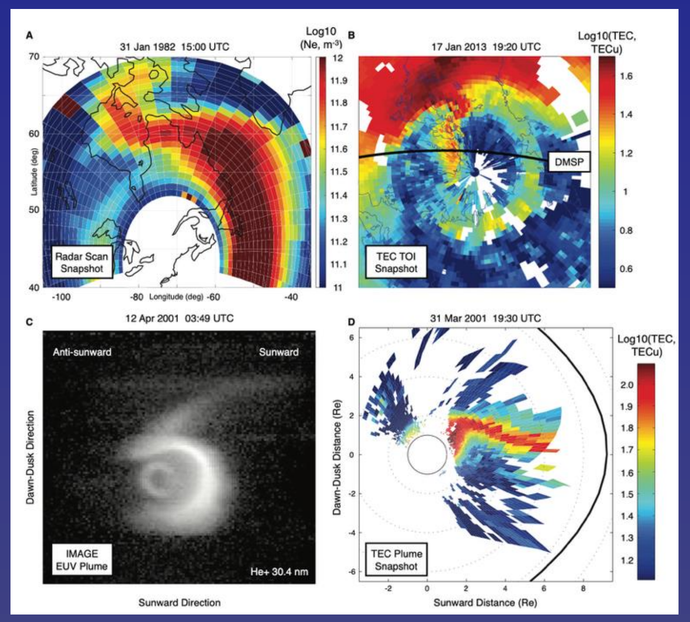
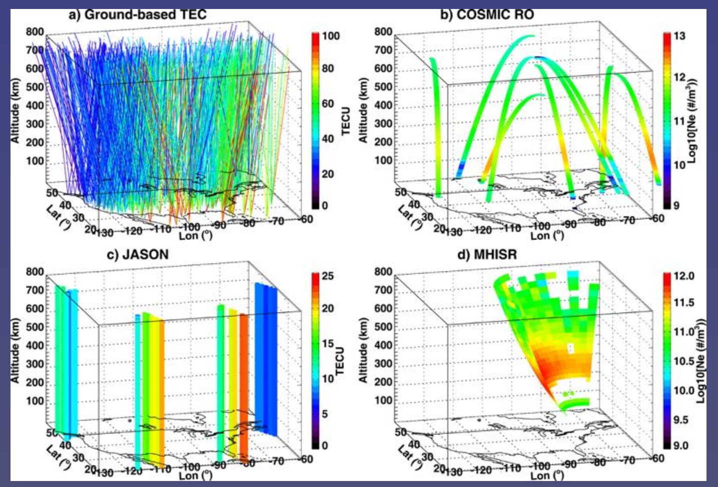
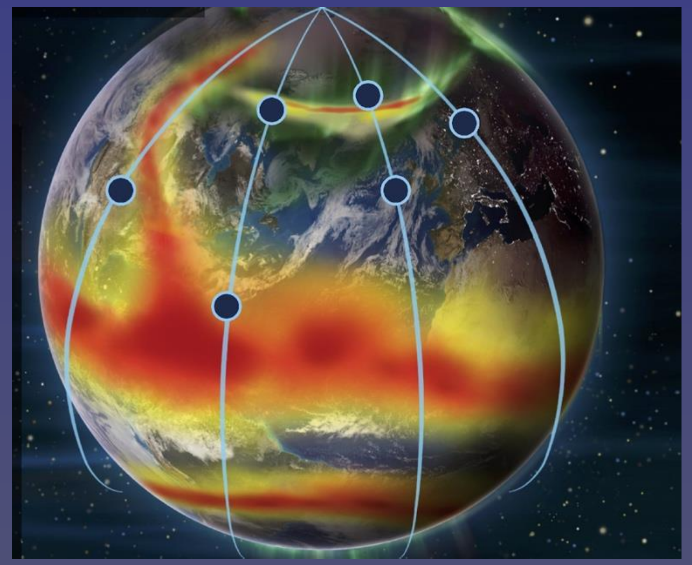
Observational Synthesis for Geospace Frontier Science: A Community Member's Perspective

P. J. Erickson
MIT Haystack Observatory



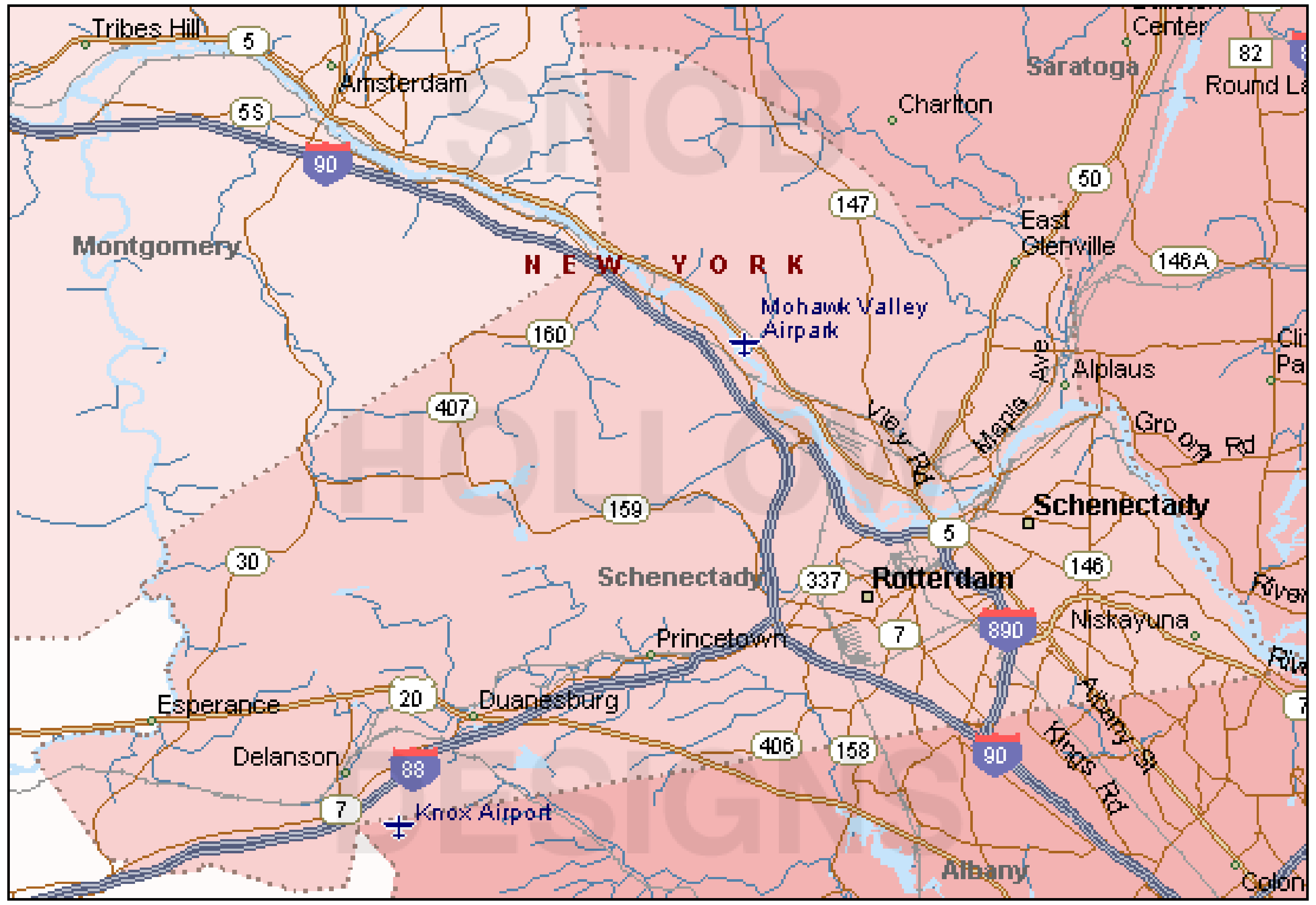




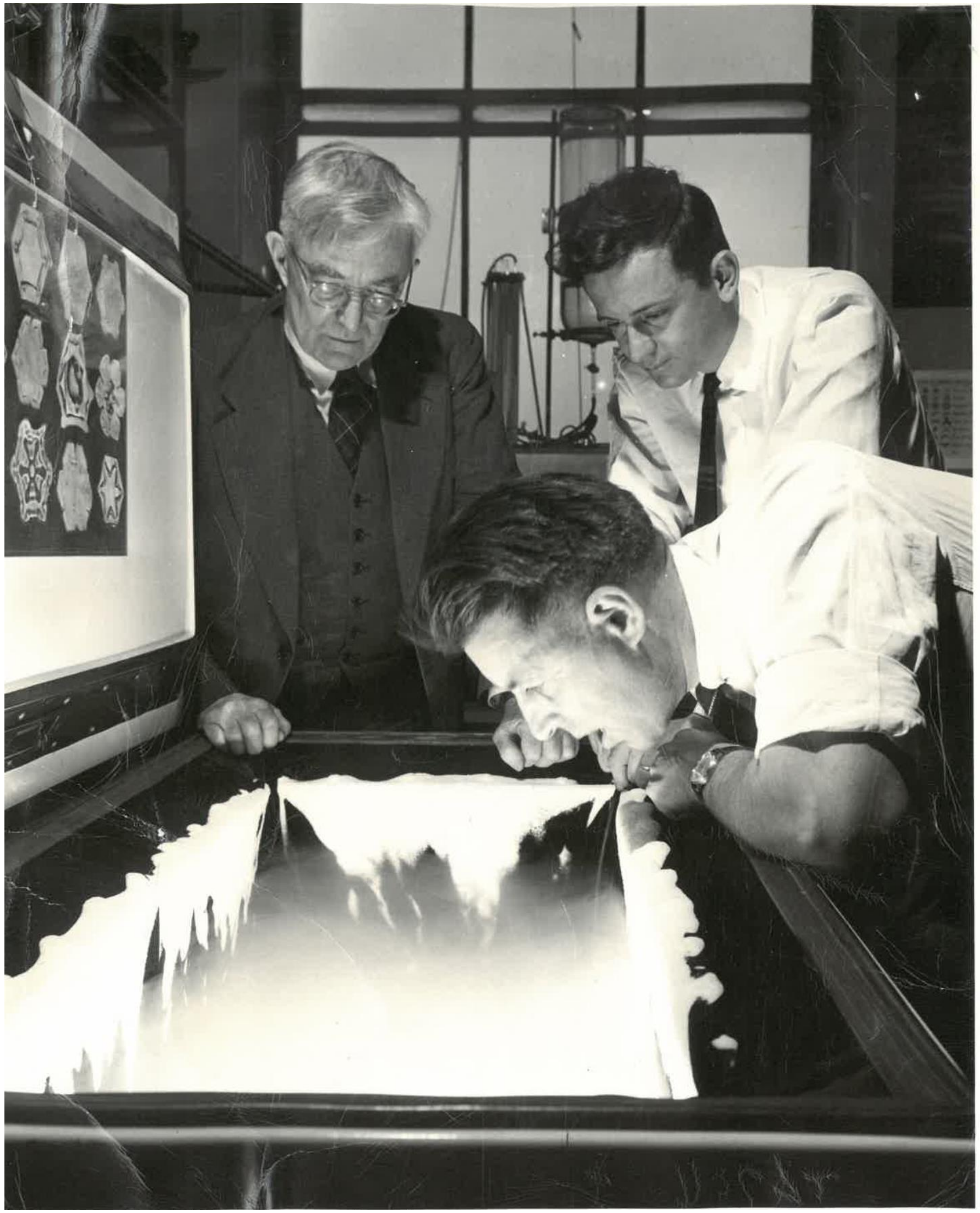
CEDAR-GEM 2025
Distinguished Lecture
Des Moines, IA

NSF CEDAR GEM Geospace Environment Modeling

Thanks to all my colleagues for support, inspiration and material



Schenectady, NY



When Langmuir arrived at the Laboratory, the director, Willis R. Whitney, told him to look around and see if there was anything he would like to "play with." Whitney would often ask him, "**Are you having any fun today?**"

One day, after three years of apparently unproductive research, Langmuir answered, "I'm having a lot of fun, but I really don't know what good this is to the General Electric Company." Whitney replied. "**That's not your worry. That's mine.**"

$$\omega_p = \left(\frac{n_0 e^2}{\epsilon_0 m}\right)^{1/2}$$

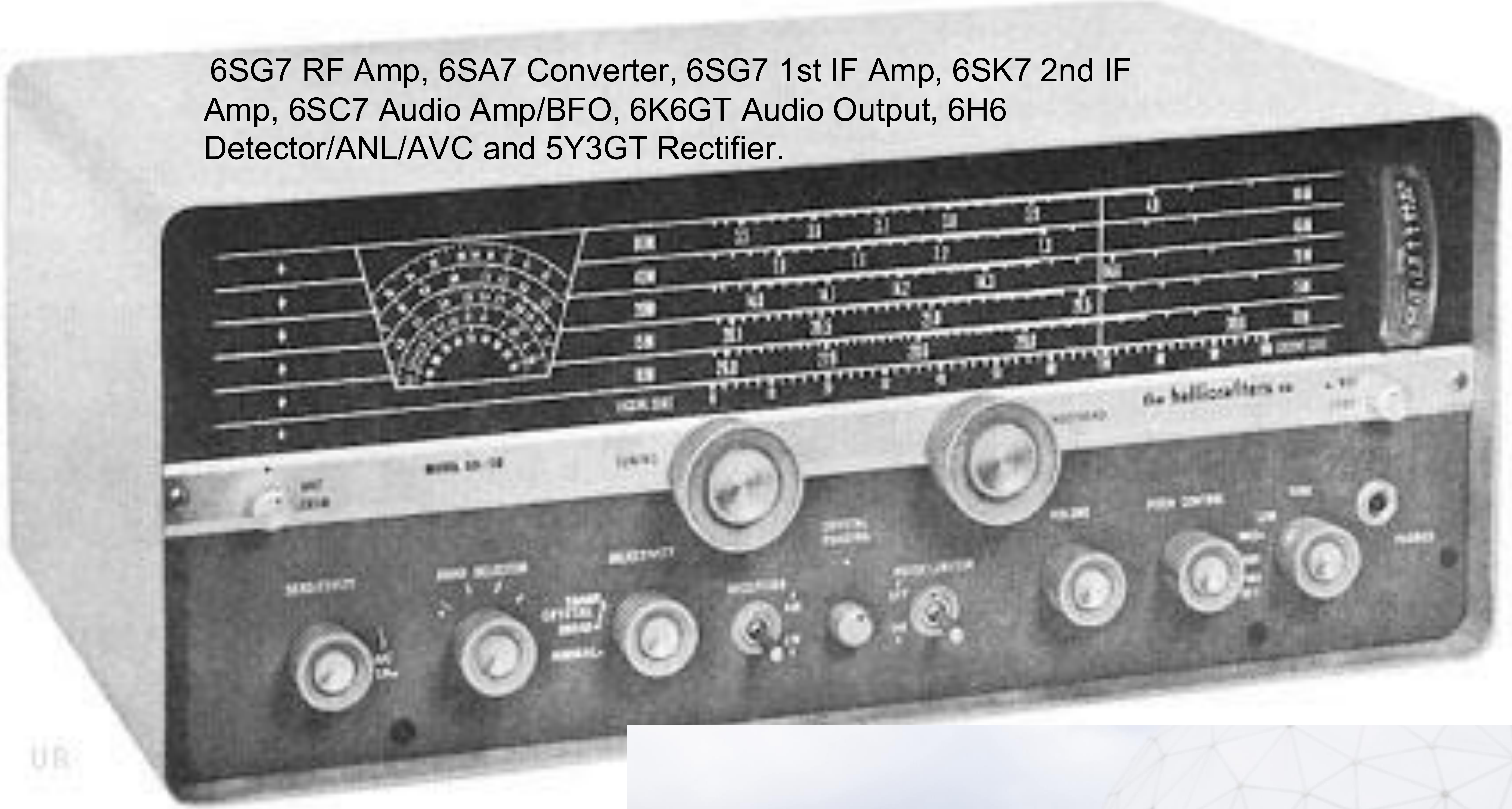
$$\omega^2 = \omega_p^2 + \frac{3}{2}k^2 v_{th}^2$$

$$v_{th}^2 = 2k_B T_e / m_e$$

Irving Langmuir (1881 - 1957)
Chief Scientist, GE
Nobel Prize, 1932, Surface Chemistry

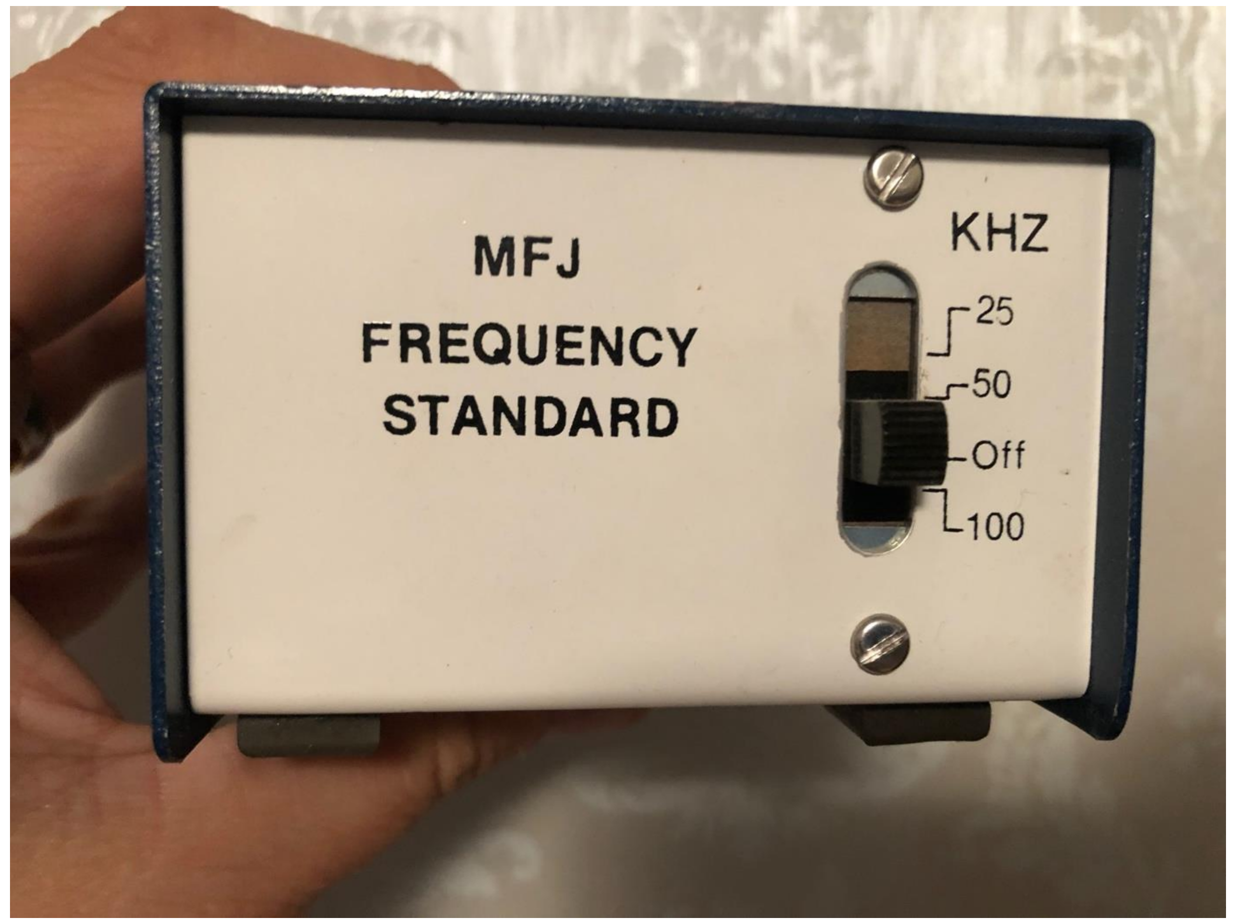
Radio beginnings

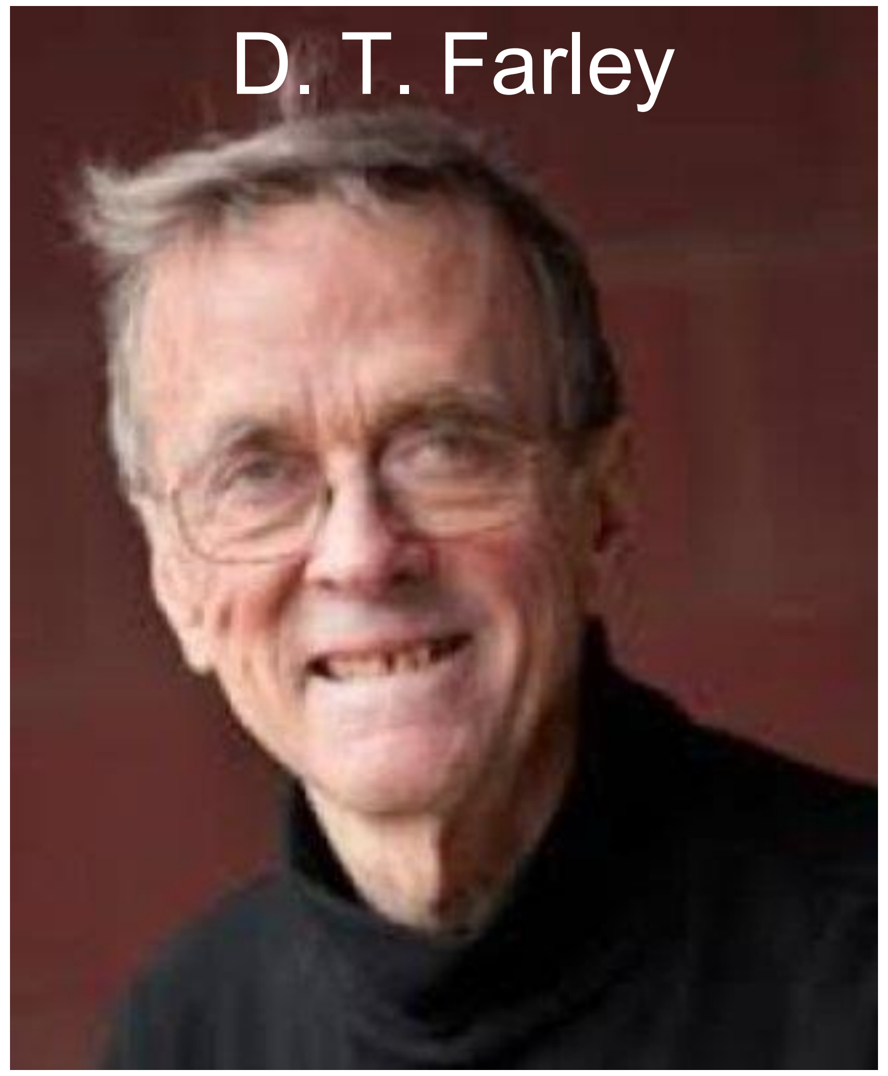
6SG7 RF Amp, 6SA7 Converter, 6SG7 1st IF Amp, 6SK7 2nd IF Amp, 6SC7 Audio Amp/BFO, 6K6GT Audio Output, 6H6 Detector/ANL/AVC and 5Y3GT Rectifier.

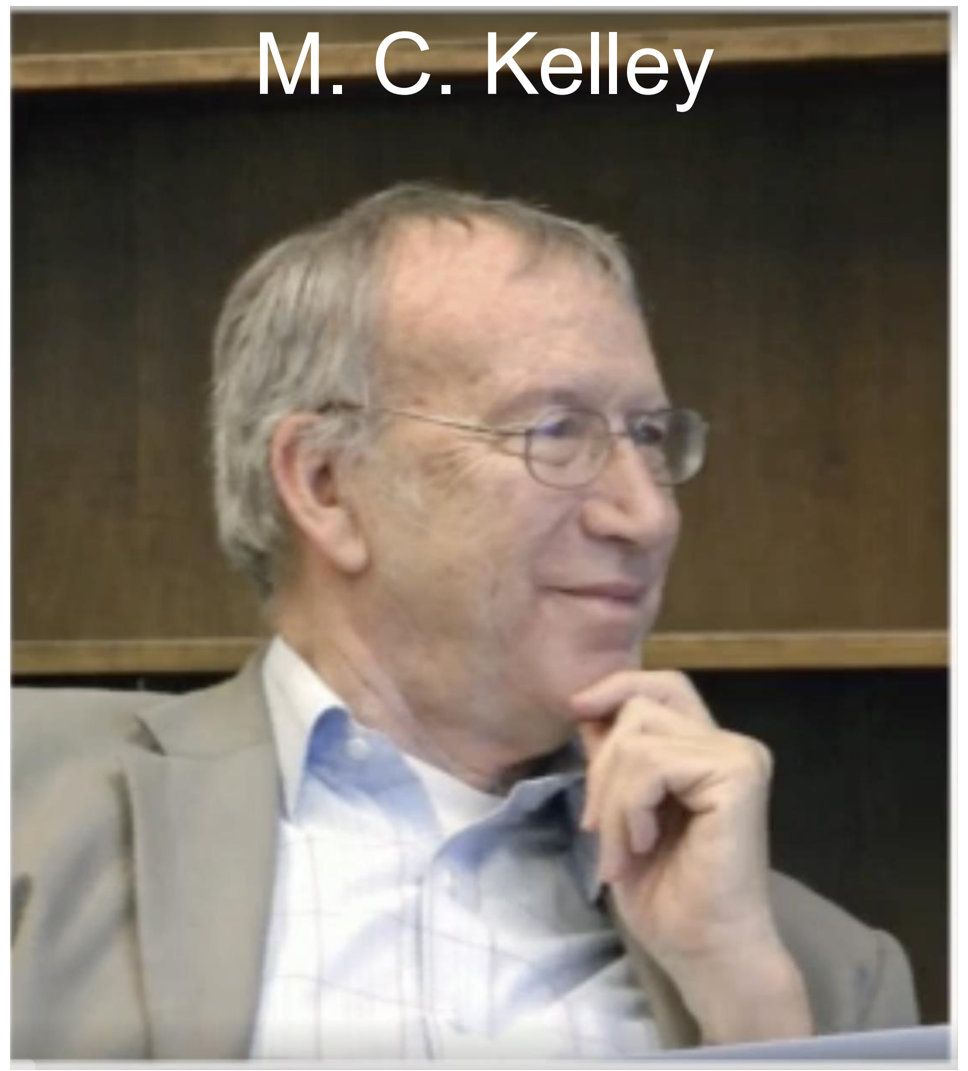


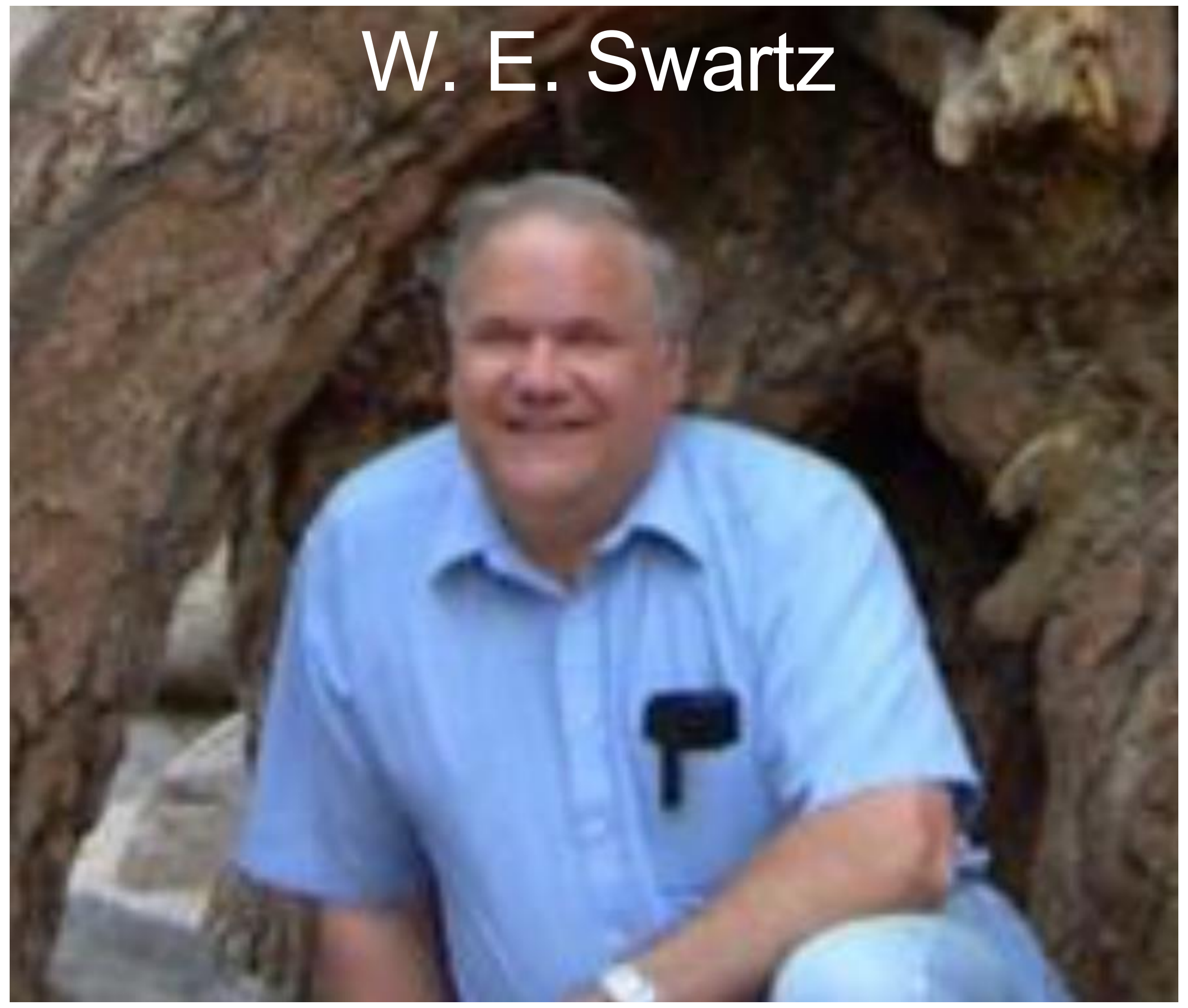
Radio Vaticana

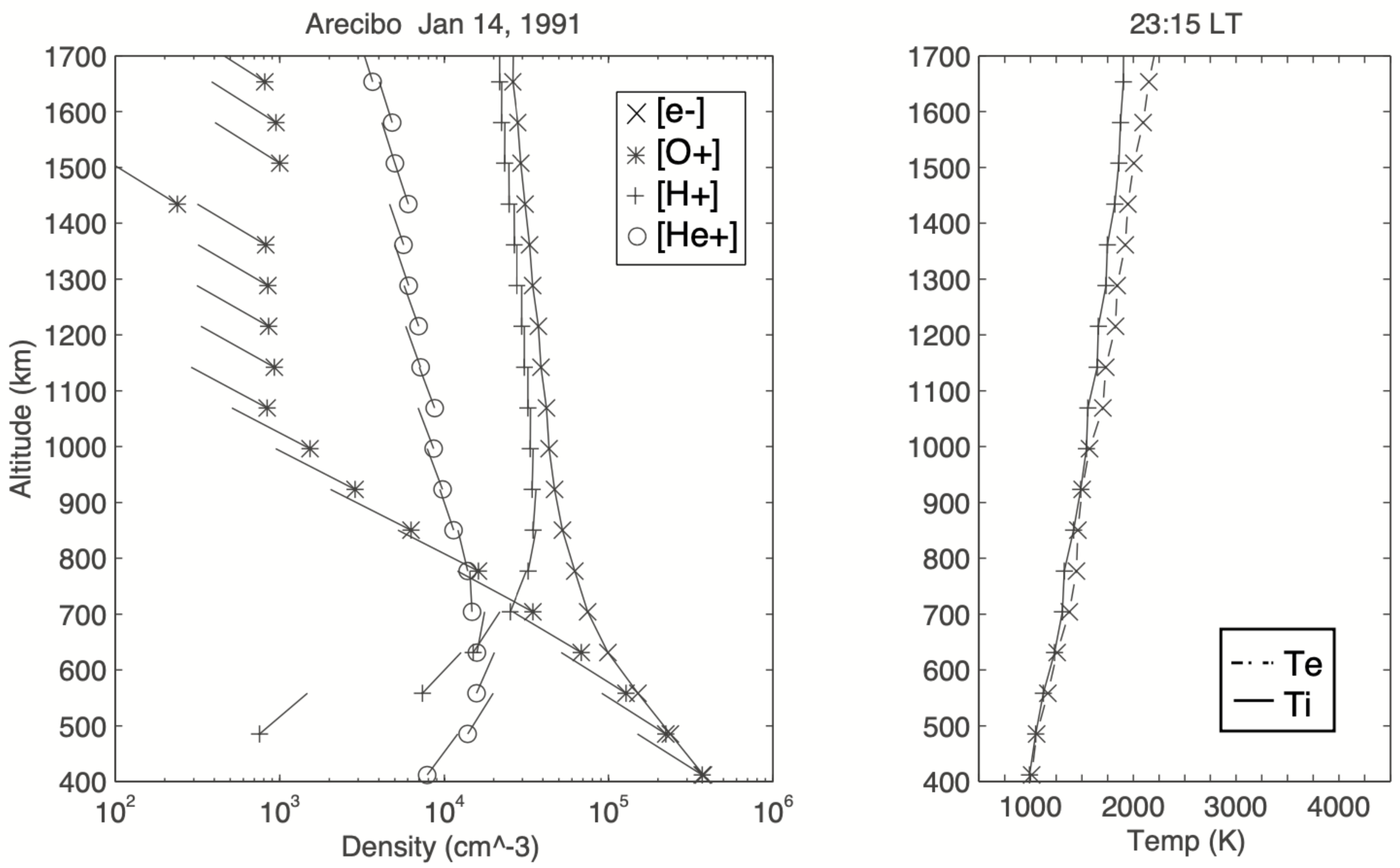
Voice of America











OBSERVATIONS OF LIGHT IONS IN THE

MIDLATITUDE AND EQUATORIAL TOPSIDE

IONOSPHERE

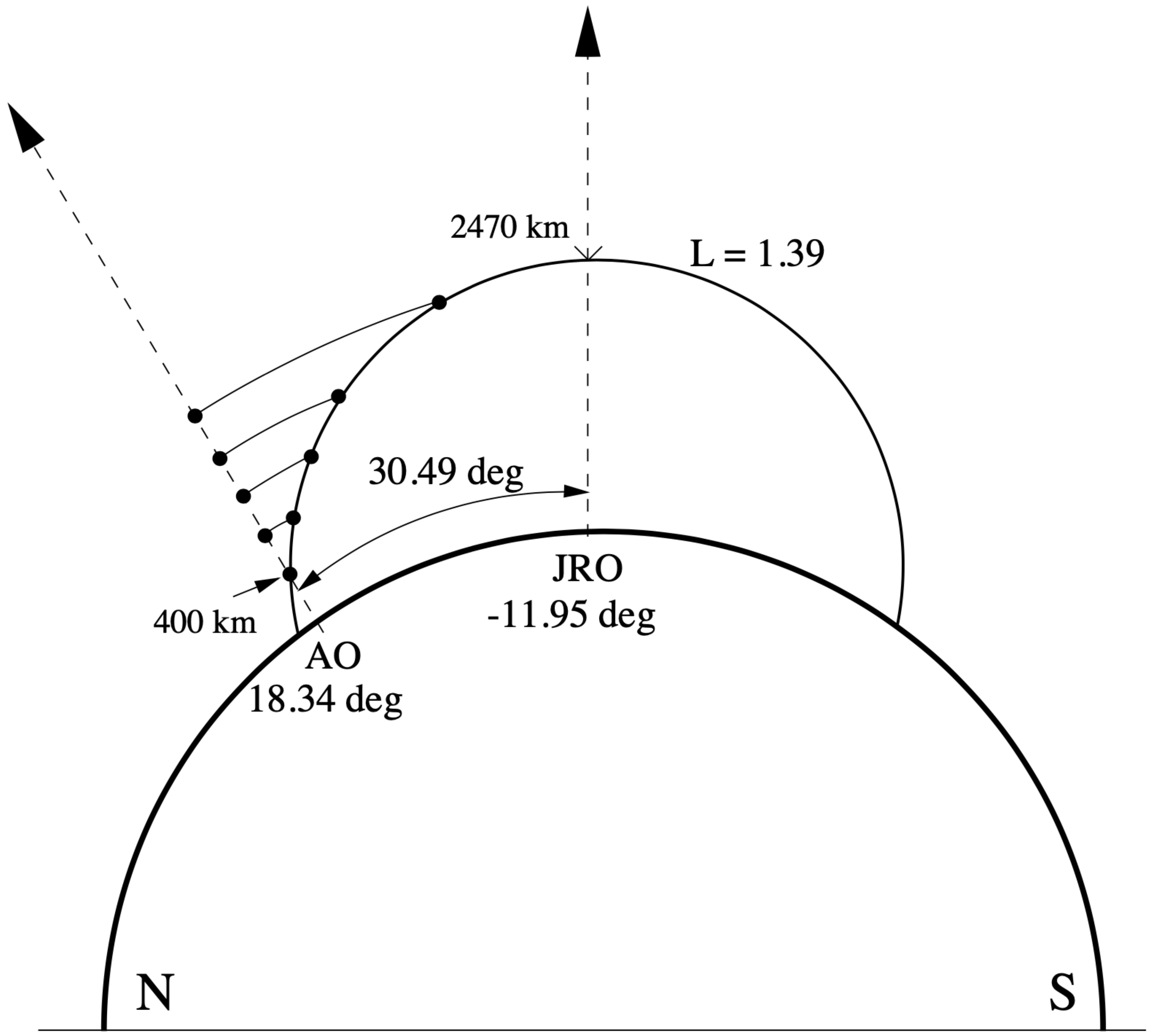
A Dissertation

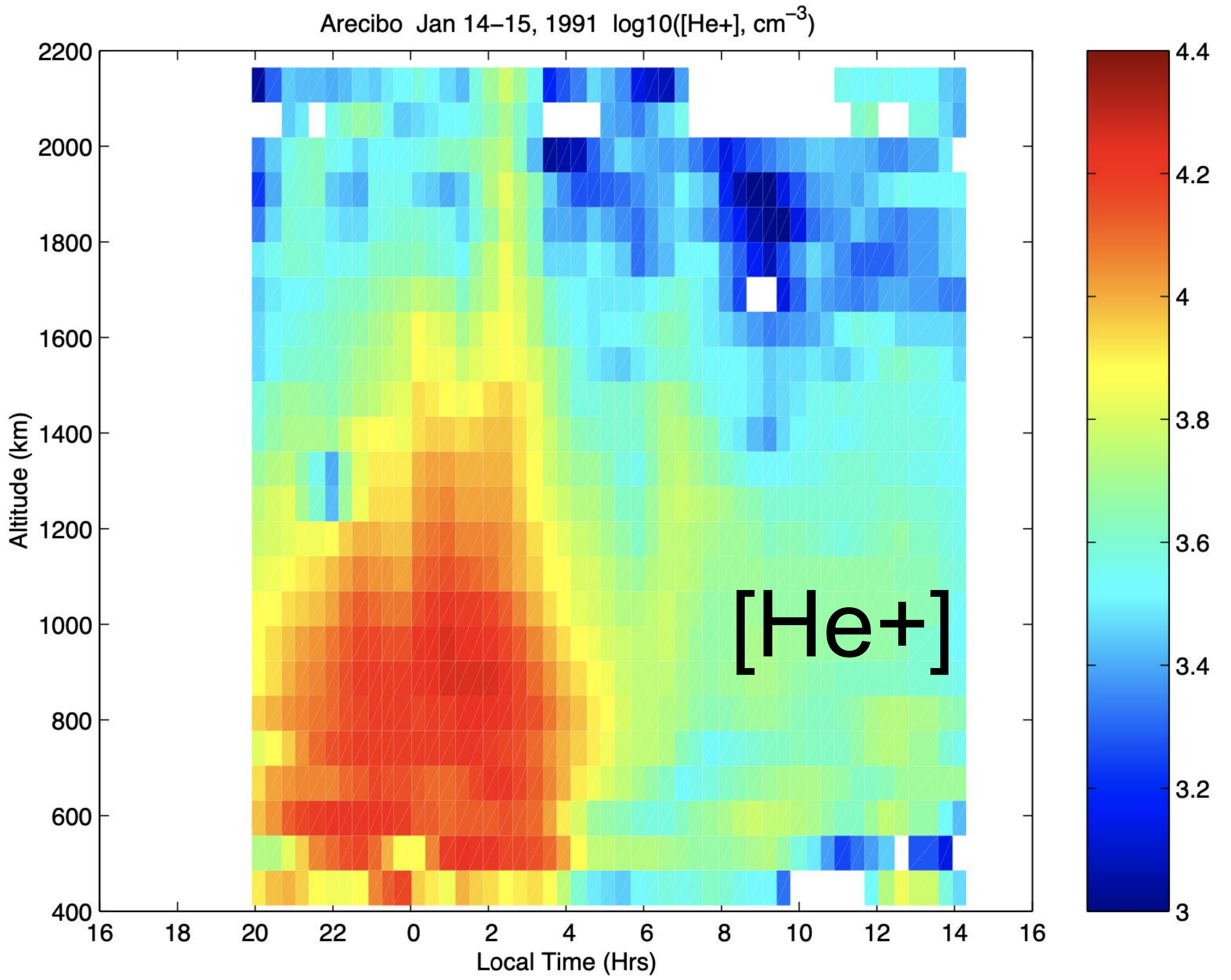
Presented to the Faculty of the Graduate School

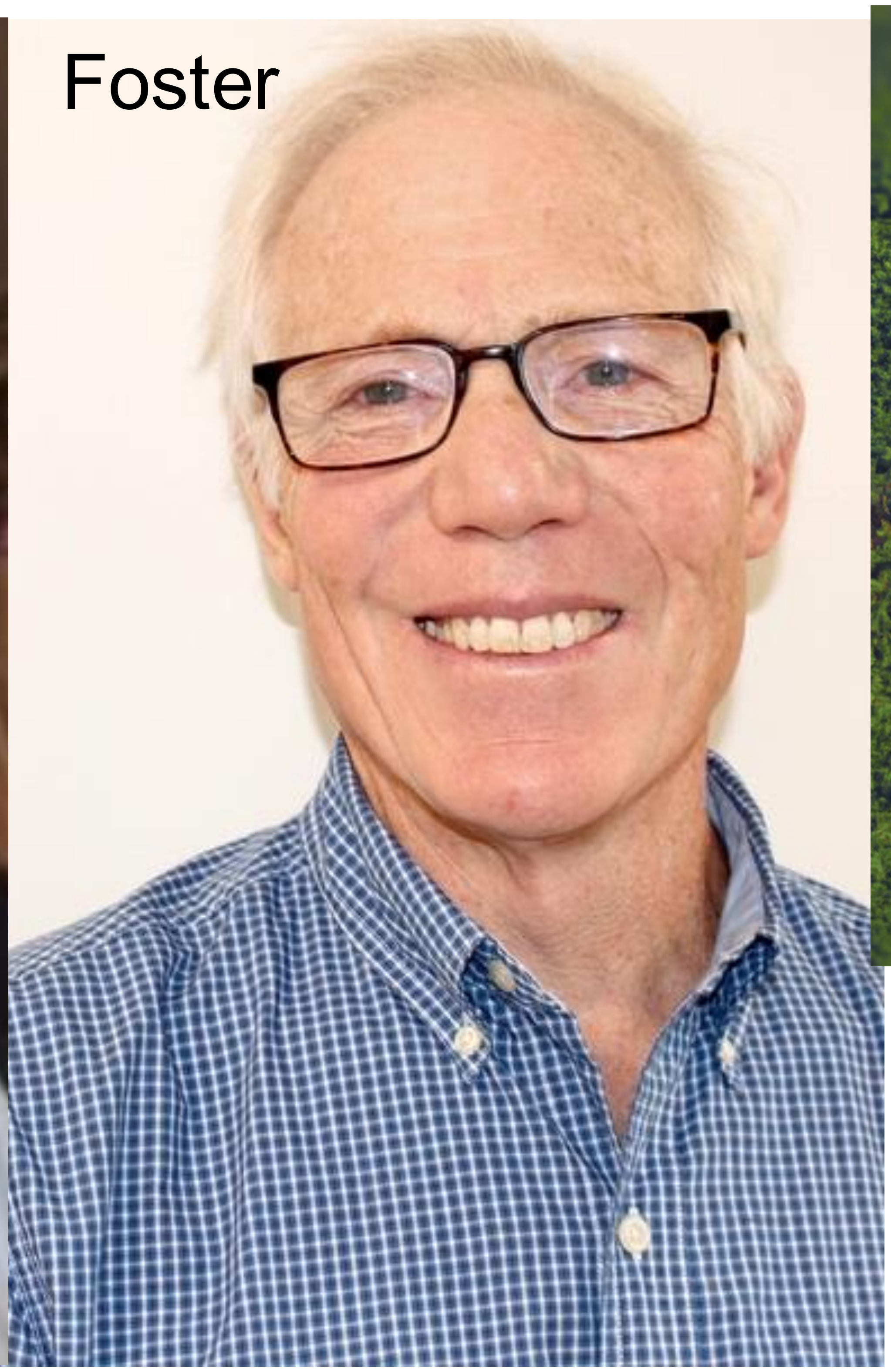
of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy







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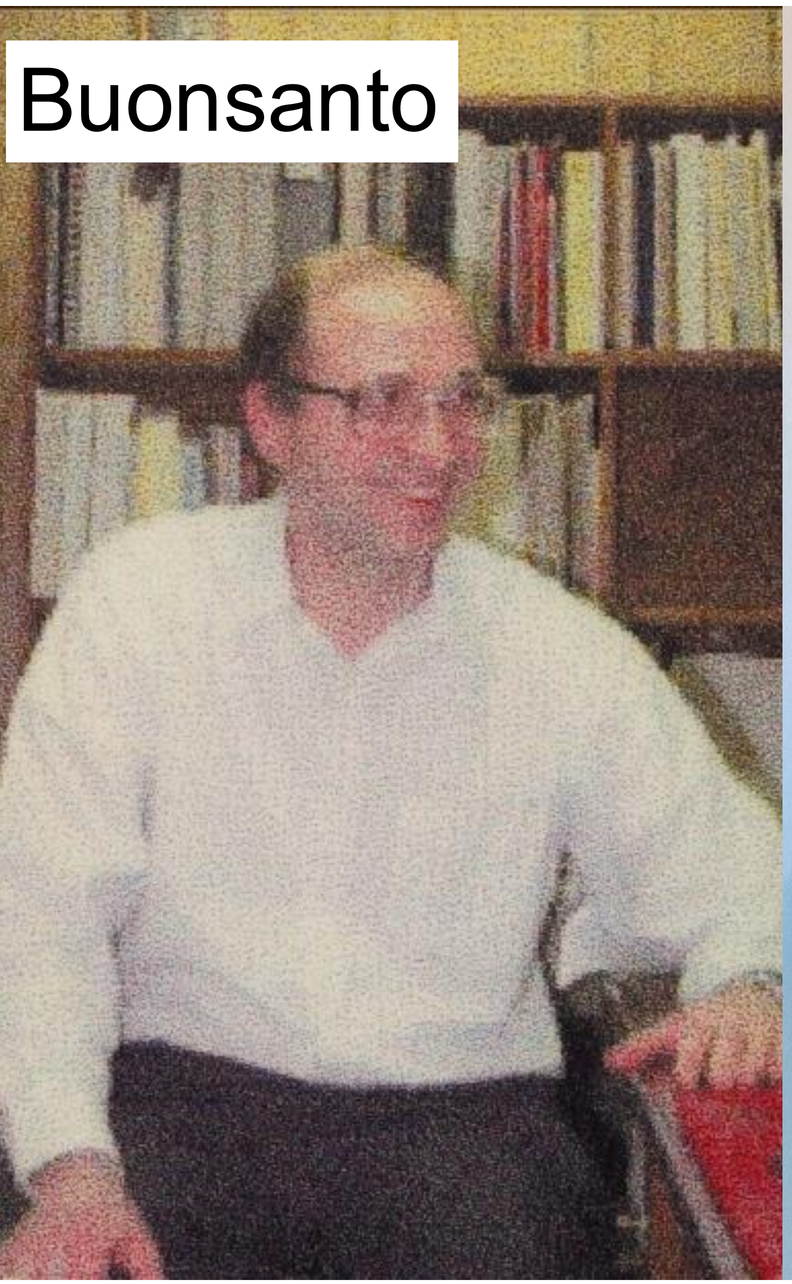
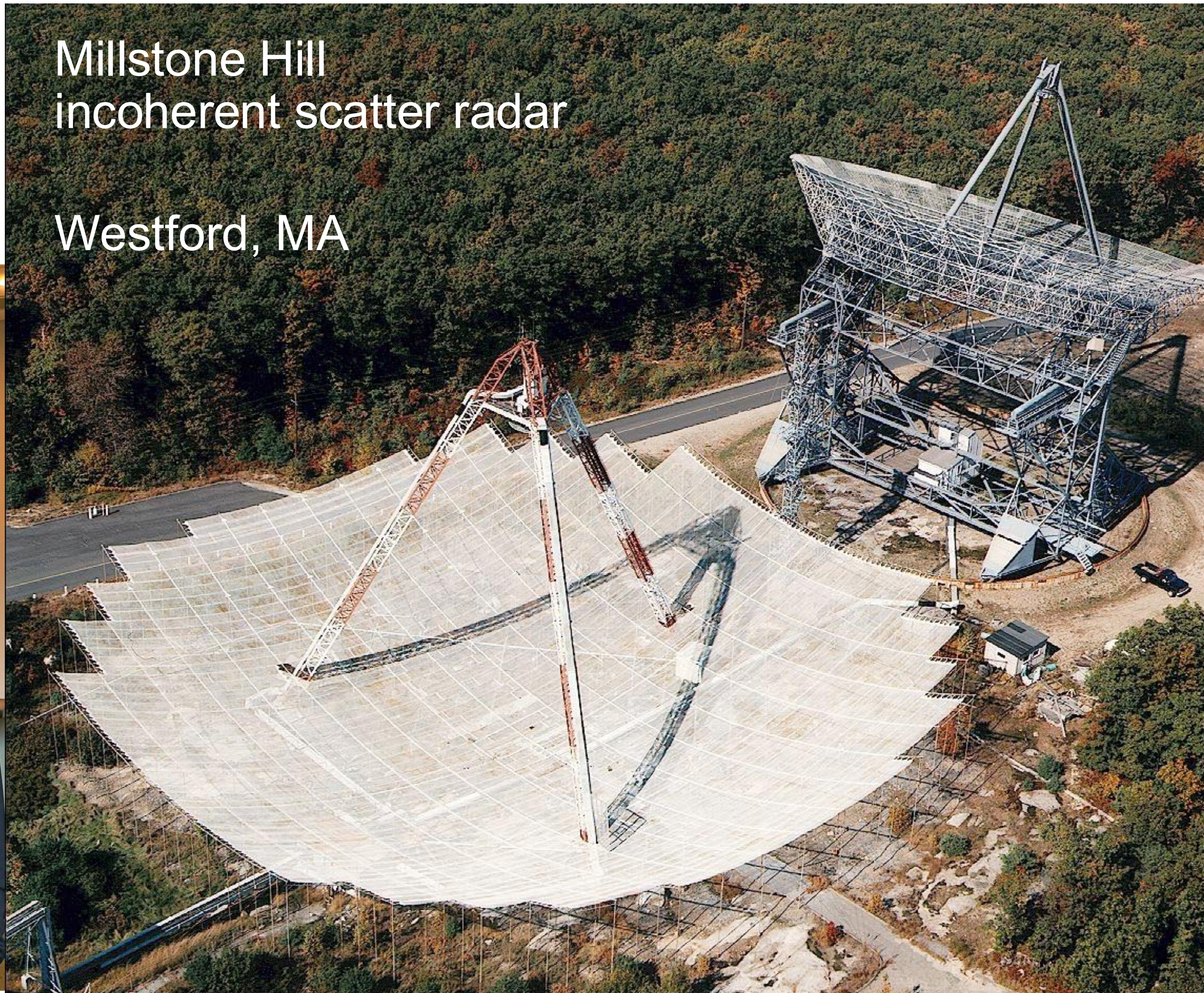




Moosejaw, Saskatchewan

Kiruna, Sweden

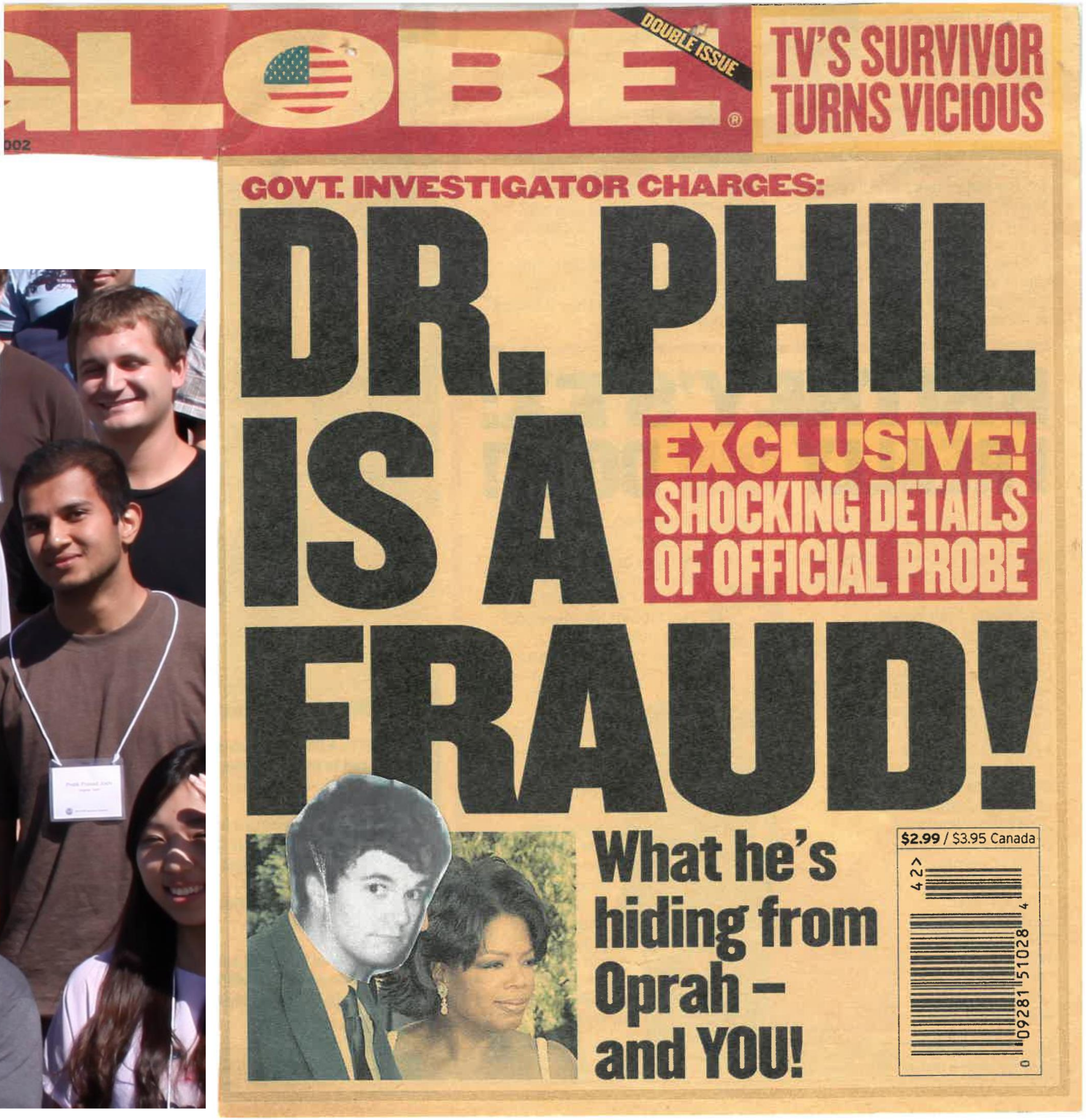
Arecibo, PR

Irkutsk, Siberia

Adventures

Jicamarca, Perú

Setting a serious tone



Haystack scientific / technical disciplines

Radio science research across many disciplines

- Radio astronomy
- Geodesy
- Atmospheric science
- Space science
- Polar science
- Data science (AI / machine learning)
- Education and public outreach: bringing radio science to everyone!

⟷

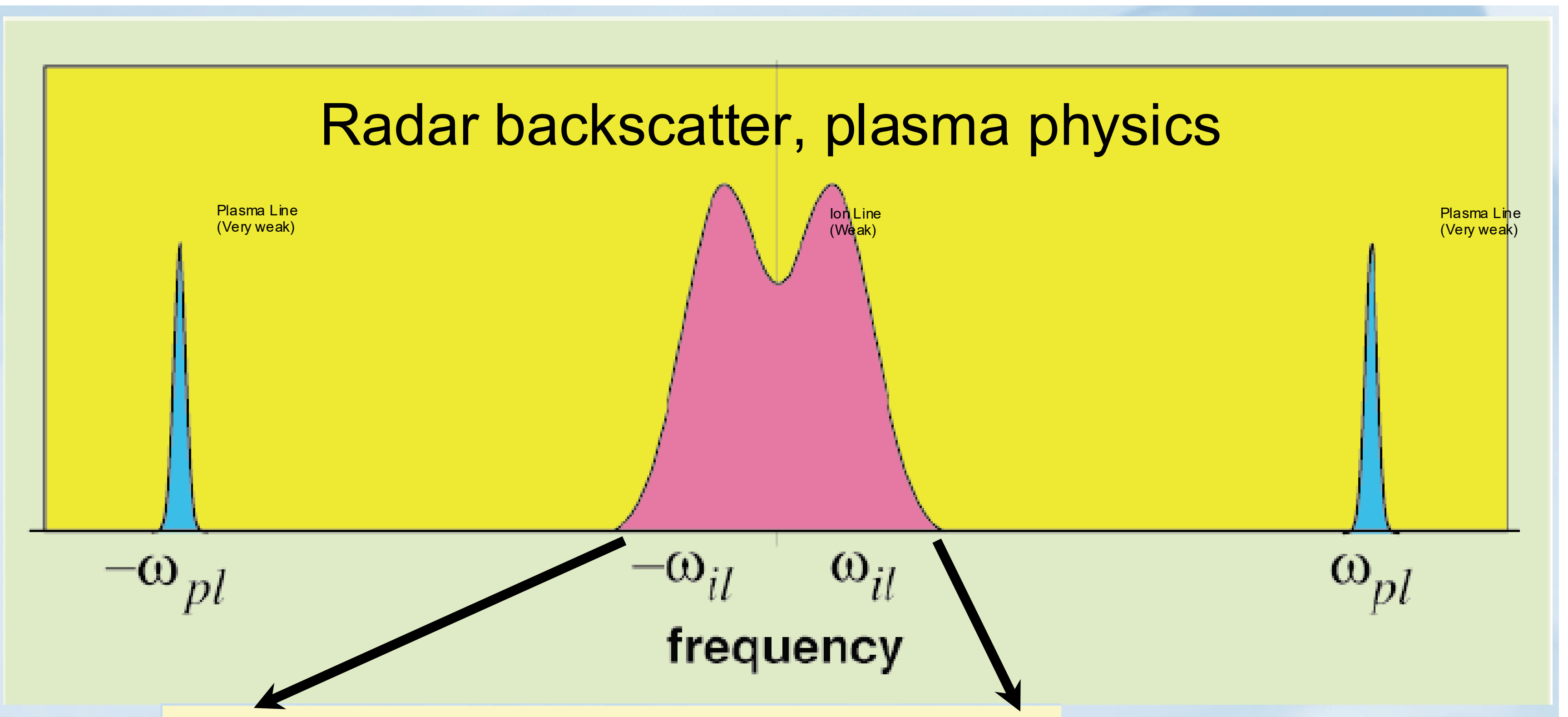
Technological innovation on multiple fronts

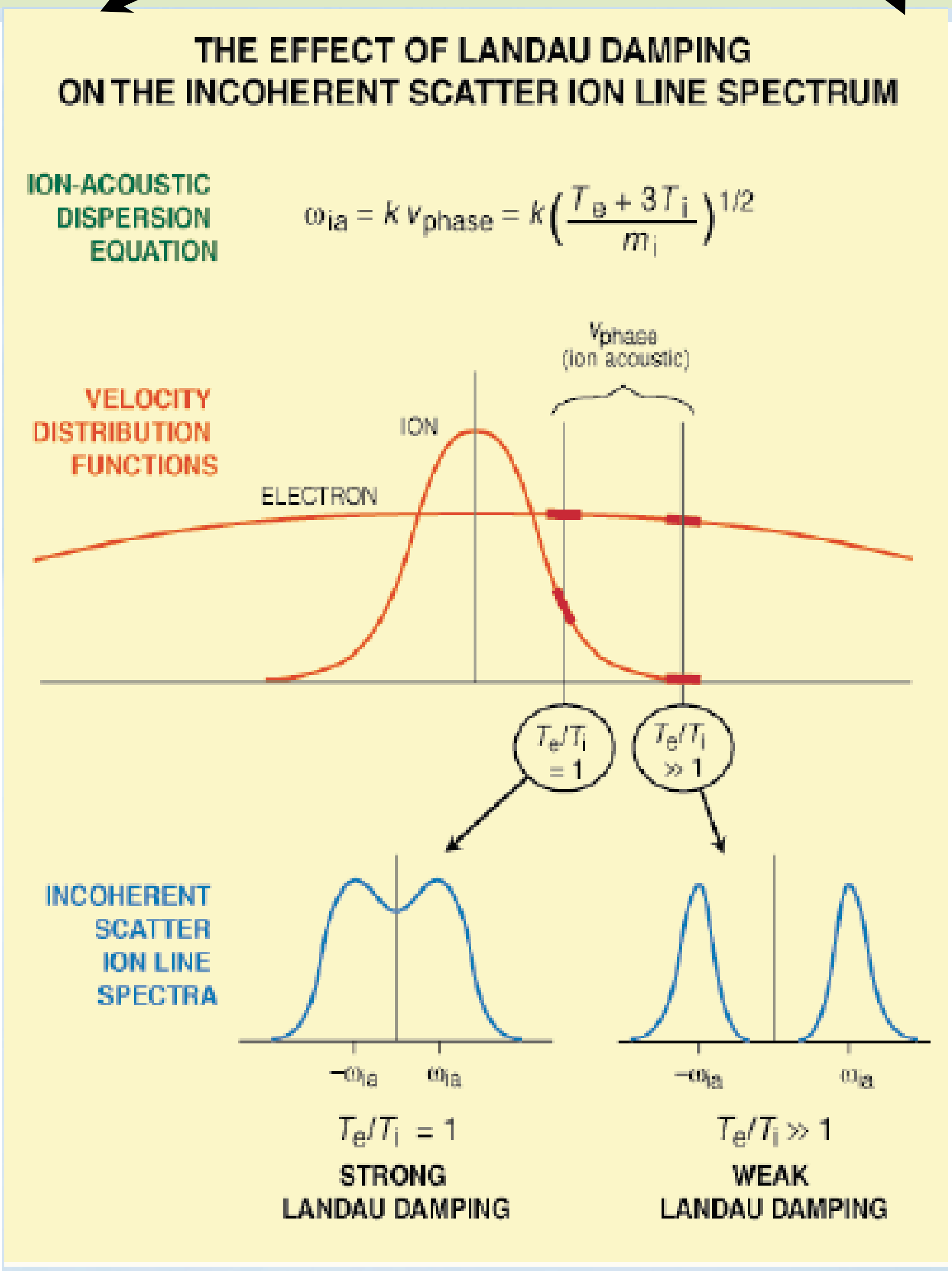
- Very long baseline interferometry (VLBI): studying distant astronomical objects
- Radio arrays for multiple projects (the sun, the atmosphere, Jupiter, and others)
- Geodetic VLBI: measuring the earth
- Polar science: studying glaciers
- Incoherent scatter radars (ISR): studying the ionosphere
- Space science: Mars rover components and CubeSat satellites

MIT HAYSTACK OBSERVATORY

~100 Staff Members: Science, Technical, Support roles

Millstone Hill Geospace Facility





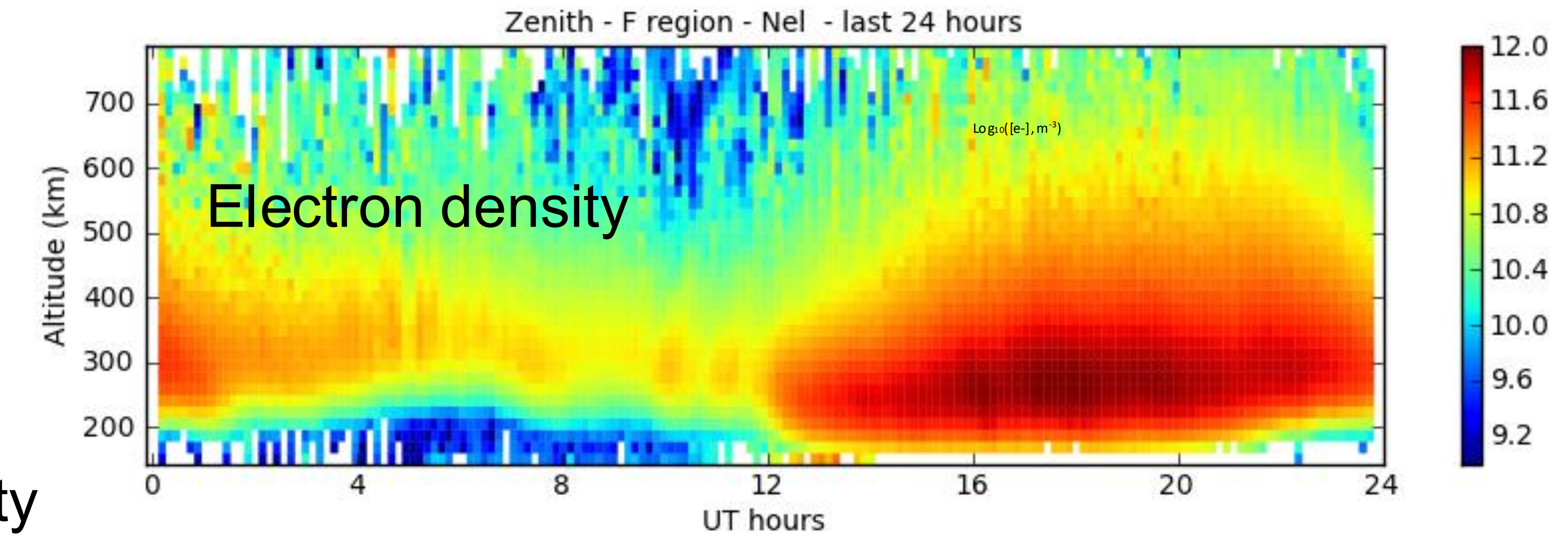
Example:
Millstone Hill ISR

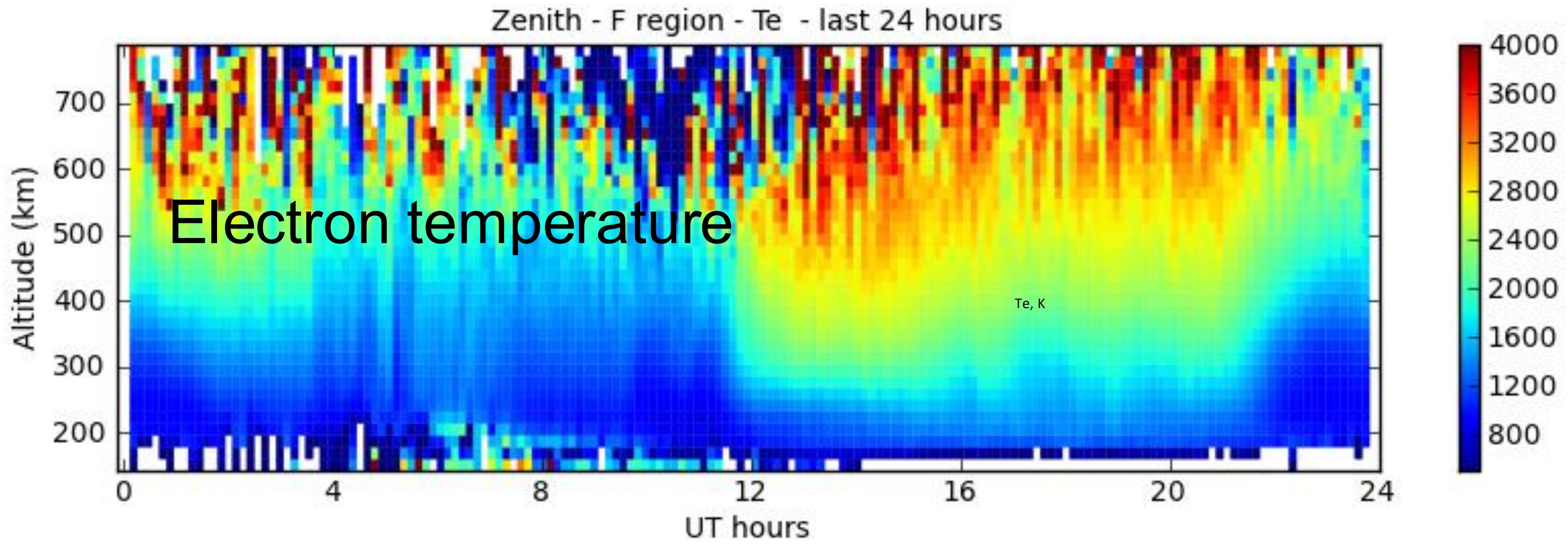
- Three pillars
  - Millstone Hill UHF incoherent scatter radar
  - Global GNSS total electron content
  - Madrigal distributed database system
- Key mid-latitude / sub auroral / community facility for geospace research

Lead: Goncharenko

Megawatt class UHF radar, sensitive antennas

Millstone Hill Geospace Facility





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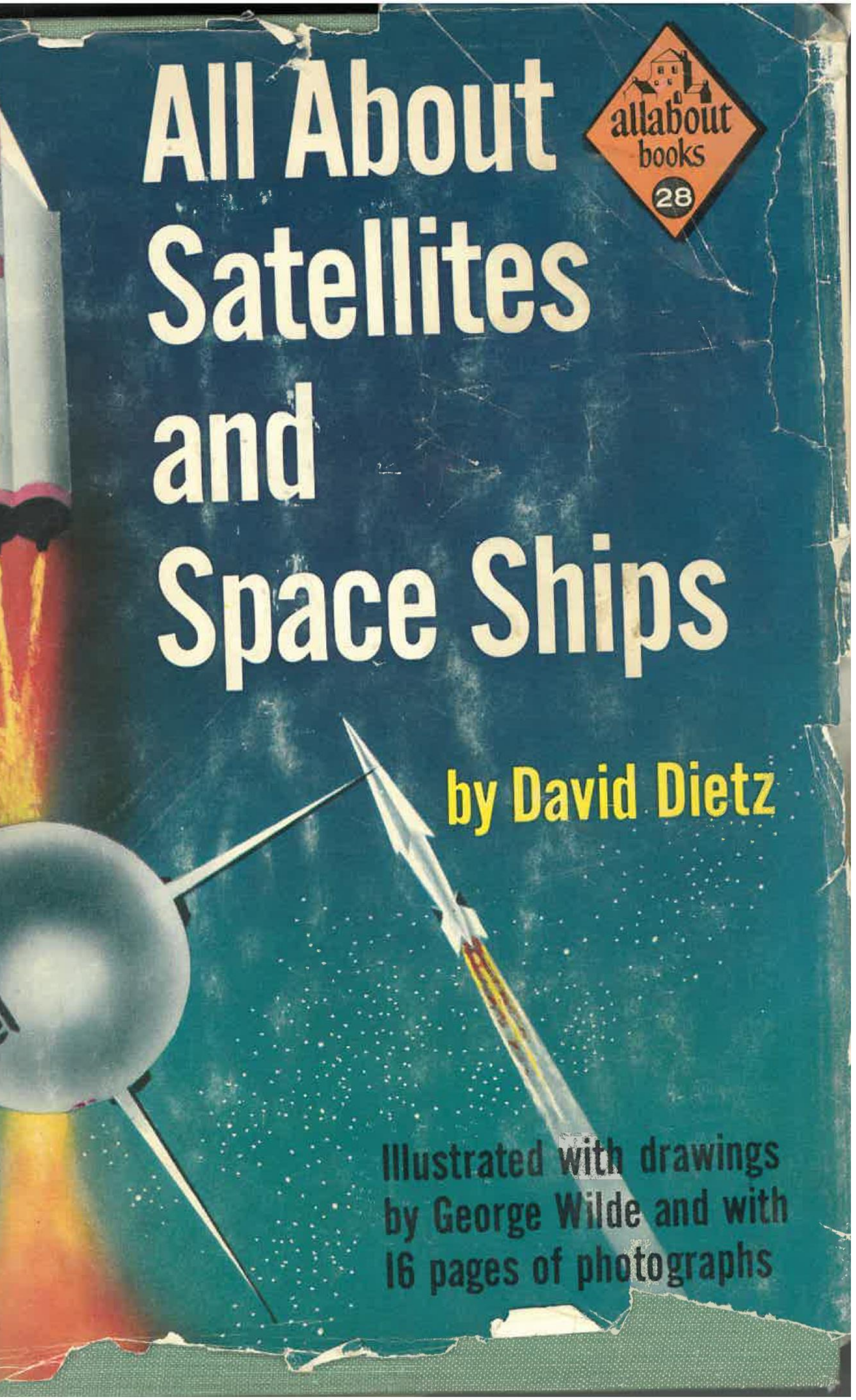
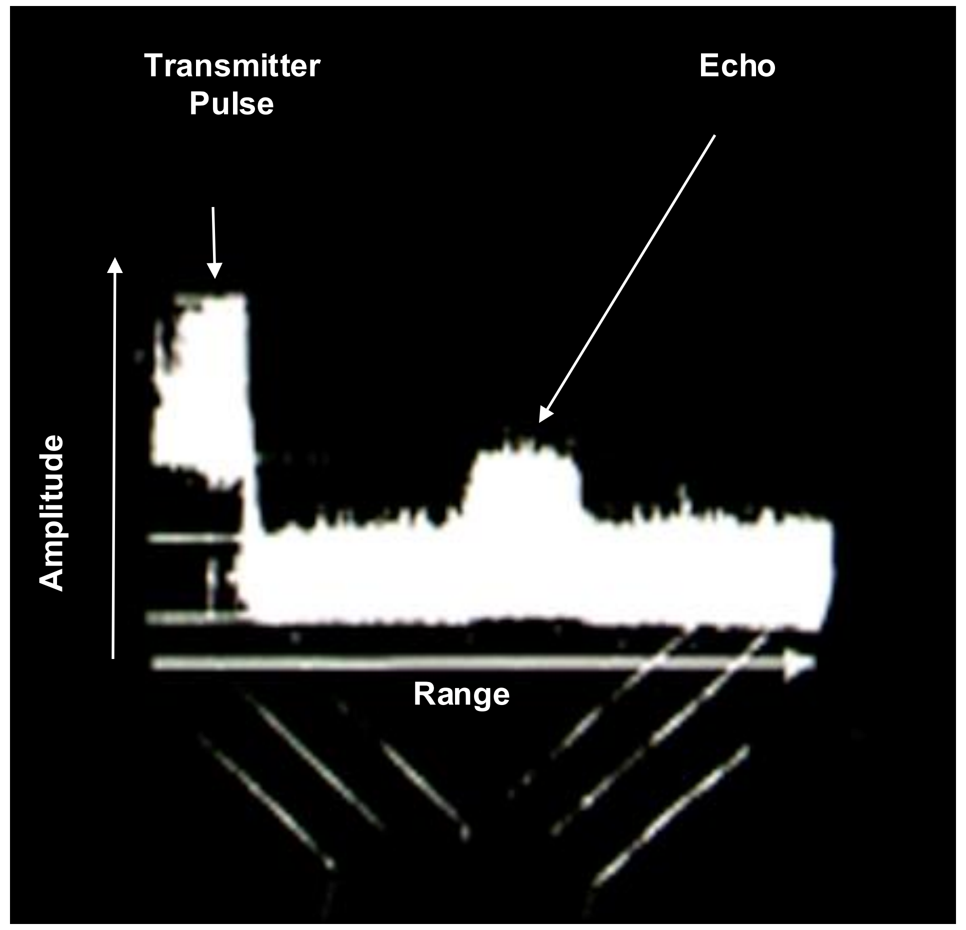
Decades-Long Technical Advancements



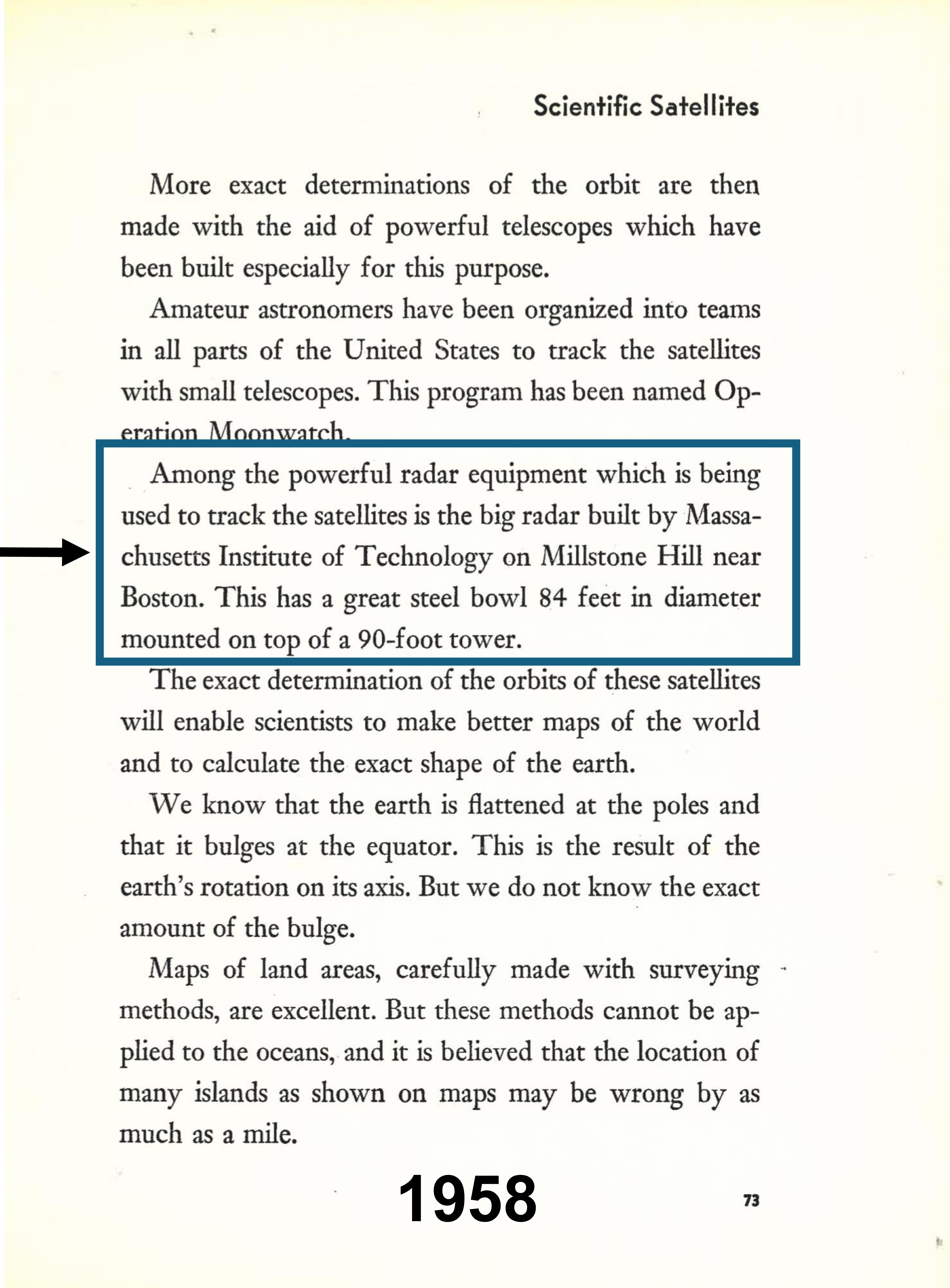
The BMEWS Prototype

Millstone Radar
1957

First in Space Surveillance



Sputnik
A-Scope Trace



Scientific Satellites

More exact determinations of the orbit are then made with the aid of powerful telescopes which have been built especially for this purpose.

Amateur astronomers have been organized into teams in all parts of the United States to track the satellites with small telescopes. This program has been named Operation Moonwatch.

Among the powerful radar equipment which is being used to track the satellites is the big radar built by Massachusetts Institute of Technology on Millstone Hill near Boston. This has a great steel bowl 84 feet in diameter mounted on top of a 90-foot tower.

The exact determination of the orbits of these satellites will enable scientists to make better maps of the world and to calculate the exact shape of the earth.

We know that the earth is flattened at the poles and that it bulges at the equator. This is the result of the earth's rotation on its axis. But we do not know the exact amount of the bulge.

Maps of land areas, carefully made with surveying methods, are excellent. But these methods cannot be applied to the oceans, and it is believed that the location of many islands as shown on maps may be wrong by as much as a mile.

73

1958

Remote Radar Sensing of Ionospheric Plasma

Sufficiently large systems can use incoherent (Thomson) scatter to measure basic ionospheric physical properties. First done in 1958.

Very different from coherent radar:

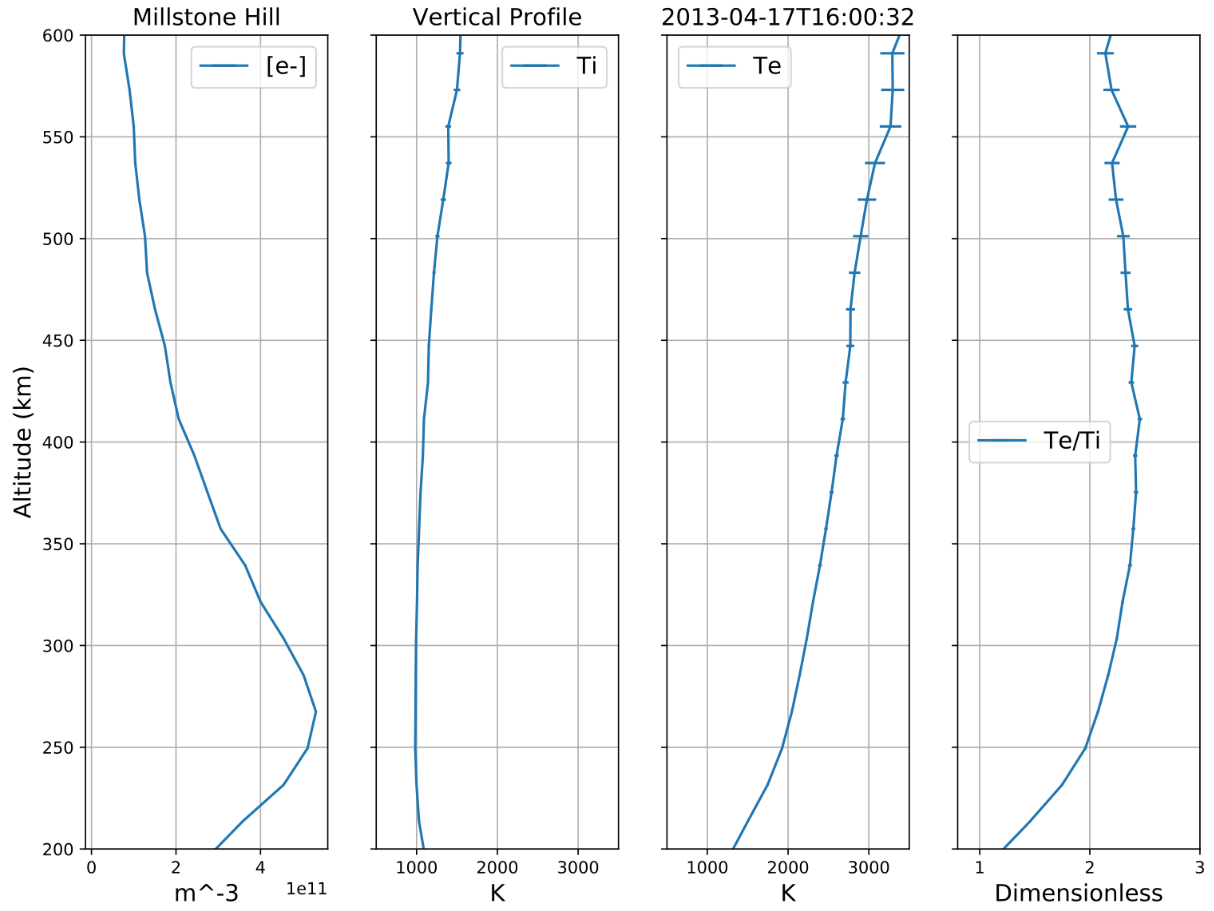
Soft radar target: beam filling (R^2 dependence)

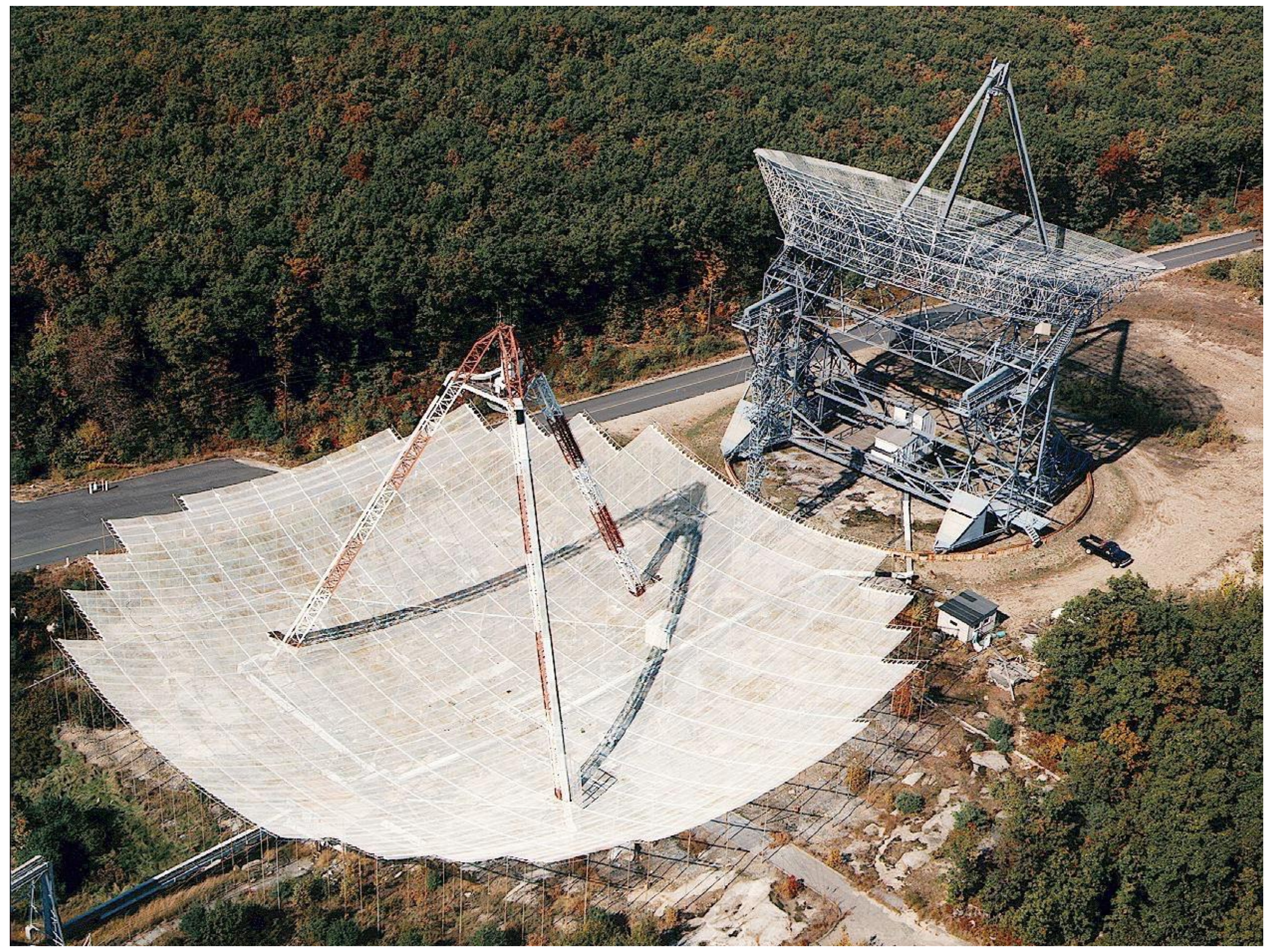
Free electron scatter, restrained by ions

Very low radar cross section (RCS): < -50 dBsm

Gaussian random process: statistical experiment

Very weak scatter : entire ionospheric profile accessible - unlike ionosondes, which only sense to F region density peak





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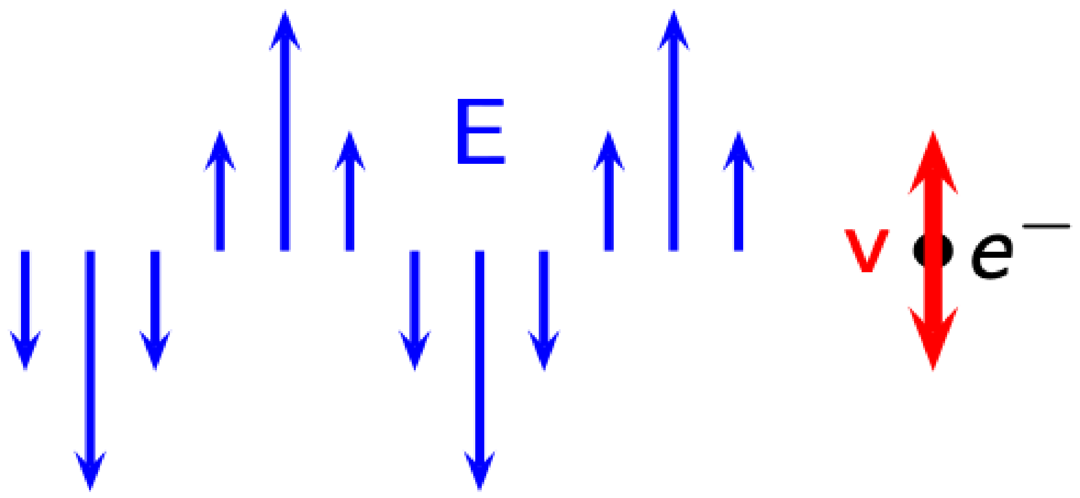
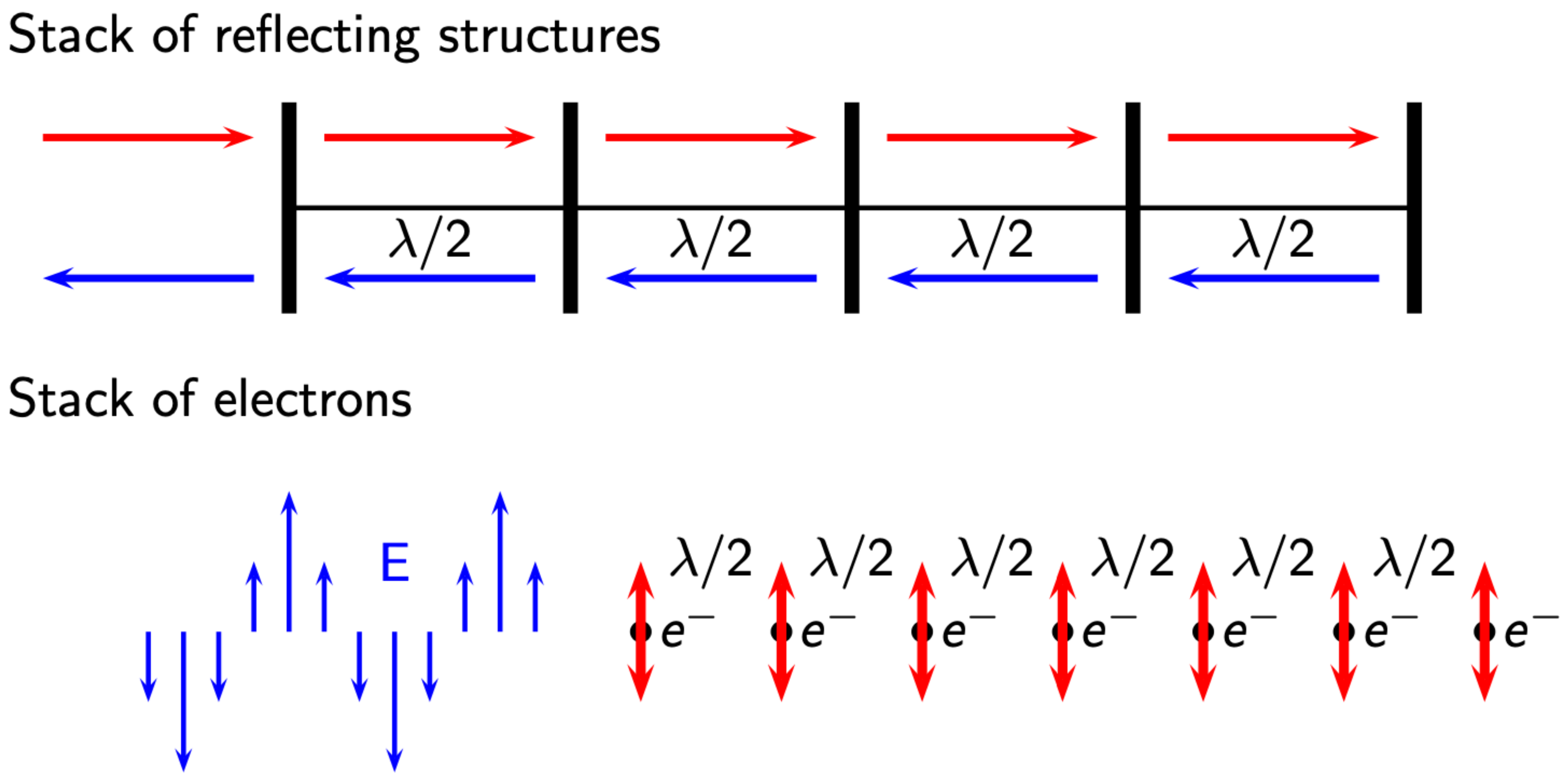
Incoherent Scatter: The Ionosphere = A Box Of Thermal Electrons ("Soft" Radar Target)

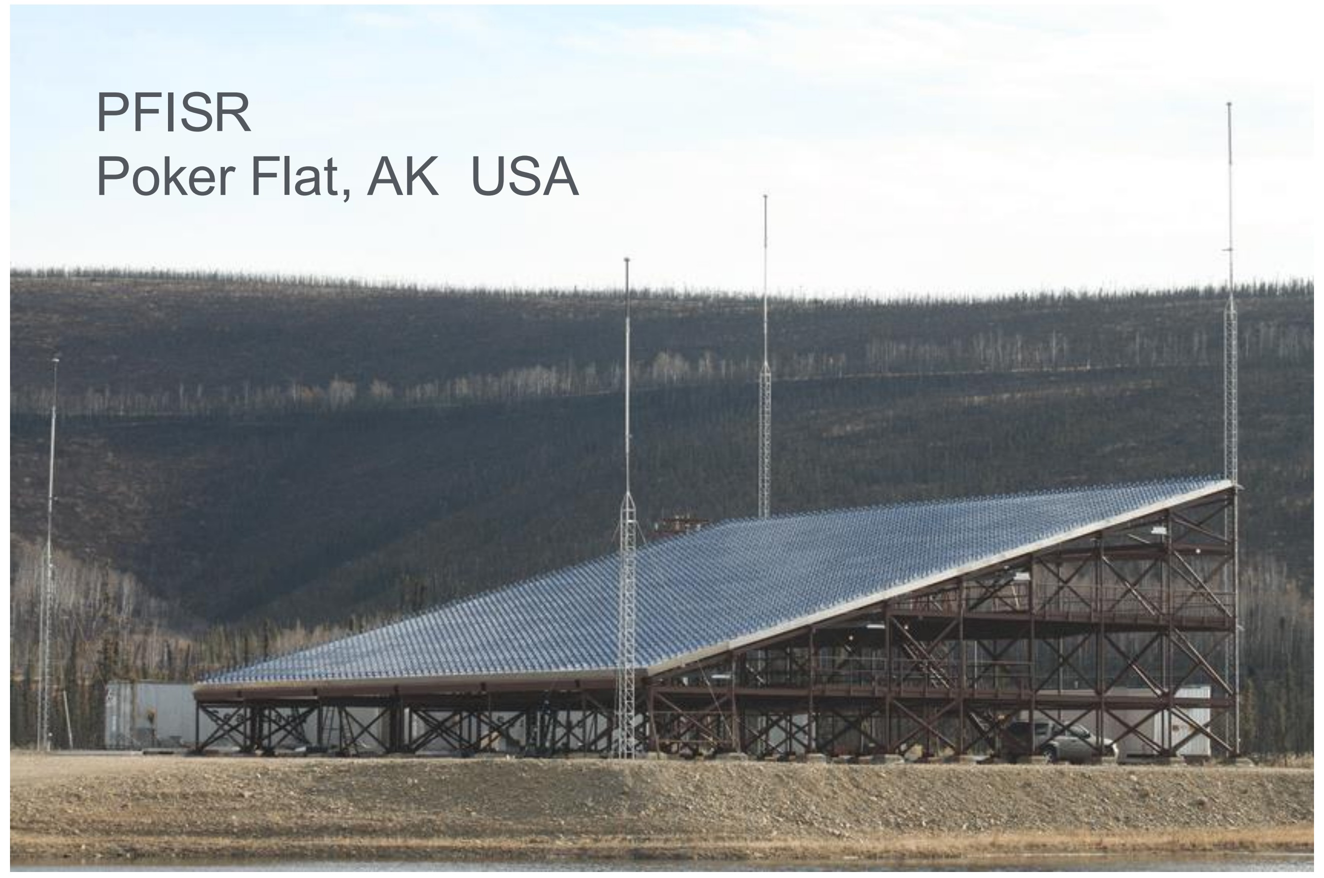
- Scatter from targets spaced by the Bragg wavelength ($\lambda/2$) add constructively
- Scatter from a large number of electrons samples the Fourier transform of the electron density distribution at the Bragg wavenumber
- Thermal plasmas are naturally full of a whole spectrum of waves
- ISR is Bragg scatter from those thermal waves that match the Bragg wavenumber



Closeup: Very weak scatter from one electron

$$\sigma_e = 10^{-28} m^2 / e^-$$





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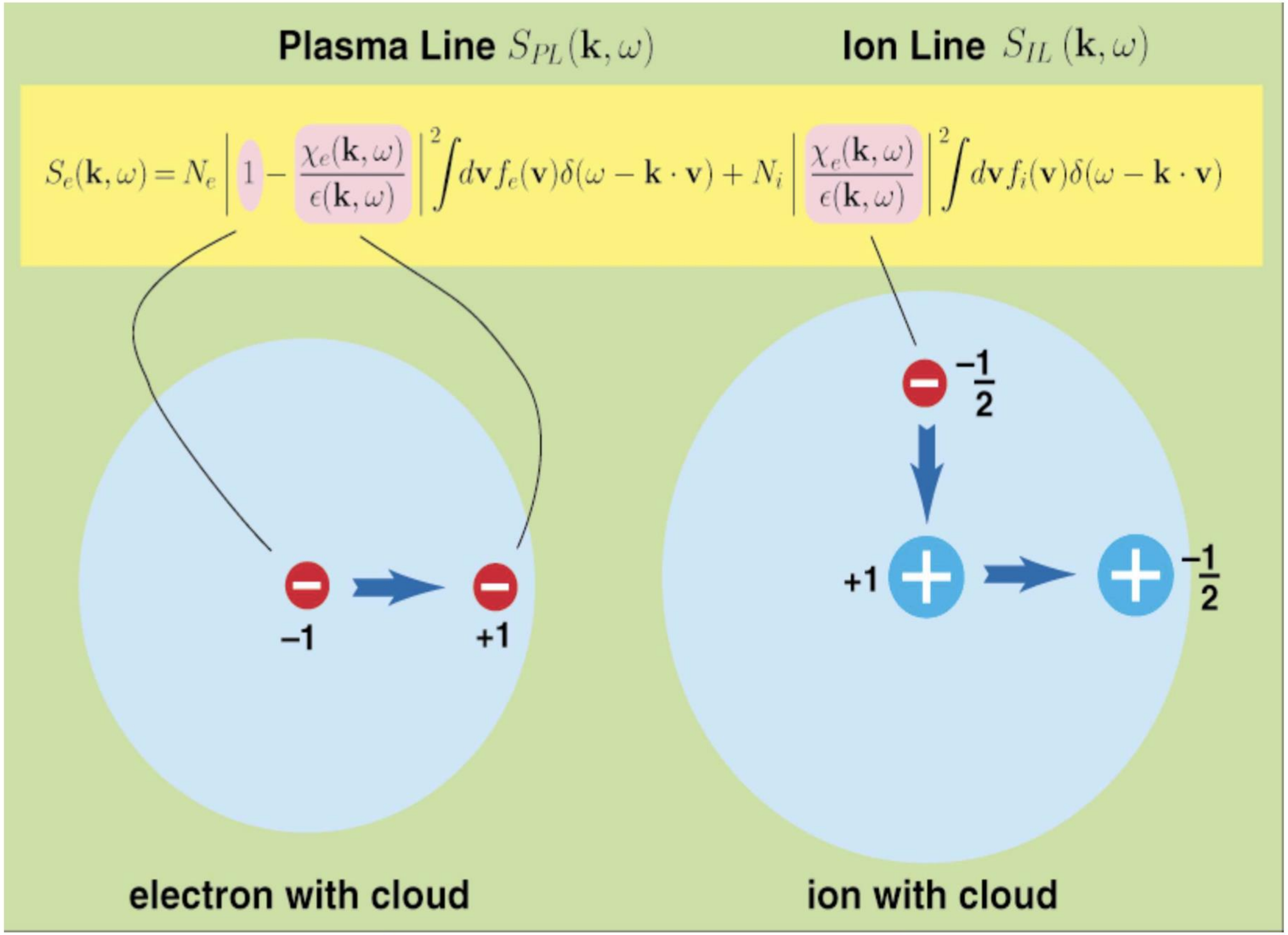
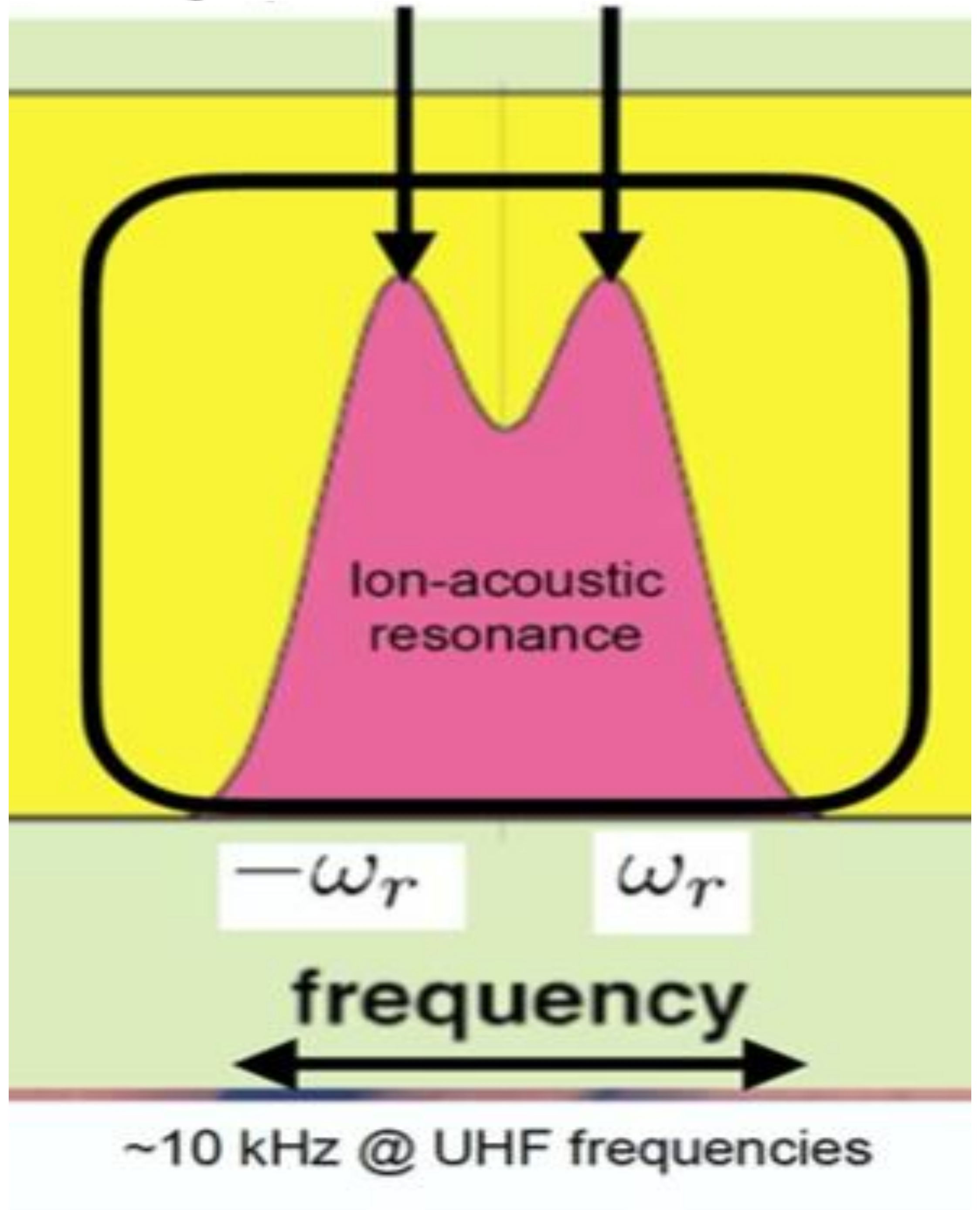
Plasma Theory: Dressed Particles

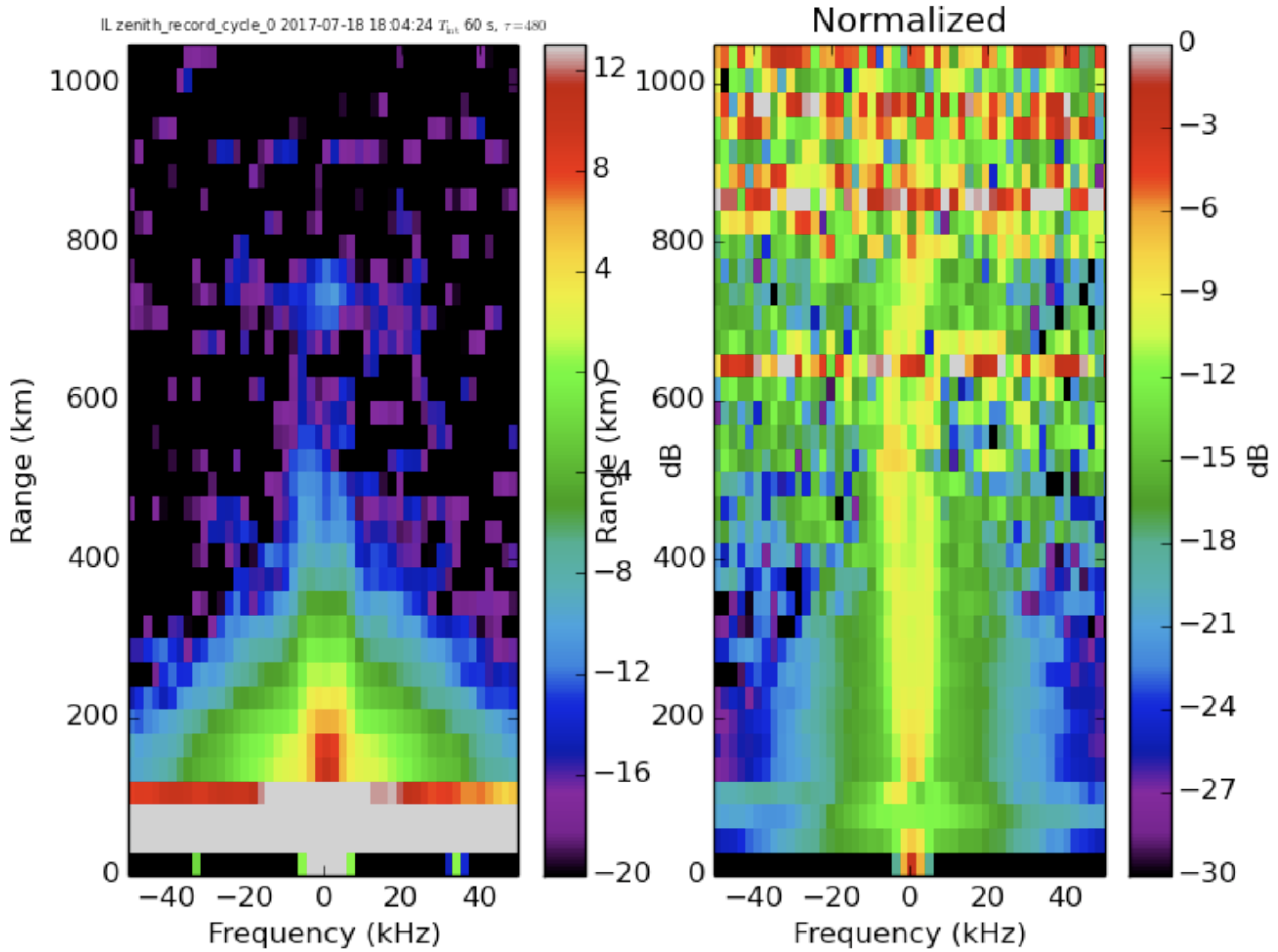


Scattering comes from electrons (light mass), but their fluctuations contain ion information as well!

Ion-Acoustic Mode (“Ion Line”): Both Electron and Ion Information

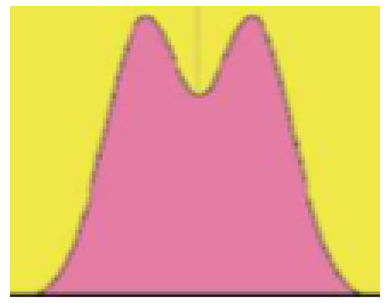
$$\omega_r = k\sqrt{\frac{k_B}{m_i}(T_e + \gamma_i T_i)} \qquad \gamma_i \approx 3$$





Thermal Motion $\longrightarrow$ Collective Effects $\longrightarrow$ ISR Spectrum

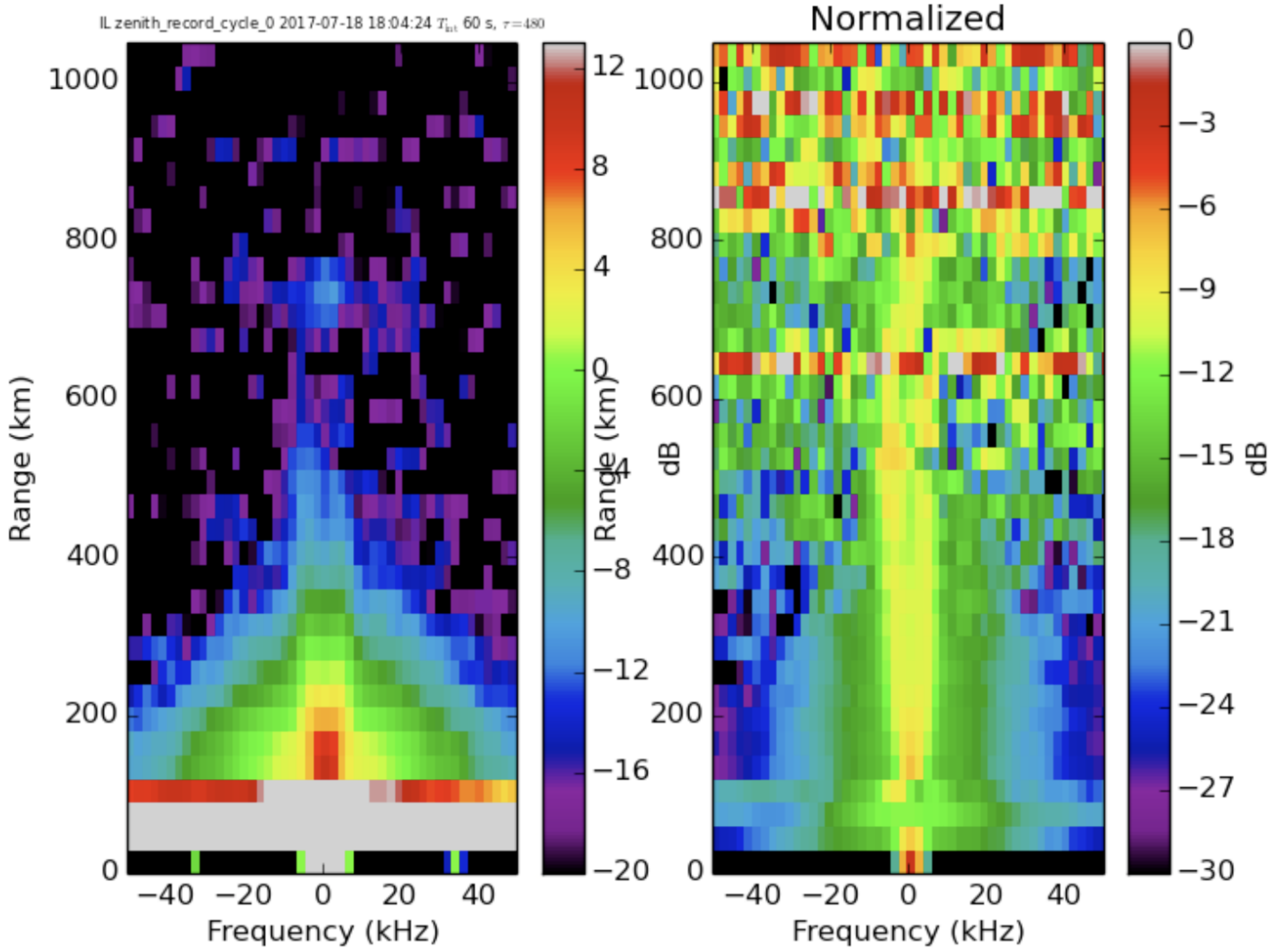
$$\left\langle |n_{ti}(\mathbf{k},\omega)|^2 \right\rangle \qquad \frac{|\chi_e|^2}{|1+\chi_i+\chi_e|^2}$$



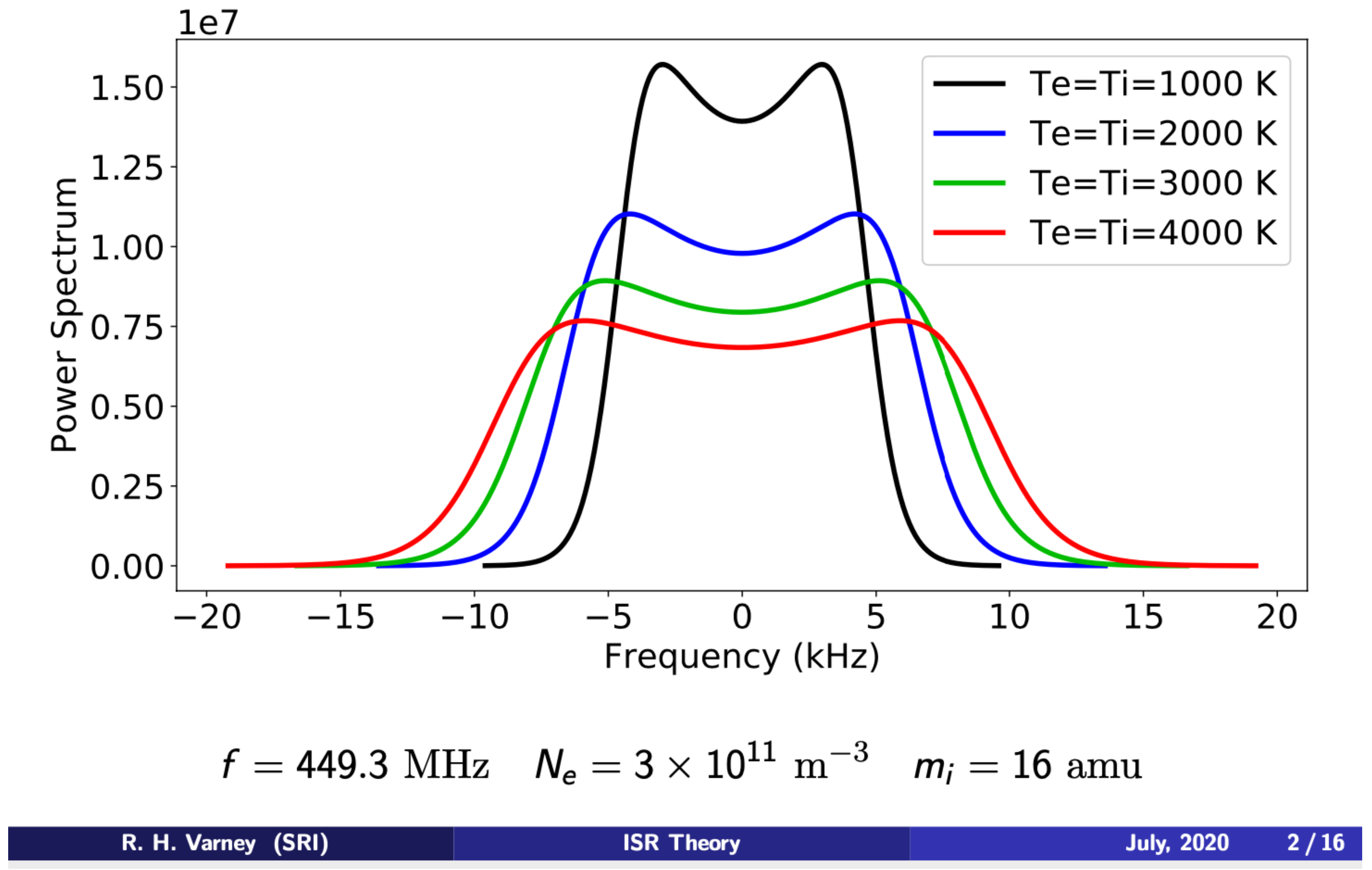
Power Spectral Example: Dependence on Plasma Temperature (Te=Ti Case)

Basic parameters:
Electron density
Plasma temperature
LOS velocity
Ion composition

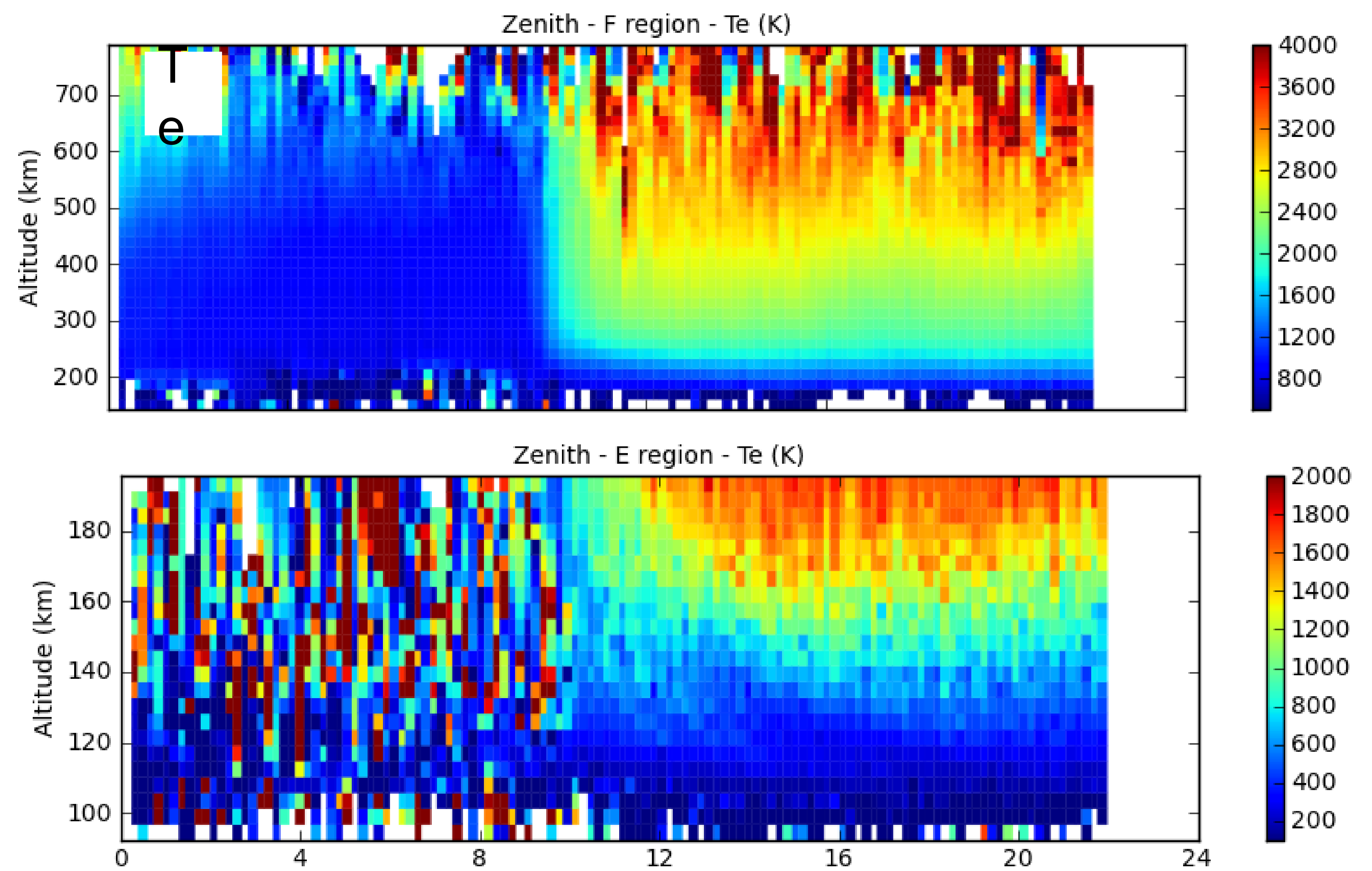
More exotic:
Field-aligned currents
Photoelectron spectra
Unequal ion temperatures
Non-Maxwellian plasmas
Etc.



plus



yields



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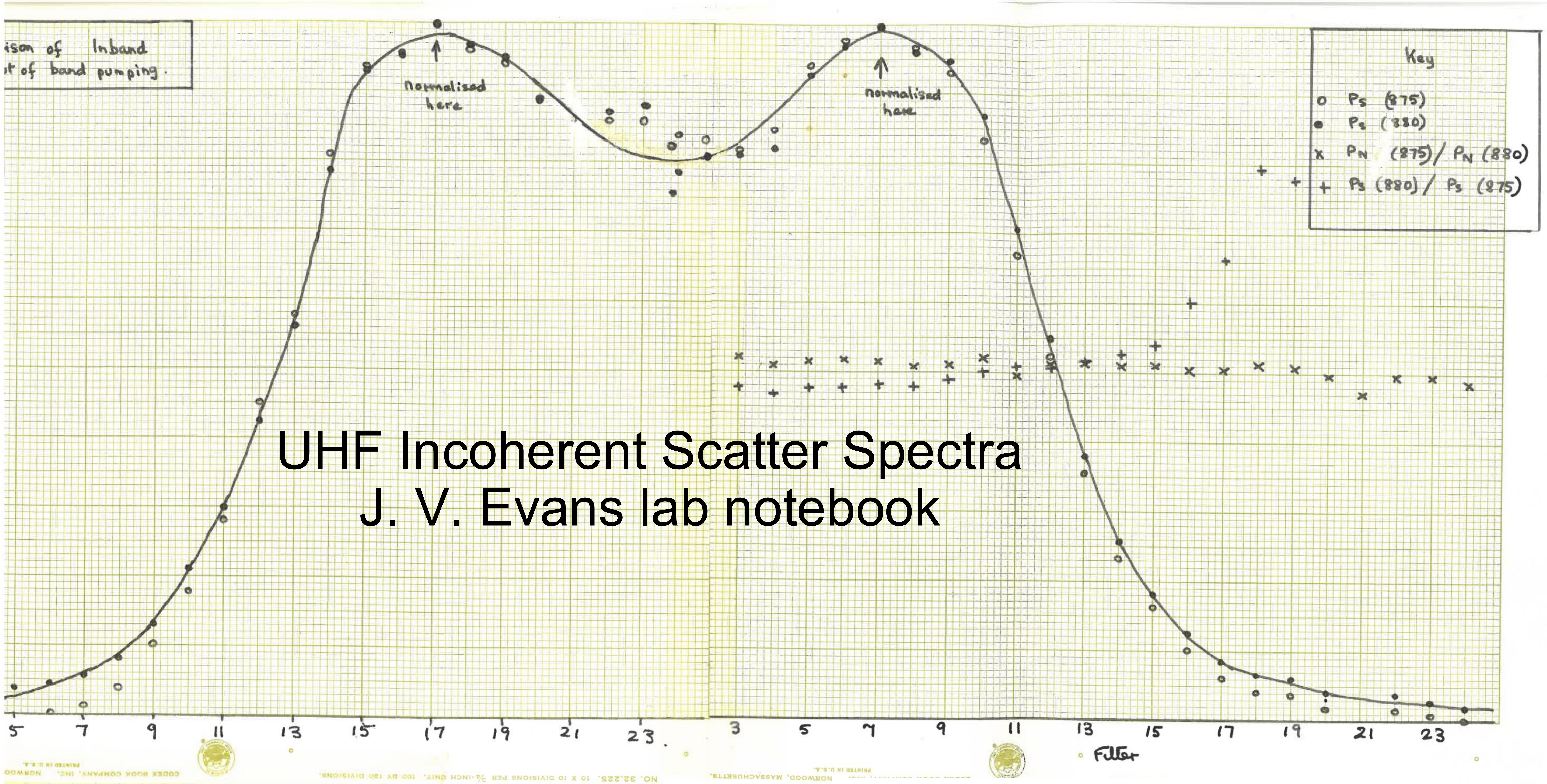
Millstone Hill 84’ tracking radar

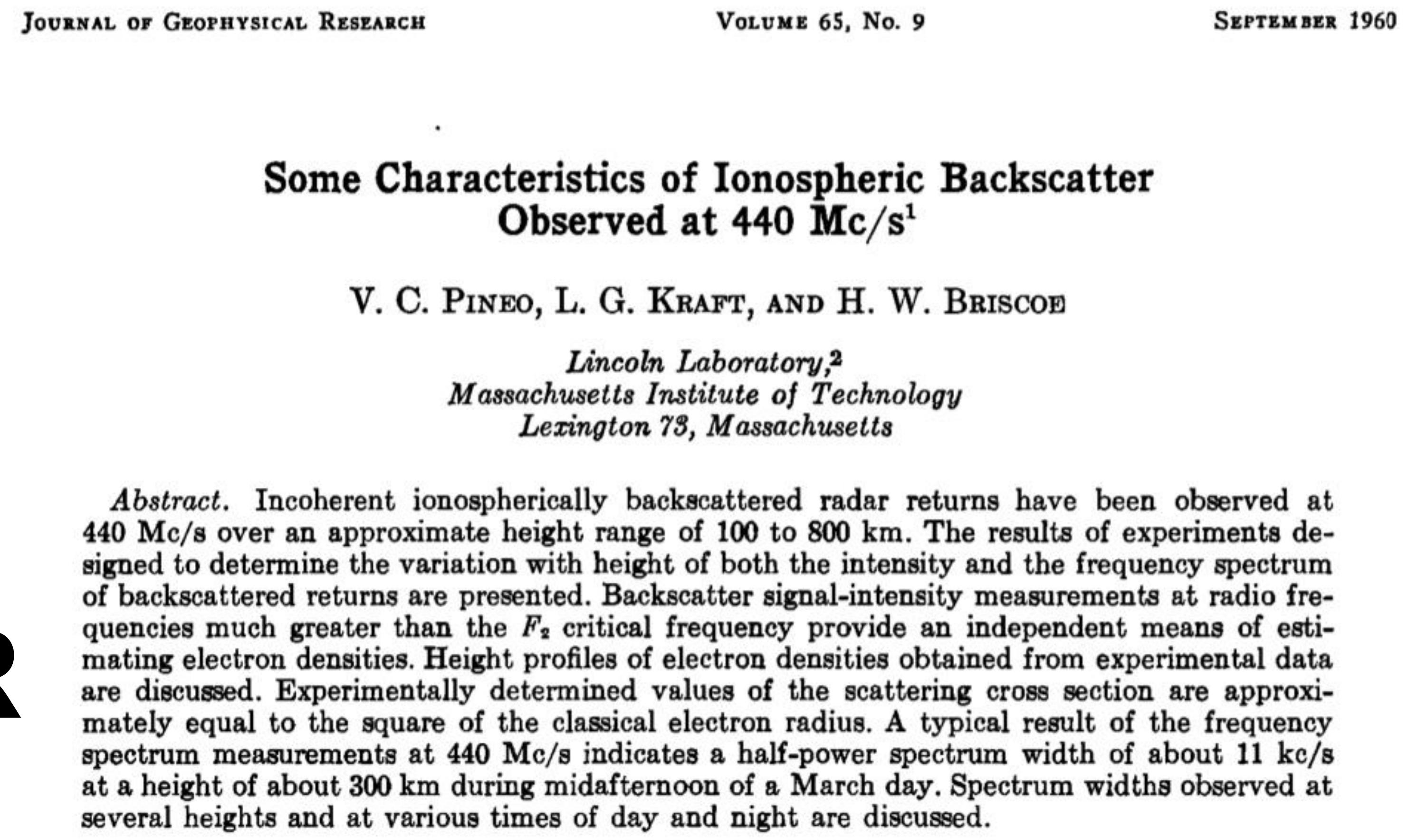
(Had a UHF horn until late 1962; now at L band)

“Nights and weekends”

UHF Incoherent Scatter Spectra
J. V. Evans lab notebook



1960 JGR


JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 65, No. 9 SEPTEMBER 1960

Some Characteristics of Ionospheric Backscatter Observed at 440 Mc/s[1]

V. C. PINEO, L. G. KRAFT, AND H. W. BRISCOE

Lincoln Laboratory,[2]
Massachusetts Institute of Technology
Lexington 73, Massachusetts

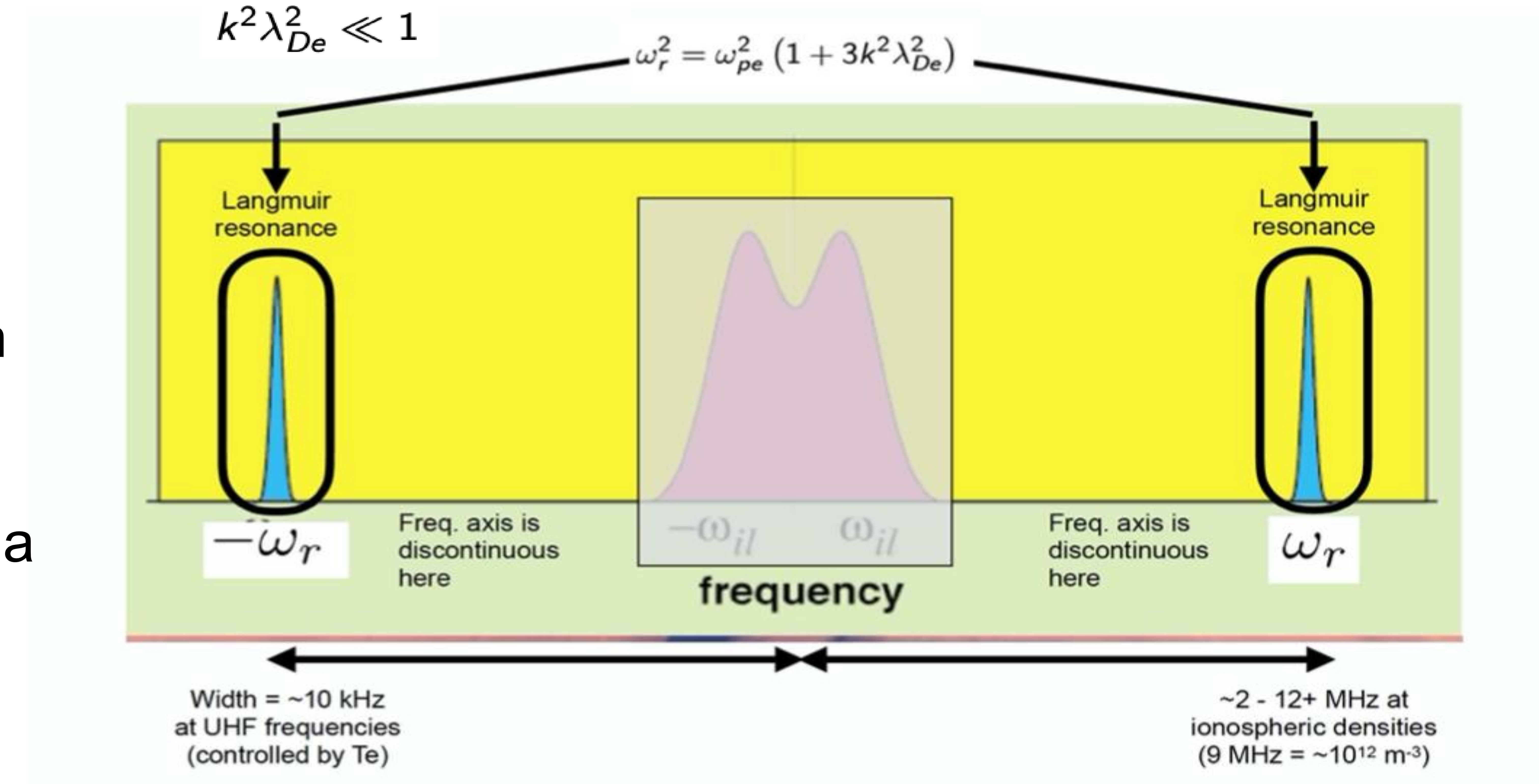
Abstract. Incoherent ionospherically backscattered radar returns have been observed at 440 Mc/s over an approximate height range of 100 to 800 km. The results of experiments designed to determine the variation with height of both the intensity and the frequency spectrum of backscattered returns are presented. Backscatter signal-intensity measurements at radio frequencies much greater than the F_2 critical frequency provide an independent means of estimating electron densities. Height profiles of electron densities obtained from experimental data are discussed. Experimentally determined values of the scattering cross section are approximately equal to the square of the classical electron radius. A typical result of the frequency spectrum measurements at 440 Mc/s indicates a half-power spectrum width of about 11 kc/s at a height of about 300 km during midafternoon of a March day. Spectrum widths observed at several heights and at various times of day and night are discussed.


Synthesize knowledge across generations:
Haystack visit by Evans
March 2022
Dr. Alan EE Rogers
Haystack radio astronomy
Early universe cosmology
Active: 1964-present
Dr. John V. Evans
IEEE Fellow
National Academy of Engineering

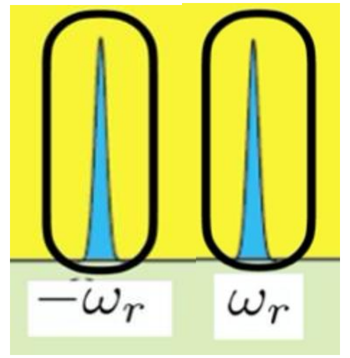
Langmuir Mode (“Plasma Line”): Precise Electron Information, In the Debye Sphere

$$k^2\lambda_{De}^2 \ll 1$$

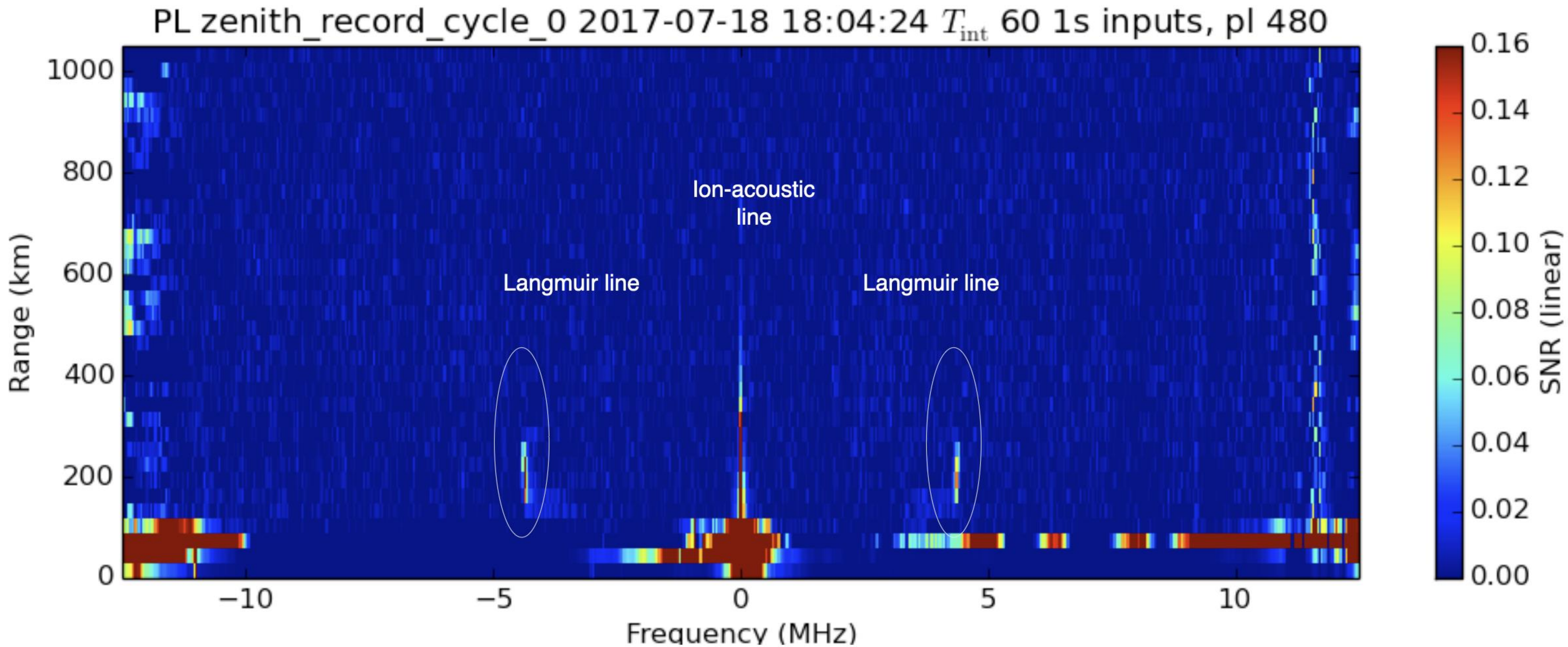
- Weak!
- Typically daytime only (enhanced photoelectron fluxes)
- Precise when visible: primary measurement is a ***frequency***, not an ***area***



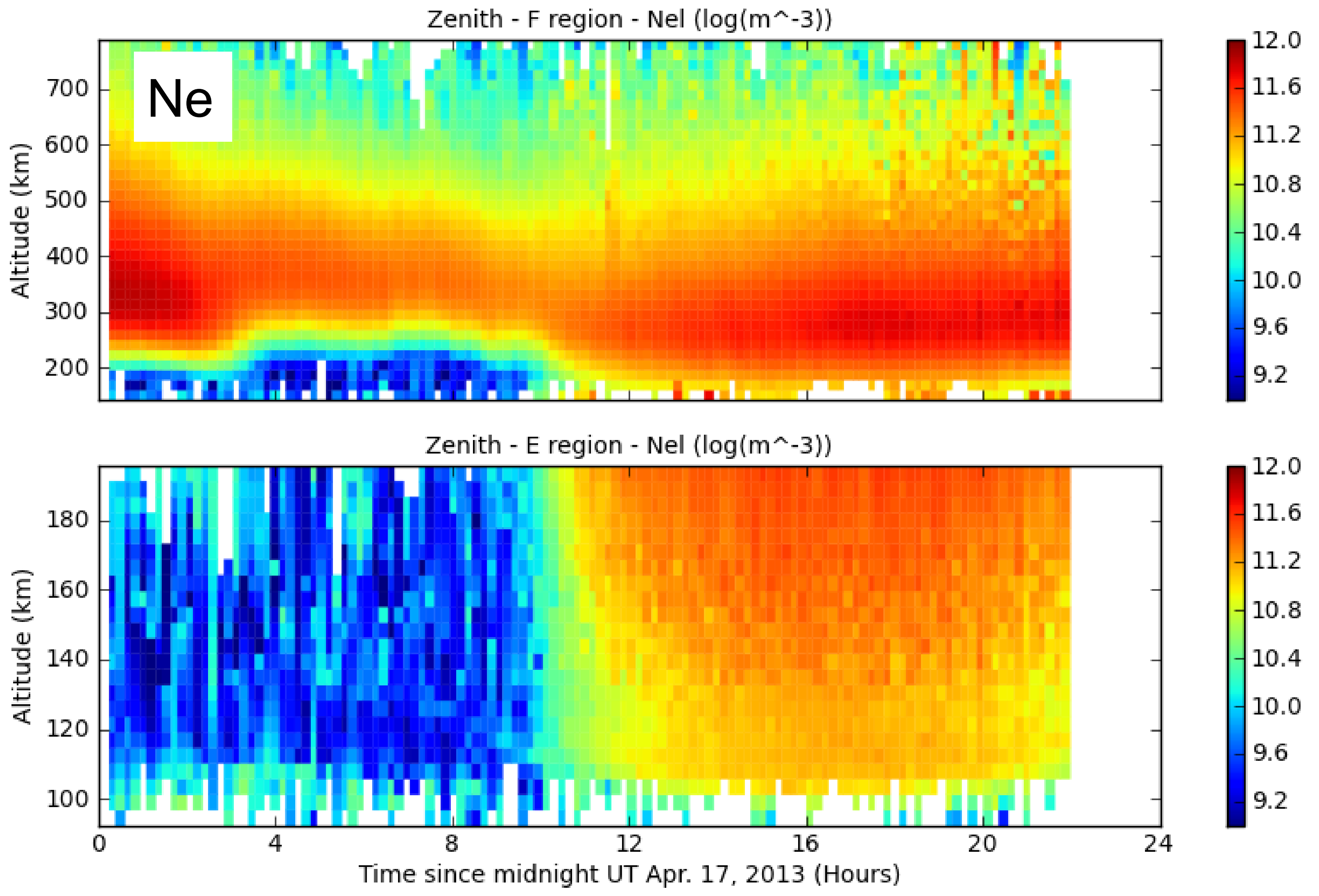
Thermal Motion $\left\langle |n_{ti}(\mathrm{k},\omega)|^2 \right\rangle$ ⟶ Collective Effects $\frac{|\chi_e|^2}{|1+\chi_i+\chi_e|^2}$ ⟶ ISR Spectrum

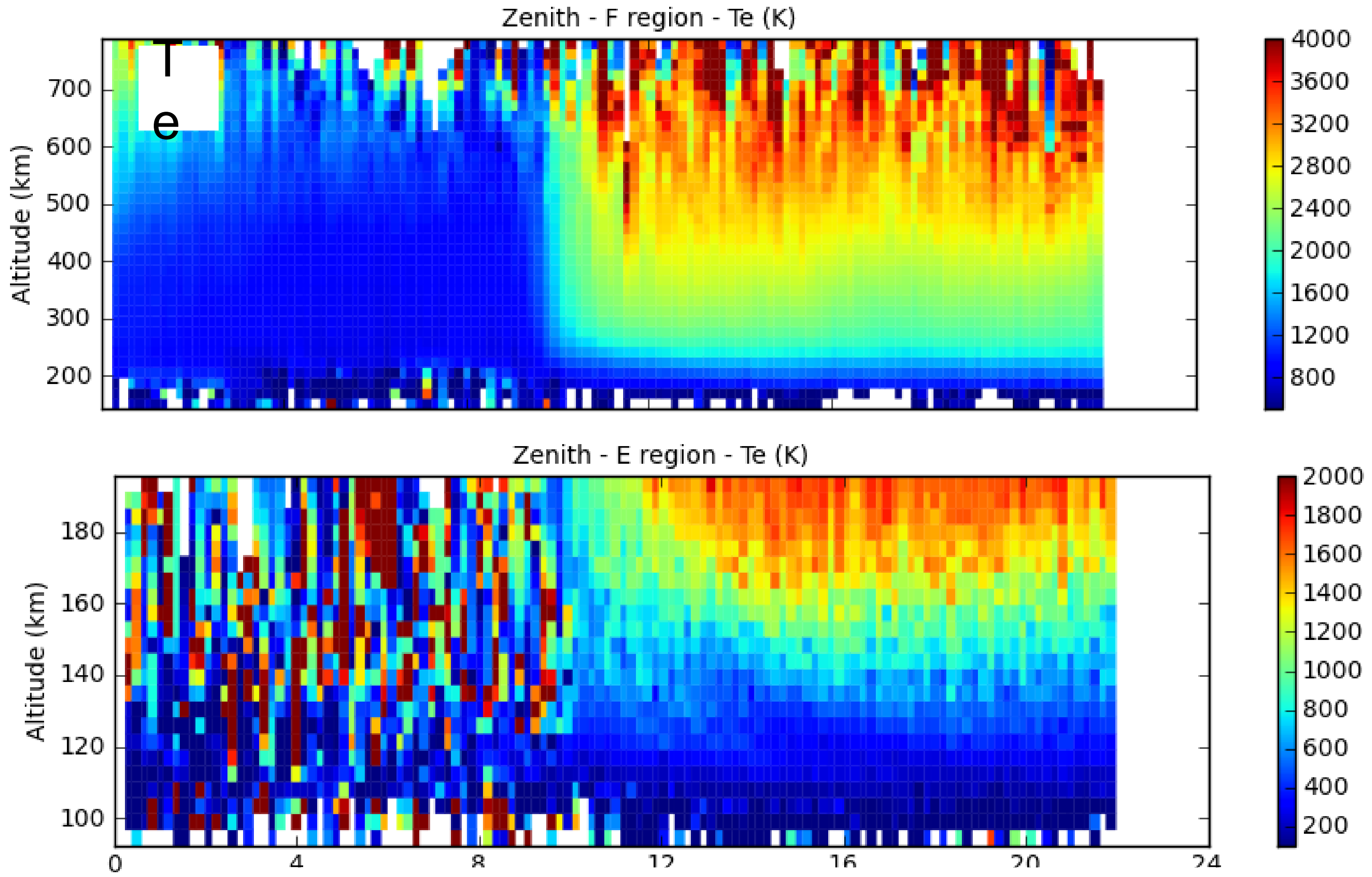


Plasma Line Spectra: Millstone Hill (60 sec integration)



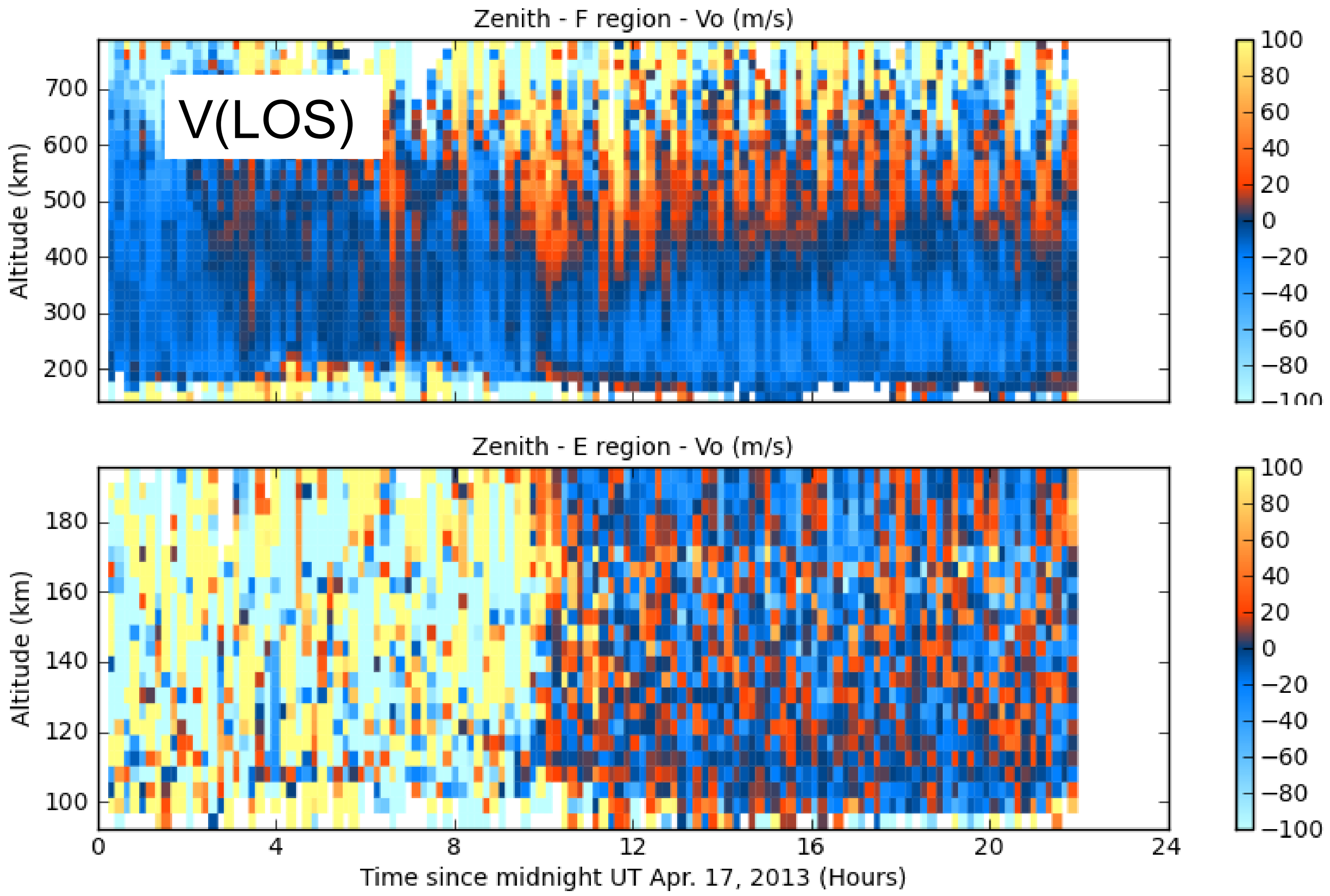
Basic IS Radar Measured Parameters (Ion Line)

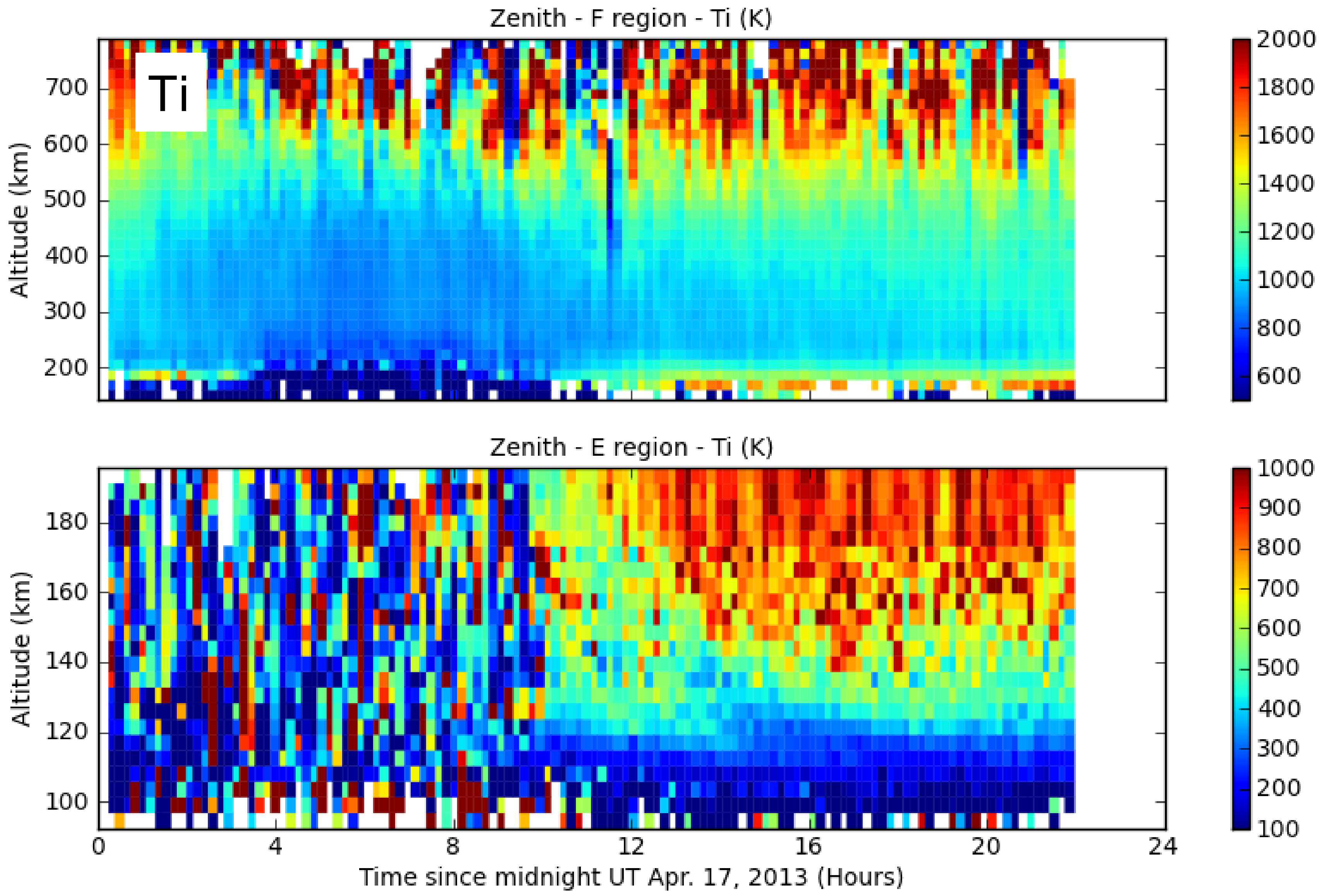




Altitude-resolved

Ionospheric
cold plasma
state parameters





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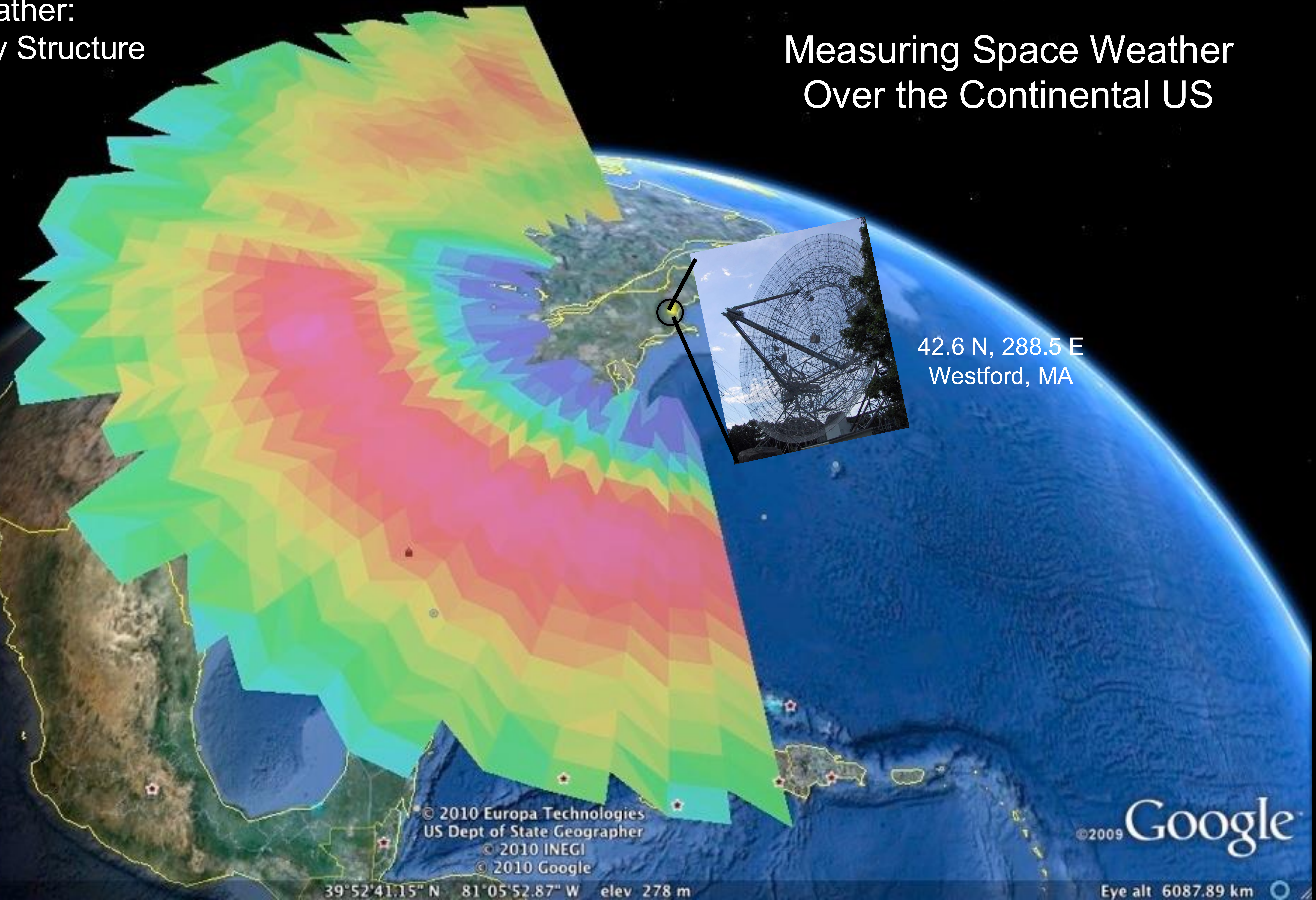
Millstone Hill Ionospheric Radar
Azimuth Scan

Space Weather:
Electron Density Structure

Millstone Hill
Incoherent Scatter Radar:

Measuring Space Weather
Over the Continental US



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NSF

A Highly Flexible Multi-Use Instrument: Not Just Ionospheric Observations

WORKSHOP REPORT

A Strategic Vision for Incoherent Scatter Radar

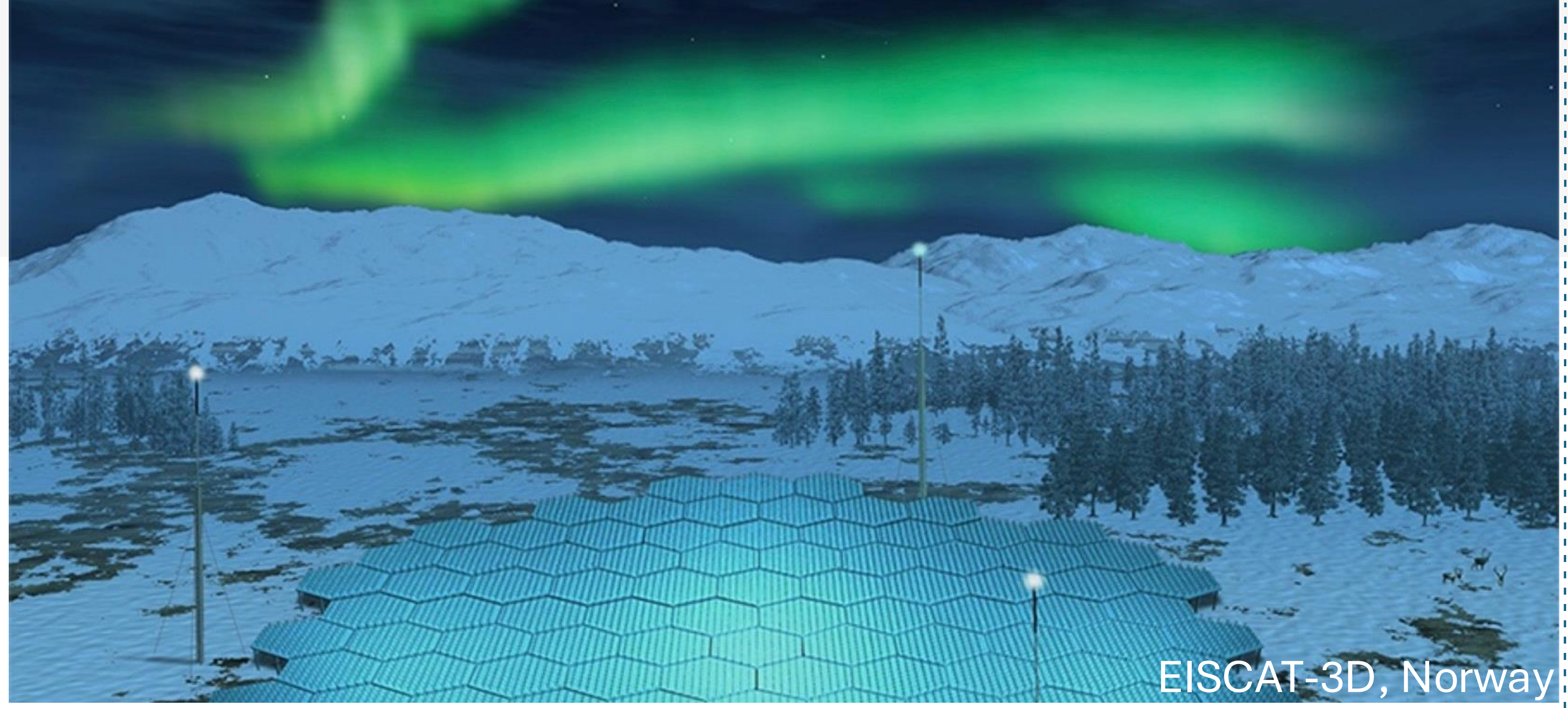
FACILITIES FOR THE 21ST CENTURY

April 26–28, 2021

http://landau.geo.cornell.edu/workshop.pdf


Sub-radar point
Doppler
Delay
EISCAT 933 MHz
Lunar map
(Delay-doppler)
Juha Vierinen

ISSI Working Group: Incoherent scatter - An invaluable tool in the field of space and plasma physics



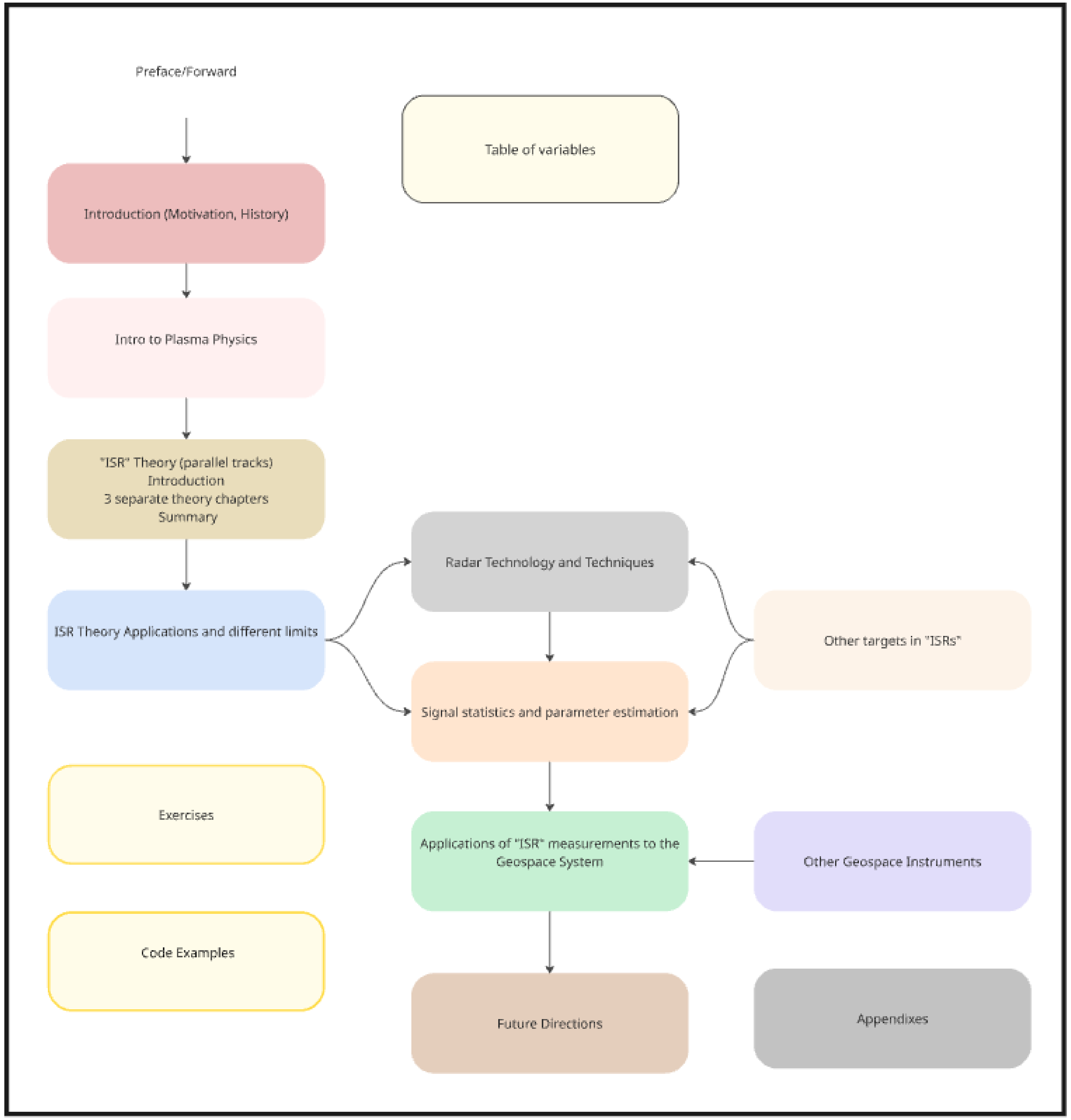
Outcome:

- Textbook will be **open access** (downloadable pdf) in the ISSI Scientific Report Series
- Supplementary computer code / exercises online
- Aimed at a broad audience, including plasma physicists, radio scientists, space physicists, and engineers.
- Suitable for Masters/PhD students and above.
- Publication expected ~2027/2028

Baddeley / Goodwin / Perry / Rexer / Lorentzen / Chau / Vierinen / Laundal / Lamarche / Erickson / Bhatt / Strømme / Kaeppler / Longley / Pepper / Milla
+ many others

First meeting at ISSI: April 2025

The Book Overview



- Masters / PhD level
- Book will concentrate on aspects of ISR not covered **in depth** coherently**,** elsewhere
- Parallel theory chapters to provide students with a choice:
  - Dressed test particle (Hagfors, Pecséli)
  - Fluctuation – Dissipation (Farley, Kudeki, Milla)
  - Plasma kinetic (Salpeter, Sheffield)
  - Discussion of different approaches also included
- Aim to include full theoretical derivations
- Additional website with GUIs / computer code

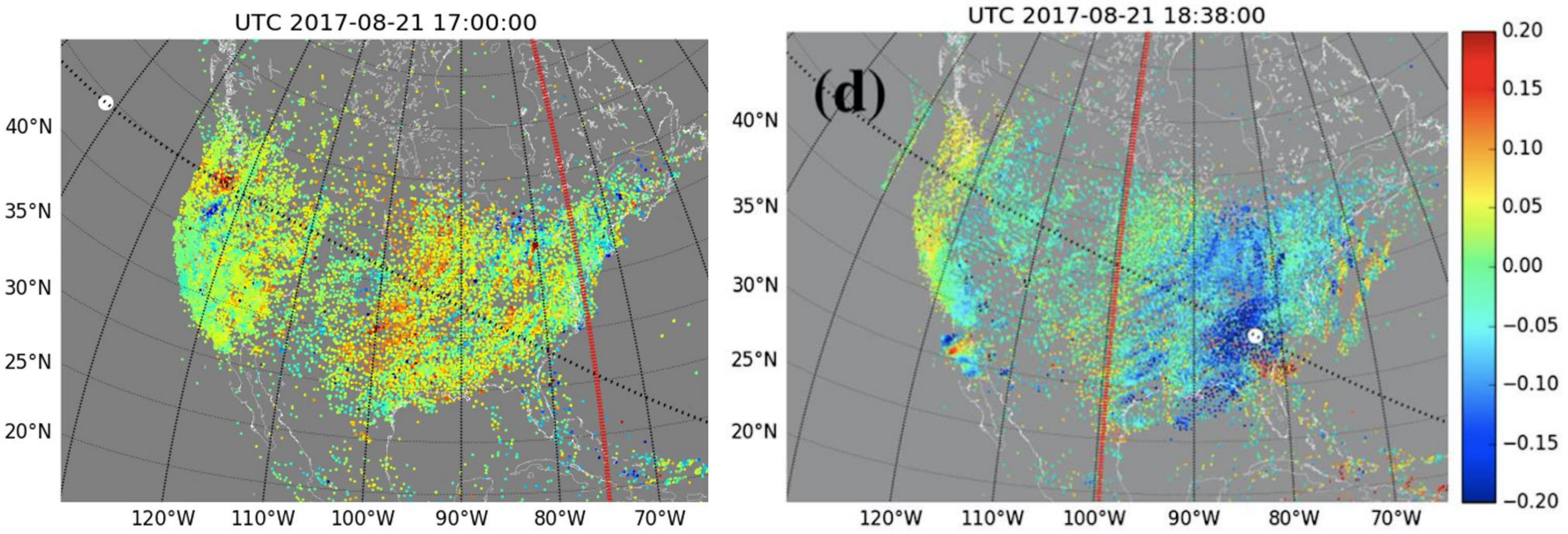
Let’s Add More: GNSS Space Weather Diagnostics - Total Electron Content

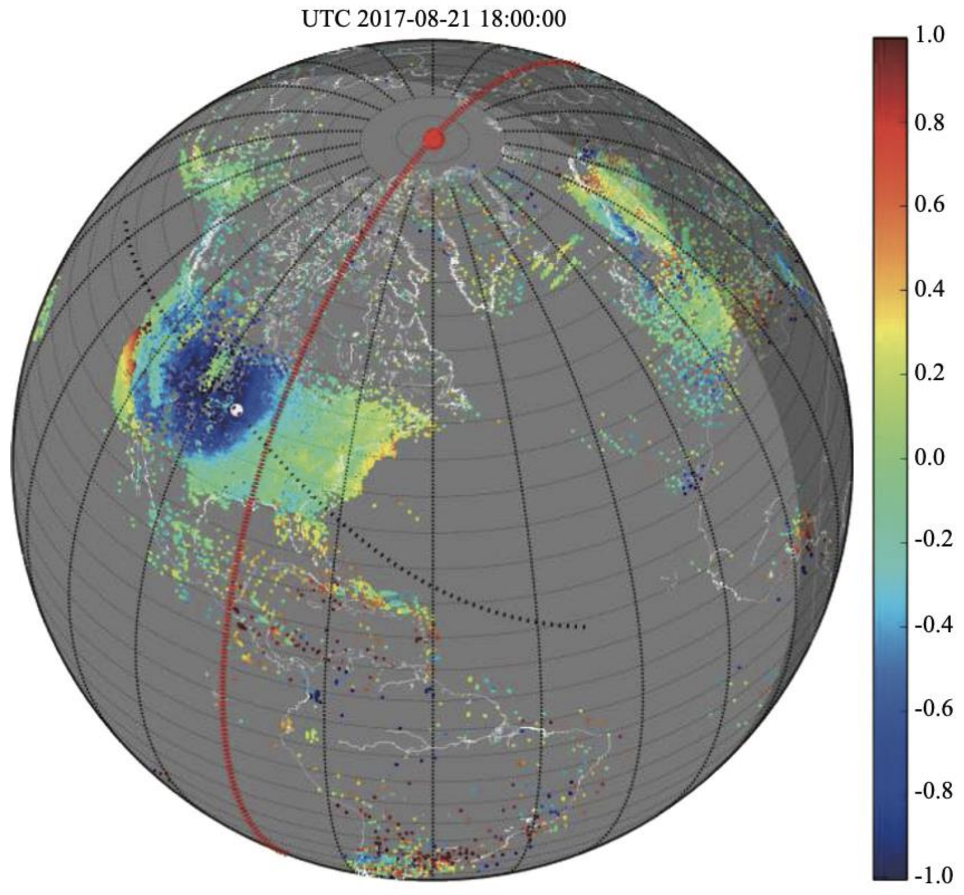
This is a Meta-Instrument!

- Differential delay on GNSS transmissions
- Line of sight
- Global TEC maps
  - Vertically binned (1 x 1 deg x 5 min)
  - Line of sight (rich information content)
  - Regional, global ionospheric dynamics
  - Critical multi-scale ionospheric structure
- Example: >450,000 LOS values in <5 minutes

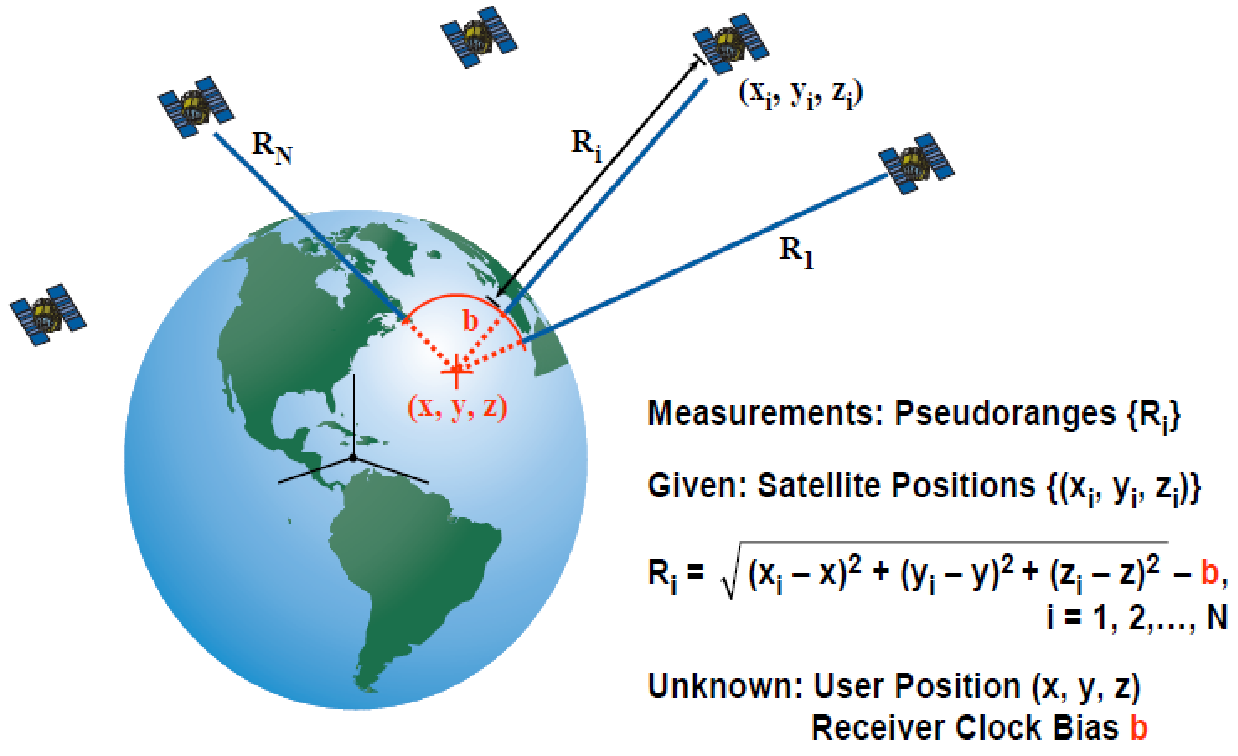
- Radio occultation paths add unique observing geometries [not shown]

August 2017 Eclipse Differential TEC https://youtu.be/8vivMEVBwys

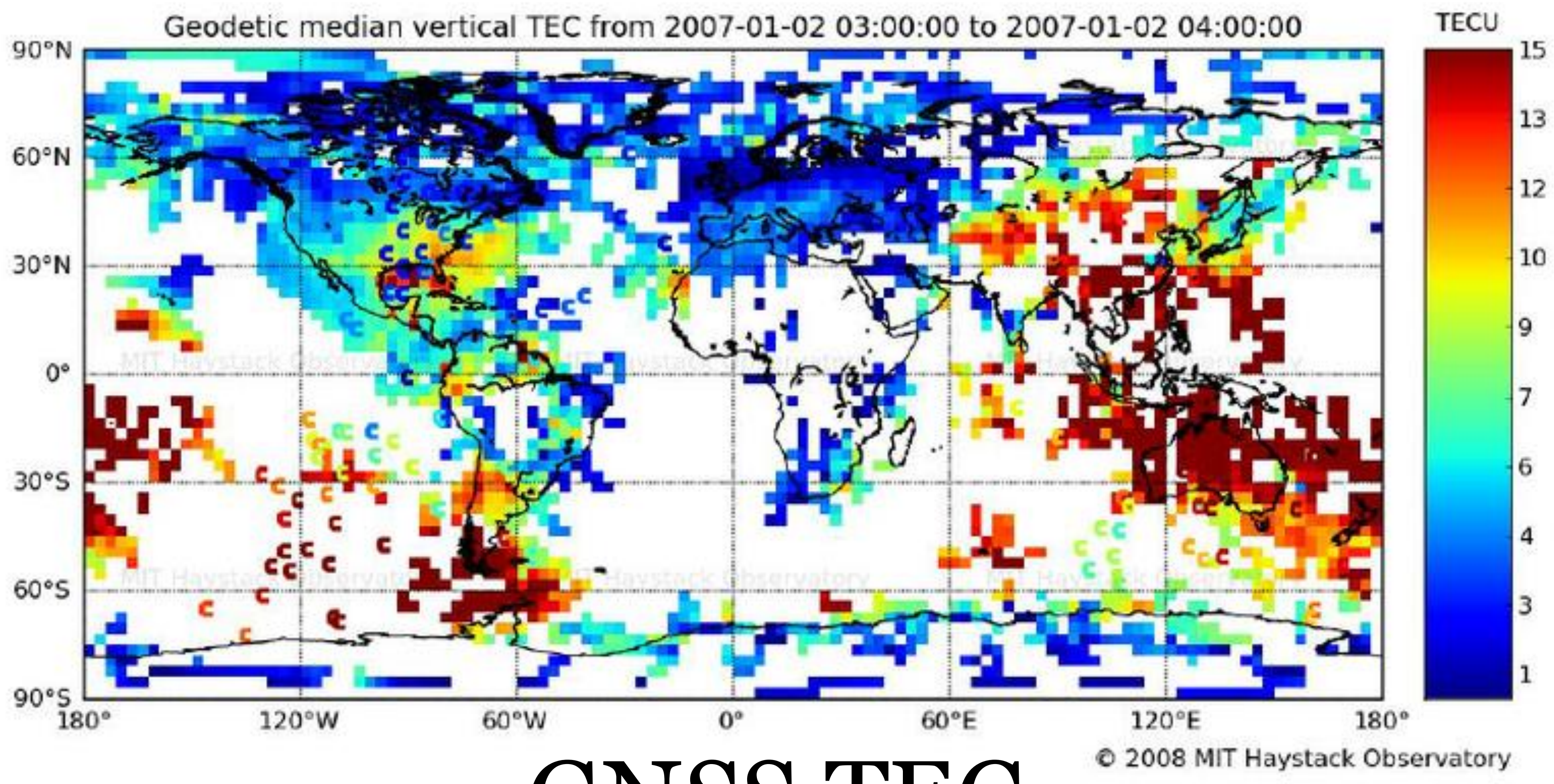




Zhang et al, EPP 2017



Let’s Add More: Madrigal distributed database



GNSS TEC

240 Diverse Instruments in Madrigal
1980-present

J. M. Holt
creator

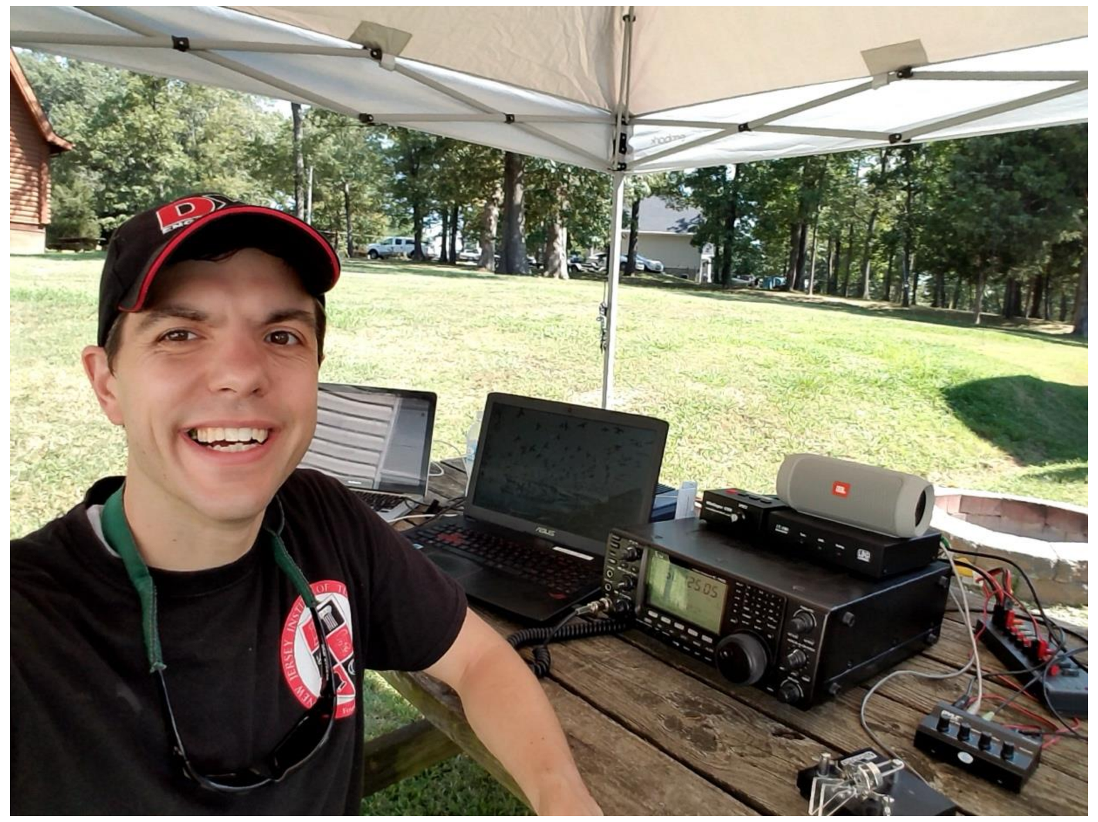
Incoherent scatter radars (ISR): 20
Lidars: 10
Meteor radars: 18

Magnetometers: 16
Photometers: 7
Fabry Perot Interferometers: 38

Also GNSS Total Electron Content (TEC), Defense Meteorological Satellite Program (DMSP), HamSCI, All-Sky Imagers, and more

HamSCI More: Ham radio Science Citizen Investigation

HamSCI at 2023 Dayton Hamvention



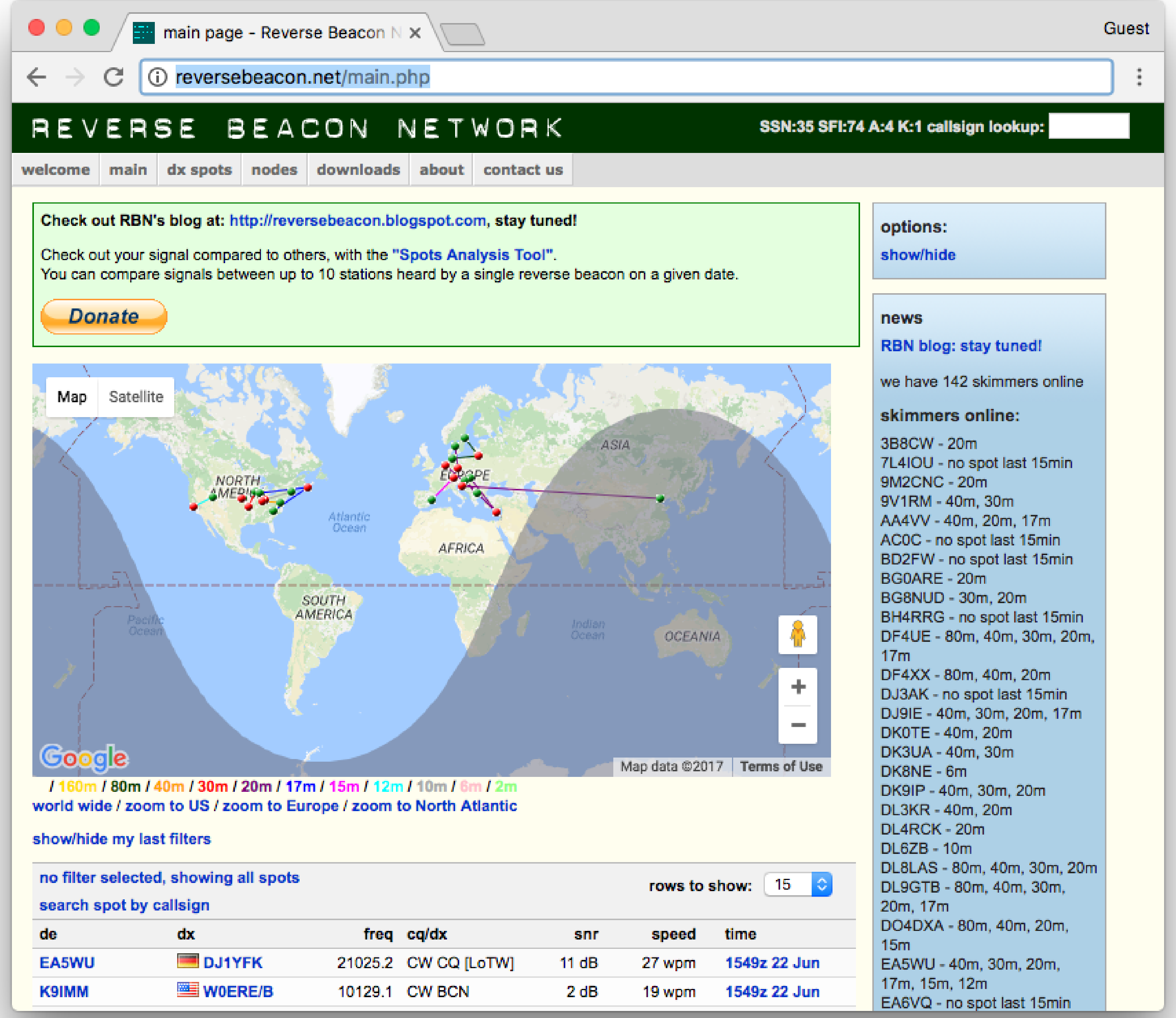
Founder/Lead HamSCI Organizer:
Dr. Nathaniel A. Frissell, W2NAF
The University of Scranton

A collective that allows university researchers to collaborate with the amateur radio community in scientific investigations.

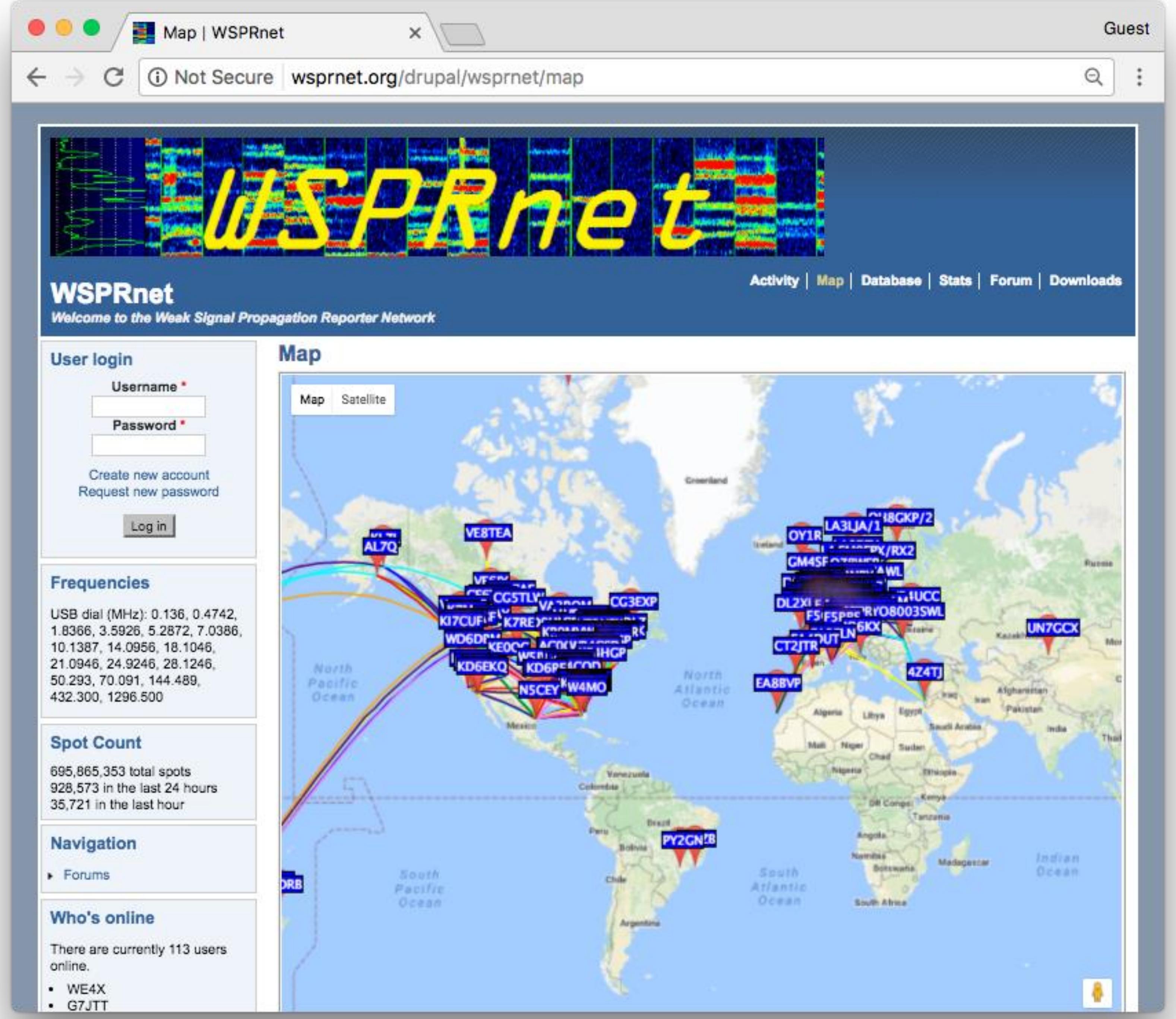
Objectives:

1. **Advance** scientific research and understanding through amateur radio activities.
2. **Encourage** the development of new technologies to support this research.
3. **Provide** educational opportunities for the amateur radio community and the general public.

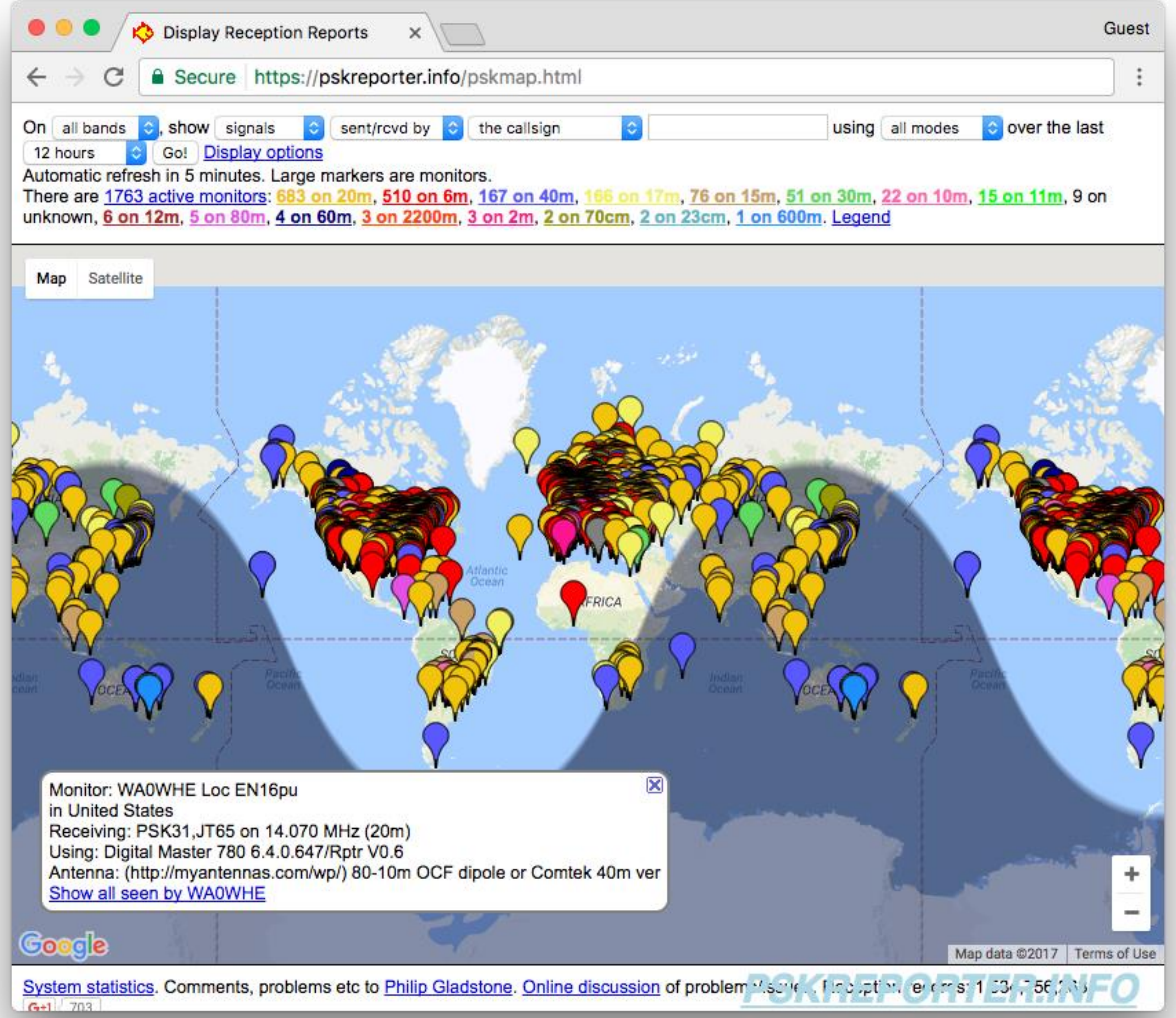
Amateur Radio Observation Networks



Reverse Beacon Network (RBN)
reversebeacon.net



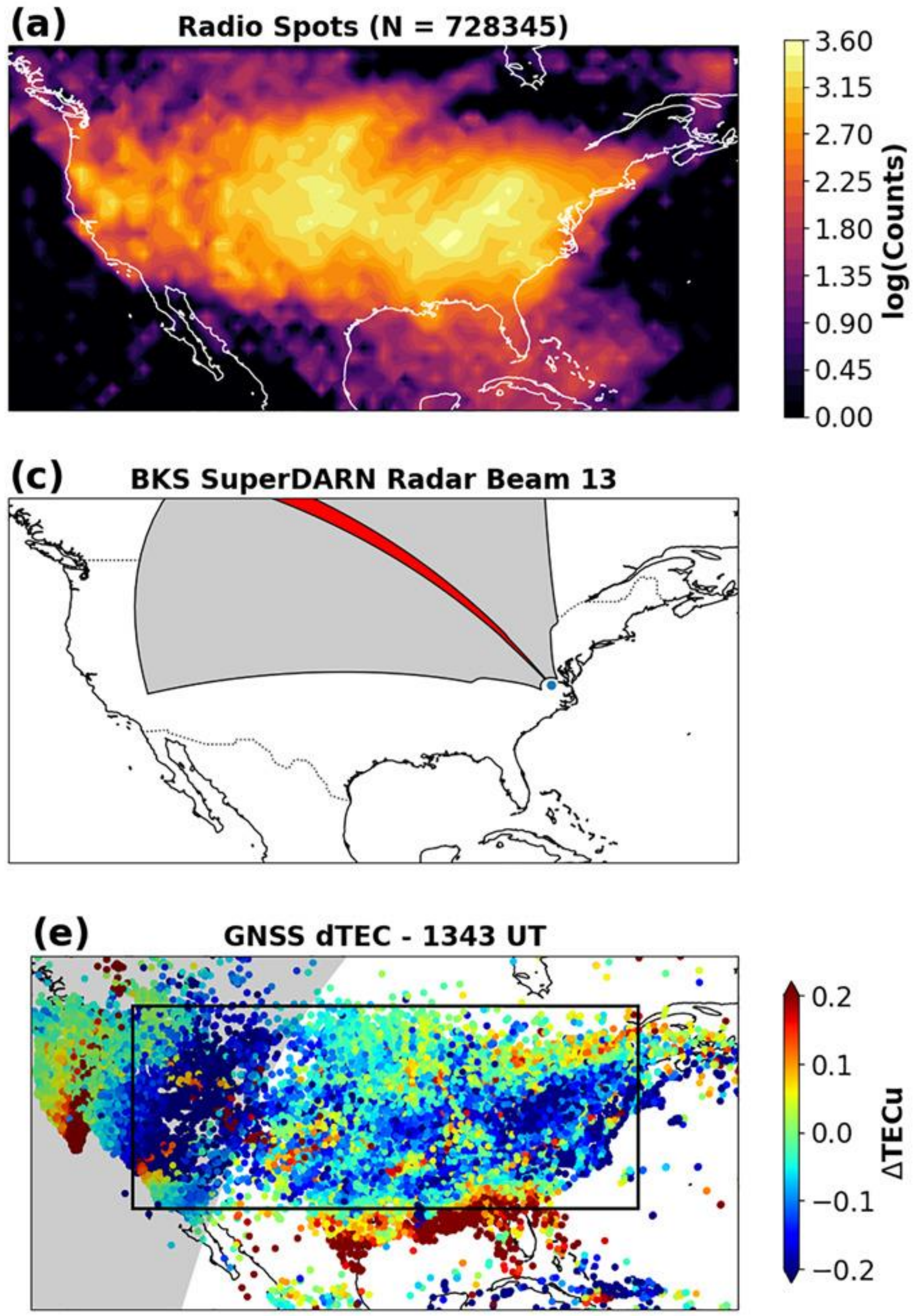
WSPRNet
wsprnet.org

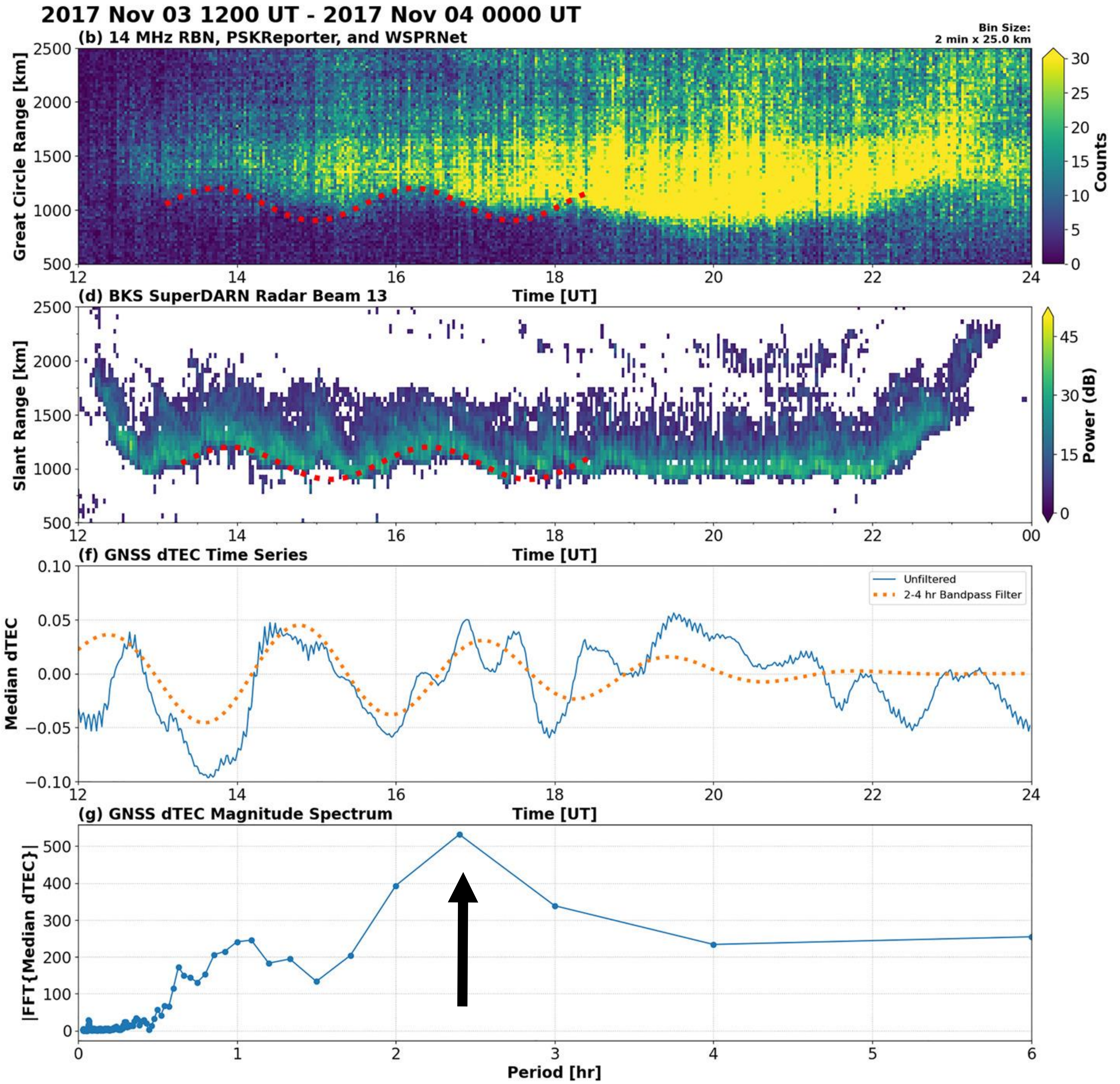


PSKReporter
pskreporter.info

- Quasi-Global
- Organic/Community Run
- Unique & Quasi-random geospatial sampling
- Data back to 2008 (A whole solar cycle!)
- Available in real-time!

Observational Synthesis leads to Insight



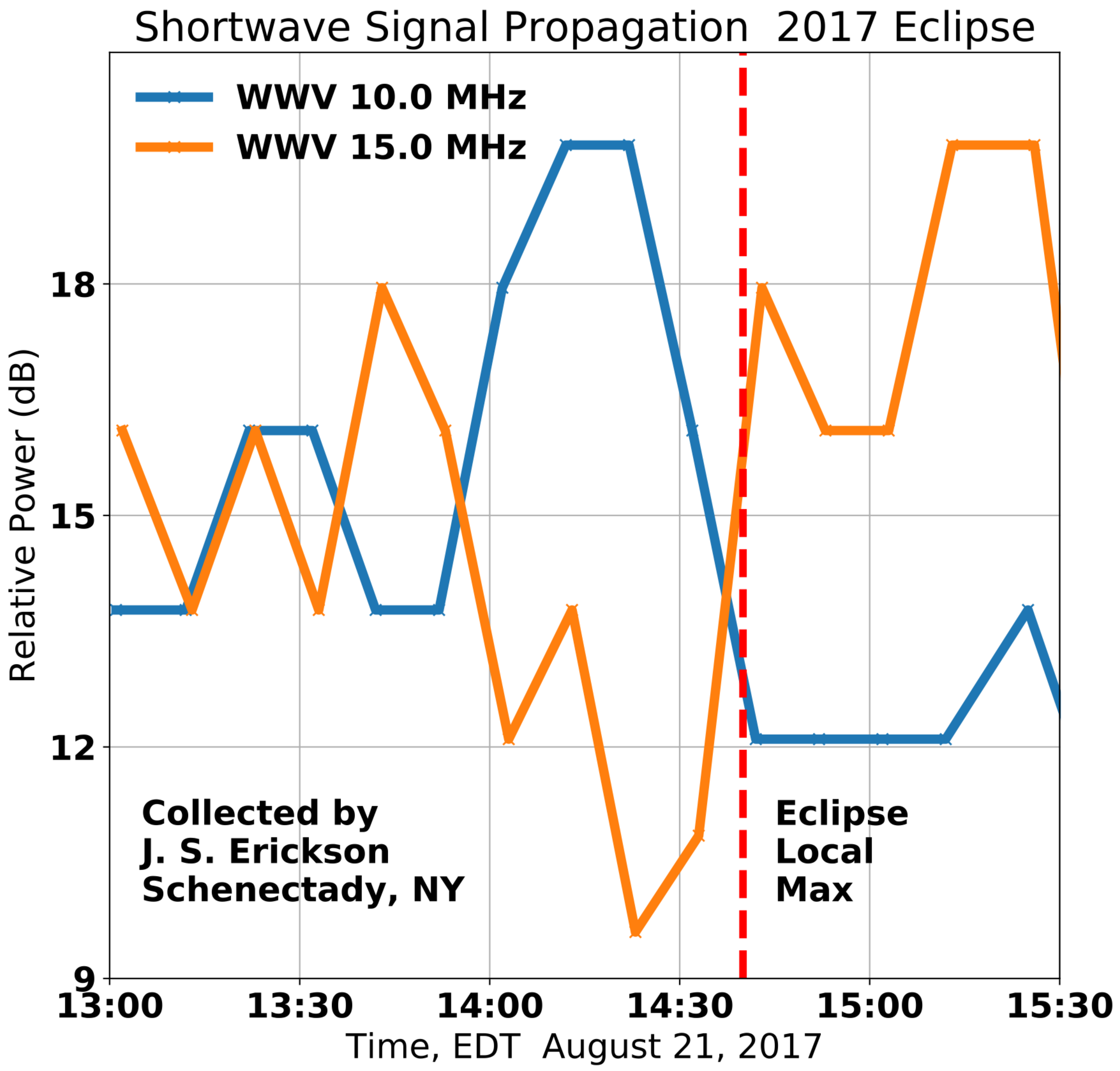


Mid-latitude **Large Scale Traveling Ionospheric Disturbances** are seen for the first time simultaneously in amateur radio, SuperDARN, and GNSS TEC data

SuperMAG SME index, PFISR (not shown) - indicates driven by auroral electrojet, Joule heating

Frissell+ 2022 https://doi.org/10.1029/2022GL097879

Citizen Science: 10 & 15 MHz HF Propagation during 2017 Eclipse

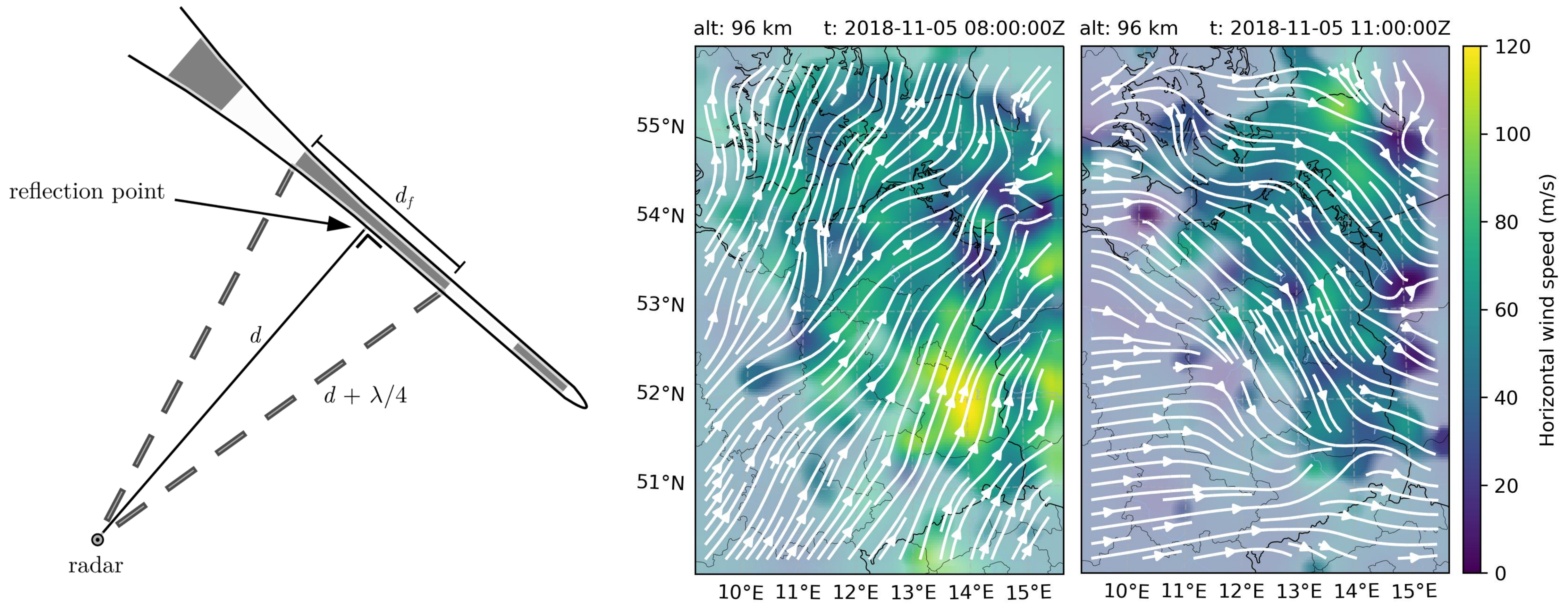


"Even shortwave listeners got into the act. Using the S meter on his Panasonic RF-4900 shortwave receiver, 88 year old John S. Erickson of Schenectady, NY … recorded the signal strength he heard from time signals WWV at 10 and 15 MHz every 10 minutes during eclipse passage."

(Erickson / Frissell / Liles+)

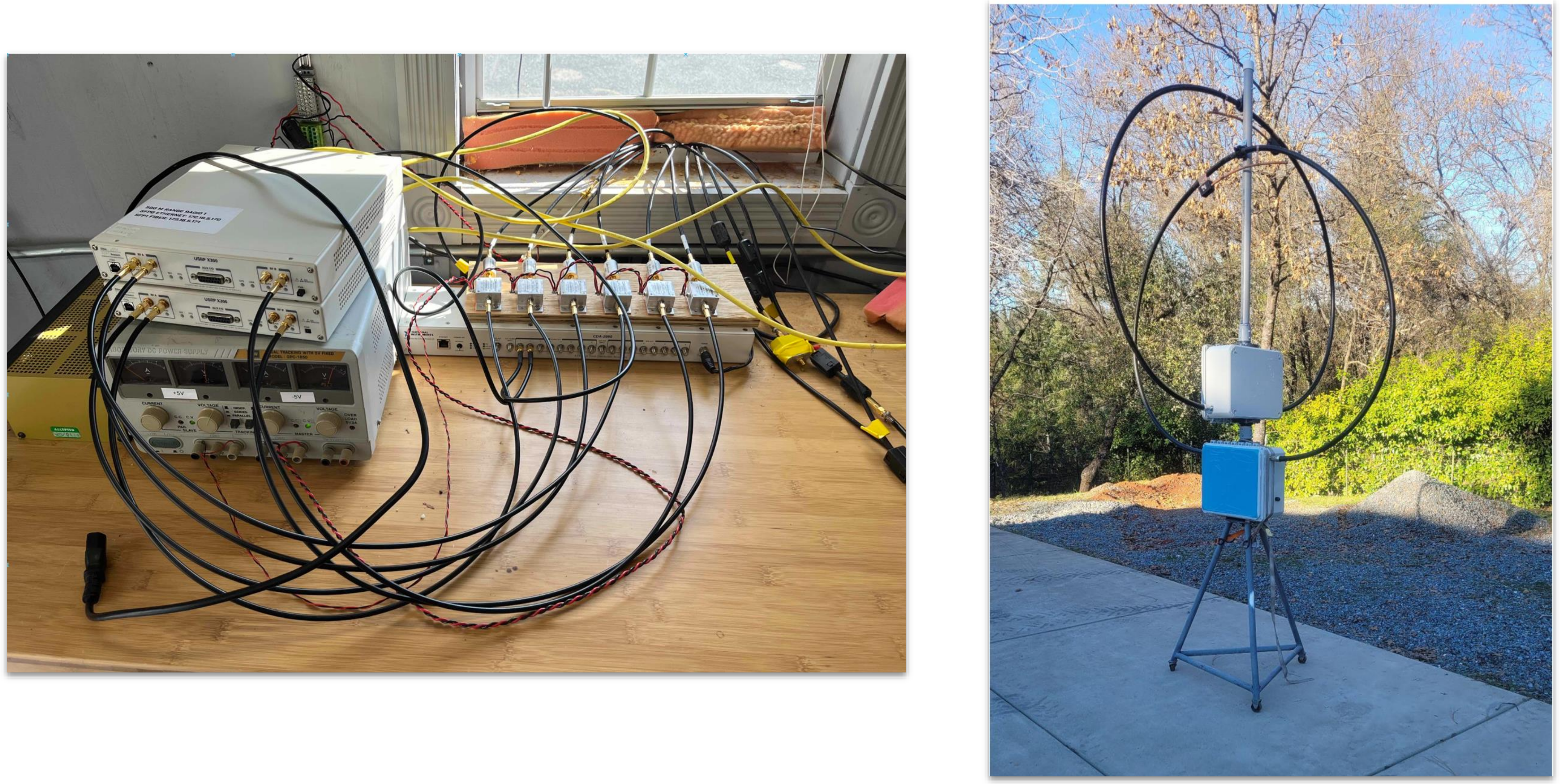
Let’s add More:
Distributed instruments for geospace remote sensing

Advanced meteor radar networks: Sensing upper atmosphere **neutral** winds
Divergence, vorticity, momentum flux (e.g.)
Mesoscale structure!



(Chau / IAP, Volz / Haystack)

Low-cost ionosonde networks:
3D volumetric electron density remote sensing from the ground



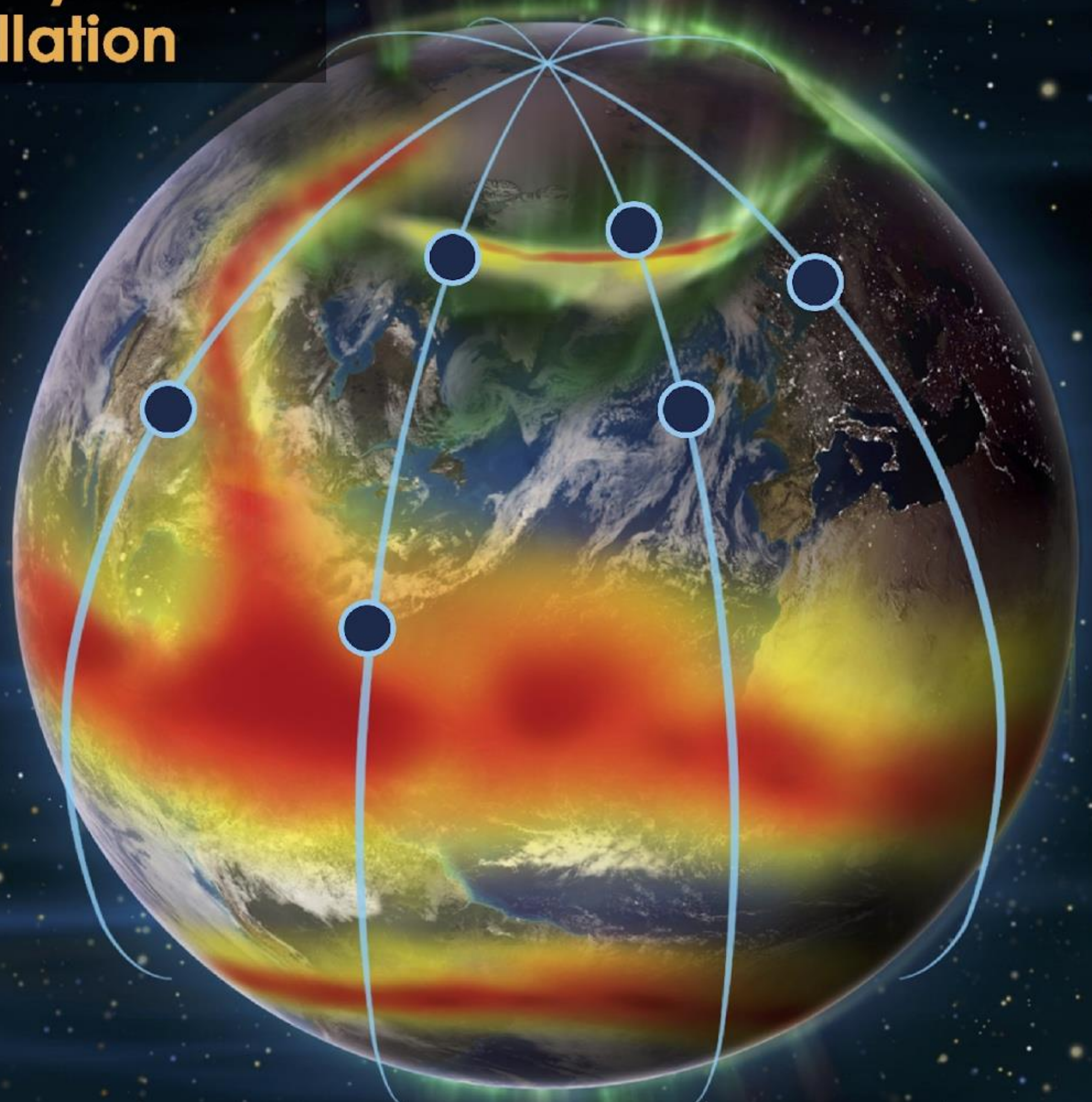
(Swoboda, Haystack)

MIT HAYSTACK OBSERVATORY

Signal processing, software radio advanced developments
= 3D understanding of upper atmospheric dynamics

Geospace Dynamics Constellation

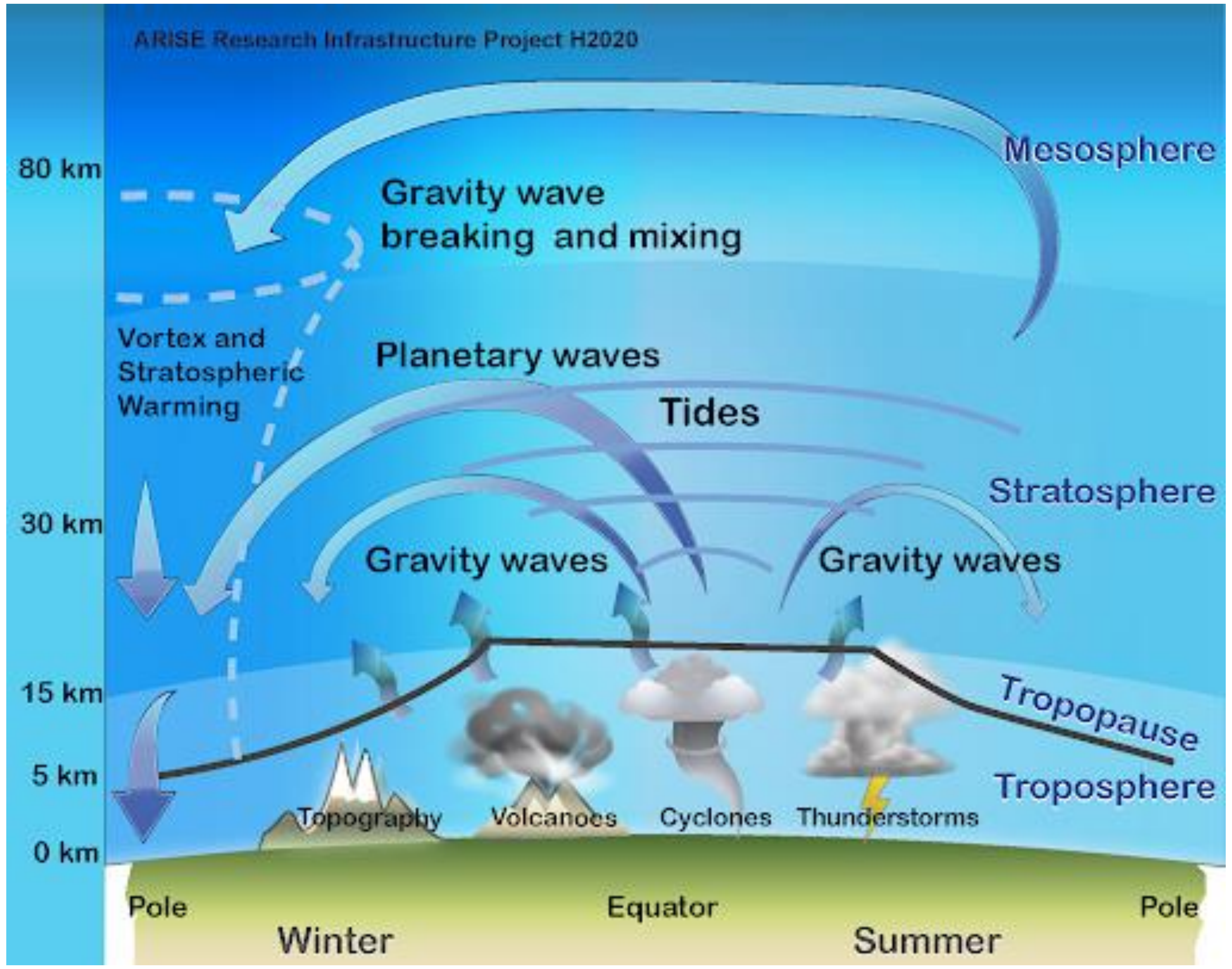
- 6 satellite mission to study the transition between Earth's atmosphere and the space environment in the ionosphere and thermosphere
- The first comprehensive measurements in this region, including energy inputs from the space environment above and the variable upper atmosphere response
- Interdisciplinary study of fundamental processes of planetary upper atmospheres, to understand the space environment role in planetary habitability
- Provides critically-needed space weather observations of the Low Earth Orbit region, enabling characterization of the orbital drag environment and understanding of space weather processes.



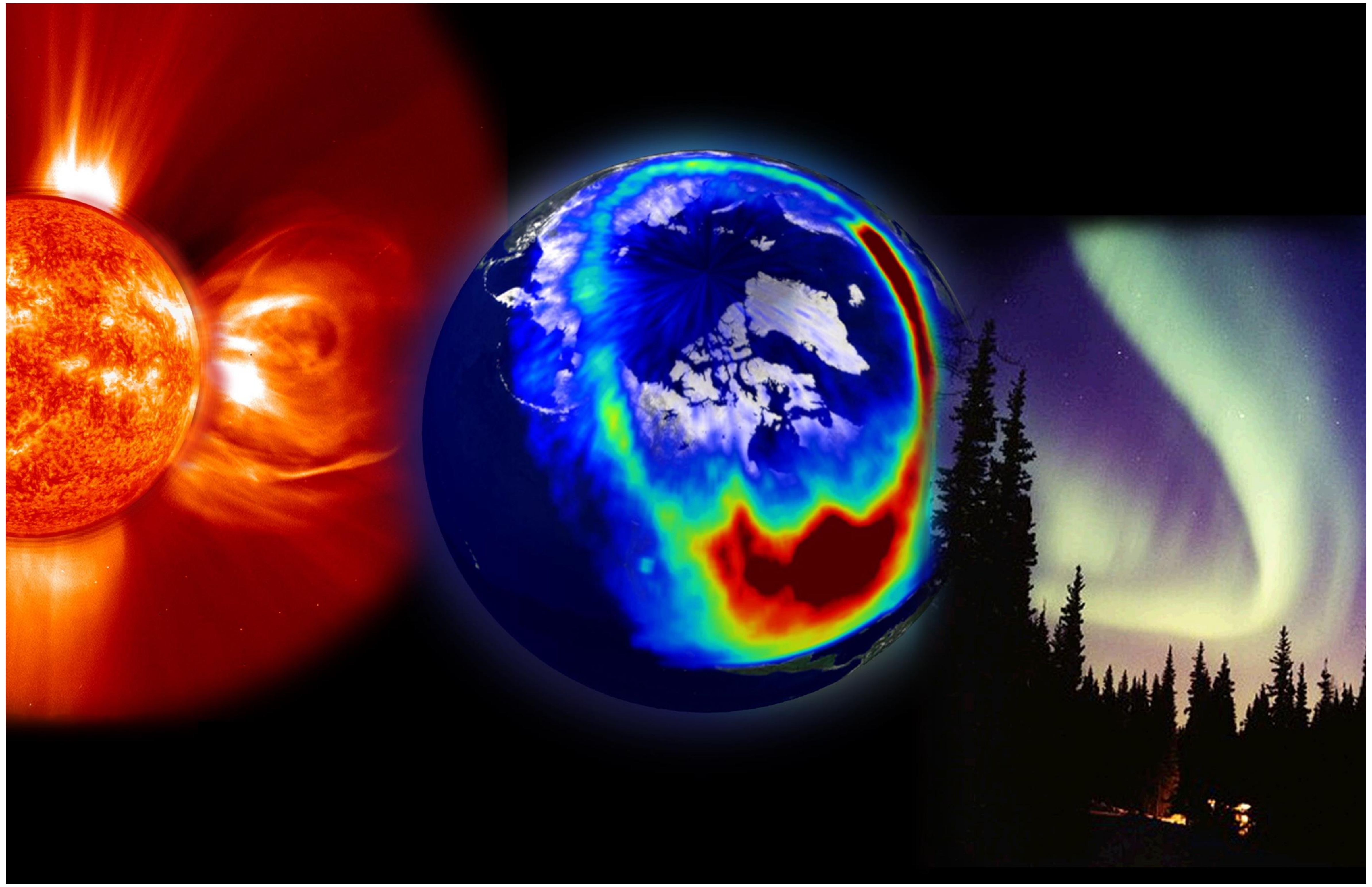
DYNAMIC Mission: Essential Observations to Study Important ~100-300 km Altitude Region (VLEO)

- **Very few observations of complex wind, temperature, composition and density in this region**
- **Very sensitive to poorly characterized forcings:**

From below: Tidal, Gravity and Planetary Atmospheric Waves



From above: Auroral Heating and Joule Heating Originating from Solar Storms

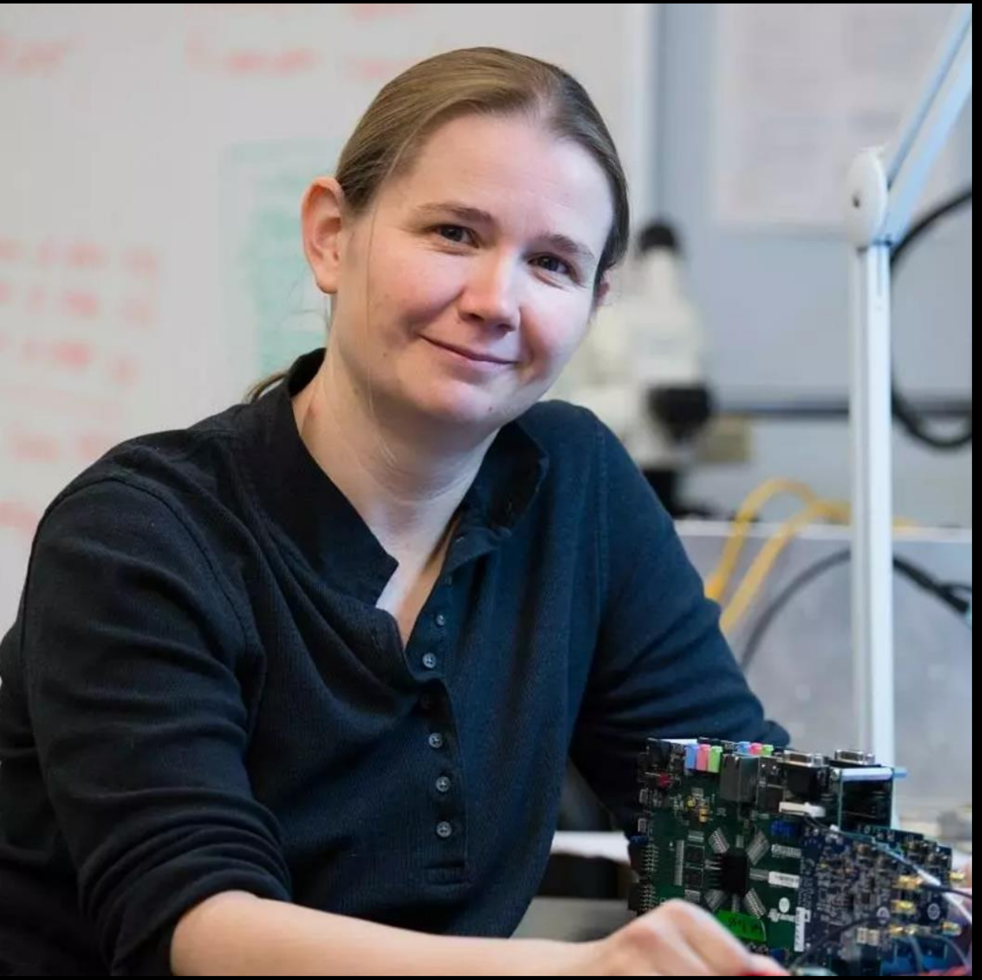


GDC-G (ground)

27 Mags (fluxgate)
27 Riometers
23 RGB ASI
8 Spectrographs
16 Red ASI
27 GNSS
6 FPI

---

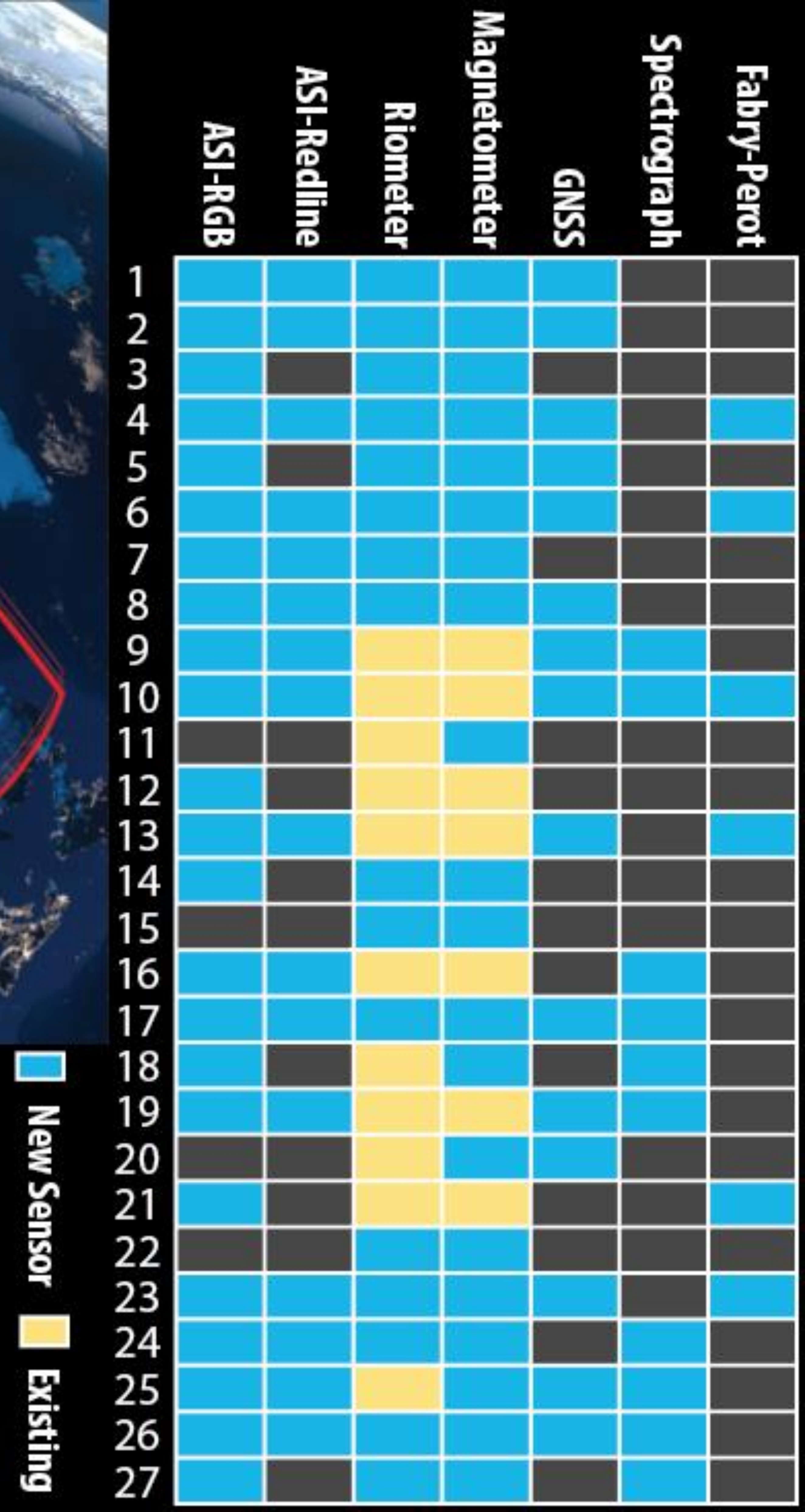
134 instruments across 27 sites



PI: Emma Spanswick

University of Calgary

1. Eureka, NU
2. Resolute Bay, NU
3. Clyde River, NU
4. Iqaluit, NU
5. Kuujjuaq, QC
6. Labrador City, NL
7. Sanikiluaq, NU
8. Kapuskasing, ON
9. Pinawa, MB
10. Gillam, MB
11. Churchill, MB
12. Rankin Inlet, NU
13. Taloyoak, NU
14. Cambridge Bay, NU
15. Contwoyto, NU
16. Rabbit Lake, SK
17. Lucky Lake, SK
18. Athabasca, AB
19. Fort Smith, NWT
20. Prince George, BC
21. Fort Simpson, MWT
22. Normal Wells, NWT
23. Sachs Harbour, NWT
24. Inuvik, YK
25. Whitehorse, NWT
26. Poker Flat, AK
27. Toolik, AK



ITM / Geospace System Science through Synthesis:

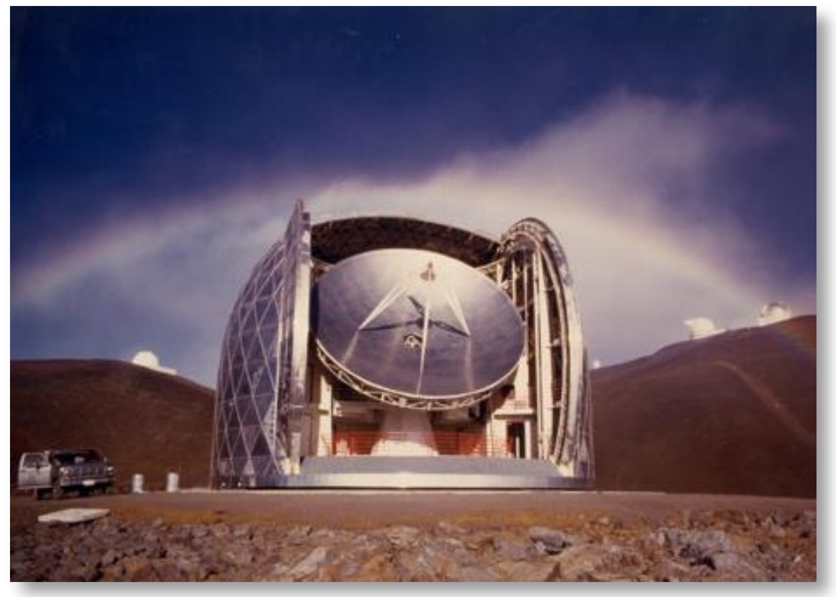
Putting It Together

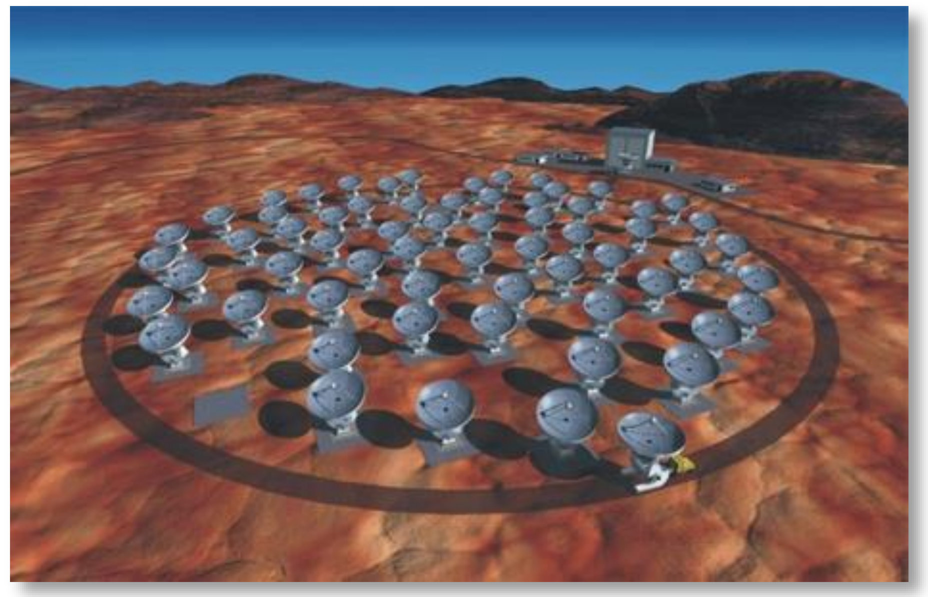
Short diversion - Haystack history wall:

Scientific impacts consistently emerge from **reimagining / synthesis** of capabilities

The Event Horizon Telescope

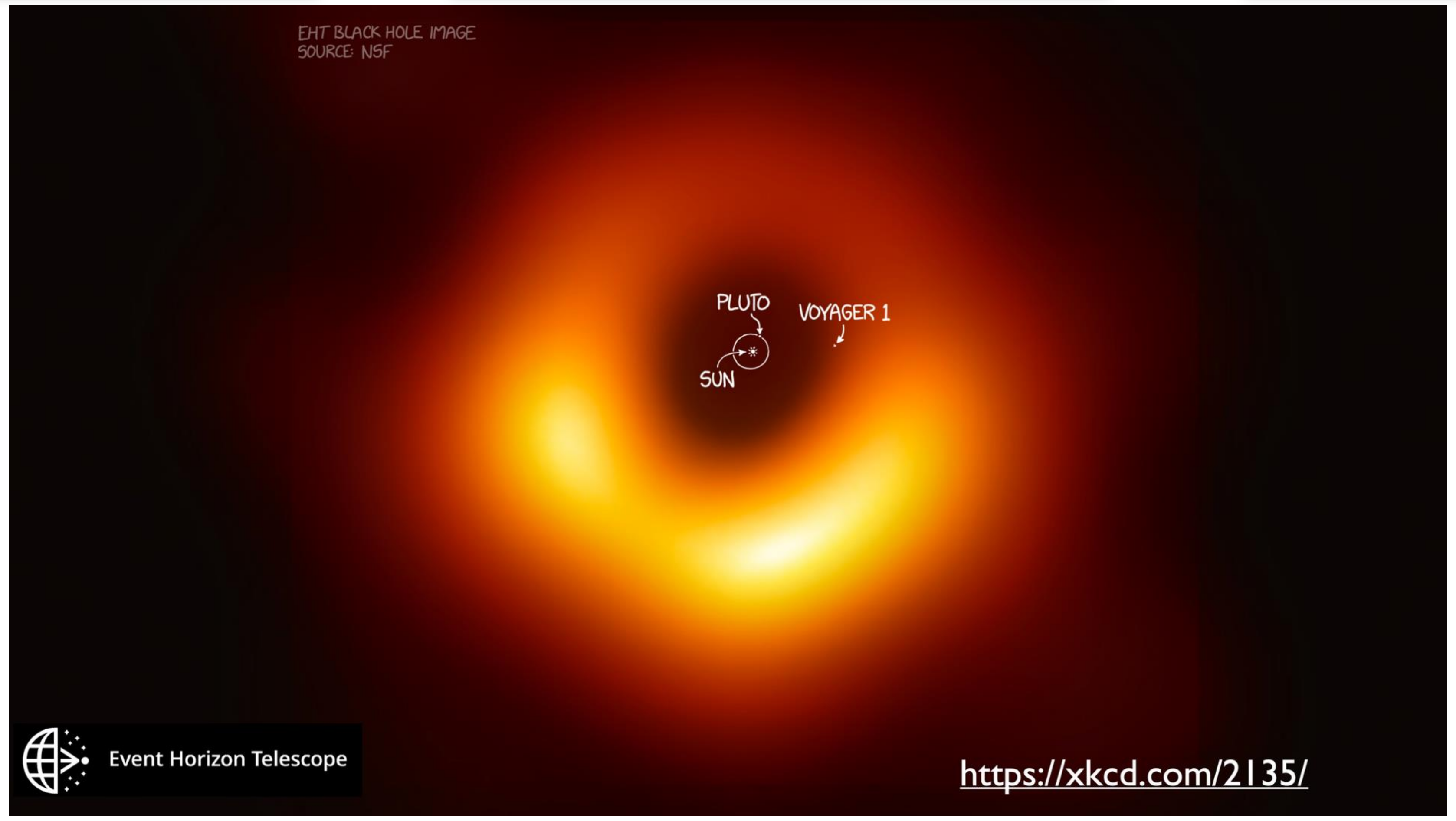
- The EHT: Planet-scale interferometer for humanity's **very first images of the environment around a black hole**
- VLBI connects multiple distant radio antennas to function as one much larger, more powerful telescope
- Result **CANNOT EXIST** until data is synthesized collectively





Sgr A* black hole
(mm-wave emissions)

Angular size:
50 micro-arc sec



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HAYSTACK
OBSERVATORY

SCIENCE is GLOBAL: The Event Horizon Telescope Collaboration

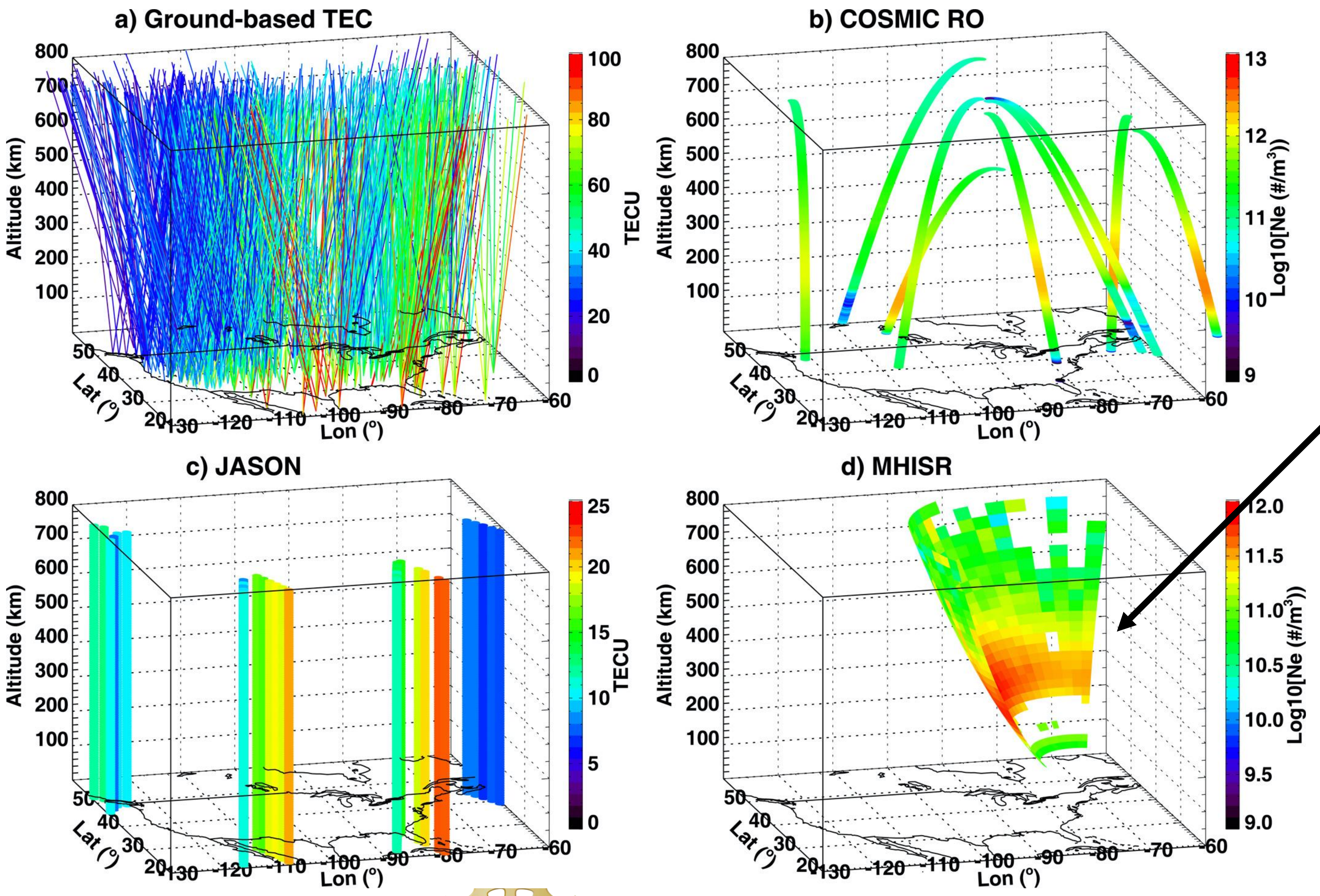
300+ Members

59+ Institutes

18+ Countries

Without the international open collaboration, no result!

Assimilating Heterogeneous Ionospheric Parameters



Electron density data sources:

- GNSS total electron content (slant/line of sight)
- Millstone Hill IS Radar profiles
- COSMIC I, II radio occultation profiles
- JASON vertical TEC (up to 1336 km altitude)
- NeQuick electron density model: 6 semi-Epstein functions anchored at available E/F1/F2 peaks

Data assimilation methods:

- Ensemble-based background error covariance estimation
- 3DVAR Data assimilation
- Sparse matrix storage (<0.3% non-zero values)

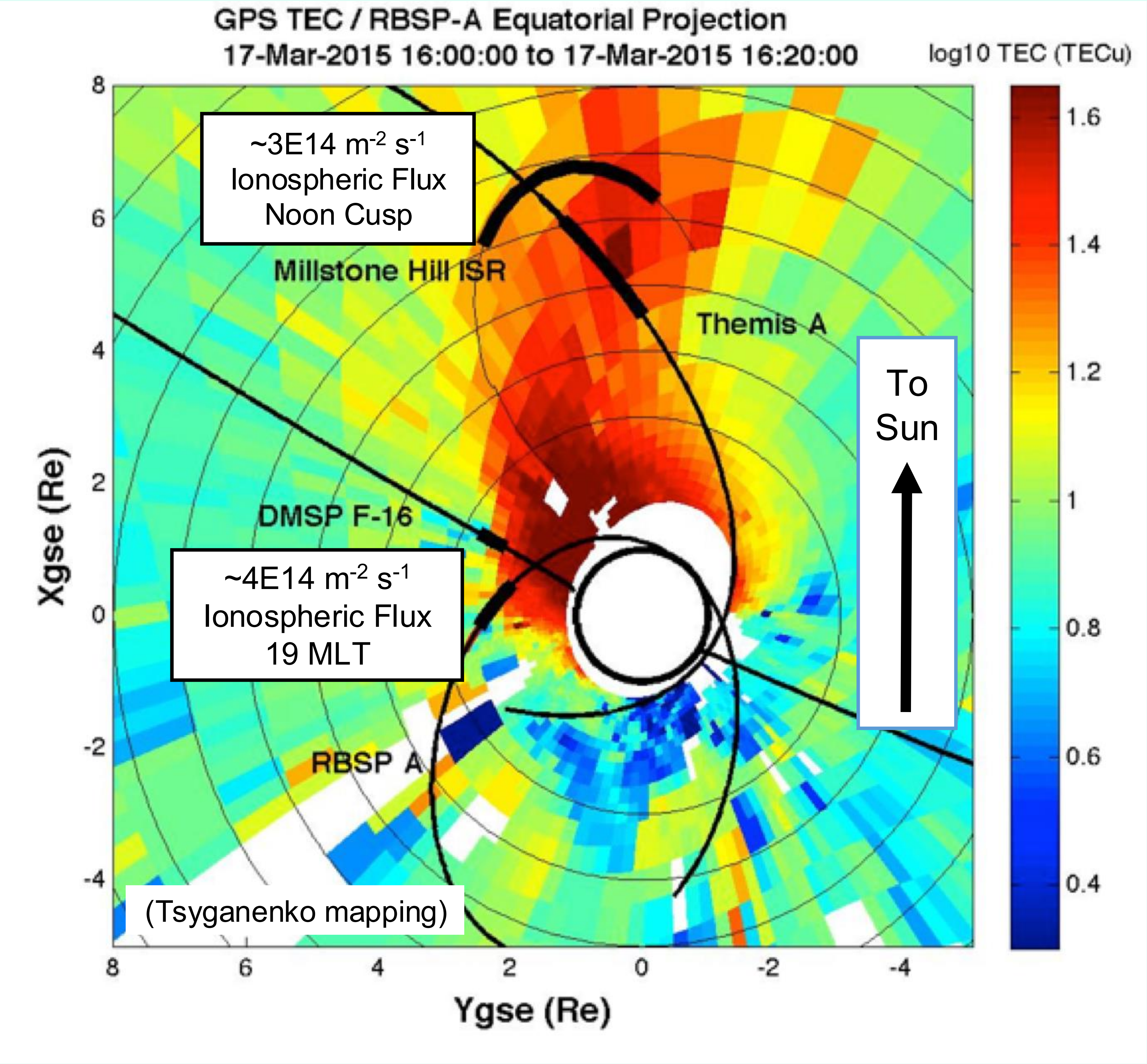
MIT HAYSTACK OBSERVATORY

NSF

TIDAS details: Aa+ 2022 https://doi.org/10.1029/2022SW003055

Subauroral / M-I Coupling Dynamic Topics: A Rich Source of Frontier Science (from 2021 Facilities workshop report)

- Synoptic **electric field mapping** between the ionosphere and magnetosphere
- Heavy, cold **ion outflows** providing significant mass loading of the magnetosphere
- **Storm enhanced density (SED) formation**, severe electron density gradients, and thermodynamics
- interactions between **plasma flows and thermospheric winds** (intensification, vortices, ion drag/Coriolis forcing)
- Ring current **electrodynamic feedback** (Region 2 coupling)
- **Sub-auroral polarization streams** (SAPS)
- Intense narrow **subauroral ion drifts** (SAID) with rapid temporal lifetimes (STEVE)
- **MSTID/LSTIDs initiation mechanisms** and electrodynamic coupling/drivers
- Scale-dependent **magnetic conjugacy**
- **Inter hemispheric asymmetries**
- **Mesoscale** (<1 - 100 km) ionospheric variability and turbulent cascade
- Direct probing of the **plasmasphere boundary layer** and inner magnetospheric coupling



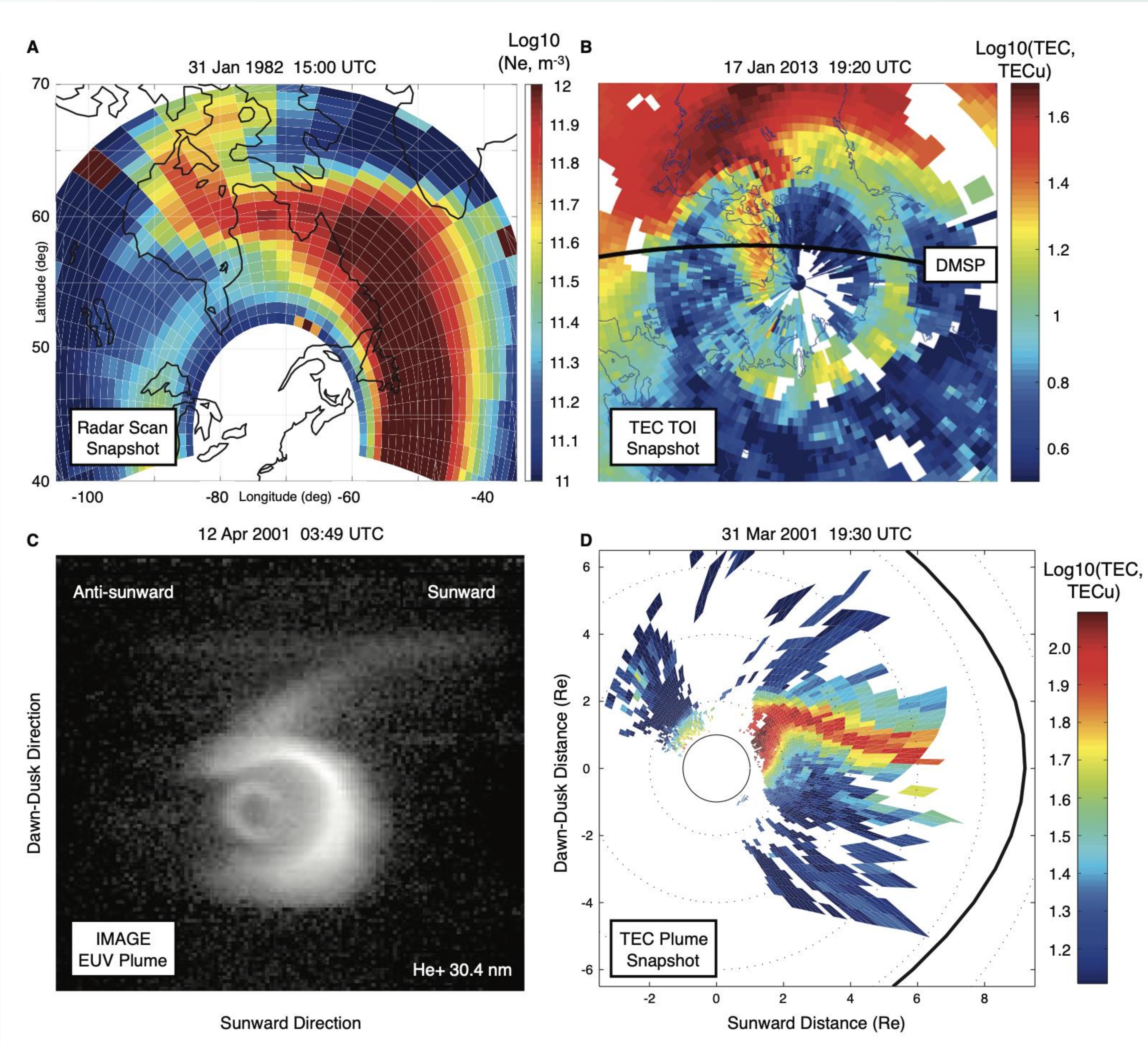
Foster et al., 2019, AGU Monograph Example: Cold Plasma Lifecycle in the Geospace System

MIT HAYSTACK OBSERVATORY

Synthesis Application: The Geospace Plume

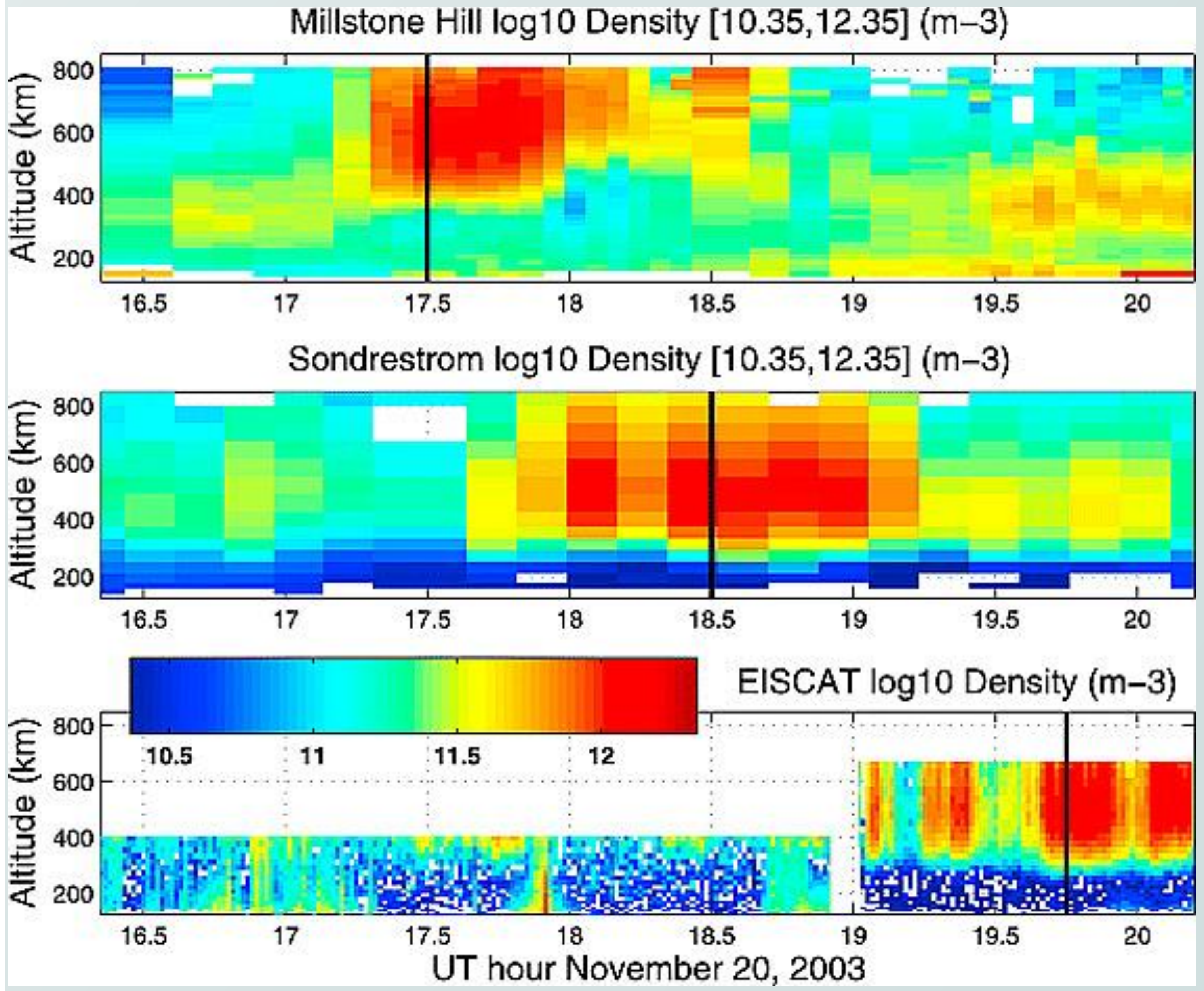
- SED base/plume formation
- Roles of SAPS, convection, PEF, and winds
- Global M-I-T Coupling context: Subauroral plasma influences on high latitude (polar) ionosphere via SED
  - Polar cap patches
  - Tongues of Ionization
  - Delivery of cold heavy O+ to cusp outflow regions, inner magnetosphere
- GDC upcoming: multi-plane ion, neutral sampling of crucial dynamic structures

Magnetosphere / Ionosphere / Plasma
Cold Plasma Flows



Foster et al 2020

SED Passage through
Multiple Ground-Based Diagnostics:
More sampling needed!



Foster et al 2005

MIT HAYSTACK OBSERVATORY

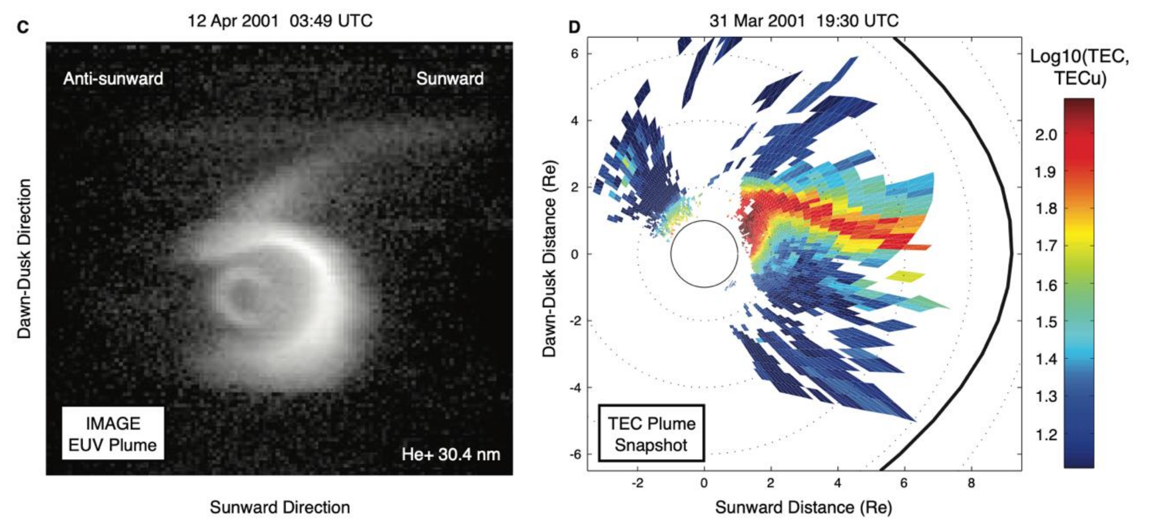
CEDAR

GEM Cold Plasma Questionnaire: Past, current future (2025; very partial list)

WHERE WE WERE 5-10 YEARS AGO	WHAT HAVE WE LEARNED IN THE LAST 5-10 YEARS?	REMAINING GAPS
How the cold electrons and cold ions can impact the magnetosphere-ionosphere system and how they can couple to other particle populations were underappreciated	The **cold particle populations have a strong impact on the magnetosphere-ionosphere system in a variety of ways, both locally and globally** (more details in the rest of the table)	The complete dynamics and effects of cold plasma is still a **long way from being fully understood**. Until the cold ions and cold electrons are fully understood, along with their controlling factors and their impacts, the **magnetosphere–ionosphere system will not be fully understood**
Ideas of substructuring around the plasmapause were hypothesized and supported by some measurements but were not settled	Measurements by missions like the Van Allen Probes have shown with unprecedented detail that the **cold plasma density is indeed highly structured inside and outside the plasmasphere**. It has become clear that this is very important for waves, wave-particle interactions and magnetosphere-ionosphere coupling	**How cold plasma structuring works and what controls it is still a mystery.** Requires **both in-situ and remote sensing** measurements
The effect of cold plasma density on wave properties was already well established	Cold plasma heating and energization by waves and nonlinear wave-wave processes mediated by cold plasma are beginning to be appreciated	**A lot of nonlinear processes and couplings are still completely unexplored. The global impact of these processes is unknown**

Gian Luca Delzanno, Joe Borovsky, Roger Varney, Natalia Buzulukova, Barbara Giles, Jeremy Dargent, Mei-Yun Lin

See Cold Plasma FG sessions: today - 1330-1530, 1600-1800 CT
Tuesday 1000-1200 CT



Geospace is a ***complex*** system

It is strongly coupled across domains and scales

Treat geospace as a whole:

- Inner and outer magnetosphere
- Ionosphere
- Thermosphere
- Atmosphere

"The tyranny of scales"

Incomplete physics

Missing parameterizations

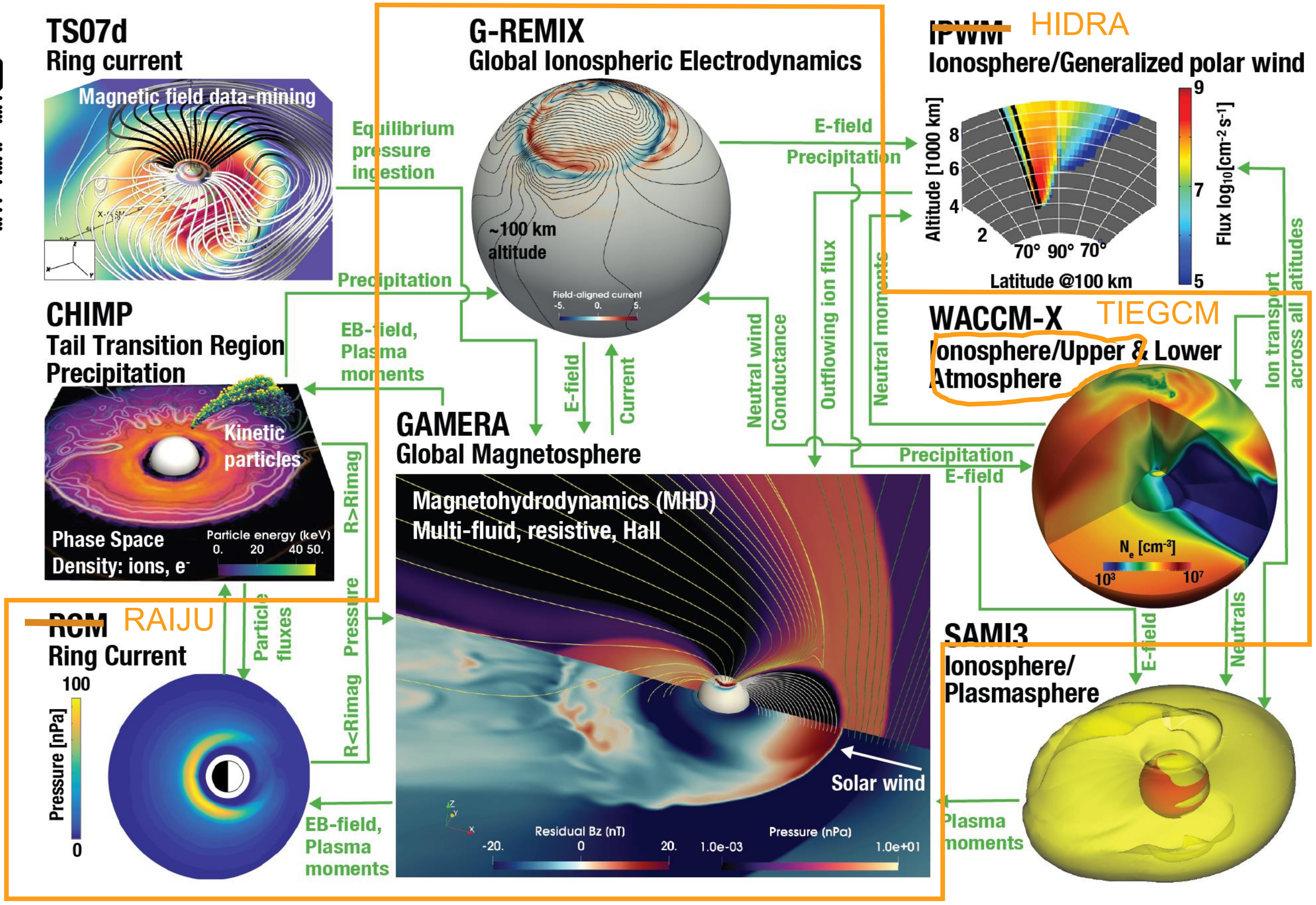
Poorly constrained initial & boundary conditions

Characterizing and predicting this system entirely from first principles is not possible

Credit: MAGE model simulation by CGS, animation by NASA/SVS

Multiscale Atmosphere-Geospace Environment (MAGE)
See Workshop: Thursday 1000-1200 CT

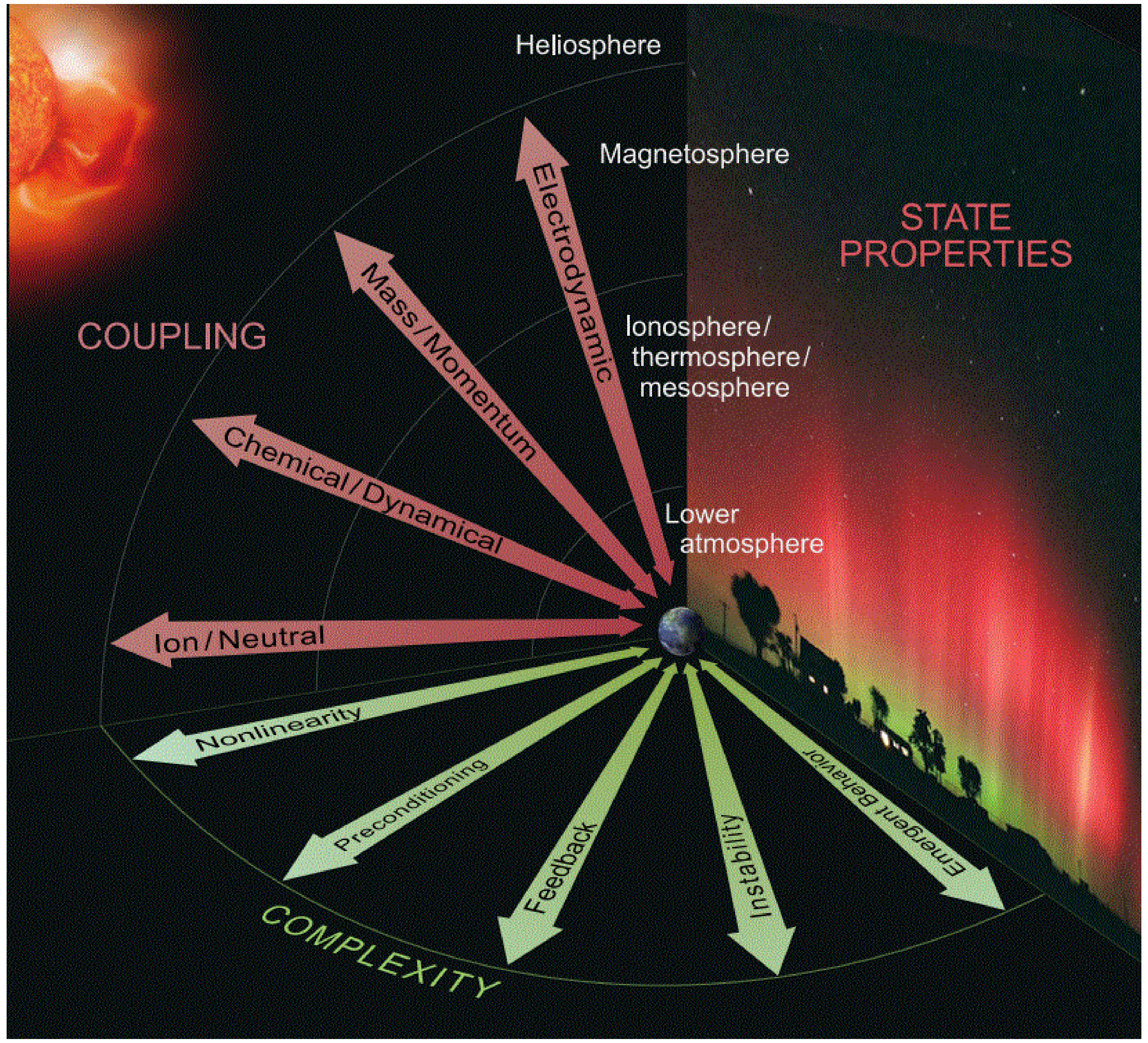
- MAGE 0.75 (GAMERA+REMIX+RCM)
  - Available for runs on request at the NASA CCMC
- MAGE 1.0 (GAMERA+REMIX+RCM*+TIEGCM)
  - Science production since 2020
  - Delivered to CCMC
  - Expect runs on request and OSS release **this month**
- Data-Model Fusion:
  - Use spacecraft constellations and remote-sensing
  - Leverage better near-Earth coverage
  - Leverage historical data



CEDAR: The New Dimension (2011 NSF strategic vision)

"In this document, no specific questions are posed; that is left to the research community to formulate and propose. Instead, a new paradigm in CEDAR research is presented…"

- Motivated the proactive development of a systems science perspective to study the upper atmosphere
- Expanded the CEDAR program scope beyond the traditional focus on *coupling* (between regions, constituents, and processes) to include system *complexity*



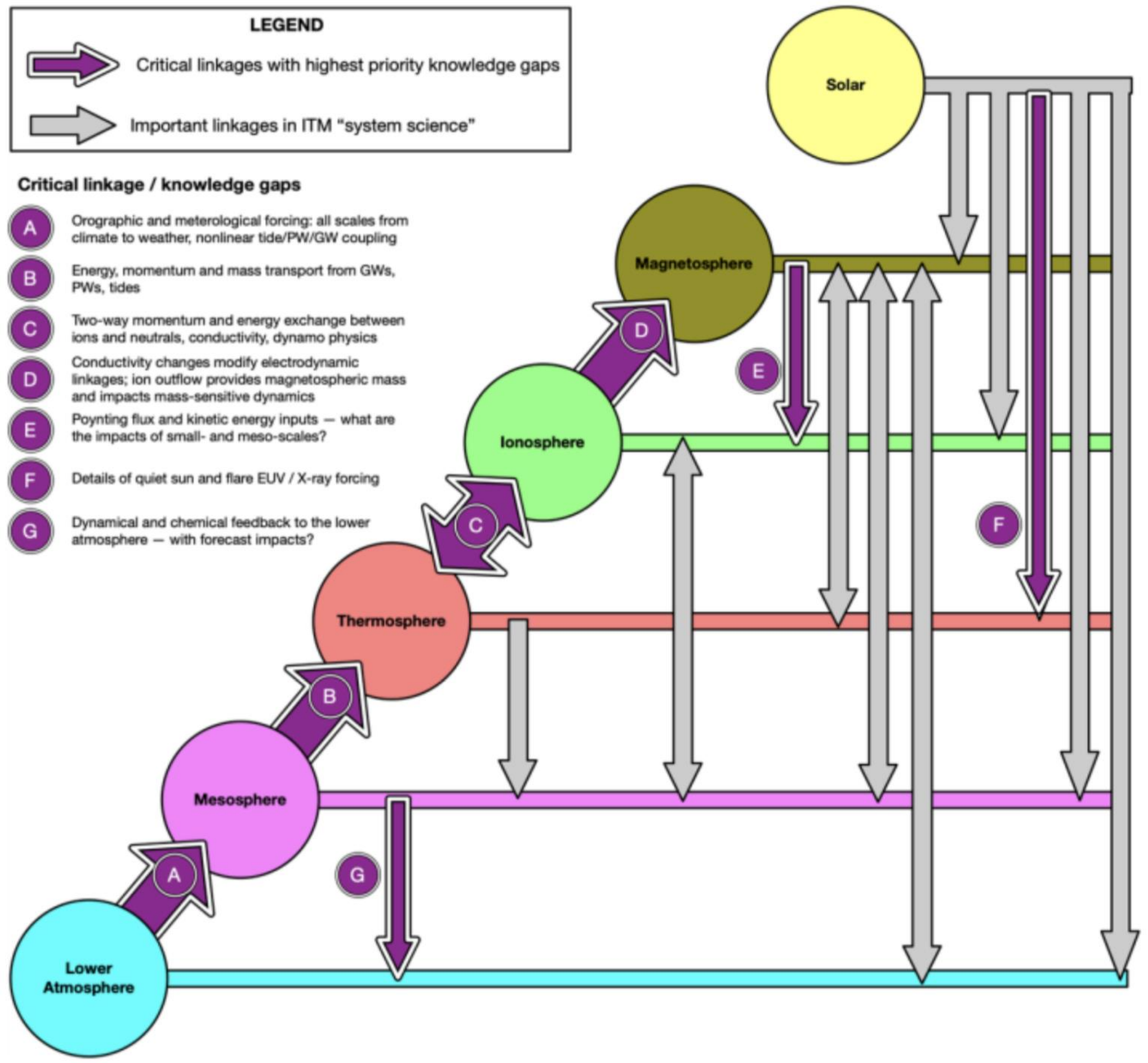
Overarching Goal of ITM Science in the next decade

Embrace a "systems" perspective as an enabling paradigm for understanding complexity in the ITM and in the geospace system in which it is embedded

ITM priority science goals are focused on:

1) processes that cross regions (altitude and latitude/longitude)
2) processes that cross scales (distance and time)
3) quantification of the relative significance of key driver/response relationships
4) the origin and impacts of persistent changes in the ITM state (slow evolution and state transitions)

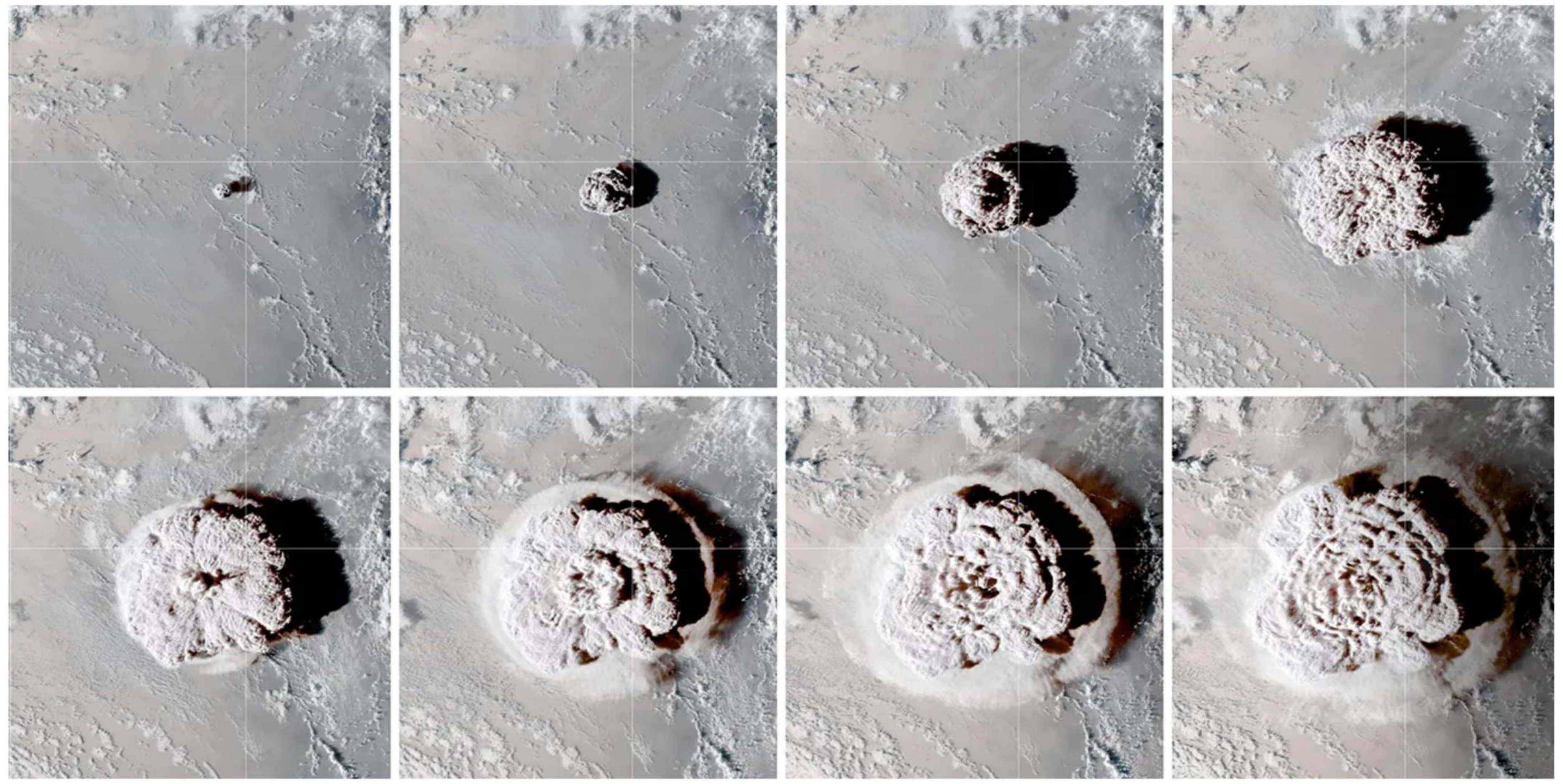
CROSS-REGIME / SYSTEM SCIENCE: SOME CRITICAL KNOWLEDGE GAPS



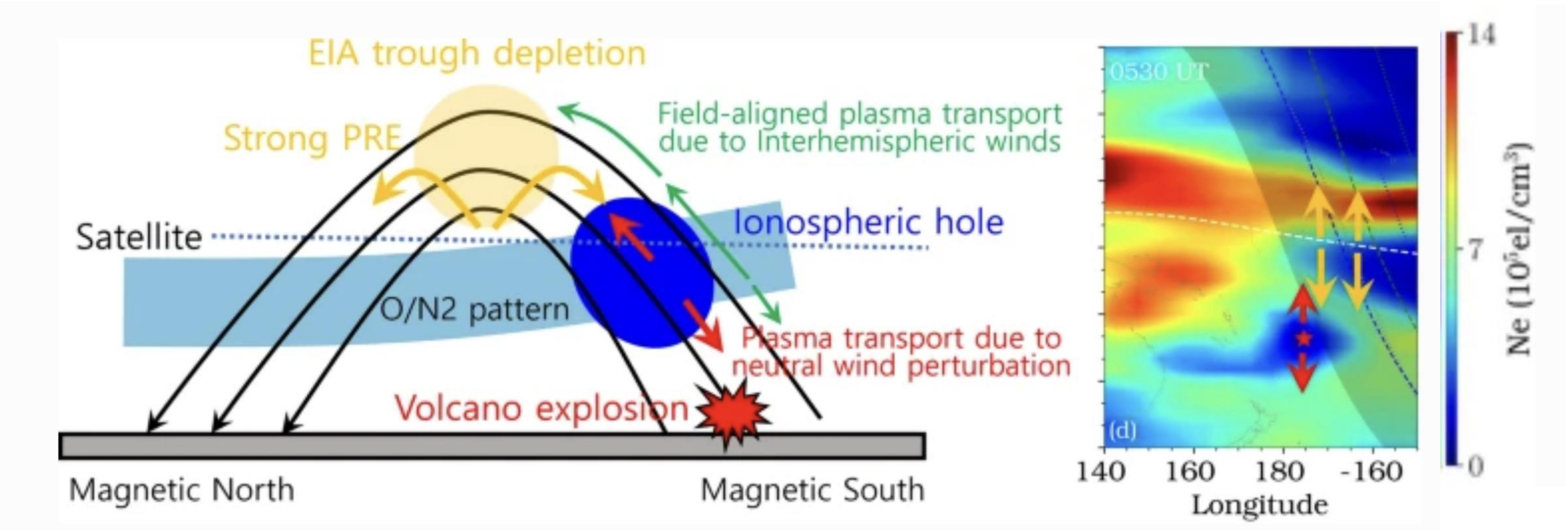
Rowland WP 347: "Cross-Scale and Cross-Regime Coupling in the ITM: Studying Weather, not just Climate, in the Middle and Upper Atmosphere

Impulsive events are opportunities to study complexity

- Geomagnetic storms
- Sudden stratospheric warmings
- Volcanic eruptions (e.g., Hunga-Tonga): Large atmospheric chemistry change + ionospheric depletions



A NASA satellite captured the explosive eruption of Hunga Tonga–Hunga Ha'apai in the South Pacific. Credit: Joshua Stevens/NASA Earth Observatory, using GOES-17 imagery courtesy of NOAA and NESDIS

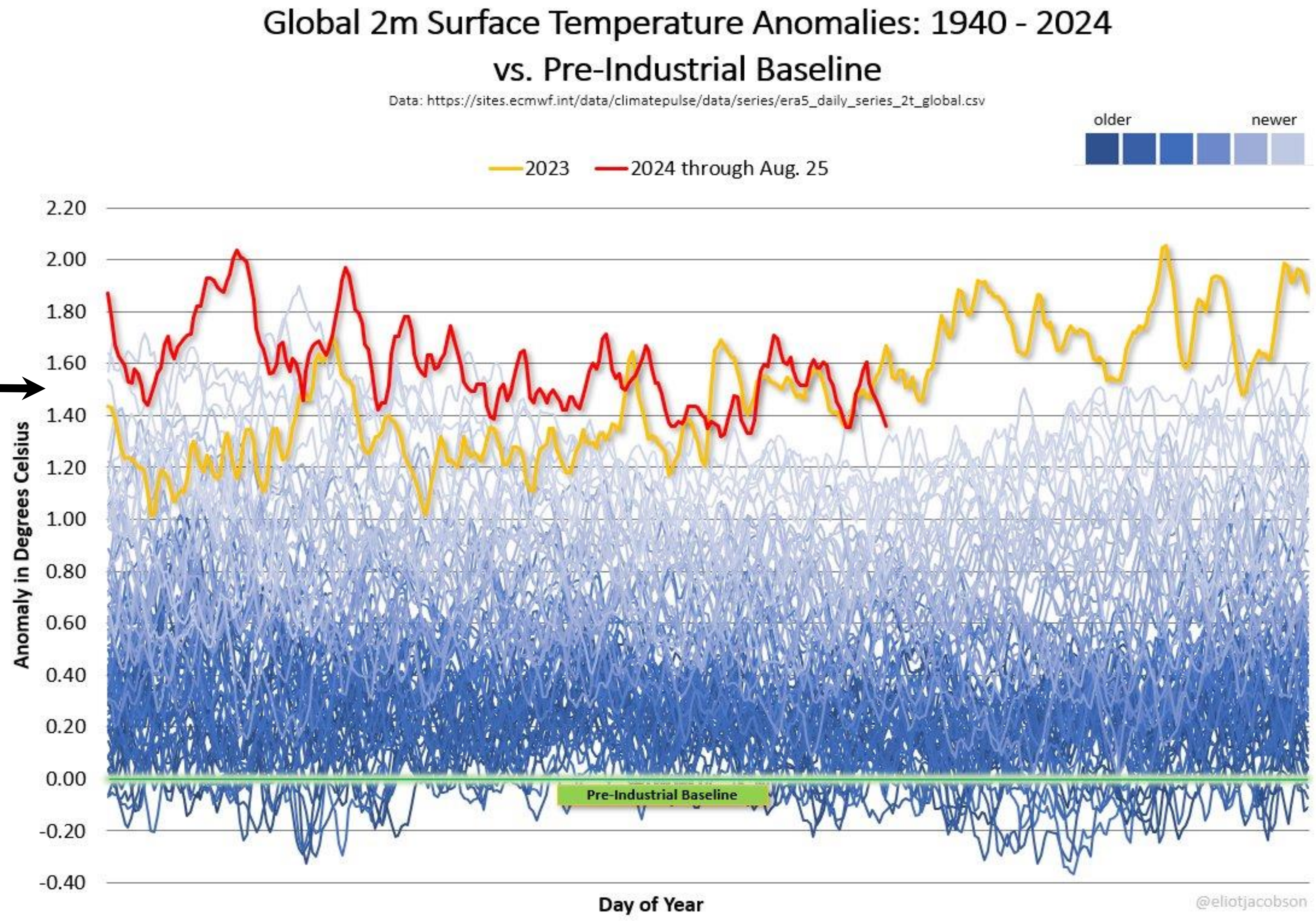


Choi et al., 2023

Geospace evolution is still poorly understood

- Detection of long-term variations in geospace system dynamics requires knowledge of the baseline state and continuous observational monitoring
- Evolution of complex dynamical systems is not always gradual, due to nonlinearity and feedbacks; physics-based modeling is needed to assess causality

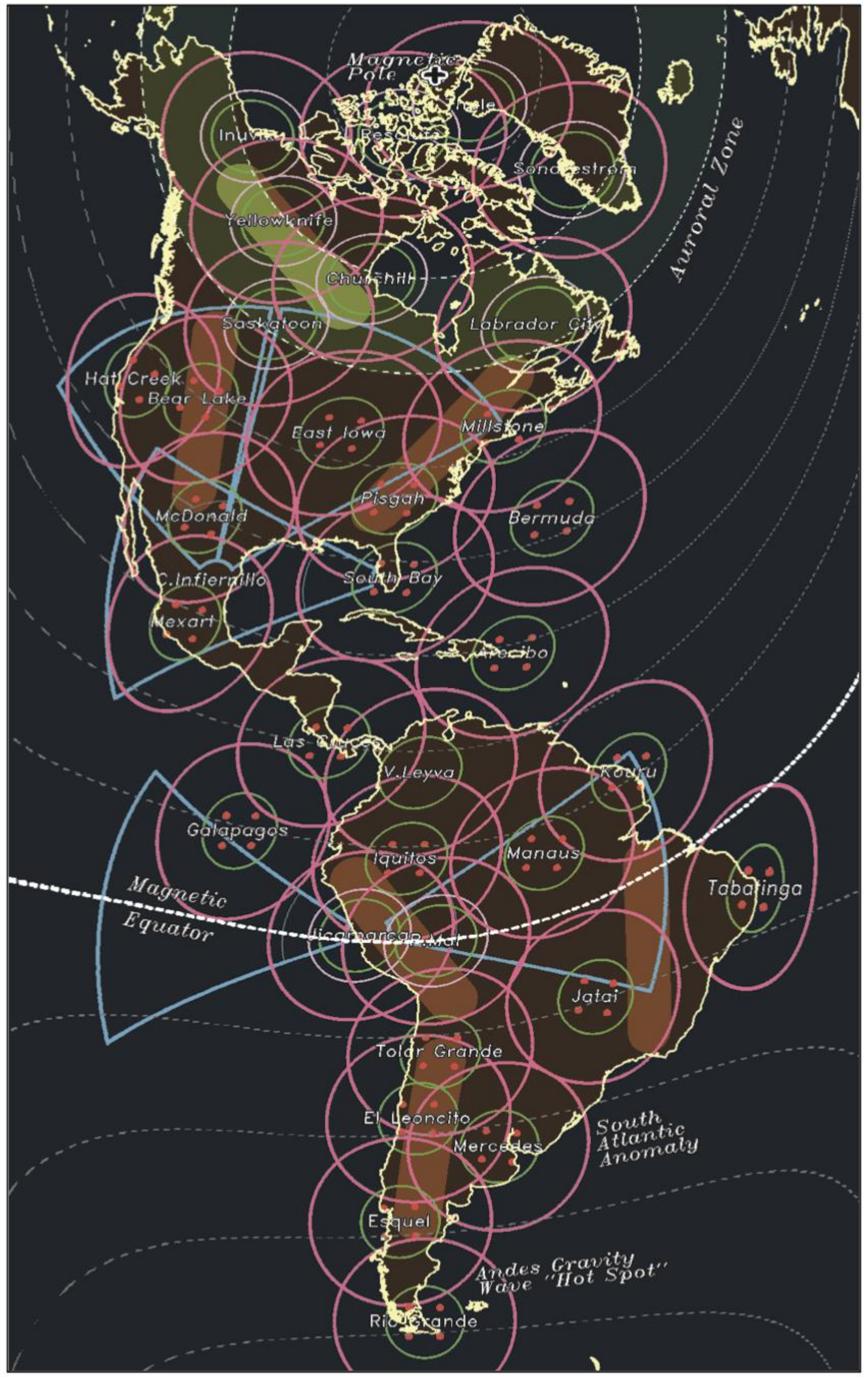
IPCC 1.5^{o} threshold



ITM ground-based network - notional concept: DASHI

- Implement a networked facility across the Americas
  - Observatories would host a baseline suite of heterogeneous, facility-supported sensors as well as accommodate hosted, PI-led instrumentation.
  - Use customized 8’x20’ shipping containers (standardized, easily deployed, and relocatable).
  - Low risk, shovel ready construction.
- Dedicated science support and management lead: streamline technical, logistical, and regulatory tasks, including systematic data archiving

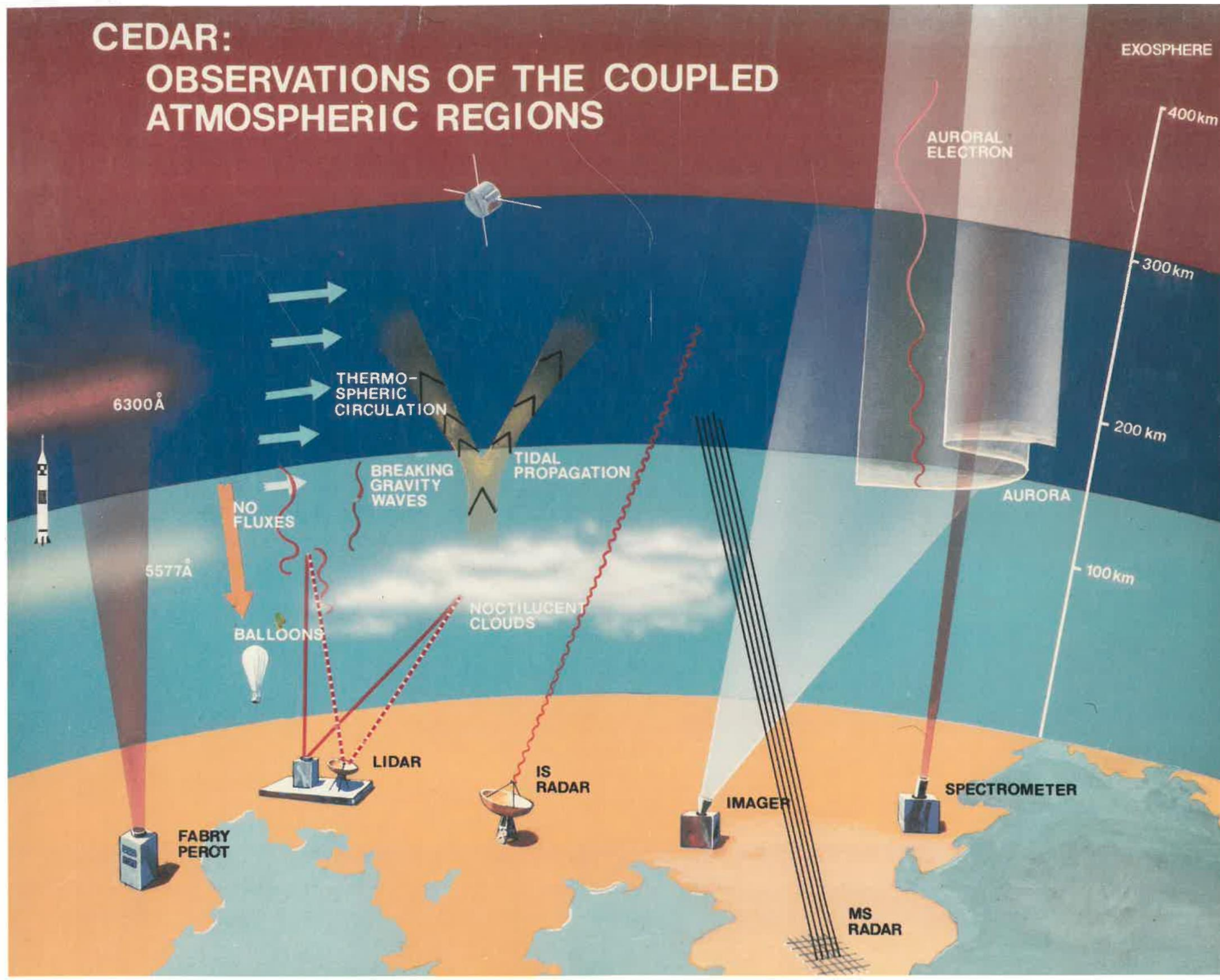
Figure 5: Fields of view (FoV) of the proposed observatories & instruments. Pink and green circles (projection distorted) indicate ground-based cameras imaging at 630 nm and 558 nm; four red dots indicate narrow-field FPI sampling; lilac circles denote SDI FoV; blue wedges show SuperDARN FoV; orange/green shadings denote the multistatic meteor radars FoV; and dashed contours show magnetic latitude.



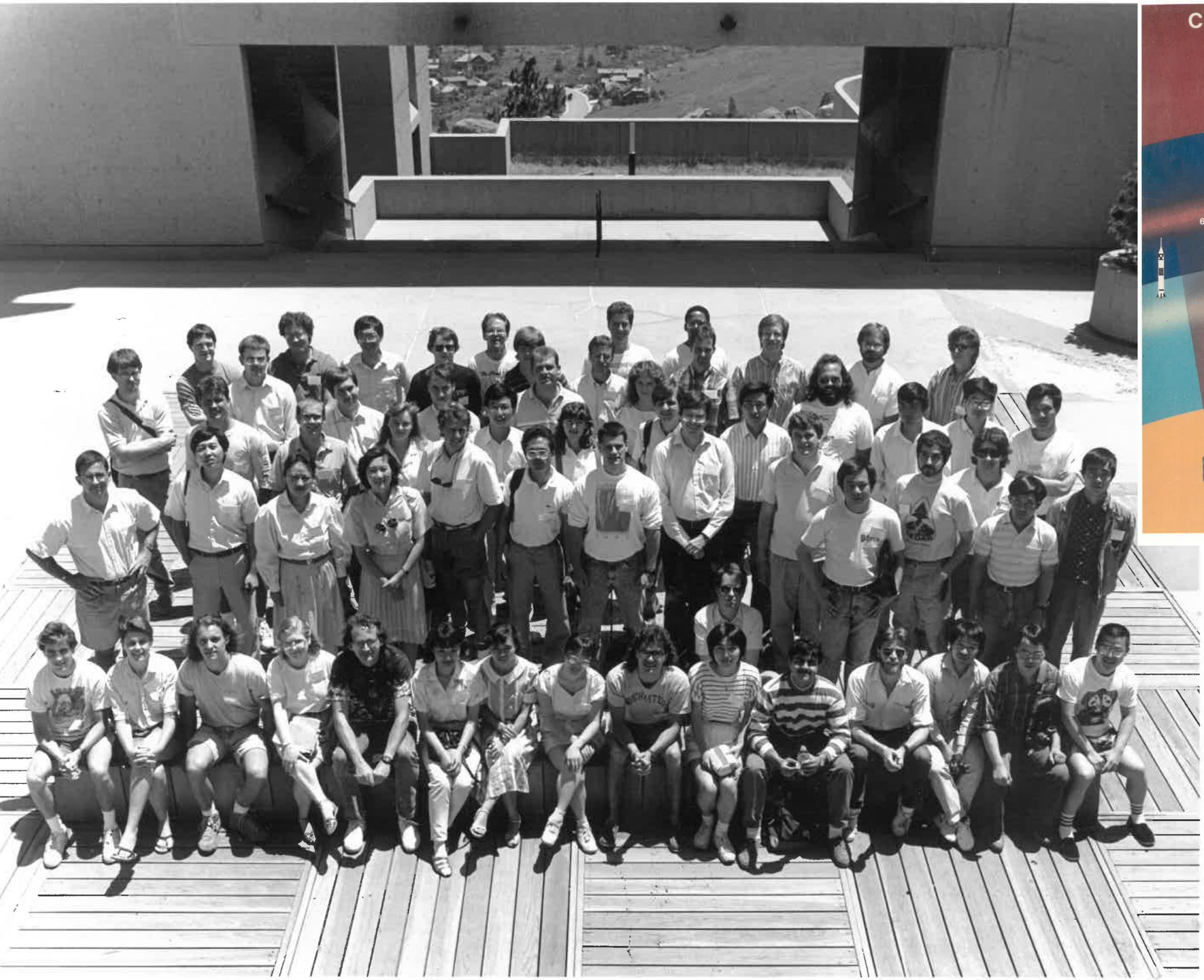
See
ITM Decadal workshop this afternoon
Monday 1330-1530

Community is Essential to Our Future
As Geospace Scientists…

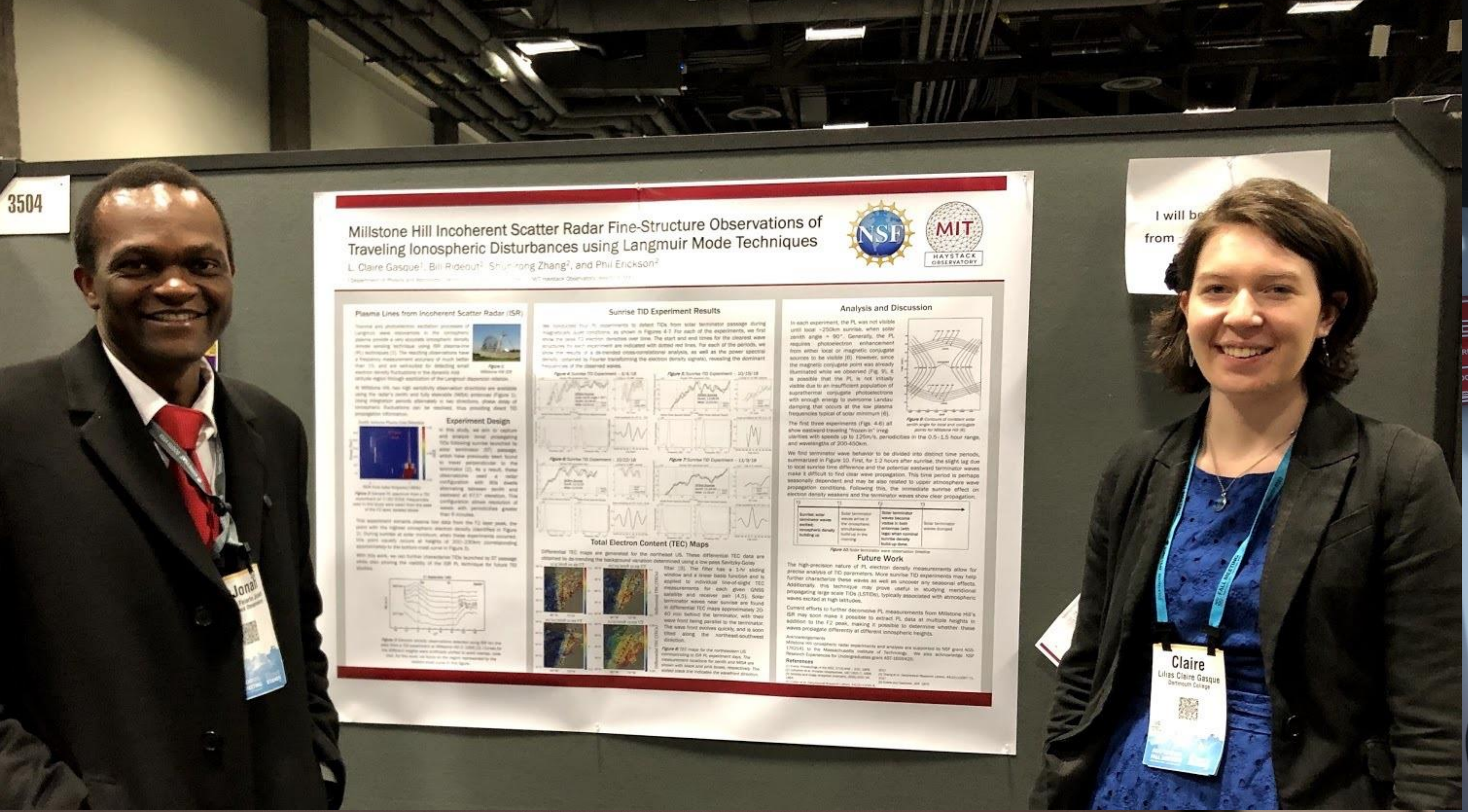
And Heliophysics is Fundamental to Society

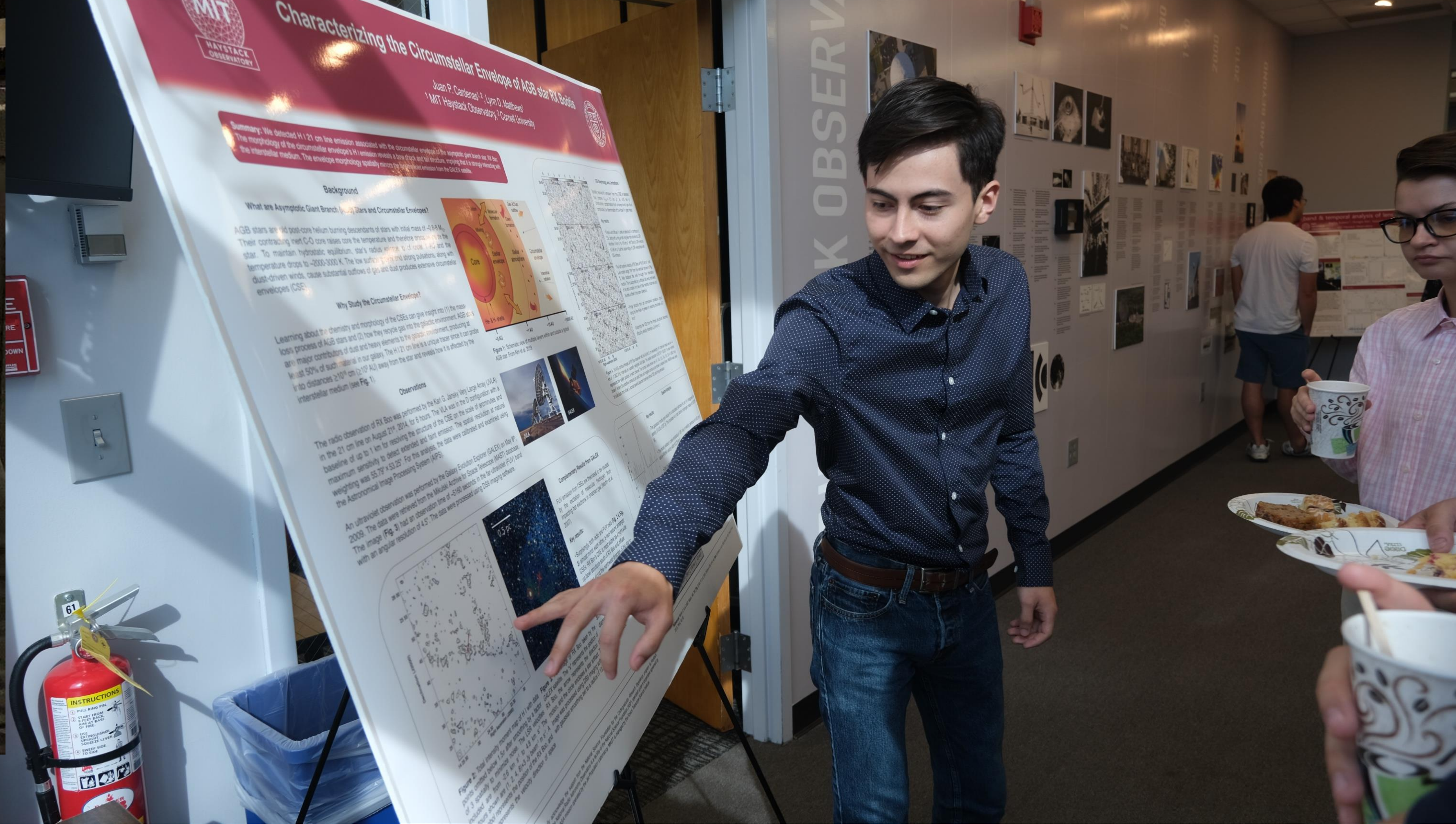


CEDAR report 1986



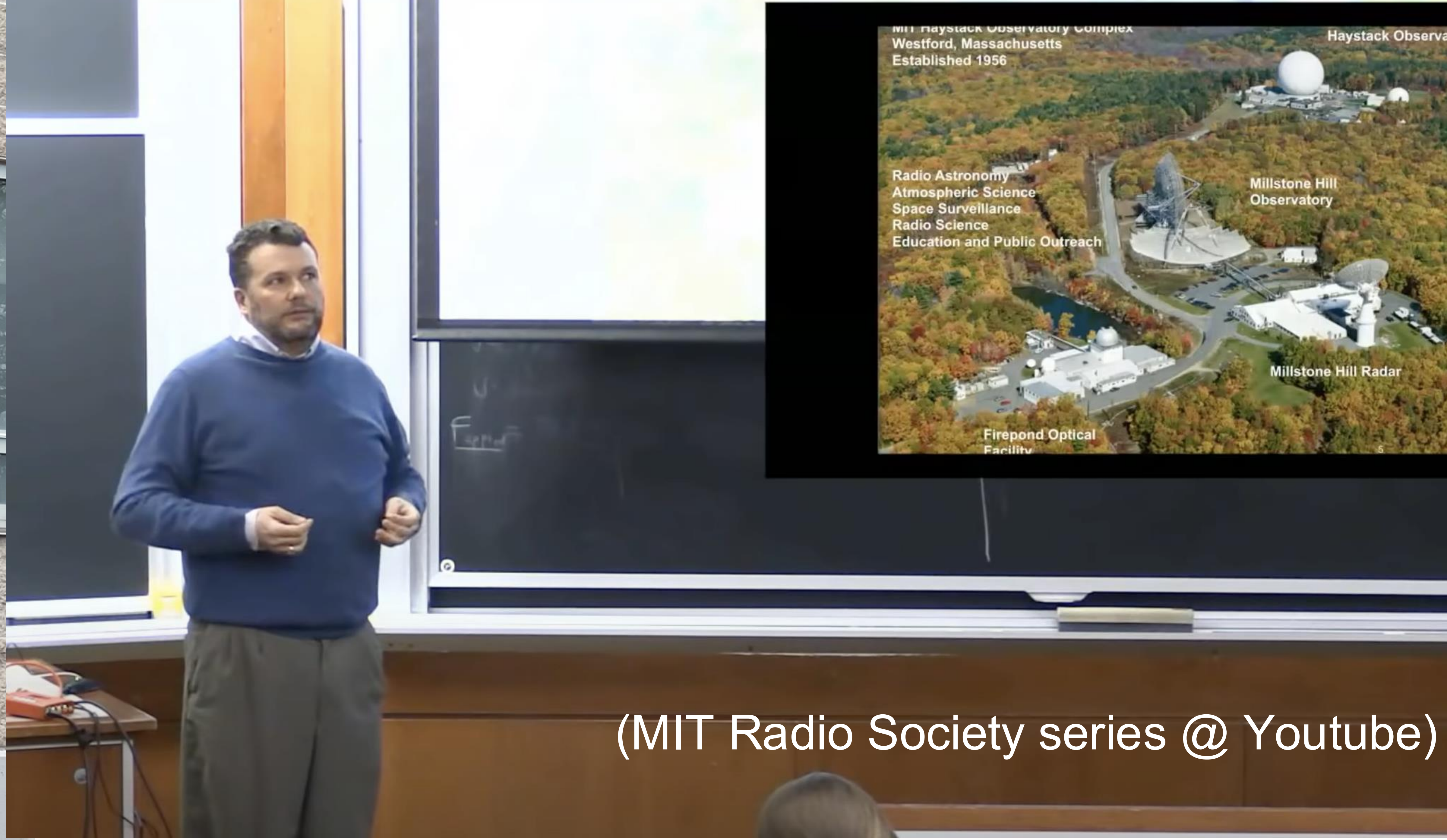
CEDAR students 1990


3504
Millstone Hill Incoherent Scatter Radar Fine-Structure Observations of
Traveling Ionospheric Disturbances using Langmuir Mode Techniques
NSF
MIT
HAYSTACK OBSERVATORY
Claire


Characterizing the Circumstellar Envelope of AGB star


ADVANCING
EARTH AND
SPACE SCIENCE


Isolating Solar Eclipse Features using
Supervised Machine Learning
Mateo Cardona Serrano (they/them)
NSF



(MIT Radio Society series @ Youtube)

Heliophysics is not just about studying the Sun.

It is about safeguarding the technological, economic, and exploratory frontiers that are vital to the future of the U.S.

Proposed FY26 cuts to NASA and NSF would be DEVASTATING to heliophysics research and cede our leadership in this critial area to China.

FY26 funding required: NASA: $25.5B (SMD: $7.5B, Heliophysics: $850M)
NSF: $9.9B

Why Heliophysics Matters

Space Weather Prediction

Heliophysics research is crucial for understanding and predicting space weather events such as solar flares and coronal mass ejections (CMEs). These events can disrupt satellite operations, GPS navigation, power grids, and even pose risks to astronauts in space.

National Security

The U.S. military relies on space-based technologies for communication, navigation, and surveillance. Accurate space weather forecasts help protect these systems from disruptions caused by solar storms.

Protection of Infrastructure

Solar storms have the potential to cause large-scale power outages by damaging transformers and electrical grids. Investing in heliophysics helps develop early warning systems to mitigate such risks.

Advancing Space Exploration

As the U.S. prepares for missions to the Moon, Mars, and beyond, understanding the space environment is critical to ensure the safety of astronauts and the success of deep space missions.

Technological Advancements

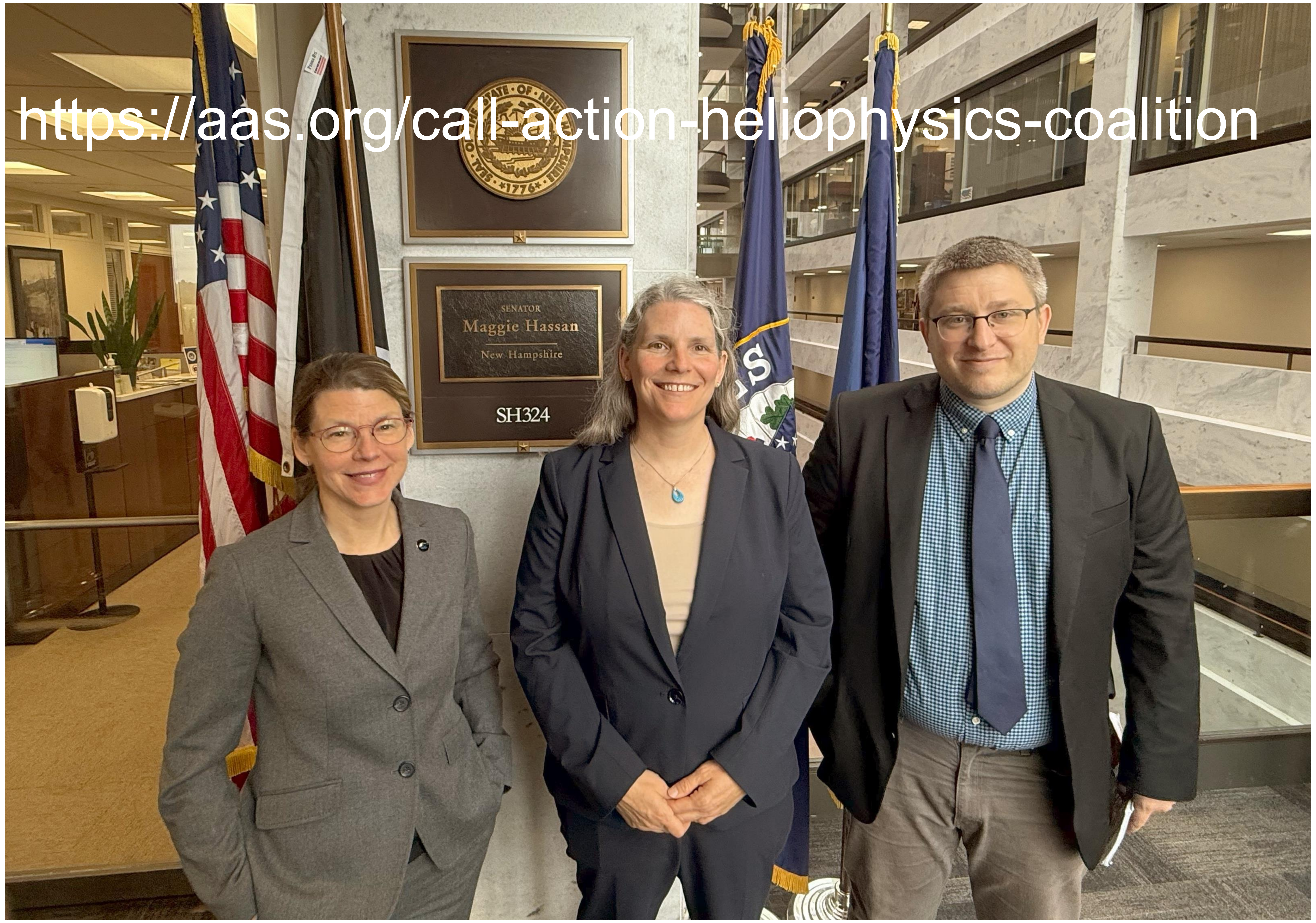
Heliophysics research drives innovation in satellite technology, sensors, and communication systems, fostering scientific and technological advancements with broader applications.

Future Modeling and Planning

Studying the Sun's behavior helps researchers better understand how it influences weather patterns and long-term trends on Earth, leading to more accurate forecasting and planning.

Heliophysics is the study of the Sun and its interactions with the Earth and the rest of the solar system, including the solar wind, magnetic fields, and space weather. It combines aspects of solar physics, space physics, and geophysics to understand how solar activity affects the space environment around our planet and beyond. It is funded by both NASA and the NSF.

AGU ADVANCING EARTH AND SPACE SCIENCE | Heliophysics Coalition | AAS AMERICAN ASTRONOMICAL SOCIETY



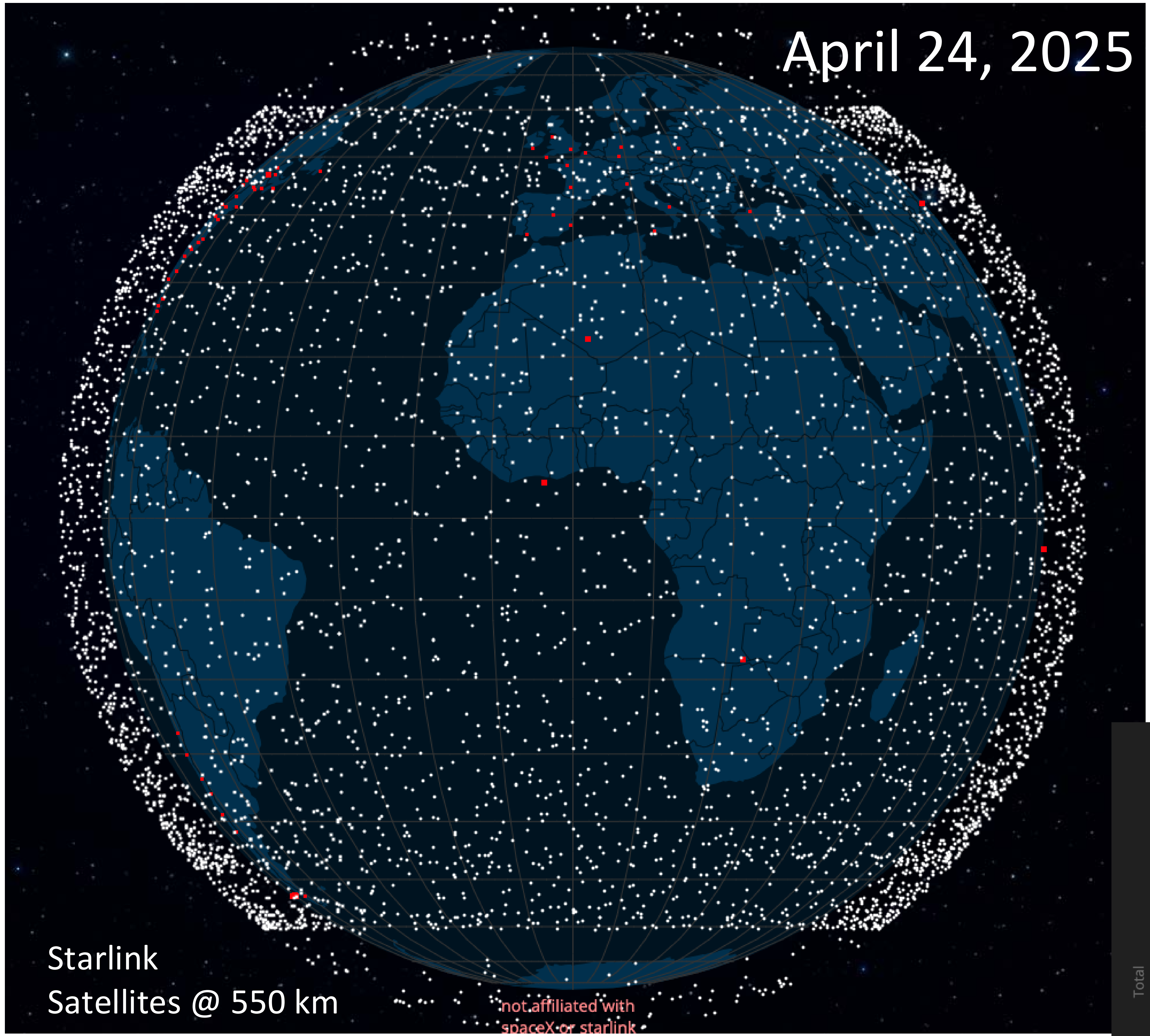
30 MAY 2025

Scientific Societies Issue Letter to Congress Regarding National Science Foundation Reorganizations and Cuts

A coalition of professional societies and organizations whose members conduct research in fields supported by the National Science Foundation (NSF) today issued a letter to the United States Congress. The letter expresses support for the NSF and concern about recent organizational and financial developments at the agency.

(See Friday townhall 1215-1315 CT)

Example: The societal challenge of low Earth Orbit



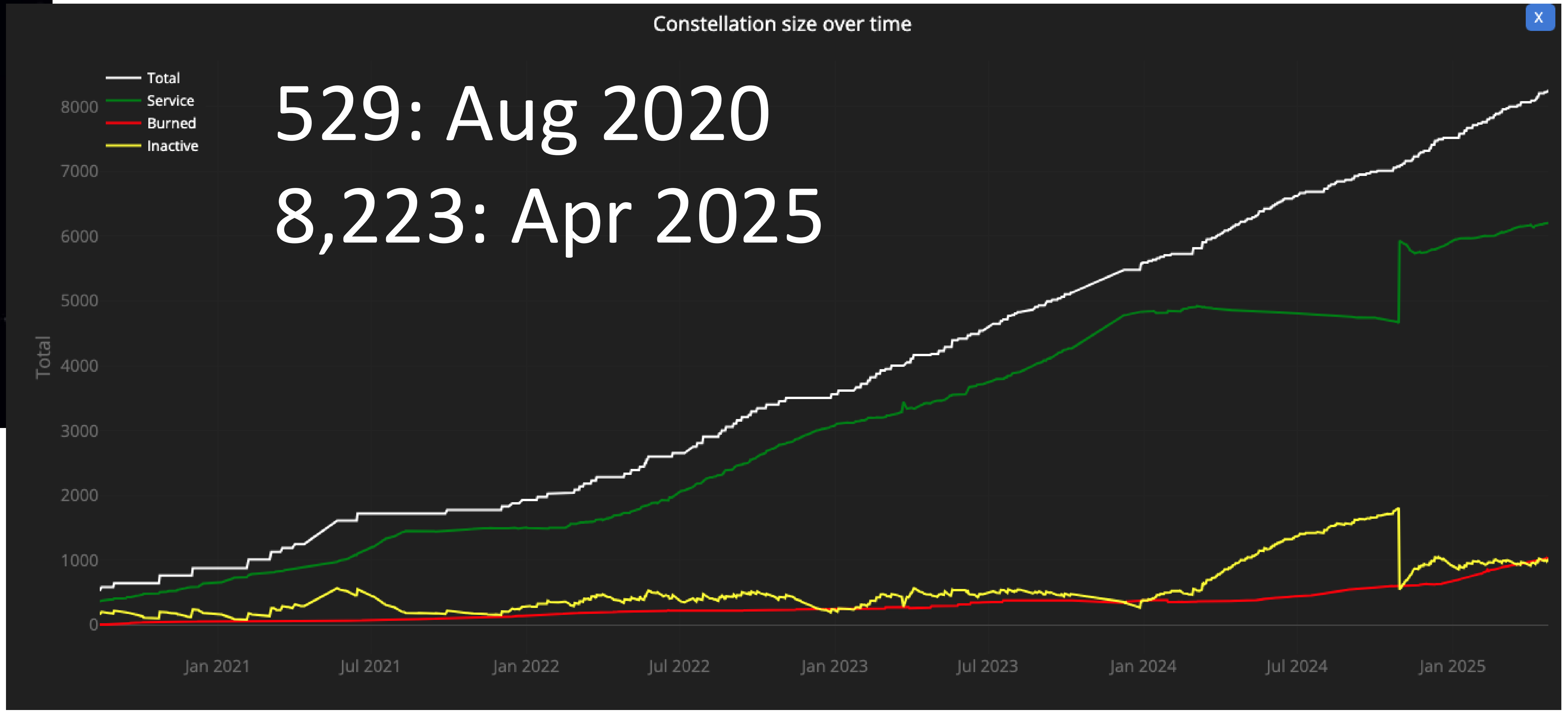
(satellitemap.space)

Low Earth orbit is becoming very crowded with commercial satellites alongside traditional government ones

Risk of debris belt from collisions is growing fast!

Debris moves ~km/sec (> 3000 mi/hr): destructive potentials from even <cm size particles

Understand the space environment: space weather!



MIT HAYSTACK OBSERVATORY

Final thoughts:

We are just getting started with an exciting system scale understanding of geospace

This takes every tool we have to unlock insight

Community is fundamental: we will persevere - <u>together</u>

NSF CEDAR GEM Geospace Environment Modeling

Thanks for listening