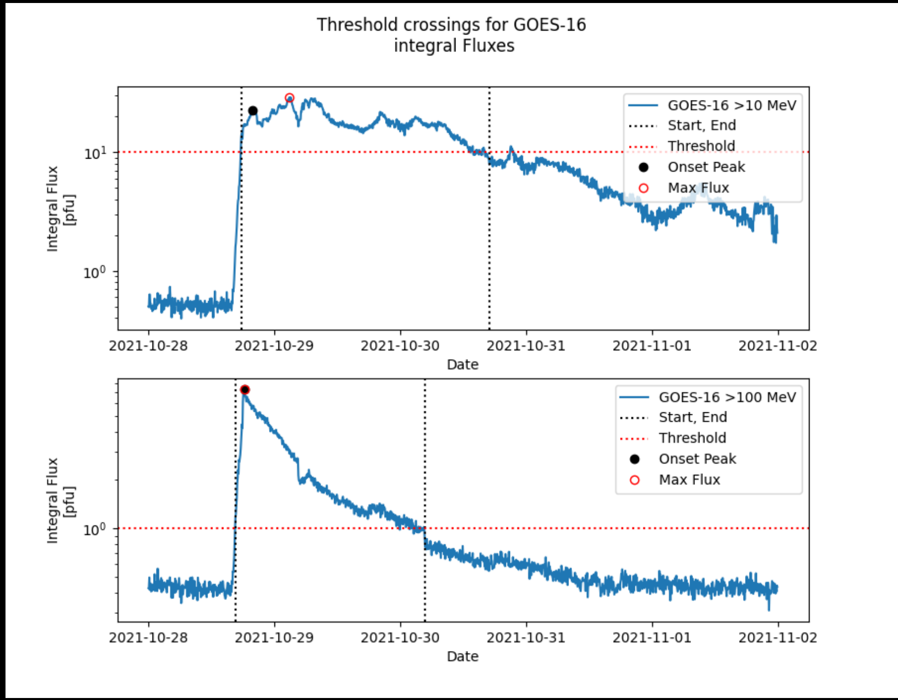
	GOES	SWPC_Day_1	MAG4_SHARP_HMI	MAG4_SHARP	MAG4_LOS_r	SEPMOD	SEPSTER	SEPSTER2D	UMASEP
> 10 MeV	Not Clear	Clear	Clear	Clear	Not Clear	Not Clear	Clear	Not Clear	Not Clear
> 100 MeV	Not Clear	No Data	No Data	No Data	No Data	Clear	No Data	Clear	Not Clear
> 500 MeV	Clear	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Clear

^ All Clear SEP Scoreboard
< Peak intensity and time intensity profile scoreboard
https://ccmc.gsfc.nasa.gov/challenges/sep.php

HOW DO WE DEFINE "ALL CLEAR"?

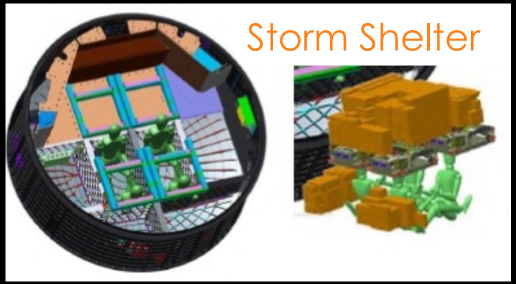
- Typically assess whether the solar energetic particle (SEP) intensity will or will not cross a threshold in a specific time window (e.g. next 6, 12, 24 hours)
- Choose thresholds and energy range combinations with operational relevance to generate a meaningful forecast
  - NOAA definition: >10 MeV exceeds 10 pfu
  - Additional SRAG definition: >100 MeV exceeds 1 pfu
- Multiple thresholds are applied to multiple energy ranges in the research community

➢ Worthwhile to set a few standard SEP All Clear definitions
  - Ensure useful forecast for operations
  - Facilitate cross-model validations and comparison



OPERATIONAL RELEVANCE OF THE SEP ALL CLEAR FORECAST

- Operational relevance stated here is presented from the perspective of SRAG for space radiation impacts to humans
- Limited SEP impact on the ISS in Low Earth Orbit due to the protection of the Earth's magnetosphere
- Astronauts onboard Artemis will be able to build a shelter within 30 minutes
- Astronauts performing a lunar EVA are required to stay within a 1-hour radius from the lander (life support systems requirement)



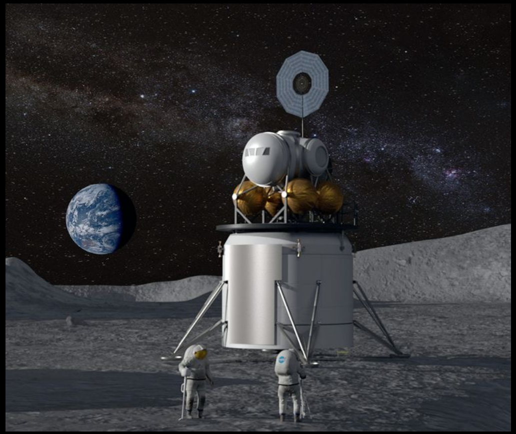


Image credits: NASA

- ➢ Astronauts can respond to an SEP event within a 30 – 60-minute timeframe. Therefore, regardless of All Clear status, if an eruptive event has not yet occurred (flare, CME), it is advantageous to carry out planned EVAs or other important tasks as the task could be completed prior to an eruption. If an SEP event does occur, astronauts can respond quickly.
- ➢ Two types of useful SEP All Clear forecasts:
  - ➢ All Clear prior to an eruption (issued every 6, 12, 24, 48, etc hours)
  - ➢ All Clear immediately following an eruption to enable quick response

PHYSICS REGIMES RELEVANT TO SEP FORECASTING

- Flare eruption and intensity characteristics, coronal configuration
- CME eruption and propagation characteristics, shock formation
- Production and availability of suprathermal seed particles
- Configuration of inner heliosphere, propagation of the solar wind, and magnetic connectivity between the particle acceleration sources and the observer
- Transport of particles within the inner heliosphere
  - Turbulence
  - Diffusion
  - Magnetic structures
- SEP characteristics at the observer

- Largest SEP events and associated M & X class flares & fast CMEs are uncommon events - low statistics and sparse data sets, challenge for modeling

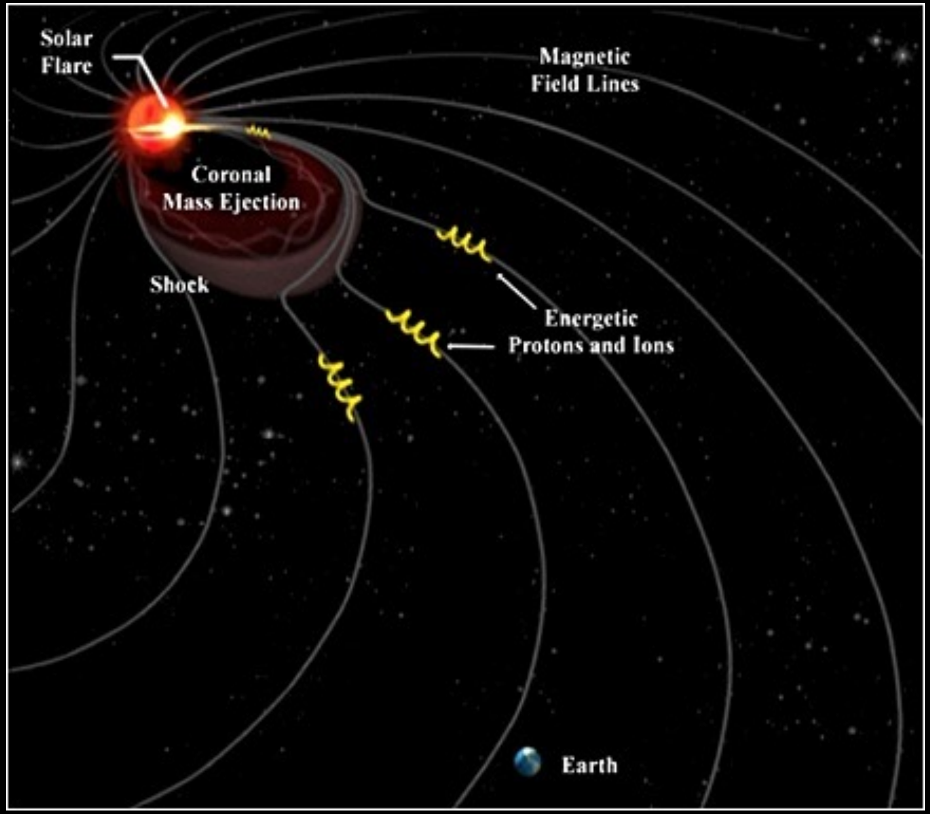
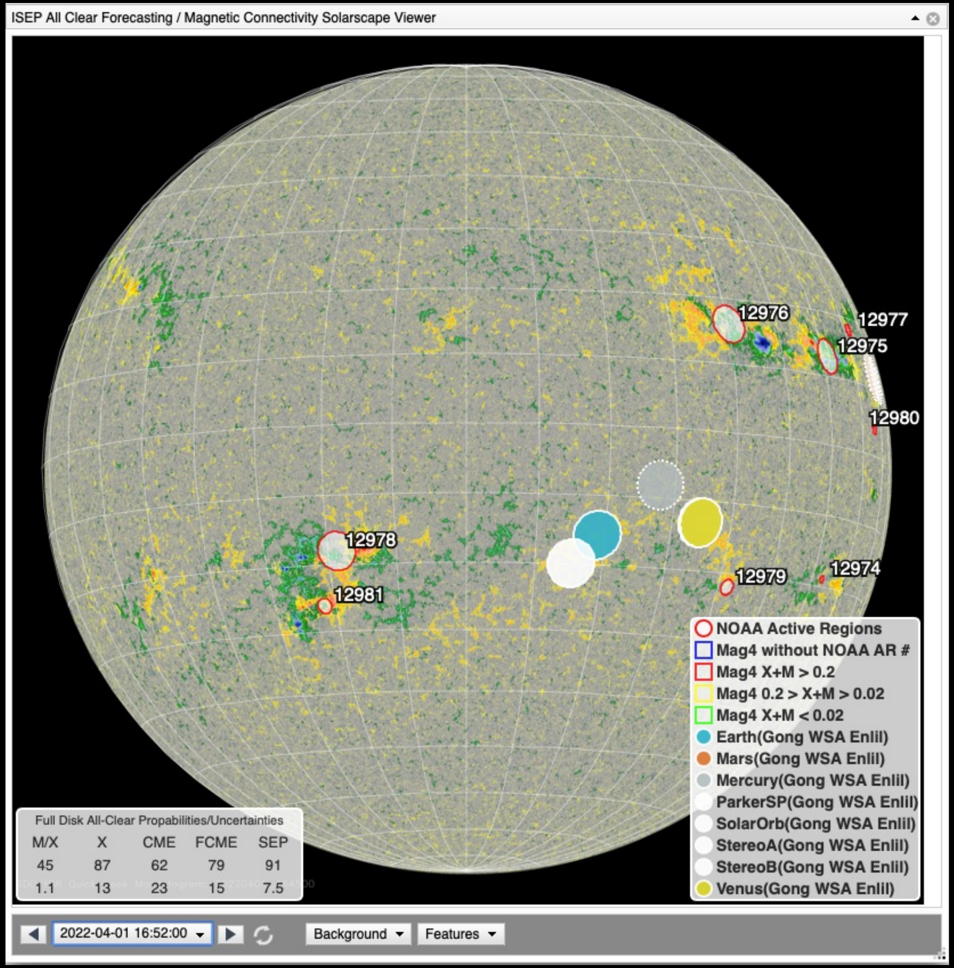


Image Credit: Núñez and Paul-Pena (2020), https://doi.org/10.3390/universe6100161

TYPICAL APPROACH TO SEP ALL CLEAR FORECASTING (PRE-ERUPTION)

Example: MAG4 forecast (ISWA)



PRE-ERUPTION ALL CLEAR

1. Calculate the likelihood that a solar flare will occur and the most likely flare class (C, M, X)
2. Fold in the likelihood that a CME will be produced by the flare and the most likely CME properties (speed, width)
3. Fold in the likelihood that an SEP event will be produced by the eruption and observed at the location of interest to calculate the probability of SEP occurrence
4. Apply a threshold probability to determine All Clear status

TYPICAL APPROACH TO ALL CLEAR SEP NOWCASTING (POST-ERUPTION)

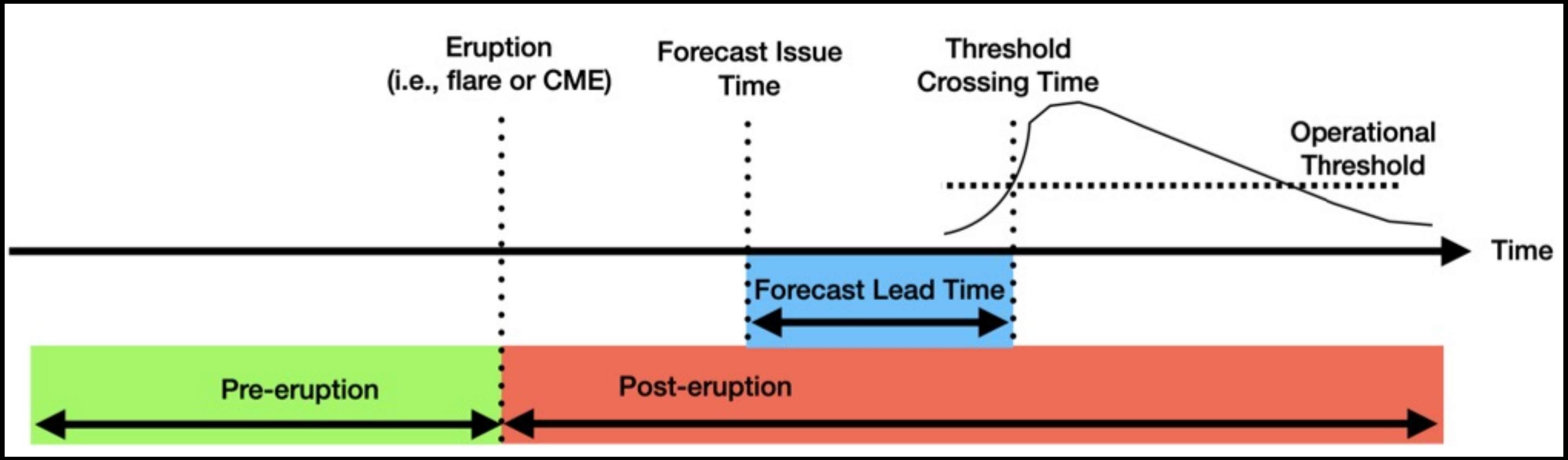


Image Credit: Phil Quinn (SRAG)

POST-ERUPTION ALL CLEAR

1. Use flare, CME, radio, electron, and/or proton information to estimate SEP characteristics

- If a model can produce a probability, peak flux, or time profile prediction ahead of the particle rise, this may be used as a post-eruption SEP All Clear
- Currently, most models cannot make a prediction before the onset of a well-connected SEP event

Table 11: Outputs produced by the solar energetic particle models summarized in this paper. Pre/Post: Pre indicates pre-eruptive forecast prior to the flare or CME, Post indicates a forecast issued after an eruptive event (flare, CME) has occurred; All Clear: binary yes/no forecast for an SEP event or specific threshold crossing; Probability: probability of occurrence; Flux Point: forecast of proton intensity levels for a single time point or a single flux value within a specific time window in the future (see main text for further description); Onset time: time of threshold crossing or SEP event start; Peak: peak intensity; Peak time: time of the peak intensity; End time: event end time or decay time; Fluence: total event time-integrated fluence; Time profile: produces intensity with time; Multi loc.: capable of producing forecasts for multiple locations in the heliosphere; 3D: produces 3D environmental data and particle info, such as pitch angle distributions. If a model outputs a time profile, then it is indicated that the model predicts onset time, peak flux and time, end time, and fluence as applicable. There are some time profile models that cannot currently simulate the full duration of the event and for these, only the predictions that are possible to derive from their time profiles are indicated.

Model	Proton Energy [MeV]	Pre/Post	All Clear	Probability	Flux Point	Onset time	Peak	Peak time	End time	Fluence	Time profile	Multi loc.	3D
ADEPT	>10, >30, >50, >100	Post					x	x	x	x	x		
AFRL PPS	>5, >10, >50	Post				x	x	x	x	x	x		
Aminalragia-Giamini model	≥5	Post	x	x									
AMPS	eV to GeV	Post				x	x	x	x	x	x	x	x
Boubrahimi model	>100	Post	x										
COMESEP SEPForecast	>10, >60	Post		x		x	x	x	x				
EPREM	5 - 1000**	Post				x	x	x	x	x	x	x	x
ESPERTA	>10	Post	x										
FORSPEF	>10, >30, >60, >100	Pre/Post		x		x	x	x	x	x			
GSU	>10	Pre	x	x									
iPATH	100 keV - GeV	Post				x	x	x	x	x	x	x	x
Lavasa Model	>10	Pre	x										
MAG4	>10	Pre	x	x									
MagPy	>10	Pre	x	x									
MEMPSEP	9-15, >5, >10, >30, >60, >100	Post		x		x	x	x	x	x			
M-FLAMPA	10 keV - 1 GeV	Post				x	x	x	x	x	x	x	x
PARADISE	keV - GeV	Post				x	x	x	x	x	x	x	x
PCA model	> 10	Post		x									
PROTONS	>10	Post		x			x	x					
REleASE	4-9; 9-15.8; 15.8-39.8; 28.2-50.1	Post		x	x								
Sadykov et al.	>10	Pre	x	x									
SAWS-ASPECS	>10 to >300	Pre/Post	x	x		x	x	x	x	x	x		
SEPCaster	100 keV - GeV	Post	x			x	x	x	x	x	x	x	x
SEPMOD	1 - 1000	Post					x	x	x		x	x	x
SEPSTER	14 - 24; >10, >30, >50, >100	Post					x	x				x	
SEPSTER2D	10 - 130; >130	Post					x	x	x	x		x	
SMARP Model	>10	Pre	x	x									
SOLPENCO(2)	0.125 - 64; 5 - 300	Post				x	x	x		x	x	x	
South African model	keV - GeV	Post				x	x	x	x	x	x	x	x
SPARX	>10, >60, >300	Post				x	x	x	x	x	x	x	x
SPREAdFAST	2 - 115	Post				x	x	x			x	x	x
SPRINTS	1, 5, 10, 30, 50, 100	Pre/Post	x	x									
STAT	1 - 1000	Post				x	x	x			x	x	x
UMASEP	>10, >30, >50, >100, >500	Post	x		x	x	x	x		x			
Zhang model	MeV - GeV	Post				x	x	x	x	x	x	x	x

Legend:
Pre-eruption forecast
Could be used for All Clear

SEP MODELS

- The research community has developed a wide variety of SEP models
  - ➢ Only a few models are operational
- 9/35 models make pre-eruption forecasts
  - ➢ Nearly every pre-eruption model applies machine learning
  - ➢ Most pre-eruption forecasts are for >10 MeV; *>100 MeV is important for space radiation*
- Most models (26/35) make post-eruption forecasts
  - ➢ Post-eruption forecasting is delayed by data latency (coronagraph, space-based radio), the manual process of measuring CME parameters, and/or run time (physics-based)
  - ➢ UMASEP and REleASE provide post-eruption forecasts with advanced warning

Whitman et al. (2022), *Review of Solar Energetic Particle Models*, submitted to a special issue of ASR for the COSPAR Space Weather Roadmap

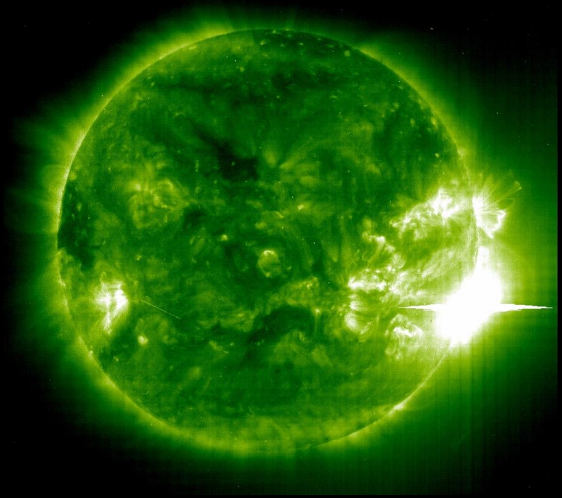
OBSERVATIONS RELEVANT TO SEP FORECASTING AND SCIENTIFIC UNDERSTANDING

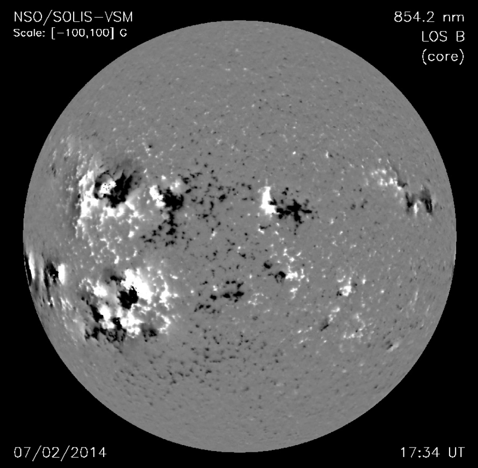
Flares

Physics Regime: Flare eruption and intensity characteristics, coronal configuration

Current Resources: Magnetograms, EUV, X-rays, optical, ground-based radio (Type III radio bursts)

Future Improvements: Extended or full-Sun coverage of magnetograms and EUV including polar imaging, helioseismology far-side techniques



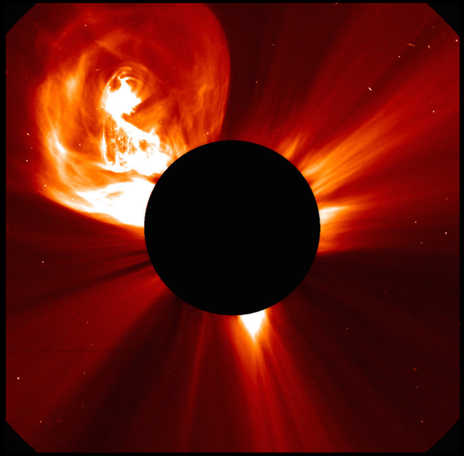


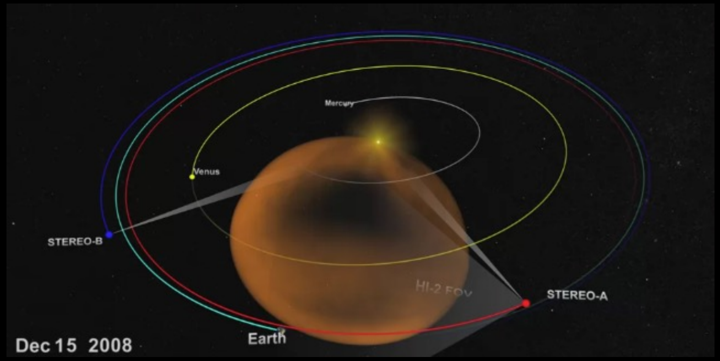
CMEs

Physics Regime: CME eruption and propagation characteristics, shock formation

Current Resources: Coronagraphs (two viewpoints), EUV, ground and space-based* radio (Type II, IV radio bursts)

Future Improvements: Operational coronagraphs with high cadence from multiple vantage points, real time space-based radio observations (~1 MHz)





Multi-viewpoint observations
Image credit: NASA

*Space-based radio observations are not currently available in real time

OBSERVATIONS RELEVANT TO SEP FORECASTING AND SCIENTIFIC UNDERSTANDING

Solar Wind and Magnetic Connectivity

Physics Regime: Propagation of solar wind, magnetic connectivity between source and observer

Current Resources: Magnetograms and EUV images, in situ magnetic field and particle measurements at 1 AU

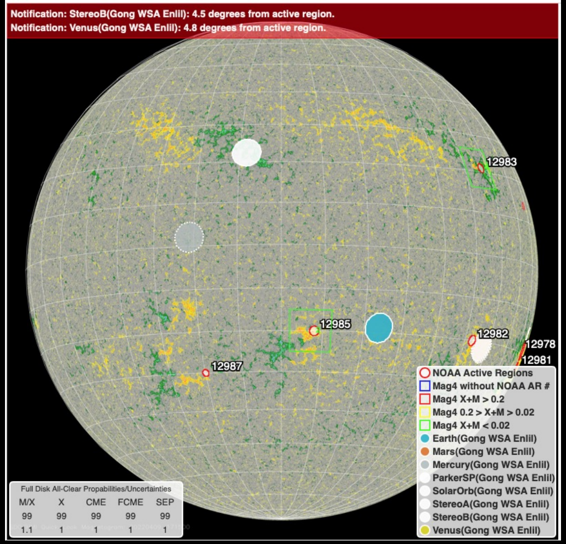
Future Improvements: Extended or full-Sun coverage of magnetograms and EUV including polar imaging, helioseismology far-side techniques, continuous real time in situ magnetic field and particle measurements closer to the Sun

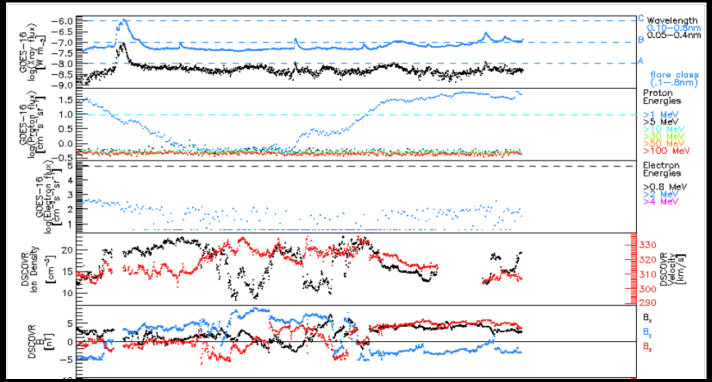
Particle Transport

Physics Regime: Transport of particles within the inner heliosphere (turbulence, diffusion, magnetic barriers)

Current Resources: Same as magnetic connectivity, limited in situ energetic particles near Sun (PSP, SO), multi-point in situ energetic particles, space-based radio

Future Improvements: Same as magnetic connectivity, constellations measuring magnetic field and particle distributions to capture multi-scale physics, real time space-based radio





Magnetic connectivity (top) and solar wind at L1 (bottom). Image Credits: ISWA

OBSERVATIONS RELEVANT TO SEP FORECASTING AND SCIENTIFIC UNDERSTANDING

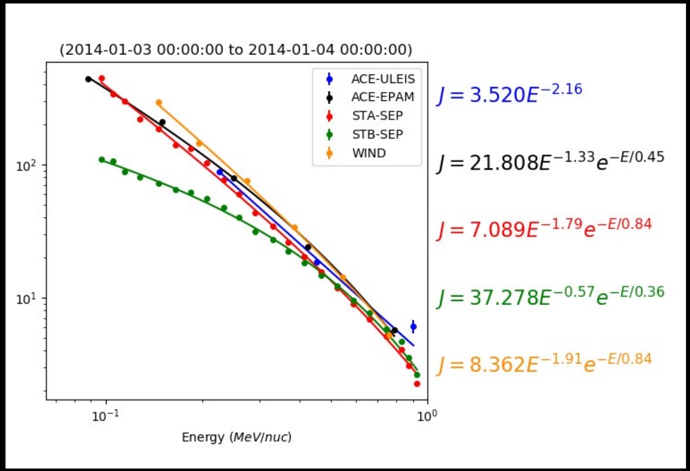
Seed Particles

Physics Regime: Production and availability of suprathermal seed particles at the acceleration source

Current Resources: In situ measurements of particles ~keV to few MeV at 1 AU, limited in situ near-Sun measurements

Future Improvements: Continuous real time in situ near Sun measurements of particles keV to few MeV

Suprathermal Particle Spectrum at 1 AU



< Image credit: Maher Dayeh, provided for https://ccmc.gsfc.nasa.gov/assessment/topics/SEP/campaign2020.php

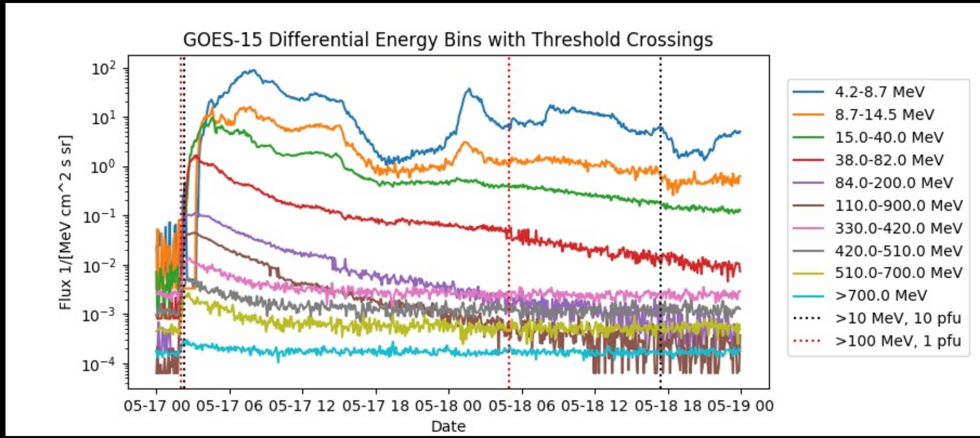
On PSP measurements of suprathermals: Desai et al. 2021, submitted to ApJ
https://arxiv.org/pdf/2111.00954.pdf
"…no single existing model or theory appears to fully account for all of the IS⊙IS/EPI-Lo observations presented in this paper, thus requiring a re-examination of existing theories of ST ion production close to the Sun."

SEP Events

Physics Regime: SEP characteristics at the observer

Current Resources: In situ measurements of energetic particles from MeV to GeV, neutron monitors

Future Improvements: Well-calibrated, high quality, continuous, real time, multipoint in situ measurements of energetic particles over the full intensity range with good energy resolution from MeV to GeV



KEY OBSERVATIONS FOR SPACE WEATHER FORECASTING

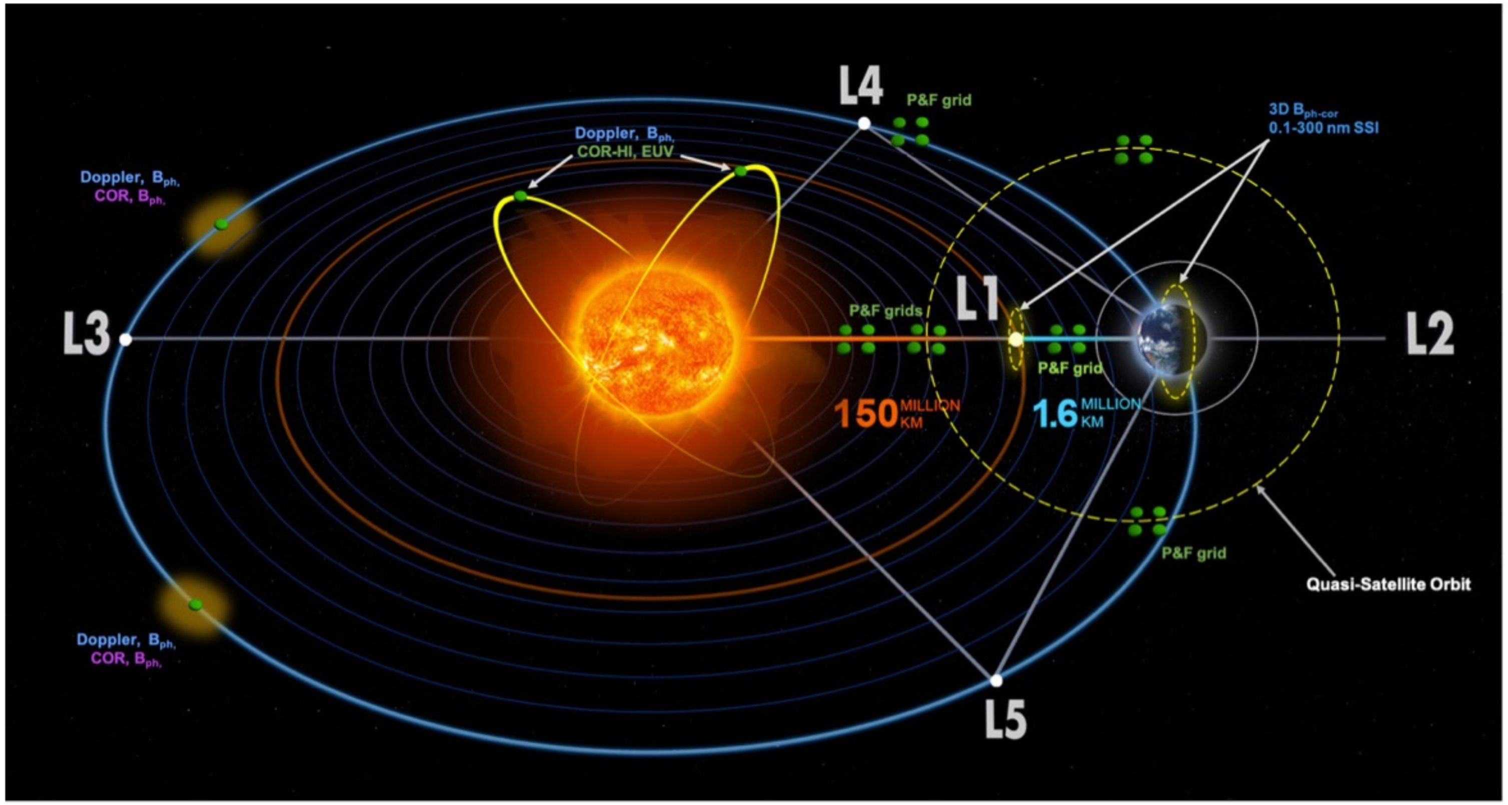


Figure 6-2. Visual representation of the locations and types of measurements that can lead to closure for several SWx research and forecasting issues. Details are provided in Table 6-4 and Section 5.

- Image Credit: *Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration (NASA).* (Vourlidas et al. 2021) https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf)

- New observations to prioritize in near future for SEP All Clear forecasting:
  - High cadence coronagraphs at L1, L4, L5
  - Magnetograms, EUV, magnetic fields, & particles at L4 and L5
- Near sun particle and mag field measurements or real time support for data from existing experiments (PSP, SO)

SEP ALL CLEAR FORECASTING IS MULTI-DISCINPLINARY

Likelihood that a flare will occur and intensity characteristics (C, M, X) + Likelihood that a CME will occur and propagation characteristics (speed, width) + Likelihood that an SEP event will occur at the observer and SEP characteristics (threshold crossing, peak, time profile) → SEP All Clear

- SEP All Clear forecasting requires reliable forecasts that involve flares, CMEs, magnetic connectivity, solar wind configuration, and SEPs
- Improvements in forecasting any of the phenomena should increase reliability of SEP All Clear forecasts
- SEP forecasting is a multi-disciplinary task that benefits from cross-disciplinary teams (including expertise in theory, observations, and computer science)
- SEP All Clear forecasting involves many types of observational inputs, particularly post-eruption forecasts that rely on various measurements that probe flare and CME eruptions and the solar wind
- Data used to train the models may not be the same as data used to trigger the models, i.e. data for training, validation, and triggering must be available to the scientific community

NEXT STEPS FOR SEP ALL CLEAR FORECASTING

- Machine Learning methods show promise and should be supported, particularly for pre-eruption SEP All Clear (see e.g., Sadykov et al. 2021, https://arxiv.org/pdf/2107.03911.pdf)
- Post-eruption SEP All Clear forecasts could be useful if these methods could provide a fast forecast. Improvements in data latency, reduction of manual steps in the forecasting process, decreased run times, and development of new approaches to using computationally-intensive physics-based models in an operational setting could make progress towards faster forecasts.
  - For exploration missions, onboard sensors coupled with models on the vehicle could give early warning of Not All Clear situations
- Forecasts must be reliable to be useful. It is important to validate models on independent data sets, *running the models as they would run operationally.*
- Space weather forecasting attempts to describe a complex 3D system with continuous measurements at only one or two points in the heliosphere. 360º views of the Sun and in situ measurements of particles and magnetic fields in as many locations as possible will improve our physical understanding, ability to monitor conditions, and forecasting accuracy.

CONCLUSIONS

- Two categories of SEP All Clear
  - Pre-eruption forecast
  - Post-eruption nowcast
- Beneficial to define a standard set of All Clear definitions that are chosen to have operational relevance and would facilitate cross-model comparisons
- SEP forecasting is a multidisciplinary effort that probes many physical regimes from the corona through the inner heliosphere to the observer
- All Clear forecasting at Mars may require additional observations, such as a coronagraph at Mars L1 (e.g., Christina Lee's poster on Wed., Posner and Strauss (2020). https://doi.org/10.1029/2019SW002354)

It is critical that operationally supported, high-cadence, reliable and accurate space weather data streams for all phenomena relevant to SEP production are publicly available for operations and the deployment and development of models that require real time observations. (Whitman et al., 2022)